UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

External Memorandum No. M-168

SUSPENDED SEDIMENT SAMPLING IN FLOWING WATER: LABORATORY STUDY OF THE EFFECTS OF NOZZLE ORIENTATION, WITHDRAWAL RATE AND PARTICLE SIZE

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February, 1983
Minneapolis, Minnesota

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LIST OF SYMBOLS AND ABBREVIATIONS

a = acceleration, isokinetic proportionality factor, particle radius

A = projected area of particle

A_n = cross-sectional area of sampling nozzle

A_s = cross-sectional area of sampled stream tube

C_D = drag coefficient

C_n = sampled particulate concentration

C_s = particulate concentration in sampled stream

d_n = diameter of nozzle opening at mouth of nozzle

d_s = diameter of the sampled stream tube

d_{50} = median diameter of particles

F_D = drag force

L = characteristic length

L_s = stop distance of a particle

m = mass of particle

Q_n = volumetric flow rate through the nozzle

Q_s = volumetric flow rate in the sampled stream-tube

Re = Reynolds number

St = Stokes number

t = time

u_n = fluid velocity at sampling nozzle entrance

u_p = particle velocity

u_{p_i} = particle velocity at time, t=i

u_s = stream velocity

V = particle volume

α = parameter related to particle stopping distance

β = function of St and u_s/u_n

Δ = increment

μ = dynamic viscosity

ν = kinematic viscosity

ρ_p = density of particle

ρ_f = density of fluid

τ = particle relaxation time

I. INTRODUCTION

Accurate measurement of suspended particulate matter in a fluid stream is important in industrial operations and environmental investigation. For example, a civil engineer needs to know the amount of suspended sediment in a river to predict the effective life of a reservoir or to determine if the river water can be used for irrigation. A chemical engineer measures suspended particulate matter in a pipe to monitor manufacturing processes. A plant manager needs to know how much particulate matter is leaving a smokestack to be able to meet environmental standards.

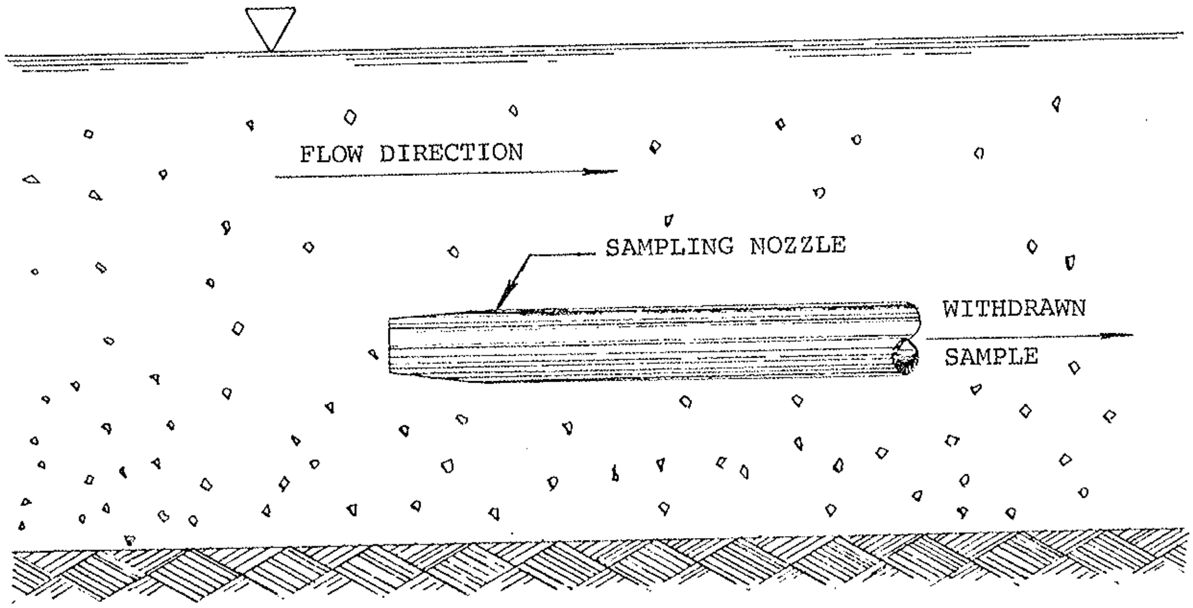
The goal of most particulate-fluid sampling programs is to obtain a representative specimen of the sampled particulate-fluid stream for analysis. To meet this goal, four requirements must be satisfied: (1) particulate concentration in the sample must be the same as in the sampled stream at the location the sample was taken and at the time it was taken, (2) various types of particulates moving past the sampling location at the time the sample was taken must be represented in their correct proportions, (3) size distribution of the various particulates must be the same in the sample as in the sampled stream at the location the sample was taken and at the same time the sample was taken, and (4) enough points must be sampled to describe the variation of particulate concentration in the flow and to obtain an accurate average particulate concentration.

Sampling methodology for particulate-fluid sampling consists of three phases: collecting the sample, accumulating and/or storing the sample, and analyzing the sample. For example, in measuring suspended sediment in a river, the sample of river water is collected through a nozzle and transported through a tube or pipe to a bottle or other container where it is stored for later analysis. Each phase of the sampling methodology can introduce errors into the sampling process. For example, the nature and amount of particulates in the sample can change while it is being collected and stored because of chemical reactions or physical interactions between the particles such as flocculation. Particulates may be lost or missed when the sample is analyzed.

A common method of collecting a sample from a particulate-fluid stream is to withdraw part of that sample through a nozzle as illustrated in Fig. I-1. Errors can be introduced into the sampling process by the nozzle design and construction, its orientation and location in the sampled particulate-fluid stream, and the ratio between the fluid velocity in the stream and the fluid velocity in the nozzle entrance. The errors introduced because of the orientation of the nozzle in the sampled stream are the subject of this study.

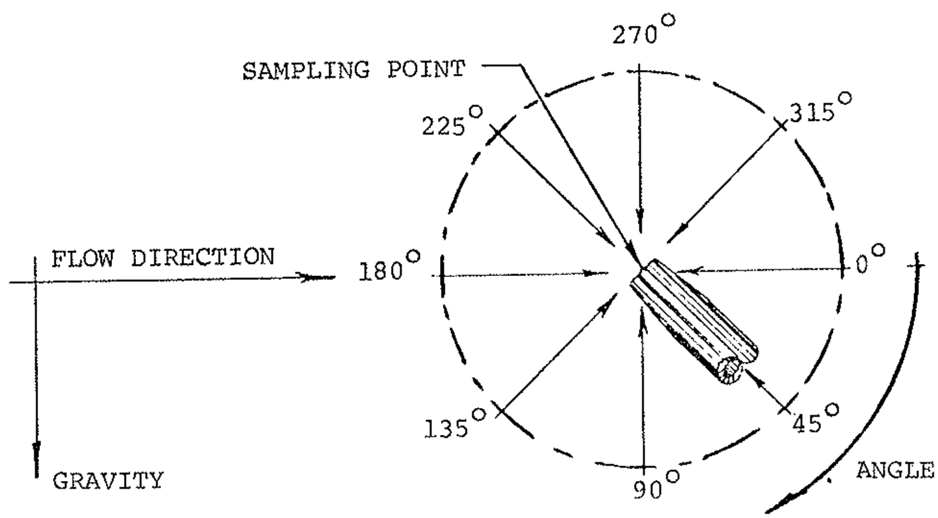
Previous research has shown that if the nozzle is not properly oriented so that it faces into the fluid flow and is aligned parallel to the fluid flow, considerable error is introduced into the sampling process (Federal Interagency Sedimentation Project, 1941). The research that has been done to determine the magnitudes and types of errors because of improper orientation is limited. Presently estimates of the error because of improper nozzle orientation cannot be made. This is a serious deficiency because it is not always possible to have the nozzle oriented upstream. For example, automated pumping samplers are being increasingly used to sample streams and sewers because they can sample unattended for extended periods of time. The sampling nozzle, however, is easily clogged by debris so that no sample can be taken. To alleviate this problem the sampling nozzle is often turned to face downstream on the principle that an inaccurate sample is better than no sample at all (Beschta, 1980).

It was the purpose of this research study to investigate the errors caused by nozzle orientation for three sizes of quartz sand in water and one set of flow parameters. Eight orientations of the nozzle with respect to the flow were studied. They are 45 degrees apart around a horizontal axis as shown in Fig. I-2. It was also the purpose of the research to determine, if possible, some of the more important physical parameters affecting the type and magnitude of the errors.



Schematic of a common method of collecting particulate-fluid samples with a nozzle.

FIGURE I-1



The eight nozzle orientations used in the study.

FIGURE I-2

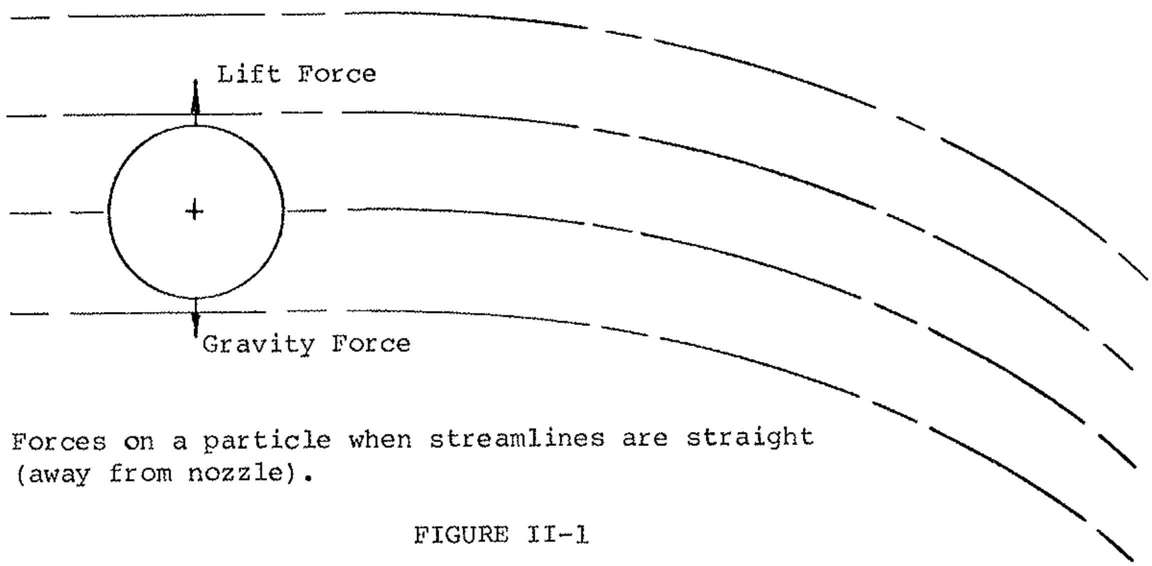
II. ANALYSIS AND LITERATURE REVIEW

A particle suspended by a fluid is subjected to several forces including a drag force, a lifting force due either to the particle's rotation or to the velocity gradient across the particle, and body forces such as gravitational or magnetic forces. The prime moving force on the particle is the drag force applied to the particle by the moving fluid (Soo, 1967).

Soo (1967), in a discussion of the drag force and other forces acting on the particle, listed the following fluid and particle parameters affecting the forces on a suspended particle: (a) fluid parameters: fluid density and viscosity; velocity, pressure, temperature, and density gradients in the fluid; fluid turbulence; and scale of turbulence, and (b) particle parameters: size, shape, and orientation of the particle; particulate concentration and concentration gradients; particle clouds; wall effects; and translatory, oscillatory, and rotational movement of the particle.

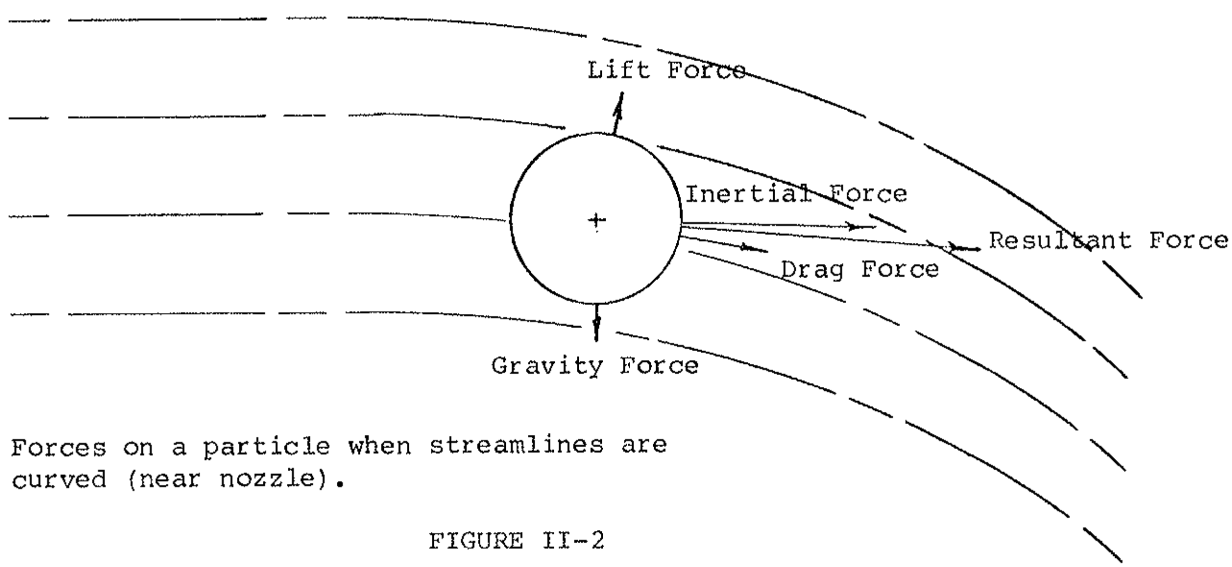
It is outside the scope of this discussion to consider all of these fluid and particle parameters in an analysis of particle movement near a sampling nozzle. For the purpose of making some qualitative observations about the motion of a particle in the fluid stream being withdrawn through a nozzle, a simplistic model will be derived based upon the following assumptions. The particle is a non-rotating sphere of uniform density and surface roughness. The fluid is irrotational, incompressible, and has uniform viscosity and density. The turbulence of the fluid is ignored except that the effect of the turbulence in suspending the particle will be included in a "lift" force that also includes the effects of a velocity gradient across the particle. The streamlines are assumed to be straight and parallel. The particle is close to the nozzle and is moving along the streamline at the velocity of the fluid. The fall velocity of the particle is balanced by the "lift" force on the particle. The force balances are summarized in Fig. II-1.

If the streamlines curve, the force balance changes as shown in Fig. II-2. The force on the particle due to its inertia is directed



Forces on a particle when streamlines are straight (away from nozzle).

FIGURE II-1



Forces on a particle when streamlines are curved (near nozzle).

FIGURE II-2

along its old path while the direction and magnitude of both the "lift" force and drag force change. The direction of the gravitational force remains unchanged. A summation of the force vectors shows that the resultant force on the particle is directed along a line between the particles old path and the direction of the streamline. Consequently, the particle is unable to follow the streamline and instead begins to cut across the streamlines.

In the following analysis the gravity and lift forces are assumed to be constant in both direction and magnitude. The direction the particle moves in will then be determined by the respective magnitudes and directions of the inertial and drag forces acting on the particle. The inertial force is a function of the particle mass and velocity. For a given particle, the mass varies as the cube of the particle's diameter. Therefore, as either the particle size or velocity increases, its inertia increases.

The drag force is a function of the particle diameter, the viscosity and density of the fluid, and the relative velocity of the fluid in relation to the particle velocity. The relationship between the drag force and the fluid and particle parameters is complicated and usually related by a drag coefficient (C_D) versus Reynolds number (Re) diagram (Olson, 1966; Soo, 1967).

To illustrate the relationship between particle size, particle mass, and the inertial and viscous forces, the particle velocity was calculated as a function of time for three sizes of quartz sand, $d_{50} = 0.1, 0.01, 0.001$ mm. The following equations were used in an iterative process in the order given.

1. Reynolds number $$Re = \frac{(u_s - u_{p_i})\ d_{50}}{\nu} \qquad (1)$$

2. Drag coefficient $$C_D = \frac{24}{Re}\left(1 + \frac{3}{16}\ Re\right)^{1/2} \qquad (2)$$

3. Drag $$F_D = C_D\ \rho_f\ \frac{(u_s - u_{p_i})^2\ A}{2} \qquad (3)$$

4. Acceleration of particle $$a = \frac{F_D}{m} \qquad (4)$$

5. Particle velocity $$u_{p_{i+1}} = a\Delta t + u_{p_i} \qquad (5)$$

where u_s = stream velocity (0.61 m/s or 2 ft/s, for this sample comparison)

u_{p_i} = particle velocity at time t=i

$u_{p_{i+1}}$ = particle velocity at time t=i+1

ν = kinematic viscosity of fluid (1.004×10^{-6} m^2/s @ $20^{\circ}C$)

A = projected area of particle

ρ_f = density of fluid (998.20 kg/m^3 @ $20^{\circ}C$)

m = mass of particle = $V\rho_p$

V = particle volume

ρ_p = particle density (2645.23 kg/m^3)

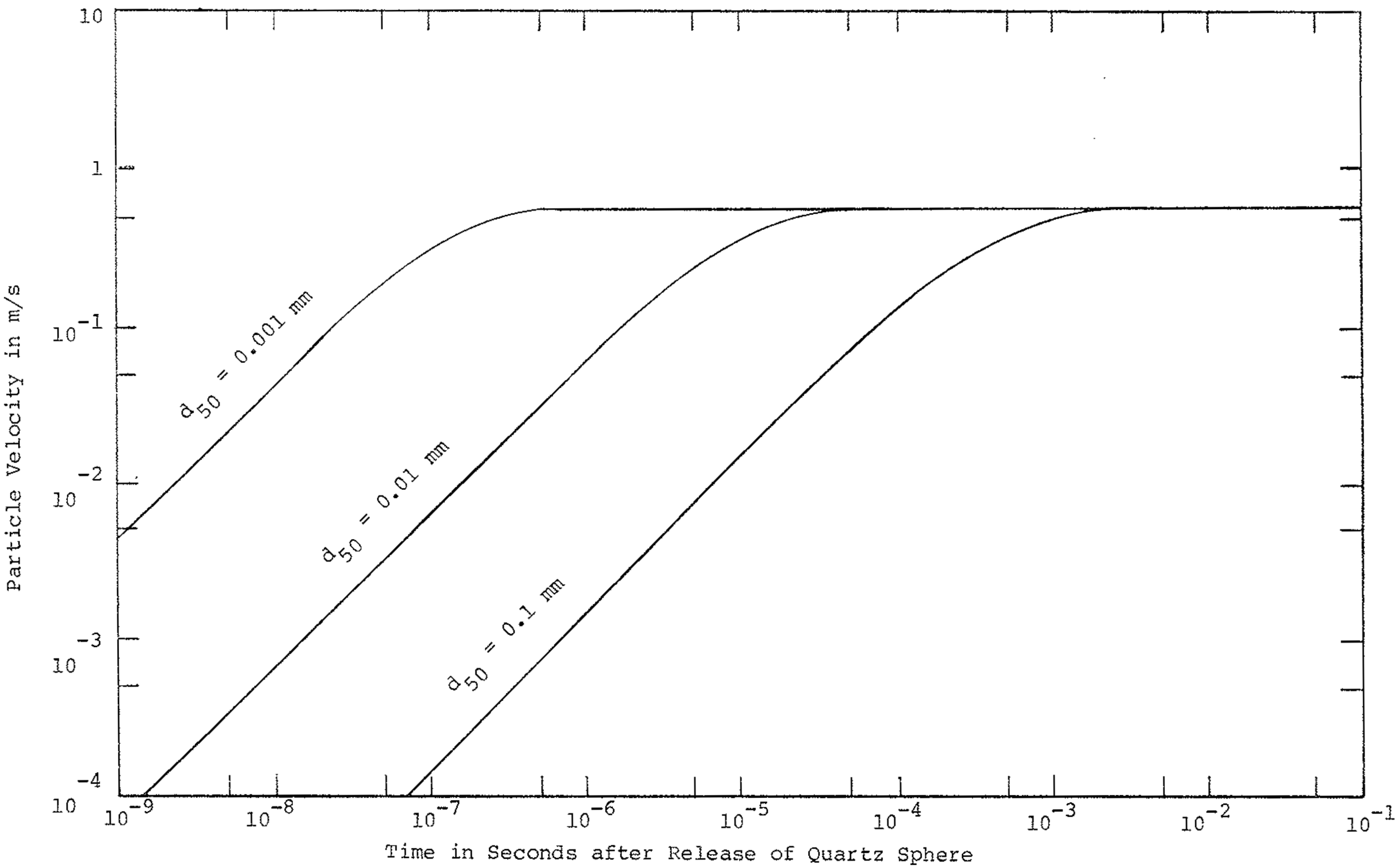
Δt = time increment

The equation for the drag coefficient is given in Olson (1966, p. 422) as an approximation valid up to Re = 100 for spheres. The time step Δt varied between 1×10^{-6} sec to 1×10^{-3} sec. The particle was assumed to have been released from rest into a moving water stream with a velocity of 0.61 m/s (2 ft/s) at time, t=0.

The resulting curves are shown in Fig. II-3. The ratio between particle inertial resistance to motion and the viscous drag force applied to it as measured by the Reynolds number decreases as particle diameter decreases; all other variables are held constant. As shown in Fig. II-3, the particle with the smaller diameter responds more quickly to changes in the fluid velocity than to the particle with the larger diameter. Extending this reasoning, one is led to look for a limit below which inertial forces would not affect the motion of the particle. That limit is somewhat ambiguous. In air pollution analysis it is set at 1 μm (3.94×10^{-5} in.) for aerosols (Raynor, 1970).

Based upon the work of the Federal Interagency Sedimentation Project (FIASP, 1941, p. 4), quartz particles less than about 10 μm ($3.94*10^{-6}$ in.) in diameter act like a molecule of water in responding to changes in velocity in the water.

The foregoing discussion was based upon the assumption that the particles were spheres. Real particles are not uniform spheres of uniform density and the response of real particles to changes in velocity



Calculated increase in velocity of 3 sizes of quartz spheres released into moving water from rest. Velocity of water is 0.61 m/s (2 fps).

FIGURE II-3

of the fluid will be different from that shown in Fig. II-3. The drag force exerted on the particles will be dependent upon the size of the particle, its shape, its orientation to the flow, and its angular and translatory motion relative to the motion of the fluid. However, the results of the above analysis indicate the basic trends of the particle reactions and should be a fairly accurate representation of what the particle reaction to changes in fluid velocity will be.

If the velocity vector of the fluid changes in either magnitude or direction, the response of the particle depends upon its size and mass. In general, as a particle size decreases, its response to changes in the velocity vector of the stream occur more quickly. For different types of particles of the same size, less massive particles respond more quickly to changes in the velocity vector.

Therefore, if the fluid streamlines are forced to curve because of the sampling process, two things will happen to the sampled particulate concentration: (1) since not all particles will be able to follow the streamlines, the measured concentration will be different from the actual concentration in the fluid stream, and (2) since smaller or less massive particles are able to follow the streamlines more closely than larger or more massive particles, both the size distribution and particle type distribution will be different from that in the fluid stream.

Two cases where the streamlines are forced to curve during the sampling process will be discussed. In each case the assumption will be made that the undisturbed streamlines are straight and parallel and the particles are following the fluid streamlines.

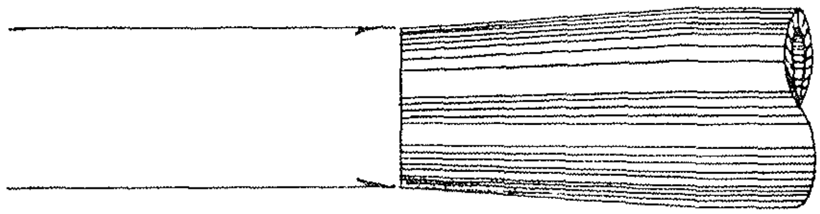
In the first case to be considered, the sampling nozzle is aligned with the flow and pointing directly upstream. It is assumed that the presence of the sampling nozzle does not disturb the streamlines in the fluid. The theory of isokinetic sampling governs this case. The theory of isokinetic samplings is supported both by experimental work (FIASP, 1941; Watson, 1954; Davies, 1968; Zenker, 1971) and by theoretical work (Vitols, 1966; Davies, 1968). The theory assumes that a stream tube coaxial with the centerline of the sampling nozzle is removed from the fluid by the sampling process. The mass flux in the stream tube removed by the sampling is the same as the mass flux in the sampling nozzle, $Q_s = Q_n$. If the stream velocity, u_s , is the same as the velocity at the sampling nozzle entrance, u_n, the sampling is called isokinetic and the diameter of the stream tube, d_s, is the same as the diameter of the nozzle, d_n. In general, since $Q_s = Q_n$

$$\frac{u_s}{u_n} = \frac{A_n}{A_s} \tag{6}$$

where A_s is the cross-sectional area of sampled stream tube and A_n is the area of sampling nozzle entrance. In this case the streamlines are undistorted, as noted in Fig. II-4, and the sampled concentration, C_n, is the same as the concentration in the fluid stream, C_s. If $u_s < u_n$, the sampling is called superisokinetic, $d_s > d_n$, and the streamlines are forced to curve inward towards the nozzle. Because of inertia, some of the particles are not able to follow the streamlines' path and are not sampled. This case is illustrated in Fig. II-5. Associated with the error, $C_s > C_n$, there will also be proportionally fewer massive particles in the sample than there are in the fluid stream. That is, the sampled size distribution will be shifted to the left, as illustrated in Fig. II-7. If $u_s > u_n$, the sampling is called subisokinetic, $d_s < d_n$, the streamlines will be forced to curve away from the nozzle and, because of inertia, some of the particles will not be able to follow the streamlines and will be captured by the nozzle as illustrated by Fig. II-6. In this case, $C_s < C_n$, and the proportion of massive particles in the sample will be greater than in the fluid stream. The size distribution will be shifted to the right as illustrated in Fig. II-7.

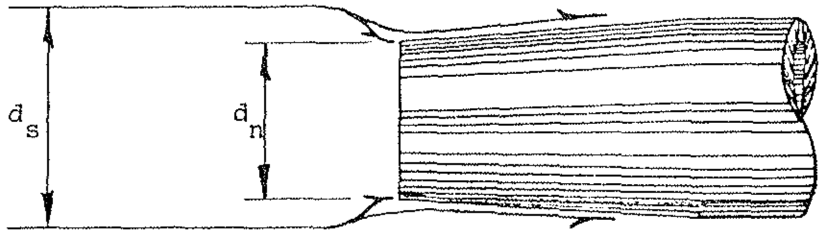
In the second case, the nozzle is turned at some angle θ to the flow path of the fluid streamline as shown in Fig. II-8. The streamlines are forced to curve towards the nozzle entrance. Therefore, $C_s > C_n$, and the particle size distribution is shifted to the left. The greater the angle θ, the greater the error in the measured concentration because the change in the velocity vector becomes greater.

Three approaches have been used to derive analytical expressions for the sampling process. Most of the studies dealt with sampling anisokinetically, with the sampling probe aligned with the flow and facing upstream. Except



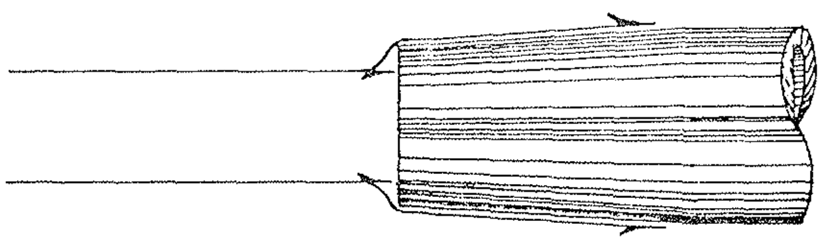
ISOKINETIC SAMPLING

FIGURE II-4



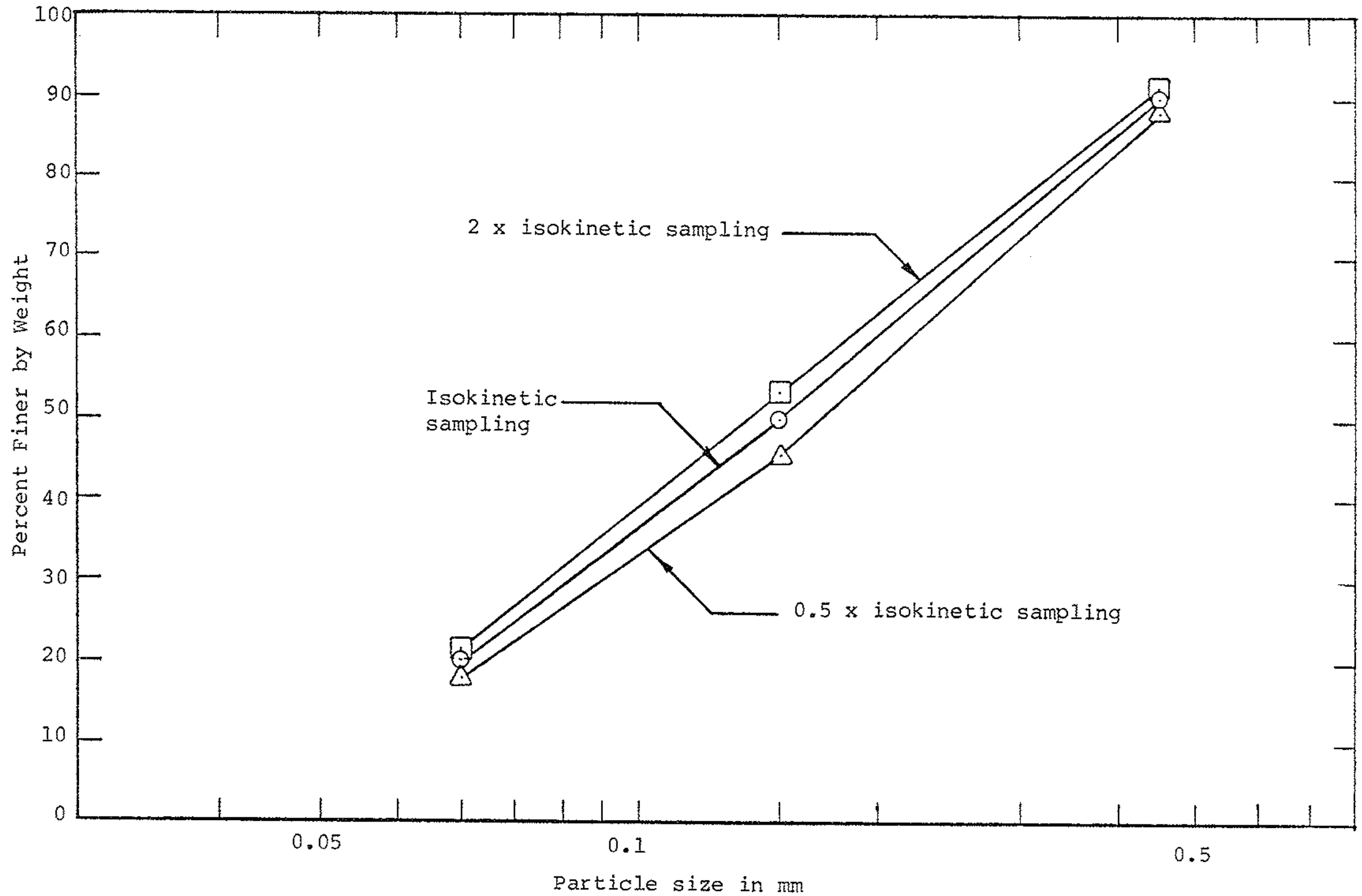
SUPER-ISOKINETIC SAMPLING

FIGURE II-5



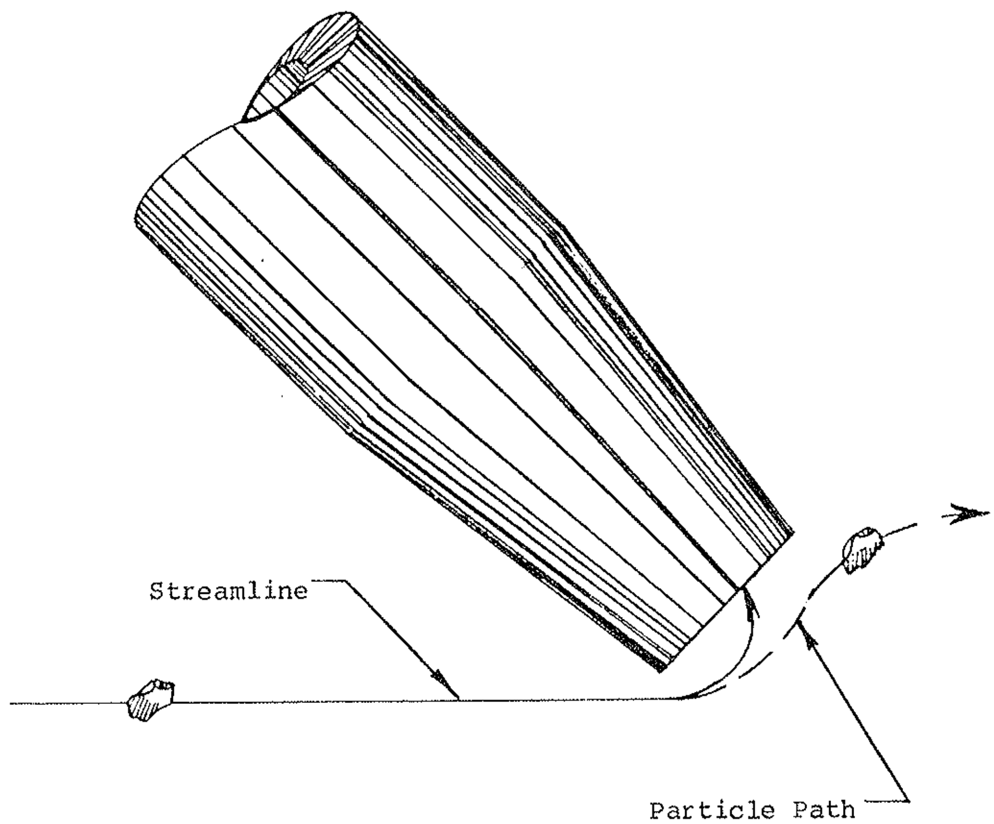
SUB-ISOKINETIC SAMPLING

FIGURE II-6



Calculated shift in particle size distribution for quartz sand in water using results of FIASP (1941).

FIGURE II-7



Sampling suspended particulates when the nozzle is turned at an angle to the flow.

FIGURE II-8

for the work of the Federal Interagency Sedimentation Project in the 1940's, the work has been done in the air pollution field (aerosol sampling).

The first analysis is strictly empirical. The results of experiments are graphed against several dimensionless variables and relationships are fitted to the data by regression analysis. The results by the FIASP (1941), Selden (1975), and Zenker (1971) are of this type. Using a second approach, Vitols (1966) and Davies (1968) calculated the position of the streamlines of the fluid and the resulting particle trajectories. From this, they derived an analytical solution for the concentration of the sample. Because of the difficulties of calculating three-dimensional streamline patterns, this method is of limited use. The third method was used by Watson (1954) and Lundgren and others (1978). Assumptions about the nature of the sampling mechanism are made and an analytical expression to estimate the concentration in the sample is derived. This expression is then fitted to experimental data by a regression analysis or by adjusting empirical coefficients.

The major problem with all these methods is that there is not enough data about the sampling process and associated errors to really fit or test the derived equations. In water-sediment sampling only the Federal Interagency Project (1941) has done experimental work. The data used for the papers on air pollution sampling came mainly from Badzioch (1959), Zenker (1971) and Hemeon and Haines (1954). In addition, as pointed out by Zenker (1971), for aerosol studies the experimental results suffered because the actual concentration in the fluid-particulate stream at the point being sampled was never known with any certainty. Simplifying assumptions, for example that the dust content was constant across the flow cross-section, had to be made,and as Zenker points out, this assumption can no longer be considered valid. The Federal Interagency Sedimentation Project, for instance, assumed that the reference sample that it collected with its standard nozzle was an accurate measure of the concentration in the stream, even though it had to assume that the isokinetic theory it was testing was correct in order to make that assumption.

In aerosol sampling several dimensionless parameters are used. The most common one is the Stokes Number or Inertial Impaction Parameter (Watson, 1954; Vitols, 1966; Zenker, 1971; Lundgren and others, 1978). The

Stokes number, St , is derived from Stokes' Law for drag on a spherical particle by inspectional analysis (Schmel, 1967) and is

$$St = \frac{d_{50}^{2} \rho_p u_s}{18 \mu L} \qquad (7)$$

where d_{50} = median particle size
ρ_p = particle density
u_s = stream velocity
μ = dynamic viscosity of fluid
L = characteristic length
= diameter of sampling orifice (Watson, 1954; Zenker, 1971) or nozzle radius (Vitols, 1966)

As Selden (1975, 1977) points out the Stokes number could be derived from dimensional analysis and contains the following dimensionless numbers: Re , ρ_p/ρ_f . The constant 1/18 is derived from Stokes' Law. However, because the assumption was made that Stokes' Law was valid, equations derived using the Stokes number are often valid only for small particle Reynolds numbers (Selden, 1975; Davies, 1968).

Another parameter that has been used in describing aerosol sampling is the relaxation time of the particle (Davies, 1968)

$$\tau = \frac{m}{6\pi a \mu} \qquad (8)$$

where m = mass of particle
a = particle radius
μ = dynamic viscosity of fluid

If it is assumed that Stokes' Law is valid, the stop distance of a particle can be defined (Davies, 1968) as $L_s = u_p \tau$ where L_s = stop distance and u_p = initial particle velocity. The stop distance, L_s , is the distance over which a particle propelled at velocity, u_p , in a certain direction will lose all motion in that direction in still air. It is a useful parameter for indicating how quickly a particle will make a 90 degree turn.

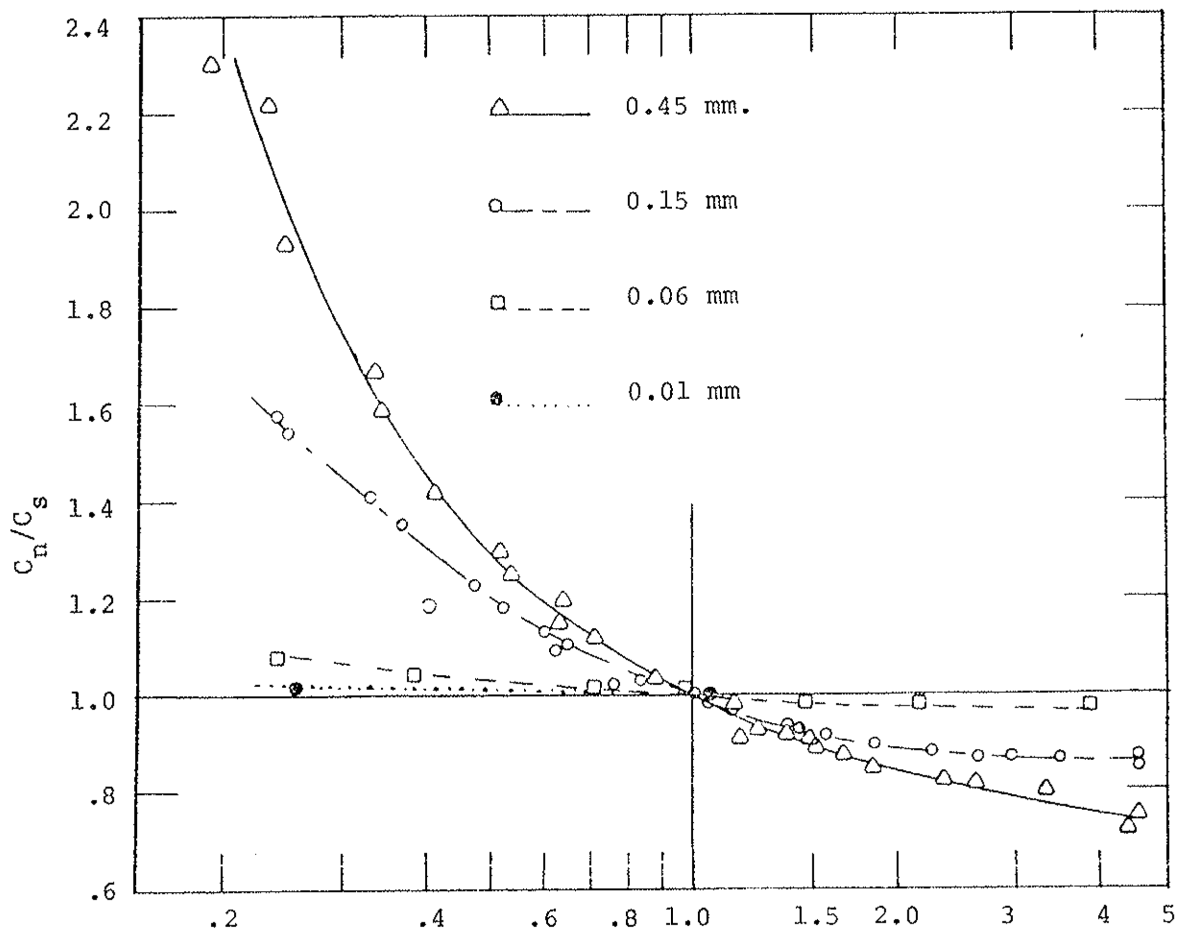
Several experimental studies have been conducted to determine the errors caused by anisokinetic sampling with the nozzle pointed directly into the flow. The results of the studies by the Federal Interagency Sedimentation Project (1941) using quartz sand in water are shown in Figs. II-9 and II-10. Experimental studies using particulates in air support the general form of the results obtained by the FIASP (Watson, 1954; Vitols, 1966; Schmel, 1967; Davies, 1968; Raynor, 1970; Zenker, 1971).

These studies show, as predicted by the theory of isokinetic sampling, that the concentrations obtained by super-isokinetic sampling are less than the concentration in the fluid, while those obtained by subisokinetic sampling are greater than the concentration in the fluid. These studies also show, in general, that the errors in measuring particulate concentration by anisokinetic sampling decrease as the particle size decreases. However, these studies cannot be directly compared because the shape, size, and mounting of the sampling nozzle affects the paths of the streamlines of the fluid flowing past the nozzle. Consequently, the laws of similarity are of no use (Raynor, 1970; Zenker, 1971).

When the sampling nozzle is turned at an angle, the sampling process changes, especially if the nozzle is rotated past right angles to the flow. Then turbulence, wake, and other effects become important. Watson (1954) presented unpublished results of the two other researchers, Maynard and Langstroth, who used diethyl phthalate aerosols in an experiment to determine how the sampling efficiency is affected by the angle between the nozzle and the flow. Their results are shown in Fig. II-11.

Using ragweed pollen and a filter holder 3.3 cm (1.3 in.) in diameter and 2.5 cm (1 in.) tall, Raynor (1970) tested the sampling efficiency of the nozzle at several wind speeds and intake rates for angles between 60 and 120 degrees. The results are presented in Figs. II-12 and II-13. The increase in efficiency as the angle is increased past 90° is attributed by Raynor to the turbulent wake moving particles against the general wind speed direction into the nozzle. This effect is dependent upon windspeed. At higher windspeeds, the efficiency continues to drop until the angle reaches 120°.

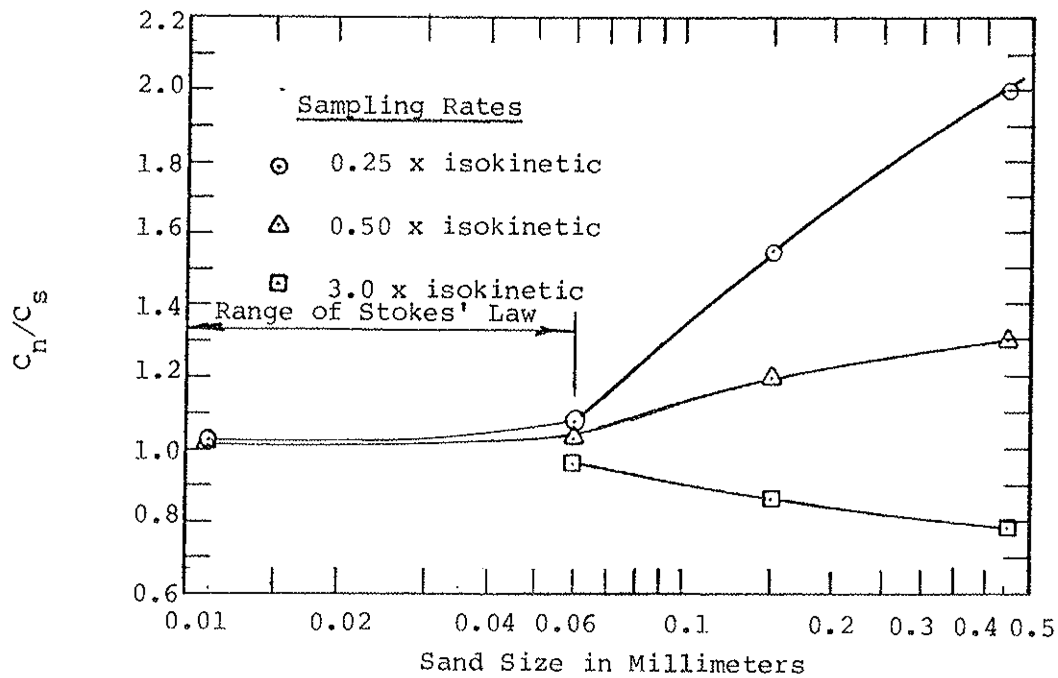
The results of FIASP (1941) using quartz sand in water is shown in Figs. II-14 through II-16. The study used a sharp-edged nozzle 0.63 cm (0.25 in.) in diameter to sample the quartz sand from a



$$\frac{\text{Intake Velocity}}{\text{Stream Velocity}} = \frac{u_n}{u_s}$$

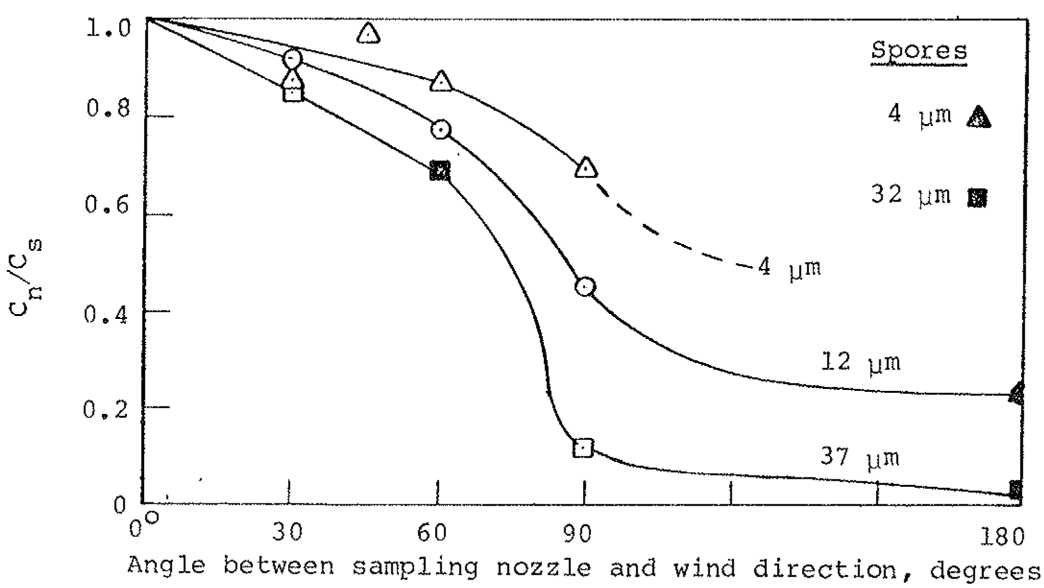
Measured relationship between concentration ratio C_n/C_s and velocity ratio u_n/u_s. (after FIASP, 1941)

FIGURE II-9



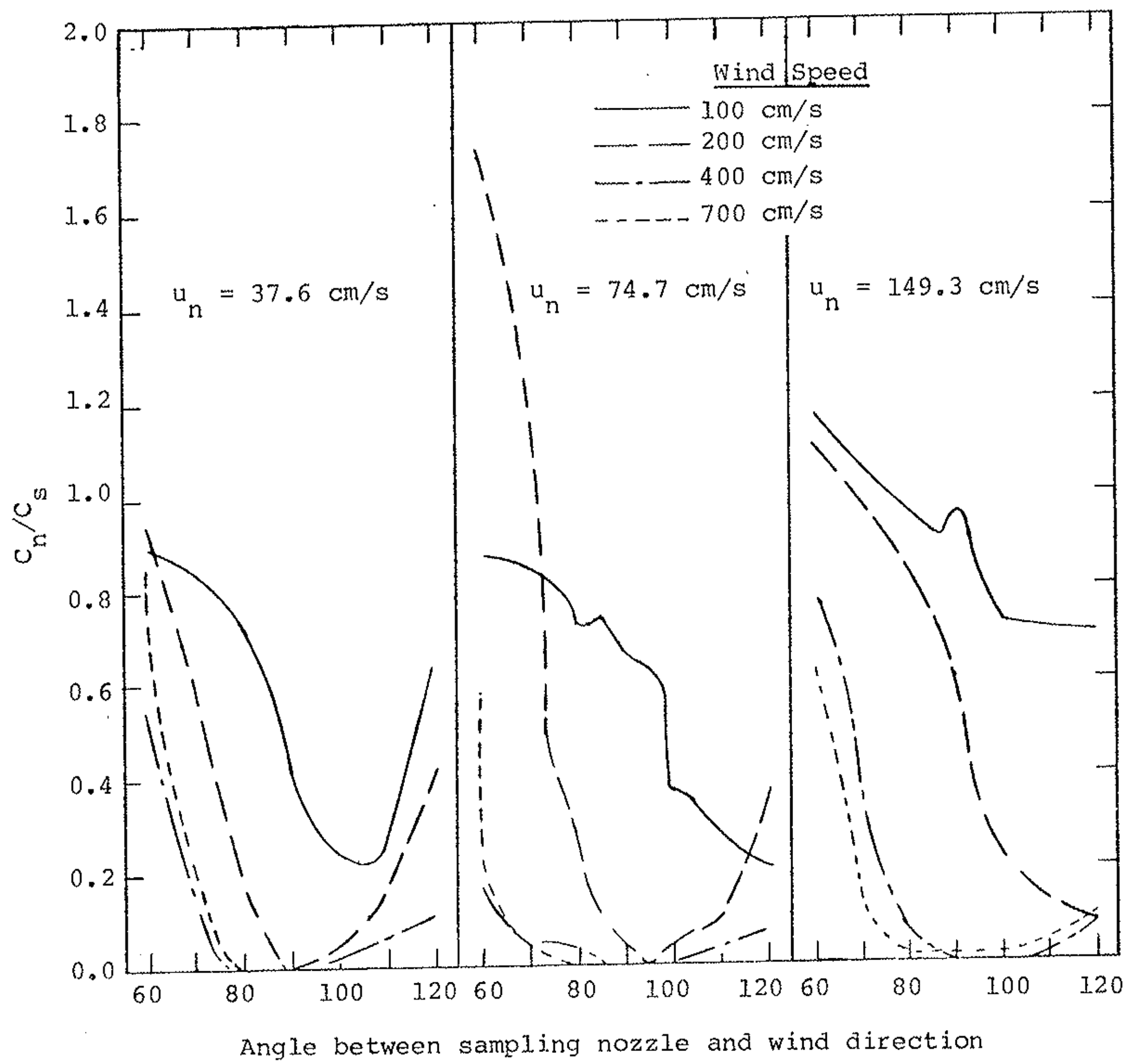
Relation of quartz sand size to errors in measuring concentration of sand in water. (after FIASP, 1941)

FIGURE II-10



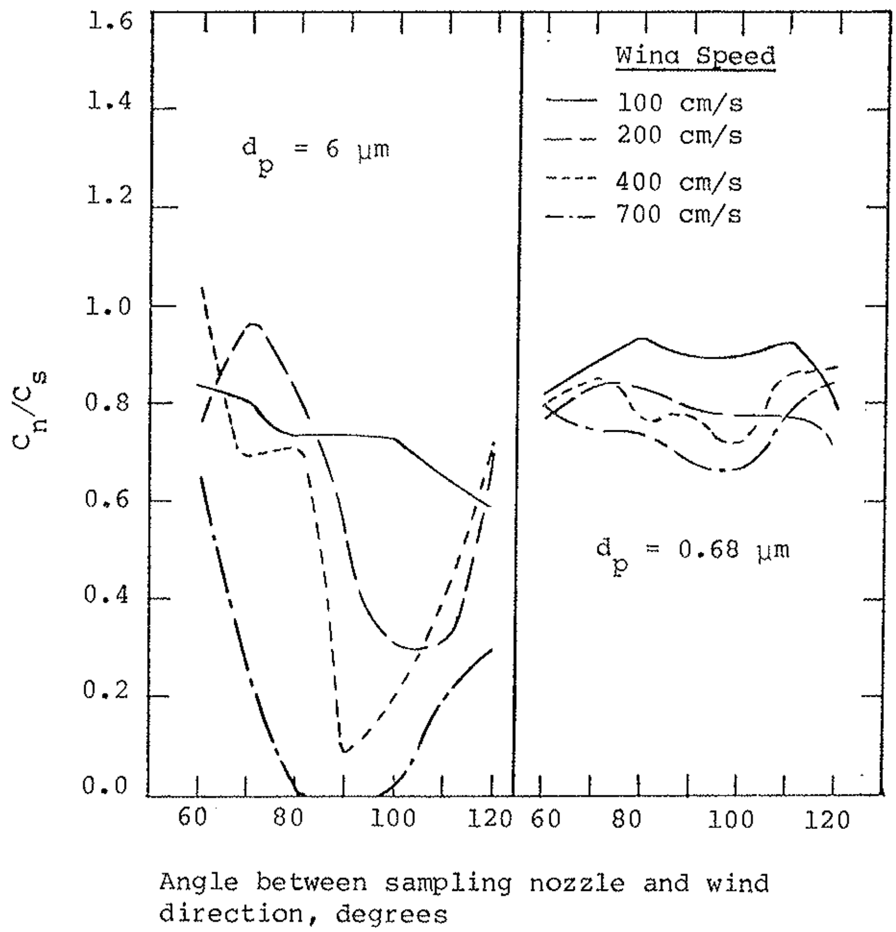
Relation of angle between sampling nozzle and wind direction to errors in measuring aerosols in air. 4, 12, 37 μm diethyl phthalate clouds, and 4 μm and 32 μm spores used. (after Watson, 1954)

FIGURE II-1



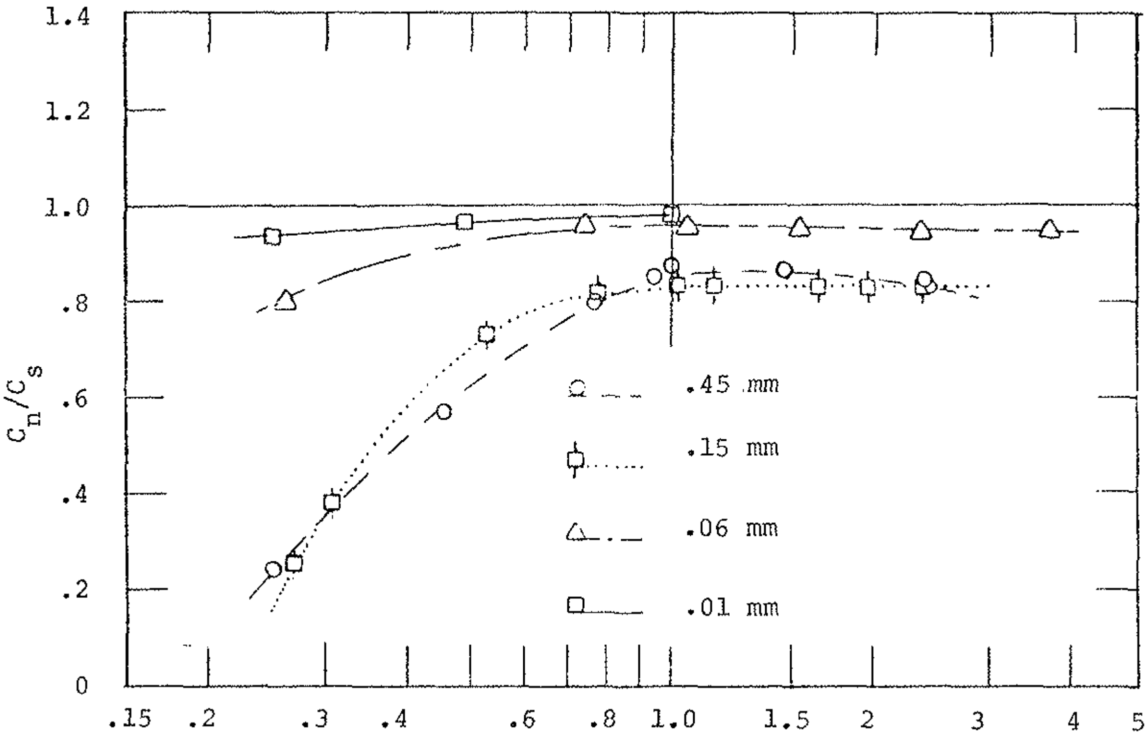
Sampling error for a 20 μm-diameter particle as a function of wind speed and angle at three intake velocities. (after Raynor, 1970)

FIGURE II-12



Sampling error for 6- and 0.68- μm- diameter particles as a function of wind speed and nozzle angle. Nozzle velocity is 74.7 cm/s. (after Raynor, 1970)

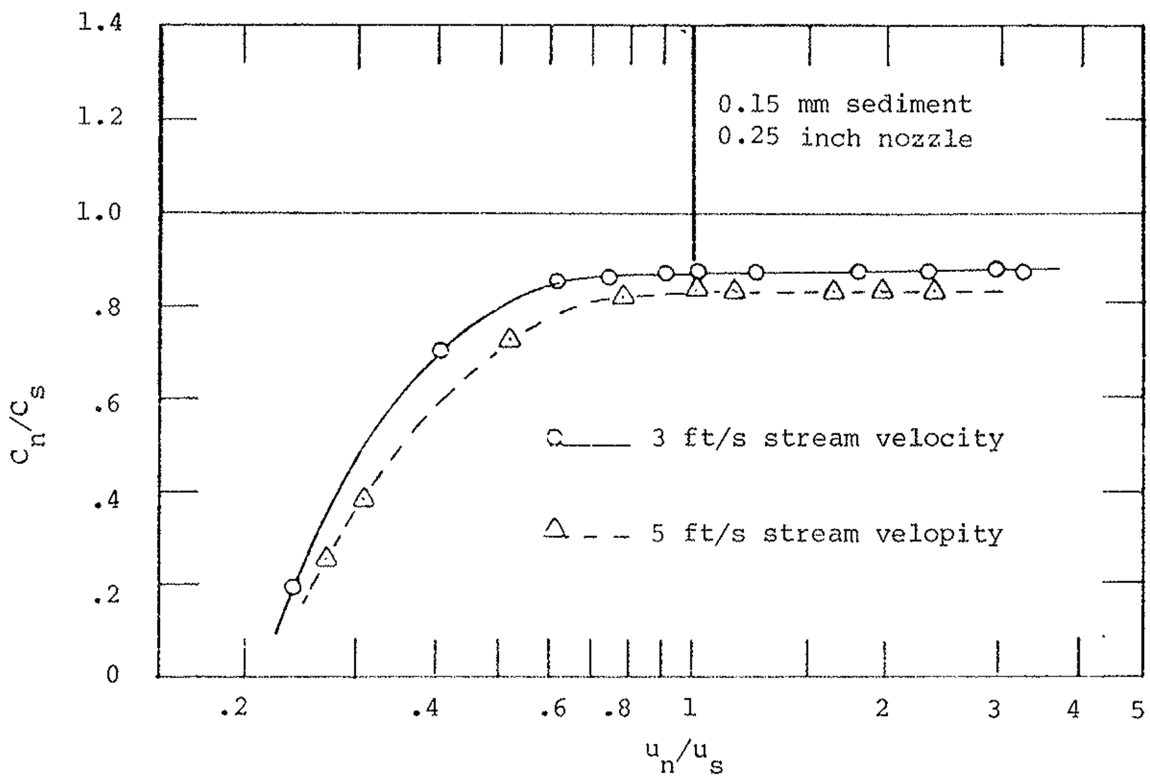
FIGURE II-13



$$\frac{\text{Intake Velocity}}{\text{Stream Velocity}} = \frac{u_n}{u_s}$$

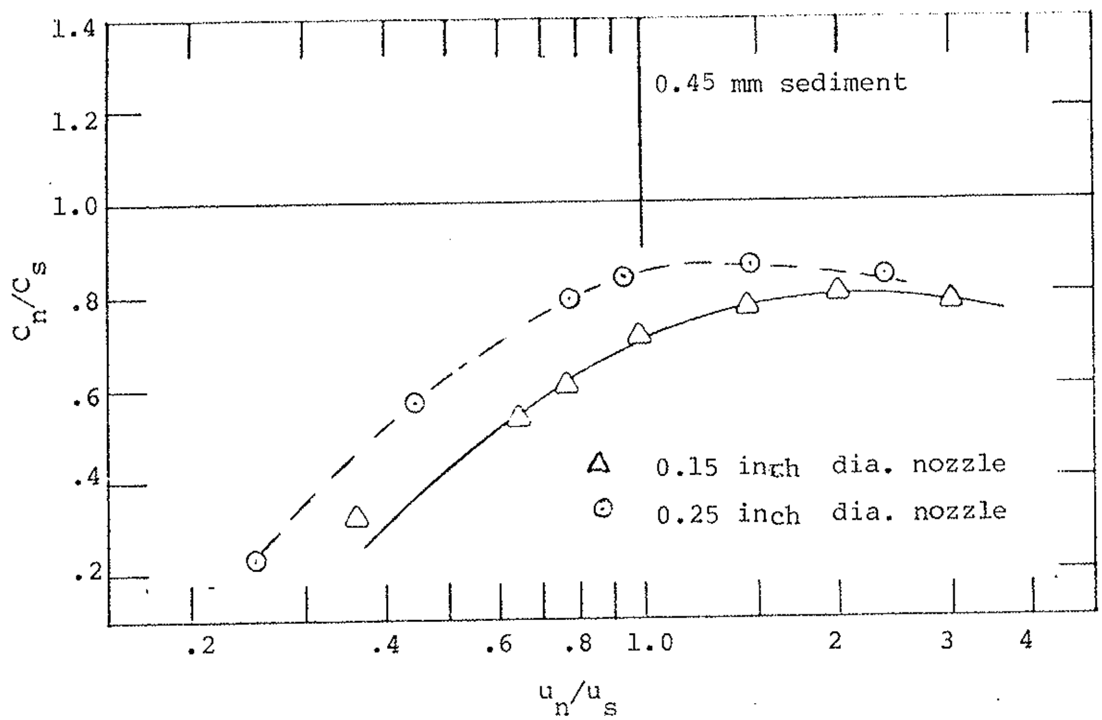
Effect of sampling rate and sediment size on errors in sediment concentration with standard nozzle in vertical position (after FISP, 1941).

FIGURE II-14



Effect of stream velocity on errors in sediment concentration with standard nozzle in vertical position. (after FIASP, 1941)

FIGURE II-15



Effect of size of sample month on errors in sediment concentration with standard nozzle in vertical position. (after FIASP, 1941)

FIGURE II-16

25.4 x 25.4 cm (10x10 in.) square duct. As in the air pollution work, their results show that the sampling efficiency, defined as the ratio C_n/C_s, decreases as the angle between the nozzle and the flow direction increases. In addition, both the stream velocity and the nozzle size affected the results. This is shown in Figs. II-15 and II-16.

In summary, experimental work has shown that sampling efficiency, defined as C_n/C_s, is affected by the following parameters: the ratio between the velocity in the nozzle and the velocity in the stream, the angle between the axis of the nozzle and flow direction, the size (or mass) of the particle, the magnitude of the stream velocity, the size of the nozzle opening and the shape of the nozzle.

Two researchers developed equations for computing the sampling efficiency of a nozzle turned at an angle to the flow. Raynor (1970) extended an equation developed by Badzioch (1959) to estimate the sampling efficiency of a nozzle at 0° to the flow by adding a term to invert the velocity ratio between 0 and 90°. The equation derived was

$$\frac{C_n}{C_s} = \alpha \left(\frac{u_n \sin\theta + u_s \cos\theta}{u_n \cos\theta + u_s \sin\theta} \right) + 1 - \alpha \qquad (9)$$

where α is a parameter related to particle stop distance. As Raynor (1970) and Lundgren and others (1978) point out, the equation has the property of becoming unity at $\theta = 45^{\circ}$ no matter what the velocity ratio is. Raynor tested his model by comparing it with data collected using corn smut spores in air at angles of 60 to 90°. He found that the model consistently over-predicted the sampling efficiency particularly when the experimental values were low.

Lundgren and others (1978) considered Raynor's equation to be seriously flawed because it gives a value of unity at 45°. The critics claim that this does not represent physical reality since the sampling efficiency is always less than or equal to one at 45°. They propose an equation based upon some experimental work and assumptions about the sampling process.

The equation is

$$\frac{C_n}{C_s} = 1+\beta \left(\frac{u_s}{u_n} \cos\theta - 1 \right) \qquad (10)$$

where β is a function of the Stokes number and the velocity ratio u_s/u_n. Although crushed gypsum rock in an air stream was sampled at various angles to the flow, data were not presented to verify the derived equation. As in the case of Raynor's equation, this equation applies only for angles of 0 to 90° between the nozzle axis and the flow.

This equation can be transformed into one of two linear equations of the form Y=MX+B:

$$(1) \quad \frac{C_n}{C_s} = \beta \cos \theta \left(\frac{u_s}{u_n}\right) + (1-\beta) \qquad (11)$$

$$(2) \quad \frac{C_n}{C_s} = \left(\frac{u_s}{u_n} \cos \theta - 1\right) \beta + 1 \qquad (12)$$

Either θ or u_s/u_n can be the independent variable in the first equation and β is the independent variable in the second equation. Both equations have the property that $C_n/C_s = 1$ when $u_s/u_n = 1/\cos \theta$.

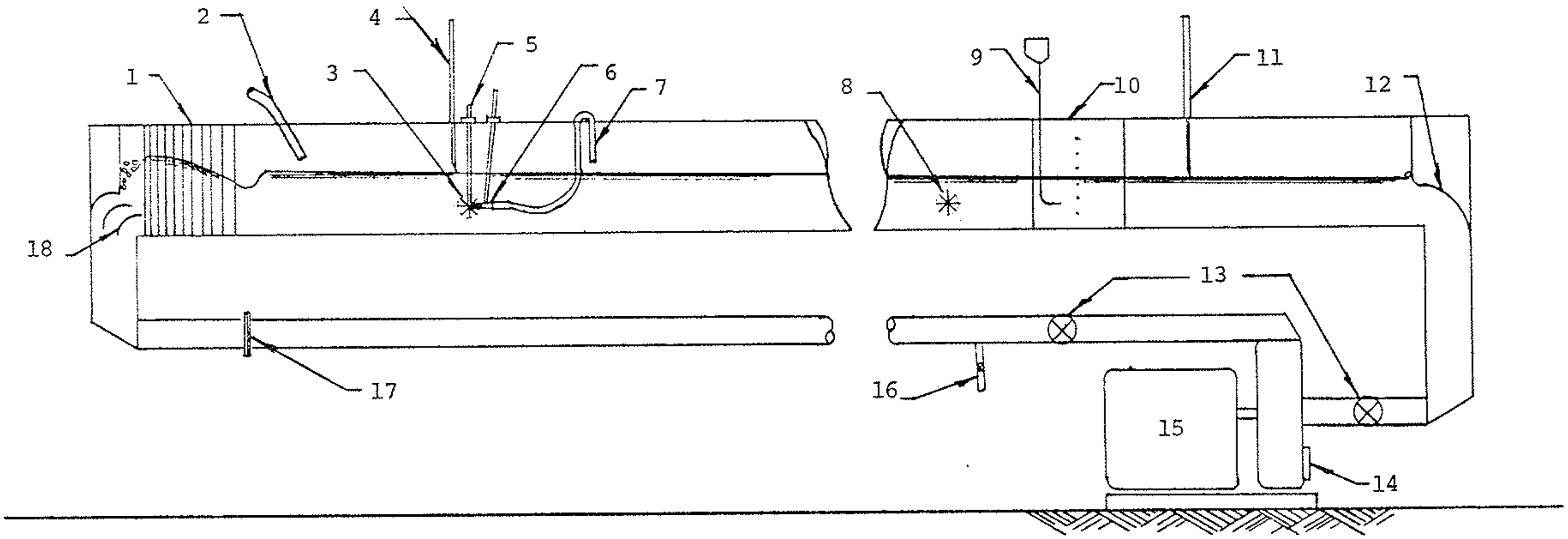
III. EXPERIMENTAL EQUIPMENT

A. Flume

To investigate the effects of sampler nozzle orientation on sampling efficiency, experiments were performed in a glass-walled flume at the St. Anthony Falls Hydraulic Laboratory. Samples were siphoned into plastic pails from the flow in the flume using one of two sampling nozzles mounted on an adjustable support. The volumetric flow rate of the recirculated water in the flume was measured by an orifice in the return piping connected to a mercury manometer. Velocity profiles in the flume were measured with a micro-propeller. Dye, injected into the water with hand-held or mounted needles, was used to visualize flow patterns. Figure III-1 is a schematic of the experimental apparatus.

The flume used was 0.156 m (6.125 in.) wide, 0.381 m (15.00 in.) deep, and 12.57 m (41.25 ft) long. A Jaeger P692 C pump, used to recirculate the water and suspended sediment, had a maximum discharge of 17.6 ℓ/sec (0.62 cfs). An orifice in the return piping and a mercury manometer were used to measure the volumetric flow rate. Because it was not possible to calibrate the orifice through the direct measurement of discharge, calculated values of discharge versus manometer deflection were used. The maximum estimated error from this method of calibrating the orifice is one percent. The rate of volumetric flow was set by a gate valve located just downstream of the pump on the return piping. Turning vanes installed at the entrance (upstream end) to the flume reduced head losses at the entrance. A sheet metal curve placed at the exit (downstream end) of the flume eliminated air entrainment at the exit.

A baffle screen made from coarse wire mesh was placed against the turning vanes at the flume entrance to reduce turbulence at the entrance



1. Baffle screen
2. Fill hose
3. Reference marks
4. Point gage
5. Nozzle holder assembly
6. Nozzle
7. Siphon tubing
8. Reference marks
9. Dye needle
10. Nozzle supports for dye studies
11. Point gage
12. Sheet metal bend
13. Gate valves
14. Pump clean out
15. Pump
16. Drain hose
17. Orifice
18. Turning vanes

Schematic of recirculating flume and experimental set-up.
(Not to scale, relative positions only.)

FIGURE III-1

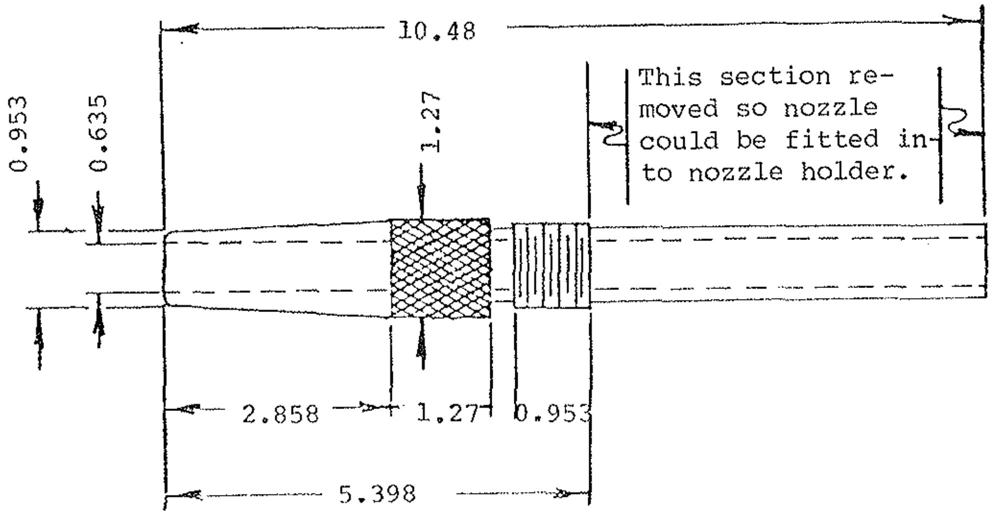
and to eliminate waves in the flume. The baffle screen had been made by corrugating and then soldering the wire mesh together. It was 0.156 m (6.125 in.) wide, 0.38 m (15.0 in.) deep and 0.30 m (12.0 in.) long. An undular hydraulic jump occurred 0.15 m (6.0 in.) downstream of the baffle screen.

Two sampling locations were used in the flume. After a series of preliminary experiments (see Section IV). the primary sampling location was selected 1.37 m (4.5 ft) downstream from the entrance to the flume. A second sampling location was also used 8.61 m (28.25 ft) downstream from the entrance to the flume and 3.96 m (13.0 ft) upstream from the exit of the flume. Flow visualization studies were conducted 0.76 m (2.5 ft) downstream from the second sampling location.

B. Sampling Equipment

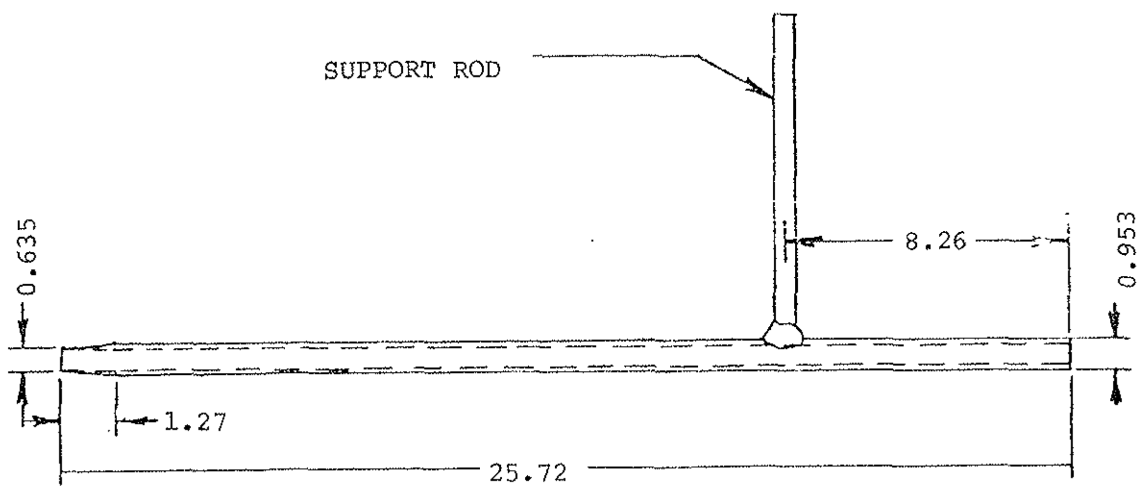
Two nozzles were used in the sampling studies. The one used for most of the studies is a standard nozzle, illustrated in Fig. III-2, used by the Federal Interagency Sedimentation Project (FIASP) for the DH-59 and DH-76 suspended sediment samplers. The second nozzle used was a brass tube 0.260 m (10.25 in.) long mounted on a rod that could be inserted in a point gage. The second nozzle is illustrated in Fig. III-3. Both nozzles have inside diameters of 0.64 cm (0.25 in.).

The adjustable holder in which the standard nozzle was mounted was constructed so that the mouth of the nozzle remained at the same location in the flume while the nozzle was moved through a complete circle around a horizontal axis. The holder could also be adjusted so any elevation in the flume could be sampled. The support held the nozzle in the center of the flume and parallel to its sides. The nozzle and holder are shown in Fig. III-4.



Standard Plastic Nozzle for the DH-59 and DH-72 Sampler

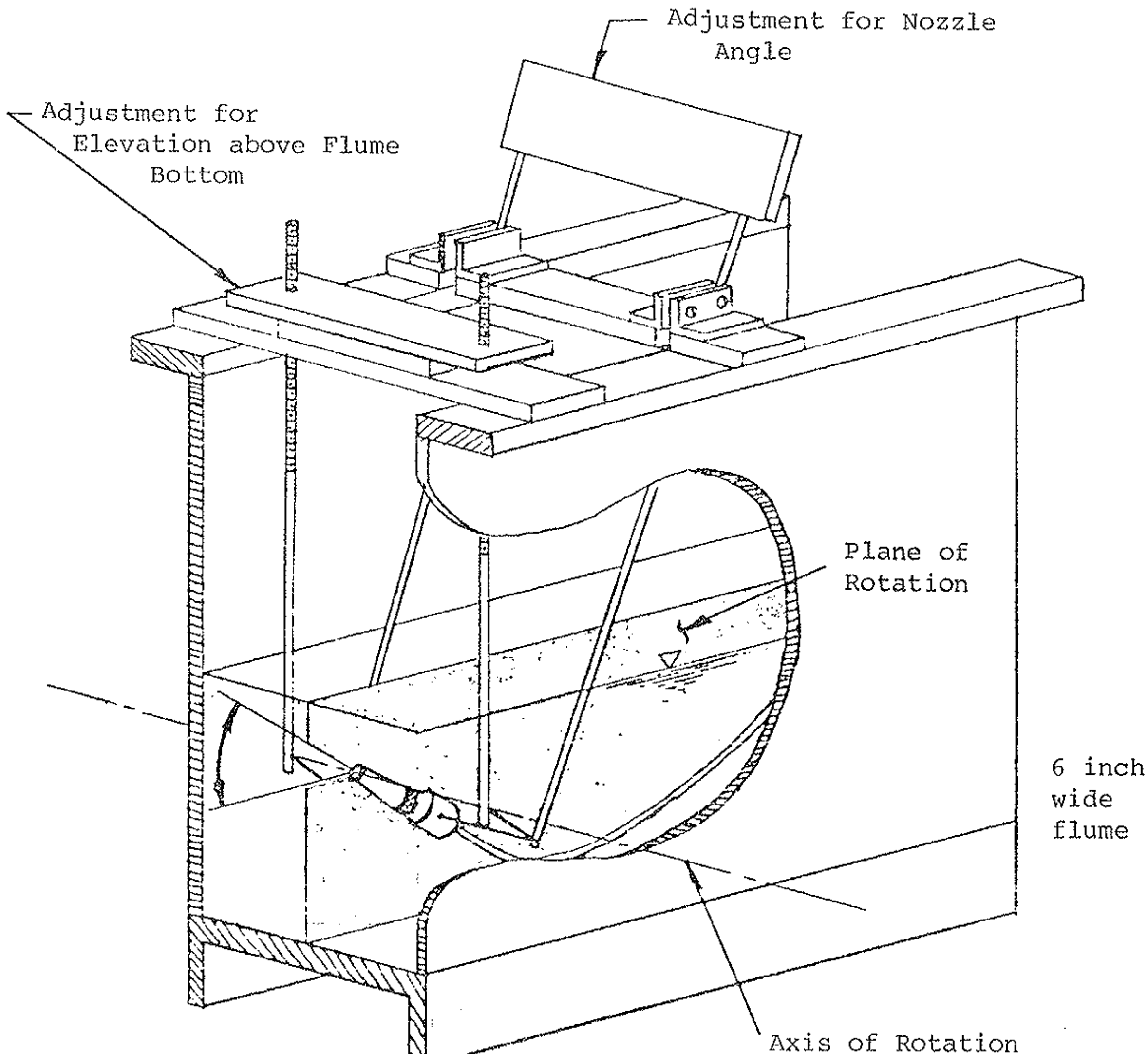
Figure III-2



Brass Nozzle

Figure III-3

(All Dimensions in Centimeters)



NOZZLE AND NOZZLE HOLDER ASSEMBLY

FIGURE III-4

Reference lines marked on the side of the flume were used to set the standard nozzle at the described angle to the flow. As shown in Fig. I-2, sampling was done with the nozzle set at one of eight angles, 0, 45, 90, 135, 180, 225, 270, or 315 degrees measured from the direction of the flow. The nozzle was visually aligned with the reference marks and then fixed into place with clamps on the nozzle support.

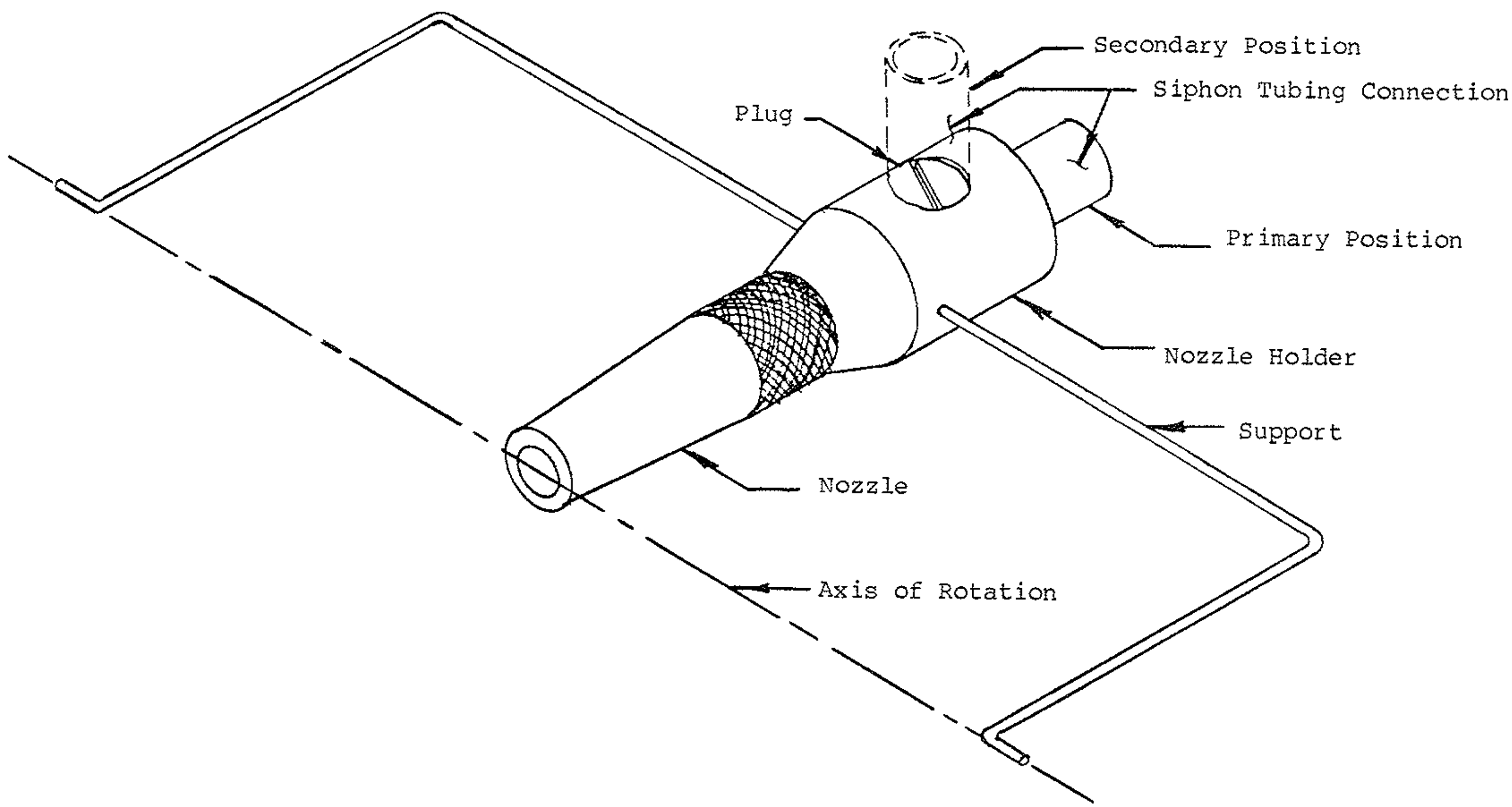
The second nozzle was mounted on a point gage on the centerline of the flume. It was adjusted by eye so that it was parallel to the sides of the flume facing either upstream or downstream. The elevation of the nozzle in the flow was set with the point gage.

C. Siphon

The samples of sediment and water were removed from the flume through a siphon. Several sizes of clear polyethelene tubing were used as a siphon. The size of the tubing was selected so that the smallest tubing possible, through which the desired intake rates could be achieved, was used. This prevented sediment from depositing in low spots of the tubing by keeping the velocities high enough to flush the tubing. Small clamps were used to fix the tubing onto connections to prevent leaks.

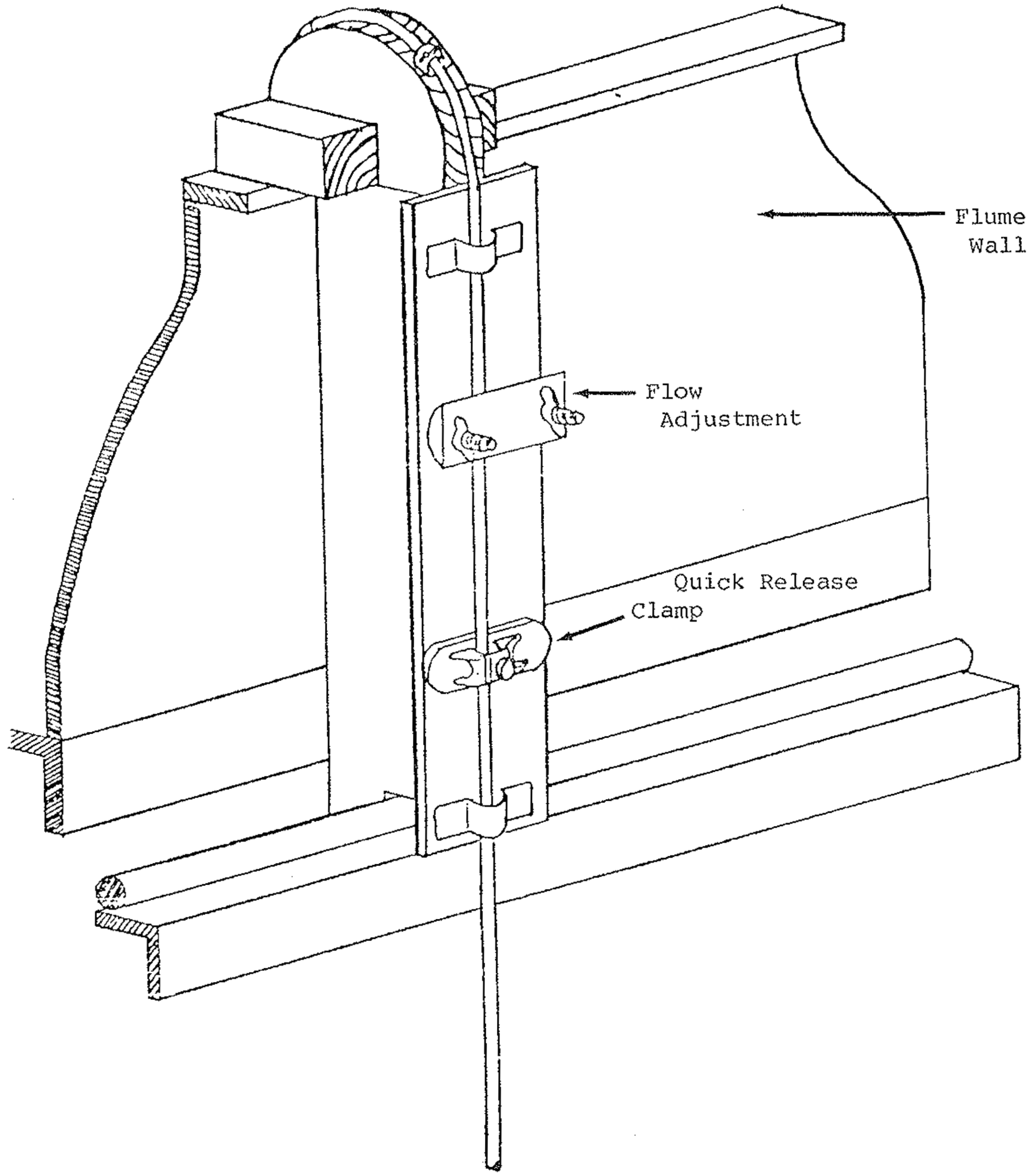
Normally, the tubing was attached at the rear of the nozzle, as shown in Fig. III-5. However, it was not possible to sample with the nozzle set at 90° with this configuration because the connection for the tubing struck the bottom of the flume before the holder was in position. In this case the tubing connection at the rear of the nozzle holder and a plug in the side of the nozzle holder were interchanged and the tubing was attached to the side of the holder. This is shown as the "Secondary Configuration" in Fig. III-5.

The siphon passed through two pinch clamps mounted on the side of the flume. The first pinch clamp was used to set the siphon rate by squeezing the siphon. The pinch clamp was made from a wooden block so that the siphon tubing would not become permanently creased. The second pinch clamp was a quick release type used to start and stop the siphon. When more than one intake rate was needed, two siphons were used, each passing through its own set of pinch clamps. The siphon setup is shown in Fig. III-6.



NOZZLE ASSEMBLY

FIGURE III-5



SIPHON ASSEMBLY SHOWN MOUNTED ON A SECTION OF THE FLUME

FIGURE III-6

D. Observation and Measuring Equipment

The majority of the flow visualization studies were conducted with a dye injection needle manufactured out of brass and stainless steel tubing mounted on a point gage. The dimensions of the dye injection needle varied as the requirements of the dye studies changed. When the dye traces were manually recorded, a very fine needle was used that ejected only a very thin streamer of dye. This thin streamer of dye did not photograph well; and therefore, a much larger diameter dye injection needle was used when the dye tracers were photographically recorded.

The point gage holding the dye injection needle was mounted on a platform that could be moved along the top of the flume. The position of the needle across the flume was determined by a steel rule clamped to the platform and a pointer fixed to the point gage. A reservoir mounted 0.6 m (2 ft) above the platform supplied dye to the dye injection needles. Dye flow was controlled by a pinch clamp on the tubing between the reservoir and the dye injection needle. To study flow patterns at the nozzle surface a dye injection needle was made by soldering a fine stainless steel tube to a hypodermic needle. The outside diameter of the tube was 0.808 mm (0.0318 in.) and the inside diameter was 0.493 mm (0.0194 in.). Its total length was 0.381 m (15.0 in.).

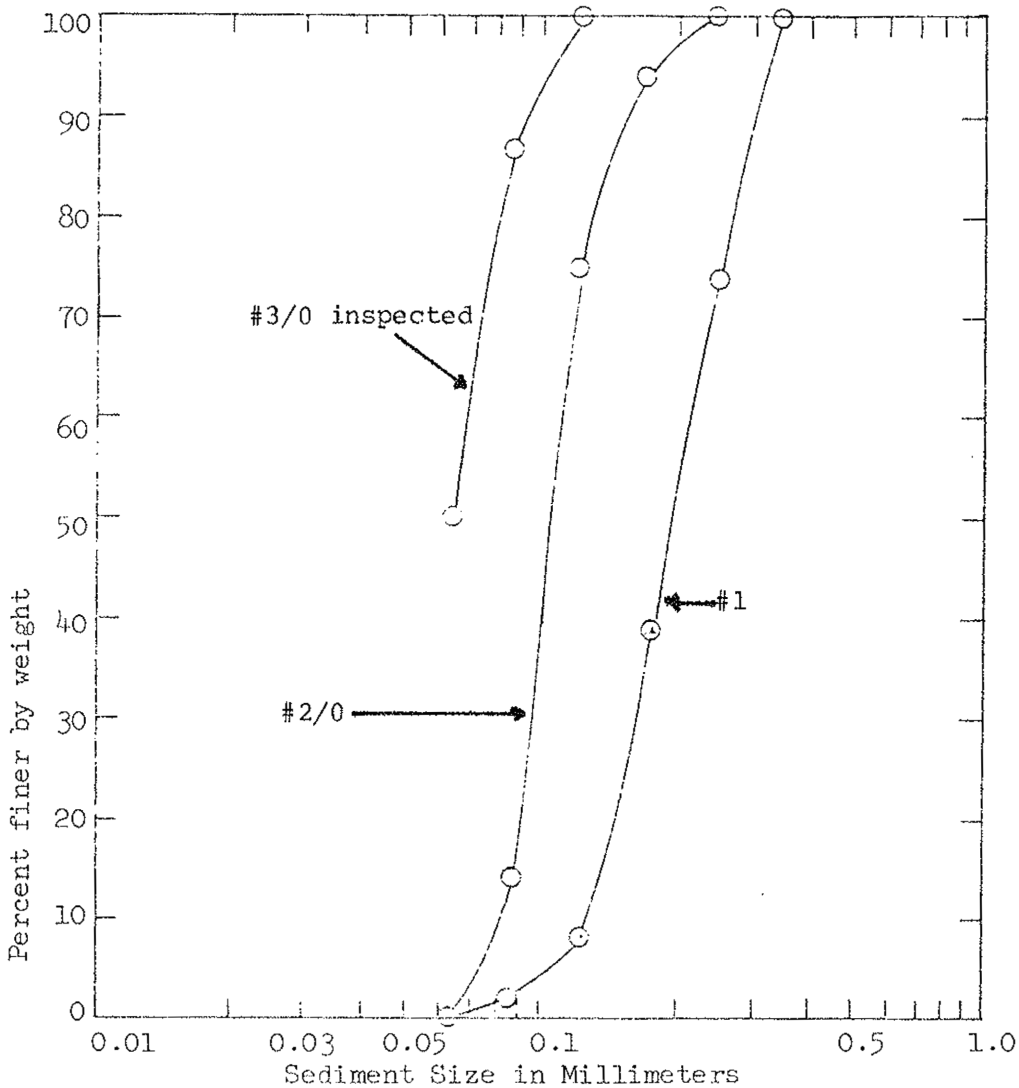
The dye used for the experiments was Red Dye No. 2 in an alcohol base. It was diluted with water to produce dye streaks of varying intensity.

A micro-propeller velocity meter manufactured by the Delft Hydraulic Laboratory, Delft, The Netherlands, was used to measure the velocity profiles at the sampling locations. The propeller has a start-up velocity of 1 to 2 cm/sec (0.03 to 0.06 fps) and a velocity range from 2 to 122 cm/sec (0.06 to 4.00 fps). The velocity meter is very responsive to changes in velocity, making it useful to determine levels of turbulence in the flume.

E. Sediment

The sediment used in the experiments was commercially graded quartz sand from the Agsco Corp., Des Plaines, Illinois. Three sizes of quartz sand were used; #3/0 Inspected, d_{50} = 0.06 mm; #2/0, d_{50}=0.11 mm; and #1, d_{50}=0.20 mm. The size distributions which were determined, using a visual accumulation tube, by personnel of the Federal Interagency Sedimentation Project are presented in Fig. III-7. The fall velocities for the sand are: d_{50} = 0.06 mm, 0.26 cm/sec; d_{50} = 0.11 mm, 0.88 cm/sec; d_{50} = 0.20 mm, 2.0 cm/sec; respectively. The fall velocities were computed using a specific gravity of 2.65, a water temperature of 10°C, and assuming that the individual sand grains were spheres. The d_{50} for each size sand was assumed to be the diameter of the sphere. The procedures used to calculate the fall velocity are given in the *Sedimentation Engineering Handbook*, American Society of Civil Engineers, 1975.

Grains of sand from each size used were examined under a stereoscopic microscope to determine the actual shape of the sand grains. Instead of being spherical, the sand grains are very irregular in shape. Some are flat disks; others are tetrahedronal or rhomboidal. Because of the low Reynolds numbers encountered in the experiments, less than 100, and the small size of the sand grains, it is felt that they can be reasonably approximated as spheres with negligible error.



Size distribution of quartz sand used in the study

FIGURE III-7

IV. EXPERIMENTAL PROCEDURES

A. Flume Preparation

Two types of studies were conducted: a suspended sediment concentration sampling study and a flow visualization study. The concentration sampling study consisted of experiments in which samples were withdrawn from the flume to study the effects of nozzle orientation on sampled concentration accuracy. The purpose of the flow visualization study was to determine the flow patterns around the nozzle for various nozzle orientations and withdrawal conditions.

The preparation of the flume was the same for both types of studies. The flume and the return piping were first thoroughly flushed to remove any sediment or scale from a previous experimental run. After the flume was flushed, it was filled using the fill hose connected to the City of Minneapolis water supply until the water depth was above the depth required for the experiments. The pump was turned on briefly to circulate the water through the return piping and to remove any air from the system. Trapped air in the return piping caused errors when the depth, and thus the volume, of water in the system was set. The pump was then turned off and the water surface allowed to become still. Using a calibration curve between depth of water in the flume and total volume of water in the system, the volume of water in the system was set by draining water out of the flume through a drain hose on the return piping. A point gage located 1.85 m (6 ft) upstream from the flume exit was used to set the water depth to the nearest 0.001 ft. This point gage was used exclusively for setting the initial water depth in the flume because the flume bottom was not quite level and, if the water depth was set anywhere else in the flume, errors were introduced into the initial volume of water. For all of the sampling experiments, the initial volume was 414 ℓ (14.6 cf) and the initial depth was 0.1707 m (0.560 ft). For flow visualization studies the initial depth varied depending upon the flow rates and flow conditions desired for the study.

The pump was then turned on and the gate valve downstream of the pump was slowly opened until the desired flow rate was approximately achieved. The manometer lines were bled of air, and the flow rate set precisely using the manometer and the orifice in the return piping. The flow rate used in all of the sampling experiments was 16.71 ℓ/sec (0.590 ft^3/s). The flow rate for the flow visualization studies varied depending upon the phenomena studied.

B. Sample Collection

The required flow rate through the siphon was calculated by using the following formula:

$$Q_n = a\, u_s\, A_n \tag{13}$$

where Q_n = volumetric flow rate through the nozzle

a = isokinetic proportionality factor. $a = 1$ for isokinetic sampling, $a = 2$ for twice isokinetic sampling

u_s = velocity in the flume at the sampling point

A_n = area of nozzle entrance $A_n = \frac{\pi d_n^2}{4}$; d_n is the inside diameter of the nozzle mouth.

For the majority of the experiments, the velocity in the flume was calculated from the average volumetric flow rate divided by the cross-sectional area of the flow. This gave the average velocity across the flume. Later velocity measurements showed that at the depth sampled, this gave a velocity about 10 percent lower than the actual velocity at the sampling point.

As the water was removed from the flume, the velocity at the sampling point increased because the depth, and thus the cross-sectional area, of the flow decreased. The velocity used to calculate the intake rate of the nozzle was the average of several mean velocities (Q/A) computed from the decreasing water depths over the course of a run. This average was adjusted slightly from time to time as more data became available from succeeding runs to produce a better average velocity.

Once the volumetric flow rate through the nozzle was calculated in liters per second, it was inverted to give the time required at that flow rate to fill a one liter volumetric beaker, in seconds per liter. To set the intake rate through the nozzle, the volumetric beaker was set under the siphon tubing and the time to fill the beaker timed to the nearest two tenths of a second with a stop watch. The adjustable pinch clamp on the siphon was tightened or loosened until the desired filling time was achieved. The elevation of the free end of the siphon tube above the floor was not changed during the calibration process or afterwards to prevent the siphon rate from changing. The nozzle acted like a pitot tube in that the siphon rate was sensitive to the stagnation pressure of the flow at the mouth of the nozzle. Therefore, the siphon rate was always set with the nozzle pointing upstream into the flow.

After the siphon rate had been adjusted and the volume of water and the velocity in the flume set, the sand was added to the flume. A theoretical concentration of 1.0 g/L was produced by adding 414 grams of sand to the flume. The sand was weighed on a two pan balance, accurate to $\pm$ 1 gram. The sand was poured slowly into the flume to evenly disperse the sand in the flow. The water temperature and the depth of water at the sampling location were measured and the first sample could be taken.

Two different types of samples were taken for each experimental run. The first type, called the reference sample, was taken to determine the concentration of suspended sediment in the flow. The second type, called the test sample, was taken with the nozzle at one end of the eight angles to the flow as shown in Fig. I-2. The reference sample was taken under isokinetic conditions with the nozzle in the zero degree position, that is, pointing directly into the flow. It was assumed, for lack of better means to determine concentration of suspended sediment in the flow, that the concentration determined by the reference sample was the concentration in the flow at that particular location and time. The comparison between the concentrations determined by the test sample and the reference sample was the primary objective of most of this sampling program.

Before each sample was taken, the water temperature and water depth were measured. These measurements were later used to calculate the Froude and Reynolds numbers. The first portion of each sample was wasted to flush the siphon free of any sediment left over from the previous sample and to establish in the siphon the concentration existing in the flume at that time. Normally the sample was wasted 20 seconds for isokinetic samples and 10 seconds for twice isokinetic samples. Therefore, the total amount of water wasted remained constant for each sample taken. From flow visualization studies it was determined that the water in the siphon tubing changed completely in less than five seconds. For most experimental runs, five samples were taken. The total length of time to collect each sample varied with the experiment.

Preliminary experiments had indicated that a sample collected over a four minute period would give a measured concentration within ± 5 per cent of the actual concentration in the flume. Also, it was determined that only 25 to 30 liters of water could be removed from the flume before the loss of water changed flow conditions so much as to make further sampling undesirable. Consequently, it was determined that five samples of about 5.5 liters a piece would be the maximum amount that could be reasonably sampled during one experimental run. At the upstream location, the sampling time for isokinetic samples was five minutes, for twice isokinetic samples, 2.5 minutes. At the downstream location and for some other experiments, the times were shorter.

In each sampling run three reference samples and two test samples were taken. The order in which the samples were taken was as follows: reference sample, test sample, reference sample, test sample, reference sample. The two test samples in each run may have been taken with the nozzle set at the same angle or two different angles. For each sample, 2 one gallon plastic pails were used, with the sample split between the pails. The pails were exchanged while the sample was being taken by placing the second pail under the siphon before removing the first pail. After each sample was taken, the quick release pinch clamp was tightened as quickly as possible to stop the siphoning.

After all five samples had been taken, the pump was shut off and the final water depth measured and recorded. The flume was drained and flushed to remove the sand. The water and sand were changed between each run so the conditions at the beginning of each run were as identical as possible.

C. Sample Analysis

The samples were analyzed following, in general, the procedures recommended by the U. S. Geological Survey (Guy, 1969). The samples were weighed either on a Mettler single pan balance accurate to 0.1 gram, or, when that became unavailable, on a two pan balance accurate to 1.0 gram.

Before the weight of the sand could be determined, the water had to be removed. Part of the water was siphoned from the pails and then the pails were tilted in a stand. The remaining water was then siphoned off until only about 20 or 30 milliters were left. Distilled water was used to flush the sand from the sides and bottom of the pail while the remaining sand and water were siphoned into a 250 milliter beaker. The excess water was poured off and the sand flushed into aluminum weighing dishes. The excess water was again siphoned off leaving only several milliters of water. The dishes were then dried in an oven to evaporate the remaining water.

The sand was weighed on a two-pan analytical balance, accurate to a tenth of a milligram. The weights for the balance had been recalibrated before the start of the experiments and the proper corrections were added to the weight of each weighing dish and sand to account for the small errors in the weights. The sand and the weighing dishes were weighed to the nearest milligram. The tares of both the weighing dishes and the plastic pails were rechecked several times during the course of the experiments.

The concentration measured was calculated by first getting the net weight of the water and sand, or the sand alone,by subtracting the tares of the pail or the weighing dish. The weight of the sand was divided by the weight of the water and sand to get a concentration in grams per kilogram. Since the weight of the sand was negligible compared to the weight of the water (typically less than 5 g of sand in 5L of water), and the specific gravity of water is 1.0 to the accuracy of the measurements made, the concentration can be converted directly to grams per liter.

As was stated earlier the purpose of most of the experimentation was to compare the concentration measured by the reference sample to that measured by the test sample. The following procedure was used to determine the ratio between the two concentrations. Since the vertical concentration gradient changed as water was removed from the flume (see Section V), the reference concentration at the sampling point changed with time. Because of this, the concentrations determined by the reference samples before and after the test sample were averaged to get the concentration in the flume when the test sample was taken. The test sample concentration was then divided by the averaged reference concentrations to determine the ratio between test concentration and the concentration in the flume. A discussion of the accuracy of this procedure is given in Section VI.

D. Flow Visualization

The procedures for the flow visualization studies were quite different from those for the sampling program. No sand was used and the velocities and water depths in the flume varied with the requirements for each of the flow visualization studies conducted. For part of the visualization program flow as nearly laminar as possible was wanted. The flume was then filled to the top and a low velocity used. For other studies conditions similar to the sampling conditions were used.

Most of the documentation of the flow visualization study was done with a 4x5" view camera and polaroid film. The lights, camera angles, dye intensity, plume intensity, and dye injection point were changed as required to meet changing conditions in the flume and to produce the best pictures. When the water became too cloudy with dye to photograph the dye streaks, the water was changed.

Similarly, when dye injection was done with the hand-held needle, the rate of injection, the intensity of the dye, and the position of the dye injection point were changed as needed to produce the best results. The results of these latter studies were recorded manually on drawings of the nozzle at various angles to the flow.

V. EXPERIMENTAL RESULTS

Group 1: Preliminary Experiments

A previous study conducted in the flume using the same quartz sand as used in this study, had shown that a concentration gradient existed at the downstream end of the flume. Since a constant concentration of suspended sediment along a vertical line at the center of the flume was desired at the sampling location, several mixing devices were tested to see if the concentration gradient could be destroyed. None proved to be satisfactory. Therefore, two experiments, P-1 and P-2, were conducted at 1.37 m and 1.68 m (4.5 ft and 5.5 ft) downstream of the flume entrance where it was hoped that turbulence from water entering the flume would prevent any vertical concentration gradients. The effect of air entrained as the water entered the flume on the sampling process at these two locations was also observed. Two sizes of sand, d_{50} = 0.06 and 0.11 mm, were used in these experiments.

In the experiments, samples were taken at five elevations in the flow. Two ten-second samples were collected at each elevation in 250 mL beakers under isokinetic conditions to determine the sand concentration at that elevation. Samples were taken both with and without the baffle screen at the flume entrance. Based on the results of these two experiments, an elevation of 9.14 cm (0.300 ft), 1.37 m (4.5 ft) downstream from the flume entrance was selected as the sampling point in the flow for future experiments. The baffle screen was left in place for all future experiments, since it prevented waves from forming in the flume.

In the previous study conducted in the flume, it had been found that the concentration of sand at any point in the flume varied with time. It was important, therefore, to find the minimum sampling time needed to obtain an accurate measurement of the sand concentration in the flume. In experimental run P-3, ten-second samples were taken at the selected sampling location in 250 mL beakers one after the other. The measured concentration from the first two samples were averaged, then the first three samples, and then the first four samples, and so on until all of the samples had been included in the average.

A "student's t" analysis was done to determine the 95 percent and 90 percent confidence limits. A sampling time of 5 minutes, within the 95 percent confidence limit, was selected. In some experiments, this sampling time was too long, and sampling times as short as 1.5 minutes were used.

In the first three sets of preliminary experiments, P-1 through P-3, an attempt was made to maintain constant conditions of flow and sand concentration in the flume. This was accomplished by adding water and sand after 10 samples had been taken to replace the water and sand removed by the sampling. However, because the exact amount of the water and sand that had been removed were never known until after the samples had been analyzed, the amount of water and sand added to the flume was an estimate of the amount that had been removed by sampling.

It was thought that this procedure would add unknown variables to the results of future experiments. A final preliminary experiment, P-4, was therefore conducted to determine if the reference sample varied over the course of an experimental run if no water and sand were added to the flume to replace the water and sand removed by sampling. Based on the results of this experiment it was decided not to attempt to replace the water and sand removed with the precaution that a reference sample was taken before and after each test sample as described in Section IV-B. It was assumed that any variations in the concentration of the reference samples would be linear with time and, consequently, an average of the reference sample concentrations would be the actual concentration at the sampling point when the test sample was taken.

Group 2: Experiments to Determine Sampling Conditions

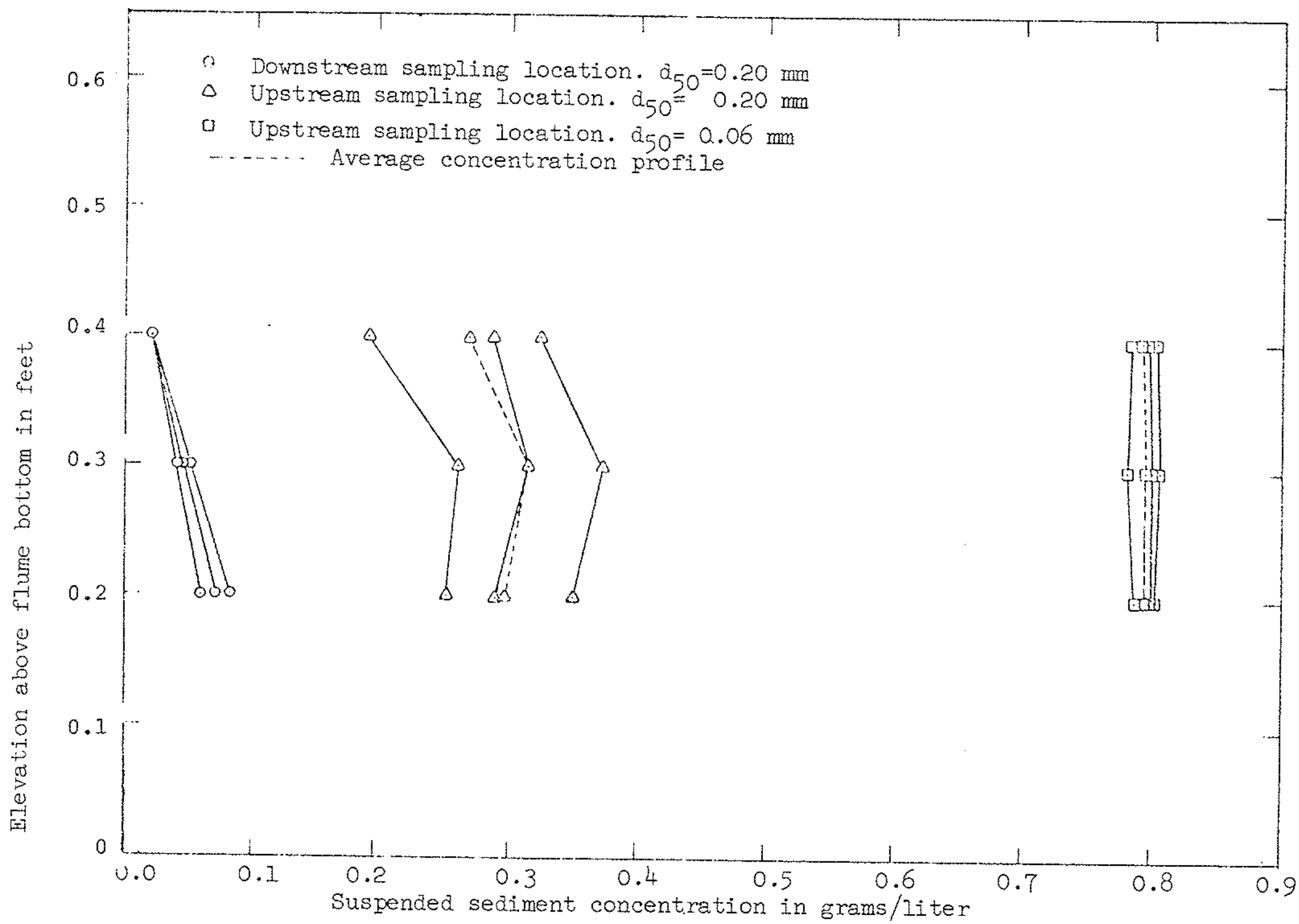
The next group of experiments, to determine the sampling conditions in the flume, were conducted toward the end of the sampling program. The experiments were done for two reasons. First, to measure the concentration and velocity gradients in the flume at the sampling locations. Second, to determine a rating curve between the computed mean velocity of the water (Q/A) and the actual velocity of the water at each sampling location and elevation.

The vertical concentration gradients for two sizes of quartz sand, d_{50} = 0.06 and 0.20 mm, were measured at the upstream sampling location in runs A-502 and A-501, respectively. The vertical concentration gradient for 0.20 mm sand was measured at the downstream sampling location in run A-503. The concentrations were measured at three elevations above the bottom of the flume at both sampling locations; 12.19 cm, 9.14 cm, 6.10 cm, (0.400 ft., 0.300 ft., 0.200 ft.), which bracketed the sampling elevation of 9.14 cm (0.300 ft.).

Three separate concentration profiles were measured over the course of the run. Because the concentration at any point in the flume changed over the course of an experimental run, a time-averaging technique for measuring the vertical concentration gradients was used. At each elevation, several thirty second samples were taken in a sequence so as to avoid any bias and combined into one sample. For comparison the gradients measured at both the upstream and the downstream sampling locations are shown in Fig. V-1. As can be seen from Fig. V-1, the concentration of the 0.06 mm sand is nearly uniform with depth, but the concentration gradient of the 0.02 mm sand is not.

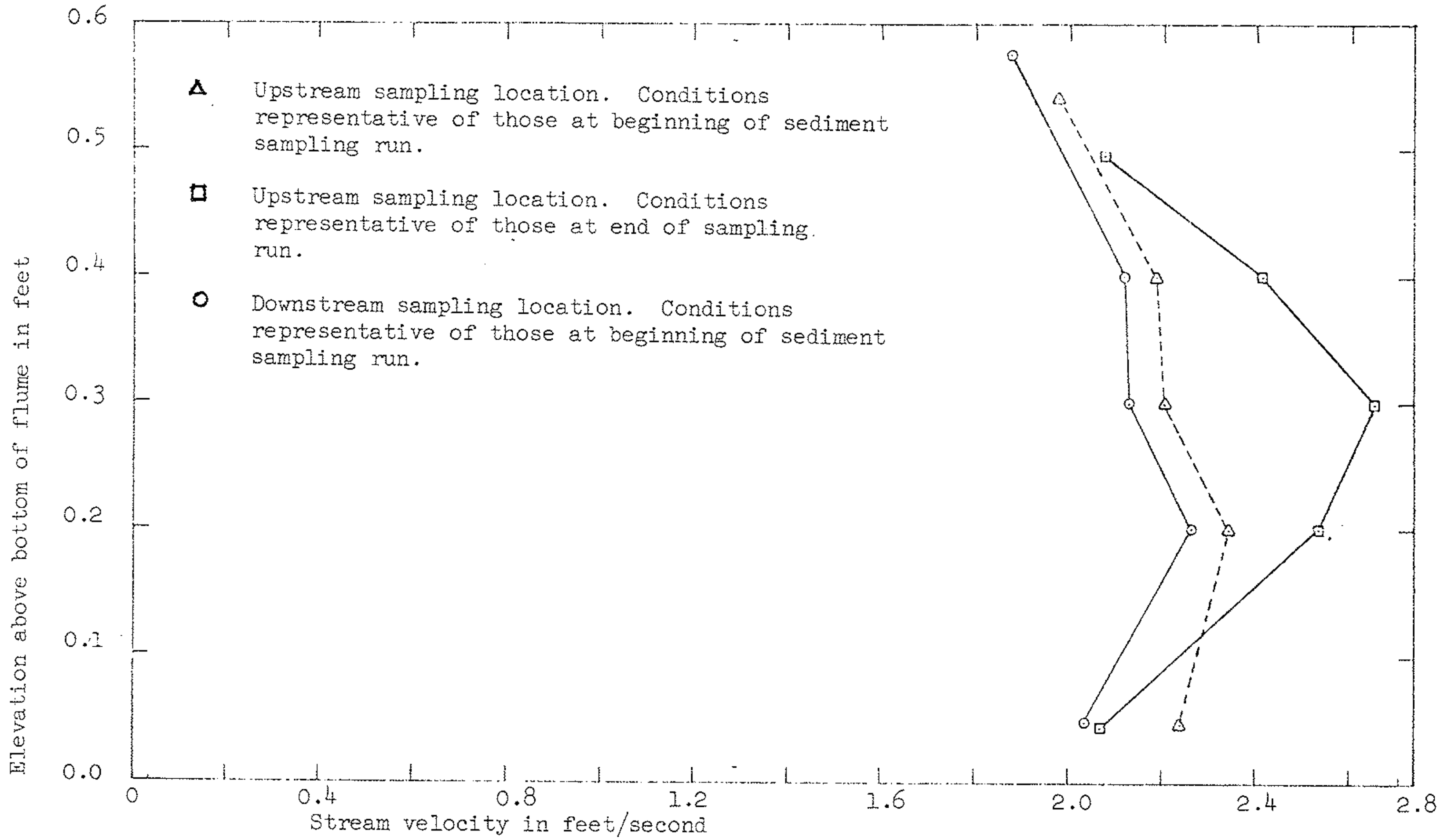
Before the velocity gradients were measured, a preliminary run, B-1, was conducted to find the minimum length of time needed to obtain an accurate average velocity at the sampling location. Ten-second averages were measured with the Delft micro-propeller velocity meter with about three seconds between each measurement. A running average of the measurements was computed and a "student's t" analysis was done. Based upon the results of this run it was felt that two minutes, within the 95 percent confidence limits, would be a sufficient time to measure the velocity.

The velocity profiles at the upstream and downstream sampling locations were measured in runs B-3 and B-6. The velocities were measured at five elevations in the flow: at the surface, at the bottom, and at 6.10 cm, 9.14 cm, and 12.19 cm (0.200 ft., 0.300 ft., 0.400 ft.) above the bottom of the flume. Twelve ten-second velocity measurements were taken at each elevation. These were averaged to obtain the velocity at that elevation. The gradients are shown in Fig. V-2 for both sampling locations. A lower water surface elevation occurred at the downstream sampling location than at the upstream sampling location because the water surface sloped between the two sampling locations.



Concentration profiles at upstream and downstream sampling locations. Quartz sand used: d_{50}= 0.06 and 0.20 mm. Runs A501 and A502 plotted.

FIGURE V-1



Velocity profiles at upstream and downstream sampling locations. Q= 0.0167 m/s (0.590 fps).

FIGURE V-2

The relationship between the mean velocity in the flume and the velocity of the water at the sampling elevation was investigated in experimental runs B-5 and B-7. The mean velocity was calculated by dividing the volumetric flow rate measured with the orifice meter by the cross-sectional area of the flow at the sampling location. The velocity at the sampling location and sampling elevation was measured with the Delft velocity meter. The results of the runs are plotted in Fig. V-3 for the upstream location and in Fig. V-4 for the downstream location.

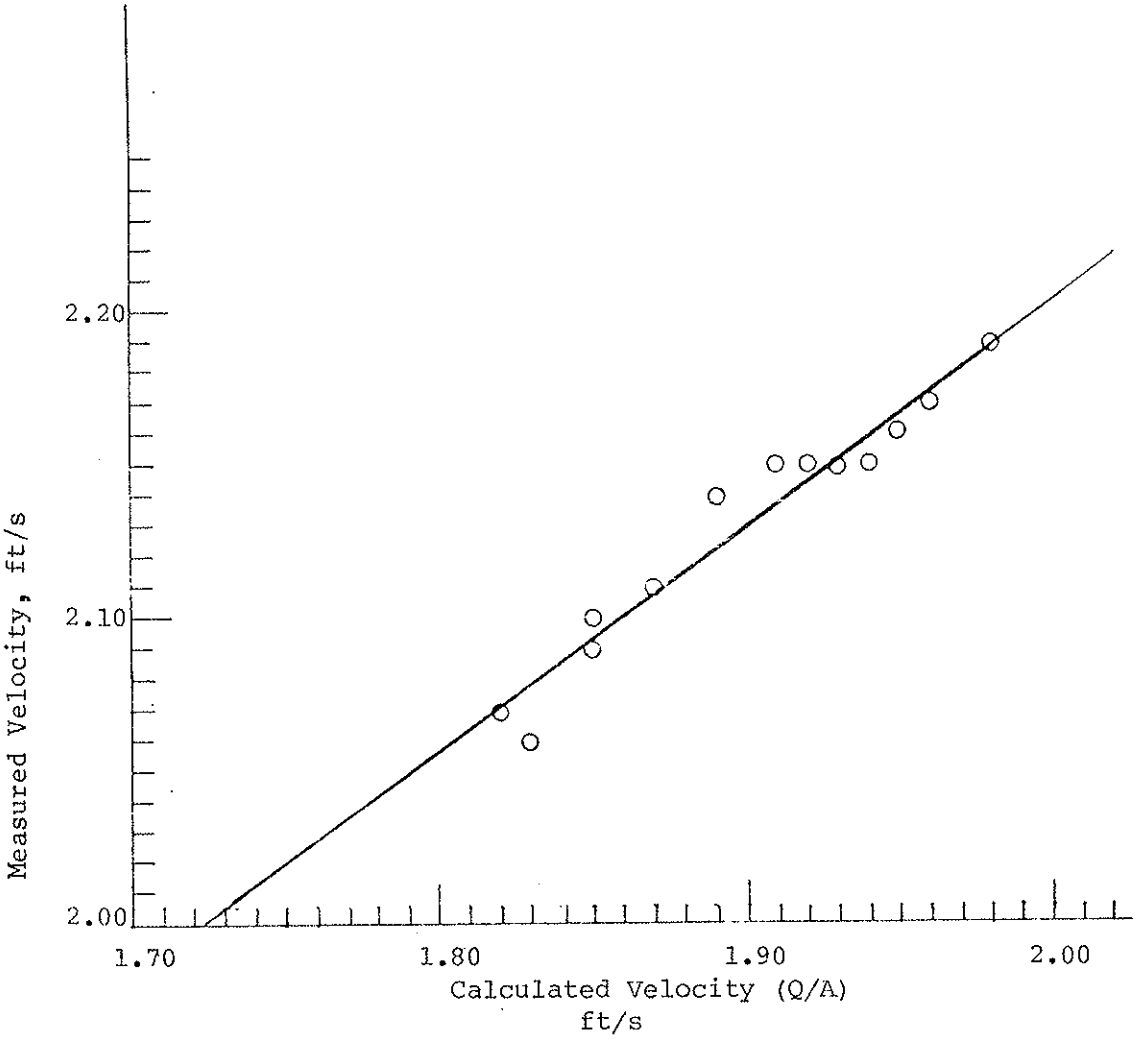
The velocity measurements were made after the majority of the sampling program was completed. The assumption had been made originally that the mean velocity calculated from the cross-sectional area and the flow rate would be a good approximation of the velocity at the sampling point. As can be seen from Fig. V-3 and Fig. V-4 the mean velocity underestimates the velocity at the sampling point be about 11.2 percent at the upstream sampling location and by about 12.4 percent at the downstream location.

Since the mean velocity was used to set the intake rate in the nozzle, this rate was about 12 percent too low for those sampling runs conducted before the velocity gradients were measured. Those conducted afterward used the velocity at the sampling point as calculated from the mean velocity and the rating curves in Figs. V-3 and V-4. The effect that this had on the results of the sampling run is discussed in Section VI.

Group 3 and 4: Isokinetic and Twice Isokinetic Sampling

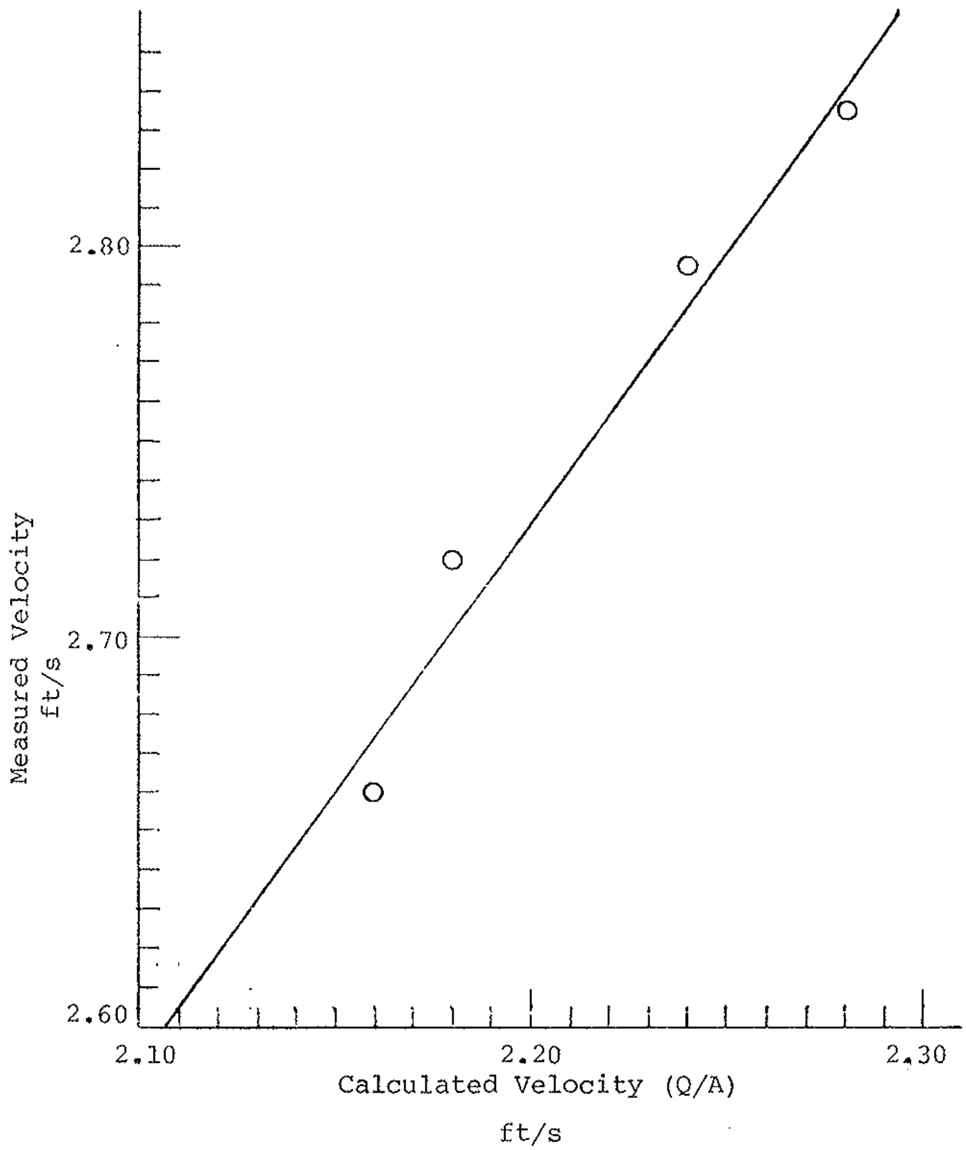
The primary purpose of the experiments was to determine the errors in measuring suspended sediment concentration because of sampling nozzle orientation. Two sets of experimental runs, 200 through 600 and 1100 through 1200, were conducted. These experiments are described below. Other experiments done to test the validity of assumptions or the accuracy of the sampling method used are described later.

Three sizes of quartz sand were used in this sampling program, d_{50} = 0.06, 0.11, 0.20 mm. Originally only 0.06 and 0.11 mm sand was intended to be used; but after evaluating the results of the runs using 0.11 mm sand, it was decided to use the larger sand to help define some trends that had been noted.



Relationship between calculated average velocity (Q/A) at upstream sampling location and measured velocity at .0914 m (0.300 ft) above flume bottom.

FIGURE V-3



Relationship between calculated velocity (Q/A) at downstream sampling location and measured velocity 0.0914 m (0.300 ft) above flume bottom.

FIGURE V-4

Although the term isokinetic has little meaning when applied to a nozzle that is withdrawing water at some other angle than directly into the flow, it is a useful way of describing the intake velocity of the sampling nozzle. Two withdrawal rates were used, "isokinetic" and "twice isokinetic." Runs numbered 200 through 600 were conducted with isokinetic withdrawal rates and runs 1100 and 1200 with twice isokinetic withdrawal rates. The sampling was done as described in Section IV. The reference samples for all runs, isokinetic and twice isokinetic, were removed from the flume isokinetically, the nozzle facing into the flow. The reference sample times were five minutes. The test samples for the isokinetic runs were removed at an isokinetic withdrawal rate, although the nozzle was oriented at one of the eight angles shown in Fig. I-2. The sample times for these samples were five minutes. The test samples for the twice isokinetic runs were removed in the same manner as the isokinetic test samples except that the withdrawal rate was twice isokinetic. The sampling times were two and a half minutes. With these shortened sampling times, the volume of water removed from the flume was the same as for the isokinetic samples.

The concentrations were determined and the concentration ratios computed as described in Section IV. The results of the experiments are listed in Table V-1 and Table A-1 for the isokinetic experiments and in Table V-2 and Table A-2 for the twice isokinetic experiments. The ratios of test sample concentrations to reference sample concentrations are plotted in Fig. V-5 for the isokinetic samples and in Fig. V-6 for the twice isokinetic samples. Only two sizes of quartz sand, 0.06 mm and 0.20 mm, were used for the twice isokinetic sampling. A comparison between sand sampled at isokinetic and twice isokinetic withdrawal rates is shown in Fig. V-7 for 0.06 mm sand and in Fig. V-8 for 0.20 mm sand. The data points plotted in Figs. V-5 through V-8 are averages of the concentration ratios computed at each angle. Not all of the ratios computed were used in determining the averages. The reasons will be discussed in Section VII.

Group 5: Miscellaneous Experiments

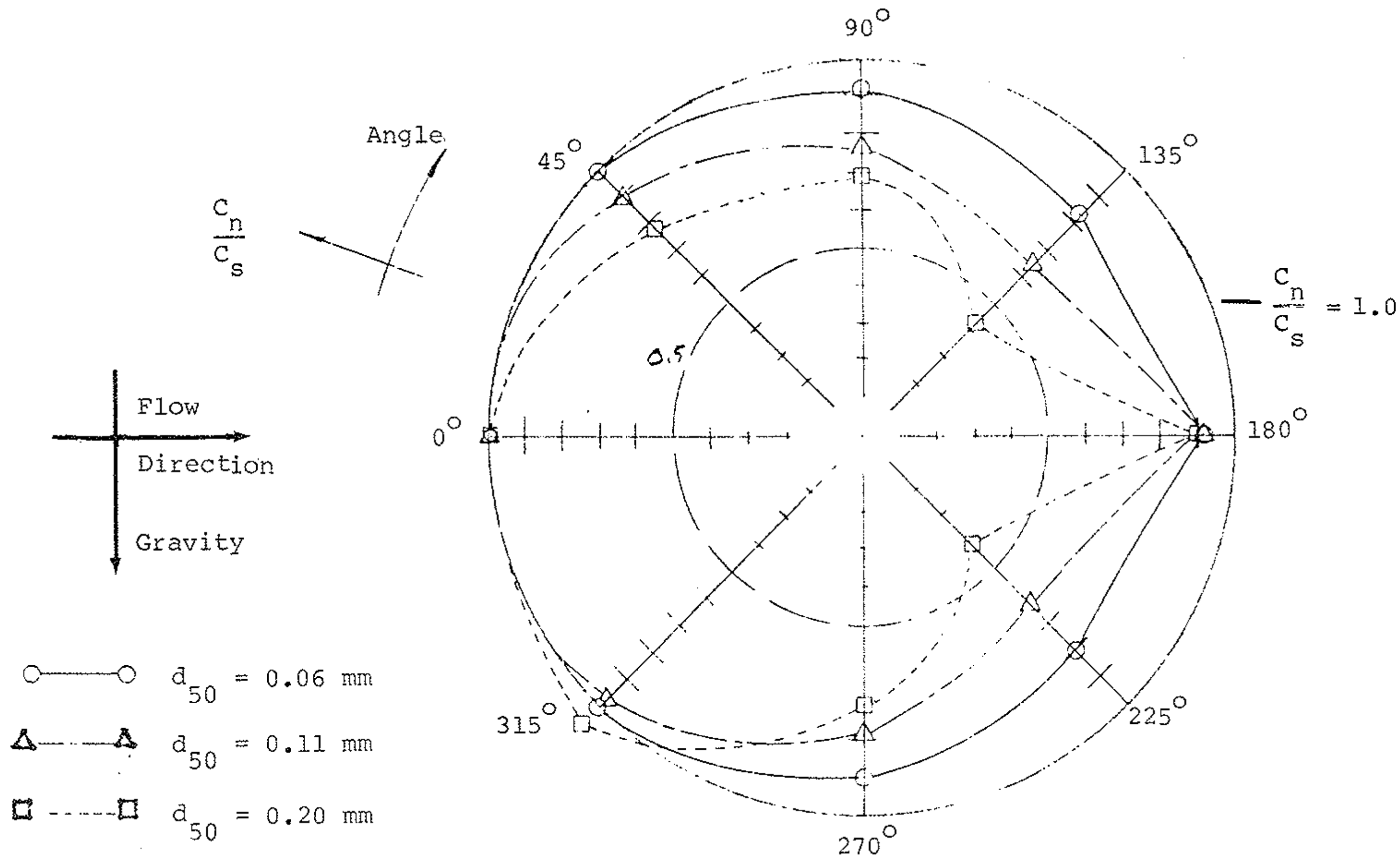
It had been assumed, when designing the experiments, that the concentration in the flume at the time the test sample was taken would be the same as the average of the reference sample concentrations taken before and after the test sample. This assumption was investigated in experimental runs A-101 and A-102.

TABLE V-1: ISOKINETIC SAMPLING CONCENTRATION RATIOS (C_n/C_s)

Sand Size mm	Nozzle Position 45	90	135	180	225	270	315
0.06	.999	.923	.833	.910	.842	.942	1.023
	.998		.843	.849	.779	.903	.989
			.823	.950		.904	
				.961			
0.11	.921	.771	.645	.914	.630	.793	.962
	.879			.873			.973
	.925			.903			
0.20	.779	.683	.415	.905	.388	.712	1.072
					.432		

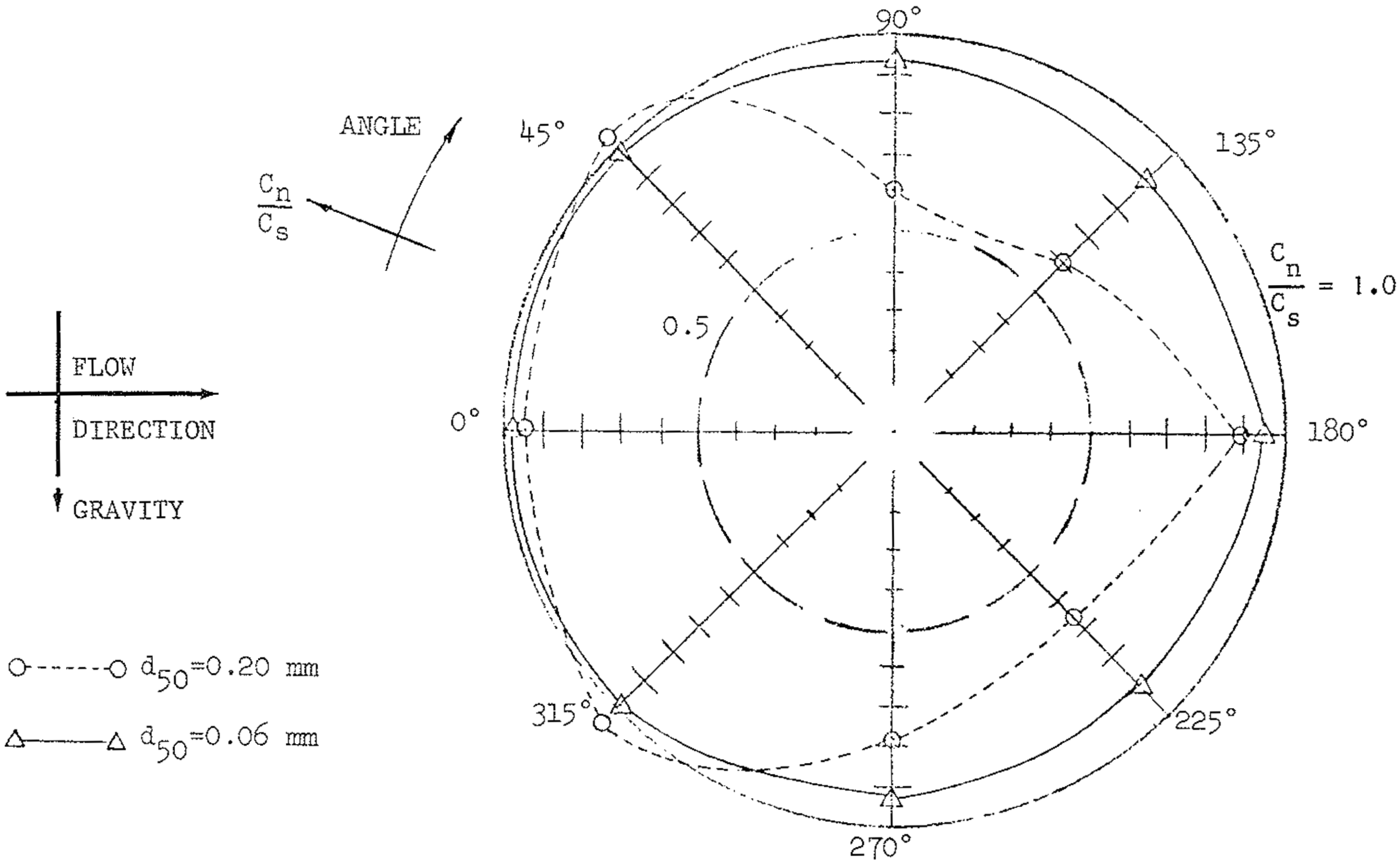
TABLE V-2: TWICE-ISOKINETIC SAMPLING CONCENTRATION RATIOS (C_n/C_s)

Sand Size mm	Nozzle Position 0	45	90	135	180	225	270	315
0.06	.978	.989	.940	.902	.962	.910	.950	.994
	.998		.946				.934	
							.943	
0.02	1.017	.745	.609	.649	.867	.705	.776	1.250
	1.356	1.059	.600		.905		.798	1.052
	1.118	1.041						1.071
	.916							
	.850							



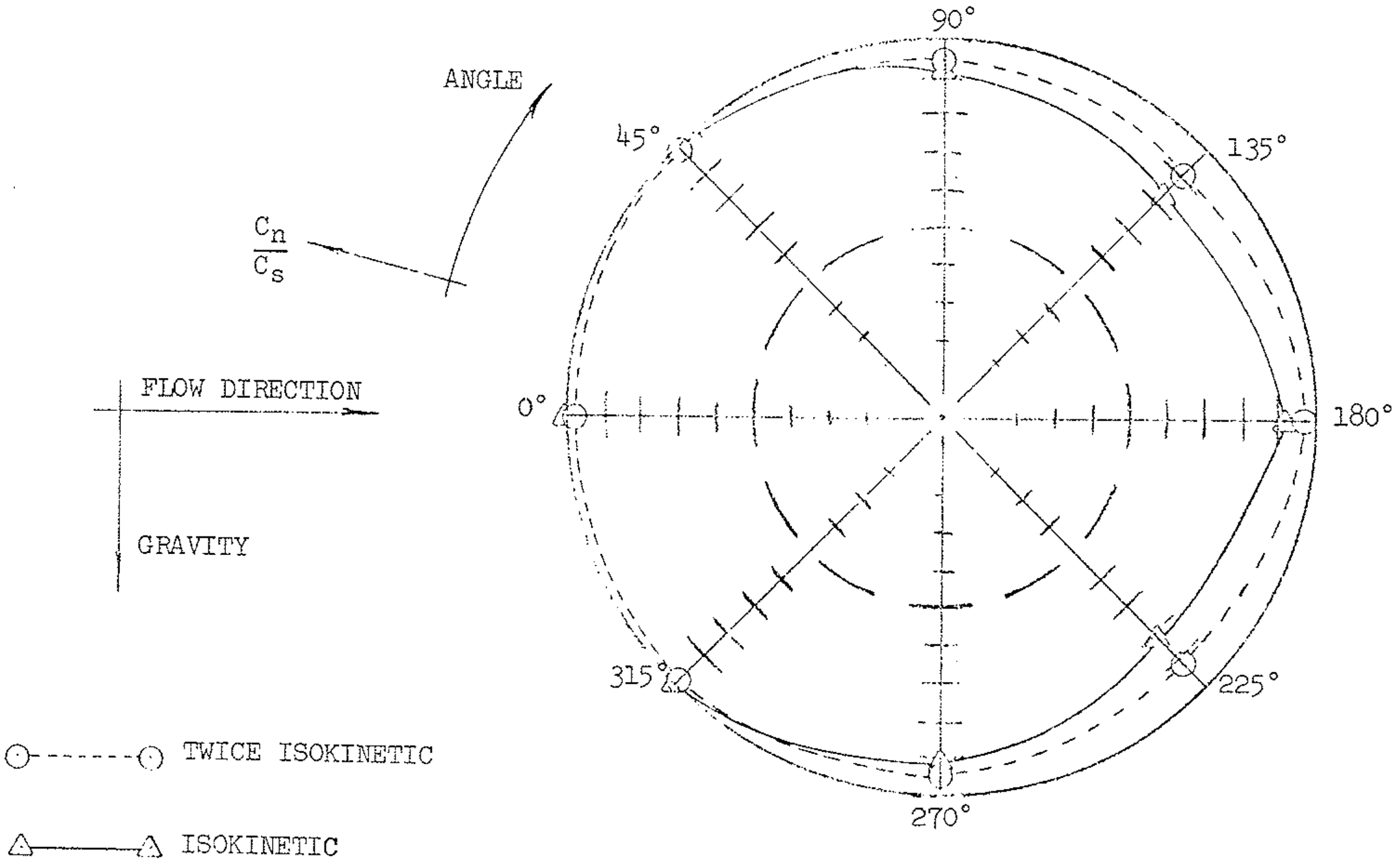
Test concentration (C_n) to reference concentration (C_s) plotted against angle of incidence of nozzle to flow. Isokinetic withdrawal rate. Three sizes of quartz sand used.

FIGURE V-5



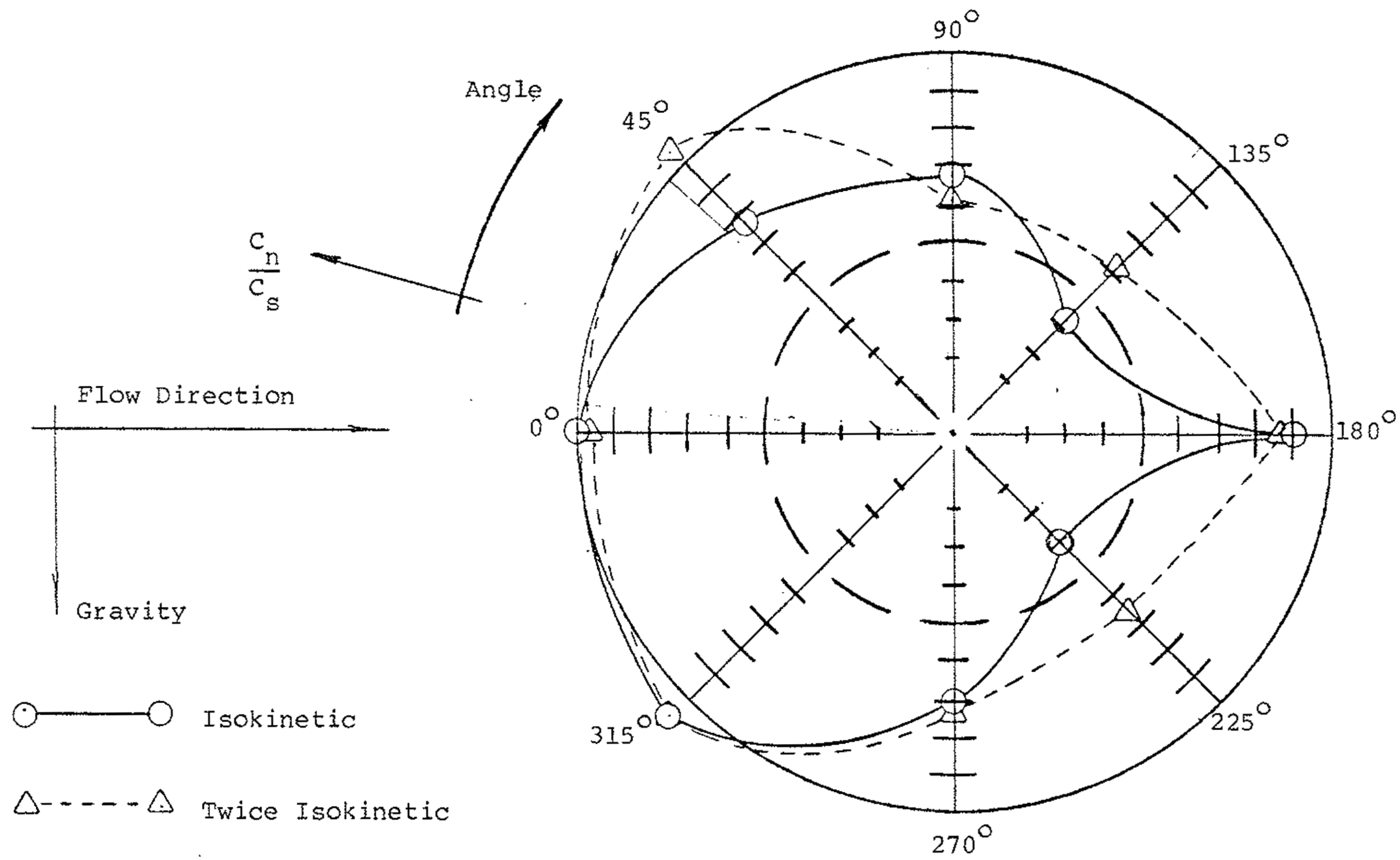
Test concentration (C_n) to reference concentration (C_s) plotted against angle of incidence of nozzle to flow. Twice isokinetic withdrawal rate. Two sizes of quartz sand used.

FIGURE V-6



Test concentration (C_n) to reference concentration (C_s) plotted against angle of incidence of nozzle to flow. Isokinetic and twice isokinetic withdrawal rates. Quartz sand used: d_{50}=0.06 mm.

FIGURE V-7



Test concentration (C_n) to reference concentration (C_s') plotted against angle of incidence of nozzle to flow. Isokinetic and twice isokinetic withdrawal rate. Quartz sand used: d_{50} = 0.20 mm.

FIGURE V-8

For each run, five isokinetic samples were taken at the upstream sampling location using the same procedures used for taking reference samples in the Group 4 experiments. The concentrations of the first and third and the third and fifth samples were averaged and are compared with the concentrations of the second and fourth samples, respectively, in Fig. V-9 for 0.06 mm sand and in Fig. V-10 for 0.20 mm sand.

The percent difference between the concentration of a sample and the approximation found by averaging the concentration of the samples taken before and after it are -0.2 and +3.3 percent for the 0.06 mm sand and -0.8 and +2.7 percent for the 0.2 mm sand. The percent differences were calculated using the following formula:

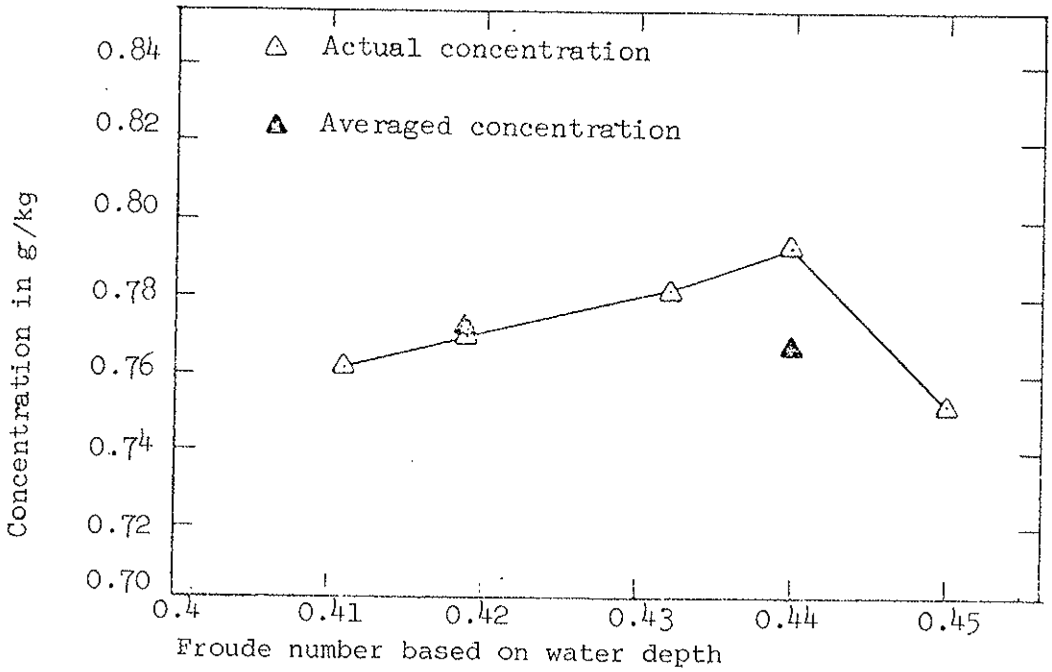
$$\Delta\% = \frac{\text{measured concentration - averaged concentration}}{\text{averaged concentration}} \times 100 \qquad (14)$$

A discussion of the possible errors introduced by the assumption is given in Section VII.

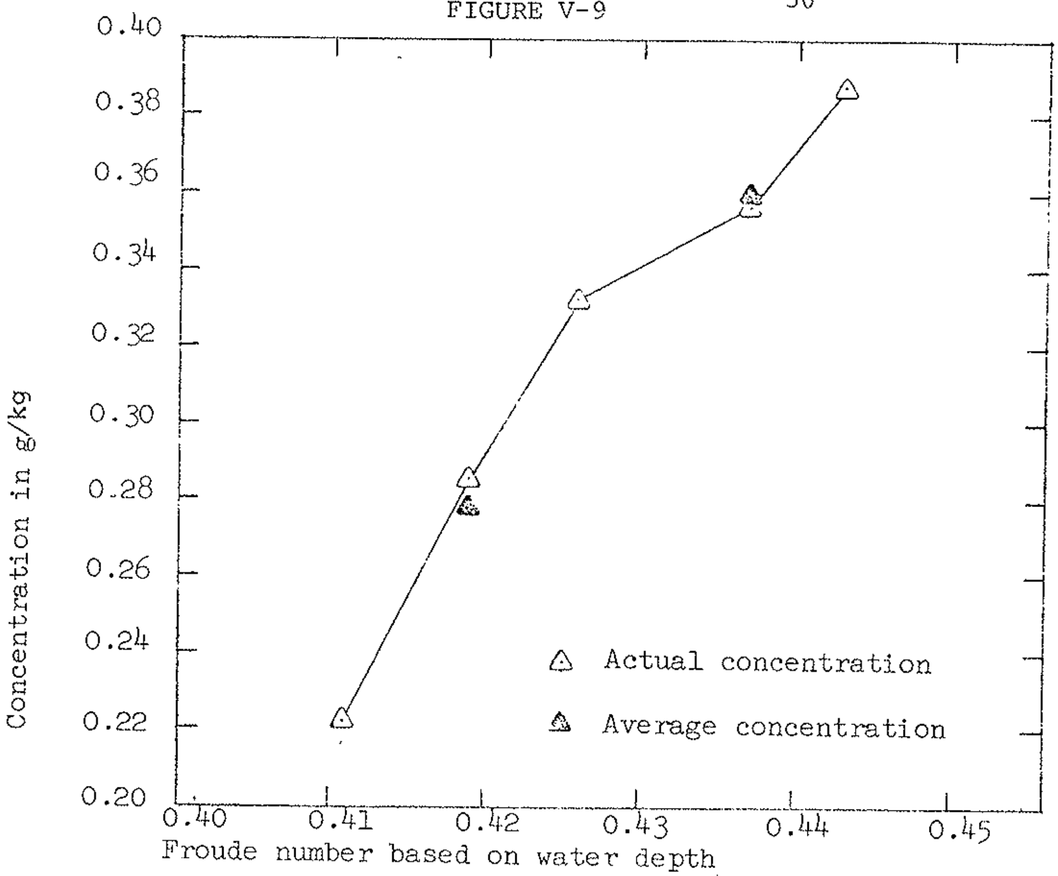
Several experiments were decided upon after analysis of the results of experiments that had been conducted. Because the results at the 180 degree position with the nozzle facing downstream were not expected and did not follow the pattern established by the results at the other angles, several additional experiments were conducted.

It was assumed that the experimental results might be influenced by the disturbance in the flow caused by the nozzle, the nozzle holder and support, and the siphon tubing. To test this supposition, the brass nozzle, illustrated in Fig. III-3 and described in Section III, was constructed. The purpose of this nozzle was to minimize the flow disturbances from the nozzle, nozzle holder, and siphon tubing at the nozzle mouth. To achieve this goal, the support rod was placed more than 18 nozzle diameters away from the nozzle mouth to allow any perturbations in the flow caused by the holder or tubing to dissipate by the time the flow reached the nozzle mouth. In addition, the nozzle was polished with emery cloth to smooth out or remove nicks and scratches on the nozzle that might perturb the flow.

Two point gages were attached to the flume, one upstream and one downstream of the sampling location, so that when the brass nozzle was mounted on either one, the nozzle mouth was at the same spot in the flume. Using this arrangement, the brass nozzle was mounted on the downstream point gage to take the reference



Comparison of averaged concentrations with actual concentrations. Quartz sand used: d_{50} = 0.06 mm.
FIGURE V-9



Comparison of averaged concentrations with actual concentrations. Quartz sand used: d_{50}=0.20 mm.

FIGURE V-10

sample. It was then removed, rotated 180 degrees, and mounted on the upstream point gage so that the test sample could be removed from the same spot in the flume. Other than the special method of supporting the nozzle, the same procedures were used as in sampling the isokinetic run samples. The upstream sampling location in the flume was used.

The results from this experiment are compared with the results from the isokinetic sampling runs in Fig. V-11 for all three sand sizes.

The influence of the concentration and velocity gradients on the results of the sampling were also of some concern. Consequently, sampling was done at the downstream sampling location to see if any effects because of changes in concentration and velocity gradients could be noticed. The 225 degree position was selected for sampling at the downstream location because it was the 225 degree position at the upstream sampling location for which the greatest error was measured. The 315 degree position was selected for isokinetic sampling downstream to see if the greater than normal concentration measured upstream was the result of special conditions in the flow at the sampling location.

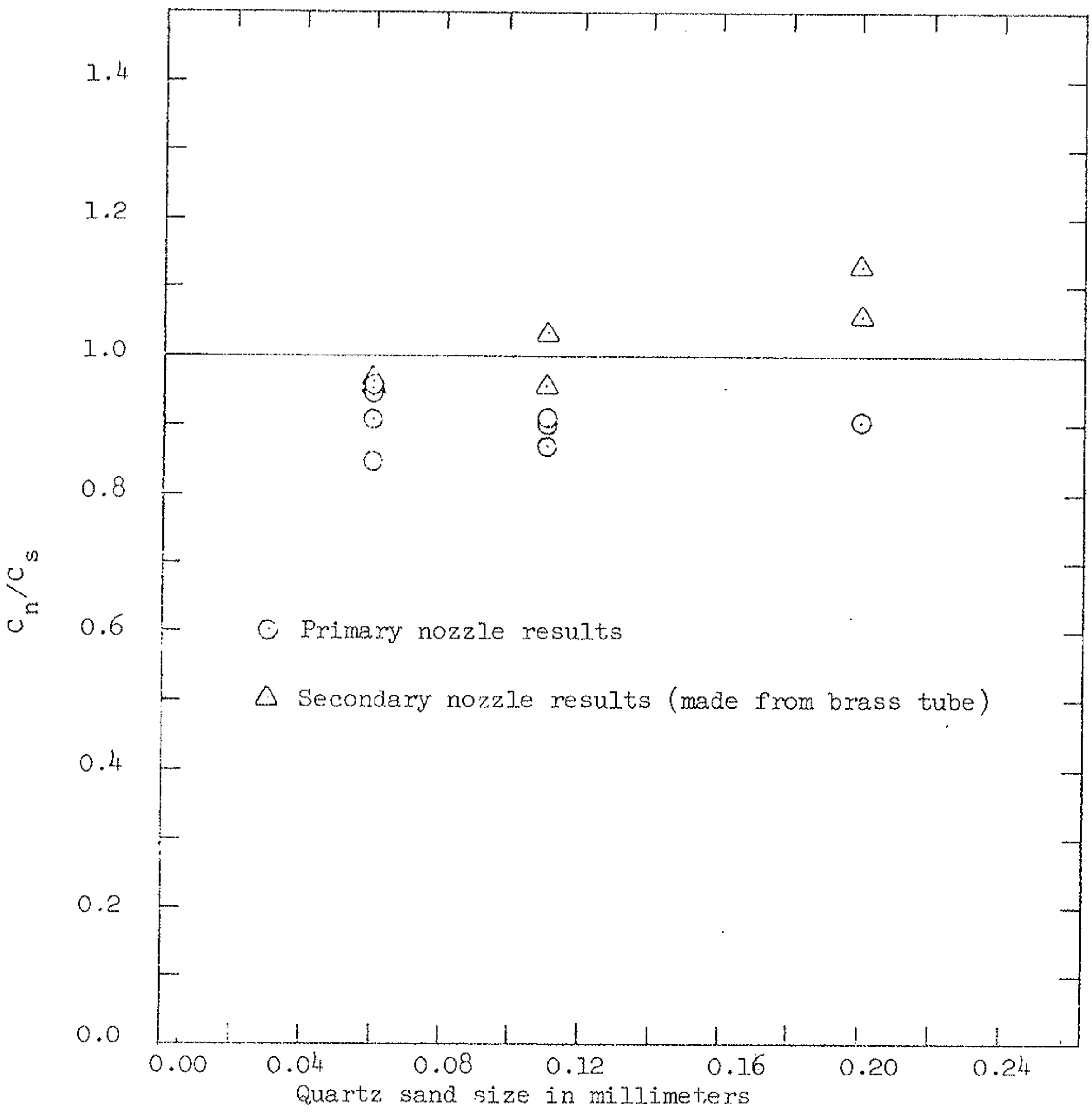
Using an isokinetic withdrawal rate, 0.06 mm and 0.20 mm sand was sampled at the 180 and 225 degree positions. In addition, the 0.20 mm sand was sampled at the 315 degree position. No sampling was done at the downstream sampling location using the 0.11 mm sand.

For at twice isokinetic withdrawal rates at the downstream sampling location, only one position at 0 degrees, and one sand, 0.20 mm, were used. This position was chosen because there was a disagreement between the concentration ratios measured at this position at the upstream sampling location and the concentration ratios computed for this position from the work of the Federal Inter-Agency Sedimentation Project (FIASP, 1971).

The results of the runs at the downstream sampling location are compared with the results from all the runs conducted at the upstream sampling location in Figs. V-12 and V-13 for isokinetic and twice-isokinetic sampling, respectively.

Group 6: Observed Flow Patterns

The flow visualization studies were conducted to observe the flow patterns into and around the sampling nozzle. Very low velocity studies, 0.06 mm/sec



Concentration ratios at 180 degree position using both the primary nozzle and the brass nozzle. Three sand sizes used.

FIGURE V-11

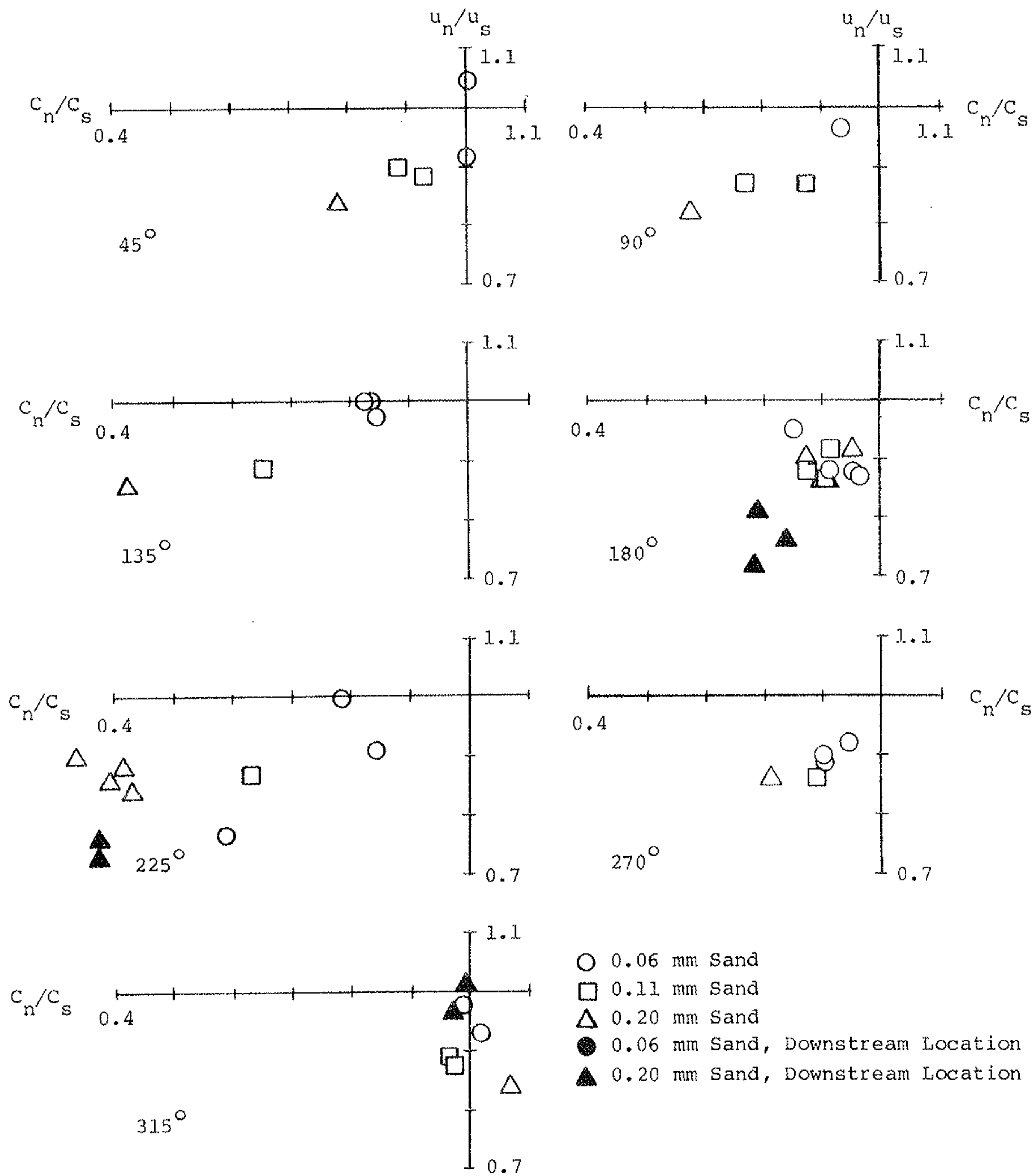


FIGURE V-12 - ISOKINETIC SAMPLING RESULTS

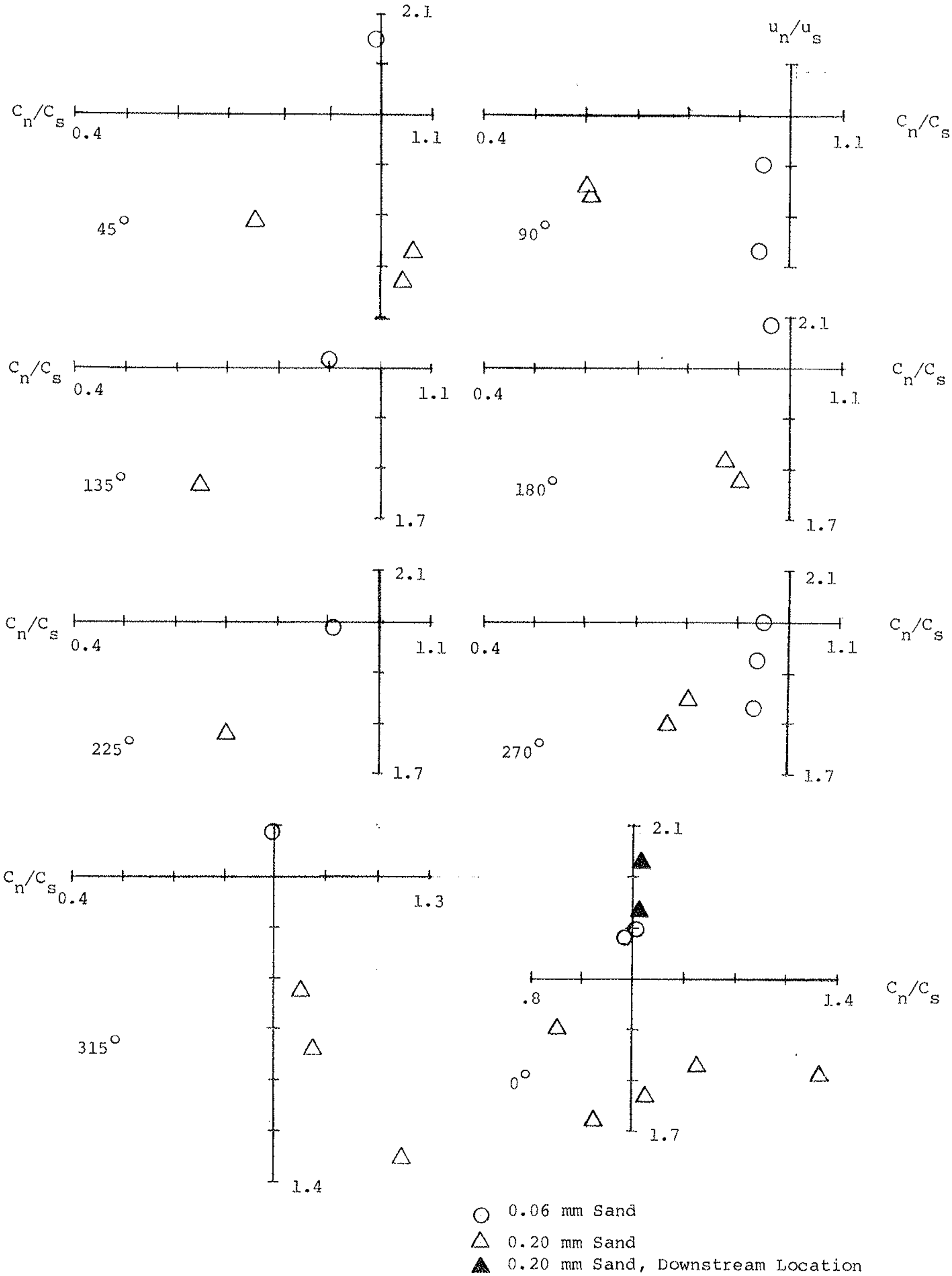


FIGURE V-13 - TWICE-ISOKINETIC SAMPLING RESULTS

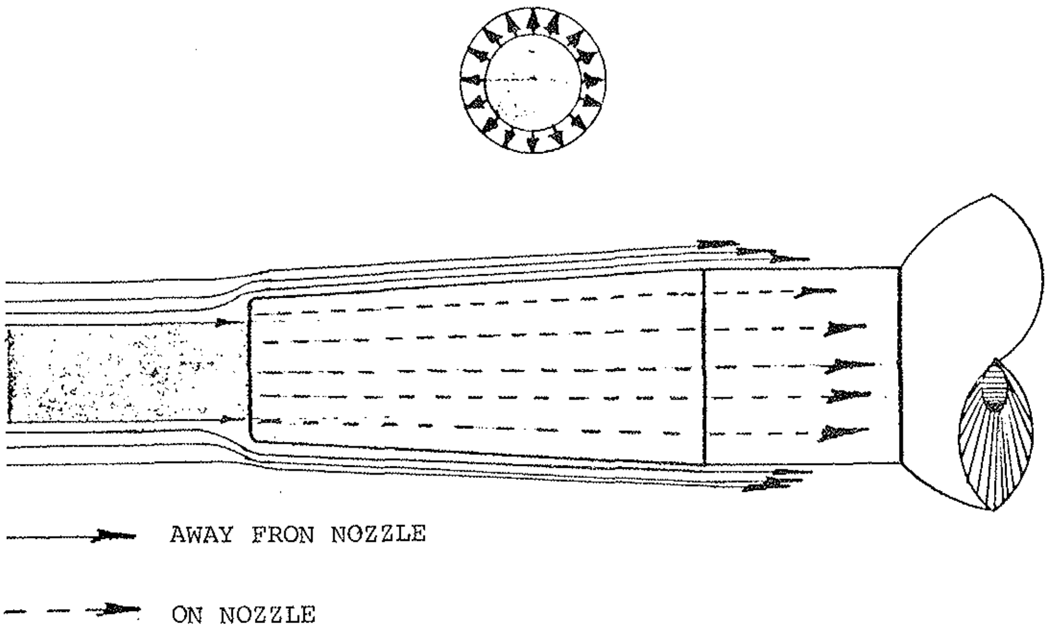
(0.2 fps) were conducted to observe the flow patterns with as little turbulence as possible affecting the flow patterns. Other studies were conducted at velocities approximating the conditions which existed in the sampling phase of the experiments.

The majority of the studies were recorded photographically using a 4x5 view camera and Poloroid film. The observed dye patterns on the photographs were sketched onto scale drawings of the nozzle. These drawings were then checked against a flow visualization study using the hand-held needle. The purpose of this study was two fold; first, to check and clarify dye patterns away from the surface of the nozzle and second, to determine and record the dye patterns at the surface of the nozzle. The advantage of using the hand-held needle was that the dye could be injected at the point in the flow where it was unclear from the photographs what the dye patterns were. Also, the dye could be injected directly at the surface of the nozzle without greatly disturbing the flow.

The observed flow patterns were affected by the stream velocity, the intake velocity, and the interference of the nozzle and its holder with the flow. The size and shape of the streamtube sampled by the nozzle was affected both by the intake velocity and the stream velocity. The effect of the intake velocity seemed limited to changing the shape of the streamtube near the nozzle mouth. The streamtube fluctuated about the nozzle mouth. The fluctuation seemed to be directly related to the amount of turbulence in the stream; it also seemed to decrease with the increasing stream velocities. A stagnation point was observed at all nozzle positions, except the 0- and 180-degree positions, at which the flow separated to go around the nozzle or into the nozzle mouth. The stagnation point moved closer to the nozzle mouth during isokinetic sampling as the stream velocity increased. At the 90-degree position the flow on the back of the nozzle was observed to go away from the nozzle mouth while at the 270-degree position it was observed to go towards the nozzle mouth. This difference in what should by hydrodynamically equivalent situations occurs because the nozzle intersected the water surface in the 270-degree position.

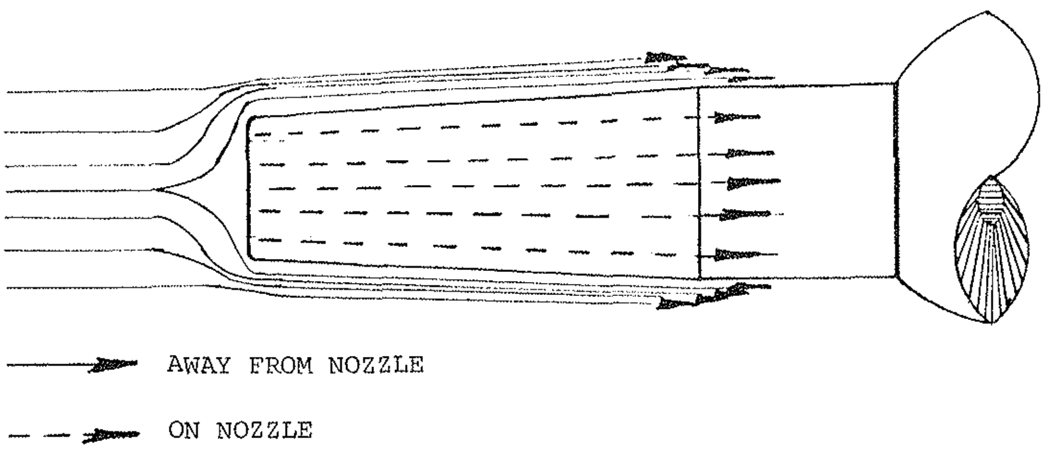
The flow patterns for one flow velocity 0.61 m/sec (2.0 fps) and two intake conditions, isokinetic withdrawal and no withdrawal at all, are shown in Figs. V-15 through V-28. All eight nozzle positions, from 0 to 315 degrees, are shown. The photographs of the other conditions studied either did not show the dye streaks clearly enough to determine the flow patterns, or the dye streaks photographed did not vary enough from the ones shown to determine the difference.

In the diagrams the flow patterns away from the surface of the nozzle are shown as unbroken lines. Those on the surface are shown as broken lines. The region from which water is withdrawn into the nozzle is shaded. The flow patterns shown in the figures are as accurate as could be achieved using the procedures outlined above.



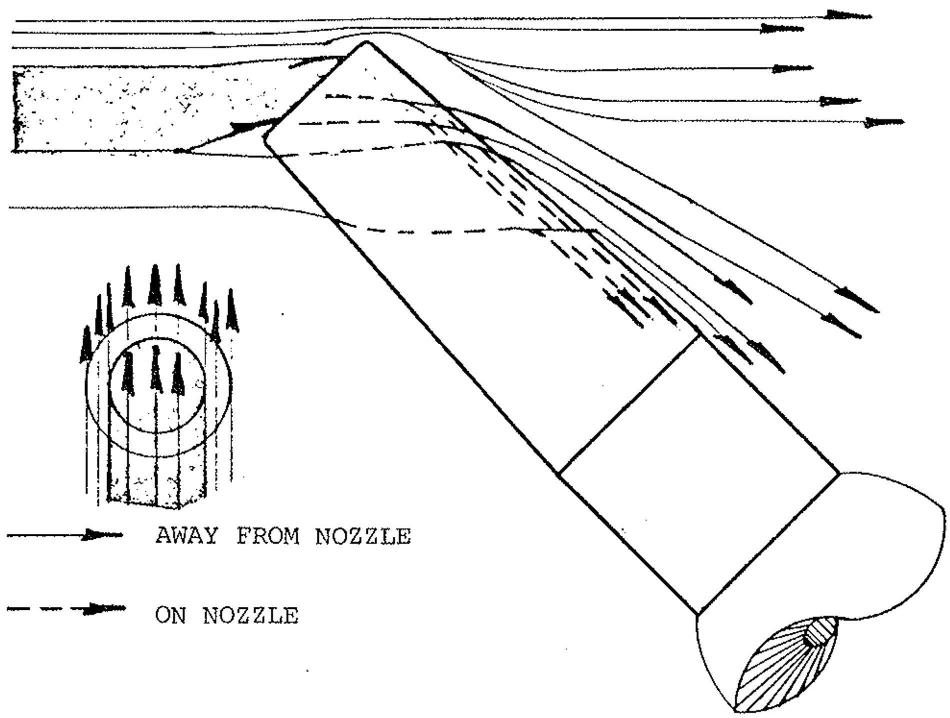
OBSERVED DYE PATTERNS, 0 DEGREE POSITION, ISOKINETIC SAMPLING

FIGURE V-14



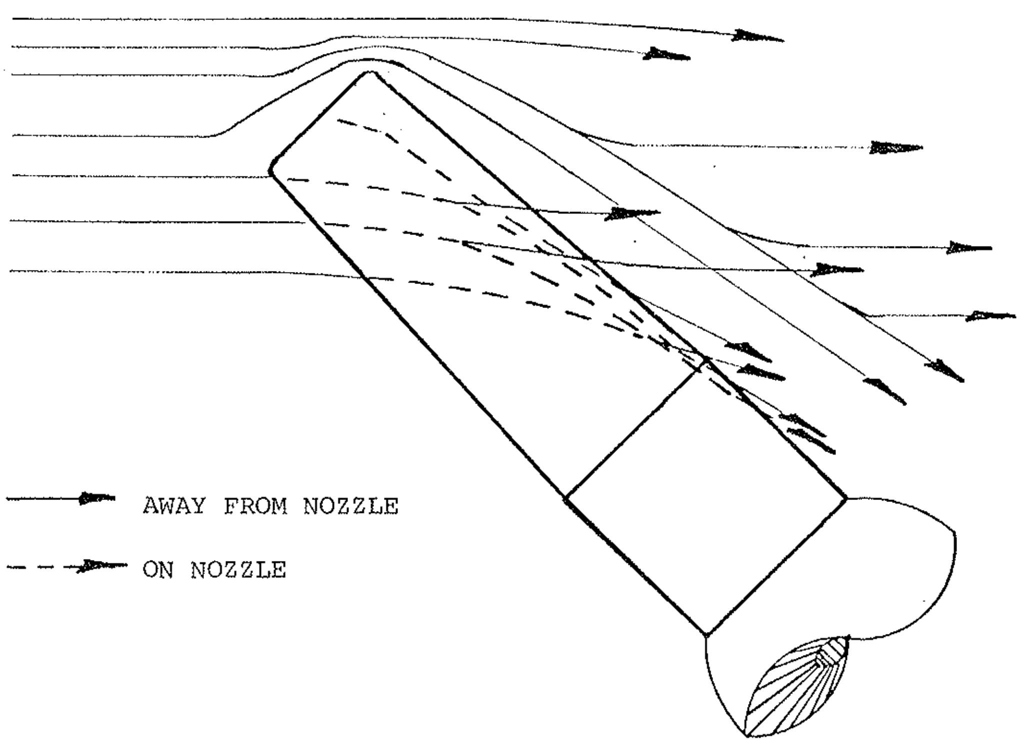
OBSERVED DYE PATTERNS, 0 DEGREE POSITION, NO SAMPLING

FIGURE V-15



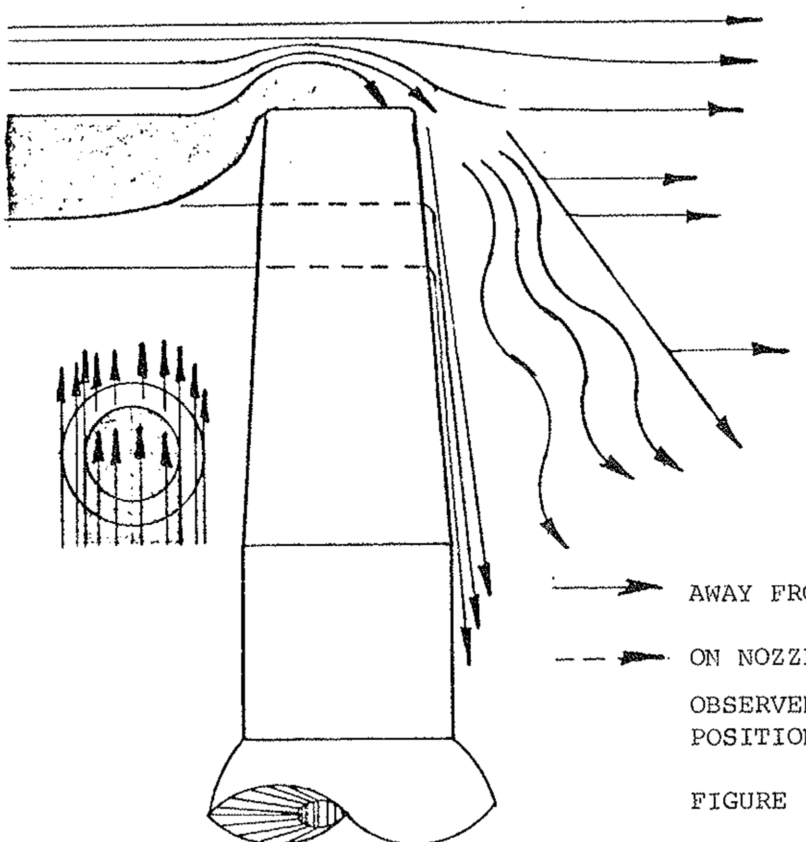
OBSERVED DYE PATTERNS, 45 DEGREE POSITION, ISOKINETIC SAMPLING

FIGURE V-16



OBSERVED DYE PATTERNS 45 DEGREE POSITION, NO SAMPLING

FIGURE V-17



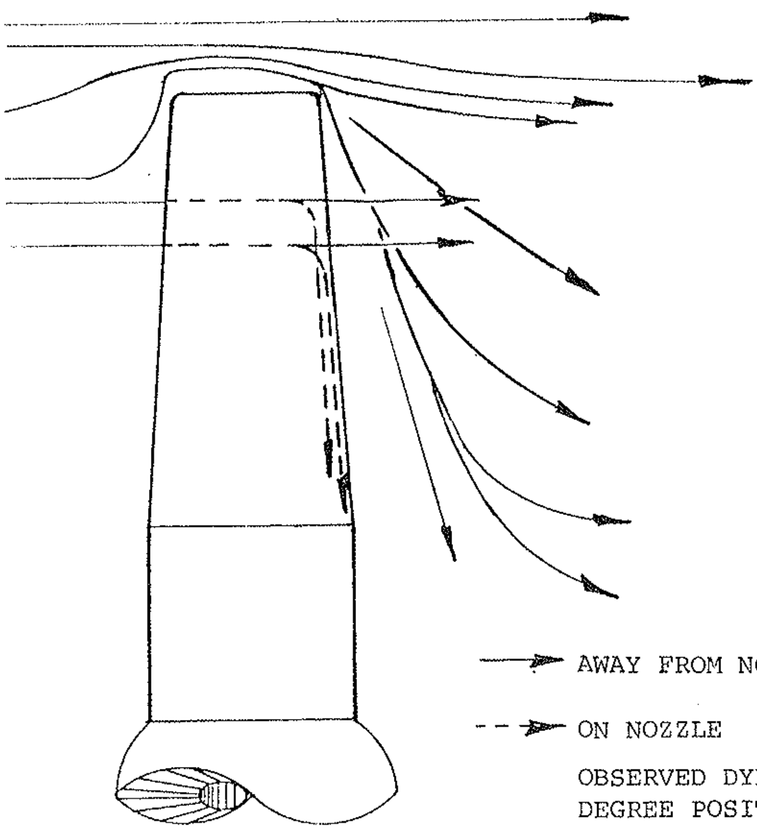
AWAY FROM NOZZLE

ON NOZZLE

OBSERVED DYE PATTERNS, 90 DEGREE POSITION, ISOKINETIC SAMPLING

FIGURE V-18

OBSERVED

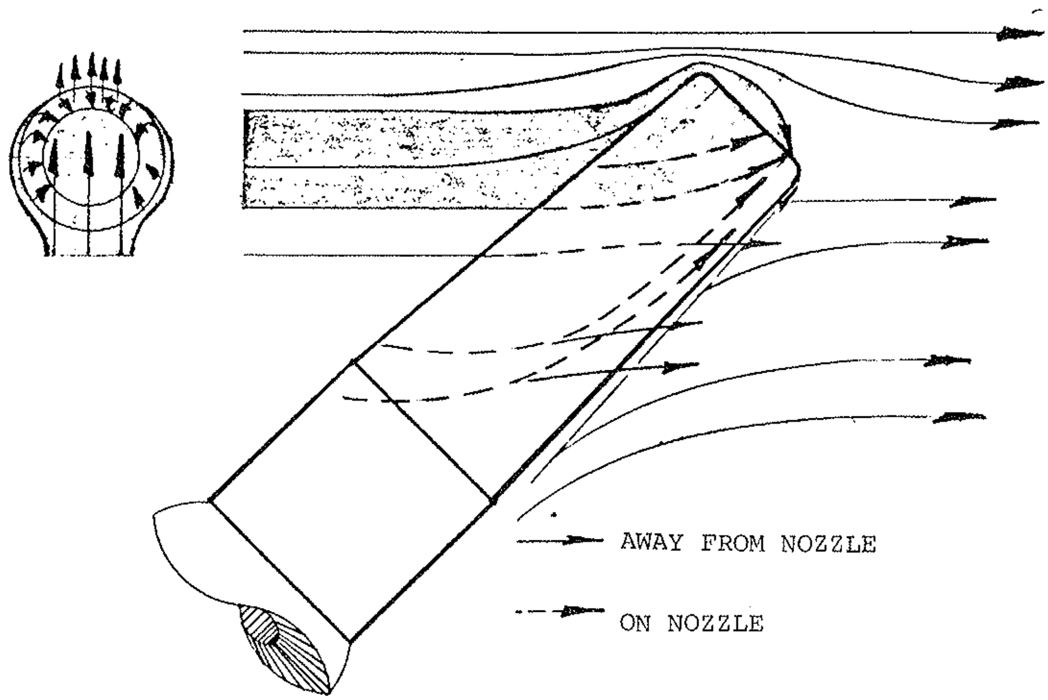


AWAY FROM NOZZLE

ON NOZZLE

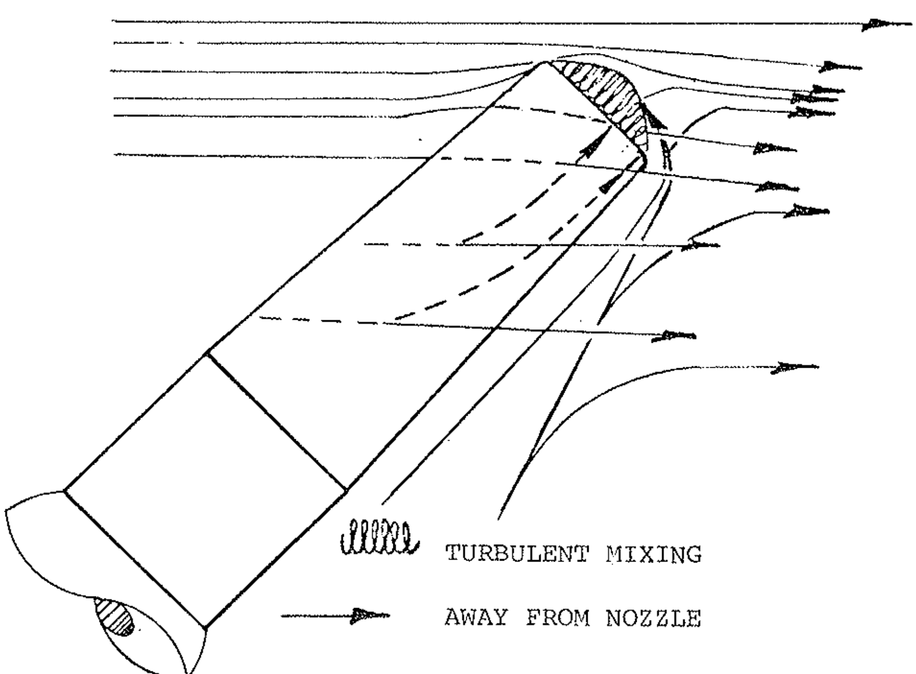
OBSERVED DYE PATTERNS, 90 DEGREE POSITION, NO SAMPLING

FIGURE V-19



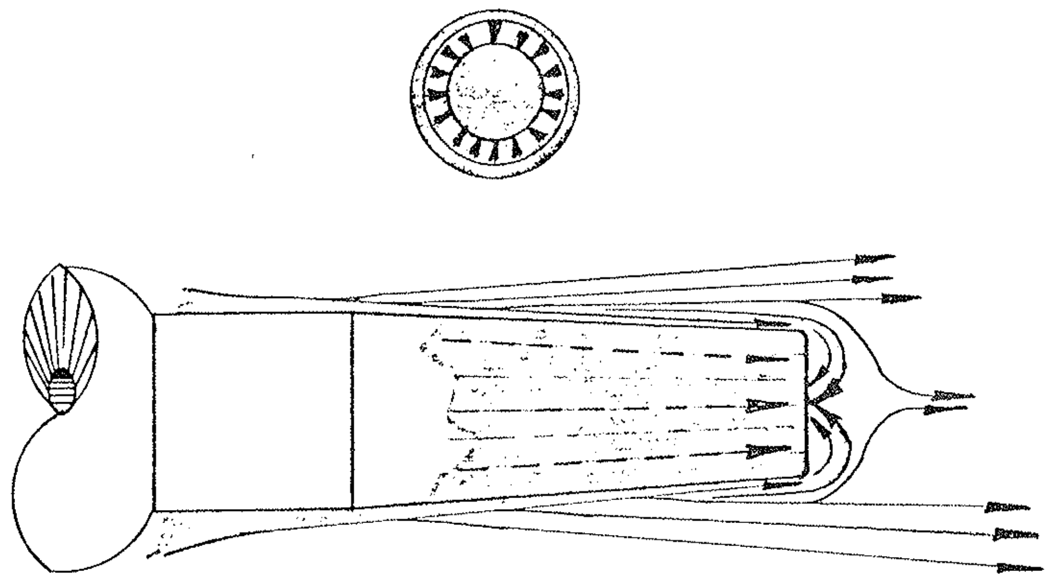
OBSERVED DYE PATTERNS, 135 DEGREE POSITION, ISOKINETIC SAMPLING

FIGURE V-20



OBSERVED DYE PATTERNS, 135 DEGREE POSITION, NO SAMPLING

FIGURE V-21



AWAY FROM NOZZLE

ON NOZZLE

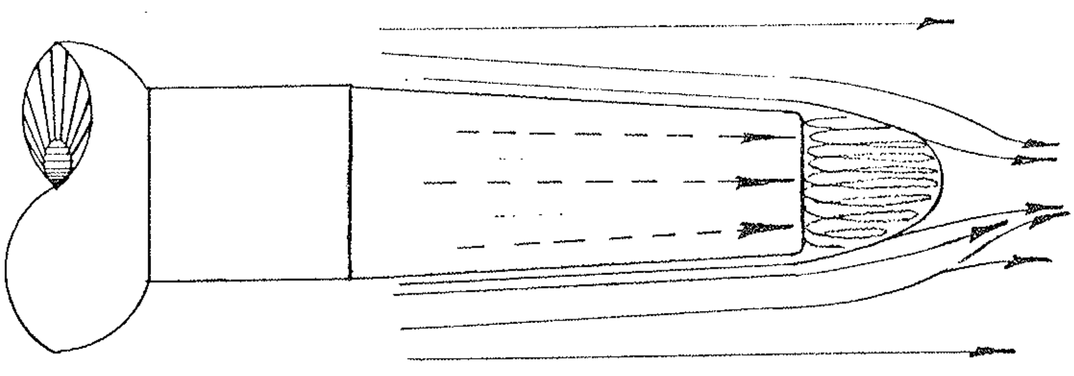
OBSERVED STREAMLINE PATTERNS, 180 DEGREE POSITION ISOKINETIC SAMPLING

FIGURE V-22

WAKE

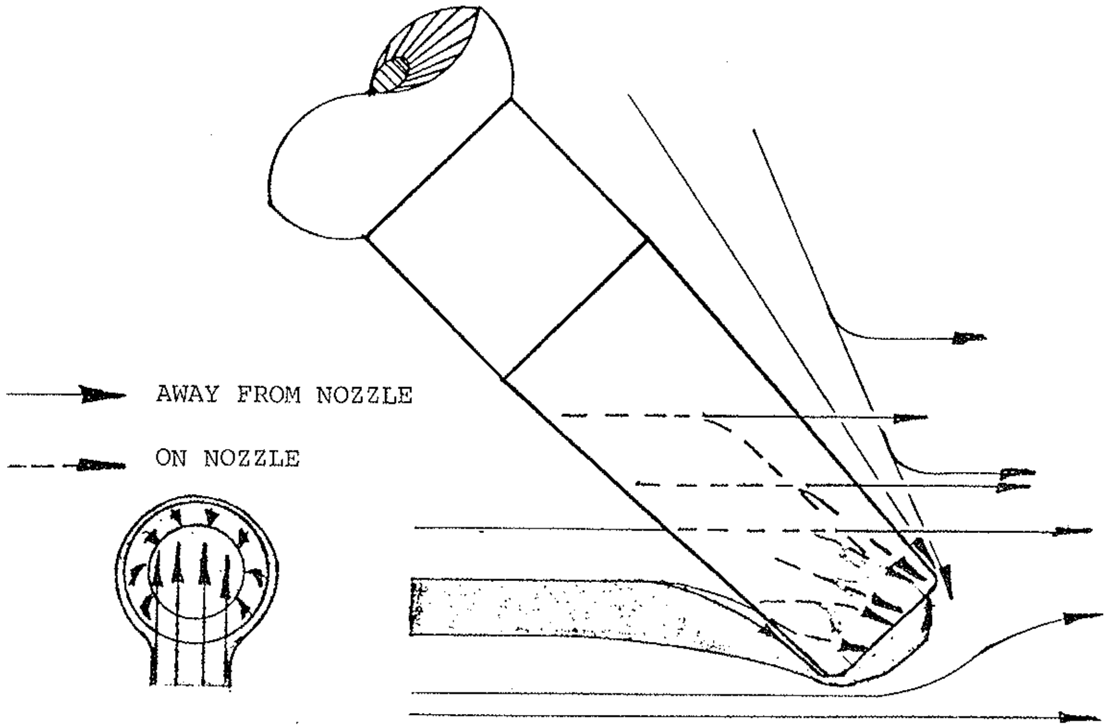
AWAY FROM NOZZLE

ON NOZZLE



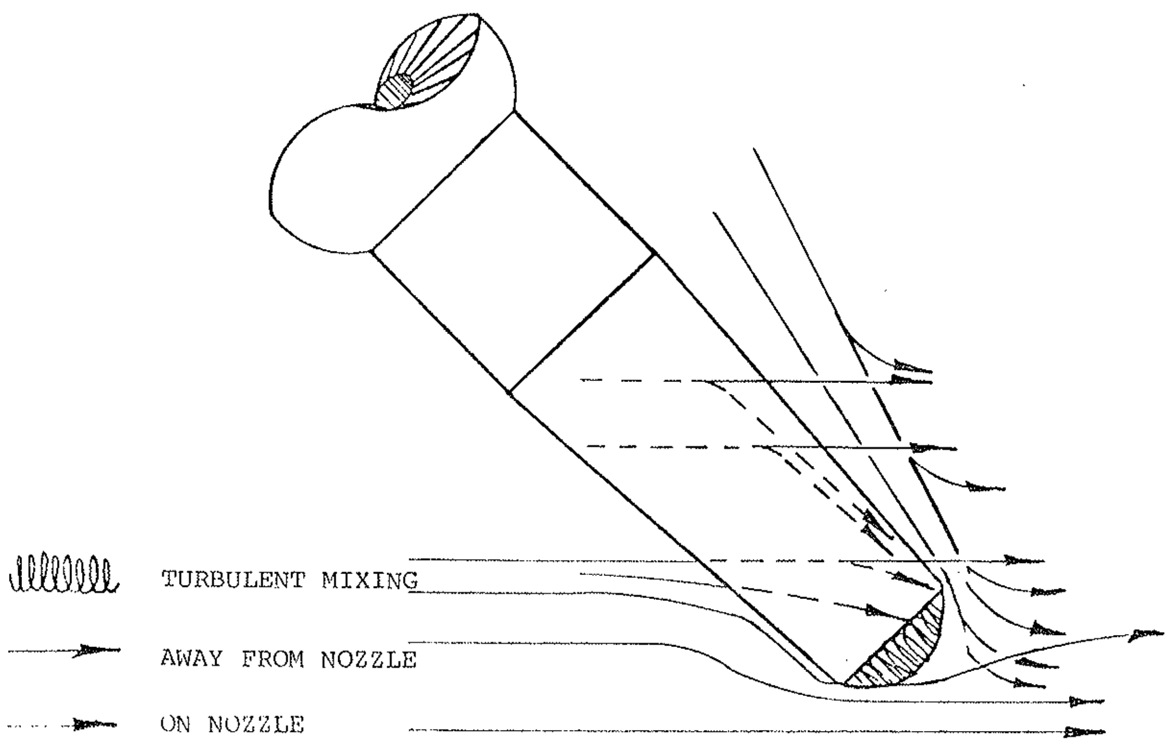
OBSERVED STREAMLINE PATTERNS, 180 DEGREE POSITION, NO SAMPLING

FIGURE V-23



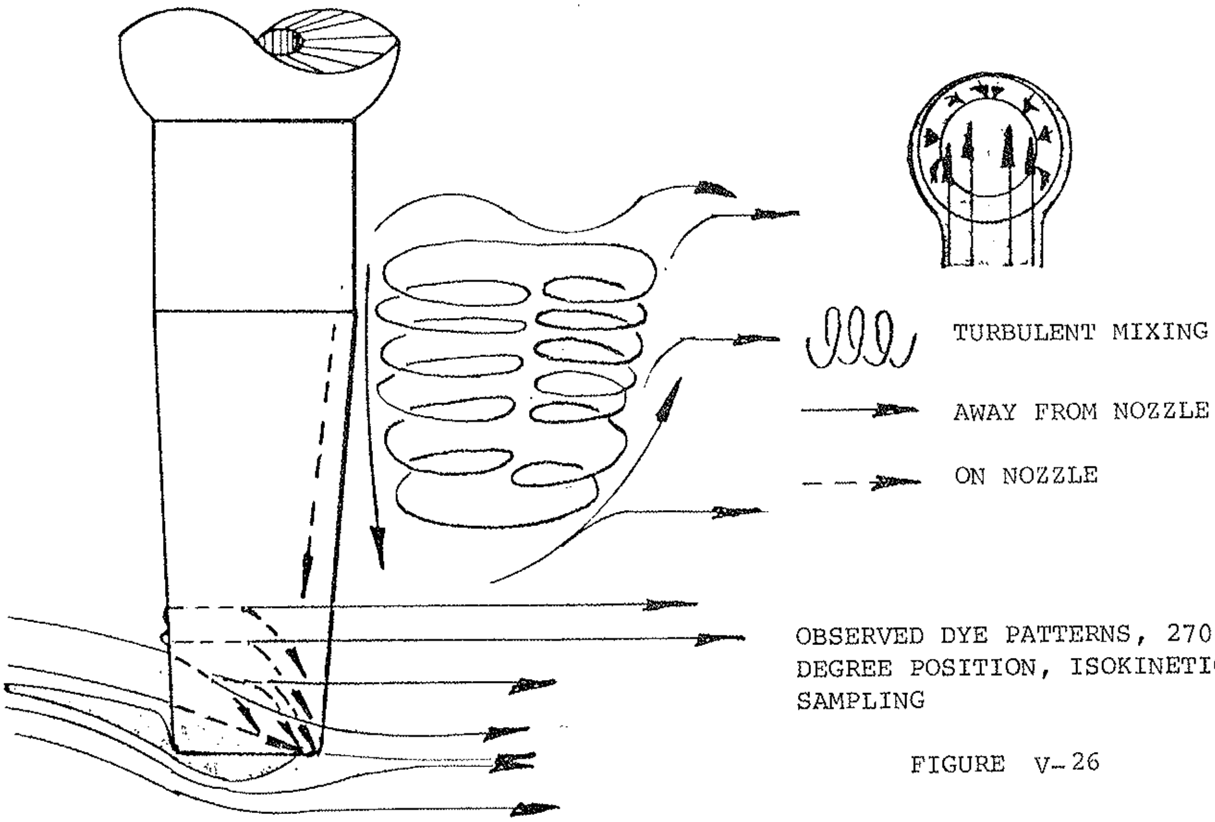
OBSERVED DYE PATTERNS, 225 DEGREE POSITION, ISOKINETIC SAMPLING

FIGURE V-24



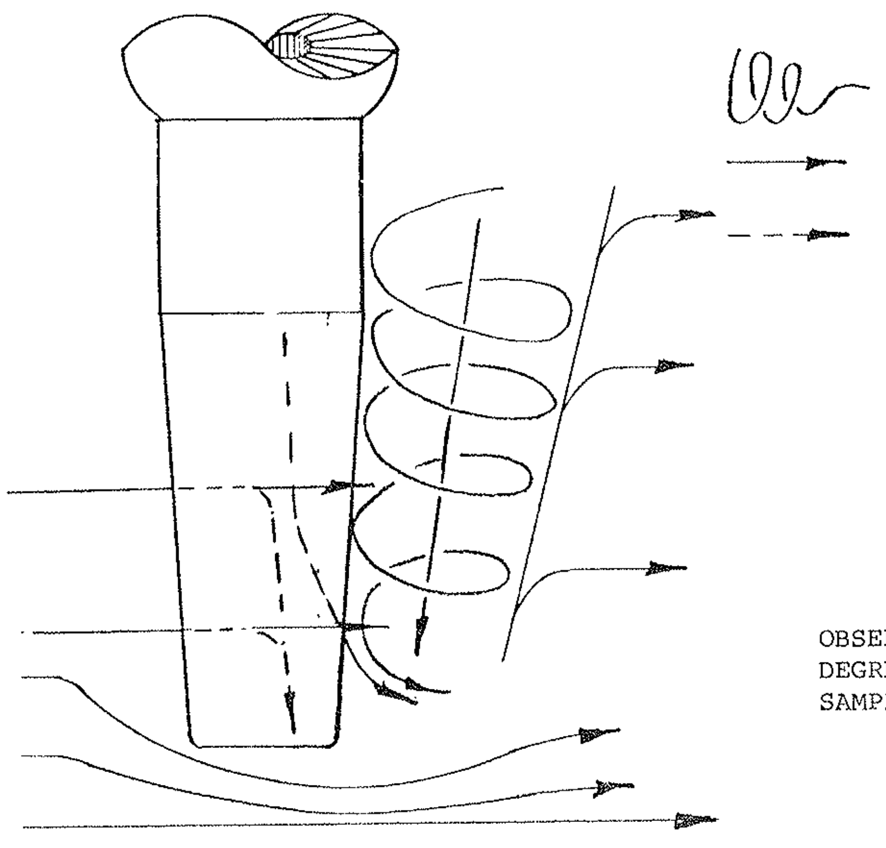
OBSERVED DYE PATTERNS, 225 DEGREE POSITION, NO SAMPLING

FIGURE V-25



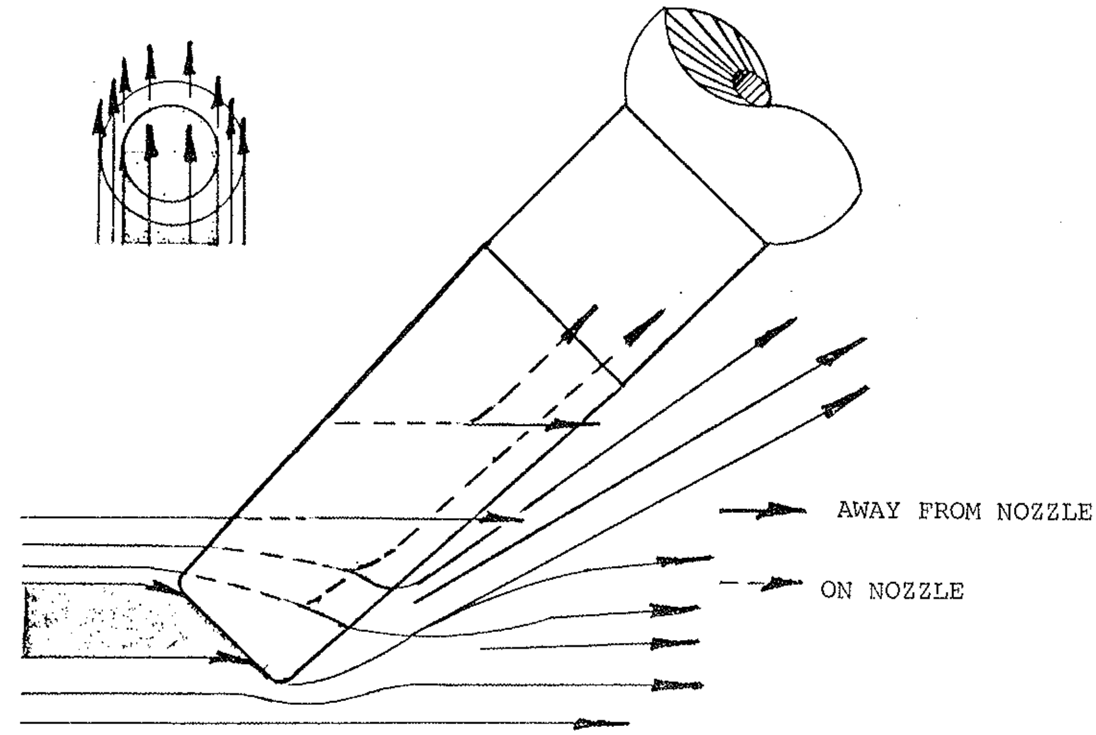
OBSERVED DYE PATTERNS, 270 DEGREE POSITION, ISOKINETIC SAMPLING

FIGURE V-26



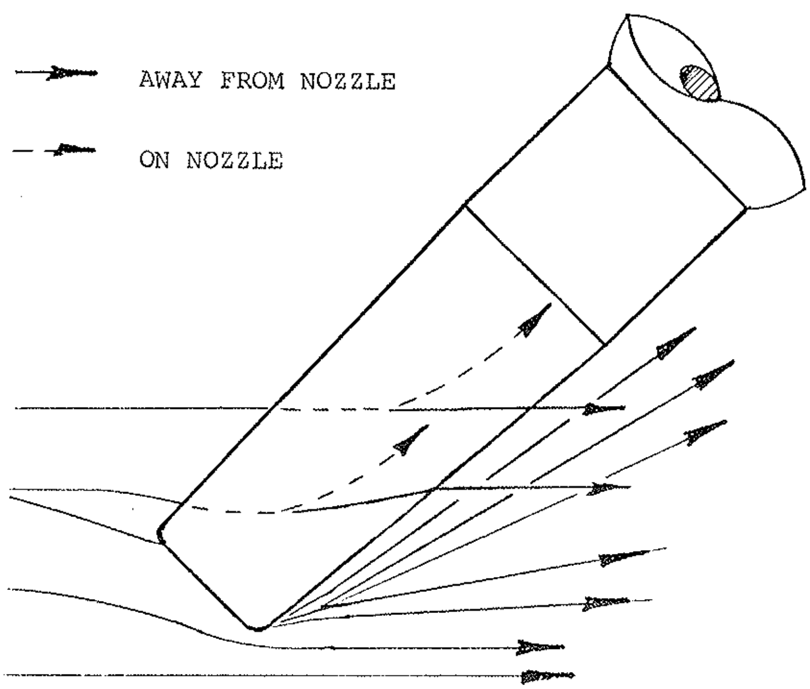
OBSERVED DYE PATTERNS, 270 DEGREE POSITION, NO SAMPLING

FIGURE V-27



OBSERVED DYE PATTERNS, 315 DEGREE POSITION, ISOKINETIC SAMPLING

FIGURE V-28



OBSERVED DYE PATTERNS, 315 DEGREE POSITION, NO SAMPLING

FIGURE V-29

VI. EXPERIMENTAL ERROR ESTIMATES

The quantity of data collected in this study was not sufficient to statistically estimate how reliable or accurate the data were. Instead, a step by step estimate of the errors in the sampling process used in this study was made. A summary of these error estimates follow.

Errors will be presented in terms of percent difference defined as

$$\Delta \% = \frac{\text{Measured value} - \text{correct value}}{\text{correct value}} \times 100 \qquad (15)$$

The sources of error fall into two groups. First, procedural errors in sampling the suspended sediment and in analyzing the samples. Second, errors because of basic assumptions made about the nature of the sampling process before the study started.

The major procedural error in sampling the suspended sediment was caused by incorrect intake velocities. Isokinetic intake velocities for the test samples range from about 20 percent less than the desired intake velocity to about 10 percent higher.

There are several reasons why this sampling error occurred. First, setting the intake velocities with the siphon system was difficult. The siphons were sensitive to small differences in the pressure of the clamps on the siphon tubing. In addition, errors were made in measuring the intake velocity with the stop watch and volumetric flask. Second, the stream velocity used to set most of the intake velocities was Q/A or the mean calculated stream velocity. This was between 10 to 20 percent lower than the actual velocity at the sampling location and elevation in the flow. Third, the intake velocities were selected to match an average stream velocity over the course of an experimental run even though the velocity varied with time. Fourth, the intake velocity was angle-dependent. That is, as the nozzle mouth was turned away from the flow, the intake velocity dropped because of the change of the impact pressure on the nozzle opening.

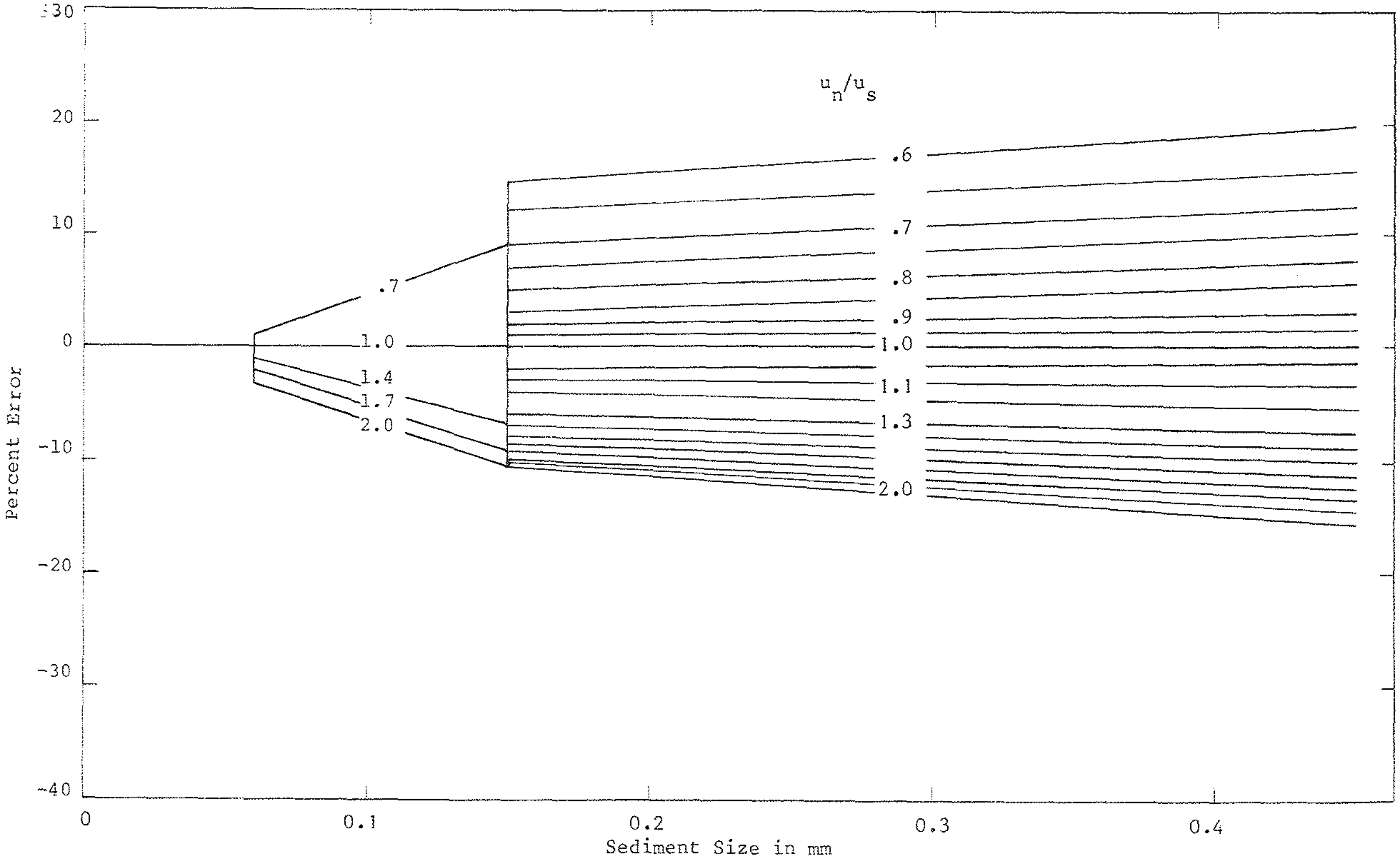
For the 0.20 mm sand (largest particle size) the resulting errors in concentration of the reference samples was estimated with the aid of Fig. VI-1 which was constructed using the results of the Federal Interagency Sedimentation Project (FIASP, 1941). The maximum error in concentration using the figure would be about 3 percent. This is increased to 5 percent as the maximum estimated error.

Errors in the test sample concentrations are more difficult to estimate since the FIASP study results apply only to the reference samples. The errors in concentration can be estimated from plots of the concentration ratios against the ratios of intake velocity to the stream velocity. The angles for which two or more data points were available are plotted in Fig. VI-2. The maximum error is about 10 percent for the twice isokinetic sampling. This is used as the maximum estimated error. Note that any errors for the reference sample concentrations are hidden in the figures.

Procedural errors in analyzing the sample result from three sources: inaccurate weighing of the entire sample, inaccurate weighing of the sand in the sample, and loss of sample or sand during the analysis.

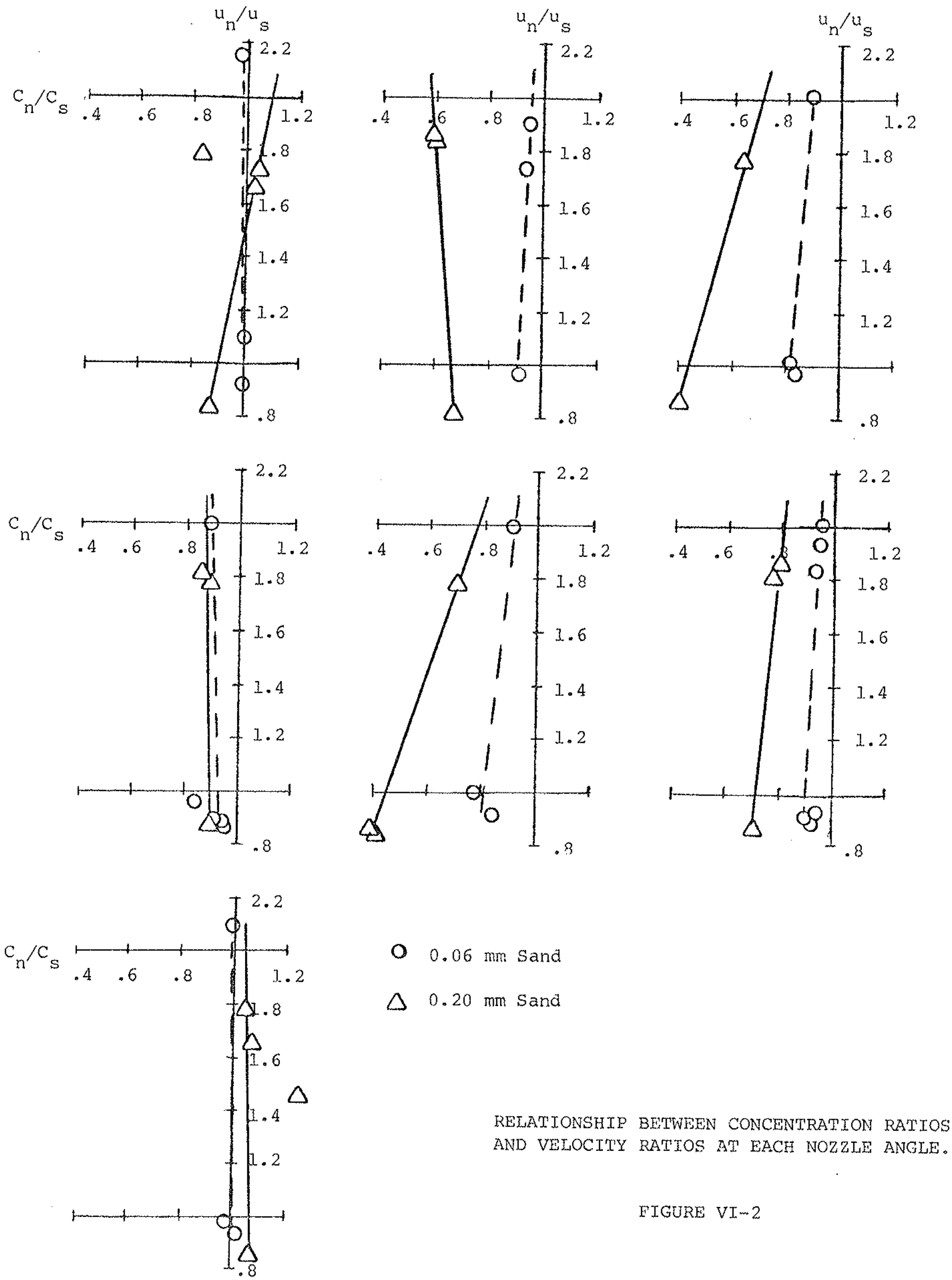
The entire sample, that is the sand and the water, was weighed on scales accurate to either 0.1 g or 1 g depending upon which scale was available. The tares of the plastic pails were measured to within 0.1 g. They were retared during the study and the new tares were all within 0.2 g of the old tares. The maximum error thought likely is ± 5 g in the weights. For the amount of sample, which was around 2500 to 3000 g per measurement (5.5 to 6.6 lbs), this is an error of less than 0.2 percent. The maximum estimated error is set at 1.0 percent.

The sand was weighed on an analytical balance accurate to within 0.1 mg. The weights had all been calibrated and were accurate to within 0.2 mg after adjustments had been made for the error in each weight. The weighing dishes were retared several times during the course of the study. The tares for the dishes fall within a range of ± 0.2 mg. The effect of dissolved solids concentration in the water on the measured weight of the sand is ignored because it was detectable. The amounts of sand weighed ranged from about 0.07 g to 5.2 g (0.002 to 0.18 oz). The maximum estimated error is less than 5 mg. Using 1 g as a reasonable lower bound for the sand weights, the error is less than 1.0 percent.



Error in concentration sampled because of anisokinetic sampling

FIGURE VI-1



RELATIONSHIP BETWEEN CONCENTRATION RATIOS AND VELOCITY RATIOS AT EACH NOZZLE ANGLE.

FIGURE VI-2

Loss of a portion of the sample in the analysis procedure must also be considered (see Section IV). Because of the care with which the samples were analyzed, it is believed that this loss can be neglected.

At the beginning of the study it was assumed that the actual concentration in the flume at the time the test sample was taken was equal to the average of the concentrations of the reference samples taken before and after the test sample. That is, it was assumed that any variations in concentration in the flume would be linear with time. As is shown in Figs. V-9 and V-10, the errors in estimating the concentration are less than about 3.3 percent. To increase the margin of safety, the maximum estimated error because of this assumption is set at ± 5 percent.

Using these maximum estimated errors, at the concentrations measured, the maximum estimated error for the ratio between the reference concentration and the test concentration is ± 27 percent of the actual value. The expected error is, however, much less than that for the following reasons.

First, the above analysis of the maximum possible error assumes that the worst errors possible occur at each step of the sampling and analysis process. Many of the errors were probably at least partically self-cancelling.

Second, several internal checks were used in analyzing the data to see if samples were consistent. The first check used was to plot the reference sample concentrations against the Froude number of the flow at the time the sample was taken. If the reference sample concentrations from an experimental run did not plot closely with the reference sample concentrations from other runs, the run was not used unless the concentration ratios determined by the run satisfied the criteria below.

For some nozzle positions, 0 and 90 degrees, the concentration ratios had been determined by the Federal Interagency Sedimentation Project (FIASP, 1941). The concentration ratios determined in this study were compared with those of the FIASP. If they did not closely agree, as with the twice isokinetic 0 degree position concentration ratios, the runs were done over again or other additional experiments were carried out to verify the results.

If more than one concentration ratio at a nozzle angle had been determined, and if these results were not within 10 percent of each other, more samples were taken at that nozzle angle. Time restrictions precluded duplication of all experiments.

How well the results plotted on a polar graph of concentration ratios against nozzle angles was a major concern (Figs. V-5 through V-8). It was expected that the graph would have at least an axis of symmetry because the nozzle positions above the horizontal plane are hydrodynamically similar to their counterparts below the plane. That symmetry was not shown by the data (see e.g. the 315 degree position). All sand sizes exhibited the same tendency. This led to the conclusion that the experimental results were correct. Additional experiments were also conducted to verify the 315° position results.

Even though there were few data to analyze, it is believed that concentration ratios shown in Figs. V-5 through V-8 are accurace to within ± 5 percent.

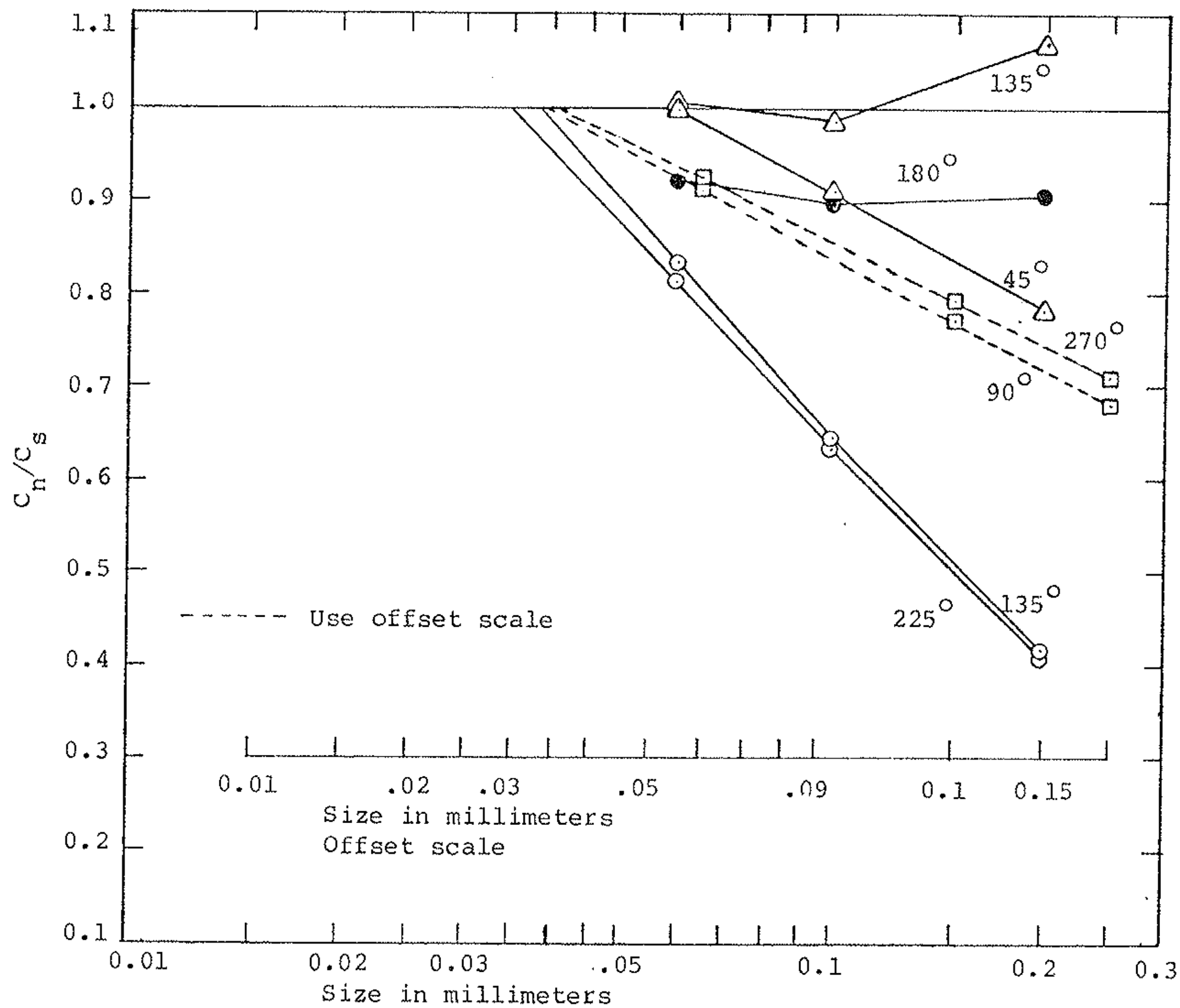
VII. SUMMARY

This study was only an exploratory investigation into the type and magnitudes of errors resulting from sampling with a nozzle at an angle to the flow; only one flow rate was used, only a small number of samples were collected, only three sand sizes were used, and the experiments were done in a small flume not a natural stream. Further studies in laboratory flumes and natural streams must be made before the magnitude of the errors can be estimated accurately. However, several conclusions can be made about the errors resulting from sampling with a nozzle at an angle.

1. As predicted by the analysis in Section II, the errors increased as either the mass of the particle or the angle of the nozzle increased, or both, except at the 180-degree position where the sampling efficiency was about 85 to 90 percent regardless of the sand size or withdrawal rate. The dye studies indicated that this may be because the sand is thrown in front of the nozzle mouth by a turbulent wake. Since the worst sampling efficiencies were found at the 135- and 225-degree positions, this anomaly may disappear a few degrees either side of the 180-degree position.

2. As predicted by the analysis in Section II, the results are symmetric about the horizontal axis for small particles; but symmetry is lost when the particles became larger (Figs. V-5 through V-8), especially at the 315-degree position. Since the sampling efficiency increased when the nozzle was pointing down, the increase in efficiency may be because the increased weight of the particles made it easier for them to follow streamlines curving downward instead of upward.

3. Sampling efficiency increases as particle size decreases. Therefore, sediment samples collected in the field with the sampling nozzle at an angle to the flow will be biased towards the smaller particles. Also, the data suggests that there is a particle size below which sampling errors, because of nozzle angle, can be ignored since they are negligible. This minimum size is a function of withdrawal rate and nozzle orientation as shown in Fig. VII-1.



Test concentration (C_n) to reference concentration (C_s) as a function of particle size and nozzle angle.

FIGURE VII-1

4. Sampling efficiency increased as intake velocities increased. Therefore, when the nozzle is at an angle to the flow, the intake velocity should be higher than the stream velocity. The work of the Federal Interagency Sedimentation Project (1941) indicates that there may be a maximum velocity ratio beyond which the sampling efficiency decreases (see Figs. II-14 through II-16).

5. Both this study and the work of the Federal Interagency Sedimentation Project (1941) indicate that for isokinetic sampling, if the nozzle angle deviates slightly from pointing directly into the flow, the errors are not significant. The maximum angle seems to be between 30 and 45 degrees.

6. This study and other studies (FIASP, 1941; Raynor, 1970) suggest that the sampling efficiency is at least a function of stream velocity, the ratio of intake to stream velocities, nozzle angle, nozzle design, sediment size, shape and mass, fluid properties, and stream characteristics such as turbulence and secondary currents. It is probably impossible, then, to develop a general theory that will adequately predict the errors for all sampling situations such as sampling from air or from water, from a pipe, or from a stream. It should be possible, however, to determine the errors for particular sampling situations such as using a single type of nozzle in a stream.

VIII. RECOMMENDATIONS

It is recommended that future investigations be conducted along one of three lines; experimental studies in laboratory flumes, computer modeling of the flow around and into the nozzle, and finally, experimental studies in natural streams to validate the results of the flume and computer modeling studies.

The following lines of research are suggested for future flume studies.

1. Investigate the following to see what their effect is on the sampling process:

   a. Stream velocity
   b. Different types of sediment such as clays and silts
   c. The vertical sediment gradient in the flume
   d. Nozzle design
   e. The nozzle holder and supports
   f. The intake velocity

2. Determine the lower sediment size below which the effects of nozzle orientation on sampling suspended sediment can be ignored for different nozzle angles.

3. Investigate sampling at or near the 180-degree position. Can the sampling efficiency be improved? At what angles does the efficiency decrease? What effects do nozzle design, stream velocity, turbulence intake velocities, sediment size and type have on the sampling efficiency?

4. Investigate sampling around the 0-degree position. How great an angle can there be before the sampling error becomes serious?

Computer modeling of the flow around and into the sampling nozzle, along with dye studies, would be useful in understanding the entire sediment sampling process. The results could be used to design improved sampling nozzles that reduce sampling error.

Finally, field studies must be made to validate the results of the flume and computer model studies. Natural stream conditions are sufficiently different from those in a flume that the results obtained in a flume may not be applicable to the natural stream.

REFERENCES

American Society of Civil Engineers, Sedimentation Engineering Manuals and Reports on Engineering Practice - No. 54, Vito A. Vanoni, ed., New York, N.Y., 1975.

Badzioch, S., "Collection of Gas-Borne Dust Particles by Means of an Aspirated Sampling Nozzle," Br. J. App. Phys., 10:26, 1959.

Beschta, Robert L., "Modifying Automated Pumping Samplers for Use in Small Mountain Streams," Water Resources Bulletin, 16(1):137-138, Feb., 1980.

Davies, C. N., "The Sampling of Aerosols, the Entry of Aerosols into Sampling Tubes and Heads," Staub Reinhaltung der Luft (English Translation), 28(6):1-9, June, 1968.

Federal Interagency Sedimentation Project, "Report #5, Laboratory Investigation of Suspended Sediment Samplers," Iowa City, Ia., 1941.

Guy, Harold P., Laboratory Theory and Methods for Sediment Analysis, U.S. Geological Survey Techniques, Water-Resources Investigation Book 3, Chapt. C2, 1969.

Hemeon, W. C. L. and Haines, G. F., "The Magnitude of Errors in Stack Dust Sampling," Air Repair, 4:159, 1954.

Lundgren, Dale, Durham, Michael D., and Mason, Kerry Wade, "Sampling of Tangential Flow Streams," American Industrial Hygiene Association Jour., 39-640-644, Aug., 1978.

Olson, Reuben M., Essentials of Engineering Fluid Mechanics, International Textbook Co., 2nd ed., 1966, 448 pp.

Raynor, Gilbert S., "Variation in Entrance Efficiency of a Filter Sampler with Air Speed, Flow Rate, Angle and Particle Size," American Industrial Hygiene Association Jour., 31:294-304, May-June 1970.

Schmel, G. A., "Estimation of Airstream Concentrations of Particulates from Subisokinetically Obtained Filter Samples," American Industrial Hygiene Jour., 28:243-252, May-June, 1967.

Selden, Jr., Jurrell, G., "Nozzle Sampling Bias," American Industrial Hygiene Assoc. Jour., 36:549-552, July, 1975.

Ibid., Estimates of Errors in Anisokinetic Sampling of Particulate Matter," Air Pollution Control Association Jour., 27:235-236, March, 1977.

Soo, S. L., Fluid Dynamics of Multiphase Systems, Blaisdell Publishing Co., Waltham, Ma., 1967.

Vitols, H., "Theoretical Limits of Errors Due to Anisokinetic Sampling of Particulate Matter," Jour. of the Air Pollution Control Assoc., 16:79-80, Feb., 1966.

Watson, H. H., "Errors Due to Anisokinetic Sampling of Aerosols," American Industrial Hygiene Assoc. Quarterly, 15:21-25, March, 1954.

Zenker, Peter, "Investigations into the Problem of Sampling from a Partial Flow with Different Flow Velocities for the Determination of the Dust Content of Flowing Gases," Staub Reinhaltung der Luft (English Translation), 31:30-36, June, 1971.

APPENDIX A

TABLE A-1. ISOKINETIC SAMPLING RESULTS

200 RUN SERIES

.06 MILLIMETER QUARTZ SAND

SAMPLE TYPE	NOZZLE ANGLE	WEIGHT TOTAL KG	WEIGHT SAND G	SAMPLE CONCEN. G/KG	CONCEN. RATIO	Q/A METER/SEC	Q/A FEET/SEC	STREAM VELOCITY (US) METER/SEC	STREAM VELOCITY (US) FEET/SEC	Q/A --- US	INTAKE VELOCITY (UN) METER/SEC	INTAKE VELOCITY (UN) FEET/SEC	UN -- US	FROUDE NO.	REYNOLDS NO.
RUN NO. 202															
REFERENCE	0	5.846	4.021	.688		.560	1.84	.635	2.08	.88	.615	2.02	.97	.464	30.9
TEST	45	5.605	4.083	.728	.999	.565	1.85	.639	2.10	.88	.590	1.94	.92	.469	31.7
REFERENCE	0	5.698	4.392	.771		.573	1.88	.645	2.12	.89	.600	1.97	.93	.478	32.5
TEST	135	6.169	3.986	.646	.833	.581	1.91	.651	2.14	.89	.649	2.13	1.00	.484	33.4
REFERENCE	0	5.681	4.436	.781		.592	1.94	.659	2.16	.90	.598	1.96	.91	.496	34.5
TEST	180	5.571	3.885	.697	.910	.600	1.97	.665	2.18	.90	.586	1.92	.88	.504	35.3
REFERENCE	0	5.610	4.215	.751		.592	1.94	.659	2.16	.90	.590	1.94	.90	.503	35.7
RUN NO. 203															
REFERENCE	0	5.800	4.622	.797		.562	1.84	.637	2.09	.88	.610	2.00	.96	.467	29.5
TEST	180	5.767	3.740	.649	.849	.568	1.86	.641	2.10	.89	.607	1.99	.95	.473	30.2
REFERENCE	0	5.919	4.330	.732		.579	1.90	.650	2.13	.89	.623	2.04	.96	.484	31.2
TEST	225	5.711	3.501	.613	.842	.593	1.95	.660	2.16	.90	.601	1.97	.91	.497	32.2
REFERENCE	0	5.954	4.312	.724		.595	1.95	.661	2.17	.90	.627	2.06	.95	.499	33.0
RUN NO. 204															
REFERENCE	0	5.822	4.204	.722		.572	1.88	.644	2.11	.89	.613	2.01	.95	.475	28.7
TEST	270	5.644	3.928	.696	.942	.572	1.88	.644	2.11	.89	.594	1.95	.92	.475	29.0
REFERENCE	0	5.896	4.459	.756		.584	1.92	.653	2.14	.89	.621	2.04	.95	.487	30.1
TEST	315	5.799	4.491	.774	1.023	.592	1.94	.659	2.16	.90	.610	2.00	.93	.494	31.0
REFERENCE	0	5.879	4.457	.758		.597	1.96	.663	2.17	.90	.619	2.03	.93	.499	31.5
RUN NO. 205															
REFERENCE	0	6.167	4.448	.721		.573	1.88	.645	2.12	.89	.649	2.13	1.01	.476	29.8
TEST	45	6.493	4.952	.763	.998	.578	1.90	.648	2.13	.89	.683	2.24	1.05	.480	30.3
REFERENCE	0	6.199	5.001	.807		.585	1.92	.654	2.15	.89	.612	2.01	.94	.488	31.8
TEST	90	6.118	4.569	.747	.923	.597	1.96	.663	2.17	.90	.633	2.08	.96	.499	32.2
REFERENCE	0	6.204	5.030	.811		.595	1.95	.661	2.17	.90	.653	2.14	.99	.497	32.6
RUN NO. 206															
REFERENCE	0	6.131	4.966	.810		.572	1.88	.644	2.11	.89	.645	2.12	1.00	.475	29.3
TEST	135	5.984	4.141	.692	.843	.578	1.90	.648	2.13	.89	.630	2.07	.97	.480	30.2
REFERENCE	0	6.210	5.163	.831		.585	1.92	.654	2.15	.89	.654	2.14	1.00	.488	31.0
TEST	315	6.103	5.014	.822	.989	.586	1.92	.655	2.15	.90	.642	2.11	.98	.490	31.7
REFERENCE	0	6.196	5.142	.830		.602	1.98	.666	2.19	.90	.652	2.14	.98	.504	32.8
RUN NO. 207															
REFERENCE	0	6.509	5.174	.795		.575	1.89	.646	2.12	.89	.685	2.25	1.06	.477	36.4
TEST	135	6.181	4.083	.661	.823	.578	1.90	.648	2.13	.89	.651	2.13	1.00	.480	37.4
REFERENCE	0	6.515	5.274	.810		.589	1.93	.657	2.16	.90	.686	2.25	1.04	.491	38.5
TEST	225	6.234	3.928	.630	.779	.591	1.94	.658	2.16	.90	.656	2.15	1.00	.493	39.2
REFERENCE	0	6.485	5.235	.807		.601	1.97	.666	2.18	.90	.683	2.24	1.03	.503	40.5

TABLE A-1. ISOKINETIC SAMPLING RESULTS (Cont'd)

200 RUN SERIES

.06 MILLIMETER QUARTZ SAND

SAMPLE TYPE	NOZZLE ANGLE	WEIGHT TOTAL KG	WEIGHT SAND G	SAMPLE CONCEN. G/KG	CONCEN. RATIO	Q/A METER/SEC	Q/A FEET/SEC	STREAM VELOCITY (US) METER/SEC	STREAM VELOCITY (US) FEET/SEC	Q/A --- US	INTAKE VELOCITY (UN) METER/SEC	INTAKE VELOCITY (UN) FEET/SEC	UN -- US	FROUDE NO.	REYNOLDS NO.
RUN NO. 208															
REFERENCE	0	5.551	4.392	.791		.578	1.90	.648	2.13	.89	.584	1.92	.90	.480	29.2
TEST	180	7.078	5.418	.765	.950	.583	1.91	.653	2.14	.89	.573	1.88	.88	.486	29.9
REFERENCE	0	6.714	5.506	.820		.589	1.93	.657	2.16	.90	.589	1.93	.90	.491	31.2
TEST	180	5.447	4.266	.783	.961	.588	1.93	.656	2.15	.90	.573	1.88	.87	.492	31.7
REFERENCE	0	5.578	4.519	.810		.593	1.95	.660	2.16	.90	.587	1.93	.89	.497	32.9
RUN NO. 209															
REFERENCE	0	5.787	4.570	.790		.571	1.87	.643	2.11	.89	.609	2.00	.95	.476	32.3
TEST	270	5.534	4.030	.728	.903	.573	1.88	.645	2.12	.89	.582	1.91	.90	.478	32.9
REFERENCE	0	5.831	4.799	.823		.581	1.91	.651	2.14	.89	.614	2.01	.94	.486	33.7
TEST	270	5.804	4.305	.742	.904	.588	1.93	.656	2.15	.90	.582	1.91	.89	.490	34.5
REFERENCE	0	5.762	4.709	.817		.595	1.95	.661	2.17	.90	.606	1.99	.92	.497	35.7

TABLE A-1. ISOKINETIC SAMPLING RESULTS (Cont'd)

300 RUN SERIES

.11 MILLIMETER QUARTZ SAND

SAMPLE TYPE	NOZZLE ANGLE	WEIGHT TOTAL KG	WEIGHT SAND G	SAMPLE CONCEN. G/KG	CONCEN. RATIO	Q/A METER/SEC	Q/A FEET/SEC	STREAM VELOCITY (US) METER/SEC	STREAM VELOCITY (US) FEET/SEC	Q/A --- US	INTAKE VELOCITY (UN) METER/SEC	INTAKE VELOCITY (UN) FEET/SEC	UN -- US	FROUDE NO.	REYNOLDS NO.
RUN NO. 301															
REFERENCE	0	5.553	2.838	.511		.563	1.85	.638	2.09	.88	.584	1.92	.92	.466	55.3
TEST	225	5.671	1.966	.347	.630	.566	1.86	.640	2.10	.88	.560	1.84	.87	.470	56.4
REFERENCE	0	5.605	3.306	.590		.579	1.90	.650	2.13	.89	.590	1.94	.91	.482	58.2
TEST	270	5.342	2.575	.482	.793	.583	1.91	.653	2.14	.89	.562	1.84	.86	.486	59.4
REFERENCE	0	5.611	3.512	.626		.596	1.96	.662	2.17	.90	.591	1.94	.89	.498	61.5
RUN NO. 302															
REFERENCE	0	5.757	2.779	.483		.564	1.85	.638	2.09	.88	.606	1.99	.95	.467	58.4
TEST	180	5.616	2.710	.483	.914	.573	1.88	.645	2.12	.89	.591	1.94	.92	.476	59.7
REFERENCE	0	5.815	3.335	.574		.582	1.91	.652	2.14	.89	.612	2.01	.94	.485	61.5
TEST	135	5.550	2.125	.383	.645	.590	1.94	.658	2.16	.90	.584	1.92	.89	.492	63.0
REFERENCE	0	5.781	3.546	.613		.599	1.97	.664	2.18	.90	.608	2.00	.92	.501	64.9
RUN NO. 303															
REFERENCE	0	5.483	2.423	.442		.563	1.85	.638	2.09	.88	.577	1.89	.91	.466	50.2
TEST	90	5.321	2.061	.387	.771	.567	1.86	.641	2.10	.89	.560	1.84	.87	.470	51.3
REFERENCE	0	5.554	3.125	.563		.580	1.90	.650	2.13	.89	.585	1.92	.90	.483	52.9
TEST	45	5.504	3.048	.554	.921	.585	1.92	.654	2.15	.89	.579	1.90	.89	.488	54.9
REFERENCE	0	5.470	3.497	.639		.600	1.97	.665	2.18	.90	.576	1.89	.87	.502	55.8
RUN NO. 304															
REFERENCE	0	5.576	2.807	.503		.570	1.87	.643	2.11	.89	.587	1.93	.91	.473	49.0
TEST	45	5.532	2.708	.490	.879	.572	1.88	.644	2.11	.89	.582	1.91	.90	.475	50.8
REFERENCE	0	5.650	3.448	.610		.589	1.93	.657	2.16	.90	.595	1.95	.91	.491	53.4
TEST	45	5.568	3.215	.577	.925	.590	1.94	.658	2.16	.90	.586	1.92	.89	.492	53.5
REFERENCE	0	5.605	3.575	.638		.602	1.98	.666	2.19	.90	.590	1.94	.89	.504	55.9
RUN NO. 305															
REFERENCE	0	5.597	3.157	.564		.566	1.86	.640	2.10	.88	.589	1.93	.92	.469	54.5
TEST	315	5.489	3.102	.565	.962	.576	1.89	.647	2.12	.89	.578	1.90	.89	.478	56.0
REFERENCE	0	5.633	3.438	.610		.587	1.93	.655	2.15	.90	.593	1.95	.90	.489	57.6
TEST	315	5.527	3.373	.610	.973	.593	1.95	.660	2.16	.90	.582	1.91	.88	.495	58.8
REFERENCE	0	5.657	3.640	.643		.602	1.98	.666	2.19	.90	.595	1.95	.89	.504	61.2
RUN NO. 306															
REFERENCE	0	5.478	2.913	.532		.568	1.86	.642	2.11	.89	.577	1.89	.90	.471	49.7
TEST	180	5.394	2.731	.506	.873	.576	1.89	.647	2.12	.89	.568	1.86	.88	.478	51.8
REFERENCE	0	5.544	3.486	.629		.587	1.93	.655	2.15	.90	.584	1.91	.89	.489	54.2
TEST	180	5.431	3.159	.582	.903	.592	1.94	.659	2.16	.90	.572	1.88	.87	.494	55.3
REFERENCE	0	5.556	3.662	.659		.600	1.97	.665	2.18	.90	.585	1.92	.88	.502	57.5

TABLE A-1. ISOKINETIC SAMPLING RESULTS (Cont'd)

400 RUN SERIES

.20 MILLIMETER QUARTZ SAND

SAMPLE TYPE	NOZZLE ANGLE	WEIGHT TOTAL KG	WEIGHT SAND G	SAMPLE CONCEN. G/KG	CONCEN. RATIO	Q/A METER/SEC	Q/A FEET/SEC	STREAM VELOCITY (US) METER/SEC	STREAM VELOCITY (US) FEET/SEC	Q/A / US	INTAKE VELOCITY (UN) METER/SEC	INTAKE VELOCITY (UN) FEET/SEC	UN / US	FROUDE NO.	REYNOLDS NO.
RUN NO. 402															
REFERENCE	0	5.583	1.486	.266		.566	1.86	.640	2.10	.88	.588	1.93	.92	.469	101.4
TEST	180	5.445	1.467	.269	.905	.577	1.89	.648	2.13	.89	.573	1.88	.88	.479	104.4
REFERENCE	0	5.631	1.855	.329		.588	1.93	.656	2.15	.90	.593	1.94	.90	.490	108.0
TEST	135	5.379	.763	.142	.415	.587	1.93	.655	2.15	.90	.566	1.86	.86	.489	109.1
REFERENCE	0	5.608	1.985	.354		.601	1.97	.666	2.18	.90	.590	1.94	.89	.503	113.1
RUN NO. 403															
REFERENCE	0	5.505	1.471	.267		.571	1.87	.644	2.11	.89	.579	1.90	.90	.475	101.3
TEST	225	5.307	.570	.107	.388	.576	1.89	.647	2.12	.89	.559	1.83	.86	.479	103.3
REFERENCE	0	5.546	1.591	.287		.575	1.89	.647	2.12	.89	.584	1.92	.90	.481	106.4
TEST	270	5.316	1.192	.224	.712	.576	1.89	.647	2.12	.89	.560	1.84	.86	.483	108.1
REFERENCE	0	5.560	1.906	.343		.587	1.93	.655	2.15	.90	.585	1.92	.89	.493	109.4
RUN NO. 404															
REFERENCE	0	5.319	1.352	.254		.569	1.87	.642	2.11	.89	.560	1.84	.87	.476	86.1
TEST	225	5.151	.654	.127	.432	.575	1.89	.647	2.12	.89	.542	1.78	.84	.482	89.7
REFERENCE	0	5.397	1.801	.334		.584	1.92	.653	2.14	.89	.568	1.86	.87	.491	93.6
TEST	315	5.303	1.938	.365	1.072	.589	1.93	.657	2.15	.90	.558	1.83	.85	.495	95.6
REFERENCE	0	5.390	1.878	.348		.605	1.99	.669	2.19	.91	.567	1.86	.85	.507	98.9
RUN NO. 405															
REFERENCE	0	5.174	1.441	.279		.569	1.87	.642	2.11	.89	.545	1.79	.85	.474	86.1
TEST	45	5.138	1.252	.244	.779	.574	1.88	.646	2.12	.89	.541	1.77	.84	.478	89.5
REFERENCE	0	5.199	1.805	.347		.582	1.91	.652	2.14	.89	.547	1.80	.84	.489	91.9
TEST	90	5.077	1.272	.251	.683	.583	1.91	.652	2.14	.89	.534	1.75	.82	.490	95.0
REFERENCE	0	5.221	2.015	.386		.596	1.96	.662	2.17	.90	.550	1.80	.83	.500	97.9

1200 RUN SERIES

.06 MILLIMETER QUARTZ SAND

SAMPLE TYPE	NOZZLE ANGLE	WEIGHT TOTAL	WEIGHT SAND	SAMPLE CONCEN.	CONCEN. RATIO	Q/A		STREAM VELOCITY (US)		Q/A --- US	INTAKE VELOCITY (UN)		UN -- US	FROUDE NO.	REYNOLDS NO.
		KG	G	G/KG		METER/ SEC	FEET/ SEC	METER/ SEC	FEET/ SEC		METER/ SEC	FEET/ SEC			
RUN NO. 1201															
REFERENCE	0	5.932	4.688	.790		.568	1.86	.642	2.11	.89	.624	2.05	.97	.471	27.8
TEST	0	6.426	5.004	.779	.978	.579	1.90	.649	2.13	.89	1.353	4.44	2.08	.480	28.9
REFERENCE	0	6.132	4.923	.803		.591	1.94	.658	2.16	.90	.645	2.12	.98	.492	29.3
TEST	0	6.604	5.217	.790	.998	.596	1.96	.662	2.17	.90	1.390	4.56	2.10	.497	30.3
REFERENCE	0	5.107	3.987	.781		.605	1.99	.669	2.19	.91	.538	1.76	.80	.507	31.5
RUN NO. 1202															
REFERENCE	0	6.095	4.412	.724		.557	1.83	.633	2.08	.88	.642	2.10	1.01	.460	26.6
TEST	180	6.285	4.442	.707	.962	.557	1.83	.633	2.08	.88	1.323	4.34	2.09	.460	28.2
REFERENCE	0	6.179	4.610	.746		.566	1.86	.640	2.10	.88	.650	2.13	1.02	.470	28.5
TEST	225	6.092	4.188	.687	.910	.574	1.88	.646	2.12	.89	1.282	4.21	1.99	.477	29.6
REFERENCE	0	6.232	4.770	.765		.587	1.93	.655	2.15	.90	.656	2.15	1.00	.489	30.4
RUN NO. 1203															
REFERENCE	0	5.954	4.557	.765		.558	1.83	.634	2.08	.88	.627	2.06	.99	.462	25.5
TEST	135	6.113	4.272	.699	.902	.566	1.86	.640	2.10	.88	1.287	4.22	2.01	.470	26.9
REFERENCE	0	6.034	4.728	.784		.579	1.90	.649	2.13	.89	.635	2.08	.98	.481	27.3
TEST	270	6.186	4.637	.750	.950	.579	1.90	.650	2.13	.89	1.302	4.27	2.00	.482	28.1
REFERENCE	0	6.106	4.848	.794		.595	1.95	.661	2.17	.90	.643	2.11	.97	.497	29.4
RUN NO. 1204															
REFERENCE	0	6.013	4.623	.769		.558	1.83	.634	2.08	.88	.633	2.08	1.00	.462	26.3
TEST	45	6.513	5.031	.772	.989	.565	1.85	.639	2.10	.88	1.371	4.50	2.15	.468	27.2
REFERENCE	0	6.088	4.828	.793		.579	1.90	.649	2.13	.89	.641	2.10	.99	.481	28.1
TEST	315	6.465	5.128	.793	.994	.583	1.91	.653	2.14	.89	1.361	4.47	2.09	.486	28.9
REFERENCE	0	6.144	4.929	.802		.597	1.96	.663	2.17	.90	.647	2.12	.98	.499	29.5
RUN NO. 1205															
REFERENCE	0	5.179	4.047	.781		.560	1.84	.636	2.09	.88	.606	1.99	.95	.464	26.7
TEST	270	5.558	4.124	.742	.934	.564	1.85	.638	2.09	.88	1.170	3.84	1.83	.467	27.6
REFERENCE	0	5.218	4.215	.808		.577	1.89	.648	2.13	.89	.610	2.00	.94	.479	28.4
TEST	90	5.308	4.019	.757	.940	.577	1.89	.648	2.13	.89	1.117	3.67	1.73	.479	29.2
REFERENCE	0	5.321	4.276	.804		.591	1.94	.658	2.16	.90	.622	2.04	.95	.493	30.1
RUN NO. 1206															
REFERENCE	0	5.833	4.496	.771		.562	1.84	.637	2.09	.88	.682	2.24	1.07	.465	26.8
TEST	90	5.785	4.310	.745	.946	.567	1.86	.641	2.10	.89	1.218	4.00	1.90	.470	27.7
REFERENCE	0	5.981	4.811	.804		.576	1.89	.647	2.12	.89	.699	2.29	1.08	.478	28.8
TEST	270	6.009	4.566	.760	.943	.587	1.93	.655	2.15	.90	1.265	4.15	1.93	.489	29.6
REFERENCE	0	5.983	4.828	.807		.597	1.96	.663	2.17	.90	.700	2.30	1.06	.499	30.8

TABLE A-2. TWICE-ISOKINETIC SAMPLING RESULTS

1100 RUN SERIES

.20 MILLIMETER QUARTZ SAND

SAMPLE TYPE	NOZZLE ANGLE	WEIGHT TOTAL KG	WEIGHT SAND G	SAMPLE CONCEN. G/KG	CONCEN. RATIO	Q/A METER/SEC	Q/A FEET/SEC	STREAM VELOCITY (US) METER/SEC	STREAM VELOCITY (US) FEET/SEC	Q/A --- US	INTAKE VELOCITY (UN) METER/SEC	INTAKE VELOCITY (UN) FEET/SEC	UN -- US	FROUDE NO.	REYNOLDS NO.
RUN NO. 1101															
REFERENCE	0	5.536	1.719	.311		.572	1.88	.644	2.11	.89	.583	1.91	.90	.475	98.3
TEST	45	5.516	1.372	.249	.745	.579	1.90	.650	2.13	.89	1.161	3.81	1.79	.482	101.9
REFERENCE	0	5.550	1.985	.358		.593	1.95	.660	2.16	.90	.584	1.92	.89	.495	104.9
TEST	315	4.559	1.823	.400	1.250	.596	1.96	.662	2.17	.90	.960	3.15	1.45	.498	106.7
REFERENCE	0	5.488	1.547	.282		.603	1.98	.667	2.19	.90	.578	1.90	.87	.505	110.4
RUN NO. 1102															
REFERENCE	0	5.547	1.423	.257		.564	1.85	.638	2.09	.88	.584	1.92	.91	.467	84.1
TEST	135	5.396	.996	.185	.649	.568	1.86	.642	2.11	.89	1.136	3.73	1.77	.471	88.5
REFERENCE	0	5.614	1.752	.312		.579	1.90	.650	2.13	.89	.591	1.94	.91	.482	91.0
TEST	225	5.645	1.264	.224	.705	.586	1.92	.655	2.15	.90	1.165	3.82	1.78	.488	94.4
REFERENCE	0	5.661	1.827	.323		.594	1.95	.661	2.17	.90	.596	1.95	.90	.496	96.6
RUN NO. 1103															
REFERENCE	0	5.617	1.376	.245		.564	1.85	.638	2.09	.88	.591	1.94	.93	.467	86.7
TEST	180	5.572	1.404	.252	.867	.573	1.88	.645	2.12	.89	1.173	3.85	1.82	.476	90.3
REFERENCE	0	5.689	1.914	.336		.583	1.91	.653	2.14	.89	.599	1.96	.92	.486	94.1
TEST	180	5.592	1.602	.286	.905	.593	1.95	.660	2.16	.90	1.177	3.86	1.78	.495	96.5
REFERENCE	0	5.935	1.761	.297		.602	1.98	.666	2.19	.90	.625	2.05	.94	.504	98.9
RUN NO. 1104															
REFERENCE	0	4.711	1.487	.316		.579	1.90	.649	2.13	.89	.496	1.63	.76	.481	90.9
TEST	0	5.491	1.867	.340	1.017	.585	1.92	.654	2.15	.89	1.156	3.79	1.77	.488	91.6
REFERENCE	0	4.800	1.696	.353		.594	1.95	.661	2.17	.90	.505	1.66	.76	.496	92.5
RUN NO. 1105															
REFERENCE	0	5.737	1.779	.310		.564	1.85	.638	2.09	.88	.604	1.98	.95	.467	94.7
TEST	90	5.617	1.176	.209	.609	.568	1.86	.642	2.11	.89	1.182	3.88	1.84	.471	96.6
REFERENCE	0	5.563	2.097	.377		.584	1.92	.653	2.14	.89	.586	1.92	.90	.487	99.7
TEST	270	5.602	1.668	.298	.776	.589	1.93	.657	2.16	.90	1.179	3.87	1.80	.491	103.0
REFERENCE	0	5.437	2.123	.390		.599	1.97	.664	2.18	.90	.572	1.88	.86	.501	104.2
RUN NO. 1106															
REFERENCE	0	5.613	1.469	.262		.561	1.84	.636	2.09	.88	.591	1.94	.93	.464	99.8
TEST	270	5.613	1.378	.246	.798	.566	1.86	.640	2.10	.88	1.182	3.88	1.85	.470	103.2
REFERENCE	0	5.714	2.020	.354		.574	1.88	.646	2.12	.89	.601	1.97	.93	.477	105.5
TEST	90	5.839	1.359	.233	.600	.576	1.89	.647	2.12	.89	1.205	3.95	1.86	.478	107.1
REFERENCE	0	5.714	2.415	.423		.594	1.95	.661	2.17	.90	.601	1.97	.91	.496	110.8

TABLE A-2. TWICE-ISOKINETIC SAMPLING RESULTS (Cont'd)

1100 RUN SERIES

.20 MILLIMETER QUARTZ SAND

SAMPLE TYPE	NOZZLE ANGLE	WEIGHT TOTAL KG	WEIGHT SAND G	SAMPLE CONCEN. G/KG	CONCEN. RATIO	Q/A METER/SEC	Q/A FEET/SEC	STREAM VELOCITY (US) METER/SEC	STREAM VELOCITY (US) FEET/SEC	Q/A --- US	INTAKE VELOCITY (UN) METER/SEC	INTAKE VELOCITY (UN) FEET/SEC	UN -- US	FROUDE NO.	REYNOLDS NO.
RUN NO. 1107															
REFERENCE	0	5.541	1.067	.193		.559	1.83	.635	2.08	.88	.583	1.91	.92	.463	88.9
TEST	0	5.519	1.686	.305	1.356	.569	1.87	.642	2.11	.89	1.162	3.81	1.81	.472	92.6
REFERENCE	0	5.687	1.467	.258		.578	1.90	.648	2.13	.89	.599	1.96	.92	.480	93.5
TEST	0	5.744	1.803	.314	1.118	.582	1.91	.652	2.14	.89	1.193	3.91	1.83	.485	96.7
REFERENCE	0	5.699	1.731	.304		.592	1.94	.659	2.16	.90	.600	1.97	.91	.494	99.2
RUN NO. 1108															
REFERENCE	0	5.644	1.565	.277		.565	1.85	.639	2.10	.88	.594	1.95	.93	.468	92.1
TEST	315	5.629	1.738	.309	1.052	.574	1.88	.646	2.12	.89	1.147	3.76	1.78	.477	95.8
REFERENCE	0	5.704	1.766	.310		.586	1.92	.655	2.15	.90	.600	1.97	.92	.488	98.5
TEST	45	5.444	1.932	.355	1.059	.588	1.93	.656	2.15	.90	1.138	3.73	1.73	.490	100.1
REFERENCE	0	5.774	2.081	.360		.605	1.99	.669	2.19	.91	.608	1.99	.91	.507	104.9
RUN NO. 1109															
REFERENCE	0	5.311	.984	.185		.559	1.83	.635	2.08	.88	.621	2.04	.98	.463	80.5
TEST	0	5.200	1.164	.224	.916	.562	1.84	.637	2.09	.88	1.095	3.59	1.72	.465	81.3
REFERENCE	0	5.360	1.628	.304		.571	1.87	.644	2.11	.89	.627	2.06	.97	.474	84.8
TEST	0	5.868	1.671	.285	.850	.579	1.90	.649	2.13	.89	1.235	4.05	1.90	.481	88.2
REFERENCE	0	5.418	1.986	.367		.588	1.93	.656	2.15	.90	.634	2.08	.97	.490	91.9
RUN NO. 1110															
REFERENCE	0	5.341	1.088	.204		.589	1.93	.656	2.15	.90	.625	2.05	.95	.479	87.8
TEST	45	5.057	1.356	.268	1.041	.564	1.85	.638	2.09	.88	1.065	3.49	1.67	.467	86.7
REFERENCE	0	5.426	1.689	.311		.579	1.90	.650	2.13	.89	.635	2.08	.98	.482	91.0
TEST	315	5.143	1.889	.367	1.071	.583	1.91	.653	2.14	.89	1.083	3.55	1.66	.486	92.7
REFERENCE	0	5.489	2.057	.375		.591	1.94	.658	2.16	.90	.642	2.11	.98	.493	94.9

TABLE A-3. CONCENTRATION GRADIENTS AT THE UPSTREAM AND DOWNSTREAM LOCATIONS

Samples Elevation (m)	Samples Elevation (ft)	Weight Water & Sand (g)	Weight Sand (g)	Concentration (g/Kg)	Average Water Depth (m)	Average Water Depth (ft)	Average Water Temperature (°C)	Average Water Temperature (°F)	Average Flow Rate (m^3/s)	Average Flow Rate (cfs)	Comments
Upstream Sampling Location	Run A501	Isokinetic Intake Rate: 48.4 ℓ/sec		Quartz sand used: d_{50} = 0.20 mm							
0.1219	0.400 *	3641	0.691	0.190	0.1875	0.615	7.0	44.6	0.0167	0.590	Set 1
0.0914	0.300	3091	0.802	0.259							Total sample time
0.0610	0.200	3098	0.782	0.252							is 2 min, 30 sec
0.1219	0.400	2479	0.711	0.287	0.1830	0.601	8.5	47.3	0.167	0.590	Set 2
0.0914	0.300 *	2484	0.784	0.316							Total sample time
0.0610	0.200	2495	0.723	0.290							is 2 min, 0 sec
0.1219	0.400	2457	0.795	0.324	0.1792	0.588	9.5	49.1	0.0167	0.590	Set 3
0.0914	0.300	2501	0.930	0.372							Total sample time
0.0610	0.200 *	2503	0.875	0.350							is 2 min, 0 sec
Upstream Sampling Location	Run A502	Isokinetic Sampling Rate: 48.4 ℓ/sec		Quartz sand used: d_{50} = 0.06 mm							
0.1219	0.400 *	2462	1.929	0.784	0.1862	0.611	10.3	50.5	0.0167	0.530	Set 1
0.0914	0.300	2463	1.927	0.782							Total sample time
0.0610	0.200	2496	1.968	0.788							is 2 min, 0 sec
0.1219	0.400	2494	1.990	0.798	0.1838	0.603	11.5	52.7	0.0167	0.590	Set 2
0.0914	0.300 *	2487	1.994	0.802							Total sample time
0.0610	0.200	2496	1.995	0.799							is 2 min, 0 sec
0.1219	0.400	2510	2.019	0.804	0.1814	0.595	12.5	54.5	0.0167	0.590	Set 3
0.0914	0.300	2483	2.004	0.807							Total sample time
0.0610	0.200 *	2517	2.020	0.803							is 2 min, 0 sec
Downstream Sampling Location	Run A503	Isokinetic Sampling: Intake Rate = 38.24 ℓ/sec		Quartz sand used: d_{50}=0.20 mm							
0.1219	0.400 *	2407	0.052	0.022	0.1652	0.542	10.0	50.0	0.0167	0.590	Set 1
0.0914	0.300	2435	0.097	0.040							Total sample time
0.0610	0.200	2400	0.148	0.062							is 1 min, 30 sec
0.1219	0.400	2424	0.049	0.020	0.1656	0.527	10.5	51.4	0.167	0.590	Set 2
0.0914	0.300 *	2427	0.110	0.045							Total sample time
0.0610	0.200	2416	0.172	0.071							is 1 min, 30 sec
0.1219	0.400	1809	0.035	0.019	0.1579	0.518	11.3	56.3	0.067	0.590	Set 3
0.0914	0.300	1588	0.084	0.053							Total sample time
0.0610	0.200 *	1617	0.135	0.083							is 1 min, 0 sec

*Sampling started at this depth for depth.

TABLE A-4. VELOCITY MEASUREMENTS

Run B-1

Measurements made at an elevation of 0.09144 meters (0.300 ft)
Depth of Water was 0.1887 meter (0.619 ft)
Flow rate was 0.0167 m^3/s (0.590 cfs)
Measurements length was 10 seconds
Average velocity Q/A = 0.01671 m^3/sec/0.02935 m^3 = 0.5693 m/sec (1.868 fps)

Total Time	Measured Velocity		Total Time	Measured Velocity		Total Time	Measured Velocity	
sec.	m/sec	fps	sec.	m/sec	fps	sec.	m/sec	fps
10	0.5776	1.895	120	0.6129	2.011	230	0.6302	2.068
20	0.6070	1.991	130	0.6426	2.108	240	0.6368	2.089
30	0.6050	1.985	140	0.6359	2.086	250	0.6262	2.054
40	0.6128	2.010	150	0.6259	2.053	260	0.6309	2.070
50	0.6288	2.063	160	0.6242	2.048	270	0.6025	1.977
60	0.6284	2.062	170	0.6191	2.031	280	0.6399	2.099
70	0.6210	2.037	180	0.6096	2.000	290	0.6487	2.128
80	0.6289	2.063	190	0.6409	2.103	300	0.6414	2.104
90	0.6307	2.069	200	0.6393	2.097	310	0.6473	2.124
100	0.6236	2.046	210	0.6352	2.084	320	0.6446	2.115
110	0.6269	2.057	220	0.6342	2.081	330	0.6338	2.079
						340	0.6407	2.102

Run B-3: Velocity Profile of Upstream Sampling Location
Depth of water was 0.1896 meters (0.622 ft)
Flow rate was 0.0167 m^3/sec (0.590 cfs)
Measurement time was 10 seconds

Measurement Elevation		Velocity		Average Velocity		Measurement Elevation		Velocity		Average Velocity	
m	ft	m/sec	fps	m/sec	fps	m	ft	m/sec	fps	m/sec	fps
0.1750	0.574	0.5836	1.915	0.5743	1.884	0.0610	0.200	0.6765	2.219	0.6705	2.200
		0.5775	1.895					0.6730	2.208		
		0.5741	1.884					0.6687	2.194		
		0.5705	1.872					0.6672	2.189		
		0.5740	1.883					0.6626	2.174		
		0.5629	1.847					0.6764	2.219		
		0.5677	1.863					0.6719	2.204		
		0.5816	1.908					0.6736	2.210		
		0.5780	1.896					0.6732	2.209		
		0.5792	1.900					0.6696	2.197		
		0.5711	1.874					0.6684	2.193		
		0.5714	1.875					0.6643	2.179		
0.1219	0.400	0.6521	2.139	0.6465	2.121	0.0140	0.046	0.6212	2.038	0.6203	2.035
		0.6454	2.117					0.6208	2.037		
		0.6484	2.127					0.6184	2.029		
		0.6490	2.129					0.6154	2.019		
		0.6449	2.116					0.6163	2.022		
		0.6492	2.130					0.6114	2.006		
		0.6358	2.086					0.6200	2.034		
		0.6342	2.081					0.6270	2.057		
		0.6526	2.141					0.6254	2.052		
		0.6482	2.127					0.6222	2.041		
		0.6456	2.118					0.6211	2.037		
		0.6531	2.143					0.6242	2.048		
0.0914	0.300	0.6519	2.139	0.6489	2.129	0.1640	0.538	0.6160	2.021	0.6044	1.983
		0.6499	2.132					0.6049	1.985		
		0.6492	2.130					0.5984	1.963		
		0.6422	2.107					0.6025	1.977		
		0.6371	2.090					0.6057	1.981		
		0.6546	2.148					0.6109	2.004		
		0.6514	2.137					0.6095	2.000		
		0.6526	2.141					0.6069	1.991		
		8.6481	2.126					0.6088	1.997		
		0.6435	2.111					0.5692	1.867		
		0.6457	2.118					0.6127	2.010		
		0.6604	2.167					0.6089	1.998		

Run B-5: Calibration Curve at Upstream Sampling Location
Sampling elevation was 0.0914 meters (0.300 ft)
Sampling time was 2 min., 0 sec.

Flow Rate		Water Depth		Average = $\bar{u}$ Velocity Q/A		Measured = u Velocity		$\bar{u}/u$
m^3/s	cfs	m	ft	m/sec	ft/sec	m/sec	ft/sec	
0.0167	0.590	0.1905	0.625	0.4696	1.850	0.6356	2.085	0.887
0.0166	0.585			0.4668	1.834	0.6289	2.063	0.889
0.0164	0.580			0.4611	1.818	0.6317	2.073	0.887
0.0167	0.590	0.1868	0.613	0.4789	1.886	0.6522	2.140	0.881
0.0166	0.585			0.4760	1.870	0.644	2.114	0.885
0.0164	0.580			0.4703	1.854	0.6396	2.098	0.884
0.0167	0.590	0.1832	0.601	0.4883	1.923	0.6558	2.152	0.894
0.0166	0.585			0.4854	1.907	0.6546	2.148	0.888
0.0164	0.580			0.4795	1.891	0.6514	2.137	0.885
0.0167	0.590	0.1798	0.590	0.5970	1.959	0.6618	2.171	0.902
0.0166	0.585			0.5934	1.943	0.6563	2.153	0.903
0.0164	0.580			0.5863	1.926	0.6553	2.150	0.896
0.0167	0.590	0.1780	0.584	0.6031	1.979	0.6679	2.191	0.903
0.0166	0.585			0.5994	1.963	0.6612	2.169	0.905
0.0164	0.580			0.5922	1.946	0.6583	2.160	0.901

Run B-6: Velocity Profile at Downstream Sampling Location
Depth of water was 0.1649 meters (0.541 ft)
Flow rate was 0.0167 m^3/sec (0.590 cfs)
Measurement time was 10 seconds

Measurement Elevation		Velocity		Average Velocity	
m	ft	m/sec	ft/sec	m/sec	ft/sec
0.1509	0.495	0.6992	2.294	0.6953	2.398
		0.7024	2.304		
		0.6942	2.272		
		0.6948	2.280		
		0.6937	2.276		
		0.6921	2.771		
		0.6934	2.275		
		0.6988	2.293		
		0.6941	2.277		
		0.6936	2.276		
		0.6931	2.274		
		0.6956	2.282		
0.1219	0.400	0.7471	2.451	0.7369	2.418
		0.7448	2.444		
		0.7430	2.438		
		0.7465	2.449		
		0.7389	2.424		
		0.7320	2.402		
		0.7308	2.398		
		0.7508	2.463		
		0.7294	2.393		
		0.7276	2.387		
		0.7321	2.402		
		0.7195	2.361		
0.914	0.300	0.8124	2.665	0.8113	2.662
		0.8069	2.647		
		0.8095	2.656		
		0.8088	2.654		
		0.8192	2.688		
		0.8095	2.656		
		0.8110	2.661		
		0.8090	2.654		
		0.8130	2.667		
		0.8139	2.670		
		0.8095	2.656		
		0.8134	2.669		

Measurement Elevation		Velocity		Average Velocity	
m	ft	m/sec	ft/sec	m/sec	ft/sec
	0.200	0.7812	2.563	0.7753	2.544
		0.7717	2.532		
		0.7725	2.534		
		0.7765	2.548		
		0.7682	2.520		
		0.7746	2.541		
		0.7726	2.535		
		0.7760	2.546		
		0.7772	2.550		
		0.7698	2.526		
		0.7831	2.569		
		0.7801	2.559		
	0.042	0.6299	2.067	0.6282	2.061
		0.6396	2.098		
		0.6272	2.058		
		0.6370	2.090		
		0.6304	2.068		
		0.6207	2.036		
		0.6273	2.058		
		0.6285	2.062		
		0.6190	2.031		
		0.6398	2.099		
		0.6231	2.044		
		0.6156	2.020		

TABLE A-4. VELOCITY MEASUREMENTS (Cont'd)

Run B-7: Calibration Curve at Downstream Sampling Location
Sampling elevation was 0.0914 meters (0.300 ft)
Sampling time was 2 min., 0 sec.
Flow rate was 0.0167 m^3/sec (0.590 cfs)

Water Depth		Average Velocity $Q/A = \bar{u}$		Measured Velocity = u		$\bar{u}/u$
m	ft	m/sec	ft/sec	m/sec	ft/sec	
0.1631	0.535	0.6585	2.161	0.8117	2.663	0.812
				0.8102	2.658	0.813
0.1615	0.530	0.6648	2.181	0.8278	2.716	0.803
				0.8281	2.717	0.803
0.1573	0.516	0.6828	2.240	0.8506	2.791	0.803
				0.8521	2.796	0.801
0.1548	0.508	0.6936	2.275	0.8632	2.832	0.803
				0.8644	2.836	0.802