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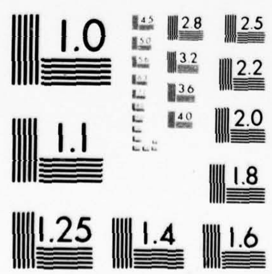

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DETERMINATION OF THEORETICAL SAMPLING EFFICIENCIES FOR ASPIRATED PARTICULATE MATTER THROUGH A DRES SAMPLING PROBE IN ANISOKINETIC FLOW (U)

by

Stanley B. Mellsen

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ABSTRACT

Sampling efficiencies are calculated for an aspirated particulate matter sampling probe under various conditions of anisokinetic flow. A mathematical model developed for the purpose was used to obtain results for a wide range of particle sizes and flow velocities. The results can be used to predict or correct sampling errors in field or laboratory experiments. Using the same test parameters as in previous experimental tests by other workers, sampling efficiencies were calculated and the results were found to agree favorably with the results of the experiments.

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NOTATION

C	particle concentration in the sample, g cm^{-3}
C_o	particle concentration in the free stream, g cm^{-3}
d	particle diameter, cm
D	distance from the inlet to the outlet cross section of the collection tube, cm
h	thickness of the collection tube wall at the outlet cross section, cm
L	length of coaxial boundary tube, cm
r	radial co-ordinate of particle position, cm
r_A	radius of coaxial boundary tube, cm
r_B	radius of collection tube, cm
$r_{p,\infty}$	radial co-ordinate of particle position far upstream, cm
$r_{s,\infty}$	far upstream radius of the stream tube that impinges on the collection tube circumference, cm
t	time, seconds
u_r	radial component of local fluid velocity, cm sec^{-1}
u_z	axial component of local fluid velocity, cm sec^{-1}
U	fluid velocity in collection tube, cm sec^{-1}
U_A	fluid velocity at boundary tube entrance, cm sec^{-1}
U_B	fluid velocity at collection tube exit, cm sec^{-1}
U_C	fluid velocity at boundary tube exit, cm sec^{-1}
U_O	free stream velocity, cm sec^{-1}
v_r	radial component of local particle velocity, cm sec^{-1}
v_z	axial component of local particle velocity, cm sec^{-1}
z	axial co-ordinate (origin at collection tube inlet) of particle position, cm
z_o	axial co-ordinate of particle far upstream, cm

NOTATION (Cont'd)

μ	absolute viscosity of fluid, poise
ρ	fluid density, g cm^{-3}
σ	particle density, g cm^{-3}
ψ	stream function, cm^3 sec^{-1}

The following are dimensionless

C_D	drag coefficient for spheres
G(1), G(2), G(3) and G(4)	dependent variables solved for by numerical integration. They represent $\bar{v}_z$, $\bar{v}_r$, $\bar{z}$ and $\bar{r}$ respectively
E_m	collection efficiency of sampling tube
H	thickness of collection tube wall, h/r_A
i,j	grid point co-ordinates in the radial and axial directions respectively
i_B,j_B	grid point co-ordinates of the edge of the collection tube inlet
j_o	axial grid point co-ordinate of a particle at the far upstream position
K	inertia parameter of particle
$\bar{r}$	radial co-ordinate of particle, r/r_B
$\bar{r}_{p,\infty}$	radial co-ordinate of particle position far upstream, $r_{p,\infty}/r_b$
$\bar{r}_{s,\infty}$	far upstream radius of the stream tube that impinges on the collection tube circumference, $r_{s,\infty}/r_b$
R	radial co-ordinate used in calculating the stream function field, r/r_A
Re	spherical particle Reynolds number in flow in the proximity of the collection tube
Re_o	spherical particle Reynolds number in free stream

NOTATION (Cont'd)

$\bar{u}_{\bar{r}}$	radial component of local fluid velocity, $d\bar{u}/d\bar{r}$
$\bar{u}_{\bar{z}}$	axial component of local fluid velocity, $d\bar{u}/d\bar{z}$
$\bar{v}_{\bar{r}}$	radial component of local particle velocity, $d\bar{r}/d\tau$
$\bar{v}_{\bar{z}}$	axial component of local particle velocity, $d\bar{z}/d\tau$
$\bar{z}$	axial co-ordinate (origin at collection tube inlet) of particle, z/r_B
$\bar{z}_o$	axial co-ordinate of particle far upstream, z_o/r_B
Z	axial co-ordinate used in calculation of the stream function field, z/r_A
α	ratio of collection tube radius to boundary tube radius, r_B/r_A
β	length of coaxial boundary tube, L/r_A
γ	distance from the inlet to the outlet cross section of the collection tube, D/r_A
δ	distance from inlet of boundary tube to inlet of collection tube, $\beta - \gamma$
τ	time, tU_A/r_B
ϕ	dimensionless group independent of particle position, Re_o^2/K
Ψ	stream function, $\psi/\frac{1}{2}U_A r_A^2$

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1. INTRODUCTION

The collection of a representative sample of finely divided particulate matter from still or moving airstreams is required where the size distribution, mass flow rate, concentration, or some other characteristic of the particulate-air system has to be determined. A sample of particulate matter will be representative only if the particle size distribution and content in the sample are the same as those in the ambient air at the point of sampling.

Particulate matter sampling instruments used at DRES consist essentially of a probe or tube through which the sample is drawn and then separated from the air stream for analysis.

Such a sampling system may be subject to three distinct types of error (Vitols, 1964) due to:

(1) particles failing to enter the sampling probe in representative concentrations;
(2) particles being deposited between the probe mouth and the separation location; and
(3) particles being shattered, aggregated, or incompletely retained by collection devices.

Particles enter the sampling probe in representative concentrations when the entrance velocity is exactly equal to the velocity of the gas being sampled, in which case the sampling is said to be isokinetic. If the velocities are unequal errors of type (1) occur, in which case the sampling is referred to as anisokinetic.

The purpose of this report is to describe a mathematical model for calculating the error due to anisokineticity for a sampling probe developed and used at DRES (Fig. 1). The nominal inside diameter of this probe is 3/4 inch. The inlet end is sharp edged and the outside surface is sloped so that the tube wall thickness increases away from the inlet with a 1 in 12 slope. The length of the tapered section is 2 3/4 inches. Results are provided for various flow conditions so that the user of the sampling probe can determine the magnitude of sampling errors and make corrections when anisokinetic sampling occurs.

2. DEFINITION OF THE PROBLEM

Due to inertial and drag forces, a particle flowing at the free stream velocity far upstream of the sampling probe will not necessarily follow a stream line in the vicinity of the probe, where radial and axial velocity components of the fluid may be changing markedly. Thus, if the estimated concentration of particles in the free stream is taken as the number of particles collected by the sampler divided by the volume of air passing through the probe, the calculated values may differ markedly from the true free stream values. The total volume of air passing through the probe will be that enclosed by a stream tube that impinges on the outer circumference of the probe opening. When the velocity at the tube inlet,

U_B, is less than the free stream velocity, U_A ($U_B/U_A < 1$), particles from outside the limiting stream tube will enter the sampler, while for $U_B/U_A > 1$ particles originally inside the limiting stream tube will pass outside the probe. All particles of the same diameter that are collected by the probe are those within the circular envelope generated by particles that just impinge on the outer circumference of the probe. Let $r_{p,\infty}$ be the upstream radius of the limiting particle trajectory envelope, and $r_{s,\infty}$ be the upstream radius of the stream tube that impinges on the probe circumference. Then the sampling efficiency is given by:

$$\left(\frac{C}{C_o}\right) = \left(\frac{r_{p,\infty}}{r_{s,\infty}}\right)^2 \qquad \text{(Eq. 1)}$$

where C_o is the particle concentration in the free stream and C is the particle concentration in the sample.

The collection efficiency of the probe is given by:

$$E_m = \left(\frac{r_{p,\infty}}{r_B}\right)^2 \qquad \text{(Eq. 2)}$$

where r_B is the radius of the probe inlet. The problem then is to calculate $r_{p,\infty}$ and $r_{s,\infty}$ so that the sampling efficiency can be found from Eq. 1 and, incidentally, so that the collection efficiency can be found from Eq. 2.

3. EQUATIONS OF MOTION

The motion of an individual particle has been shown (Vitols, 1964 and Batchelor, 1956) to be determined by the following ordinary differential equations:

$$\frac{d\overline{v_r}}{d\tau} = \frac{C_D Re(\overline{u_r} - \overline{v_r})}{24\ K} \qquad \text{(Eq. 3)}$$

$$\frac{d\overline{v_z}}{d\tau} = \frac{C_D Re(\overline{u_z} - \overline{v_z})}{24\ K} \qquad \text{(Eq. 4)}$$

where $$\mathrm{Re} = \mathrm{Re}_o[(\bar{u}_{\bar{r}} - \bar{v}_{\bar{r}})^2 + (\bar{u}_{\bar{z}} - \bar{v}_{\bar{z}})^2]^{\frac{1}{2}} \qquad \text{(Eq. 5)}$$

$$K = \frac{\sigma d^2 U_A}{18 \mu r_B} \quad \text{particle inertia parameter} \qquad \text{(Eq. 6)}$$

$$\mathrm{Re}_o = \frac{U_A d \rho}{\mu} \quad \text{free stream Reynolds number} \qquad \text{(Eq. 7)}$$

The symbols are defined in the notation section near the front of this report and the basic geometry of the flow system is illustrated in Fig. 2.

Several assumptions are inherent in the use of Eqs. 3 and 4 for calculating the collection and sampling efficiencies due to a stream of particles, including:

(a) uniform particle distribution;
(b) no gravitational or electrostatic forces of consequence;
(c) monodisperse spherical particles with diameter very small in relation to the inlet diameter of the probe; and
(d) free stream flow that is steady, incompressible and irrotational.

The drag coefficient is a function of Reynolds number and is available in the form of definitive empirical equations (Davies, 1945). These equations are stated as follows:

$$\mathrm{Re} = \frac{C_D \mathrm{Re}^2}{24} - 2.3363 \times 10^{-4} (C_D \mathrm{Re}^2)^2 + 2.0154 \times 10^{-6} (C_D \mathrm{Re}^2)^3 - 6.9105 \times 10^{-9} (C_D \mathrm{Re}^2)^4 \qquad \text{(Eq. 8)}$$

for $\mathrm{Re} < 4$ or $C_D \mathrm{Re}^2 < 140$

$$\log_{10}\mathrm{Re} = -1.29536 + 9.86 \times 10^{-1} (\log_{10} C_D \mathrm{Re}^2) - 4.6677 \times 10^{-2} (\log_{10} C_D \mathrm{Re}^2)^2 + 1.1235 \times 10^{-3} (\log_{10} C_D \mathrm{Re}^2)^3 \qquad \text{(Eq. 9)}$$

for $3 < \mathrm{Re} < 10^4$ or $C_D \mathrm{Re}^2 < 4.5 \times 10^7$

4. AIR FLOW FIELD EQUATIONS

The equations of fluid velocity were derived from the stream function for ideal flow over and through the collection probe. To solve the problem, an outer boundary was used around the collection tube in the form of a coaxial tube of radius r_A (Fig. 3), which was chosen large enough so that the effect of the boundary tube on flow in the proximity of the collection tube is negligible. The collection tube was inserted a distance D into the downstream end of the boundary tube. Since the flow is axisymmetric only a radial plane containing both tubes has to be considered.

The fluid enters the boundary tube with steady velocity U_A, and separates into a central stream with velocity U_B at the entrance of the collection tube, and an annular stream, with velocity U_C, at the downstream end of the boundary tube. The axial velocities U_A, U_B and U_C are uniform. Also, there is no radial flow at the end cross sections.

The boundary conditions on the flow can now be completely specified so that the flow field can be obtained by solution of the equation of the stream function.

The axially symmetric stream function $\psi(r,z)$ (Batchelor, 1967) satisfies:

$$\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial z^2} = 0 \qquad \text{(Eq. 10)}$$

The two velocity components (Fig. 2) are given by:

$$u_z = \frac{1}{r}\frac{\partial\psi}{\partial r} \qquad \text{(Eq. 11)}$$

$$u_r = -\frac{1}{r}\frac{\partial\psi}{\partial z} \qquad \text{(Eq. 12)}$$

When U_A and U_B are specified continuity gives U_C as follows:

$$U_C = \frac{U_A - \alpha^2 U_B}{1 - \left[\left(\frac{r_B + h}{r_B}\right)\alpha\right]^2} \qquad \text{(Eq. 13)}$$

where $\alpha = \frac{r_B}{r_A}$ (Eq. 14)

and h is the thickness of the collection tube wall at the outlet end (Fig. 3).

For uniform velocity profiles, the stream function is of the form:

$$\psi = \tfrac{1}{2}ur^2 \qquad \text{(Eq. 15)}$$

To allow for greater generality, the stream function and the geometric variables were restated in the following dimensionless form:

$$\Psi = \frac{\psi}{\tfrac{1}{2}U_A r_A{}^2} \qquad \text{(Eq. 16)}$$

$$R = \frac{r}{r_A} \qquad \text{(Eq. 17)}$$

$$Z = \frac{z}{r_A} \qquad \text{(Eq. 18)}$$

$$\beta = \frac{L}{r_A} \qquad \text{(Eq. 19)}$$

$$\gamma = \frac{D}{r_A} \qquad \text{(Eq. 20)}$$

$$H = \frac{h}{r_A} \qquad \text{(Eq. 21)}$$

The boundary values for the stream function and the geometric configuration in terms of the dimensionless variables are shown in Fig. 4.

The axially symmetric stream function equation (Eq. 10) becomes:

$$\frac{\partial^2\Psi}{\partial R^2} - \frac{1}{R}\frac{\partial\Psi}{\partial R} + \frac{\partial^2\Psi}{\partial R^2} = 0 \qquad \text{(Eq. 22)}$$

5. DISCRETIZATION SCHEME FOR THE AIR FLOW FIELD

The equation for the axially symmetric stream function (Eq. 22) is discretized as follows:

$$\frac{\Psi_{i-1,j} - 2\Psi_{i,j} + \Psi_{i+1,j}}{\Delta R^2} - \frac{\Psi_{i+1,j} - \Psi_{i-1,j}}{2i\Delta R^2} + \frac{\Psi_{i,j-1} - 2\Psi_{i,j} + \Psi_{i,j+1}}{\Delta Z^2} = 0 \qquad \text{(Eq. 23)}$$

where i and j are the grid point numbers in the R and Z directions respectively (Fig. 5). Eq. 23 can be rearranged to give a simple equation by choosing a square grid so that ΔZ and ΔR are equal. The resulting equation, which is suitable for Gauss-Seidel iteration (Carnahan et al., 1969), is given as follows:

$$\Psi_{i,j} = \frac{\Psi_{i-1,j} + \Psi_{i+1,j} + \Psi_{i,j-1} + \Psi_{i,j+1}}{4} - \frac{\Psi_{i+1,j} - \Psi_{i-1,j}}{8i} \qquad \text{(Eq. 24)}$$

Eq. 24 is suitable for all interior points, which are defined as points for which the nearest boundary is at least one grid size unit away. A grid can be chosen such that all points not right on the boundary are interior points, with the exception of the outside boundary of the collection tube which has a slope of 1/12. To handle these points, which herein are called special boundary points (Fig. 6), a Taylor series expansion for a point near the boundary was used, as is generally applied to curved boundaries (Carnahan et al., 1969). The resulting finite difference equation is suitable for these points instead of Eq. 24.

$$\Psi_{i,j} = \frac{a}{2(a+1)}\left[\Psi_{i,j-1} + \Psi_{i,j+1} + \frac{2\Psi_A}{a(a+1)} + \frac{2\Psi_{i+1,j}}{a+1} + \frac{\Psi_A - \Psi_{i+1,j}}{i(1+a)}\right] \qquad \text{(Eq. 25)}$$

where a is the distance, in terms of the grid size unit, from the grid point to the sloping boundary at point A and $0 < a < 1$.

The grid size was chosen so that the thickness of the collection tube wall at the downstream end corresponded to exactly two units. Then the length of the tube must be 24 grid units since the slope of the outer collection tube boundary is 1/12. The boundary tube radius and the distance, δ, (Fig. 4) to the upstream end of the boundary tube were chosen so that they are at least five times the radius of the inlet to the collection tube, so that particles travelling in the flow toward the tube inlet will behave as if they are coming from far upstream and into the collection tube in free space. Now, to satisfy these conditions, and to ensure adequate core storage space in the DRES IBM 1130 computer, while maintaining a fineness of grid for sufficient accuracy, the collection tube radius was chosen to be 12 units, the boundary tube radius 60 units, and the boundary tube length 88 units (Fig. 5).

The stream function at each point was then obtained by means of Gauss-Seidel iteration (Carnahan et al., 1969) using Eq. 24 and Eq. 25. The boundary conditions were set initially and held fixed throughout the course of the solution (Fig. 4) and,as a starting point for the iteration, the value of the stream function at all points not right on the boundary was set to zero. The calculations were done with the DRES IBM 1130 computer by means of a Fortran program, the listing of which is shown in Appendix A.

6. SOLUTION OF THE EQUATIONS OF MOTION

As previously stated in Section 2 of this report, the problem is to find the upstream radii $r_{p,\infty}$ and $r_{s,\infty}$ so that the sampling and collection efficiencies can be calculated. In the same dimensionless form used in Eqs. 3 and 4 the value of $\bar{r}_{p,\infty}$ (notation) was found by an iterative procedure called the half interval method (Carnahan et al., 1969). The value of $\bar{r}_{p,\infty}$ for a critical particle was estimated far upstream, the path followed to the plane of the collection tube opening, and the miss distance calculated. Next, the half interval method, previously mentioned, was applied to determine a better initial estimate. Then the path was followed again to the plane of the collection tube opening for another calculation of the miss distance. This process was repeated several times until sufficient accuracy was achieved. The initial upstream position in a plane perpendicular to the flow direction was located far enough from the collection tube opening so that free stream conditions prevailed. A distance of five target radii upstream of the target centre was considered adequate (Batchelor, 1956).

The path of an individual particle was determined step-by-step by applying a fourth order Runge-Kutta method (Carnahan et al., 1969) to the equations of motion (Eqs. 3 and 4). The values of Re and K in these equations were easily found for each new step by direct substitution of previously determined values into Eqs. 5, 6 and 7, but the value of $C_D Re$ in Eqs. 3 and 4 had to be calculated in each step by numerical solution of the definitive empirical equations (Eqs. 8 and 9). This was done using Newton's method (Carnahan et al., 1969) for finding the zero of a function. The values of $\bar{u}_{\bar{r}}$ and $\bar{u}_{\bar{z}}$ were calculated in each step from the stream function field as follows:

$$\bar{u}_{\bar{r}} = \frac{\Psi_{i,j-1} - \Psi_{i,j+1}}{4(i-1)(\Delta R)^2} \qquad \text{(Eq. 26)}$$

$$\bar{u}_{\bar{z}} = \frac{\Psi_{i+1,j} - \Psi_{i-1,j}}{4(i-1)(\Delta R)^2} \qquad \text{(Eq. 27)}$$

where i and j define the grid point of the particle position. Since the radius of the collection tube was chosen to be 12 grid units these are given by:

$$i = 1 + 12\bar{r} \qquad \text{(Eq. 28)}$$

$$j = j_o + 12(\bar{z} - \bar{z}_o) \qquad \text{(Eq. 29)}$$

where j_o and $\bar{z}_o$ are the starting point values of j and $\bar{z}$. The values of i and j obtained from Eqs. 28 and 29 were rounded off to the nearest lower integer value in each calculation. The value of $\bar{r}_{s,\infty}$ was obtained directly from the stream function by:

$$\bar{r}_{s,\infty} = \frac{\Delta R(i-2)r_A}{r_B}\sqrt{\frac{\Psi_{i_B,j_B}}{\Psi_{i-1,j_o}}} \qquad \text{(Eq. 30)}$$

calculated at the lowest value of i satisfying:

$$\Psi_{i,j_o} > \Psi_{i_B,j_B} \qquad \text{(Eq. 31)}$$

where i_B and j_B define the grid point at the edge of the collection tube inlet. The calculations to obtain the solutions were done with the DRES IBM 1130 computer by means of a Fortran program, the listing of which is shown in Appendix B. The sampling and collection efficiencies given by Eqs. 1 and 2 were also obtained by this program after the values of $\bar{r}_{p,\infty}$ and $\bar{r}_{s,\infty}$ had been calculated.

7. RESULTS

A sample stream function field for one set of input data is shown after its associated computer program (Appendix A), and a sample calculation of the sampling and collection efficiencies is shown after their associated computer program (Appendix B). Using these two computer programs many more calculations were made to produce the graphical results shown in Figs. 7 to 14. These results are described in greater detail as follows.

Many experimenters have measured sampling efficiencies over the last sixty-five years (Vitols, 1964). An experimental study using zinc sphere test dust in a wind tunnel was done for sampling tubes of 0.65 to 1.90 cm diameter (Badzioch, 1959). The tubes were blunt-edged with a wall thickness of 0.6 mm. The results for some of these experiments are shown in Fig. 7. Using the same test parameters as in these experiments, sampling efficiencies were calculated for various velocity ratios, U_B/U_A, and the results plotted in Fig. 7 assuming that U_B/U_A, of the mathematical model, is equivalent to U/U_0 in the experiments of Badzioch. The results agree favorably even though the tube shapes were slightly different. However, calculations for various input parameters, keeping $U_B/U_A = 1$, gave sampling efficiencies between 0.9900 and 1.0000, indicating that the tapered outside wall of the collection tube does not disturb the flow so as to cause deviations for isokinetic velocity conditions. Therefore, the two tubes can, for practical purposes, be considered equivalent.

The sampling and collection efficiencies are functions of two dimensionless groups, the inertial parameter, K, and the free stream particle Reynolds number, Re_0. A new dimensionless group:

$$\phi = \frac{Re_o^{\ 2}}{K} \qquad \text{(Eq. 32)}$$

independent of particle size can be introduced (Friedlander, 1977). According to the rules of dimensional analysis this is permissible, but the efficiencies are still determined by two groups chosen to be K and ϕ. The calculated sampling efficiency is plotted against the inertia parameter in Figs. 8 and 9 for sampling rates of 5 and 40 litres per minute respectively. Curves are plotted for values of U_B/U_A of 1/3, 1, 3 and 10 in each of the two figures. Note that equal values of U_B/U_A correspond to a different value of ϕ in Figs. 8 and 9. This is due to two different sampling rates because sampling rate and the corresponding free stream velocity were the only dimensional parameters which were changed. The calculated collection efficiencies were plotted in Figs. 10 and 11 for the same velocity ratios and sampling rates as the sampling efficiencies shown in Figs. 8 and 9.

To show the effect of varying the flow velocity in the sampling tube while maintaining a constant velocity ratio, the sampling efficiency was plotted against the inertia parameter in Fig. 12. Curves were plotted for the two sampling rates of 5 and 40 litres per minute as before. Similar curves are shown for the collection efficiencies in Fig. 13.

To illustrate directly the drastic effect of varying free stream velocity on the sampling efficiency for constant sampling velocity and particle size the sampling efficiency was plotted against the velocity ratio, U_B/U_A, for a particle size of 100 μm in Fig. 14.

8. DISCUSSION

As can be seen in Fig. 7, where the experiments of Badzioch are compared to the results obtained by means of the present mathematical model, the effect of anisokineticity produces sampling errors of greater than 100 percent even when the sampling velocity differs from the free stream velocity by less than a factor of three. These results are for 23 micron spherical particles. Smaller particles give rise to smaller sampling error. The exact errors for very small particles cannot be determined by the present model because the computing errors increase with decreasing particle size for very small particles. Experience shows that, in addition to the requirement of a small grid size for calculating the stream function field, reliable results can only be achieved if the values of the time step increment $d\tau$ is at least less than the inertia parameter K. So, as particle size decreases, and correspondingly K decreases, a larger number of calculations are required which, in itself, can give rise to computing errors. However, the results did indicate that the sampling errors for particles in the order of 10 microns can be at least 50 percent. For example, for a sampling rate of 5 litres per minute and a sampling velocity which is a third of the free stream velocity, Fig. 8 shows a value of the sample concentration which is 1.5 times the free stream concentration when the inertia parameter is 0.029. This corresponds to a particle size of 10 microns when the particle density is 1 g cm^{-3} and 5 microns when the particle density is 4 g cm^{-3}. The density of zinc sulfide, which is sometimes used as phosphorescent trace material with particle sizes of about 5 microns, is 4.1 g cm^{-3} (Sehmel, 1973).

Although the model cannot be used for calculations using completely still air, very low free stream velocities can be treated. For a sampling rate of 5 litres per minute and a velocity ratio $U_B/U_A = 10$, as used in one of the curves in Fig. 8, the corresponding free stream velocity is 3 cm sec^{-1}. This is about the wind velocity expected in an enclosure such as an ordinary, normally ventilated, room.

Another point to note, when considering sampling errors, is that even when the velocity ratio and particle size are kept constant, the sampling error varies somewhat with the absolute value of the sampling tube velocity. This is indicated by the difference in the two curves (Fig. 12) for sampling rates of 5 and 40 litres per minute.

The drastic effect on sampling efficiency of varying the free stream velocity while maintaining a constant sampling velocity is illustrated in Fig. 14 where the calculated results for a particle size of 100 microns are plotted directly.

9. CONCLUSIONS

The effect of anisokineticity on sampling with the DRES sampling probe used in field conditions is large enough so that drastic errors in sampling can occur. The results obtained by the mathematical model described herein can be used to estimate the size of these sampling errors. They can also be used to correct measured samples if the wind velocity and sampling rate are also measured, and the particle size and density are known. Long sampling periods are best, so that effects due to wind speed changes which occur over short time periods are averaged out.

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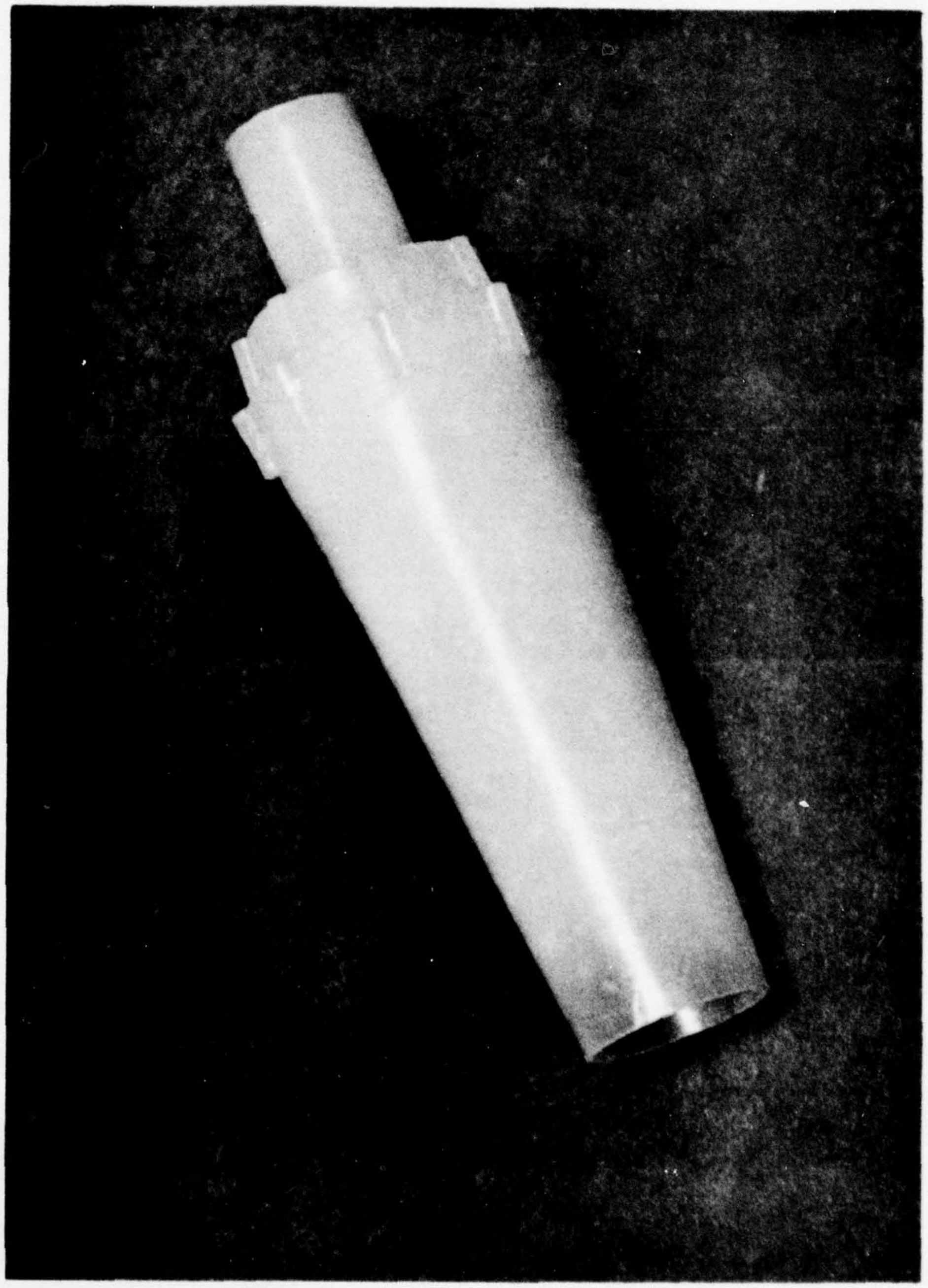

Figure 1: Collection Tube for Sampling Particulates in Air

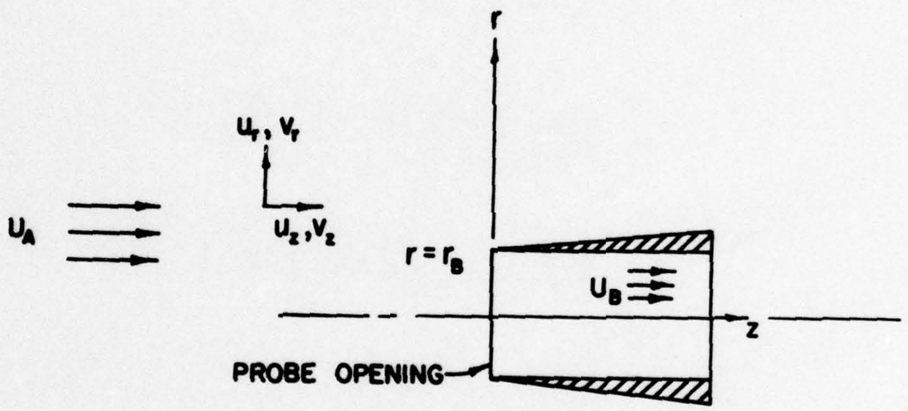

FIGURE 2: CO-ORDINATE SYSTEM FOR AXIAL FLOW IN THE PROXIMITY OF THE COLLECTION TUBE

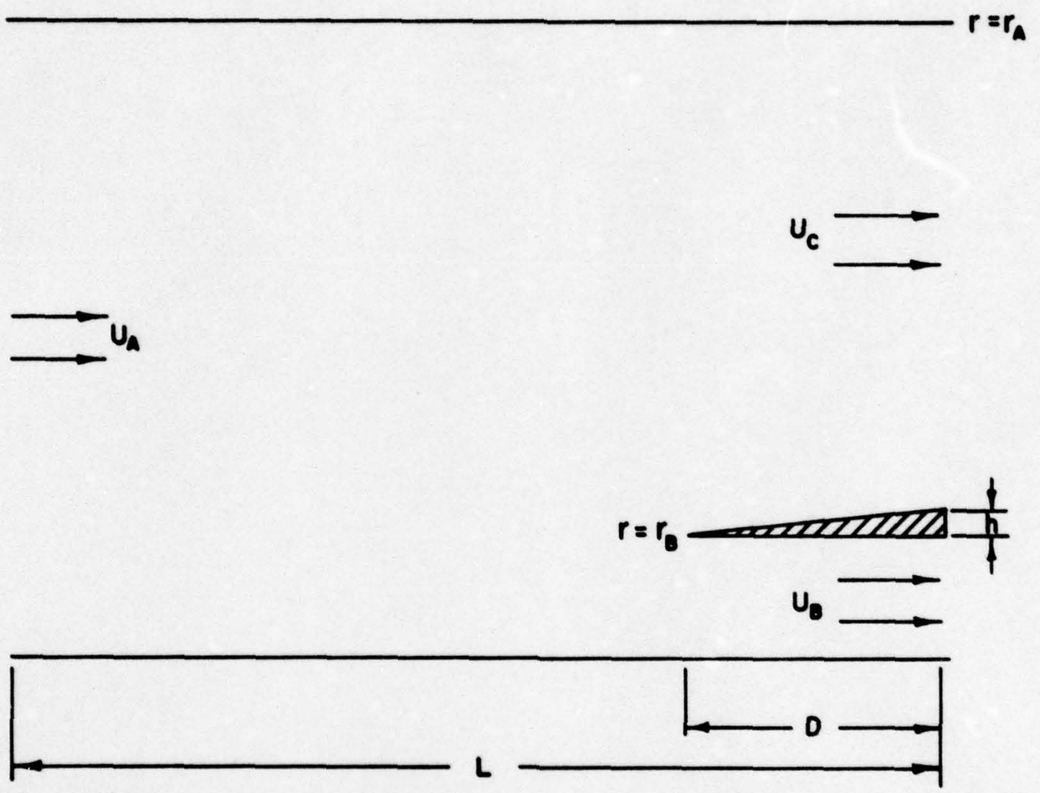

FIGURE 3: GEOMETRIC MODEL FOR FLOW FIELD IN THE PROXIMITY OF THE COLLECTION TUBE

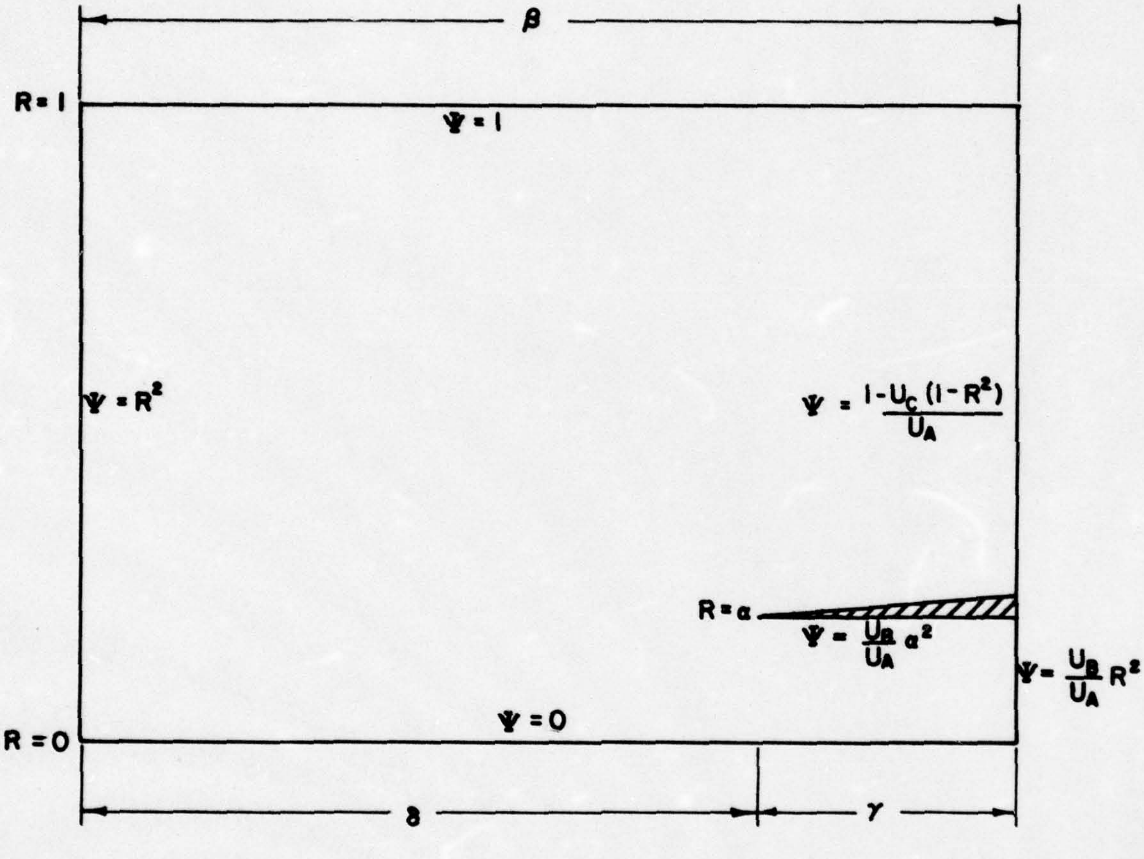

FIGURE 4: STREAM FUNCTION BOUNDARY CONDITIONS

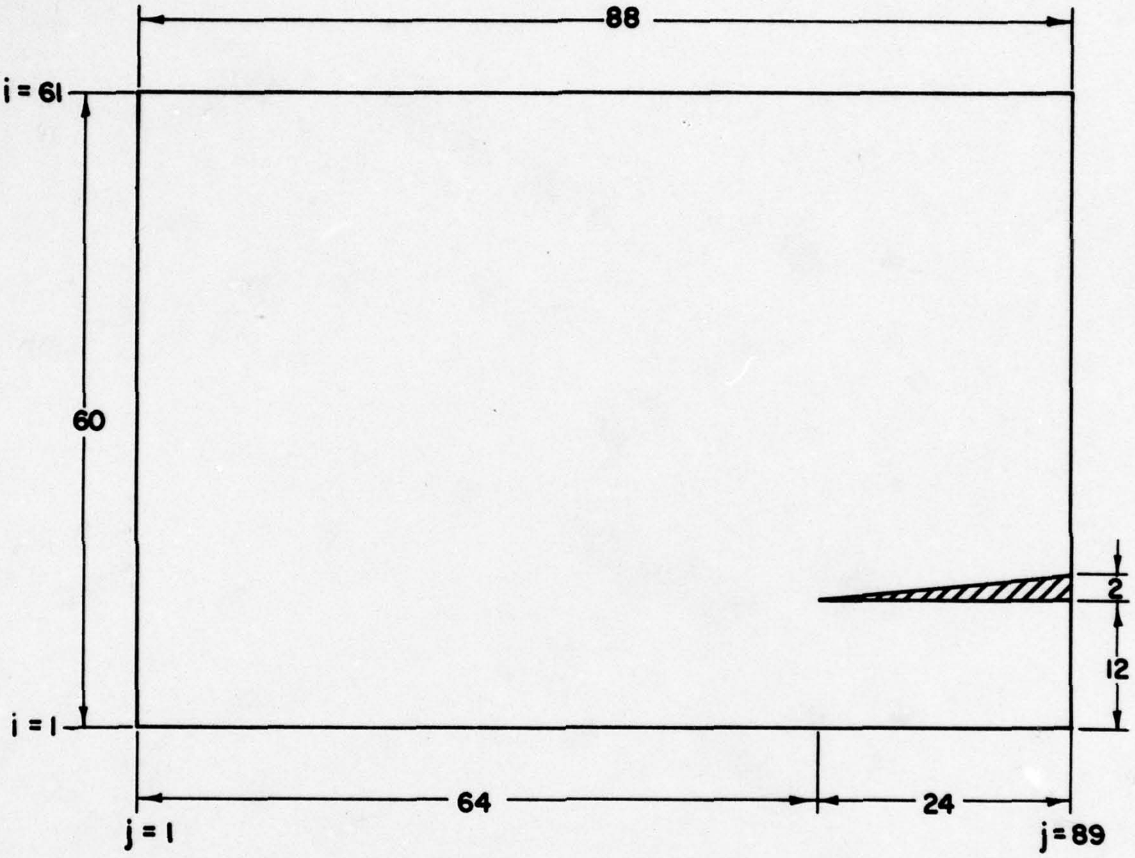

FIGURE 5: DIMENSIONS OF DISCRETIZATION GRID FOR AIR FLOW FIELD

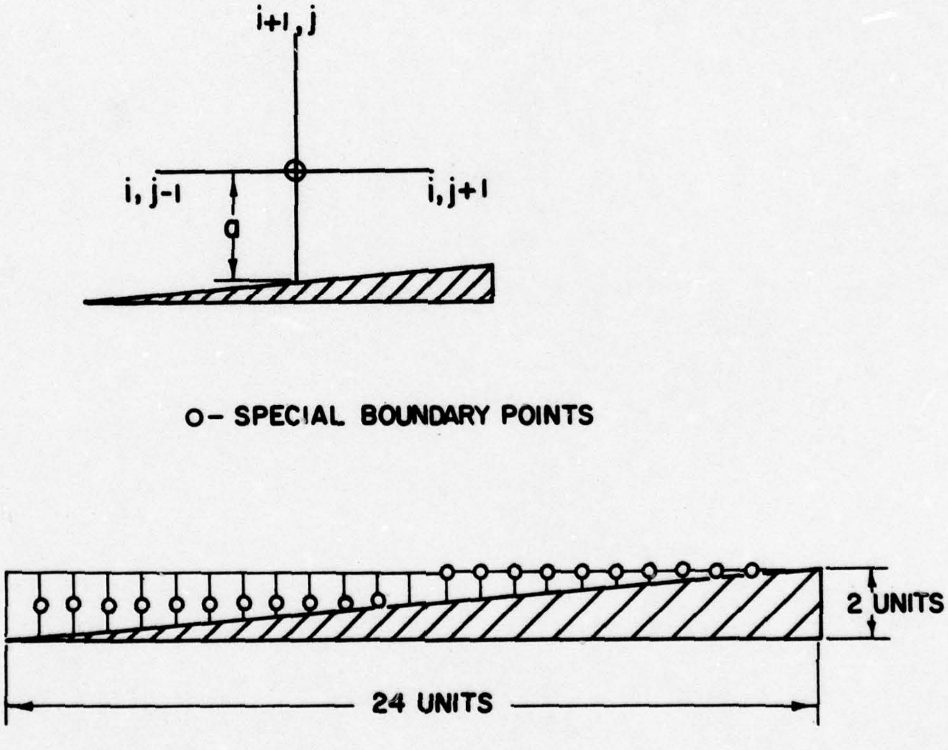

FIGURE 6: GRID POINTS ALONG SLOPING BOUNDARY OF COLLECTION TUBE

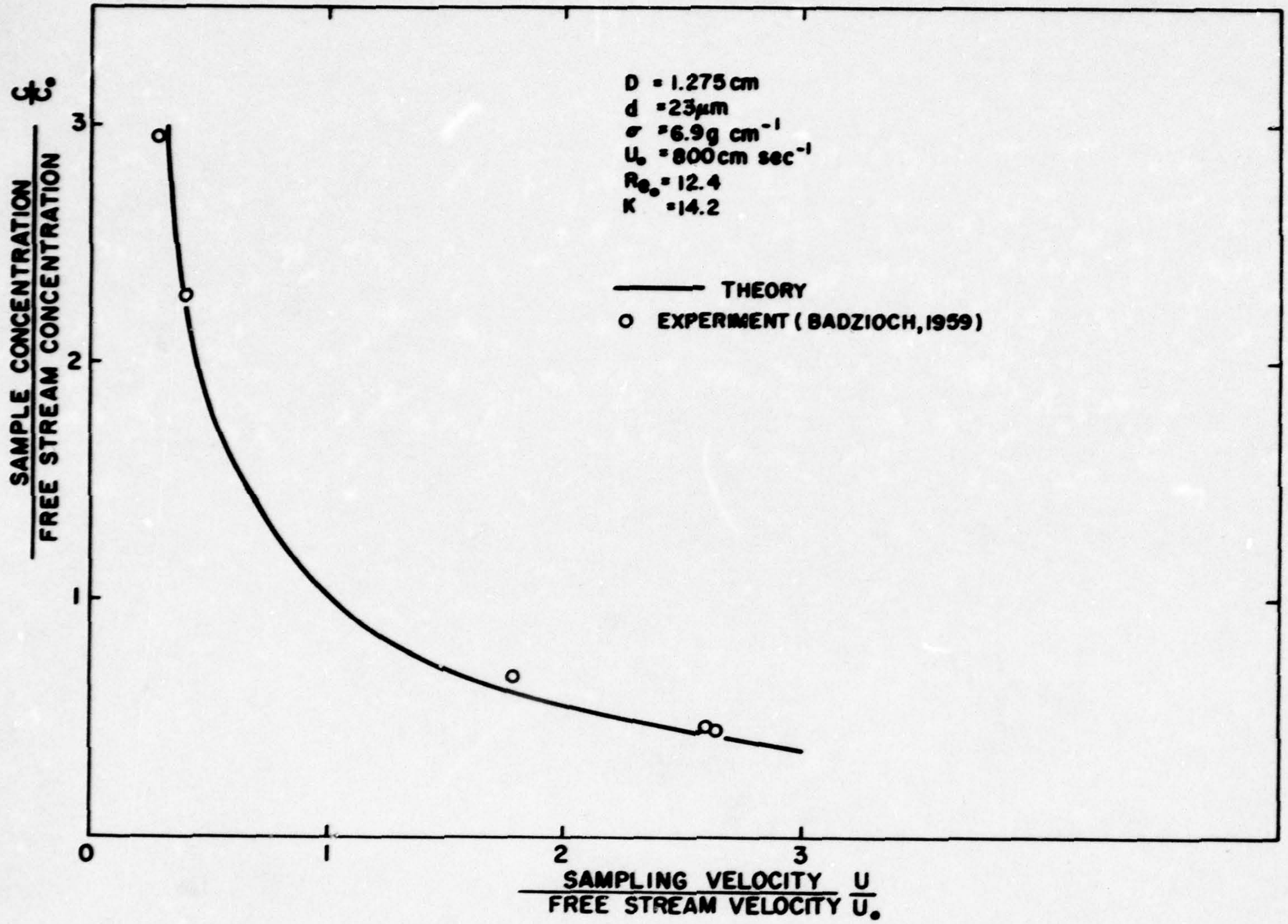

FIGURE 7: COMPARISON OF THEORETICAL AND EXPERIMENTAL EFFECTS OF ANISOKINETIC SAMPLING FOR ZINC SPHERE TEST DUST

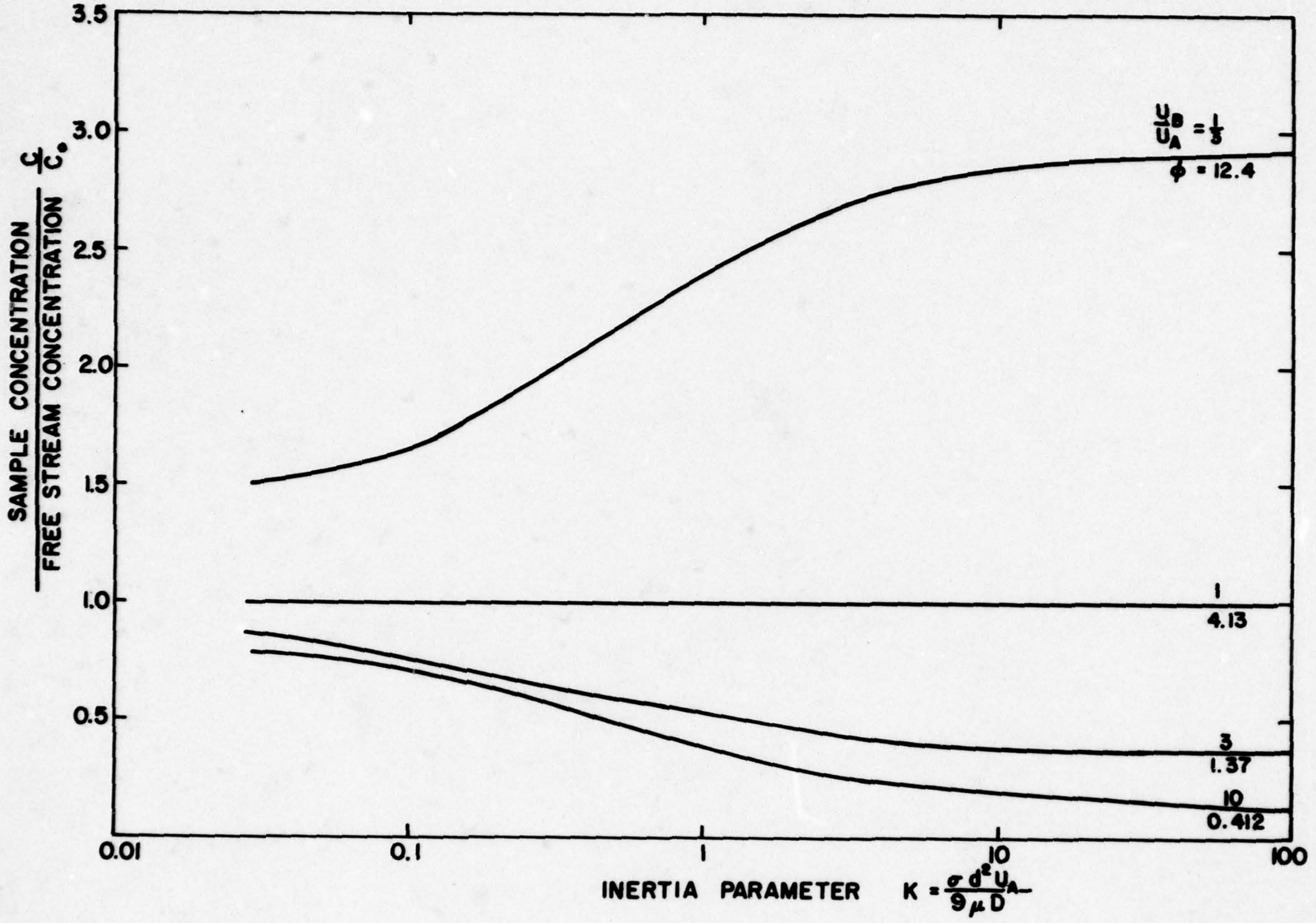

FIGURE 8: EFFECT OF VELOCITY RATIO ON SAMPLING EFFICIENCY FOR FIXED SAMPLING RATE (5 L min^{-1})

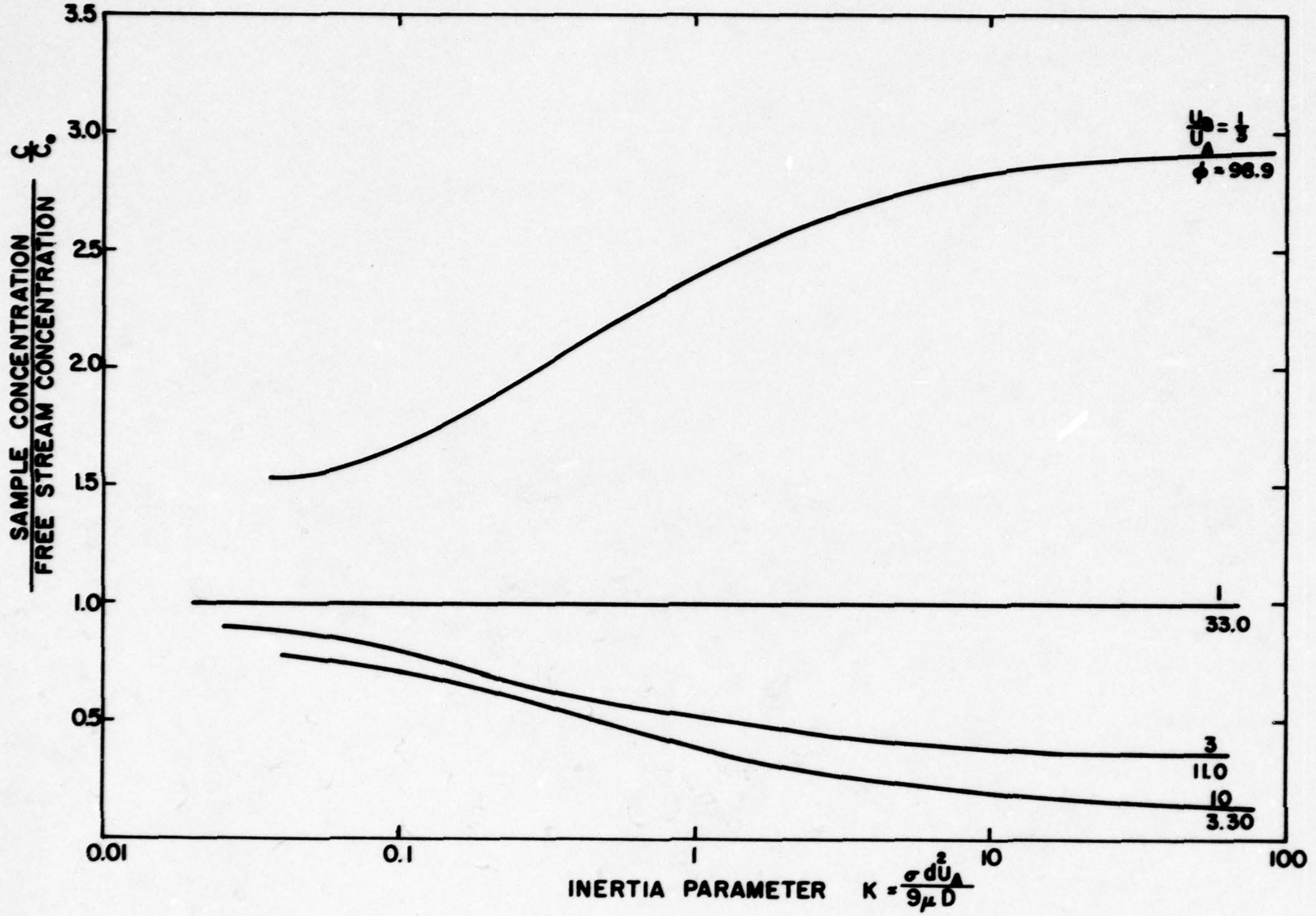

FIGURE 9: EFFECT OF VELOCITY RATIO ON SAMPLING EFFICIENCY FOR FIXED SAMPLING RATE (40 L min^{-1})

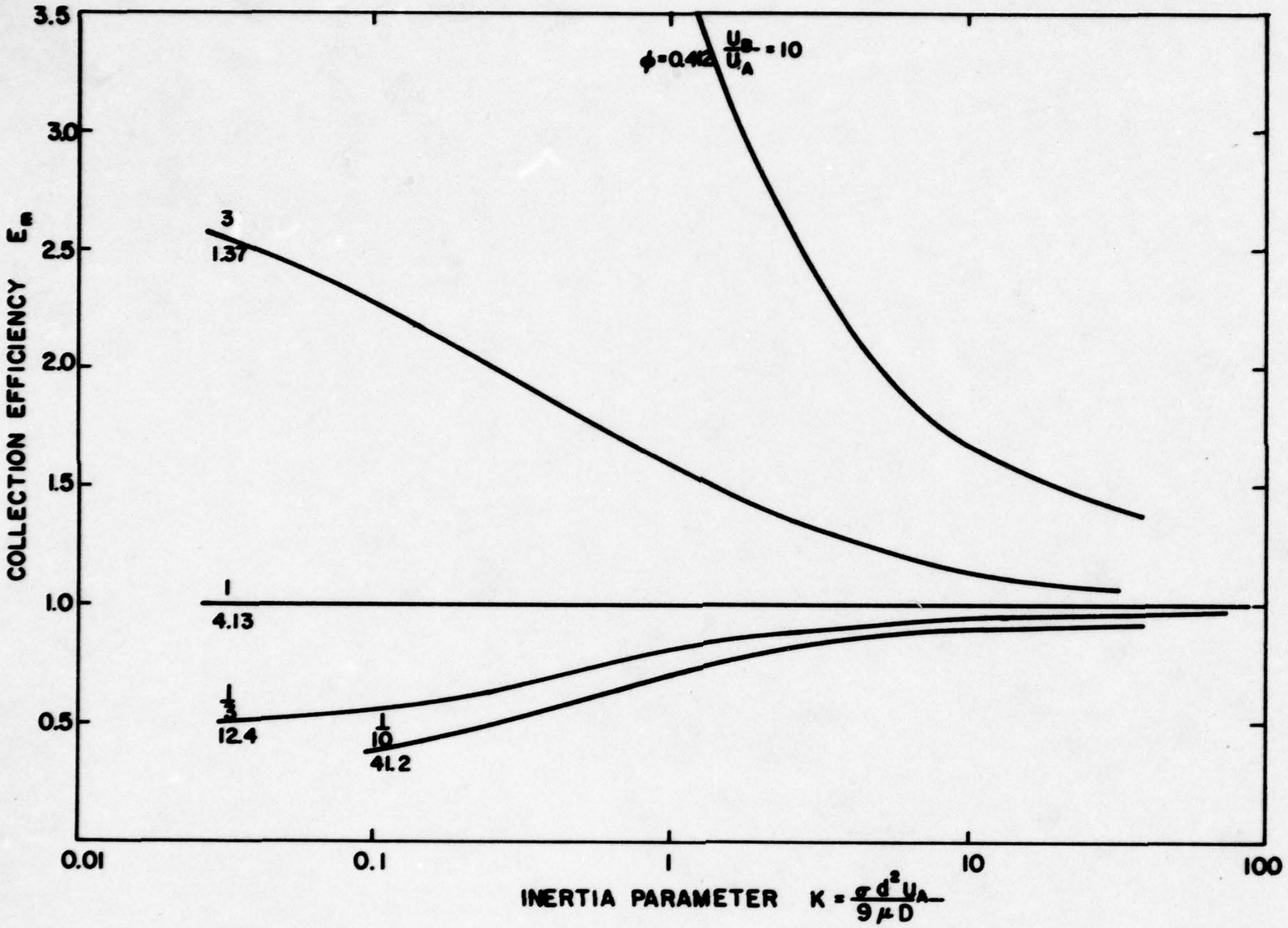

FIGURE 10: EFFECT OF VELOCITY RATIO ON COLLECTION EFFICIENCY FOR FIXED SAMPLING RATE (5 L min^{-1})

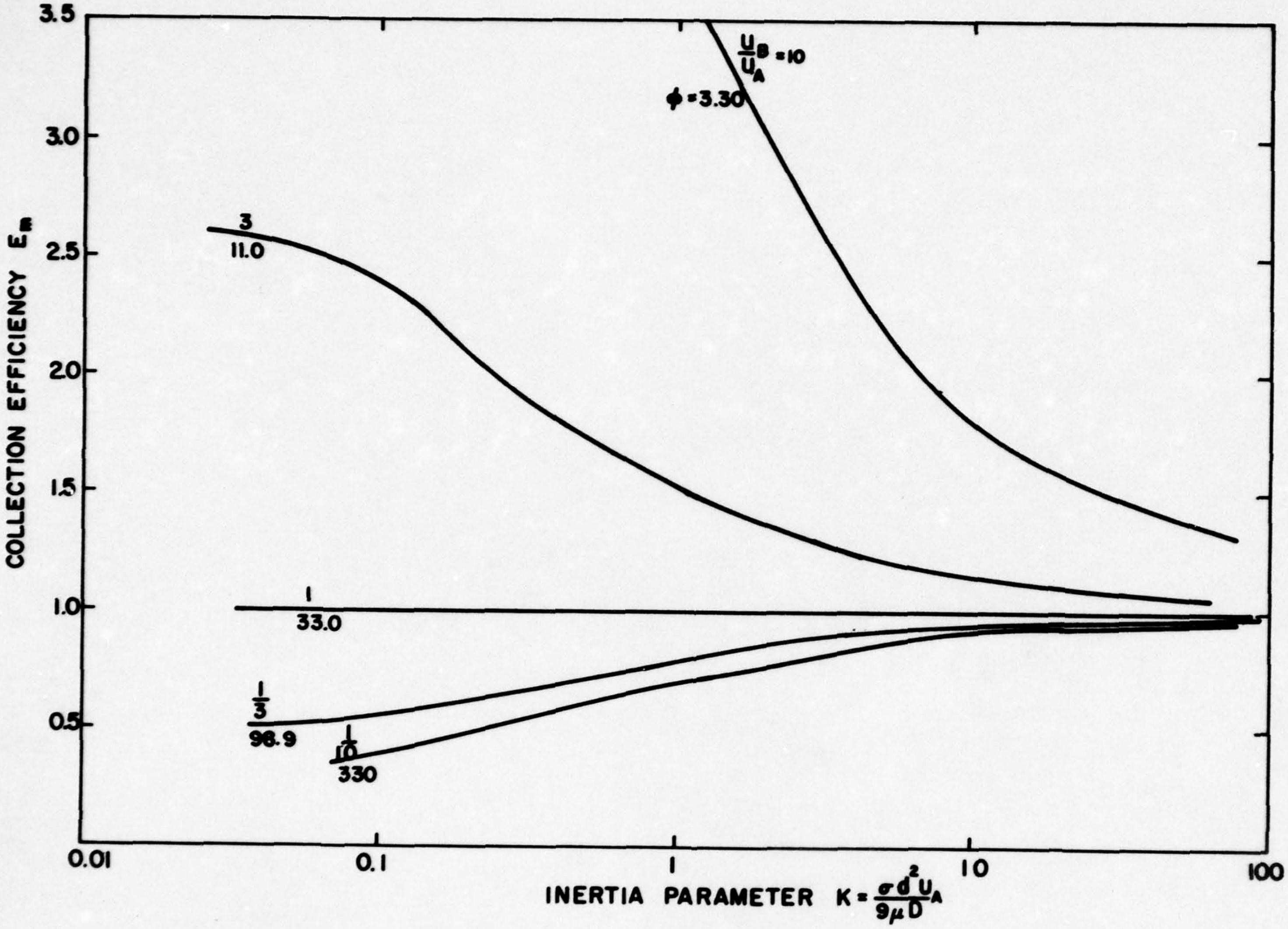

FIGURE 11: EFFECT OF VELOCITY RATIO ON COLLECTION EFFICIENCY FOR FOR FIXED SAMPLING RATE (40 L min^{-1})

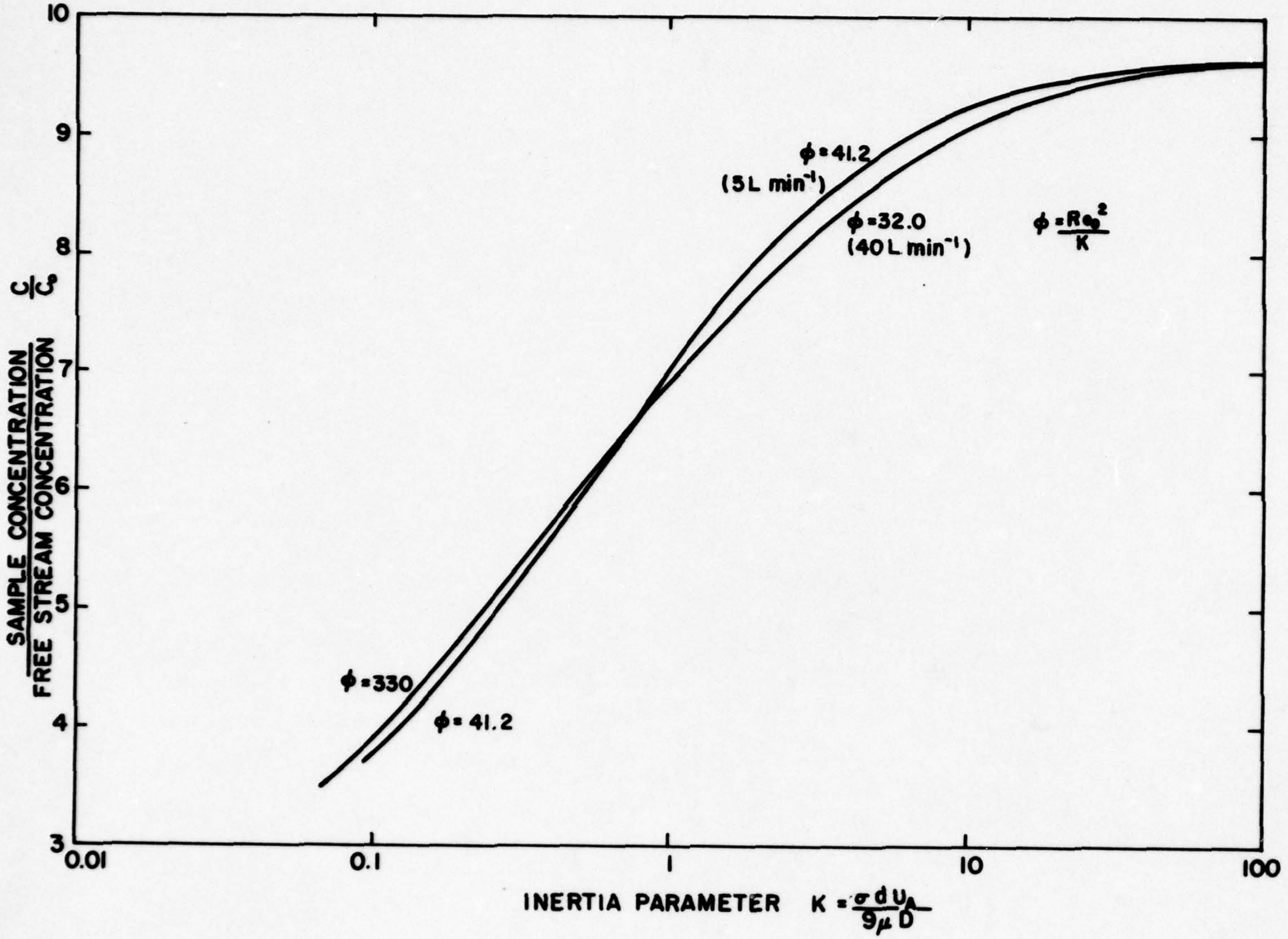

FIGURE 12: EFFECT OF FLOW VELOCITY IN SAMPLING TUBE ON SAMPLING EFFICIENCY FOR FIXED VELOCITY RATIO ($\frac{U_0}{U_A} = \frac{1}{10}$)

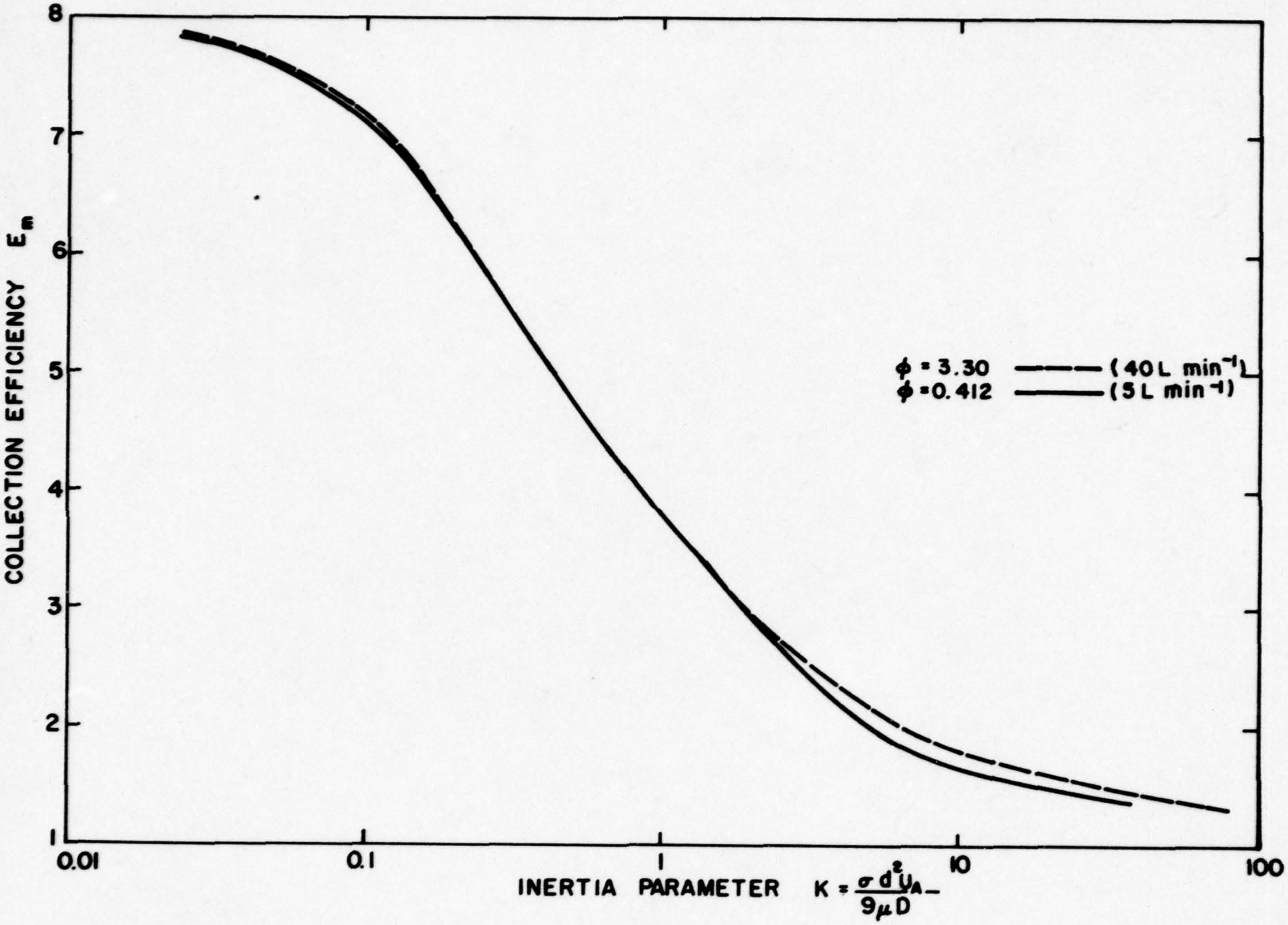

FIGURE 13: EFFECT OF FLOW VELOCITY IN SAMPLING TUBE ON COLLECTION EFFICIENCY FOR FIXED VELOCITY RATIO $(\frac{U_{[illegible]}}{U_A} = \frac{1}{10})$

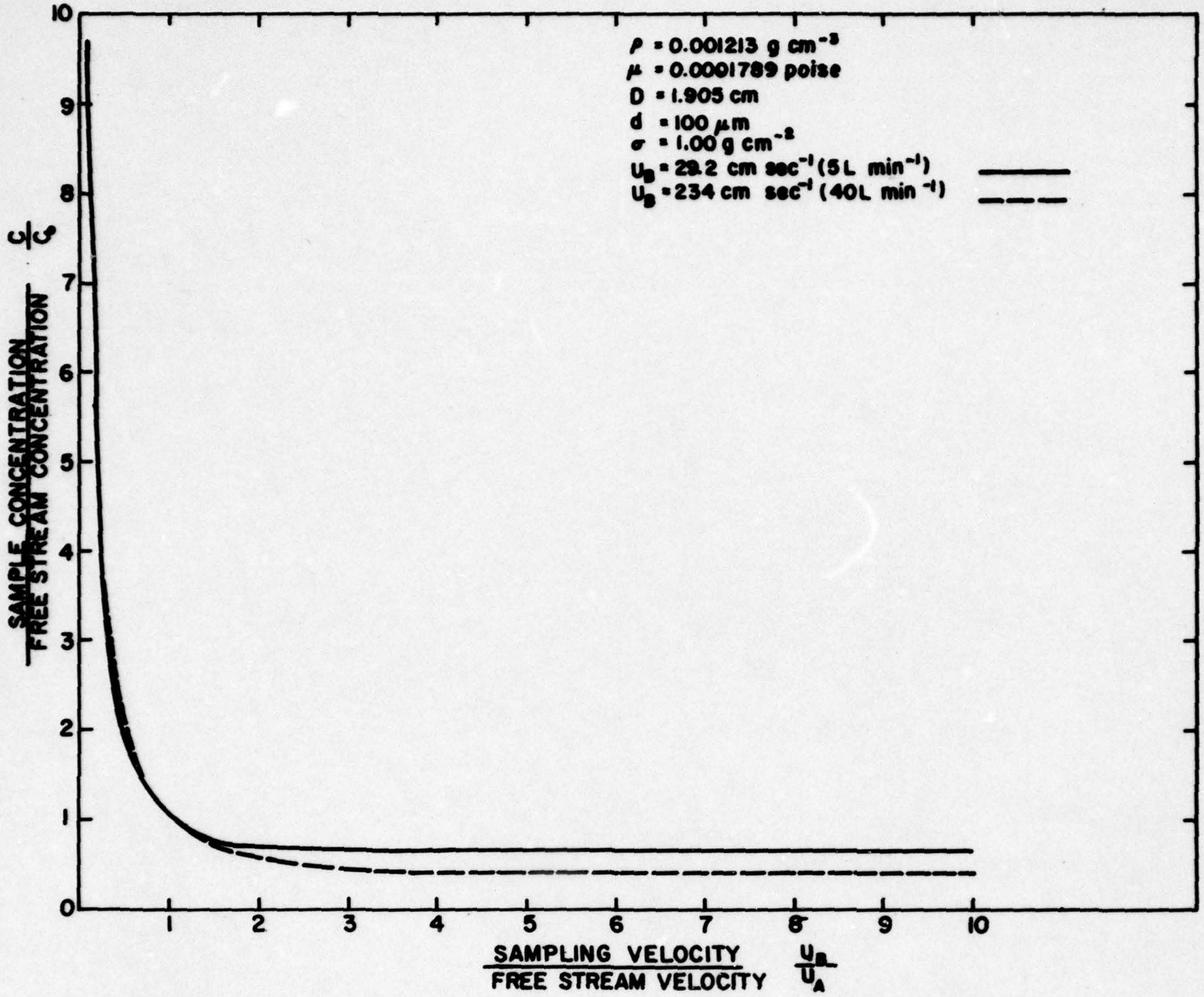

FIGURE 14: EFFECT OF FREE STREAM VELOCITY ON SAMPLING EFFICIENCY FOR ONE PARTICLE SIZE AND CONSTANT LOW VELOCITY IN SAMPLING TUBE

APPENDIX A

COMPUTER PROGRAM FOR CALCULATING THE STREAM FUNCTION

```
PAGE   1

// JOB T  0108

LOG DRIVE   CART SPEC   CART AVAIL  PHY DRIVE
  0000        0108        0108        0000

V2 M11   ACTUAL 16K  CONFIG 16K

// FOR
*ONE WORD INTEGERS
*LIST ALL
      SUBROUTINE REPSI
      COMMON PSI(61,89),ITERS,URAT,UA,RB,NPRB,NPZB,UB,RA,NPZ,NPR
      COMMON INTVL,INDEX,ITER
      READ(1'1)PSI,ITERS,URAT,UA,RB,NPRB,NPZB,UB,RA,NPZ,NPR
      WRITE(3,200)
      WRITE(3,201)RA,RB,NPZ,NPR,NPZB,NPRB,URAT,UA,UB,ITERS
      WRITE(3,202)
      DO 24 J=1,NPZ,INTVL
   24 WRITE(3,203)(PSI(I,J),I=1,NPR,INTVL)
  200 FORMAT(20H1 DISK STORAGE CHECK)
  201 FORMAT(65H0STREAM FUNCTION FOR FLOW IN TWO CONCENTRIC PIPES WITH P
     1ARAMETERS/ 10H0RA      = ,F7.2/ 10H RB      = ,F7.2/ 10H NPZ     = ,
     2I5 / 10H NPR     = ,I5/ 10H NPZB    = ,I5/ 10H NPRB    = ,I5 /
     310H URAT    = ,F9.4/10H UA      = ,F9.4/10H UB      = ,F9.4 /
     410H ITERS   = ,I5)
  202 FORMAT(45H1THE CURRENT VALUES OF PSI STORED ON DISK ARE)
  203 FORMAT('0',16F7.4)
      RETURN
      END
VARIABLE ALLOCATIONS
  PSI(RC)=7FFE-5596 ITERS(IC)=5595       URAT(RC)=5592          UA(RC)=5590           RB(RC)=558E        NPRB(IC)=558D
 NPZB(IC)=558C         UB(RC)=558A         RA(RC)=5588         NPZ(IC)=5587          NPR(IC)=5586       INTVL(IC)=5585
INDEX(IC)=5584       ITER(IC)=5583          J(I )=0000           I(I )=0001

STATEMENT ALLOCATIONS
 200  =0006  201  =0012  202  =0085  203  =009E  24   =00E2

FEATURES SUPPORTED
 ONE WORD INTEGERS

CALLED SUBPROGRAMS
 SWRT    SCOMP   SIOFX    SIOF    SIOI    SUBSC    SDRED    SDAF     SDF      SDI

INTEGER CONSTANTS
     1=0004      3=0005

CORE REQUIREMENTS FOR REPSI
 COMMON  10878  VARIABLES      4  PROGRAM    262
```

```
PAGE   2

RELATIVE ENTRY POINT ADDRESS IS 00A3 (HEX)

END OF COMPILATION

// DUP

*STORE       WS   UA   REPSI
CART ID 0108   DB ADDR  4C00   DB CNT    0012

// EJECT
```

```
// FOR
*ONE WORD INTEGERS
*LIST ALL
C
C      THIS SUBROUTINE CALCULATES THE STREAM FUNCTION FOR FLOW THROUGH
C      TWO CONCENTRIC PIPES WITH A TAPERED OUTSIDE WALL ON THE
C      INSIDE PIPE
C
       SUBROUTINE SBM24
       COMMON PSI(61,89),ITERS,URAT,UA,RB,NPRB,NPZB,UB,RA,NPZ,NPR
       COMMON INTVL,INDEX,ITER
C
C      READ AND CHECK INPUT PARAMETERS
C
       READ(2,100)NZ,NR,ITMAX,EPSMX
       READ(2,101)RA,RB,XL,D,UA,UB
       WRITE(3,200)NZ,NR,ITMAX,EPSMX,RA,RB,XL,D,UA,UB,INTVL,ITER
C
C      CALCULATE AND WRITE DIMENSIONLESS PARAMETERS
C
       ALPHA=RB/RA
       BETA=XL/RA
       GAMMA=D/RA
       DELTA = (BETA-GAMMA)/ALPHA
       UC=(UA-ALPHA**2*UB)/(1.-(((RB+2.0)/RB)*ALPHA)**2)
       URAT = UB/UA
       UCRA=UC/UA
       PSIR=URAT*ALPHA**2
       WRITE(3,201)ALPHA,BETA,GAMMA,DELTA,URAT,UCRA
C
C      R=RD/RA,  Z=ZD/RA,  PSI=PSID/((1.0/2.0)*UA*RA**2)
C
C      ESTABLISH BOUNDARY POINTS
C
       NPZ=NZ+1
       NPR=NR+1
       DELR=1.0/FLOAT(NR)
       XZB=((XL-D)/XL)*FLOAT(NZ)
       NZB=IFIX(XZB + 0.1)
       NPZB=NZB+1
       NPZS=NPZB+12
       XRB=ALPHA*FLOAT(NR)
       NRB=IFIX(XRB + 0.1)
       NPRB=NRB+1
       NPRS = NPRB+1
       NPRC = NPRB + 2
```

```
C
C     IF PSI IS PARTIALLY CALCULATED AND IN FILE
C     GO DIRECTLY TO FURTHER ITERATIONS
C
      IF(INDEX)1,1,8
    1 CONTINUE
C
C     ESTABLISH INITIAL GUESSES FOR STREAM FUNCTION
C     AND SET BOUNDARY CONDITIONS ON CENTRE LINE
C     AND INLET OF OUTSIDE PIPE
C
      DO 2 I=1,NR
      RI=FLOAT(I-1)
      PSI(I,1)=(RI*DELR)**2
      DO 2 J=2,NPZ
    2 PSI(I,J)=0.0
C
C     SET BOUNDARY CONDITION AT OUTLET OF INSIDE PIPE
C
      DO 3 I = 2,NPRB
      RI=FLOAT(I-1)
    3 PSI(I,NPZ) = URAT*(RI*DELR)**2
C
C     SFT BOUNDARY CONDITION AT OUTLET OF OUTSIDE PIPE
C
      DO 4 I = NPRC,NR
      RI=FLOAT(I-1)
    4 PSI(I,NPZ)=1.0-UCRA*(1.0-(RI*DELR)**2)
C
C     SET BOUNDARY CONDITION AT INSIDE WALL OF INSIDE PIPE
C
      DO 5 J=NPZB,NPZ
    5 PSI(NPRB,J)=PSIB
C
C     SET BOUNDARY CONDITION AT WALL OF OUTSIDE PIPE
C
      DO 6 J=1,NPZ
    6 PSI(NPR,J)=1.0
C
C     POINTS WITHIN PIPE MATERIAL ON FIRST GRID LINE
C     AFTER INSIDE PIPE RADIUS
C
      DO 7 J = NPZS,NPZ
    7 PSI(NPRS,J) = PSIB
C
C     COMPUTE SUCCESSIVELY BETTER APPROXIMATIONS FOR
```

```
C     THE STREAM FUNCTION AT ALL GRID POINTS, ITERATING BY
C     THE GAUSS-SEIDEL METHOD UNTIL THE CONVERGENCE CRITERION
C     IS SATISFIED
C
    8 EPS=0.0
      ITER=ITER+1
      ITERS = ITER
      DO 70 I=2,NR
      DO 70 J=2,NZ
C
C     INTERIOR POINTS FROM CENTRE LINE TO INSIDE PIPE RADIUS
C
      IF(I-NPRB)15,16,20
   15 CONTINUE
      HOLDT=PSI(I,J)
      PSI(I,J)=(PSI(I,J+1)+PSI(I,J-1)+PSI(I+1,J)+PSI(I-1,J))/4.0
     1-(PSI(I+1,J)-PSI(I-1,J))/(8.0*FLOAT(I-1))
      EPS=EPS+ABS(PSI(I,J)-HOLDT)
      GO TO 70
C
C     GRID LINE ON INSIDE PIPE RADIUS
C
   16 CONTINUE
      IF (J - NPZB)17,18,18
   17 CONTINUE
      HOLDT=PSI(I,J)
      PSI(I,J)=(PSI(I,J+1)+PSI(I,J-1)+PSI(I+1,J)+PSI(I-1,J))/4.0
     1-(PSI(I+1,J)-PSI(I-1,J))/(8.0*FLOAT(I-1))
      EPS=EPS+ABS(PSI(I,J)-HOLDT)
   18 CONTINUF
      GO TO 70
   20 CONTINUE
C
C     FIRST GRID LINE AFTER INSIDE PIPE RADIUS
C
      IF(I-NPRB-1)70,25,30
   25 IF(J-NPZB)26,26,27
   26 CONTINUE
      HOLDT=PSI(I,J)
      PSI(I,J)=(PSI(I,J+1)+PSI(I,J-1)+PSI(I+1,J)+PSI(I-1,J))/4.0
     1-(PSI(I+1,J)-PSI(I-1,J))/(8.0*FLOAT(I-1))
      EPS=EPS+ABS(PSI(I,J)-HOLDT)
      GO TO 70
   27 CONTINUE
      IF(J-NPZB-12)28,30,30
   28 CONTINUE
```

```
C
C     POINTS FOR WHICH INTERPOLATION IS REQUIRED
C     ON FIRST GRID LINE AFTER INSIDE PIPE RADIUS
C
      HOLDT=PSI(I,J)
      A=FLOAT(NPZ-12-J)/12.0
      XK1=A /(2.0*(A+1.0))
      XK2=PSI(I,J-1)+PSI(I,J+1)
      XK3=2.0*PSIB/(A*(A+1.0))
      XK4=2.0*PSI(I+1,J)/(A+1.0)
      XK5=(PSIB-PSI(I+1,J))/(FLOAT(I-1)*(A+1.0))
      PSI(I,J)=(XK2+XK3+XK4+XK5)*XK1
      EPS=EPS+ABS(PSI(I,J)-HOLDT)
      GO TO 70
   30 CONTINUE
C
C     SECOND GRID LINE FROM INSIDE PIPE RADIUS
C
      IF(I-NPRB-2)70,35,40
   35 CONTINUE
      IF(J-NPZB-12)36,36,37
   36 CONTINUE
      HOLDT=PSI(I,J)
      PSI(I,J)=(PSI(I,J+1)+PSI(I,J-1)+PSI(I+1,J)+PSI(I-1,J))/4.0
     1-(PSI(I+1,J)-PSI(I-1,J))/(8.0*FLOAT(I-1))
      EPS=EPS+ABS(PSI(I,J)-HOLDT)
      GO TO 70
   37 CONTINUE
C
C     POINTS FOR WHICH INTERPOLATION IS REQUIRED
C     ON SECOND GRID LINE AFTER INSIDE PIPE RADIUS
C
      HOLDT=PSI(I,J)
      A=FLOAT(NPZ-J)/12.0
      XK1=A /(2.0*(A+1.0))
      XK2=PSI(I,J-1)+PSI(I,J+1)
      XK3=2.0*PSIB/(A*(A+1.0))
      XK4=2.0*PSI(I+1,J)/(A+1.0)
      XK5=(PSIB-PSI(I+1,J))/(FLOAT(I-1)*(A+1.0))
      PSI(I,J)=(XK2+XK3+XK4+XK5)*XK1
      EPS=EPS+ABS(PSI(I,J)-HOLDT)
      GO TO 70
   40 CONTINUE
C
C     INTERIOR POINTS BETWEEN INSIDE AND OUTSIDE PIPE
C
```

```
      HOLDT=PSI(I,J)
      PSI(I,J)=(PSI(I,J+1)+PSI(I,J-1)+PSI(I+1,J)+PSI(I-1,J))/4.0
     1-(PSI(I+1,J)-PSI(I-1,J))/(8.0*FLOAT(I-1))
      EPS=EPS+ABS(PSI(I,J)-HOLDT)
   70 CONTINUE
C
C     STORE TEMPORARY VALUE OF STREAM FUNCTION ON DISK
C
      ITTD = ITER/100*100
      IF(ITTD-ITER)80,74,80
   74 WRITE(3,205)ITER
      DO 75 J=1,NPZ,INTVL
   75 WRITE(3,203)(PSI(I,J),I=1,NPR,INTVL)
      WRITE(1'1)PSI,ITERS,URAT,UA,RB,NPRB,NPZB,UB,RA,NPZ,NPR
      WRITE(3,206)
   80 CONTINUE
C
C     STOP ITERATIONS IF COMPUTED VALUES SHOW LITTLE FURTHER
C     CHANGE, OR IF NUMBER OF ITERATIONS IS TOO LARGE
C
      IF(FPS-EPSMX)83,83,82
   82 CONTINUE
      IF(ITER-ITMAX)8,8,85
C
C     PRINT VALUES OF ITERATION COUNTER
C     ITER AND THE FINAL STREAM FUNCTION FIELD
C
   83 WRITE(3,202)ITER
      DO 84 J=1,NPZ,INTVL
   84 WRITE(3,203)(PSI(I,J),I=1,NPR,INTVL)
      GO TO 300
C
C     COMMENT IN CASE ITER EXCEEDS ITMAX
C
   85 WRITE(3,204)
      DO 86 J=1,NPZ,INTVL
   86 WRITE(3,203)(PSI(I,J),I=1,NPR,INTVL)
C
C     FORMATS FOR INPUT AND OUTPUT STATEMENTS
C
  100 FORMAT ( 11X,I4,11X,I4,11X,I4,E8.1)
  101 FORMAT(6F10.4)
  200 FORMAT(65H1STREAM FUNCTION FOR FLOW IN TWO CONCENTRIC PIPES WITH P
     1ARAMETERS/ 10HONZ       = ,I5/ 10H NR       = ,I5/ 10H ITMAX    = ,I5,/
     110H EPSMX    = , E12.2/ 10H RA       = ,F7.2/ 10H RB       = ,F7.2/
     110H XL       = ,F7.2/ 10H D        = ,F7.2/ 10H UA       = ,F7.2/
```

```
     110H UB        = ,F7.2/ 10H INTVL   = ,I5/ 10H ITER   =  ,I5)
  201 FORMAT(37H0CALCULATED DIMENSIONLESS PARAMETERS /
     110H0ALPHA =  ,F9.4/ 10H BETA   =  ,F9.4/ 10 H GAMMA =  ,F9.4/
     1 10H DELTA =  ,F9.4/ 10H URAT   =  , F9.4/ 10H UCRA   =  ,F9.4)
  202 FORMAT(46H1CONVERGENCE CONDITION HAS BEEN REACHED AFTER ,
     1I5, 11H ITERATIONS/ 38H THE STREAM FUNCTION FIELD IS GIVEN BY)
  203 FORMAT(1H0, 16F7.4)
  204 FORMAT(42H1NO CONVERGENCE. CURRENT VALUES OF PSI ARE)
  205 FORMAT(26H1 THE ITERATION COUNTER IS,I5,
     134H AND THE CURRENT VALUES OF PSI ARE )
  206 FORMAT(20H DISK WRITE COMPLETE)
  300 RETURN
C
      END
VARIABLE ALLOCATIONS
  PSI(RC)=7FFE-5596 ITERS(IC)=5595         URAT(RC)=5592          UA(RC)=5590          RB(RC)=558E        NPRB(IC)=558D
 NPZB(IC)=558C          UB(RC)=558A          RA(RC)=5588         NPZ(IC)=5587         NPR(IC)=5586       INTVL(IC)=5585
INDEX(IC)=5584        ITER(IC)=5583      EPSMX(R )=0000          XL(R )=0002            D(R )=0004       ALPHA(R )=0006
 BETA(R )=0008       GAMMA(R )=000A      DELTA(R )=000C          UC(R )=000E         UCRA(R )=0010        PSIB(R )=0012
 DELR(R )=0014         XZB(R )=0016        XRB(R )=0018          RI(R )=001A          EPS(R )=001C       HOLDT(R )=001E
    A(R )=0020         XK1(R )=0022        XK2(R )=0024         XK3(R )=0026          XK4(R )=0028         XK5(R )=002A
   NZ(I )=0032          NR(I )=0033      ITMAX(I )=0034         NZB(I )=0035         NPZS(I )=0036         NRB(I )=0037
 NPRS(I )=0038        NPRC(I )=0039          I(I )=003A           J(I )=003B         ITTD(I )=003C

STATEMENT ALLOCATIONS
 100  =0057  101  =005F  200  =0062  201  =00E5  202  =C12A  203  =C160  204  =0165  205  =017C  206  =019E  1    =029A
 2    =02BA  3    =02E6  4    =030F  5    =0331  6    =0349  7    =0361  8    =0375  15   =0393  16   =03FD  17   =0403
 18   =046B  20   =046D  25   =0477  26   =047D  27   =04E7  28   =04EF  30   =0591  35   =059B  36   =05A3  37   =060D
 40   =06AD  70   =0715  74   =0737  75   =0741  80   =0785  82   =078C  83   =0794  84   =079E  85   =07C5  86   =07CD
 300  =07F2

FEATURES SUPPORTED
 ONE WORD INTEGERS

CALLED SUBPROGRAMS
 FABS     FADD     FADDX    FSUB     FSUBX    FMPY     FMPYX    FDIV     FLD      FLDX     FSTO     FSTOX    FSBR     FDVR     FAXI
 IFIX     FLOAT    SRED     SWRT     SCOMP    SIOFX    SIOF     SIOI     SUBSC    SDWRT    SDCOM    SDAF     SDF      SDI

REAL CONSTANTS
 .100000E 01=0044    .200000E 01=0046    .100000E 00=0048    .000000E 00=004A    .400000E 01=004C    .800000E 01=004E
 .120000E 02=0050

INTEGER CONSTANTS
     2=0052         3=0053         1=0054        12=0055       100=0056

CORE REQUIREMENTS FOR SBM24
 COMMON   10878  VARIABLES       68  PROGRAM     1968
```

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PAGE   9

RELATIVE ENTRY POINT ADDRESS IS 01AA (HEX)

END OF COMPILATION

// DUP

*STORE       WS   UA   SBM24
CART ID 0108    DB ADDR   4C12    DB CNT    0088

// EJECT
```

```
// FOR
*ONE WORD INTEGERS
*IOCS(CARD)
*IOCS(1132 PRINTER)
*IOCS(DISK)
*LIST ALL
      DEFINE FILE 1(5439,2,U,IB)
      COMMON PSI(61,89),ITERS,URAT,UA,RB,NPRB,NPZB,UB,RA,NPZ,NPR
      COMMON INTVL,INDEX,ITER
      READ(2,100) ITER,INTVL
      IF(ITER)1,1,2
    1 INDEX=-1
      CALL SBM24
      WRITE(1'1)PSI,ITERS,URAT,UA,RB,NPRB,NPZB,UB,RA,NPZ,NPR
      GO TO 3
    2 INDEX =1
      CALL REPSI
      CALL SBM24
      WRITE(1'1)PSI,ITERS,URAT,UA,RB,NPRB,NPZB,UB,RA,NPZ,NPR
    3 CONTINUE
  100 FORMAT(2I5)
      CALL EXIT
      END
VARIABLE ALLOCATIONS
   PSI(RC)=7FFE-5596 ITERS(IC)=5595        URAT(RC)=5592          UA(RC)=5590          RB(RC)=558E        NPRB(IC)=558D
  NPZB(IC)=558C         UB(RC)=558A          RA(RC)=5588         NPZ(IC)=5587         NPR(IC)=5586        INTVL(IC)=5585
 INDEX(IC)=5584       ITER(IC)=5583          IB(I )=0008

STATEMENT ALLOCATIONS
 100   =000C  1    =0033  2    =0057  3    =007A

FEATURES SUPPORTED
 ONE WORD INTEGERS
 IOCS

CALLED SUBPROGRAMS
 SBM24   REPSI   FLD     FSTO    CARDZ   PRNTZ   SRED    SFIO    SIOI    SDFIO   SDWRT   SDCOM   SDAF    SDF     SDI

INTEGER CONSTANTS
     2=000A      1=0008

CORE REQUIREMENTS FOR
 COMMON  10878  VARIABLES      10  PROGRAM     114

END OF COMPILATION
```

```
// XFQ            1
*FILES(1,PSI18)
```

```
 DISK STORAGE CHECK

STREAM FUNCTION FOR FLOW IN TWO CONCENTRIC PIPES WITH PARAMETERS

RA      =   60.00
RB      =   12.00
NPZ     =    89
NPR     =    61
NPZB    =    65
NPRB    =    13
URAT    =    3.0000
UA      =    1.0000
UB      =    3.0000
ITERS   =  2800
```

```
THE CURRENT VALUES OF PSI STORED ON DISK ARE
 0.0000 0.0044 0.0177 0.0399 0.0711 0.1111 0.1599 0.2177 0.2844 0.3599 0.4444 0.5377 0.6399 0.7511 0.8711 1.0000
 0.0000 0.0044 0.0178 0.0400 0.0712 0.1113 0.1602 0.2181 0.2848 0.3603 0.4448 0.5381 0.6402 0.7513 0.8712 1.0000
 0.0000 0.0044 0.0178 0.0402 0.0714 0.1115 0.1606 0.2184 0.2852 0.3608 0.4452 0.5384 0.6405 0.7515 0.8713 1.0000
 0.0000 0.0044 0.0179 0.0403 0.0716 0.1118 0.1609 0.2189 0.2857 0.3613 0.4457 0.5389 0.6409 0.7517 0.8714 1.0000
 0.0000 0.0045 0.0180 0.0404 0.0719 0.1122 0.1614 0.2194 0.2862 0.3618 0.4462 0.5394 0.6413 0.7520 0.8716 1.0000
 0.0000 0.0045 0.0181 0.0407 0.0722 0.1127 0.1620 0.2201 0.2869 0.3625 0.4469 0.5400 0.6418 0.7524 0.8718 1.0000
 0.0000 0.0045 0.0182 0.0409 0.0727 0.1133 0.1627 0.2209 0.2878 0.3634 0.4477 0.5407 0.6424 0.7528 0.8720 1.0000
 0.0000 0.0046 0.0184 0.0413 0.0733 0.1141 0.1637 0.2220 0.2889 0.3645 0.4487 0.5416 0.6431 0.7533 0.8722 1.0000
 0.0000 0.0046 0.0186 0.0418 0.0741 0.1152 0.1650 0.2234 0.2904 0.3659 0.4500 0.5427 0.6440 0.7539 0.8726 1.0000
 0.0000 0.0047 0.0190 0.0426 0.0752 0.1167 0.1667 0.2252 0.2922 0.3676 0.4516 0.5440 0.6450 0.7546 0.8729 1.0000
 0.0000 0.0049 0.0196 0.0437 0.0769 0.1187 0.1690 0.2276 0.2945 0.3697 0.4534 0.5456 0.6462 0.7555 0.8734 1.0000
 0.0000 0.0051 0.0205 0.0454 0.0793 0.1216 0.1721 0.2306 0.2973 0.3723 0.4556 0.5474 0.6476 0.7565 0.8739 1.0000
 0.0000 0.0055 0.0219 0.0481 0.0829 0.1256 0.1761 0.2344 0.3008 0.3753 0.4582 0.5495 0.6492 0.7575 0.8744 1.0000
 0.0000 0.0062 0.0243 0.0523 0.0883 0.1313 0.1814 0.2392 0.3049 0.3788 0.4610 0.5518 0.6510 0.7587 0.8750 1.0000
 0.0000 0.0073 0.0284 0.0597 0.0968 0.1391 0.1881 0.2447 0.3095 0.3826 0.4641 0.5542 0.6528 0.7599 0.8757 1.0000
 0.0000 0.0090 0.0355 0.0737 0.1101 0.1492 0.1958 0.2508 0.3144 0.3865 0.4673 0.5567 0.6547 0.7612 0.8763 1.0000
 0.0000 0.0110 0.0456 0.1199 0.1274 0.1599 0.2035 0.2567 0.3191 0.3904 0.4704 0.5591 0.6565 0.7624 0.8769 1.0000
 0.0000 0.0124 0.0512 0.1199 0.1372 0.1679 0.2098 0.2619 0.3233 0.3939 0.4733 0.5614 0.6582 0.7636 0.8775 1.0000
 0.0000 0.0130 0.0527 0.1199 0.1398 0.1720 0.2141 0.2658 0.3268 0.3969 0.4759 0.5635 0.6599 0.7647 0.8781 1.0000
 0.0000 0.0132 0.0531 0.1199 0.1398 0.1737 0.2165 0.2684 0.3294 0.3994 0.4780 0.5654 0.6613 0.7657 0.8786 1.0000
 0.0000 0.0133 0.0532 0.1199 0.1388 0.1739 0.2177 0.2701 0.3314 0.4013 0.4799 0.5670 0.6626 0.7667 0.8791 1.0000
 0.0000 0.0133 0.0533 0.1199 0.1372 0.1735 0.2181 0.2712 0.3328 0.4029 0.4815 0.5684 0.6638 0.7675 0.8796 1.0000
 0.0000 0.0133 0.0533 0.1199 0.1355 0.1727 0.2182 0.2720 0.3340 0.4043 0.4829 0.5698 0.6649 0.7683 0.8800 1.0000
```

```
STREAM FUNCTION FOR FLOW IN TWO CONCENTRIC PIPES WITH PARAMETERS
NZ     =    88
NR     =    60
ITMAX  =  5000
EPSMX  =     0.10E-02
RA     =   60.00
RB     =   12.00
XL     =   88.00
D      =   24.00
UA     =    1.00
UB     =    3.00
INTVL  =     4
ITER   =  2800

CALCULATED DIMENSIONLESS PARAMETERS

ALPHA =     0.2000
BETA  =     1.4666
GAMMA =     0.4000
DELTA =     5.3333
URAT  =     3.0000
UCRA  =     0.9306
```

```
CONVERGENCE CONDITION HAS BEEN REACHED AFTER  2890 ITERATIONS
THE STREAM FUNCTION FIELD IS GIVEN BY
 0.0000 0.0044 0.0177 0.0399 0.0711 0.1111 0.1599 0.2177 0.2844 0.3599 0.4444 0.5377 0.6399 0.7511 0.8711 1.0000
 0.0000 0.0044 0.0178 0.0401 0.0712 0.1113 0.1602 0.2181 0.2848 0.3604 0.4448 0.5381 0.6402 0.7513 0.8712 1.0000
 0.0000 0.0044 0.0178 0.0402 0.0714 0.1116 0.1606 0.2185 0.2852 0.3608 0.4452 0.5385 0.6406 0.7515 0.8713 1.0000
 0.0000 0.0044 0.0179 0.0403 0.0716 0.1119 0.1610 0.2189 0.2857 0.3613 0.4457 0.5389 0.6409 0.7517 0.8714 1.0000
 0.0000 0.0045 0.0180 0.0405 0.0719 0.1122 0.1614 0.2194 0.2863 0.3619 0.4462 0.5394 0.6413 0.7520 0.8716 1.0000
 0.0000 0.0045 0.0181 0.0407 0.0722 0.1127 0.1620 0.2201 0.2870 0.3626 0.4469 0.5400 0.6418 0.7524 0.8718 1.0000
 0.0000 0.0045 0.0182 0.0409 0.0727 0.1133 0.1627 0.2209 0.2879 0.3635 0.4478 0.5407 0.6424 0.7528 0.8720 1.0000
 0.0000 0.0046 0.0184 0.0413 0.0733 0.1141 0.1637 0.2220 0.2890 0.3646 0.4488 0.5416 0.6431 0.7533 0.8723 1.0000
 0.0000 0.0046 0.0186 0.0419 0.0741 0.1152 0.1650 0.2234 0.2904 0.3660 0.4501 0.5427 0.6440 0.7540 0.8726 1.0000
 0.0000 0.0047 0.0190 0.0426 0.0753 0.1167 0.1667 0.2253 0.2923 0.3677 0.4516 0.5441 0.6451 0.7547 0.8730 1.0000
 0.0000 0.0049 0.0196 0.0437 0.0769 0.1188 0.1690 0.2276 0.2945 0.3698 0.4535 0.5456 0.6463 0.7555 0.8734 1.0000
 0.0000 0.0051 0.0205 0.0454 0.0793 0.1216 0.1721 0.2307 0.2974 0.3724 0.4557 0.5474 0.6477 0.7565 0.8739 1.0000
 0.0000 0.0055 0.0219 0.0481 0.0829 0.1257 0.1762 0.2345 0.3008 0.3754 0.4582 0.5495 0.6493 0.7576 0.8744 1.0000
 0.0000 0.0062 0.0243 0.0523 0.0883 0.1313 0.1815 0.2392 0.3049 0.3788 0.4611 0.5518 0.6510 0.7587 0.8750 1.0000
 0.0000 0.0073 0.0284 0.0597 0.0968 0.1392 0.1881 0.2448 0.3095 0.3826 0.4642 0.5542 0.6528 0.7600 0.8757 1.0000
 0.0000 0.0090 0.0355 0.0737 0.1101 0.1493 0.1958 0.2508 0.3144 0.3866 0.4674 0.5567 0.6547 0.7612 0.8763 1.0000
 0.0000 0.0110 0.0456 0.1199 0.1274 0.1600 0.2036 0.2568 0.3191 0.3904 0.4705 0.5592 0.6565 0.7625 0.8769 1.0000
 0.0000 0.0124 0.0512 0.1199 0.1372 0.1679 0.2099 0.2619 0.3234 0.3939 0.4733 0.5615 0.6583 0.7636 0.8776 1.0000
 0.0000 0.0130 0.0527 0.1199 0.1398 0.1720 0.2141 0.2658 0.3268 0.3969 0.4759 0.5636 0.6599 0.7647 0.8781 1.0000
 0.0000 0.0132 0.0531 0.1199 0.1398 0.1737 0.2165 0.2685 0.3295 0.3994 0.4781 0.5654 0.6613 0.7657 0.8786 1.0000
 0.0000 0.0133 0.0532 0.1199 0.1388 0.1739 0.2177 0.2702 0.3314 0.4013 0.4799 0.5670 0.6626 0.7667 0.8791 1.0000
 0.0000 0.0133 0.0533 0.1199 0.1373 0.1735 0.2181 0.2712 0.3328 0.4029 0.4815 0.5684 0.6638 0.7675 0.8796 1.0000
 0.0000 0.0133 0.0533 0.1199 0.1355 0.1727 0.2182 0.2720 0.3340 0.4043 0.4829 0.5698 0.6649 0.7683 0.8800 1.0000
```

APPENDIX B

COMPUTER PROGRAM FOR SOLVING THE EQUATIONS OF MOTION

```
PAGE   1

// JOB T

LOG DRIVE    CART SPEC    CART AVAIL   PHY DRIVE
  0000         0108         0108         0000
                            4000         0001

V2 M11    ACTUAL 16K   CONFIG 16K

// FOR
*ONE WORD INTEGERS
*LIST ALL
      SUBROUTINE GTPSI
C
C     THIS SUBROUTINE RETRIEVES THE STREAM FUNCTION ARRAY AND ASSOCIATED
C     CONSTANTS FROM DISK
C
      COMMON PSI(61,80),URAT,RB,NPRB,NPZB,RA,NPR,INTVL
      READ(1'1)PSI
      READ(1'5430)ITERS,URAT,UA,RB,NPRB,NPZB,UB,RA,NPZ,NPR
      WRITE(3,200)
      WRITE(3,201)RA,RB,NPZ,NPR,NPZB,NPRB,URAT,UA,UB,ITERS
      WRITE(3,202)
      NPZM9 = NPZ - 9
      DO 24 J=1,NPZM9,INTVL
   24 WRITE(3,203)(PSI(I,J),I=1,NPR,INTVL)
  200 FORMAT(20H0 DISK STORAGE CHECK)
  201 FORMAT(65H0STREAM FUNCTION FOR FLOW IN TWO CONCENTRIC PIPES WITH P
     1ARAMETERS/ 10H0RA      = ,F7.2/ 10H RB      = ,F7.2/ 10H NPZ     = ,
     2I5 / 10H NPR      = ,I5/ 10H NPZB    = ,I5/ 10H NPRB    = ,I5 /
     310H URAT    = ,F9.4/10H UA      = ,F9.4/10H UB      = ,F9.4 /
     410H ITERS   = ,I5)
  202 FORMAT(45H1THE CURRENT VALUES OF PSI STORED ON DISK ARE)
  203 FORMAT('0',16F7.4)
      RETURN
      END
VARIABLE ALLOCATIONS
   PSI(RC)=7FFE-59F0  URAT(RC)=59DE          RB(RC)=59DC          NPRB(IC)=59DB          NPZB(IC)=59DA            RA(RC)=59D8
   NPR(IC)=59D7       INTVL(IC)=59D6         UA(R )=0000            UB(R )=0002        ITERS(I )=0004          NPZ(I )=0005
 NPZM9(I )=0006          J(I )=0007           I(I )=0008

STATEMENT ALLOCATIONS
 200   =000E  201  =001A  202  =008D  203  =00A6  24   =00F3

FEATURES SUPPORTED
 ONE WORD INTEGERS
```

```
PAGE   2

CALLED SUBPROGRAMS
 SWRT     SCOMP    SIOFX    SIOF     SIOI     SUBSC    SDRED    SDAF     SDF      SDI

INTEGER CONSTANTS
       1=000A   5430=000B    3=000C       9=000D

CORE REQUIREMENTS FOR GTPSI
 COMMON    9770  VARIABLES       10  PROGRAM     272

RELATIVE ENTRY POINT ADDRESS IS 00AB (HEX)

END OF COMPILATION

// DUP

*STORE       WS  UA  GTPSI
CART ID 0108   DB ADDR  4E20   DB CNT   0013

// EJECT
```

```
// FOR
*ONE WORD INTEGERS
*LIST ALL
C
      FUNCTION CDRE(RE)
C
C     THIS FUNCTION COMPUTES THE PRODUCT OF DRAG COEFFICIENT
C     AND REYNOLDS NUMBER FOR A SPHERE AS A FUNCTION OF
C     REYNOLDS NUMBER
C
C     CONSTANT COEFFICIENTS
C
      A1=1./24.
      A2=-2.3363*1.E-04
      A3=2.0154*1.E-06
      A4=-6.9105*1.E-09
      B0=-1.29536
      B1=9.86*1.E-01
      B2=-4.6677*1.E-02
      B3=1.1235*1.E-03
C
C     CHOOSE THE APPROPRIATE POLYNOMIAL
C
      IF(RE-4.0)2,7,7
C
C     INITIAL ESTIMATE
C
    2 IF(RE-0.00001)3,4,4
    3 CDRE = 24.0
      GO TO 30
    4 X=24.*RE
C
C     BEGIN NEWTON METHOD ITERATION
C
      CONTINUE
      DO 6 ITER=1,20
      FX=A1*X+A2*X**2+A3*X**3+A4*X**4-RE
      FPX=A1+2.*A2*X+3.*A3*X**2+4.*A4*X**3
      DELX=FX/FPX
      X=X-DELX
C
C     CHECK FOR CONVERGENCE
C
      EPS=1.E-06
      IF(ABS(DELX/X)-EPS)5,5,6
    5 CDRE=X/RE
```

```
PAGE   4
       GO TO 30
     6 CONTINUE
       GO TO 29
C
C      INITIAL ESTIMATE
C
     7 CD = 1.0
       FLOG = 0.434294481903252
       X=ALOG(CD*RE**2)*ELOG
C
C      BEGIN NEWTON METHOD ITERATION
C
       DO 24 ITER=1,20
       FX=B0+B1*X+B2*X**2+B3*X**3 - ALOG(RE)*ELOG
       FPX=B1+2.*B2*X+3.*B3*X**2
       DELX=FX/FPX
       X=X-DELX
C
C      CHECK FOR CONVERGENCE
C
       EPS=1.E-06
       IF(ABS(DELX/X)-EPS)22,22,24
    22 CORE=10.**X/RE
       GO TO 30
    24 CONTINUE
    29 WRITE(3,202)
    30 RETURN
C
C      FORMATS FOR OUTPUT STATEMENTS
C
   202 FORMAT(16H0 NO CONVERGENCE)
C
       END
VARIABLE ALLOCATIONS
  CORE(R )=0000       A1(R )=0002        A2(R )=0004        A3(R )=0006        A4(R )=0008        B0(R )=000A
    B1(R )=000C       B2(R )=000E        B3(R )=0010         X(R )=0012        FX(R )=0014       FPX(R )=0016
  DELX(R )=0018      EPS(R )=001A        CD(R )=001C      ELOG(R )=001E      ITER(I )=0028

STATEMENT ALLOCATIONS
 202   =0059   2   =00A8   3   =00AF   4   =00B5   5   =012D   6   =0135   7   =0140  22   =01B8  24   =01C3  29   =01CC
 30    =01D0

FEATURES SUPPORTED
 ONE WORD INTEGERS

CALLED SUBPROGRAMS
 FABS    FALOG   FAXB    FADD    FSUB    FMPY    FDIV    FLD     FSTO    FSBR    FAXI    SWRT    SCOMP   SNR     SUBIN
```

```
REAL CONSTANTS
  .100000E 01=002A   .240000E 02=002C   .233630E 01=002E   .100000E-03=0030   .201540E 01=0032   .100000E-05=0034
  .691050E 01=0036   .100000E-08=0038   .129536E 01=003A   .986000E 01=003C   .100000E 00=003E   .466770E 01=0040
  .100000E-01=0042   .112350E 01=0044   .100000E-02=0046   .400000E 01=0048   .100000E-04=004A   .200000E 01=004C
  .300000E 01=004E   .434294E 00=0050   .100000E 02=0052

INTEGER CONSTANTS
    1=0054     20=0055     2=0056     3=0057     4=0058

CORE REQUIREMENTS FOR CORE
 COMMON        0  VARIABLES      42  PROGRAM     426

RELATIVE ENTRY POINT ADDRESS IS 0063 (HEX)

END OF COMPILATION

// DUP

*STORE      WS  UA  CORE
CART ID 0108   DB ADDR  4E33   DB CNT    0022

// EJECT
```

```
// FOR
*ONF WORD INTEGERS
*LIST ALL
      SUBROUTINE SRM22(N,Y,F,X,H,IRUNG,M)
C
C     FOURTH ORDER RUNGE KUTTA METHOD
C     FOR N FIRST ORDER C.D.E.
      DIMENSION PHI(50),SAVY(50),Y(50),F(50)
C
      GO TO (2,3,4,5,6),M
C
C     PASS 1
C
    2 IRUNG=1
      RETURN
C
C     PASS 2
C
    3 DO 22 J=1,N
      SAVY(J)=Y(J)
      PHI(J)=F(J)
   22 Y(J)=SAVY(J)+0.5*H*F(J)
      X=X+0.5*H
      IRUNG=1
      RETURN
C     PASS 3
    4 DO 33 J=1,N
      PHI(J)=PHI(J)+2.0*F(J)
   33 Y(J)=SAVY(J)+0.5*H*F(J)
      IRUNG=1
      RETURN
C
C     PASS 4
    5 DO 44 J=1,N
      PHI(J)=PHI(J)+2.0*F(J)
   44 Y(J)=SAVY(J)+H*F(J)
      X=X+0.5*H
      IRUNG=1
      RETURN
C     PASS 5
    6 DO 55 J=1,N
   55 Y(J) = SAVY(J) + (PHI(J) + F(J))*H/6.0
      IRUNG=2
      RETURN
C
      END
```

```
PAGE    7

VARIABLE ALLOCATIONS
   PHI(R )=0062-0000  SAVY(R )=00C6-0064      J(I )=00C8

STATEMENT ALLOCATIONS
 2    =0105  3    =0108  22   =011E  4    =0141  33   =0152  5    =016D  44   =017E  6    =019F  55   =01A3

FEATURES SUPPORTED
 ONE WORD INTEGERS

CALLED SUBPROGRAMS
 FADD    FADDX    FMPY    FMPYX   FDIV   FLD    FLDX    FSTO    FSTOX   SUBSC   SUBIN

REAL CONSTANTS
  .5000000E 00=00CA   .2000000E 01=00CC    .6000000E 01=00CE

INTEGER CONSTANTS
     1=0000     2=0001

CORE REQUIREMENTS FOR SBM22
 COMMON      0  VARIABLES     202  PROGRAM   250

RELATIVE ENTRY POINT ADDRESS IS 00D2 (HEX)

END OF COMPILATION

// DUP

*STORE      WS  UA  SBM22
CART ID 0108    DB ADDR   4E55    DB CNT    0012

// EJECT
```

```
PAGE   8

// FOR
*ONE WORD INTEGERS
*IOCS(CARD)
*IOCS(1132 PRINTER)
*IOCS(DISK)
*LIST ALL
      DIMENSION G(4),DG(4)
      COMMON PSI(61,80),URAT,RB,NPRB,NPZB,RA,NPR,INTVL
      DEFINE FILE 1(5439,2,U,IB)
    1 READ(2,100)G4LFT,G4RIT,SIGNL,DTAU,NIBP,NSBP,NX
      WRITE(3,200)
      WRITE(3,201)G4LFT,G4RIT,SIGNL,DTAU,NIBP,NSBP,NX
C
C     ESTABLISH PHYSICAL PROPERTIES FOR CALCULATING COLLECTION
C     EFFICIENCY
C
C     DC     IS CYLINDER DIAMETER, CM
C     DP     IS PARTICLE DIAMETER, CM
C     RHO    IS FLUID DENSITY, GM/CC
C     SIGMA IS PARTICLE DENSITY, GM/CC
C     XMU    IS ABSOLUTE VISCOSITY OF FLUID, POISE
C     UB IS FLUID VELOCITY IN INSIDE PIPE CM/SEC
C     ISR    IS STARTING RATIO Z/RB = -G(3)
C
      READ(2,101)DC,DP,RHO,SIGMA,XMU,UB,ISR
C
C     IF CORRECT STREAM FUNCTION VALUES ARE ALREADY IN TEMPORARY
C     STORAGE PASS BY RETRIEVAL FROM DISK STORAGE
C
      READ(2,111) ICONF
      IF(ICONF)2,3,3
    2 CONTINUE
C
C     CALL STREAM FUNCTION ARRAY FROM DISK STORAGE
C     AND SET CONSTANTS FOR FLUID VELOCITY CALCULATION
C
      READ(2,111) INTVL
      CALL GTPSI
      WRITE(3,211) INTVL
    3 CONTINUE
C
C     UA     IS FREE STREAM VELOCITY, CM/SEC
C
      UA = UB/URAT
      REZ=RHO*DP*UA/XMU
      XK=SIGMA*DP**2*UA/(9.*XMU*DC)
```

```
      P = REZ**2/XK
      WRITE(3,208)
      WRITE (3,202)  REZ,XK,P,DC,DP,RHO,SIGMA,XMU,UA,UB,ISR
C
C     ESTABLISH GRID STEP SIZE
C
      NR = NPR - 1
      DFLR = 1.0/FLOAT(NR)
      FDRSQ = 4.0*DFLR**2
      RR=RR+0.001
C
C     HALF INTERVAL ITERATION FOR INITIAL G4 VALUE
C
      DO 21 ITER=1,NX
C
C     SET AND PRINT INITIAL CONDITIONS
C
      M=0
      NSTEP=0
      TAU=0.0
      G3ZER = -FLOAT(ISR)
      G(3) = G3ZER
      G4ZER=(G4LFT+G4RIT)/2.0
      G(4)=G4ZER
      I = 1+IFIX(RR*G(4))
      JC=NPZB-(NPRB-1)*ISR
      J = JC
      RI=FLOAT(I-1)
      UZ=(PSI(I+1,J)-PSI(I-1,J))/(FDRSQ*RI)
      UR=(PSI(I,J-1)-PSI(I,J+1))/(FDRSQ*RI)
      G(1)=UZ
      G(2)=UR
      RF=REZ*((UR-G(2))**2+(UZ-G(1))**2)**0.5
      XCDRF=CDRF(RF)
      IP=ITER/NIBP*NIBP
      IF(IP-ITER)5,7,5
    5 CONTINUE
      IF(ITER-1)6,7,6
    6 CONTINUE
      IF(ITER-NX)8,7,8
    7 CONTINUE
      WRITE (3,205)
      WRITE(3,203)ITER,G4LFT,G4ZER,G4RIT,TAU,G(1),G(2),G(3),G(4),UZ,UR,
     1XCDRF
C
C     CALL ON RUNGE KUTTA SUBROUTINE
```

```
C
    8 CONTINUE
      M=M+1
      CALL SBM22(4,G,DG,TAU,DTAU,IRUNG,M)
      IF(IRUNG-1)10,9,10
    9 RE=REZ*((UR-G(2))**2+(UZ-G(1))**2)**0.5
      XCDRE=CDRE(RE)
      DG(1)=((XCDRE)/(24.0*XK))*(UZ-G(1))
      DG(2)=((XCDRE)/(24.0*XK))*(UR-G(2))
      DG(3)=G(1)
      DG(4)=G(2)
      GO TO 8
   10 CONTINUE
      M=0
C
C     CALCULATE FLUID VELOCITY AT PARTICLE POSITION
C
      I = 1+IFIX(RB*G(4))
      J =JO+IFIX(RB*(G(3)-G3ZER))
      RI=FLOAT(I-1)
      UZ=(PSI(I+1,J)-PSI(I-1,J))/(FDRSO*RI)
      UR=(PSI(I,J-1)-PSI(I,J+1))/(FDRSO*RI)
C
C     PRINT SOLUTIONS
C
      IS = ITER/NIBP*NIBP
      IF(IS-ITER)11,13,11
   11 CONTINUE
      IF(ITER-1)12,13,12
   12 CONTINUE
      IF(ITER-NX)17,13,17
   13 CONTINUE
      NSTEP=NSTEP+1
      IF(NSTEP-NSBP)17,14,17
   14 CONTINUE
      NSTEP=0
      TAW = TAU + 0.0001
      WRITE(3,204)TAW,G(1),G(2),G(3),G(4),UZ,UR,XCDRE
C
C     INTEGRATE ACROSS ANOTHER STEP IF REQUIRED
C
   17 HITS=G(3)
      IF(HITS)8,18,18
   18 CONTINUE
C
C     FIND INTERVAL HALF WITH THE SIGN CHANGE
```

```
C
      IF((G(4)-1.0)*SIGNL-0.0)19,19,20
   19 G4RIT=G4ZER
      GO TO 21
   20 G4LFT=G4ZER
   21 CONTINUF
C
C     PRINT SOLUTIONS FOR FINAL VALUF OF TAU
C
      TAW = TAU + 0.0001
      WRITE(3,204)TAW,G(1),G(2),G(3),G(4),UZ,UR,XCDRE
C
C     CALCULATF THE COLLECTION EFFICIFNCY
C
      WRITE(3,209) G4ZFR
      FM = G4ZFR**2
      WRITE(3,206)FM
C
C     CALCULATF THF SAMPLING EFFICIENCY
C
      RSINF=SQRT(PSI(NPRB,NPZB))*RA/RB
      PSIHT = PSI(NPRB,NPZB)
      DO 25 I=1,NPR
      IF(PSI(I,J0)-PSIHT)25,25,24
   24 RSINF = FLOAT(I-2)*SQRT(PSIHT/PSI(I-1,J0))*DELR*RA/RB
      GO TO 28
   25 CONTINUF
   28 CONTINUF
      WRITE(3,210) RSINF
      CR=(G4ZFR/RSINF)**2
      WRITE(3,207) CR
      READ(2,111)NSTOP
      IF(NSTOP)1,30,30
   30 CALL EXIT
C
C     FORMATS FOR INPUT AND OUTPUT STATEMENTS
C
  100 FORMAT(10X,F10.7,20X,F10.7,19X,F3.0/ 10X,F10.7,20X,I3,25X,I4/
     1    9X,I3)
  101 FORMAT(F10.5,F10.7,F10.6, F10.6,F10.7,F10.4,I5)
  111 FORMAT(I5)
  200 FORMAT( 1H1, 37X, 40HCOLLECTION EFFICIENCY OF A CIRCULAR TUBE/
     1    1H0 )
  201 FORMAT(  10H0G4LEF =  ,F10.6/ 10H G4RIT =  ,F10.6/10H SIGNL =  ,
     1    F4.0/ 10H DTAU  =  ,F10.6/ 10H NIBP  =  ,I4/ 10H NSBP  =  ,I4/
     2    10H NX    =  ,I4)
```

```
  202 FORMAT(  10HOREZ     =   ,F12.7/10H XK      =   ,E12.6/
    1   10H P      =   ,E10.4/
    2   10HODC     =   , F10.5/10H DP      =   ,F10.7/10H RHO     =   ,F10.6/
    3   10H SIGMA =    , F10.6/10H XMU     =   ,F10.7/10H UA      =   ,F10.4/
    4 10H UB      =   ,F10.4/10H ISR     =   ,I5)
  203 FORMAT( 10HOITER   =   ,I3/ 10H G4LEF =   ,F10.6/ 10H G4ZER =   ,
    1   F10.6/ 10H G4RIT =   ,F10.6/ 7H0   TAU, 11X, 4HG(1), 12X,
    2   4HG(2), 12X, 4HG(3), 12X, 4HG(4), 13X, 2HUZ, 14X,  2HUR ,
    3   12X, 4HCDRE /
    4   1H0, F7.4, 4F16.6, 3F16.4 )
  204 FORMAT ( 1H , F7.4, 4F16.6, 3F16.4 )
  205 FORMAT ( 46H1THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY )
  206 FORMAT( 30H0THE COLLECTION EFFICIENCY IS , E10.4)
  207 FORMAT( 29H0THE SAMPLING EFFICIENCY IS  ,E10.4)
  208 FORMAT(  28H1THE PHYSICAL PARAMETERS ARE )
  209 FORMAT(  34H0THE UPSTREAM PARTICLE RADIUS IS  ,E10.4)
  210 FORMAT( 31H0THE UPSTREAM FLUID RADIUS IS  ,E10.4)
  211 FORMAT(39H0THE INTERVAL OF THE WRITTEN VALUES IS ,I5)
C
      END
VARIABLE ALLOCATIONS
   PSI(RC)=7FFE-59E0  URAT(RC)=59DE          RB(RC)=59DC        NPRB(IC)=59DB       NPZB(IC)=59DA          RA(RC)=59D8
   NPR(IC)=59D7     INTVL(IC)=59D6          G(R )=000E-0008     DG(R )=0016-0010 G4LFT(R )=0018      G4RIT(R )=001A
 SIGNL(R )=001C      DTAU(R )=001E          DC(R )=0020          DP(R )=0022       RHO(R )=0024      SIGMA(R )=0026
   XMU(R )=0028        UB(R )=002A          UA(R )=002C         REZ(R )=002E        XK(R )=0030          P(R )=0032
  DELR(R )=0034     FDRSQ(R )=0036          RR(R )=0038         TAU(R )=003A     G3ZER(R )=003C      G4ZER(R )=003E
    RI(R )=0040        UZ(R )=0042          UR(R )=0044          RE(R )=0046     XCDRE(R )=0048        TAW(R )=004A
  HITS(R )=004C        EM(R )=004E       RSINF(R )=0050       PSIMT(R )=0052        CR(R )=0054          IB(I )=005C
  NIEP(I )=005D      NSBP(I )=005E          NX(I )=005F         ISR(I )=0060     ICONF(I )=0061          NR(I )=0062
  ITER(I )=0063         M(I )=0064       NSTEP(I )=0065           I(I )=0066        J0(I )=0067           J(I )=0068
    IP(I )=0069     IRUNG(I )=006A          IS(I )=006B       NSTOP(I )=006C

STATEMENT ALLOCATIONS
 100   =008D  101   =009F  111   =00A6  200   =00A8  201   =00C4  202   =00FC  203   =0154  204   =019C  205   =01A4  206   =01BD
 207   =01CF  208   =01E1  209   =01F1  210   =0205  211   =0218  1     =0248  2     =0289  3     =0296  5     =03CC  6     =03D2
 7     =03D8  8     =0400  9     =0415  10    =046B  11    =04EA  12    =04F0  13    =04F6  14    =0502  17    =0528  18    =0533
 19    =0540  20    =0546  21    =054A  24    =05B4  25    =05DB  28    =05E4  30    =0601

FEATURES SUPPORTED
 ONE WORD INTEGERS
 IOCS

CALLED SUBPROGRAMS
 GTPSI    CORE     SPM22    FSQRT    FAXB     FADD     FSUB     FSUBX    FMPY     FMPYX    FDIV     FDIVX    FLD      FLDX     FSTO
 FSTOX    FDVR     FAXI     IFIX     FLOAT    CARDZ    PRNTZ    SRED     SWRT     SCOMP    SFIO     SIOFX    SIOF     SIOI     SUBSC
 SNR      SDFIO
```

```
REAL CONSTANTS
  .900000E 01=0076    .100000E 01=0078    .400000E 01=007A    .100000E-02=007C    .000000E 00=007E    .200000E 01=0080
  .500000E 00=0082    .240000E 02=0084    .100000E-03=0086

INTEGER CONSTANTS
     2=0088       3=0089        1=008A        0=008B        4=008C

CORE REQUIREMENTS FOR
 COMMON    9770  VARIABLES     118  PROGRAM    1420

END OF COMPILATION

// XEQ          1

*FILES(1,PSI13)
```

```
                                  COLLECTION EFFICIENCY OF A CIRCULAR TUBE

G4LEF  =    0.500000
G4RIT  =    2.000000
SIGNL  =   -1.
DTAU   =    0.020000
NIBP   =    10
NSBP   =    10
NX     =    20

 DISK STORAGE CHECK

STREAM FUNCTION FOR FLOW IN TWO CONCENTRIC PIPES WITH PARAMETERS

RA      =   60.00
RB      =   12.00
NPZ     =    89
NPR     =    61
NPZB    =    65
NPRB    =    13
URAT    =    3.0000
UA      =    1.0000
UB      =    3.0000
ITERS   =   2890
```

```
THE CURRENT VALUES OF PSI STORED ON DISK ARE
 0.0000 0.0044 0.0177 0.0399 0.0711 0.1111 0.1599 0.2177 0.2844 0.3599 0.4444 0.5377 0.6399 0.7511 0.8711 1.0000
 0.0000 0.0044 0.0178 0.0401 0.0712 0.1113 0.1602 0.2181 0.2848 0.3604 0.4448 0.5381 0.6402 0.7513 0.8712 1.0000
 0.0000 0.0044 0.0178 0.0402 0.0714 0.1116 0.1606 0.2185 0.2852 0.3608 0.4452 0.5385 0.6406 0.7515 0.8713 1.0000
 0.0000 0.0044 0.0179 0.0403 0.0716 0.1119 0.1610 0.2189 0.2857 0.3613 0.4457 0.5389 0.6409 0.7517 0.8714 1.0000
 0.0000 0.0045 0.0180 0.0405 0.0719 0.1122 0.1614 0.2194 0.2863 0.3619 0.4462 0.5394 0.6413 0.7520 0.8716 1.0000
 0.0000 0.0045 0.0181 0.0407 0.0722 0.1127 0.1620 0.2201 0.2870 0.3626 0.4469 0.5400 0.6418 0.7524 0.8719 1.0000
 0.0000 0.0045 0.0182 0.0409 0.0727 0.1133 0.1627 0.2209 0.2879 0.3635 0.4478 0.5407 0.6424 0.7528 0.8720 1.0000
 0.0000 0.0046 0.0184 0.0413 0.0733 0.1141 0.1637 0.2220 0.2890 0.3646 0.4488 0.5416 0.6431 0.7533 0.8723 1.0000
 0.0000 0.0046 0.0186 0.0419 0.0741 0.1152 0.1650 0.2234 0.2904 0.3660 0.4501 0.5427 0.6440 0.7540 0.8726 1.0000
 0.0000 0.0047 0.0190 0.0426 0.0753 0.1167 0.1667 0.2253 0.2923 0.3677 0.4516 0.5441 0.6451 0.7547 0.8730 1.0000
 0.0000 0.0049 0.0196 0.0437 0.0769 0.1188 0.1690 0.2276 0.2945 0.3698 0.4535 0.5456 0.6463 0.7555 0.8734 1.0000
 0.0000 0.0051 0.0205 0.0454 0.0793 0.1216 0.1721 0.2307 0.2974 0.3724 0.4557 0.5474 0.6477 0.7565 0.8739 1.0000
 0.0000 0.0055 0.0219 0.0481 0.0829 0.1257 0.1762 0.2345 0.3008 0.3754 0.4582 0.5495 0.6493 0.7576 0.8744 1.0000
 0.0000 0.0062 0.0243 0.0523 0.0883 0.1313 0.1815 0.2392 0.3049 0.3788 0.4611 0.5518 0.6510 0.7587 0.8750 1.0000
 0.0000 0.0073 0.0284 0.0597 0.0968 0.1392 0.1881 0.2448 0.3095 0.3826 0.4642 0.5542 0.6528 0.7600 0.8757 1.0000
 0.0000 0.0090 0.0355 0.0737 0.1101 0.1493 0.1958 0.2508 0.3144 0.3866 0.4674 0.5567 0.6547 0.7612 0.8763 1.0000
 0.0000 0.0110 0.0456 0.1199 0.1274 0.1600 0.2036 0.2568 0.3191 0.3904 0.4705 0.5592 0.6565 0.7625 0.8769 1.0000
 0.0000 0.0124 0.0512 0.1199 0.1372 0.1679 0.2099 0.2619 0.3234 0.3939 0.4733 0.5615 0.6583 0.7636 0.8776 1.0000
 0.0000 0.0130 0.0527 0.1199 0.1398 0.1720 0.2141 0.2658 0.3268 0.3969 0.4759 0.5636 0.6599 0.7647 0.8781 1.0000
 0.0000 0.0132 0.0531 0.1199 0.1398 0.1737 0.2165 0.2685 0.3295 0.3994 0.4781 0.5654 0.6613 0.7657 0.8786 1.0000
THE INTERVAL OF THE WRITTEN VALUES IS      4
```

```
THE PHYSICAL PARAMETERS ARE

REZ    =      0.3303983
XK     =  0.794345E-01
P      =  0.1374E 01

DC     =      1.90500
DP     =    0.0050000
RHO    =     0.001213
SIGMA  =     1.000000
XMU    =    0.0001789
UA     =       9.7458
UB     =      29.2374
ISR    =       5
```

```
THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY

ITER  =     1
G4LFF =     0.500000
G4ZER =     1.250000
G4RIT =     2.000000

   TAU          G(1)          G(2)          G(3)          G(4)          UZ          UR          CDRE

 0.0000       1.002017     -0.004612     -5.000000      1.250000      1.0020     -0.0046     24.0000
 0.2000       1.002612     -0.004523     -4.799558      1.249095      1.0032     -0.0046     24.0006
 0.4000       1.003966     -0.004862     -4.598900      1.248159      1.0043     -0.0049     24.0004
 0.6000       1.005386     -0.005347     -4.397952      1.247135      1.0063     -0.0057     24.0003
 0.8000       1.007127     -0.006074     -4.196700      1.245995      1.0078     -0.0063     24.0008
 1.0000       1.008980     -0.006957     -3.995085      1.244693      1.0103     -0.0076     24.0005
 1.2000       1.011183     -0.008124     -3.793057      1.243181      1.0122     -0.0087     24.0013
 1.4000       1.013678     -0.009561     -3.590579      1.241419      1.0144     -0.0100     24.0010
 1.6000       1.016748     -0.011458     -3.387547      1.239326      1.0183     -0.0125     24.0020
 1.8000       1.020335     -0.013817     -3.183848      1.236808      1.0214     -0.0145     24.0014
 2.0000       1.024671     -0.016849     -2.979363      1.233756      1.0269     -0.0185     24.0030
 2.2000       1.029368     -0.020324     -2.773988      1.230065      1.0314     -0.0218     24.0027
 2.4000       1.035049     -0.024776     -2.567551      1.225563      1.0393     -0.0283     24.0019
 2.6000       1.042709     -0.031212     -2.359786      1.219981      1.0457     -0.0338     24.0042
 2.8000       1.051016     -0.038706     -2.150419      1.213004      1.0572     -0.0446     24.0030
 3.0000       1.062152     -0.049674     -1.939117      1.204200      1.0665     -0.0541     24.0067
 3.2000       1.076004     -0.064810     -1.725401      1.192889      1.0832     -0.0732     24.0118
 3.4000       1.091695     -0.084059     -1.508673      1.178094      1.0966     -0.0903     24.0085
 3.6000       1.119230     -0.112612     -1.288249      1.158742      1.1347     -0.1254     24.0214
 3.8000       1.150578     -0.149771     -1.061076      1.132598      1.1703     -0.1807     24.0128
 4.0000       1.187810     -0.214183     -0.827169      1.096348      1.2138     -0.2688     24.0245
 4.2000       1.275572     -0.328062     -0.581631      1.042921      1.3305     -0.4319     24.0498
 4.4000       1.445531     -0.541864     -0.313697      0.957491      1.6108     -0.7548     24.1132
 4.6000       2.185671     -0.843110      0.031483      0.810398      2.8384     -0.6267     24.4007
```

```
THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY

ITER  =    10
G4LEF =     1.528320
G4ZER =     1.529785
G4RIT =     1.531250

   TAU          G(1)          G(2)          G(3)          G(4)        UZ        UR       CORE

 0.0000      1.001737     -0.005172     -5.000000      1.529785    1.0017   -0.0051   24.0000
 0.2000      1.002163     -0.005297     -4.799630      1.528744    1.0026   -0.0054   24.0005
 0.4000      1.003264     -0.005708     -4.599087      1.527645    1.0036   -0.0058   24.0004
 0.6000      1.004420     -0.006262     -4.398308      1.526445    1.0052   -0.0066   24.0002
 0.8000      1.005826     -0.007085     -4.197280      1.525113    1.0063   -0.0074   24.0006
 1.0000      1.007310     -0.008078     -3.995962      1.523597    1.0083   -0.0088   24.0004
 1.2000      1.009054     -0.009383     -3.794316      1.521846    1.0099   -0.0100   24.0011
 1.4000      1.011001     -0.010975     -3.592316      1.519818    1.0116   -0.0115   24.0008
 1.6000      1.013358     -0.013054     -3.389887      1.517425    1.0146   -0.0141   24.0018
 1.8000      1.016059     -0.015611     -3.186950      1.514567    1.0169   -0.0164   24.0012
 2.0000      1.018824     -0.018397     -2.983451      1.511160    1.0209   -0.0206   24.0010
 2.2000      1.022584     -0.022467     -2.779315      1.507084    1.0240   -0.0241   24.0023
 2.4000      1.026567     -0.027099     -2.574399      1.502133    1.0294   -0.0306   24.0016
 2.6000      1.033905     -0.033359     -2.368416      1.496097    1.0366   -0.0359   24.0040
 2.8000      1.040381     -0.040775     -2.160969      1.488698    1.0448   -0.0466   24.0026
 3.0000      1.048098     -0.051472     -1.952122      1.479502    1.0510   -0.0558   24.0056
 3.2000      1.055963     -0.063867     -1.741715      1.467992    1.0615   -0.0736   24.0040
 3.4000      1.065591     -0.081855     -1.529555      1.453473    1.0692   -0.0892   24.0087
 3.6000      1.074775     -0.102978     -1.315505      1.435034    1.0808   -0.1198   24.0063
 3.8000      1.091054     -0.138016     -1.099379      1.411255    1.1033   -0.1519   24.0198
 4.0000      1.110081     -0.185728     -0.878923      1.379064    1.1151   -0.2116   24.0282
 4.2000      1.115664     -0.248841     -0.656165      1.335886    1.1122   -0.2979   24.0180
 4.4000      1.137621     -0.377618     -0.429785      1.273719    1.1353   -0.4177   24.0428
 4.6000      1.128942     -0.626759     -0.201396      1.177222    1.0917   -0.7361   24.1233
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```
THE MOTION OF A CRITICAL PARTICLE IS GIVEN BY

ITER  =    20
G4LEF =      1.529885
G4ZER =      1.529886
G4RIT =      1.529888

   TAU          G(1)           G(2)           G(3)           G(4)          UZ           UR          CDRE

  0.0000      1.001737      -0.005172      -5.000000      1.529886      1.0017      -0.0051      24.0000
  0.2000      1.002163      -0.005297      -4.799630      1.528845      1.0026      -0.0054      24.0005
  0.4000      1.003264      -0.005708      -4.599087      1.527747      1.0036      -0.0058      24.0004
  0.6000      1.004420      -0.006262      -4.398308      1.526547      1.0052      -0.0066      24.0002
  0.8000      1.005826      -0.007085      -4.197280      1.525214      1.0063      -0.0074      24.0006
  1.0000      1.007310      -0.008078      -3.995962      1.523699      1.0083      -0.0088      24.0004
  1.2000      1.009054      -0.009383      -3.794316      1.521948      1.0099      -0.0100      24.0011
  1.4000      1.011001      -0.010975      -3.592316      1.519920      1.0116      -0.0115      24.0008
  1.6000      1.013358      -0.013054      -3.389887      1.517527      1.0146      -0.0141      24.0018
  1.8000      1.016059      -0.015611      -3.186950      1.514669      1.0169      -0.0164      24.0012
  2.0000      1.018824      -0.018397      -2.983451      1.511261      1.0209      -0.0206      24.0010
  2.2000      1.022584      -0.022467      -2.779315      1.507185      1.0240      -0.0241      24.0023
  2.4000      1.026567      -0.027099      -2.574399      1.502235      1.0294      -0.0306      24.0016
  2.6000      1.033905      -0.033359      -2.368416      1.496198      1.0366      -0.0359      24.0040
  2.8000      1.040381      -0.040775      -2.160969      1.488800      1.0448      -0.0466      24.0026
  3.0000      1.048098      -0.051472      -1.952122      1.479604      1.0510      -0.0558      24.0056
  3.2000      1.055963      -0.063867      -1.741715      1.468093      1.0615      -0.0736      24.0040
  3.4000      1.065591      -0.081855      -1.529555      1.453574      1.0692      -0.0892      24.0087
  3.6000      1.074775      -0.102978      -1.315505      1.435136      1.0808      -0.1198      24.0063
  3.8000      1.088347      -0.137111      -1.099478      1.411389      1.1033      -0.1519      24.0224
  4.0000      1.109863      -0.185655      -0.879219      1.379264      1.1151      -0.2116      24.0283
  4.2000      1.115647      -0.248836      -0.656477      1.336091      1.1122      -0.2979      24.0180
  4.4000      1.137620      -0.377618      -0.430098      1.273925      1.1353      -0.4177      24.0428
  4.6000      1.125415      -0.623691      -0.202871      1.178444      1.0917      -0.7361      24.1253
  4.7799      1.290820      -1.631347       0.003258      1.008198      1.6846      -1.5900      24.9538

THE UPSTREAM PARTICLE RADIUS IS  0.1529E 01

THE COLLECTION EFFICIENCY IS 0.2340E 01

THE UPSTREAM FLUID RADIUS IS  0.1730E 01

THE SAMPLING EFFICIENCY IS  0.7818E 00
// PAUS
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Sampling efficiencies are calculated for an aspirated particulate matter sampling probe under various conditions of anisokinetic flow. A mathematical model developed for the purpose was used to obtain results for a wide range of particle sizes and flow velocities. The results can be used to predict or correct sampling errors in field or laboratory experiments. Using the same test parameters as in previous experimental tests by other workers, sampling efficiencies were calculated and the results were found to agree favorably with the results of the experiments.

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KEY WORDS

Particulate Sampling

Collection Efficiency

Sampling Probe

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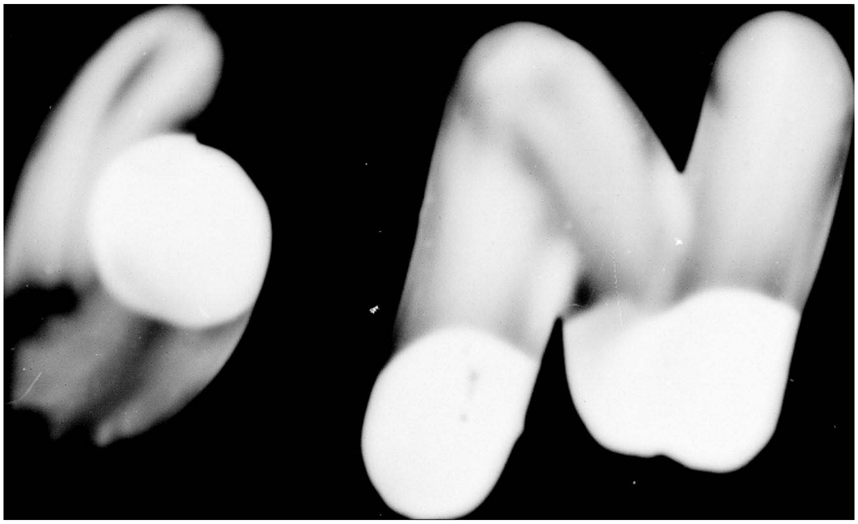

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DETERMINATION OF THEORETICAL SAMPLING EFFICIENCIES FOR ASPIRATED PARTICULATE MATTER THROUGH A DRES SAMPLING PROBE IN ANISOKINETIC FLOW (U)

by

Stanley B. Mellsen

ERRATA SHEET

"D" in Figures 7 to 14 denotes the diameter of the collection tube. In terms of the symbols defined under Notation this should read $2r_B$.

Figure 14 caption, second line, should read "constant flow velocity".