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INERTIAL IMPACTION EFFICIENCY OF
CYLINDRICAL COLLECTORS BY DIGITAL
TECHNIQUES AND EFFECTS OF PARTICLE
SIZE DISTRIBUTIONS

Arthur K. Stuempfle, et al

Edgewood Arsenal
Aberdeen Proving Ground, Maryland

October 1974

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EC-TR-74050

INERTIAL IMPACTION EFFICIENCY OF CYLINDRICAL COLLECTORS
BY DIGITAL TECHNIQUES AND EFFECTS
OF PARTICLE SIZE DISTRIBUTIONS

by

Arthur K. Stuempfle
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Chemical Laboratory

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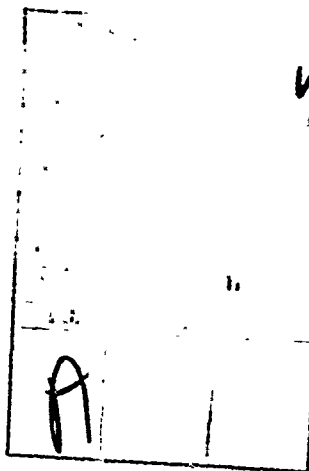
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER EC-TR-74050	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INERTIAL IMPACTION EFFICIENCY OF CYLINDRICAL COLLECTORS BY DIGITAL TECHNIQUES AND EFFECTS OF PARTICLE SIZE DISTRIBUTIONS		5. TYPE OF REPORT & PERIOD COVERED Technical Report February-May 1974
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Arthur K. Stuempfle Claude R. Pellegrino		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Commander, Edgewood Arsenal Attn: SAREA-CL-POA Aberdeen Proving Ground, Maryland 21010		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1W162116A08402
11. CONTROLLING OFFICE NAME AND ADDRESS Commander, Edgewood Arsenal Attn: SAREA-TS-R Aberdeen Proving Ground, Maryland 21010		12. REPORT DATE October 1974
		13. NUMBER OF PAGES 41
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE NA
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Chemical test and assessment technology		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
Droplet	Cylinders	Interception
Aerosol	Collectors	Particle impaction
Sampling	Deposition	Inertial impaction
Particles	Efficiency	Inertial parameter
Impaction	Impingement	Isokinetic sampling
		Sampling efficiency
		Impaction efficiency
		Collection efficiency
		Deposition efficiency
		Weibull distribution
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The theory of inertial impaction of particles on cylinders has been analyzed and used to develop standard inertial impaction efficiency curves. Unique exponential functions have been generated by a digital computer that accurately fit the inertial impaction theory with a maximum relative error of less than 1%. Interpolative routines have been adapted for the computer program to obtain inertial impaction efficiency predictions for all inertial parameter and velocity field scaling parameter values in the range of $0.13 < K \leq 300$ and $0 \leq \phi \leq 10,000$. The complete computer program with examples and solutions of test cases are presented in the appendix. (Continued)		

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19. KEYWORDS

Drop size distribution
Digital computer program

20. ABSTRACT

The Weibull distribution function has been adapted to analyze the effects of particle size distributions on the impaction efficiency of cylinders. Use of the mass median diameter to characterize a particle size distribution is unsatisfactory for predicting the impaction efficiency from heterogeneous aerosols. Use of the particle size distribution to predict efficiency of impaction yields good agreement between theory and experiment.

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PREFACE

The work described in this report was authorized under Task IW162116A08402, Chemical Test and Assessment Technology. This work was started in February and completed in May 1974.

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INERTIAL IMPACTION EFFICIENCY OF CYLINDRICAL COLLECTORS BY DIGITAL TECHNIQUES AND EFFECTS OF PARTICLE SIZE DISTRIBUTIONS

I. INTRODUCTION.

The deposition of particles of intermediate size (10 to 200 μm diameter) on collectors in a flow stream is principally based on the inertial impaction mechanism. Inertial impaction of particles on collectors is of interest in diversified areas such as crop dusting, mosquito spraying, air pollution control, aircraft icing, particulate buildup on heat exchangers, and in practically any circumstance where matter in particulate form is removed from a transport fluid. The efficiency with which the particles are removed from the flow stream is a function of the particle size, collector size, and flow field conditions. For a stationary cylinder in a moving airstream, the impaction efficiency is defined as the ratio of the cross-sectional area of the upstream envelope containing the trajectories of the particles which intersect the collector surface to the cross-sectional area of the cylindrical collector normal to the direction of flow. Estimates of the impaction efficiency for a given set of conditions can be found by computing the trajectories of the particles that challenge the collector or by graphically determining the efficiency from curves constructed from the point-by-point trajectory calculations. These methods are adequate when only a few data points are of interest but the technique becomes tedious when estimating efficiencies for a variety of possible impaction conditions. In addition, the aerosol that challenges the collector generally consists of a wide range of sizes depending on the method used for particle generation. It is recognized that, if a single parameter, such as the mass median diameter (MMD), is used to characterize the particle size distribution for computational purposes, the expected theoretical impaction efficiency can be grossly different from the experimental efficiency. These differences can be attributed in part to the turbulent nature of the flow field and to the nonlinear character of the inertial impaction efficiency curves. The objectives of this study have been to develop a computer program that rapidly calculates the inertial impaction efficiency of cylindrical collectors for any given set of laminar flow conditions and to devise a technique to assess the effects of a particular particle size distribution on impaction efficiency.

II. BACKGROUND.

The theory of inertial impaction of spherical particles on cylindrical collectors in an ideal flow field is based on a numerical solution of the equations of motion of the particles undergoing transport around the bluff body. Development of the theory and associated digital computer techniques has been described in a previous study¹ and provides the basis for this report. Langmuir and Blodgett² proposed the following dimensionless form of the equations of motion for a particle in Cartesian coordinates.

$$\frac{dv_x}{d\tau} = \frac{C_D Re}{24} \frac{1}{K} (u_x \cdot v_x) \quad (1)$$

$$\frac{dv_y}{d\tau} = \frac{C_D Re}{24} \frac{1}{K} (u_y \cdot v_y) \quad (2)$$

where

v_x, v_y = particle velocity components normalized by the free-stream velocity

u_x, u_y = airstream velocity components normalized by the free-stream velocity

$\bar{U}$ = free-stream velocity at an infinite distance from the cylinder surface

$$\begin{aligned}
C_D &= \text{drag coefficient for spherical particles in fluid} \\
Re = \frac{\rho_a d_p \bar{v}}{\mu} &= \text{particle Reynolds number with respect to local relative velocity} \\
\rho_a &= \text{fluid density} \\
\mu &= \text{fluid viscosity} \\
d_p &= \text{particle diameter} \\
K = \frac{\rho d_p^2 \bar{U}}{18\mu R} &= \text{inertial parameter of particle} \quad (3) \\
\rho &= \text{particle density} \\
R &= \text{cylinder radius} \\
\tau = \frac{\bar{U}}{R} t &= \text{time scale}
\end{aligned}$$

The inertial parameter, K , is a measure of the inertia of the particle and relates to the magnitude of the external force required to cause a change in its direction of motion. If Stokes' law of resistance is assumed, the inertial parameter represents the ratio of the "stopping" distance of a particle projected with velocity $\bar{U}$ into still air to the radius of the cylinder. A second dimensionless parameter proposed by Langmuir and Blcdgett is the velocity field scaling parameter, ϕ , originally defined in terms of the free-stream particle Reynolds number. The ϕ parameter is used to calculate the magnitude of the instantaneous Reynolds number of the particle at any point in the flow field and can be related to the Reynolds number of the cylindrical collector as follows:

$$\phi = \frac{Re_o^2}{K} \frac{18\rho_a^2 \bar{U} R}{\mu \rho} = \frac{9\rho_a}{\rho} (Re_c) \quad (4)$$

where

$$\begin{aligned}
Re_o &= \frac{d_p \rho_a \bar{U}}{\mu} = \text{free-stream Reynolds number of the particle} \\
Re_c &= \text{free-stream Reynolds number of the cylindrical collector}
\end{aligned}$$

The magnitude of the ϕ parameter at any point in the particle path is a measure of the deviation from Stokes' law due to the forces acting on the particle.

The starting point for a mathematical description of the fluid flow field around the collector is the Navier-Stokes equation. A solution to the general Navier-Stokes equation is possible after a number of limiting assumptions are made with respect to the fluid and flow conditions. One form of solution can be found if the fluid is assumed to be ideal; i.e., constant density, irrotational, and without viscosity. The flow pattern around the cylinder under steady-state conditions is dependent on the Reynolds number of the collector. Where the Reynolds number of the cylinder is one thousand or greater ($\phi \geq 10$ in air), the flow can be considered ideal in the absence of turbulence and the flow field is adequately described by potential theory for an incompressible fluid. The streamlines for flow outside the cylinder can be obtained and the airstream velocity components can be written in dimensionless terms as simple functions of the reduced position coordinates¹; namely,

$$u_x = 1 + \frac{y^2 - x^2}{(x^2 + y^2)^2} \quad (5)$$

$$u_y = - \frac{2xy}{(x^2 + y^2)^2} \quad (6)$$

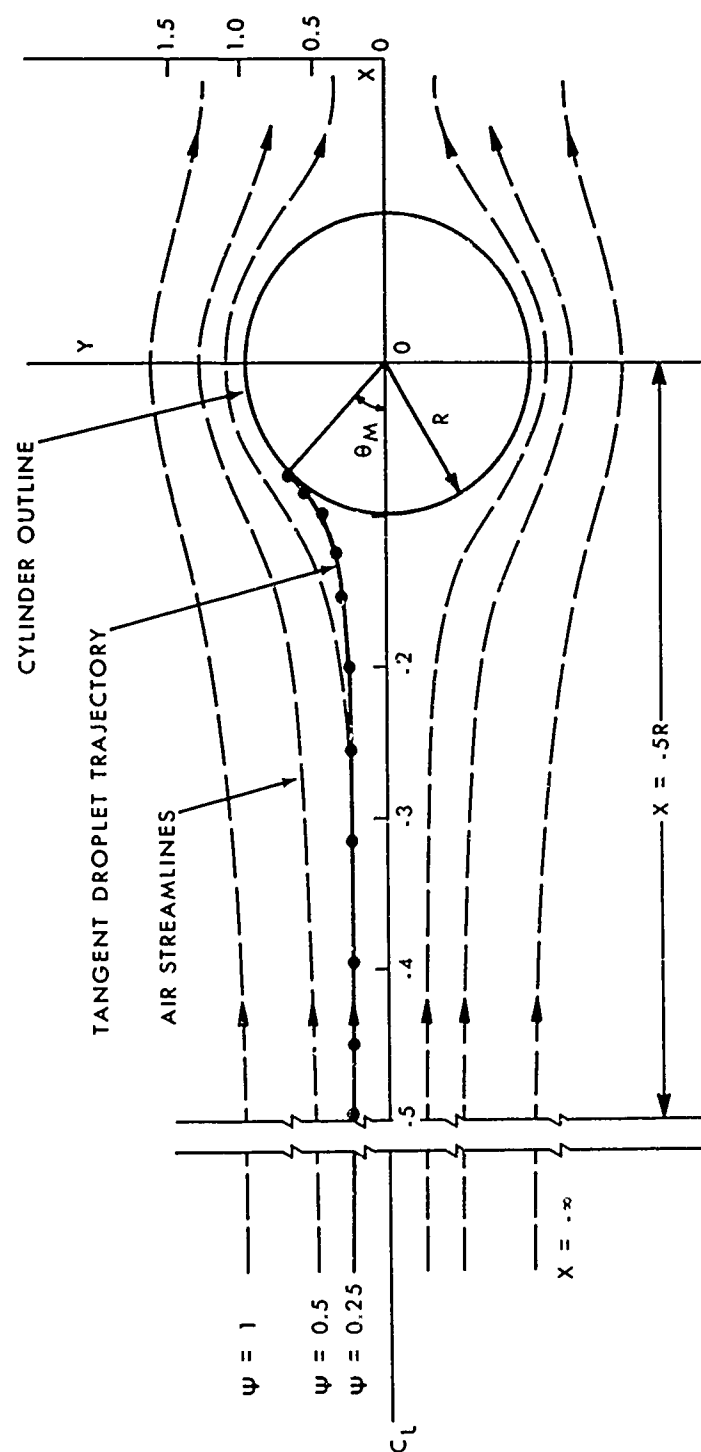


Figure 1. Coordinate System for Cylinder in Potential Flow Field

where the Cartesian coordinates have been normalized with respect to the cylinder radius.

A numerical solution of the differential equations of motion given above requires the instantaneous drag force on the particle to be estimated as the trajectory is developed. The steady-state drag coefficient of the sphere is a function of the Reynolds number, and the reliable experimental data as tabulated by Fuchs³ have been interpolated to obtain these estimations. The probable error in the drag coefficient for solid spheres is claimed by Fuchs to be less than 4% over the Reynolds number range of 0.01 to 500. These data are nearly identical to the experimental data cited by Schlichting⁴ as adopted and reported by Hussein and Tabakoff.⁵ Over the Reynolds number range of 0.10 to 7.0, the earlier approximations used by Langmuir and Blodgett differ from the current drag coefficient data.

The Cartesian coordinate system used in calculating the trajectory of particles around the cylindrical collector is identical to that of Brun, Lewis, Perkins, and Serafini⁶ and is shown in figure 1. The motion of the particles is in a plane perpendicular to the cylinder axis which is the origin of the coordinate system. Theoretically, the maximum angle of impingement, θ_M , is the angle beyond which no deposition occurs by the inertial mechanism.

Several simplifying assumptions have been made in the derivations and in computing the trajectory of a particle. These assumptions include the following:

1. At an infinite distance upstream of the cylinder, the particles have horizontal and vertical velocity components equal to the free-stream air.
2. The particles are spherical, monometric (uniform size), and monodisperse (single particles), and they do not evaporate or deform.
3. Gravitational, electrostatic, and any other external forces are negligible.
4. The particle radius is negligible with respect to the cylinder radius. (For interception effect considerations, see previous publication.⁷)
5. The boundary layer about the cylinder surface does not affect the particle trajectory.
6. The airflow around the cylinder is described as ideal and without circulation and is unaffected by the presence of the particles.
7. The instantaneous drag force coefficient for the particle is given by the steady-state data and is not subjected to acceleration effects.
8. All particles that strike the collector adhere to it.

Results of the digital computer trajectory calculations to determine the efficiency of impaction of spherical particles on cylindrical collectors in an ideal flow field as a function of the K and ϕ scaling parameters are shown in figure 2. The impaction data for inertial parameter values less than one ($K \leq 1$) are displayed in figure 3. In addition to the impaction efficiency, the maximum-angle-of-impingement data are plotted in figure 4. The theory has been experimentally verified under laminar flow conditions for a wide range of inertial parameter and velocity field scaling parameter values.⁸⁻¹¹ In general, however, the theory is inappropriate for accurately predicting the impaction efficiency of particles possessing small inertial parameter values on collectors in fluid flows that exhibit turbulence intensity levels above 7.5% or when the Reynolds number of the collector is less than approximately one thousand ($\phi \approx 10$ in air).¹¹ Further, the collection efficiency of a cylinder that is challenged by a distribution of particle sizes is not accurately predicted by a single particle parameter such as the mass median diameter.^{9,12} For many practical circumstances, though, the theory is quite sufficient, and this study has been undertaken so that impaction efficiency predictions can be rapidly made by computer with minimum input data requirements or computer programming background.

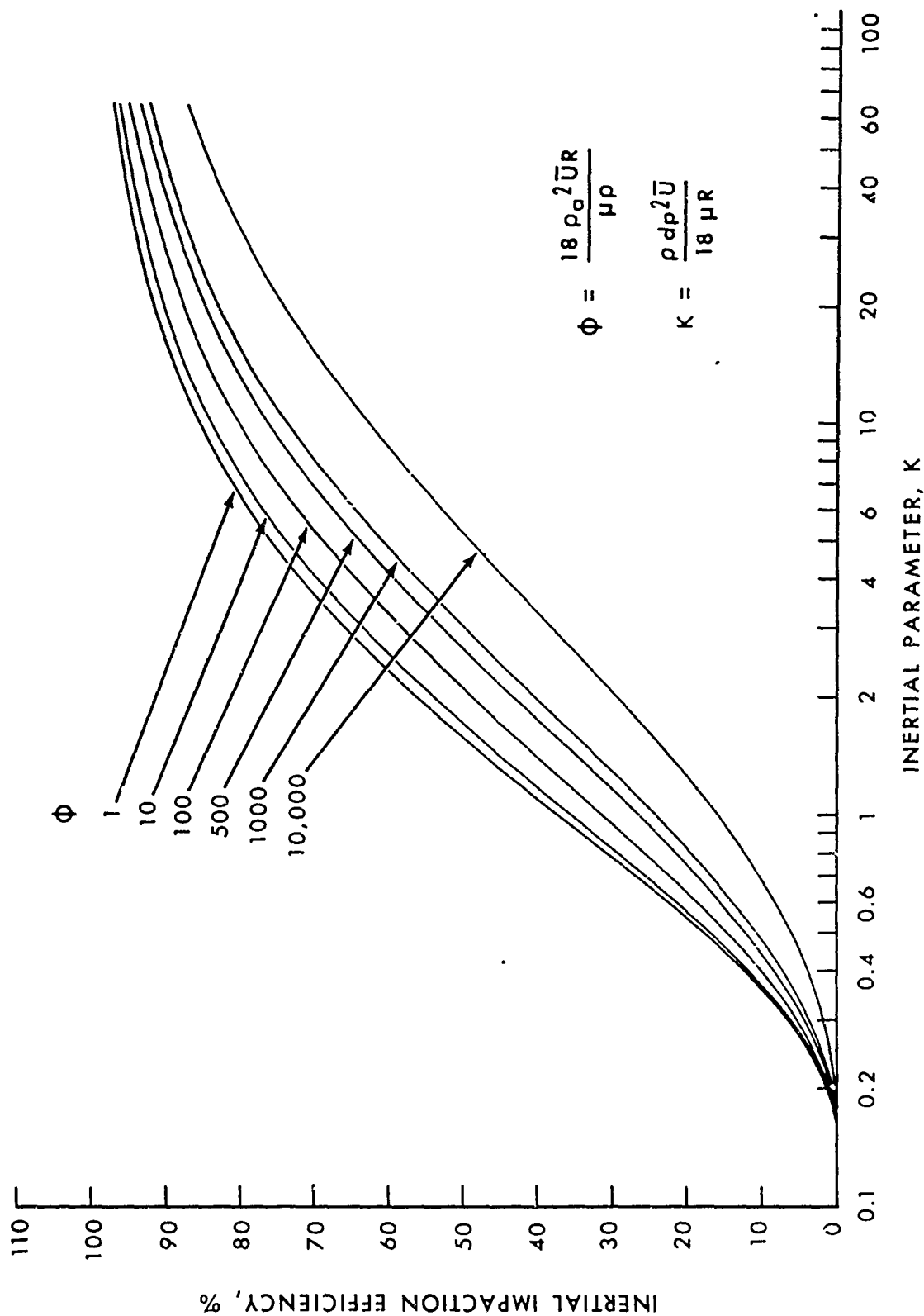


Figure 2. Inertial Impaction Theory

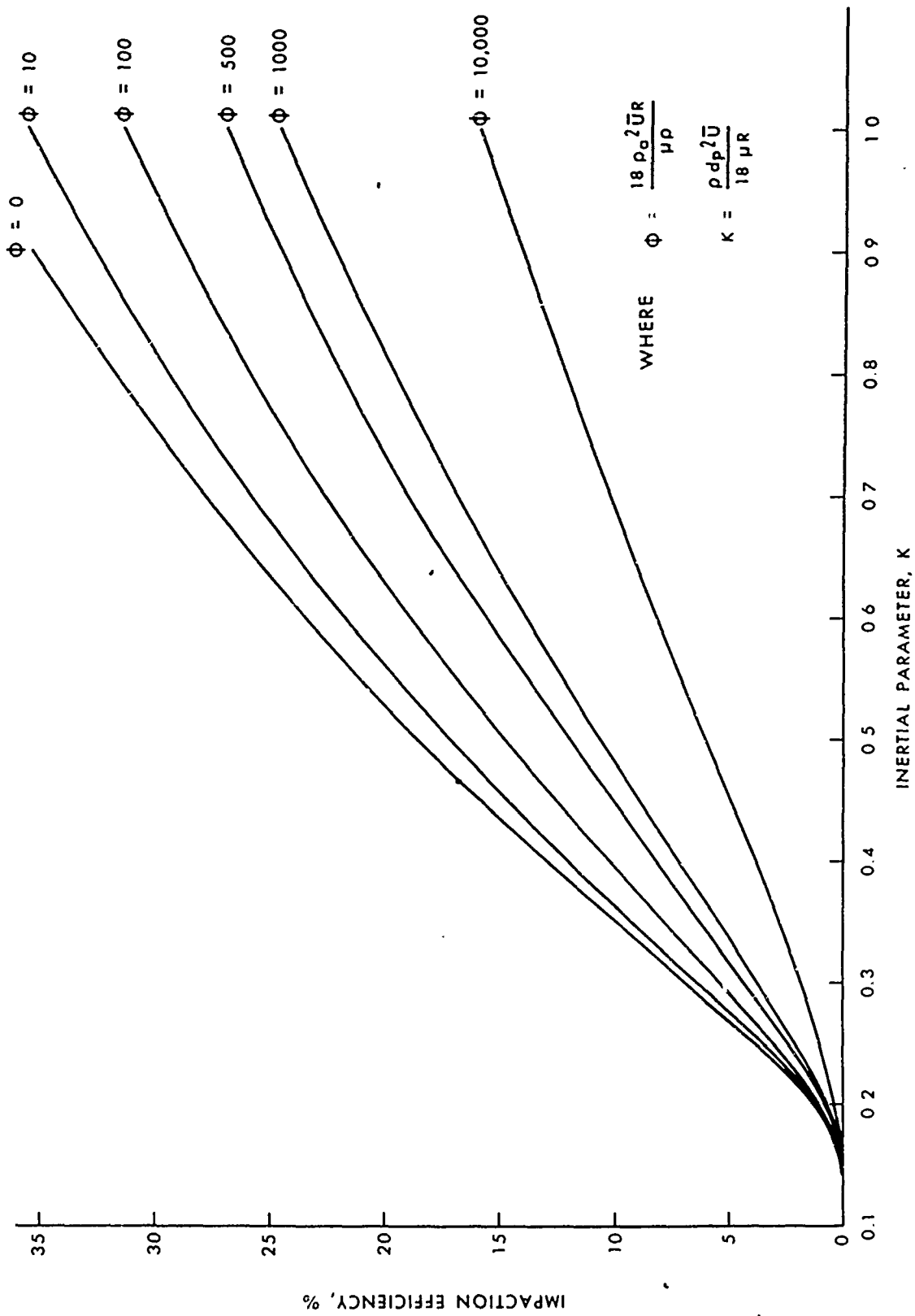


Figure 3. Impact Efficiency for Cylinder for $K \leq 1.0$

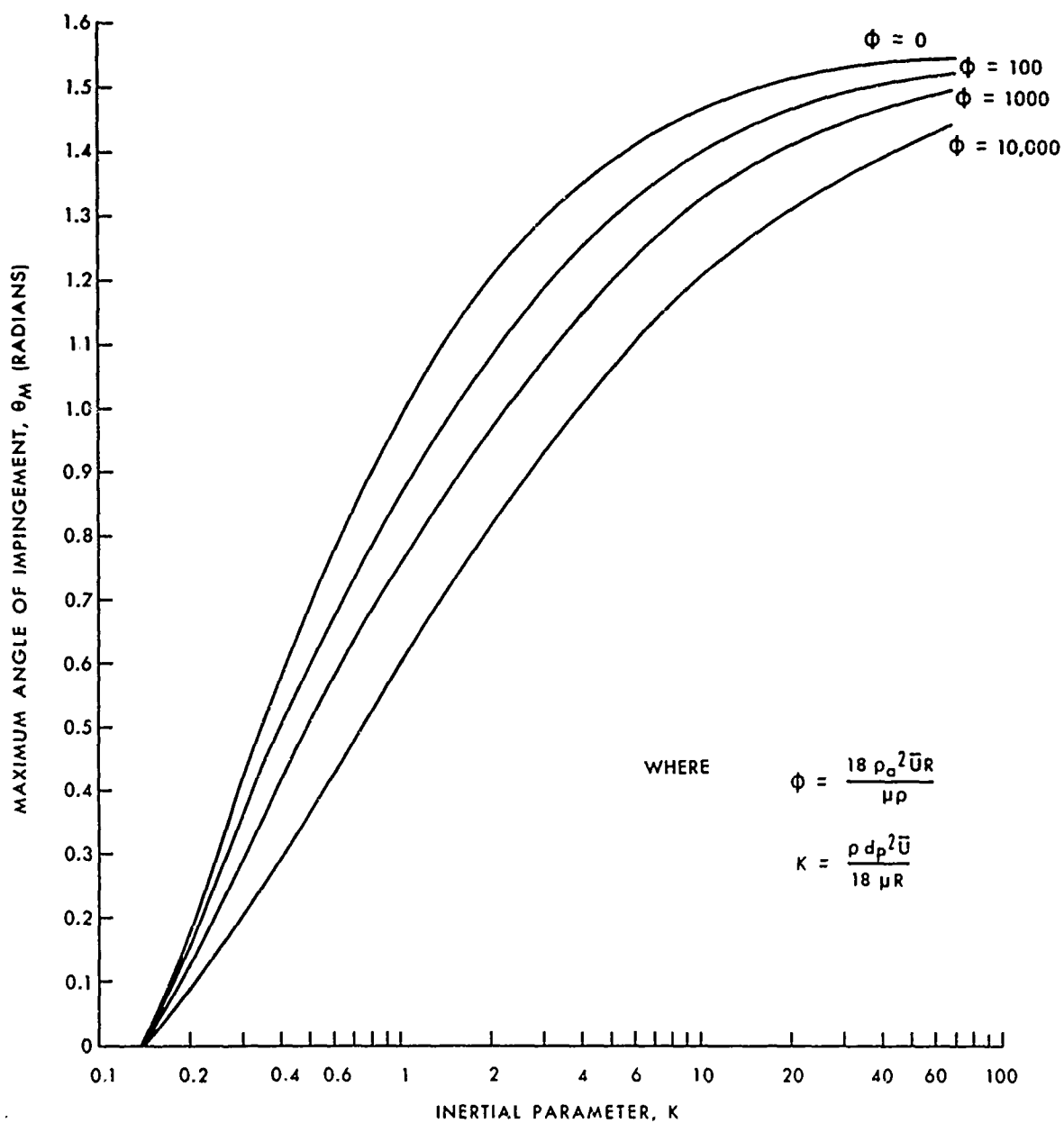


Figure 4. Maximum Angle of Impingement on Cylinders

III. METHODS AND RESULTS.

Results of the point-by-point trajectory calculations define the inertial impaction theory as shown in figures 2 and 3 and provide the impaction efficiency as a function of the K and ϕ scaling parameters. These data serve as the standards for which unique exponential functions have been obtained to fit the curves. The analytical expressions for the standard ϕ curves can then be interpolated to determine the impaction efficiency for any nonstandard K and ϕ value. A digital computer program has been developed to perform these calculations and only a minimum of input data is necessary for operation.

The standard velocity field scaling parameter curves selected for fit include $\phi = 0; 1; 2.2; 5; 10; 22; 50; 100; 200; 500; 1,000; 2,210; 5,000; \text{ and } 10,000$. Each curve has been subdivided into four inertial parameter ranges and each portion, respectively, has been fitted by the same form of the unique exponential functions. Any differences that occur between the computed efficiency, along a standard ϕ curve and the point-by-point impaction efficiency data are in the third or higher significant digit position and the maximum relative error observed has been less than 1%.

Lagrange's interpolation formula has been used to compute impaction efficiency values for velocity field scaling parameters enclosed within the aforementioned standard ϕ values that are equal to or greater than one. The formulation used in this study has been defined as

$$E_{\phi} = E_{\phi_i} \frac{\prod_{j=1, j \neq i}^M (\ln \phi - \ln \phi_j)}{\prod_{j=1, j \neq i}^M (\ln \phi_i - \ln \phi_j)} \quad (7)$$

where

$$E_{\phi_i} = 1.0 / \left\{ \exp \left[\exp(A_N (\ln K)^N + A_{N-1} (\ln K)^{N-1} + \dots + A_2 (\ln K)^2 + A_1 \ln K + A_0) \right] \right\} \quad (8)$$

and

$$0.13 < K \leq 64$$

$$\phi_i, \phi_j = 1; 2.2; 5; 10; \dots 5,000; 10,000$$

$$i, j = 1, 2, \dots, 13$$

$$M = 1, 2, \dots, 13$$

$$N = 4-7$$

If $64 < K \leq 300$,

$$\phi_i, \phi_j = 1; 5; 22; 100; 500; 2,210; 10,000$$

$$i, j = 1, 2, \dots, 7$$

$$M = 7$$

where K = inertial parameter value of interest; $0.13 < K \leq 300$.

One advantage of Lagrange's interpolation formula over other interpolative routines is that equidistance values of the independent variable are not necessary to obtain a reliable value of the dependent variable. For ϕ values between 0 to 1, where the potential flow assumption may not be valid, a linear interpolation has been employed.

Comparisons have been made between impaction efficiency values obtained by the interpolative method, and the point-by-point trajectory technique and relative errors are less than 1% when the absolute impaction efficiency is greater than 5%. For impaction efficiencies less than 5%, the largest relative error observed has been within 10% of the point-by-point trajectory calculated efficiency value and is due principally to round-off (four-place accuracy). The trajectory calculations had been terminated at the inertial parameter value of 64. However, the interpolative routine extends this range to K values of 300 where the impaction efficiency curves asymptotically approach the theoretical limiting efficiency of 100% for point-mass particles. Consequently, for all practical purposes, the interpolative routine provides an accurate prediction of the impaction efficiency of spherical particles on cylindrical collectors over an extensive range of inertial parameter values. A complete and detailed description of the digital computer program developed in this study is contained in the appendix.

Experimental verification of the inertial impaction theory has been accomplished over a wide range of parameter values. The theory turns out to be remarkably accurate for the monometric (single-size) particles used in the experimental efforts especially in view of the assumptions that have been made regarding fluid properties and flow conditions.

In practical applications, however, the aerosol that impacts on a collector will seldom consist of particles of uniform size. The size distribution of the aerosol is a function of the methods and techniques used in generation of the particles. A single empirical or theoretical equation does not exist that can universally predict the particle size distribution resulting from the dispersion of liquids by spray nozzles, hot and cold gas atomizers, and explosive disseminators or the dispersion of solids from mechanical dispersers.

A vast literature has been developed by various authors in their attempts to obtain mathematical distribution functions that characterize experimentally generated particle size distributions. Familiar examples include the Nukiyama-Tanasawa equation for drop sizes in sprays generated by air atomization, the Rosin-Rammler equation for pulverized coal, Roller's formula for powder materials, the normal distribution function for symmetrically distributed particles of narrow size range such as plant spores, and the log-normal distribution for a large number of condensation, natural, and mechanically generated aerosols. However, the intent of this study is not to generalize on particle size distributions or delve into their specific merits and methods but rather to examine the necessity of accounting for the particle size distribution when predicting the impaction efficiency of a particular cylindrical collector.

A simple technique used to obtain a size distribution has been to microscopically observe and measure a representative sample of an aerosol population. The number of particles that lie between radius r and $r + dr$ can be found as a function of the radius. The fraction of the total number of particles that lie in an interval is given as $dn = \tilde{n}(r)dr$

where $\int_0^{\infty} \tilde{n}(r)dr = 1$.

The relative frequency distribution curve is found by plotting the resulting data representing dn , and the various distribution functions mentioned above can provide a mathematical expression of the function, $f(r)$.

Distribution functions can be mathematically expressed and used in a number of ways depending on the problem requirements. In some instances, the cumulative fraction of particles having radii greater or less than some radius is convenient. Thus, respectively,

$$F(r) = \int_r^{\infty} f(r)dr \text{ or } F(r) = \int_0^r f(r)dr$$

In addition to the number distribution, the mass distribution function can be determined and is useful in many practical applications. The mass fraction of particles having radii between x and $x + dx$ is written as $df = f(x)dx$ and $\int_0^{\infty} f(x)dx = 1$. The mass distribution function is related to the number distribution function as

$$f(x) = \omega m_r f(r)$$

where

m_r = mass of particle with radius r

ω = proportionality constant

With respect to impaction of particles on collectors, one is usually interested in the mass distribution function because the dose acquired by the collector is dependent on the aerosol mass that is deposited over the sampling period. In order to estimate the mass collected, an average particle size is generally computed and applied to the inertial impaction theory. The objectives of using an average diameter or other measure of central tendency are to provide a single number that will simply describe the behavior of the entire aerosol population and to eliminate an extraordinary number of tedious calculations. The problem is that the inertial parameter value computation makes use of the square of the particle diameter and, further, the impaction curves are a nonlinear function of the inertial parameter. Consequently, an accurate estimation of impaction efficiency or mass deposit can only be expected when a single particle size estimator is used if the particle size distribution is over a very narrow range.

In order to demonstrate the effect that a particle size distribution has on the impaction efficiency, experimental data are required for comparison purposes. Most of the experimental work that has been performed in the past to verify the inertial impaction theory has been conducted with monometric (single-size) aerosols. One notable exception is that of Landahl and Herrmann.¹² Several authors refer to these data but they consider the results to be of limited value due to the use of heterogeneous aerosols, especially at small values of the inertial parameter.

Landahl and Herrmann studied the deposition of aerosols on wires and cylinders with particles generated by an impinger-type atomizer and by a "modified Brink's nozzle." The size distributions were obtained by cascade impactors, and microscopic observations and representative distributions of the clouds produced are illustrated in the following table:

Percent*	Diameter		
	Small particle cloud	Medium particle cloud	Large particle cloud
	μm	μm	μm
5	(0.8)	1.8	5
10	1.0	2.9	8
50	4.0	13	28
90	12	40	58
98	(20)	55	75

*Percent of mass less than stated diameter.

These data are not easily fitted or well represented by the aforementioned distribution functions. However, a general statistical distribution function that has found wide applicability recently is the Weibull distribution function.¹³⁻¹⁵ This distribution function has been successfully used in processes involving limits and maxima/minima problems that include lifetime and failure rate distributions of electrical systems. It has also been used for describing bounded particle size distributions.

The cumulative distribution function of the Weibull distribution has been applied to the Landahl and Herrmann data and has been expressed in the following form:

$$F(x) = 1 - \exp \left[- \left(\frac{x - \gamma}{\eta - \gamma} \right)^\beta \right] \quad (9)$$

where

- $F(x)$ = cumulative mass fraction
- x = particle diameter (μm)
- γ = minimum size; location parameter (μm)
- η = characteristic size; scale parameter (μm)
- β = shape parameter

The trial-and-error method of estimating the Weibull parameters has been described by Nelson¹⁵ and a digital computer program has been developed¹⁶ to estimate the parameters of the distribution function for the

small, medium, and large particle clouds. The parameter approximations obtained by the principle of maximum likelihood method turn out to be as follows:

Parameter	Small cloud	Medium cloud	Large cloud
η	5.3053	17.9678	34.4356
β	0.9532	1.1183	1.7461
γ	0.5919	0.5269	-1.7375

Evaluating the cumulative mass function for the experimental particle diameters to assess the Weibull distribution fit yields the following comparisons:

Experimental F(x)	Small cloud		Medium cloud		Large cloud	
	x	F(x) calculated	x	F(x) calculated	x	F(x) calculated
%	μm	%	μm	%	μm	%
5	0.8	5	1.8	5	5	5
10	1.0	9	2.9	10	8	10
50	4.0	52	13	50	28	51
90	12	90	40	92	58	91
98	20	98	55	97	75	98

As observed, an adequate fit is obtained for all clouds considering the limited available data and the wide size distributions that are involved. It must be emphasized again that the objective is not to find the "correct" distribution function to describe a particular particle size distribution, but rather to approximate the function as simply as possible and to test whether the resultant distribution significantly affects the impaction efficiency predictions.

Given the above distribution functions and approximate values for the Weibull parameters, one can solve equation 9 for the particle size as a function of the cumulative mass fraction, F(x); namely,

$$x = \gamma + (\eta - \gamma) \left[\ln \left(\frac{1}{1 - F(x)} \right) \right]^{1/\beta} \quad (10)$$

Subsequently, by selecting appropriate values for F(x), the average particle size associated with a given particle mass interval can be determined by difference. For example, if 30% of the cloud mass has particle sizes below 7.4 μm and 31% of the cloud mass has particles less than 7.6 μm in diameter, then 1% of the cloud mass is represented by particles with an average diameter of approximately 7.5 μm . The impaction efficiency for each size interval can then be computed and an average efficiency can be obtained for the entire distribution.

A computer program has been written to perform the tedious computations for each 1% mass interval, and the average distribution impaction efficiency is found based on 96% of the cloud mass. In addition, the program provides the impaction efficiency based strictly on the mass median diameter of the cloud. The only supplementary input requirements necessary for use of the distribution function option to the computer program are the Weibull parameters η, β, γ .

The sample distribution functions have been used to compute average impaction efficiencies for comparison with the experimentally obtained efficiencies of Landahl and Herrmann. The results of these computations are included in table 1. The velocity field scaling parameter values for the Landahl and Herrmann tests are very low and theoretically the potential flow assumptions regarding the fluid flow field should not apply. Further, Landahl and Herrmann state that the airflow was turbulent, but the degree of turbulence is not indicated. In addition, the illustrative particle size distributions provided by Landahl and Herrmann do not correspond with their reported efficiency data except for the 13- μ m-MMD case. Nevertheless, examination of table 1 clearly shows that the theoretical impaction efficiencies for the distribution functions more closely predict the observed impaction efficiencies than the mass median diameter computed efficiencies for almost all circumstances. This is especially true for the 13- μ m-MMD case where the assumed particle size distribution apparently matches the experimental mass median diameter and the theoretical efficiencies turn out to be considerably more accurate than the mass median diameter prediction. Note that the small- and large-cloud particle size distributions have mass median diameters that exceed the experimental mass median diameters and, therefore, tend to overestimate the theoretical efficiencies from the distribution function. Thus, to summarize the results, when the particle size distribution is used to compute the average impaction efficiency for the cloud, the prediction corresponds much more closely to the observed efficiency than that of a simple mass median diameter prediction. The predictions are relatively accurate when the particle size distribution is known as evidenced by the 13- μ m-MMD test case.

IV. DISCUSSION.

The important conclusion that can be drawn from the theoretical and experimental data presented in table 1 is that use of the mass median diameter to describe a particle size distribution will seldom result in an accurate prediction of the impaction efficiency for the cloud. In general, at large values of the inertial parameter, K , the mass median diameter overestimates the impaction efficiency of the distribution, whereas, for small values of the parameter where the theoretical efficiency for the mass median diameter is less than 1%, the efficiency can be underestimated by orders of magnitude. These differences are due to the nonlinear character of the inertial impaction theory. However, when the particle size distribution is considered in the predictions, the agreement between theory and experiment is much better.

Calculations were performed using the typical particle size distributions previously given to determine the range of inertial parameter values over which the mass median diameter predictions were within $\pm 10\%$ of the average impaction efficiencies for the distributions. In general, if the mass median diameter yields a K value between 1 and 2, for all ϕ values, the effect of the distribution on efficiency need not be considered. When the inertial parameter value based on the mass median diameter lies outside this range, the average distribution efficiency will differ from the mass median diameter predicted efficiency by more than 10%. To accurately predict the impaction efficiency for heterogeneous aerosols when the K value for the mass median diameter is less than one, the particle size distribution must be taken into account. Unfortunately, data are not available to determine the degree of monodispersity of the distribution that is required in order that the mass median diameter or other average particle diameter will adequately represent the population over the entire inertial impaction region of interest.

Table 1. Experimental and Theoretical Impaction Efficiencies

$\bar{U}$ (cm/sec) D Cylinder diameter cm		0.9 mph = 40.2			3 mph = 134.1			8 mph = 357.6		
		MMD (μm)			MMD (μm)			MMD (μm)		
		Parameter			Parameter			Parameter		
0.008	ϕ	EXP	E (%) ^a	0.022	3.7	13	27	3.7	13	27
	DIST	E (%) ^b	75	0.074	34	89	93	46	87	100
	MMD	E (%) ^c	66 79	81 92	47 51	81 92	94 98	63 74	89 97	97 99
0.025	ϕ	EXP	E (%)	0.069	20	0.232	85	31	0.619	84
	DIST	E (%)	50	69	28	67	87	44	73	93
	MMD	E (%)	49 54	80	18	80	94	46	91	98
0.10	ϕ	EXP	E (%)	0.278	8.4	0.928	54	16	2.47	64
	DIST	E (%)	25	40	10	45	71	21	53	82
	MMD	E (%)	25 15	48	0	48	81	8.3	60 71	91
0.90	ϕ	EXP	E (%)	2.50	0.70	8.35	15	2.1	22.3	28
	DIST	E (%)	4.3	7.6	0.23	11	29	2.0	19 23	47
	MMD	E (%)	2.5 0	0.21	0	0.21	27	0	13	52

^aLandahl and Hermann experimental efficiency.

^bAverage efficiency from typical particle size distributions.

^cEfficiency from mass median diameter of typical distribution, 4, 13, and 28 μm , respectively.

It is also interesting that the predicted efficiencies are close to the experimentally measured efficiencies even though the velocity scaling parameter values are much less than 10 in some cases. In general, the lower ϕ values would lead to reduced impaction efficiencies because the flow field would tend to exhibit viscous flow properties. On the other hand, no account of interception effects has been made for the interpolation routine, and interception could occur since the particle to collector diameter ratios are substantial. The mass median diameter to collector diameter ratio ranges from 4.1×10^{-4} to 3.4×10^{-1} . The effect of interception would be to substantially increase the values of the mass median diameter efficiency. However, with such large diameter ratios, the collection efficiency may not equal the theoretical impaction efficiency due to particle bounce-off and re-entrainment from the collector surface.

The Weibull distribution function is a simple mathematical function that adequately fits the data of Landahl and Herrmann. It may not apply to all particle size distributions of interest but as stated by Professor Weibull, "The only practical way of progressing is to choose a simple function, test it empirically, and stick to it as long as none better has been found."¹³ The graphical technique for estimating the Weibull parameters as presented by Nelson¹⁵ was found to be convenient and simple to use, and best estimates of the three parameter values can be rapidly found by digital computer.¹⁶

The computer program prepared for this study and presented in the appendix enables impaction efficiency predictions to be made over practically the entire region of interest of inertial impaction on cylinders. Four optional computational methods are provided for the user depending on the amount of input information available. Option 1 provides the impaction efficiency of a cylinder and assumes unit density particles and an ambient temperature of 20°C. The only input requirements are the mean windspeed, cylinder diameter, and particle diameter in centimeter-gram-second units. Option 2 makes use of all the variables required to compute the K and ϕ parameters defined by equations 3 and 4, but the program provides the necessary calculations based on these input values. Option 3 assumes that the user has computed the K and ϕ parameter values from equations 3 and 4 and desires only the predicted efficiency. Thus, only the K and ϕ input values are required. Option 4 considers the Weibull distribution function and requires all input data from option 2 except for the particle diameter for which the Weibull parameter estimates of η , β , and γ are substituted. The program computes the average impaction efficiency of the distribution, as well as the efficiency based on the mass median diameter of the distribution. Option 4 has been separated from the main program so that the reader could substitute his own distribution function, if required, with only a few minor program changes. A detailed explanation, sample input cards, test cases with sample outputs, and the complete program are provided in the appendix for the convenience of the reader.

The approximation methods developed in this study to calculate the impaction efficiency of a cylinder for any K and ϕ value have reduced the computational time for the point-by-point trajectory calculations used to develop the inertial impaction theory from 5.6 seconds to 13 milliseconds per data point on a digital computer comparable to a Univac 1108 computer without sacrificing the accuracy of the prediction.

V. CONCLUSIONS.

1. Standard inertial impaction efficiency curves for cylinders developed from point-by-point trajectory calculations have been fitted by unique exponential functions.
2. Lagrange's interpolation formula has been adopted and applied to compute the impaction efficiency of a cylinder for any parameter values of $0.13 < K \leq 300$ and $0 \leq \phi \leq 10.000$.
3. The accuracy of the impaction efficiency computations by use of the digital computer program is within 1% of the point-by-point efficiency predictions.

4. The cumulative distribution function of the Weibull distribution has been incorporated into the digital computer program and has been used to fit the experimental particle size distributions of Landahl and Herrmann.

5. The average impaction efficiency for the particle size distributions and the mass median diameter impaction efficiencies have been compared to the experimental data obtained by Landahl and Herrmann for heterogeneous aerosols.

6. Use of a mass median diameter to characterize a particle size distribution does not accurately predict the experimentally obtained impaction efficiency. For large values of the inertial parameter, the mass median diameter overestimates the efficiency and, at small inertial parameter values, the mass median diameter significantly underestimates the impaction efficiency.

7. Consideration of the particle size distribution in impaction efficiency predictions results in good agreement between theory and experiment.

LITERATURE CITED

1. Stuempfle, A. K. EATR 4705. Impaction Efficiency of Cylindrical Collectors in Laminar and Turbulent Fluid Flow. Part I. Inertial Impaction Theory. March 1973. UNCLASSIFIED Report.
2. Langmuir, I., and Blodgett, K. B. Army Air Forces Air Materiel Command. Technical Report 5418. A Mathematical Investigation of Water Droplet Trajectories. Contract W-33-038-ac-9151. General Electric Company. February 19, 1946. UNCLASSIFIED Report.
3. Fuchs, N. A. The Mechanics of Aerosols. Chapter II. p. 32. Pergamon Press Book. The Macmillan Company, New York, New York. 1964.
4. Schlichting, H. Boundary Layer Theory. McGraw-Hill Book Company, Inc., New York, New York. 1968.
5. Hussein, M. F., and Tabakoff, W. Project Themis Report No. 72-27. Calculation of Particle Trajectories in a Stationary Two-Dimensional Cascade. Department of Aerospace Engineering. University of Cincinnati, Cincinnati, Ohio. June 1972.
6. Brun, R. J., Lewis, W., Perkins, P. J., and Serafini, J. S. Impingement of Cloud Droplets on a Cylinder and Procedure for Measuring Liquid-Water Content and Droplet Sizes in Supercooled Clouds by Rotating Multicylinder Method. National Advisory Committee for Aeronautics Report 1215. 1955.
7. Stuempfle, A. K. EATR 4708. Impaction Efficiency of Cylindrical Collectors in Laminar and Turbulent Fluid Flow. Part II. The Interception Effect. March 1973. UNCLASSIFIED Report.
8. Ranz, W. E., and Wong, J. B. Impaction of Dust and Smoke Particles on Surface and Body Collectors. Ind. Eng. Chem. 44, 1371 (1952).
9. May K. R., and Clifford, R. The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons and Discs. Ann. Occup. Hyg. 10, 83 (1967).
10. Householder, M. K., and Goldschmidt, V. W. The Impaction of Spherical Particles on Cylindrical Collectors. J. Colloid Interface Sci. 31, 464 (1969).
11. Stuempfle, A. K. EATR 4732. Impaction Efficiency of Cylindrical Collectors in Laminar and Turbulent Fluid Flow. Part III. Experimental. March 1973. UNCLASSIFIED Report.
12. Landahl, H. D., and Herrmann, R. G. Sampling of Liquid Aerosols by Wires, Cylinders, and Slides and the Efficiency of Impaction of the Droplets. J. Colloid Sci. 4, 103 (1949).
13. Weibull, W. A Statistical Distribution Function of Wide Applicability. J. Applied Mech. 18 (1), 293 (1951).
14. Plait, A. The Weibull Distribution with Tables. Ind. Quality Control 19, 17 (1962).
15. Nelson, L. S. Weibull Probability Paper. *Ibid.* 23, 452 (1967).
16. Stuempfle, A. K., and Pellegrino, C. R. EC-TM-74007. Weibull Distribution Parameter Estimation by Digital Techniques and Application to Particle Size Distributions. June 1974. UNCLASSIFIED Report.

APPENDIX

DIGITAL COMPUTER PROGRAM FOR INERTIAL IMPACTION EFFICIENCY COMPUTATIONS

I. INTRODUCTION.

The computer program IMPEF and its subroutines LAGRNG, WEIBUL, and POLY have been written for the Edgewood Arsenal Univac 1108, time-sharing, multiprocessor system.

IMPEF has four executable options. Three of these enable the user to input various particle and fluid flow conditions to obtain an inertial impaction efficiency value. The fourth option computes the average impaction efficiency for a particle size distribution generated from the Weibull distribution function and provides the impaction efficiency for the mass median diameter (MMD) of the distribution.

II. MATHEMATICAL BASIS OF PROGRAM IMPEF.

The first step in the development of the approximation methods has been to employ the point-by-point particle trajectory method* to obtain the inertial impaction efficiency curves for 14 selected velocity field scaling parameter values chosen as standards ($\phi = 0; 1; 2.2; 5; 10; 22; 50; 100; 200; 500; 1,000; 2,210; 5,000; 10,000$).

Polynomial equations have been developed that accurately fit the standard ϕ curves. Each curve has been sectioned into four parts representing four intervals of the inertial parameter, K (0.13-0.22; 0.22-0.5; 0.5-1.0; 1.0-64.0). The polynomial coefficients are stored in the subroutine POLY. If the K parameter lies between 0 and 0.13, the impaction efficiency is assumed equal to zero based on results obtained from the point-by-point trajectory model computations.

In order to approximate the impaction efficiency for any nonstandard ϕ value over the range $1 \leq \phi < 10,000$, Lagrange's interpolation formula has been applied after assuming a functional relationship exists among the efficiencies at a given K value. The advantage of Lagrange's interpolation routine is that equidistant values of the independent variable are not necessary to obtain a reliable result. A linear interpolation has been used for those cases where the ϕ value falls between 0 and 1.

Lagrange's routine is utilized with alternating standard ϕ curves (1; 5; 22; 100; 500; 2,210; 10,000) to compute efficiencies for inertial parameter values in the extrapolated range of $64 < K \leq 300$.

The adaptation of Lagrange's interpolation formula used in the LAGRNG subroutine of the program IMPEF is written as:

$$E_{\phi} = E_{\phi_i} \frac{\prod_{j=1, j \neq i}^M (\ln \phi - \ln \phi_j)}{\prod_{j=1, j \neq i}^M (\ln \phi_i - \ln \phi_j)}$$

$i = 1$

*Stuempfle, A. K. EATR 4705. Impaction Efficiency of Cylindrical Collectors in Laminar and Turbulent Fluid Flow. Part I. Inertial Impaction Theory. March 1973. UNCLASSIFIED Report.

where

$$E_{\phi_i} = 1.0 / \{ \exp[\exp(A_N(\ln K)^N + A_{N-1}(\ln K)^{N-1} + \dots + A_2(\ln K)^2 + A_1 \ln K + A_0)] \}$$

and K = inertial parameter value of interest; $0.13 < K \leq 300$.

If $0.13 < K \leq 64$,

$\phi_i, \phi_j = 1; 2.2; 5; 10; 22; 50; 100; 200; 500; 1,000; 2,210; 5,000; 10,000$

$i, j = 1, 2, \dots, 13$

$M = 1, 2, \dots, 13$

$N = 4, 5, 6 \text{ or } 7$

If $64 < K \leq 300$,

$\phi_i, \phi_j = 1; 5; 22; 100; 500; 2,210; 10,000$

$i, j = 1, 2, \dots, 7$

$M = 7$

A_M 's are the coefficients obtained from the fit of the standard ϕ curves and are given in the subroutine POLY.

III. EXPLANATION OF INPUT FOR PROGRAM IMPEF WITH EXAMPLES.

Option One.

Computes the velocity field scaling parameter, ϕ , the inertial parameter, K , and the inertial impaction efficiency assuming an ambient temperature of 20°C and unit density particles. Requires input of particle diameter, cylinder diameter, and free-stream wind velocity.

Format for Input Cards

<u>Card</u>	<u>Column</u>	<u>Format</u>	<u>Symbol</u>	<u>Denotation</u>	<u>Unit</u>
1	1	I1	IOP	Option	
	2-80	79A1	ID	Data identification	
2	1-10	F10.0	U	Free-stream velocity	cm/sec
	11-20	F10.0	D	Collector diameter	cm
	21-30	F10.0	PDM	Particle diameter	microns

Sample Input

[illegible]

Sample Output

TEST CASE FOR OPTION ONE
 PARTICLE DENSITY = 1.0000+00 GM/CC FLUID DENSITY = 1.2047-03 GM/CC
 FLUID VISCOSITY = 1.8100-04 POISE COLLECTOR DIAMETER = 1.4000 CM
 FREE-STREAM VELOCITY = 424.650 CM/SEC
 PARTICLE DIAMETER = 55.000 MICRONS
 VELOCITY FIELD SCALING PARAMETER, PHI = 42.9023
 INERTIAL PARAMETER, K = 5.6326
 INERTIAL IMPACTION EFFICIENCY = .7353164

Option Two.

Computes the velocity field scaling parameter, ϕ , the inertial parameter, K , and the inertial impaction efficiency for the applicable input conditions. Requires input of particle diameter and density, collector diameter, fluid density and viscosity, and free-stream wind velocity at the applicable temperature.

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Format for Input Cards

<u>Card</u>	<u>Column</u>	<u>Format</u>	<u>Sy.nbol</u>	<u>Denotation</u>	<u>Unit</u>
1	1	11	IOP	Option	
	2-80	79A1	ID	Data identification	
2	1-10	E10.0	RHO	Particle density	gm/cc
	11-20	E10.0	RHOA	Fluid density	gm/cc
	21-30	E10.0	RMU	Fluid viscosity	poise
3	1-10	F10.0	U	Free-stream velocity	cm/sec
	11-20	F10.0	D	Collector diameter	cm
	21-30	F10.0	PDM	Particle diameter	microns

Sample Input

[illegible]

Sample Output

```

TEST CASE FOR OPTION TWO
PARTICLE DENSITY = 1.0430+00 GM/CC      FLUID DENSITY = 1.2047-03 GM/CC
FLUID VISCOSITY = 1.8100-04 POISE      COLLECTOR DIAMETER = 1.2000 CM
FREE-STREAM VELOCITY = 312.500 CM/SEC
PARTICLE DIAMETER = 75.000 MICRONS
VELOCITY FIELD SCALING PARAMETER, PHI = 25.9459
INERTIAL PARAMETER, K = 9.3793
INERTIAL IMPACTION EFFICIENCY = .8221419

```

Option Three.

Computes the inertial impaction efficiency for a given set of K and ϕ input parameter values.

Format for Input Cards

<u>Card</u>	<u>Column</u>	<u>Format</u>	<u>Symbol</u>	<u>Denotation</u>
1	1	I1	IOP	Option
	2-80	79A1	ID	Data identification
2	1-10	F10.0	PHI	Velocity scaling parameter
	11-20	F10.0	RK	Inertial parameter

Sample Input

[illegible]

Sample Output

```
TEST CASE FOR OPTION 3
VELOCITY FIELD SCALING PARAMETER, PHI =      8.4367
INERTIAL PARAMETER, K = 23.9025
INERTIAL IMPACTION EFFICIENCY = .9223695
POTENTIAL FLUID FLOW MAY NOT APPLY
```

Computes a particle size distribution generated from the Weibull distribution function, the average inertial impaction efficiency for the distribution, and the efficiency for the mass median diameter of the distribution. Requires the Weibull parameter values of the distribution, particle density, collector diameter, fluid density and viscosity, and free-stream wind velocity.

<u>Card</u>	<u>Column</u>	<u>Format</u>	<u>Symbol</u>	<u>Denotation</u>	<u>Unit</u>
1	1 2-80	I1 79A1	IOP ID	Option Data identification	
2	1-10 11-20 21-30	E10.0 E10.0 E10.0	RHO RHOA RMU	Particle density Fluid density Fluid viscosity	gm/cc gm/cc poise
3	1-10 11-20	F10.0 F10.0	U D	Free-stream velocity Collector diameter	cm/sec cm
4	1-10 11-20 21-30	F10.0 F10.0 F10.0	ETA BETA GAMMA	Weibull scale parameter Weibull shape parameter Weibull location parameter	microns microns

[illegible]

TEST CASE FOR OPTION FOUR

PARTICLE DENSITY = 1.0430+00 GM/CC FLUID DENSITY = 1.2047-03 GM/CC
 FLUID VISCOSITY = 1.8100-04 POISE COLLECTOR DIAMETER = .9000 CM
 FREE-STREAM VELOCITY = 357.600 CM/SEC
 VELOCITY FIELD SCALING PARAMETER, PHI = 22.2678
 WEIBULL PARAMETERS: SCALE = 34.4356 SHAPE = 1.7461 LOCATION = -1.7375
 AVERAGE INERTIAL IMPACTION EFFICIENCY = .4666792

CUMULATIVE PER CENT MASS	MAXIMUM PART DIAM (MICRONS)	INTERVAL AVERAGE (MICRONS)	INERTIAL PARAMETER	INERTIAL IMPACTION EFFICIENCY
2	2.134			
		2.647	.0178	.0000000
3	3.160			
		3.607	.0331	.0000000
4	4.055			
		4.459	.0506	.0000000
5	4.864			
		5.238	.0698	.0000000
6	5.612			
		5.964	.0905	.0000000
7	6.315			
		6.648	.1124	.0000000
8	6.982			
		7.300	.1356	.0000111
9	7.619			
		7.925	.1598	.0015139
10	8.232			
		8.528	.1850	.0071181
11	8.824			
		9.112	.2112	.0161853
12	9.399			
		9.679	.2383	.0288266
13	9.959			
		10.232	.2664	.0429852
14	10.506			
		10.773	.2953	.0584635
15	11.041			
		11.303	.3250	.0748713
16	11.565			
		11.823	.3556	.0916102
17	12.081			
		12.335	.3871	.1084189
18	12.589			
		12.840	.4194	.1253332
19	13.090			
		13.337	.4525	.1422780
20	13.585			
		13.829	.4865	.1585318
21	14.073			
		14.315	.5213	.1749852
22	14.557			
		14.797	.5570	.1913652
23	15.037			
		15.274	.5935	.2068813

CUMULATIVE PER CENT MASS	MAXIMUM PART DIAM (MICRONS)	INTERVAL AVERAGE (MICRONS)	INERTIAL PARAMETER	INERTIAL IMPACTION EFFICIENCY
24	15.512			
		15.748	.6303	.2219787
25	15.984			
		16.219	.6592	.2369364
26	16.453			
		16.686	.7053	.2518721
27	16.919			
		17.151	.7484	.2665775
28	17.383			
		17.614	.7893	.2809087
29	17.845			
		18.076	.8312	.2948875
30	18.306			
		18.535	.8747	.3091317
31	18.765			
		18.994	.9178	.3237512
32	19.223			
		19.452	.9628	.3370823
33	19.681			
		19.909	1.0084	.3495515
34	20.138			
		20.366	1.0552	.3591455
35	20.594			
		20.823	1.1037	.3703211
36	21.051			
		21.280	1.1527	.3823278
37	21.506			
		21.737	1.2020	.3932511
38	21.960			
		22.195	1.2532	.4052273
39	22.424			
		22.654	1.3055	.4163736
40	22.884			
		23.114	1.3592	.4271942
41	23.345			
		23.576	1.4147	.4377713
42	23.807			
		24.039	1.4701	.4481161
43	24.271			
		24.504	1.5275	.4582405
44	24.737			
		24.971	1.5867	.4681546
45	25.205			
		25.447	1.6465	.4779582
46	25.675			
		25.912	1.7061	.4873904
47	26.148			
		26.387	1.7713	.4967296
48	26.625			
		26.864	1.8367	.5059345
49	27.104			
		27.345	1.9023	.5149924



CUMULATIVE PER CENT MASS	MAXIMUM PART DIAM (MICRONS)	INTERVAL AVERAGE (MICRONS)	INERTIAL PARAMETER	INERTIAL IMPACTION EFFICIENCY
50	27.587		1.9361	.5193225 MMD
		27.830	1.9703	.5237306
51	28.073			
		28.318	2.0401	.5324161
52	28.564			
		28.811	2.1117	.5403554
53	29.058			
		29.308	2.1852	.5493548
54	29.558			
		29.810	2.2607	.5576204
55	30.062			
		30.317	2.3382	.5657579
56	30.572			
		30.829	2.4179	.5737727
57	31.087			
		31.347	2.4998	.5816702
58	31.608			
		31.871	2.5842	.5894555
59	32.135			
		32.402	2.6709	.5971336
60	32.669			
		32.940	2.7603	.6047093
61	33.210			
		33.485	2.8524	.6121873
62	33.759			
		34.038	2.9474	.6195723
63	34.316			
		34.599	3.0454	.6268686
64	34.882			
		35.170	3.1467	.6340808
65	35.457			
		35.749	3.2513	.6412132
66	36.042			
		36.339	3.3595	.6482703
67	36.637			
		36.940	3.4715	.6552563
68	37.243			
		37.553	3.5876	.6621757
69	37.862			
		38.177	3.7079	.6690328
70	38.493			
		38.815	3.8329	.6758322
71	39.138			
		39.468	3.9628	.6825782
72	39.798			
		40.135	4.0980	.6892757
73	40.473			
		40.819	4.2389	.6959295
74	41.166			
		41.521	4.3859	.7025444
75	41.877			
		42.242	4.5395	.7091258

CUMULATIVE PER CENT MASS	MAXIMUM PART DIAM (MICRONS)	INTERVAL AVERAGE (MICRONS)	INERTIAL PARAMETER	INERTIAL IMPACTION EFFICIENCY
76	42.608	42.984	4.7007	.7156791
77	43.360	43.748	4.8521	.7222182
78	44.136	44.537	5.0462	.7287754
79	44.938	45.353	5.2329	.7352315
80	45.769	46.199	5.4238	.7417357
81	46.630	47.078	5.6320	.7482463
82	47.525	47.992	5.8595	.7547723
83	48.459	48.948	6.0951	.7613240
84	49.430	49.948	6.3465	.7679128
85	50.460	51.000	6.6165	.7745772
86	51.539	52.113	6.9087	.7812577
87	52.660	53.286	7.2235	.7880478
88	53.833	54.541	7.5577	.7949450
89	55.189	55.886	7.9457	.8019760
90	56.584	57.341	8.3845	.8091771
91	58.038	58.927	8.8303	.8165211
92	59.757	60.677	9.3864	.8242775
93	61.598	62.637	9.9511	.8323191
94	63.675	64.873	10.7565	.8408314
95	66.071	67.435	11.6893	.8500710
96	68.919	70.594	12.7140	.8601790
97	72.469	74.863	14.2399	.8718560
98	77.268			

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ABRPT PRINTS

CLAUDE PELLEGRINO IMPEF

1	C	MAIN PROGRAM IMPEF	IMPEF001
2		DIMENSION PD(98),APD(97),RKS(97),E(97),ID(79)	IMPEF002
3		IPRT=0	IMPEF003
4	1	READ (5,34)END=29) IOP,ID	IMPEF004
5		IF (IOP.LT.1.OR.IOP.GT.4) GO TO 26	IMPEF005
6		GO TO (2,4,5,11), IOP	IMPEF006
7	2	READ (5,35) U,D,PDM	IMPEF007
8		RHC=1.0	IMPEF008
9		RHOA=1.2747E-3	IMPEF009
10		RMU=1.81E-4	IMPEF010
11	3	RK=(PDM-PDM*1.3E-8)/((RHO*U)/(9.0*RMU*D))	IMPEF011
12		PHI=(9.0*RHOA-RHOA*U*D)/(RMU*RHO)	IMPEF012
13		GO TO 6	IMPEF013
14	4	READ (5,36) RHO,RHOA,RMU,U,D,PDM	IMPEF014
15		GO TO 3	IMPEF015
16	5	READ (5,38) PHI,RK	IMPEF016
17	6	IF (IPRT) 7,7,6	IMPEF017
18	7	WRITE (6,32) ID	IMPEF018
19		GO TO 9	IMPEF019
20	8	WRITE (6,33) ID	IMPEF020
21	9	IF (IOP.EQ.3) GO TO 10	IMPEF021
22		WRITE (6,41) RHC,RHOA,RMU,D,J	IMPEF022
23		WRITE (6,42) PDM	IMPEF023
24	10	IF (RK.GT.0.13.AND.RK.LE.300.) GO TO 12	IMPEF024
25		IF (RK.LE.0.03.OR.RK.GT.300.) GO TO 27	IMPEF025
26		EFF=0.0	IMPEF026
27		GO TO 22	IMPEF027
28	11	READ (5,37) RHO,RHOA,RMU,U,D	IMPEF028
29		PHI=(9.0*RHOA-RHOA*U*D)/(RMU*RHO)	IMPEF029
30	12	IF (PHI.LT.0.002.PHI.GT.10000.0) GO TO 28	IMPEF030
31		IF (PHI.LE.1.0) GO TO 13	IMPEF031
32		CALL NUMRTR (PHI)	IMPEF032
33	13	IF (IOP.NE.4) GO TO 21	IMPEF033
34		WRITE (6,32) ID	IMPEF034
35		WRITE (6,41) RHO,RHOA,RMU,D,J	IMPEF035
36		WRITE (6,43) PHI	IMPEF036
37		CHLD=((RHO*U)/(9.0*RMU*D))*1.0E-8	IMPEF037
38		CALL WEIBUL (CHLD,RKMMU,PD,APD,RKS)	IMPEF038
39		SUME=0.0	IMPEF039
40		DO 16 I=2,97	IMPEF040
41		IF (RKS(I).LE.0.13) GO TO 14	IMPEF041
42		CALL LAGPAG (PHI,RKS(I),E(I))	IMPEF042
43		GO TO 15	IMPEF043
44	14	E(I)=0.0	IMPEF044
45	15	SUME=SUME+E(I)	IMPEF045
46	16	CONTINUE	IMPEF046
47		AVGE=SUME/96.	IMPEF047
48		WRITE (6,44) AVGE	IMPEF048
49		WRITE (6,31)	IMPEF049
50		WRITE (6,45)	IMPEF050
51		LINES=12	IMPEF051
52		DO 20 I=2,97	IMPEF052
53		LINES=LINES+2	IMPEF053
54		IF (I.EQ.50) GO TO 17	IMPEF054
55		WRITE (6,46) I,PD(I),APD(I),RKS(I),E(I)	IMPEF055
56		IF (LINES.LT.55) GO TO 20	IMPEF056

57		LINES=4	IMPEF07
58		WRITE (6,30)	IMPEF08
59		WRITE (6,45)	IMPEF09
60		GO TO 20	IMPEF10
61	17	IF (RKMMO.LE.0.13) GO TO 19	IMPEF11
62		CALL LAGRNG (PHI,RKMMO,EFF)	IMPEF12
63	18	WRITE (6,47) I.PD(I),RKMMO,EFF,APD(I),RKS(I),F(I)	IMPEF13
64		GO TO 20	IMPEF14
65	19	EFF=0.0	IMPEF15
66		GO TO 18	IMPEF16
67	20	CONTINUE	IMPEF17
68		I=98	IMPEF18
69		WRITE (6,46) I.PD(I)	IMPEF19
70		IPRT=-1	IMPEF20
71		GO TO 23	IMPEF21
72	21	CALL LAGRNG (PHI,RK,EFF)	IMPEF22
73	22	WRITE (6,39) PHI,RK,EFF	IMPEF23
74		IPRT=1	IMPEF24
75	23	IF (PHI-10.) 24,25,25	IMPEF25
76	24	WRITE (6,40)	IMPEF26
77	25	WRITE (6,31)	IMPEF27
78		GO TO 1	IMPEF28
79	26	WRITE (6,48) IOP	IMPEF29
80		GO TO 29	IMPEF30
81	27	WRITE (6,49) RK	IMPEF31
82		GO TO 29	IMPEF32
83	28	WRITE (6,50) PHI	IMPEF33
84	29	CALL EXIT	IMPEF34
85	30	FORMAT (1H1)	IMPEF35
86	31	FORMAT (/)	IMPEF36
87	32	FORMAT (1H1,79A1)	IMPEF37
88	33	FORMAT (1H ,79A1)	IMPEF38
89	34	FORMAT (11,79A1)	IMPEF39
90	35	FORMAT (3F10.0)	IMPEF40
91	36	FORMAT (3E10.0/3F10.0)	IMPEF41
92	37	FORMAT (3F10.0/2F10.0)	IMPEF42
93	38	FORMAT (2F10.0)	IMPEF43
94	39	FORMAT (40H VELOCITY FIELD SCALING PARAMETER, PHI =.F11.4/24H INF	IMPEF44
95		ITIAL PARAMETER, K =.F9.4/32H INERTIAL IMPACTION EFFICIENCY =.F9.7)	IMPEF45
96	40	FORMAT (35H POTENTIAL FLUID FLOW MAY NOT APPLY)	IMPEF46
97	41	FORMAT (19H PARTICLE DENSITY =.1PE10.4,6H GM/CC,4X,15HFLUID DENSITY	IMPEF47
98		1Y =.1PE10.4,6H GM/CC/18H FLUID VISCOSITY =.1PE10.4,6H POISL,4X,	IMPEF48
99		220HCOLLECTOR DIAMETER =.0PF7.4,3H CM/23H FREE STREAM VELOCITY =,	IMPEF49
100		30PF9.3,7H CM/SEC)	IMPEF50
101	42	FORMAT (20H PARTICLE DIAMETER =.F8.3,8H MICRONS)	IMPEF51
102	43	FORMAT (40H VELOCITY FIELD SCALING PARAMETER, PHI =.F11.4)	IMPEF52
103	44	FORMAT (40H AVERAGE INERTIAL IMPACTION EFFICIENCY =.F9.7)	IMPEF53
104	45	FORMAT (3X,10HCUMULATIVE,6X,7HMAXIMUM,6X,8HINTERVAL,17X,	IMPEF54
105		18HINERTIAL/4X,6HPER CENT,6X,9HPART DIAM,5X,7HAVEPAGE,4X,	IMPEF55
106		28HINERTIAL,6X,9HIMPATION/6X,4HMASS,8X,9H(MICRONS),4X,9H(MICRONS),	IMPEF56
107		33X,9HPARAMETER,4X,10HEFFICIENCY)	IMPEF57
108	46	FORMAT (6X,13,5X,F8.3/31X,F8.3,3X,F9.4,5X,F9.7)	IMPEF58
109	47	FORMAT (6X,13,9X,F8.3,16X,F9.4,5X,F9.7,4H MMD/31X,F8.3,3X,F9.4,5X,	IMPEF59
110		1F9.7)	IMPEF60
111	48	FORMAT (17H OPTION,12,17H IS NOT AVAILABLE)	IMPEF61
112	49	FORMAT (24H INERTIAL PARAMETER, K =.E14.9,13H OUT OF RANGE)	IMPEF62
113	50	FORMAT (40H VELOCITY FIELD SCALING PARAMETER, PHI =.F14.9,13H OUT	IMPEF63
114		1OF RANGE)	IMPEF64
115		END	IMPEF65

LAUDE*PELLEGRINO*WEIBUL

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1      SUBROUTINE WEIBUL (CHLD,RKMND,PD,APD,RKS)
2      DIMENSION PD(98),APD(97),RKS(97)
3      READ (5,2) ETA,BETA,GAMMA
4      WRITE (6,3) ETA,BETA,GAMMA
5      POWER=1.0/BETA
6      DIFF=ETA-GAMMA
7      DO 1 INC=2,98
8      PD(INC)=GAMMA+(DIFF*(ALOG(1.0/(1.0-(FLOAT(INC)/100.))))**POWER))
9      IF (INC.EQ.2) GO TO 1
10     I=INC-1
11     APD(I)=(PD(INC)+PD(I))/2.
12     RKS(I)=APD(I)*APD(I)*CHLD
13     1 CONTINUE
14     RKMND=PD(50)*PD(50)*CHLD
15     RETURN
16     2 FORMAT (3F10.0)
17     3 FORMAT (28H WEIBULL PARAMETERS: SCALE =,F10.4,9H SHAPE =,F7.4,
18     112H LOCATION =,F9.4)
19     END

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WEIBUL71
 WEIBUL72
 WEIBUL73
 WEIBUL74
 WEIBUL75
 WEIBUL76
 WEIBUL77
 WEIBUL78
 WEIBUL79
 WEIBUL10
 WEIBUL11
 WEIBUL12
 WEIBUL13
 WEIBUL14
 WEIBUL15
 WEIBUL16
 WEIBUL17
 WEIBUL18
 WEIBUL19

CLAUDE PELLEGRINO LAGRNG

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1      SUBROUTINE LAGRNG (PHI,RK,EFF)
2      DIMENSION EN(13),ED(13),DIF(13),X(13),ELD(7),ELN(7),DIFL(7),Y(2)
3      LRNT(3)
4      DATA X/D.0.,.788457356,1.60943791,2.30258510,3.09174245,3.91202371,LAGRNG04
5      14.60517019,5.29831737,6.21460807,6.90775526,7.70074779,8.51719320,LAGRNG05
6      29.21034038/ED/22357020.1,-1812698.47,269447.688,-88311.7591,
7      341628.3997,-22779.8643,18228.2921,-24986.1752,45785.7457,-
8      489020.3004,330206.731,-1864839.07,17170287.1/ELD/10098.2753,-
9      51523.10928,610.97745,-379.26176,640.540964,-1501.68156,8921.7671/,LAGRNG09
10     6RNT/D.22,0.5,1.0/
11     KIN=1
12     1 IF (RK.LT.RNT(KIN)) GO TO 2
13     KIN=KIN+1
14     IF (KIN-3) 1,1,2
15     2 RKLX=ALOG(RK)
16     IF (PHI.LE.1.0) GO TO 5
17     EFF=0.0
18     INC=1
19     IF (RK.GT.64.0) INC=2
20     DO 4 N=2,14,INC
21     CALL POLY (N,KIN,RKLX,E)
22     IF (INC.EQ.2) GO TO 3
23     EFF=EFF+EN(N-1)/ED(N-1)*E
24     GO TO 4
25     3 I=N/2
26     EFF=EFF+ELN(I)/ELD(I)*E
27     4 CONTINUE
28     RETURN
29     5 DO 6 N=1,2
30     CALL POLY (N,KIN,RKLX,E)
31     Y(N)=E
32     6 CONTINUE
33     EFF=Y(1)*(1.-PHI)+Y(2)*PHI
34     RETURN
35     ENTRY NUMRTR(PHI)
36     PHIL=ALOG(PHI)
37     DO 7 I=1,13
38     DIF(I)=(PHIL-X(I))
39     IF (I.GT.7) GO TO 7
40     DIFL(I)=(PHIL-X(2*I-1))
41     7 CONTINUE
42     DO 9 I=1,13
43     ENUM=1.0
44     ELNUM=1.0
45     DO 8 J=1,13
46     IF (I.EQ.J) GO TO 8
47     ENUM=DIF(J)*ENUM
48     IF (I.GT.7.OR.J.GT.7) GO TO 8
49     ELNUM=DIFL(J)*ELNUM
50     8 CONTINUE
51     EN(I)=ENUM
52     IF (I.GT.7) GO TO 9
53     ELN(I)=ELNUM
54     9 CONTINUE
55     RETURN
56     END

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LAUDE • PELLEGRINO • POLY

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1 SUBROUTINE POLY (N,KIN,X,E) POLY0001
2 DIMENSION NCOF(56),P(14,4,8) POLY0002
3 DATA NCOF/6,7,7,8,6,6,6,7,6,7,7,7,6,7,7,8,6,6,7,7,6,7,7,7,6,6,7,7, POLY0003
4 16,6,6,8,6,7,7,8,6,6,6,7,7,8,7,6,6,7,7,8,6,7,7,8,5,8,7,8/ POLY0004
5 C PHI = 0 POLY0005
6 DATA (P(1,1,I),I=1,6)/-12.200402,-35.459569,-297.18542,-462.32274, POLY0006
7 1-360.06598,-111.55255/(P(1,2,J),J=1,7)/62.348775,355.99417, POLY0007
8 21030.9451,1408.1269,1064.5792,421.75102,68.7841330/(P(1,3,K),K=1, POLY0008
9 371/-62.940926,-120.18487,-85.164326,-27.596719,-3.9510734,- POLY0009
10 4.97751282,-3.9181877E-2/(P(1,4,L),L=1,81)/-1.0536954E-5,1.9332078E- POLY0010
11 54,-1.6152915E-3,8.3885181E-3,-2.2809549E-2,4.0923174E-3,- POLY0011
12 6.79783478,-3.9181353E-2/ POLY0012
13 C PHI = 1 POLY0013
14 DATA (P(2,1,I),I=1,6)/4.9845675,52.832639,217.59407,403.96104, POLY0014
15 1376.12181,137.7212/(P(2,2,J),J=1,6)/-3.6211216E-2,-1.7775906,- POLY0015
16 2.54651109,-.75115414,-1.2866331,-.13762106/(P(2,3,K),K=1,6)/- POLY0016
17 31.7649616,-.28038164E-1,-1.4690678,-.22811208,-.77448736,- POLY0017
18 41.119515E-2/(P(2,4,L),L=1,7)/9.3879216E-5,-1.4051483E-3, POLY0018
19 59.6292892E-3,-2.9244455E-2,1.8173188E-2,-.78756638,-1.1119545E-2/ POLY0019
20 C PHI = 2.2 POLY0020
21 DATA (P(3,1,I),I=1,6)/-26.205198,-212.34232,-688.74366,-1116.7436, POLY0021
22 1-935.75446,-293.15808/(P(3,2,J),J=1,7)/-2.9697585,-19.546255,- POLY0022
23 252.775889,-74.952536,-59.950642,-25.135597,-4.1293537/(P(3,3,K),K= POLY0023
24 31,71/1.6140825,1.0850372,-.96742653,-.93007128,-.15264606,- POLY0024
25 4.76202787,2.4042651E-4/(P(3,4,L),L=1,7)/2.0318435E-5,-5.9133702E- POLY0025
26 54,5.5930552E-3,-2.1070663E-2,1.2375939E-2,-.77654255,2.4063257E-4/ POLY0026
27 C PHI = 5 POLY0027
28 DATA (P(4,1,I),I=1,6)/-26.212424,-214.28974,-701.61274,-1148.343,- POLY0028
29 1941.31809,-307.88626/(P(4,2,J),J=1,7)/.45517389,2.6995224, POLY0029
30 26.5915579,8.3665223,5.9148874,1.4364731,.3573586/(P(4,3,K),K=1,7)/ POLY0030
31 3-5.8102354,-14.826274,-13.629123,-5.4803251,-.8580772,-.78031089, POLY0031
32 41.7312087E-2/(P(4,4,L),L=1,81)/-3.6119607E-5,6.3913339E-4,- POLY0032
33 54.7997086E-3,2.0067387E-2,-4.7588177E-2,3.7991413E-2,-.77708922, POLY0033
34 6.01731202/ POLY0034
35 C PHI = 10 POLY0035
36 DATA (P(5,1,I),I=1,6)/-50.664987,-423.64833,-1415.6474,-2361.2307, POLY0036
37 1-1965.8164,-652.49849/(P(5,2,J),J=1,6)/-.062968392,-.19555374,- POLY0037
38 2.24037953,.011244131,-.60911288,.097500309/(P(5,3,K),K=1,7)/ POLY0038
39 31.4597121E-2,9.49348899E-2,.28102331,.3238649,.20596467,- POLY0039
40 4.76590523,3.7057228E-2/(P(5,4,L),L=1,7)/9.6683056E-5,-1.6339242E- POLY0040
41 53,1.1191886E-2,-3.5935414E-2,3.336479E-2,-.7862475,3.7357191E-2/ POLY0041
42 C PHI = 22 POLY0042
43 DATA (P(6,1,I),I=1,6)/-76.950465,-651.69666,-2206.645,-3732.3263,- POLY0043
44 13153.5891,-1063.8574/(P(6,2,J),J=1,7)/5.7644622,37.522245, POLY0044
45 2100.76219,142.69011,112.43495,45.959403,8.0517842/(P(6,3,K),K=1,7) POLY0045
46 3/-4.7767558,-12.444464,-11.500556,-4.5950604,-.68987081,- POLY0046
47 4.74831659,6.6480331E-2/(P(6,4,L),L=1,7)/1.7177586E-4,-2.6882966E- POLY0047
48 53,1.6780465E-2,-4.9847116E-2,4.9792698E-2,-.75707841,6.648065E-2/ POLY0048
49 C PHI = 50 POLY0049
50 DATA (P(7,1,I),I=1,6)/-59.938282,-501.29199,-1675.1358,-2793.8696, POLY0050
51 1-2325.6901,-771.90225/(P(7,2,J),J=1,6)/-1.40153928,-1.7185120,- POLY0051
52 22.6991333,-1.6266652,-.89185129,-.21709087/(P(7,3,K),K=1,7)/ POLY0052
53 35.7990554E-2,.31663007,.67074199,.61650862,.30036899,-.66225648, POLY0053
54 4.10659907/(P(7,4,L),L=1,7)/1.853713E-4,-2.7976853E-3,1.7395729E-2, POLY0054
55 5-5.069296E-2,5.2031505E-2,-.73985798,.10659903/ POLY0055
56 C PHI = 100 POLY0056

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57 DATA (P(8.1.I),I=1.6)/-17.064731,-135.07757,-427.92071,-677.22163,POLYD057
58 1-535.96207,-168.81351/(P(8.2.J),J=1.6)/-34226461.24416096,POLYD058
59 26.3623809,7.9466487,4.0134799,1.223011/(P(8.3.K),K=1.6)/-POLYD059
60 36.3096724,-9.4214242,-4.5663823,-.73041192,-.71550948,.14857452/POLYD060
61 4(P(8.4.L),L=1.8)/9.0060305E-5,-1.2733944E-3,6.5331656E-3,-POLYD061
62 51.2515114E-2,-3.0812454E-3,1.7035729E-2,-.71366247,.14657444/POLYD062
63 C PHI = 200 POLYD063
64 DATA (P(9.1.I),I=1.6)/-42.396161,-355.31647,-1192.8833,-2003.9678,POLYD064
65 1-1684.9216,-566.20499/(P(9.2.J),J=1.7)/1.0660894,8.7591944,POLYD065
66 228.501044,47.240843,42.393325,18.867897,3.8321726/(P(9.3.K),K=1.7),POLYD066
67 3/-39.460761,-83.456781,-60.748291,-20.641773,-2.9597241,-POLYD067
68 4.80941524,.19835457/(P(9.4.L),L=1.8)/-3.4881657E-4,5.4965192E-3,-POLYD068
69 53.465441E-2,-.11210716,-.19695587,.16083493,-.7357441,.19605452/POLYD069
70 C PHI = 500 POLYD070
71 DATA (P(10.1.I),I=1.6)/-12.020613,-92.568931,-284.75887,-POLYD071
72 1436.40904,-333.62156,-107.80133/(P(10.2.J),J=1.6)/-1.4257360,-POLYD072
73 28.0514717,-18.340894,-19.614001,-11.357255,-1.9831740/(P(10.3.K),POLYD073
74 3K=1.6)/4.2113941,7.1224666,4.1790245,1.0121884,-.58806253,POLYD074
75 4.27458546/(P(10.4.L),L=1.7)/1.9737683E-4,-2.726578E-3,1.4653205E-POLYD075
76 52,-3.7207501E-2,2.6369855E-2,-.66753359,.27450544/POLYD076
77 C PHI = 1000 POLYD077
78 DATA (P(11.1.I),I=1.5)/14.829388,97.320297,240.33938,263.37799,POLYD078
79 1109.15044/(P(11.2.J),J=1.8)/17.029397,137.42034,477.41882,POLYD079
80 2895.10322,987.87372,653.645,236.55692,36.739044/(P(11.3.K),K=1.7)/POLYD080
81 347.983167,101.37274,80.5671,29.548404,4.8616024,-.38993037,POLYD081
82 4.34078307/(P(11.4.L),L=1.8)/-5.0706425E-5,4.594885E-4,-1.3181914E-POLYD082
83 53.1.7151807E-3,-2.9558258E-3,-1.233578E-2,-.63346749,.340783/POLYD083
84 C PHI = 2210 POLYD084
85 DATA (P(12.1.I),I=1.6)/-63.364116,-536.67989,-1818.2790,-POLYD085
86 13078.5398,-2604.6811,-879.71803/(P(12.2.J),J=1.7)/6.4439511,POLYD086
87 241.998908,112.46264,156.04802,122.85226,49.373179,8.7539736/(P(12.3.K),POLYD087
88 33,K=1.7)/-36.484327,-77.532174,-62.802408,-24.102723,-POLYD088
89 44.3251476,-.9208608,.427816/(P(12.4.L),L=1.8)/-3.7367973E-6,POLYD089
90 53.6233045E-5,-2.3078772E-4,2.1297687E-3,-1.0367251E-2,2.6019194E-POLYD090
91 63,-.62493408,.42781593/POLYD091
92 C PHI = 5000 POLYD092
93 DATA (P(13.1.I),I=1.6)/-103.53582,-883.60206,-3015.1879,-POLYD093
94 15139.6048,-4376.3562,-1487.8046/(P(13.2.J),J=1.7)/4.6788015,POLYD094
95 231.950727,89.903464,133.11754,109.29784,46.482057,6.8405497/(P(13.3.K),POLYD095
96 33,K=1.7)/34.132168,69.52454,53.281663,19.749472,3.2204642,-POLYD096
97 4.38616475,.53065892/(P(13.4.L),L=1.8)/-4.4636683E-5,7.1149327E-4,-POLYD097
98 54.7031388E-3,1.7822142E-2,-4.2369884E-2,4.4434352E-2,-.63295244,POLYD098
99 6.53065886/POLYD099
100 C PHI = 10000 POLYD100
101 DATA (P(14.1.I),I=1.5)/10.993253,71.125908,173.31109,187.3633,POLYD101
102 177.147214/(P(14.2.J),J=1.8)/10.660898,84.798844,286.49179,POLYD102
103 2532.49198,587.36483,384.06109,137.03167,21.438196/(P(14.3.K),K=1,POLYD103
104 371/-16.237284,-32.2699,-24.002293,-8.3489724,-1.3820594,-POLYD104
105 4.69722816,.61335532/(P(14.4.L),L=1.8)/-1.0477396E-4,1.6059967E-3,-POLYD105
106 59.7271265E-3,3.050984E-2,-5.4851738E-2,4.4704111E-2,-.60594781,POLYD106
107 6.61335528/POLYD107
108 NS=4*(N-1)+KIN POLYD108
109 M=NCOF(NS) POLYD109
110 RLLRE=P(N,KIN,1) POLYD110
111 DO 1 I=2,M POLYD111
112 RLLRE=RLLRE*X+P(N,KIN,I) POLYD112
113 1 CONTINUE POLYD113

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114 E=1./(EXP(EXP(ALLRE)))
115 RETURN
116 END

POLYD114
POLYD115
POLYD116

BACKPT PRINTS