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EATR 4732

IMPACTION EFFICIENCY OF CYLINDRICAL COLLECTORS IN LAMINAR AND TURBULENT FLUID FLOW

PART III. EXPERIMENTAL

by

Arthur K. Stuempfle

Chemical Laboratory

March 1973

DEPARTMENT OF THE ARMY
Headquarters, Edgewood Arsenal
Aberdeen Proving Ground, Maryland 21010

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Physical Research Division
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Task 1W062116A08402

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FOREWORD

The work described in this report was authorized under Task 1W062116A08402, Chemical Test and Assessment Technology. This work was started in May 1971 and completed in June 1972. The experimental data are recorded in notebooks TSD 8156, 8452, and 8589.

Acknowledgment

The author wishes to acknowledge the technical advice of Bernard V. Gerber, the technical assistance of Wilbur E. Geho and the statistical analysis of data performed by PVT Claude Pellegrino and Thomas Himmelheber.

DIGEST

The collection efficiencies of paper-coated glass cylinders at low values of the particle inertial parameter relevant to chemical operations were determined in a wind tunnel under laminar and controlled turbulent flow conditions. Impaction efficiencies computed by the inertial impaction theory for inertial parameters approaching the theoretical cutoff value accurately predict the collection efficiency of cylinders under laminar flow conditions and levels of turbulence less than 7.4%. Manyfold increases in the collection efficiency of cylinders at low inertial parameter values were observed as a function of relative turbulence intensity and Eulerian longitudinal macroscale of the turbulent flow field. The collection efficiency data for cylinders can be properly ordered by the Taylor parameter. The leeward deposition efficiency was substantial and exceeded the windward collection efficiency for most flow circumstances.

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IMPACTION EFFICIENCY OF CYLINDRICAL COLLECTORS IN LAMINAR AND TURBULENT FLUID FLOW

PART III. EXPERIMENTAL

I. INTRODUCTION.

Intermediate size aerosols (10 to 100 μm in diameter) are deposited on collectors of interest in chemical operations principally by the inertial impaction mechanism. The theory of the inertial impaction of point-mass particles[1] and of finite-sized particles[2] on cylindrical collectors in a potential flow field have been previously presented in detail. However, the theory has been developed for laminar flow conditions, whereas in any normal operational circumstance the airflow will generally be turbulent in nature. A man target under field conditions will often be located behind trees, bushes and vehicles which produce a mechanically generated turbulent flow field. It has been postulated* that airflow turbulence can significantly increase the deposition of aerosols on man-size targets and that inertial theory predictions can greatly underestimate the collection efficiency of cylinders in the turbulent flow field. The experiments conducted in this study of aerosol deposition on cylinders under controlled turbulent and laminar flow conditions strongly support the hypothesis.

II. BACKGROUND.

The principal scaling parameters used in developing the inertial impaction theory have been defined as follows:[1,2]

$$K = \frac{\rho d_p^2 \bar{U}}{18 \mu R} = \text{inertial parameter} \quad (1)$$

$$\phi = \frac{9 \rho_a (Re_c)}{\rho} = \frac{18 \rho_a^2 \bar{U} R}{\mu \rho} = \text{velocity field parameter} \quad (2)$$

where

Re_c = Reynolds number of collector

ρ = particle density

ρ_a = air density

μ = air viscosity

d_p = particle diameter

$\bar{U}$ = mean windspeed

R = radius of cylindrical collector

[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] 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.

* Bernard Gerber. Private communication. Chemical Laboratory, Edgewood Arsenal. 1965.

The equations of motion for particles undergoing transport around a cylinder placed in a flow field described by potential theory are numerically integrated by digital computer techniques and particle trajectories are obtained as a function of the scaling parameters. The impaction efficiency of the cylinder can be defined as the ratio of the number of particles that impinge on the windward side of the cylinder to the number contained in the volume swept out by the cylinder.

The inertial impaction theory consists of a family of curves of expected impaction efficiencies corresponding to particular K and ϕ parameter values.

The theory for impaction of point-mass particles on cylinders is summarized in figure 1 and the theory for impaction of finite size particles on cylinders is summarized in figure 2. The theory has been well documented and experimentally verified under laminar flow conditions for large inertial parameter values and small ϕ parameter values.[3,4,5] However, little experimental data has been presented when the impacting particles exhibit K parameter values approaching the theoretical cutoff value ($K_c = 0.125$) and practically no data are available for inertial impaction of particles under turbulent flow conditions.

Particles possessing inertial parameter values less than K_c are theoretically precluded from impinging on the collector by inertial mechanisms. However, measurable collection efficiencies for cylinders have been observed for these circumstances and have been reported by Asset, Kimball, and Hoff.[6] Additional experiments conducted by these investigators when $K << 0.125$ under low levels of longitudinal turbulence (<5%) suggested that turbulence did not significantly change the collection efficiency. Levesque[7] conducted impaction efficiency experiments under higher turbulence level conditions ($\approx$10%) with particles exhibiting large inertial parameter values ($K > 2$) and concluded that the effects of turbulence were insignificant. On the other hand, Kimball[8] examined the collection efficiency of cylinders in medium levels of turbulence (9%-28%) with small particles having K values less than 0.125 and observed significant increases in efficiency with increasing longitudinal turbulence levels. Results of impaction efficiency experiments conducted under turbulent flow conditions for particles possessing inertial parameter values relevant to chemical operations have been reported by Torgeson,[9] and substantial increases in efficiency were noted. Turbulence has been shown to be a significant factor that can increase the collection efficiency of man-sized targets for conditions normally encountered in chemical operations, but the reported effects require clarification and quantification of the mechanisms involved.

[3] Ranz, W. E., and Wong, J. B. Impaction of Dust and Smoke Particles on Surface and Body Collectors. Ind. Eng. Chem. 44, 1371 (1952).

[4] May, K. R., and Clifford, R. The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons and Discs. Ann. Occup. Hyg. 10, 83 (1967).

[5] Householder, M. K., and Goldschmidt, V. W. The Impaction of Spherical Particles on Cylindrical Collectors. J. Colloid Interface Sci. 31, 464 (1969).

[6] Asset, G., Kimball, D., and Hoff, M. EATR 4225. Small-Particle Collection Efficiency of Vertical Cylinders in Flows of Low-Intensity Turbulence. January 1969. UNCLASSIFIED Report.

[7] Levesque, R. J. Suffield Technical Paper 131. Defence Research Board, Canada. An Experimental Verification of the Theory of Particle Collection on Vertical Cylinders. September 1958. UNCLASSIFIED Report.

[8] Kimball, D. V. EATR 4624. Small-Particle Collection Efficiency of Vertical Cylinders in Flows of Medium-Intensity Turbulence. March 1972. UNCLASSIFIED Report.

[9] Torgeson, W. L. Applied Science Division, Litton Systems, Inc. Summary Report Phase II. Contract DA-18-035-AMC-340(A). Investigation of Impaction Mechanisms of Particles on Collectors in Turbulent Flow (U). August 1967. CONFIDENTIAL Report.

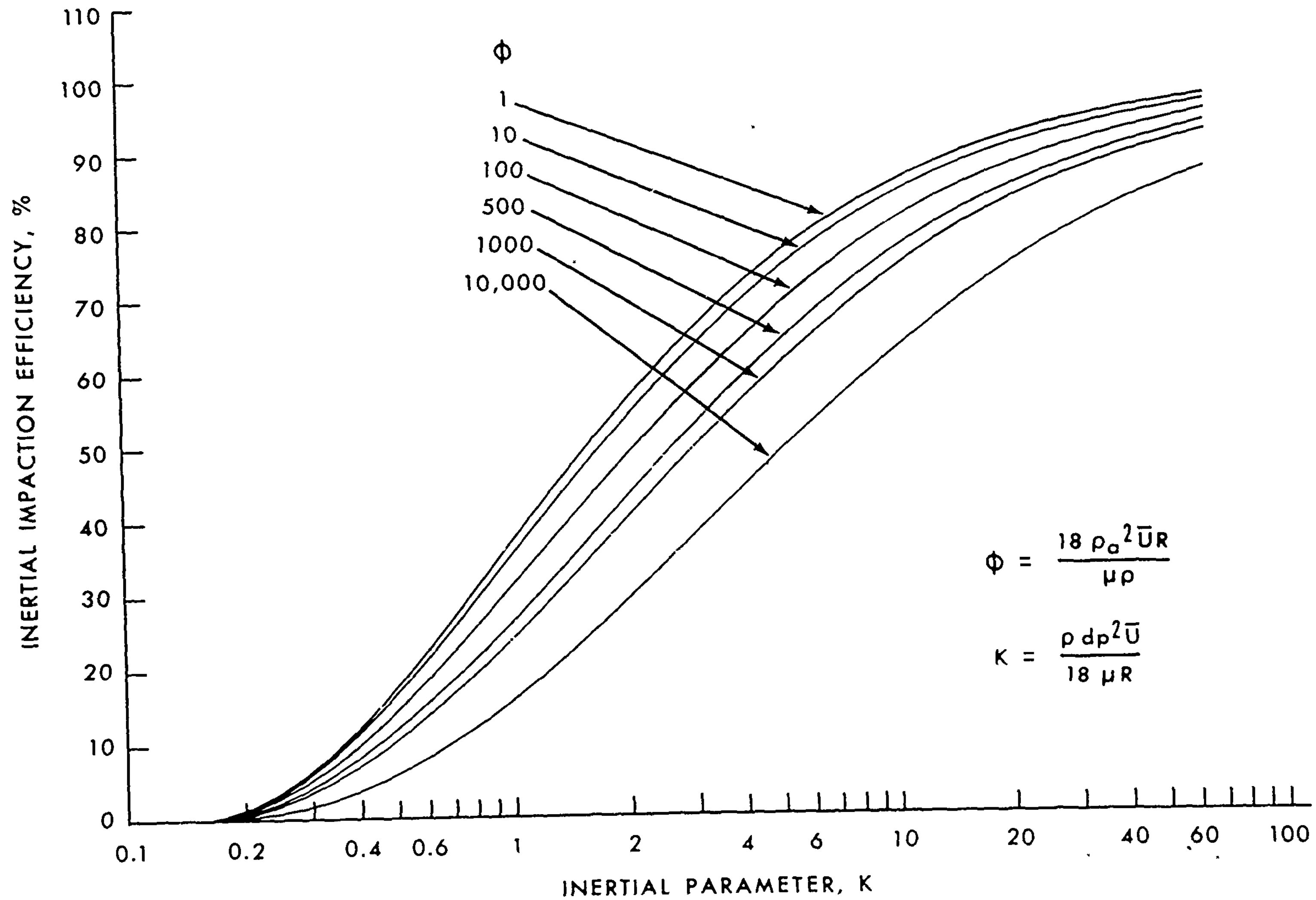

Figure 1. Inertial Impaction Theory

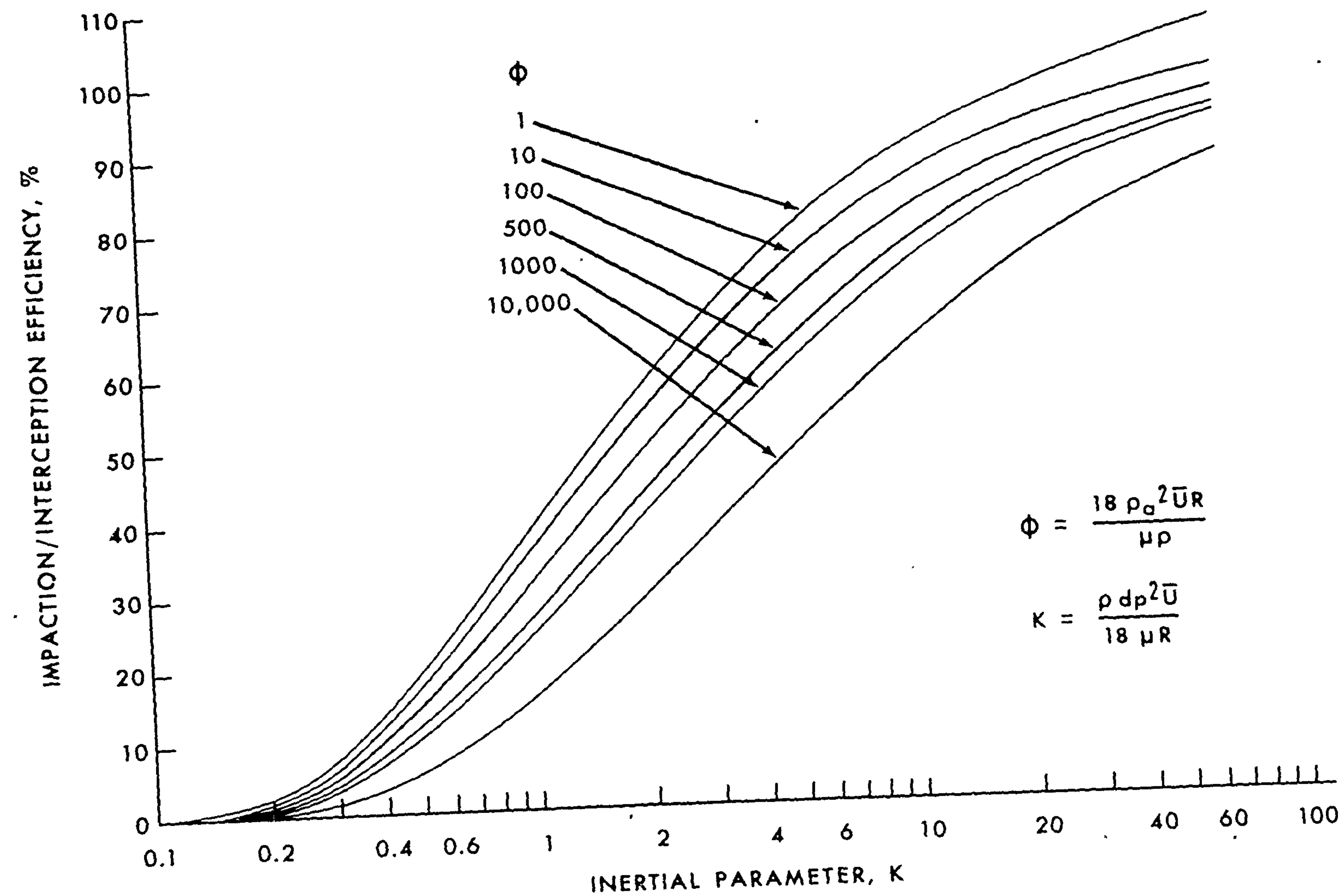

Figure 2. Inertial Impaction Theory with Interception Effects

The studies of turbulence and turbulent flow processes are novel areas that have gained considerable attention recently. The development of new techniques and instruments for measuring turbulence has contributed to an increased understanding of this complex phenomenon. However, the problems of turbulent flow are far from being solved In this study of particle impaction under turbulent flow, only the basic elements of turbulence theory are used in order to gain an insight to the effects of turbulence and to assess the potential influence of turbulence in chemical operations.

Hinze[10] has defined turbulence in the following manner, "Turbulent fluid motion is an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned." Turbulence has frequently been pictured as consisting of swirling eddies on top of larger eddies; that is, regions of seemingly periodic motions superimposed on larger regions of seemingly periodic motions, etc. These eddies can be quantitatively characterized by measuring various time or space averages for certain variables of the turbulent motion.

In this report, an Eulerian description of the flow field is used; i.e., the time-varying properties of the fluid flow are assigned to points in space having fixed reference coordinates. Consider the instantaneous velocity in the longitudinal direction of flow to be composed of an average velocity component on which an instantaneous fluctuation from the average is super-imposed

$$U = \overline{U} + u' \qquad (3)$$

where, by definition, the time average of u' is zero, $\overline{u}' = 0$. The temporal mean value of the velocity at a point in a flow field is theoretically defined as

$$\overline{U} = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} U dt$$

For practical circumstances, the time average must be obtained for some definite time interval In general, the selected interval must be less than the period of any slow fluctuation of the flow that is not considered to be part of the process under study and, at the same time, the interval must be much greater than any fluctuation considered to be part of the process. In this study, the mean flow has been considered to be independent of the origin of t such that $\overline{U}$ can be redefined as

$$\overline{U} = \frac{1}{T} \int_{0}^{T} U(t+\tau) d\tau \qquad (4)$$

[10] Hinze, J. O. Turbulence. Chapter 1. McGraw-Hill Book Company, Inc., New York, New York. 1959.

The violence of the turbulence fluctuations is measured as the root-mean-square (RMS) value of the velocity fluctuations which is defined as turbulence intensity

$$U_{RMS} = \sqrt{\overline{(u')^2}} \tag{5}$$

In many applications, one is interested in the violence of the fluctuations relative to the mean motion, and numerous expressions are found to denote this ratio. Relative intensity, level of turbulence, turbulence level, and degree of turbulence are all defined as

$$\frac{\sqrt{\overline{(u')^2}}}{\overline{U}} \tag{6}$$

However, measurement of turbulence intensity or relative intensity is not sufficient information with which to characterize a turbulent flow field, for the simple reason that the same RMS of the fluctuating components can arise from considerably different variations of U. Additional statistically distinct characteristics are needed.

A number of simplifying assumptions must generally be applied to a complex subject such as turbulent motion in order to develop a practical approach to the problem. In theoretical studies, one is concerned largely with homogeneous, isotropic, and stationary turbulence (HIST).[11] Homogeneous turbulence suggests that the velocity fluctuations are random and that average turbulent characteristics are independent of position in the flow field, i.e., invariant with respect to axis translation. If the velocity fluctuations are invariant with respect to axis rotation and reflection, then the flow field is isotropic, that is, independent of direction. Isotropic turbulence implies homogeneous turbulence but, in some cases, such as the decay of the turbulence developed behind a properly designed grid, the turbulence is approximately isotropic at a point yet the flow field is not homogeneous with distance from the grid. Stationary implies that a steady state exists at every point in the flow field and that the time-averaged turbulent quantities at a point do not change with time.

Taylor[12] has suggested that a statistical correlation could be used to quantitatively describe the fluctuating velocity terms in turbulence. Regardless of how one defines the diameter of an eddy, he pointed out that a high degree of correlation should exist between the velocities at two points in space if the distance between the points is small compared with eddy diameter. Conversely, if the distance between the points is much greater than the eddy diameter, then little correlation should be expected. Instead of two space measurements, suppose that the velocity is measured at a single point in space as a function of time and that the signal is compared with an

[11] Brodkey, R S The Phenomena of Fluid Motions. Chapter 14. Addison-Wesley Publishing Company, Reading, Massachusetts. 1967.

[12] Taylor, G. I. Statistical Theory of Turbulence. Proc. Roy. Soc. A151, 421 (1935).

idential signal that has been delayed by a time interval τ. A high degree of correlation should exist when τ is small; and, for large values of τ, the correlation would be expected to approach zero. When it is assumed for approximation purposes that the velocity fluctuations are small compared with the constant mean velocity in a homogeneous field, Taylor[13] hypothesized that the changes in u′ with time at a fixed point are caused by movement of a "frozen" turbulent flow field passing the fixed point. Consequently, a space correlation can be approximated by an equivalent time correlation, assuming the relationship $x = \overline{U}_X t$ is valid. The autocorrelation for the point measurement then defines an Eulerian time correlation function in the longitudinal direction as

$$R(\tau) = \frac{\overline{u'(t)u'(t+\tau)}}{\overline{(u')^2}} \tag{7}$$

where the bar refers to temporal averages.

The Eulerian correlation function is a widely used statistical characteristic of random functions of time and is useful in HIST measurements as an indication of the "scale" of turbulence. For the purposes of this report, the Eulerian integral time scale can be obtained which is related to an Eulerian space integral scale by Taylor's hypothesis. The resulting Eulerian macroscale of turbulence in the longitudinal direction is defined as

$$L_X = \overline{U}\int_0^\infty R(\tau)d\tau = \overline{U}\int_0^\infty \frac{\overline{u'(t)u'(t+\tau)}}{\overline{(u')^2}}\, d\tau \tag{8}$$

As a simplified physical interpretation of this turbulence characteristic, one associates the Eulerian macroscale with a measure of the average size of the large eddies or the "energy-containing" eddies in the longitudinal direction of the turbulent flow field. Quantitatively, the autocorrelation function and the one dimensional energy spectrum can be shown to be Fourier cosine transforms. Thus, if the turbulence consists of only large eddies, the integral time scale will be large and this would show up in the energy frequency spectrum which would exist primarly in the low frequency region. However, if the autocorrelation curve rapidly decreases to zero, i.e., τ is small, then the energy spectrum would reveal high values in the high frequency region.

A second scale characteristic of turbulence results from consideration of the shape of the autocorrelation function curve. The macroscale was concerned with the large-size eddies in the system and was obtained from the autocorrelation function through an integration process. Qualitatively, one assumes that these large eddies are unstable and transfer energy in some unspecified manner to smaller eddies which, in turn, give rise to still smaller eddies, etc. Eventually, some point in eddy size is reached where viscous forces become important and the energy of these small eddies is dissipated into heat. A measure of the average size of the smallest

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[13] Taylor, G. I. The Spectrum of Turbulence. Proc. Roy. Soc. A164, 476 (1938).

eddies in the turbulent field that are dissipated by viscosity effects is the Eulerian microscale. Several procedures are available for determining the microscale of isotropic turbulence in the longitudinal direction, λ_X. One method employs the fitting of a parabola to the radius of curvature of the autocorrelation function for times (distances) approaching zero. A second method involves the use of physically measured quantities and for isotropic turbulence yields the following expression for the Eulerian microscale

$$\lambda_X = \frac{\bar{U} \sqrt{\overline{(u')^2}}}{\sqrt{\overline{(\delta u'/\delta t)^2}}} \qquad (9)$$

Routine and conventional instrumentation, methodologies, and techniques have been used to measure and compute the turbulence intensities and macroscales and microscales of turbulence presented in section III B, below.

The experimental efforts reported herein have a twofold objective; namely, (1) to demonstrate that the inertial impaction theories extended in references 1 and 2 to include small inertial parameter values are valid for inertial impaction under laminar flow conditions and (2) to ascertain the effects of longitudinally measured turbulence level and Eulerian macroscales and Eulerian microscales of turbulence on the impaction of liquid droplets on cylinders placed in the controlled turbulent flow field.

III. EXPERIMENTATION.

A. Aerodynamic Equipment.

A low-speed, open-circuit wind tunnel of the draw-through type has been used for the experimental study of particle impaction. Figure 3 is a picture of the modified wind tunnel as used in this study and figure 4 is a general schematic of the tunnel prior to modification. The wind tunnel, which is constructed of fiber glass, has a test section that is 24 inches wide by 30 inches high by 72 inches long. The windspeed range is 8.8 to 33 ft/sec with a nominal free-stream turbulence level of approximately 0.3%. The region of uniform intensity is at least 10 inches wide by 10 inches high throughout the test section of the tunnel. Details of the modifications, velocity, and turbulence intensity profiles and characteristics of the facility have been previously published.[14]

B. Turbulence Generation.

Turbulence of a controlled nature is generated by monoplane and biplane grids of varying dowel and mesh size inserted at the entrance to the test section of the tunnel. The longitudinal turbulence levels, Eulerian macroscales, and Eulerian microscales of the grid generated turbulent flow fields are functions of downstream distance from the grids.

[14] Cooper, W. A. EATR 4636. Modifications and Characterization of a Low Speed Open-Circuit Wind Tunnel. April 1972. UNCLASSIFIED Report.

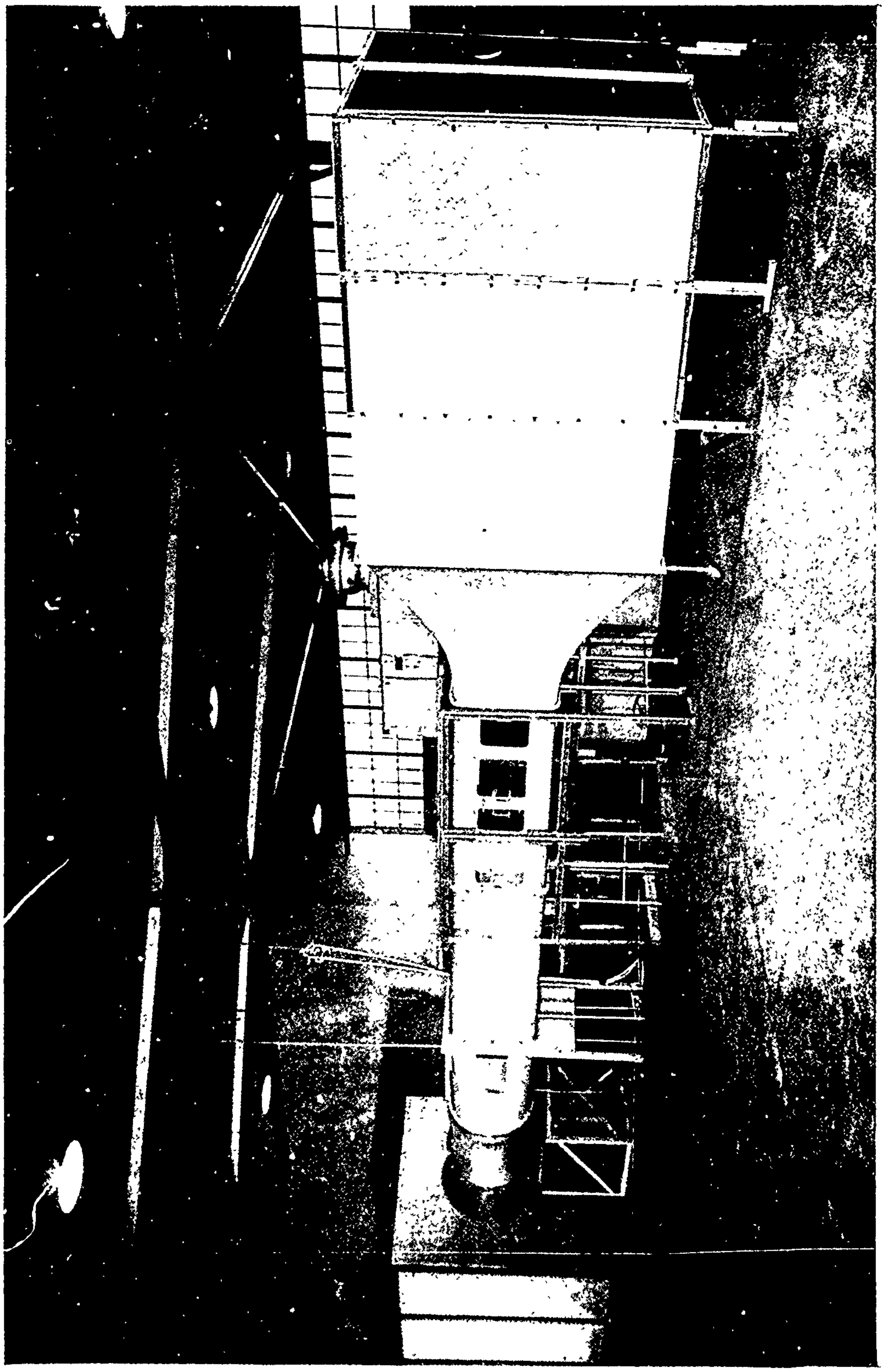

Figure 3. Modified Aerosol Wind Tunnel

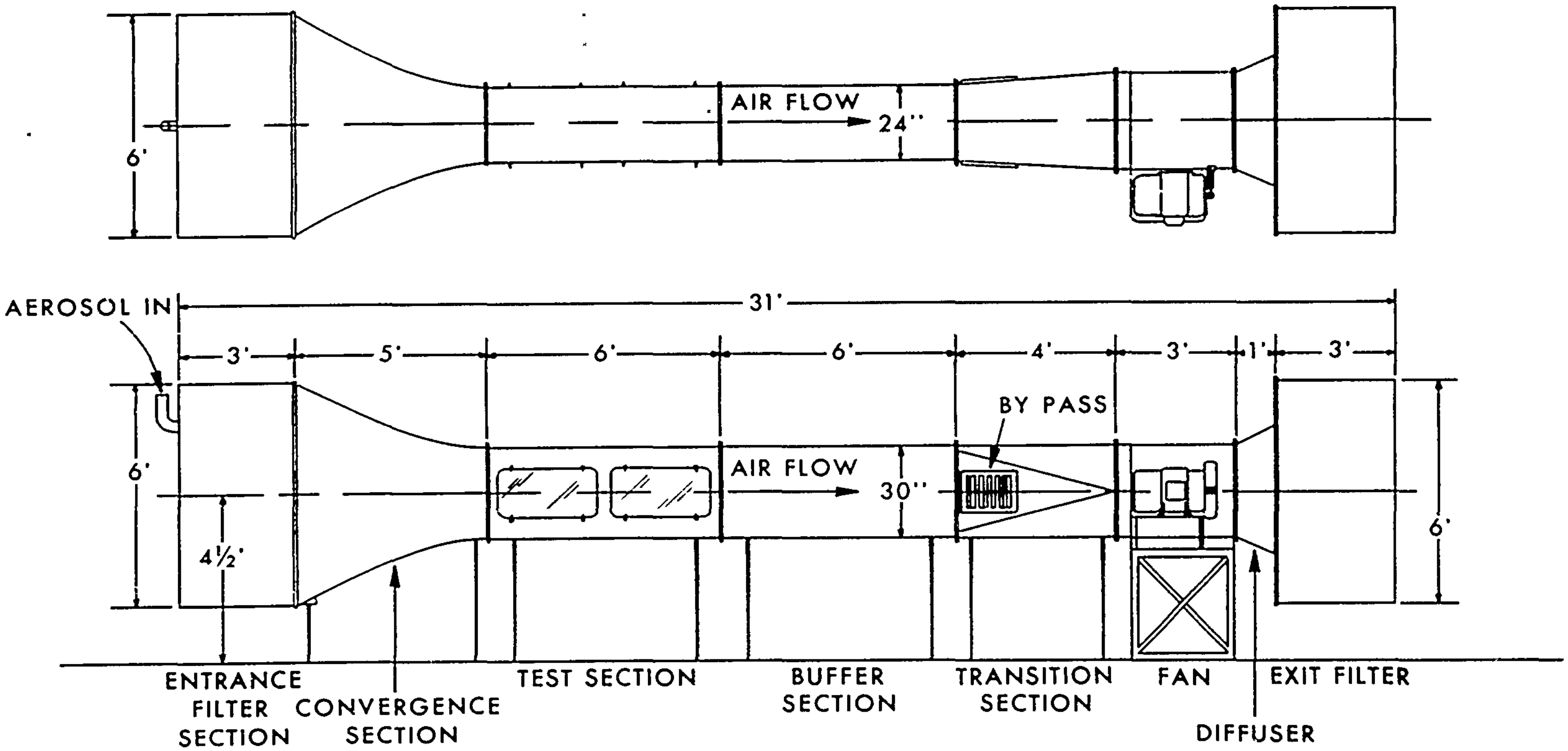

Figure 4. Schematic of Original Aerosol Wind Tunnel

Grids have been used frequently in the past to generate a turbulent flow field because the resultant flow characteristics can be easily related to the physical properties of the grid. Further, the grid-produced turbulence in the planes parallel to the grid is essentially homogeneous when the distance-to-mesh ratio (X/M) exceeds about 10 or 15.[10]

Four grids have been designed and fabricated and three grids were used for this study. Pertinent characteristics are listed in table I.

Table I. Grid Characteristics

Parameter \ Case	Grid A	Grid B	Grid C	Grid D
Type	Monoplane	Monoplane	Biplane	Monoplane
Rod cross section	Circular	Circular	Circular	Square
Mesh, M (in.)	3	1.375	0.625	4
Rod width, b (in.)	1	0.375	0.125	1
M/b	3	3.67	5.00	4
Solidity, S	0.55	0.47	0.36	0.19

Where solidity is the ratio of closed area to total area, $S = \frac{b}{M}(2 - \frac{b}{M})$. Measurement of the downstream characteristics of the grid-generated turbulent flow field has been accomplished by use of a Thermo-Systems Model 1050 constant-temperature anemometer, Model 1052 linearizer and Model 1057 signal conditioner.* The standard deviation of the longitudinal velocity has been measured by a TSI Model 1060 True RMS voltmeter.* The hot-wire probes were conventional single-wire variety having a tungsten wire sensing element of 0.00015-inch diameter and 0.050-inch length. Autocorrelation functions were obtained by use of a Princeton Applied Research (PAR) Model 101 signal correlator with PAR Model 102 Fourier analyzer.** Experimental data acquired in an extensive series of measurements have been used to characterize the turbulent flow fields generated by the grids.† The essential results of the characterization are summarized in figures 5 through 7 for a mean windspeed of 20 ft/sec. Figure 5 shows the longitudinal turbulence intensity as a function of the downstream distance for the various grids. Figure 6 provides the estimated macroscale increase with downstream distance and figure 7 represents the corresponding increase in microscale with downstream distance for the four grids under study. These data have been used in constructing the experimental design discussed in section III E, below.

C. Aerosol Generation.

The effects of turbulence characteristics on inertial impaction were observed for fixed cylinder size, mean transport speed, and particle size so that constant values of the K and ϕ

*Thermo-Systems, Inc., Saint Paul, Minnesota.

**Princeton Applied Research Corporation, Princeton, New Jersey.

†Cooper, W. A. Unpublished laboratory data recorded in notebooks TSD 8014, 8488, 8565. Test and Evaluation Division, Edgewood Arsenal. 1963, 1970, 1971, respectively.

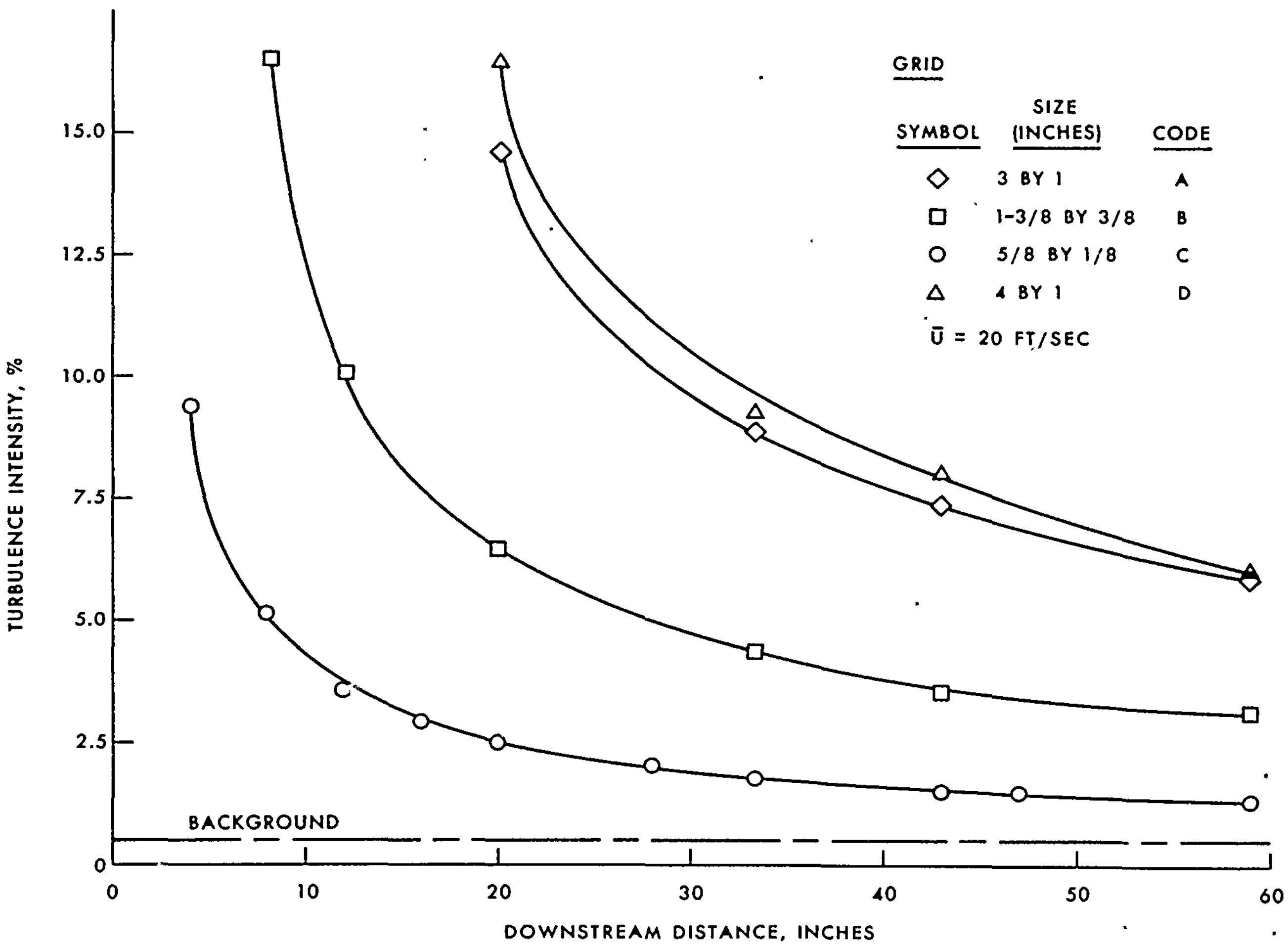

Figure 5. Grid-Induced Longitudinal Turbulence Intensity

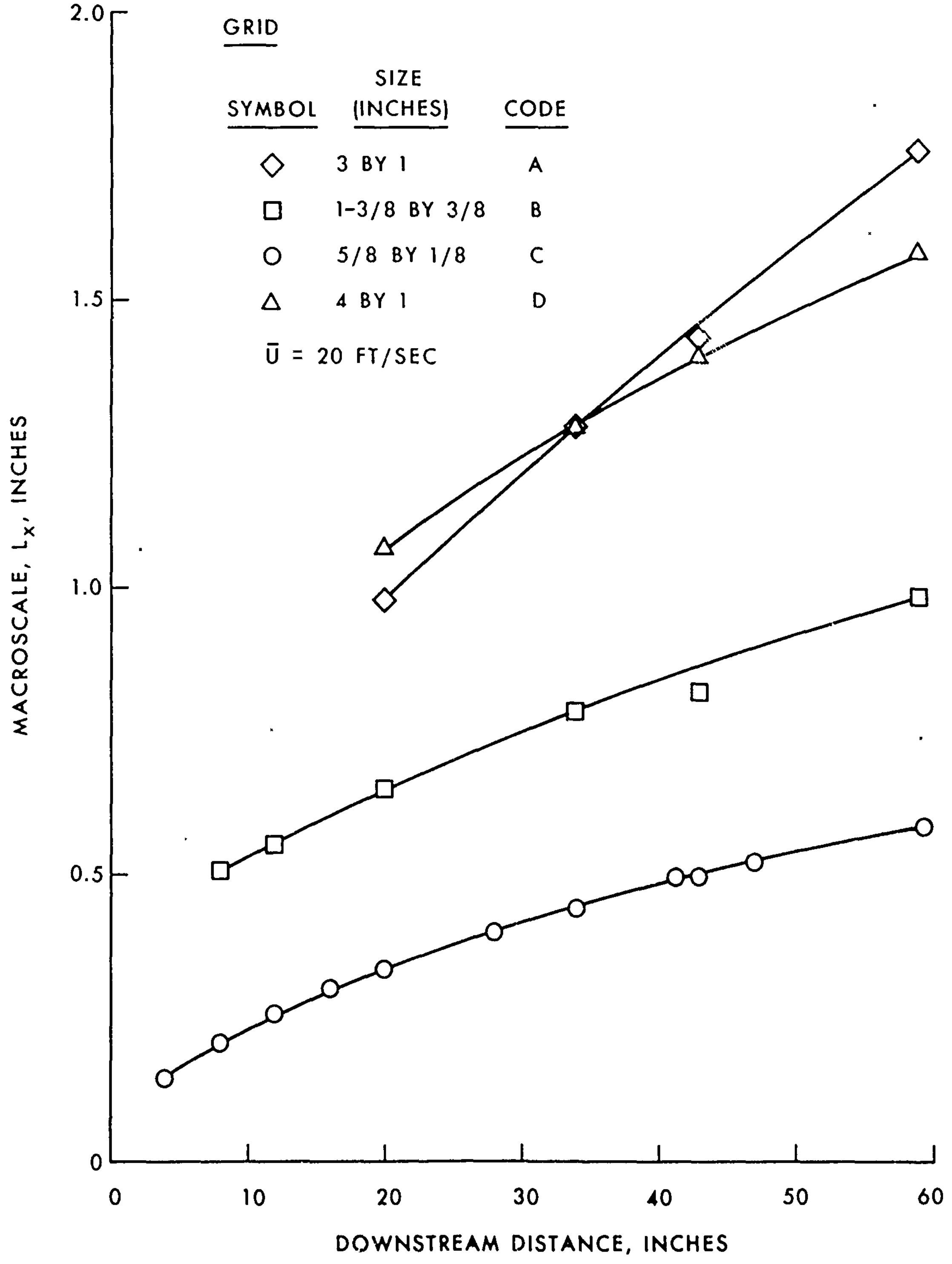

Figure 6. Grid-Induced Eulerian Macroscale

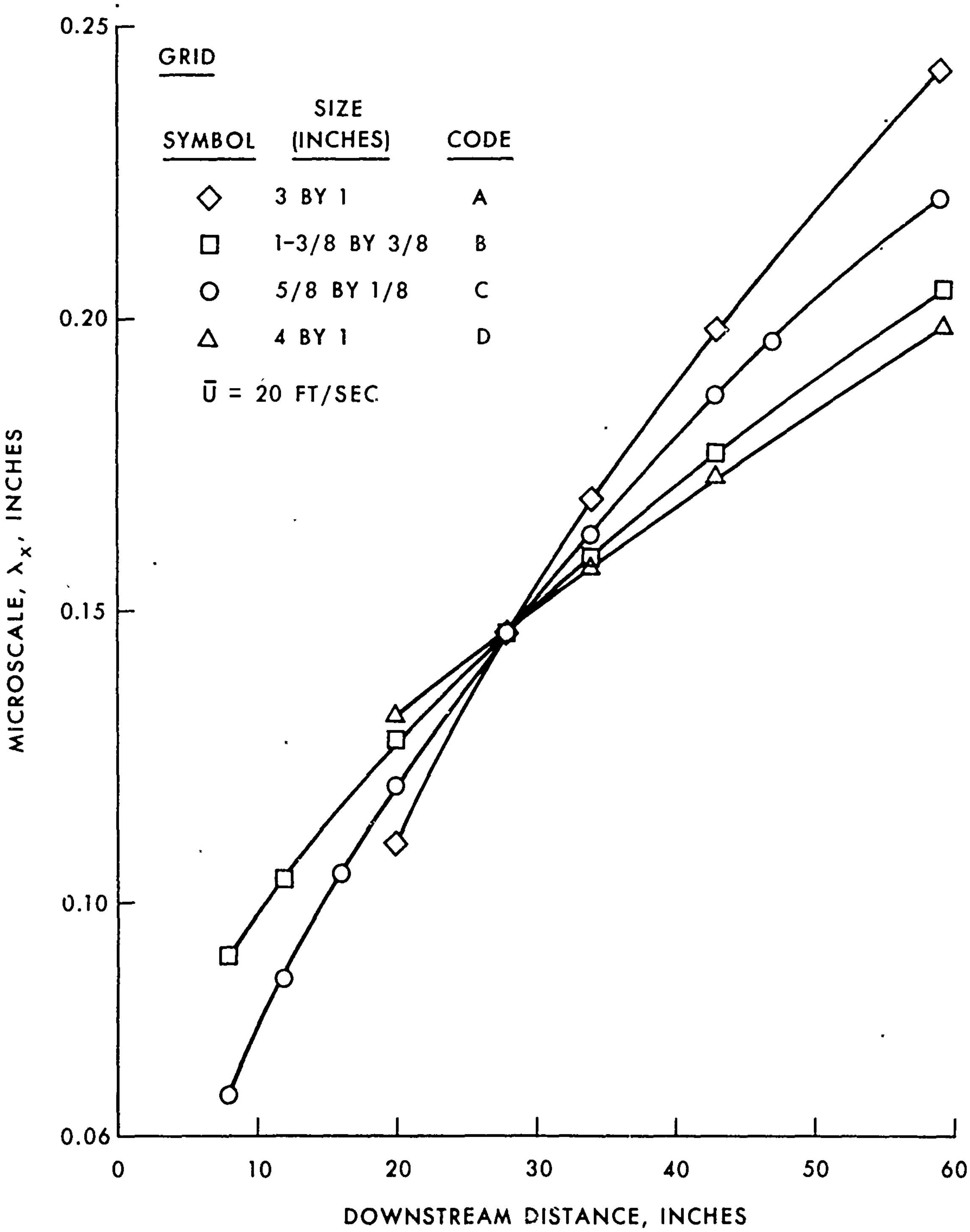

Figure 7. Grid-Induced Eulerian Microscale

parameters were maintained through the experimental program. The liquid droplets were produced by a commercially available, spinning disk, aerosol generator.* An 8% by volume solution of di-2-ethyl hexyl phthalate (DEHP, ρ = 0.983 gm/ml at 20°C) in ethyl alcohol was uniformly fed through a No. 22 gage hypodermic needle onto the surface of the 1-inch disk which was rotating at 60,000 rpm. The satellite droplets formed during the generation process were eliminated from the primary droplets by a satellite removal system built into the apparatus. Evaporation of the ethyl alcohol takes place within the generator and the remaining nearly monometric (single-sized) droplets of DEHP were transported through a mixing chamber and introduced into the air intake section of the wind tunnel. Additional dispersion and mixing of the aerosol occurred in the intake section before the aerosol was drawn through the test section. Considering experimental accuracies and the relatively long sample times used for the impaction study, the aerosol distribution in the potential core of the test section was sufficiently uniform for test purposes. The representative vertical profile of the distribution as shown in figure 8 was obtained by exposing a 25 by 700-mm ribbon to 20-μm-diameter particles undergoing transport through the test section at 20 ft/sec.

Particle-size measurements to assess the monometricity of the aerosol generated by the spinning disk were made for each experiment. Samples from the dynamic aerosol in the wind tunnel were extracted by use of a "snap" sampler whereby a volume of the cloud was instantaneously captured in a container and allowed to settle onto glass microscope slides placed on the bottom of the sampler. The slides contained deposits of gelatin, and, after reheating the slides, a second drop of molten gelatin caused the drops to be encapsulated in the gelatin matrix. Measurement of the spherical droplets was then made by conventional microscopic methods. However, due to the tedious and delicate nature of the sampling, an alternative method was developed. Microscope slides were coated with a Nyebar** film and, upon simultaneous exposure and comparison with the gelatin results, no discernible differences in average drop size or standard deviation were observed for droplets less than 20 μm in diameter. The Nyebar film method was subsequently used in particle-size measurements for the majority of tests reported herein. A minimum of 66 droplets was microscopically sized to obtain the average droplet size for each experiment. The spinning disk turned out to be highly consistent and reliable in producing nearly uniform droplets (13.4 μm in diameter) from each batch of solution.

D. Test Objects.

A glass cylinder wrapped with precleaned, smooth-surfaced, cellulose paper was inserted in a vertical position at preselected locations downstream of the test-section entrance. The cylinder with sample paper exhibited a mean diameter of 4.13 centimeters. The fraction of the aerosol that is deposited on the windward side of the cylinder to the total aerosol challenge to the cylinder determines the collection efficiency. Aerosol challenge is simultaneously obtained from the aerosol mass deposited on a vertically positioned thin wire (330 μm in diameter) located on center and 4 inches in front of the cylinder axis. The wire has been calibrated under laminar flow conditions by use of an isokinetic sampling probe† and has been found to be approximately 100% efficient for all practical purposes. It is assumed that the wire efficiency

*ERC Model 8320, Environmental Research Corporation, Saint Paul, Minnesota.

**Nyebar barrier film, Type C, W. F. Nye, Inc., Fairhaven, Massachusetts.

†Gelman Model 7023 isokinetic probe with No. 2220 filter holder, Gelman Instrument Company, McLean, Virginia

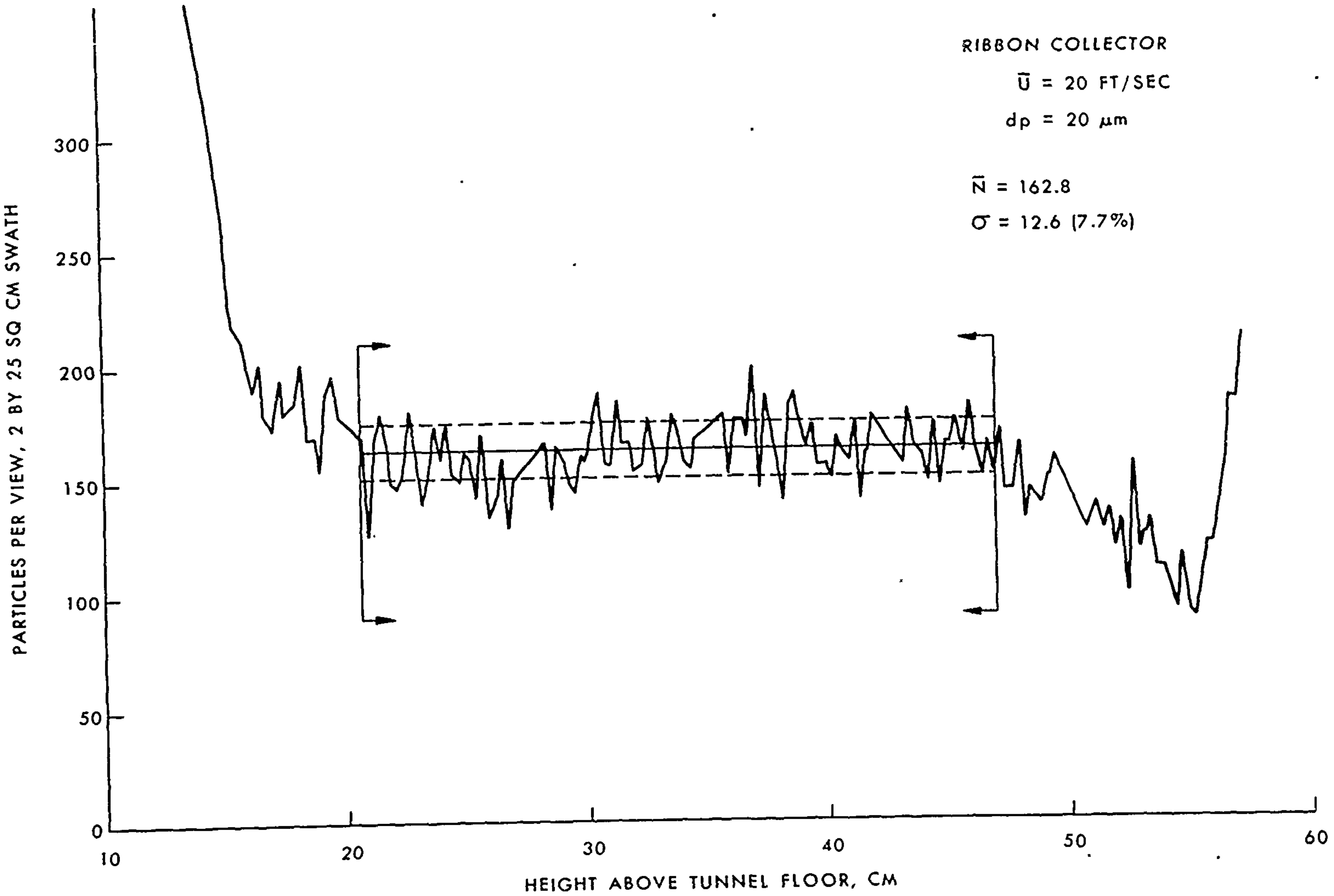

Figure 8. Vertical Profile of Aerosol in Test Section

remains at 100% even under turbulent flow deposition. Simultaneous anisokinetic sampling and/or isokinetic sampling of an aerosol in turbulent flow has not been used to obtain the aerosol challenge to the cylinder because the technique is considered highly questionable under these flow conditions. Consequently, the reported collection efficiencies for the cylinder under turbulent flow are probably based on conservative aerosol challenge measurements.

It was observed early in the experimental program that significant aerosol deposits occurred on the leeward side of the cylinder in both laminar and turbulent flow fields. Subsequently, windward and leeward depositions were analyzed, and corresponding collection efficiencies were determined.

E. Experimental Design.

Experimental evidence generated by previous investigators[8,9] has shown that an observed increase in collection efficiency of cylinders can be associated with an increase in the longitudinal turbulence level of the flow field. Intuitively, however, the microstructure of the turbulent flow field should be important and could influence a system's response to the aerosol challenge. From a grossly simplified viewpoint, suppose the turbulent flow field consists of very large "eddies" whose macroscale is considerably larger than the collector. The resultant flow field around the collector should be effectively unchanged from its laminar flow counterpart and the system response would be unaffected since the collector is totally enveloped by the eddy. Similarly, if the macroscale is very small relative to the collector, then only particle diffusivity should be affected and an insignificant change in the flow field should result. In between these plausible extremes, the microstructure effects of turbulence on collection efficiency are unknown.

Quantitatively, a maximum amount of information relevant to the impaction of particles on cylindrical collectors in a turbulent flow field can be obtained by a statistically designed set of experiments. Considering the limited resources available and the time element involved, a full factorial experimental design to account for all possible treatments was impractical to achieve. Consequently, a selected approach to examine turbulence effects on collection efficiency was taken since the main effects of windspeed, particle size, and collector size are well known for laminar flows.

The three factors of turbulence level, Eulerian macroscale, and Eulerian microscale were considered at two levels for fixed K and ϕ parameters. The particular K and ϕ values were selected for two reasons. (1) the effects of turbulence on collection efficiency should produce a significant change, if applicable, and (2) the laminar flow experiments should test inertial impaction theory. Unfortunately, the experimental design was complicated in that all required treatments could not be physically realized with the available wind tunnel facilities.

The turbulent flow fields were generated by the grids described in section III B, above, and the measured turbulence characteristics at downstream distances from the grid were assumed to describe the flow field when the collector was inserted at the corresponding location. The treatments that were examined in this study are summarized in table II. Six replications of each case were performed and the order of experiment was randomized to reduce any temporal bias in the results.

Table II. Grid and Treatment Parameters

Parameter	Treatments	Case 0	Case 1	Case 2	Case 4	Case 5	Case 7	Case 8
Rod cross section		Empty tunnel	Circular	Circular	Circular	Circular	Circular	Circular
Mesh, M (in.)		24 by 30	3	1.375	0.625	3	1.375	0.625
Rod width, b (in.)			1	0.375	0.125	1	0.375	0.125
M/b			3	3.667	5.00	3	3.667	5.00
Solidity, S			0.555	0.47	0.36	0.555	0.47	0.36
Distance between grid and cylinder	X (in.)	12,16,28,43,59	43	59	59	28	12	16
	X/M	–	14.3	42.9	94.4	9.3	8.73	25.6
	X/b	–	43	157.3	472.0	28.0	32.0	128.0
Relative turbulence intensity	$\frac{\sqrt{\overline{(u')^2}}}{\bar{U}}$	0.005-L	0.074-H	0.032-L	0.014-L	0.102-H	0.101-H	0.030-L
Mean windspeed (ft/sec)		20	20	20	20	20	20	20
Turbulence macroscale estimates*	L_x (in.)	2.4-H	1.43-H	0.98-H	0.58-L	1.15-H	0.557-L	0.303-L
	L_x/D	1.48	0.88	0.60	0.36	0.71	0.34	0.19
	L_x/b		1.43	2.61	4.64	1.15	1.48	2.42
	L_x/M		0.48	0.71	0.93	0.38	0.41	0.48
Turbulence microscale estimates*	λ_x (in.)		0.198-H	0.204-H	0.220-H	0.146-L	0.104-L	0.105-L
	λ_x/D		0.122	0.126	0.135	0.090	0.064	0.065
	λ_x/b		0.198	0.544	1.76	0.146	0.277	0.840
	λ_x/M		0.066	0.148	0.352	0.049	0.076	0.168

*H = high level
L = low level
D = cylinder diameter = 1.625 inches
S = solidity = $\frac{b}{M}(2 - \frac{b}{M})$

F. Procedures.

The test procedure used throughout the experimental program was to insert the appropriate grid, if required, in the test-section entrance of the wind tunnel in accordance with the randomly selected treatment plan. The average test-section windspeed was set at 20 ft/sec (609.6 cm/sec) for the particular test location. The glass cylinder was washed in 200 proof ethyl alcohol and completely wrapped with three abutting 3-inch-wide paper strips, and the 4.13-cm-diameter collector was inserted in a vertical position at the prescribed test location. A precalibrated, 330-μm-diameter copper wire was positioned 4 inches in front of the center axis of the collector and marked to indicate height above tunnel floor that coincided with the corresponding sample strip. The spinning disk aerosol generator was stabilized, and the test aerosol passed through the grid network and test section for a 2000-second exposure to ensure adequate deposits. The test aerosol was dynamically sampled downstream of the collector and a minimum of 66 randomly selected droplets was measured to obtain a mean aerosol size for the test. After exposure, uniform vertical slices (3-inch lengths) of the paper from the windward and leeward surfaces of the cylinder were moved with a specially fabricated cutting tool. The aerosol-challenge measuring wire was cut into appropriate 3-inch sections and the wire and collector samples were diluted with 200 proof ethyl alcohol. The mass deposits of di-2-ethyl hexyl phthalate aerosol on the samples were measured by use of a Beckman DK-2A spectrophotometer.

Figure 9 is a picture of the hot-wire anemometer sensing probe in position for measuring turbulence characteristics of grid C. Figure 10 shows the cylindrical collector in position for collection efficiency determination under turbulent flow conditions.

IV. CALCULATIONS.

The aerosol challenge to the cylindrical collector is measured by use of a thin wire which has been calibrated using an isokinetic sampling probe as a standard.

Let C_o be the aerosol mass concentration in the wind tunnel test section. The aerosol mass deposited on the precleaned Millipore glass-fiber filter paper in the isokinetic probe is given by

$$M_p = C_o \bar{U} t A_p P_p \tag{10}$$

where

$\bar{U}$ = average windspeed = sampling port velocity

t = sampling period

A_p = probe area

P_p = collection efficiency of isokinetic probe

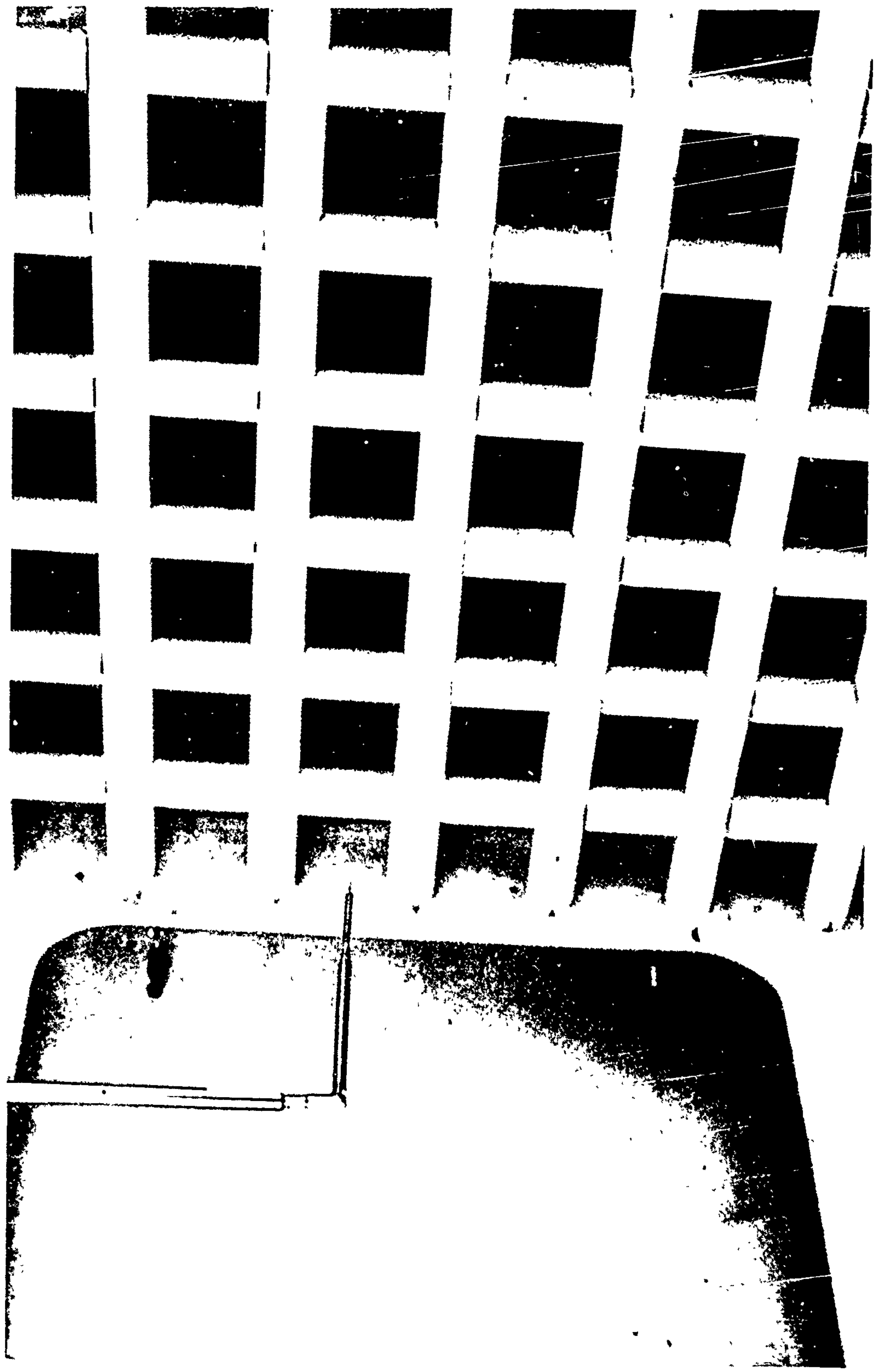

Figure 9. Hot-Wire Sensing Element

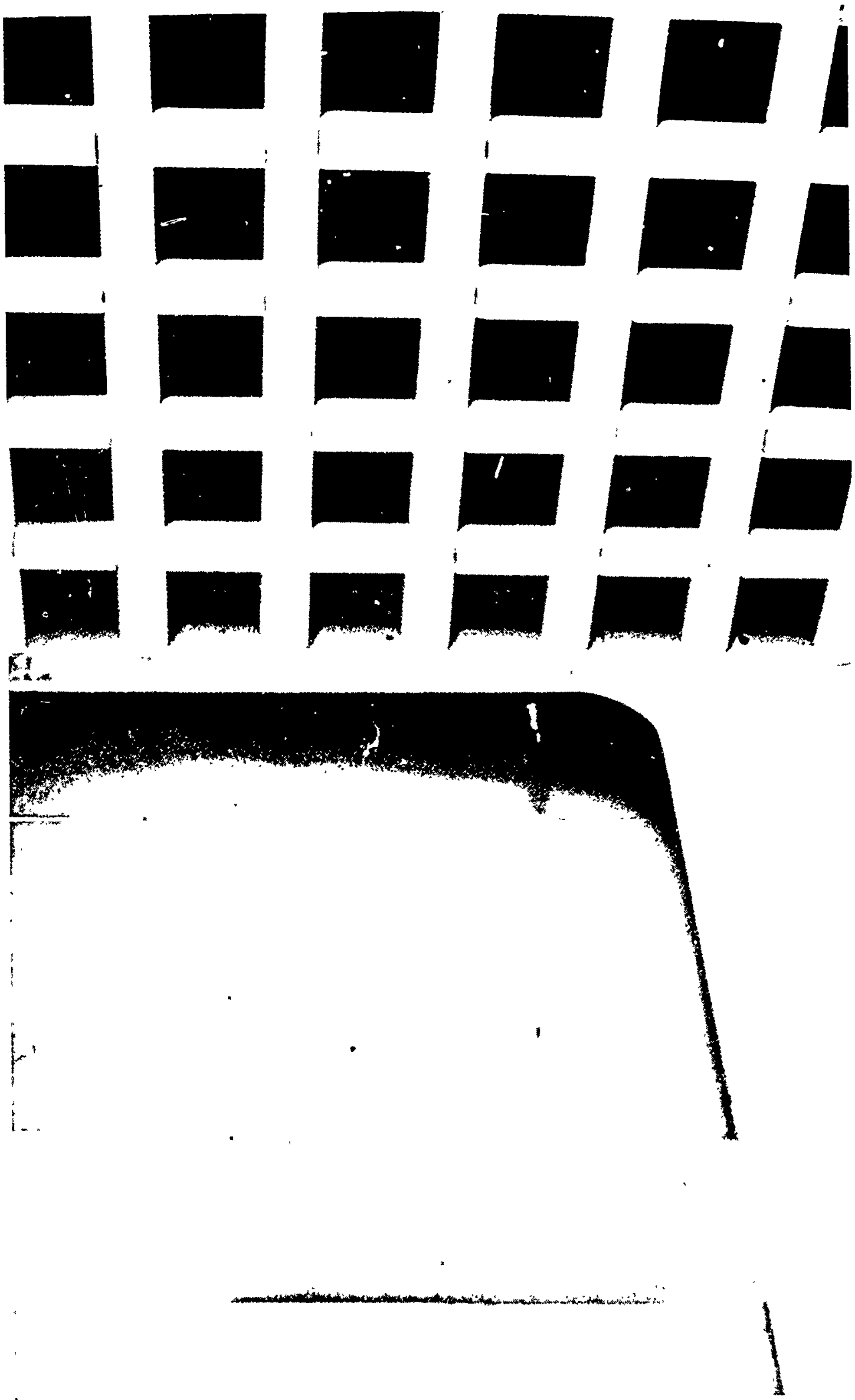

Figure 10. . Cylinder Orientation in Turbulent Flow

The probe is assumed to be 100% efficient for the laminar-flow test conditions and monometric droplets used in the calibration study.[15]

The aerosol mass deposited on the wire undergoing calibration is given by

$$M_1 = C_O \overline{U} t A_1 P_1 \qquad (11)$$

where

A_1 = projected area of wire

P_1 = collection efficiency of wire

The wire efficiency can be calculated from equations 10 and 11 as

$$P_1 = \frac{A_P M_1}{A_1 M_P} \qquad (12)$$

By replacing the isokinetic probe with the test cylinder and using the wire as a secondary standard, the collection efficiency of the cylinder can be determined. The aerosol mass deposited on the windward surface of the cylinder is given by

$$M_O = C_O \overline{U} t A_O E_O \qquad (13)$$

where

A_O = projected area of cylinder

E_O = collection efficiency of cylinder

The windward collection efficiency of the cylinder can then be computed from equations 11 and 13 as

$$E_O = \frac{A_1}{A_O} \frac{M_O}{M_1} P_1 \qquad (14)$$

From the inertial impaction theory and by definition, the impaction efficiency of the collector does not consider the aerosol deposition that may occur on the leeward side of the cylinder. However, substantial deposits have been observed on the downstream side of the collector and it is appropriate to evaluate the leeward deposition efficiency. The leeward deposition efficiency, E_R, is herein defined as the ratio of the aerosol mass deposited on the

[15] Chakko, M. K. Syracuse University Research Institute. Final Report. Contract DA-18-108-AMC-49(A). Measurement of Aerosol Concentration in Turbulent Flows. November 1963. UNCLASSIFIED Report.

downstream side of the collector to the aerosol mass contained in the volume swept out by the cylinder in the upstream direction. Simply stated, E_R is the leeward mass deposited, M_R, divided by the aerosol mass challenge to the cylinder and can be experimentally determined from the equation:

$$E_R = \frac{A_1}{A_O} \frac{M_R}{M_1} P_1 \qquad (15)$$

Other calculations required in this study include the principal scaling parameter values defined by equations 1 and 2.

V. RESULTS.

The impaction efficiency of the thin-wire secondary standard has been predicted by use of inertial impaction theories[1,2] for the experimental conditions under which calibration was performed. With $K \cong 19.7$ and $\phi = 1.5$, the predicted impaction efficiency turns out to be 91.9% for point-mass droplets and 96.0% when interception effects are included. Eighteen determinations of collection efficiency were made at several locations in the test section for exposure times ranging from 1000 to 2000 seconds. The average collection efficiency was found to be 98.5% with a standard deviation of 8.8%. Considering the inherent inaccuracies in the experiment, the wire was assumed to be 100% efficient for all practical purposes.

Inertial impaction theories were used to predict the impaction efficiency of the 4.13-cm-diameter cylinder under laminar flow conditions. Results of these computations for a velocity field parameter value of 183 are given in table III for the expected range of experimental inertial parameter values.

Table III. Theoretical Impaction Efficiency

ϕ = 183 K, inertial parameter	Efficiency with interception, E_1	Inertial impaction efficiency E
	%	%
0.148	0.127	0.032
0.149	0.135	0.036
0.150	0.142	0.042
0.151	0.149	0.048
0.152	0.156	0.054
0.153	0.163	0.062
0.155	0.184	0.077
0.156	0.193	0.087
0.157	0.202	0.098
0.158	0.211	0.107
0.159	0.224	0.117
0.160	0.237	0.130
0.161	0.250	0.142
0.162	0.261	0.153
0.163	0.273	0.163
0.164	0.284	0.180
0.165	0.302	0.195
0.166	0.318	0.210
0.167	0.334	0.223

Particle impaction experiments to test the inertial impaction theories were conducted at several locations in the test section of the wind tunnel under laminar flow conditions (case 0, no grid). The theoretical and experimental results are shown in figure 11 and clearly demonstrate that inertial impaction theories adequately predict the collection efficiency of a cylinder in laminar flow for low inertial parameter values approaching the theoretical cutoff value.

The aerosol mass challenges to the cylindrical collectors as measured by the thin-wire standards were analyzed by routine statistical methods. In general, there was no statistically significant difference at the 95% confidence level between the laminar-flow aerosol challenge and the turbulent-flow aerosol challenge to the collector at any particular location downstream of the test section entrance. The total aerosol mass deposited on the thin-wire standard was statistically independent of the relative turbulence intensity of the airstream. These data are shown in figure 12. However, the total aerosol mass deposited on the windward side of the cylinder was dependent on the turbulence characteristics of the flow field. When the relative turbulence intensity was less than 7.4%, the collection efficiency of the cylinder was statistically the same as the collection efficiency for laminar flow which followed the inertial impaction theory. For relative turbulence intensities exceeding 7.4%, the measured collection efficiencies are functions of the relative turbulence intensity and longitudinal Eulerian macroscale of the flow field. It is obvious from the experimental results shown in figure 13 that turbulence has a significant influence on the windward collection efficiency of cylinders at low inertial parameter values. Depending on the turbulence characteristics of the flow field, a manyfold increase in collection efficiency can result. It is also of interest to note that the leeward deposition efficiency defined by equation 15 was greater than the windward collection efficiency in most cases. Consequently, more aerosol mass was deposited on the rear of the cylinder than on the windward side. The experimental results in figure 14 show that the leeward deposition efficiency is dependent on the relative turbulence intensity but, unlike the windward efficiency, no dependence on the Eulerian macroscale is indicated. In addition to the experimental results obtained during this program, the turbulent impaction data acquired by Torgeson[9] for a range of inertial parameter values are significant. The turbulent flow field was generated by a 1- by 3/8-inch monoplane grid, and relative turbulence intensities of 13.1% and 9.1% at a 30 ft/sec mean windspeed were measured at 7.75 and 10.75 inches, respectively, downstream of the 8-inch-diameter test-section entrance. The Eulerian macroscale and microscale characteristics of the turbulent flow field were not measured. Torgeson's results for the collection efficiency of a 7-cm-diameter cylinder exposed to monometric aerosols of various sizes are shown with the theoretical impaction efficiency predictions in figure 15. Dramatic increases in collection efficiency were observed with increased relative turbulence intensities of the flow field. Under ordinary field operations, turbulence levels exceeding 10% to 15% would be a common occurrence, and the collection efficiency of man-sized target elements can be underestimated manyfold through use of the inertial impaction theory for laminar flow conditions.

VI. DISCUSSION.

Analysis of the experimental impaction data has shown that low levels of turbulence had little influence on the collection efficiency of cylinders and that the inertial impaction theory adequately predicted the result. When the relative turbulence intensity of the flow field increased beyond the 7.4% level, the inertial impaction theory greatly underestimated the actual

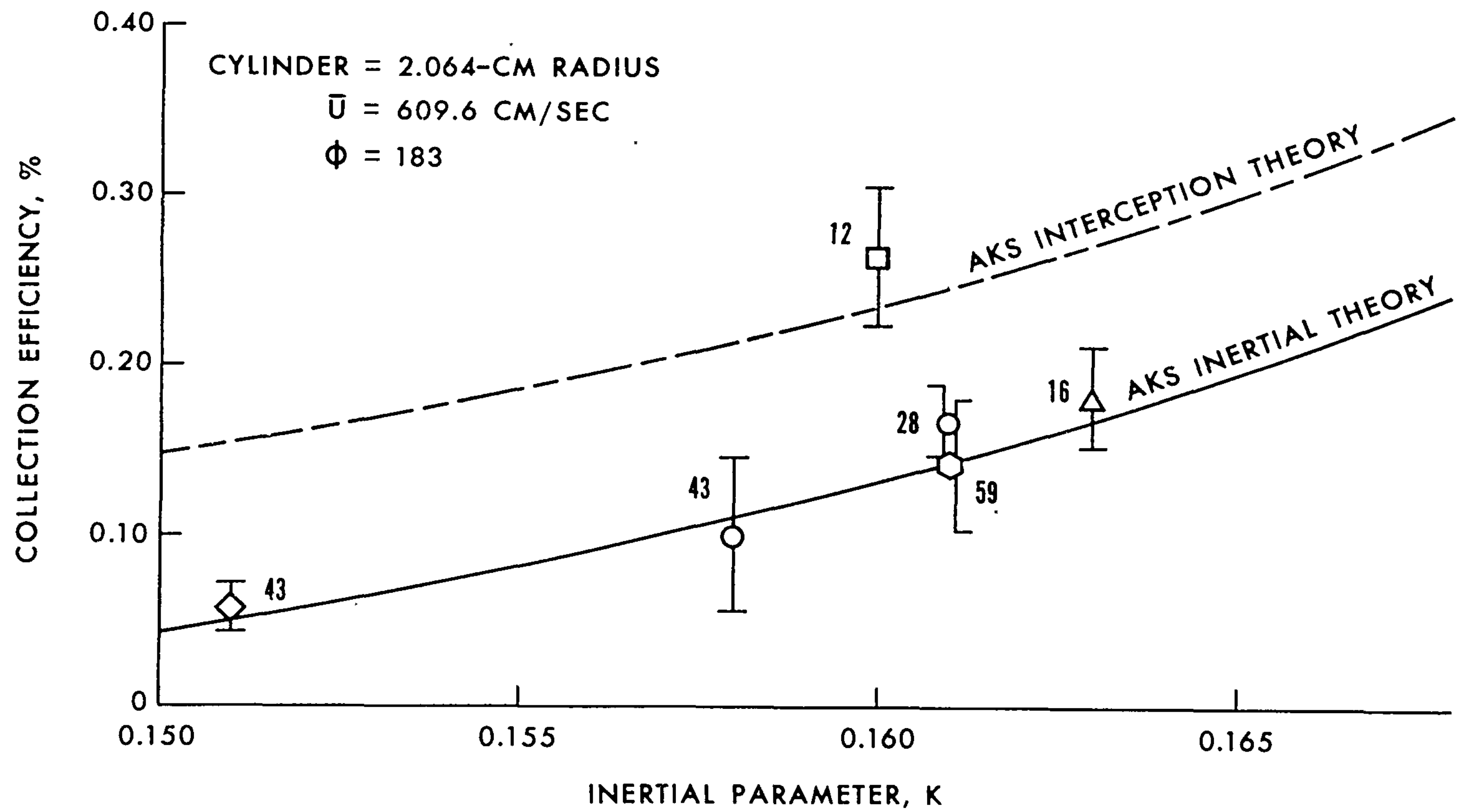

Figure 11. Laminar Flow Collection Efficiency for Various Downwind Distances

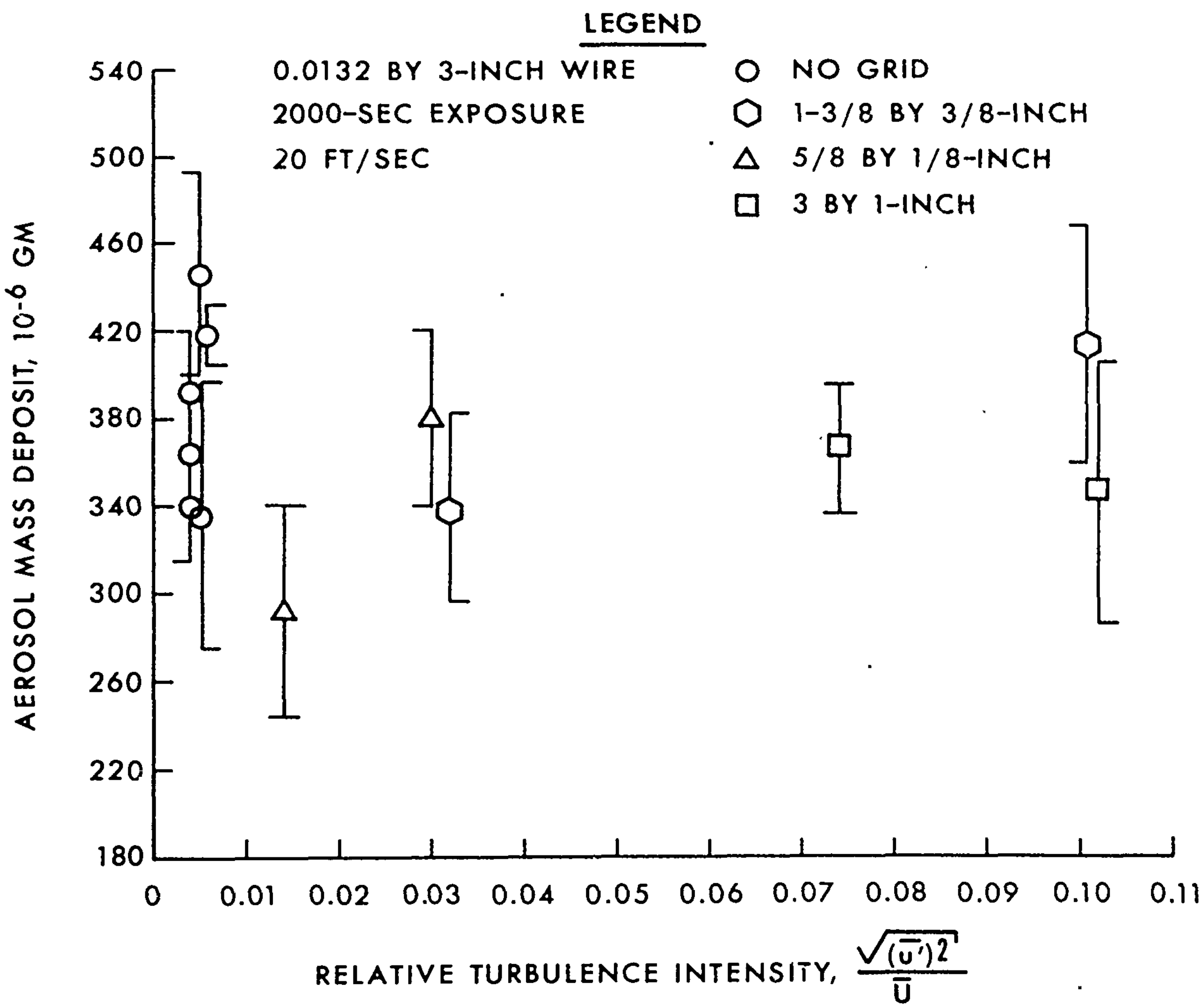

Figure 12. Aerosol Mass Deposit Versus Relative Turbulence Intensity

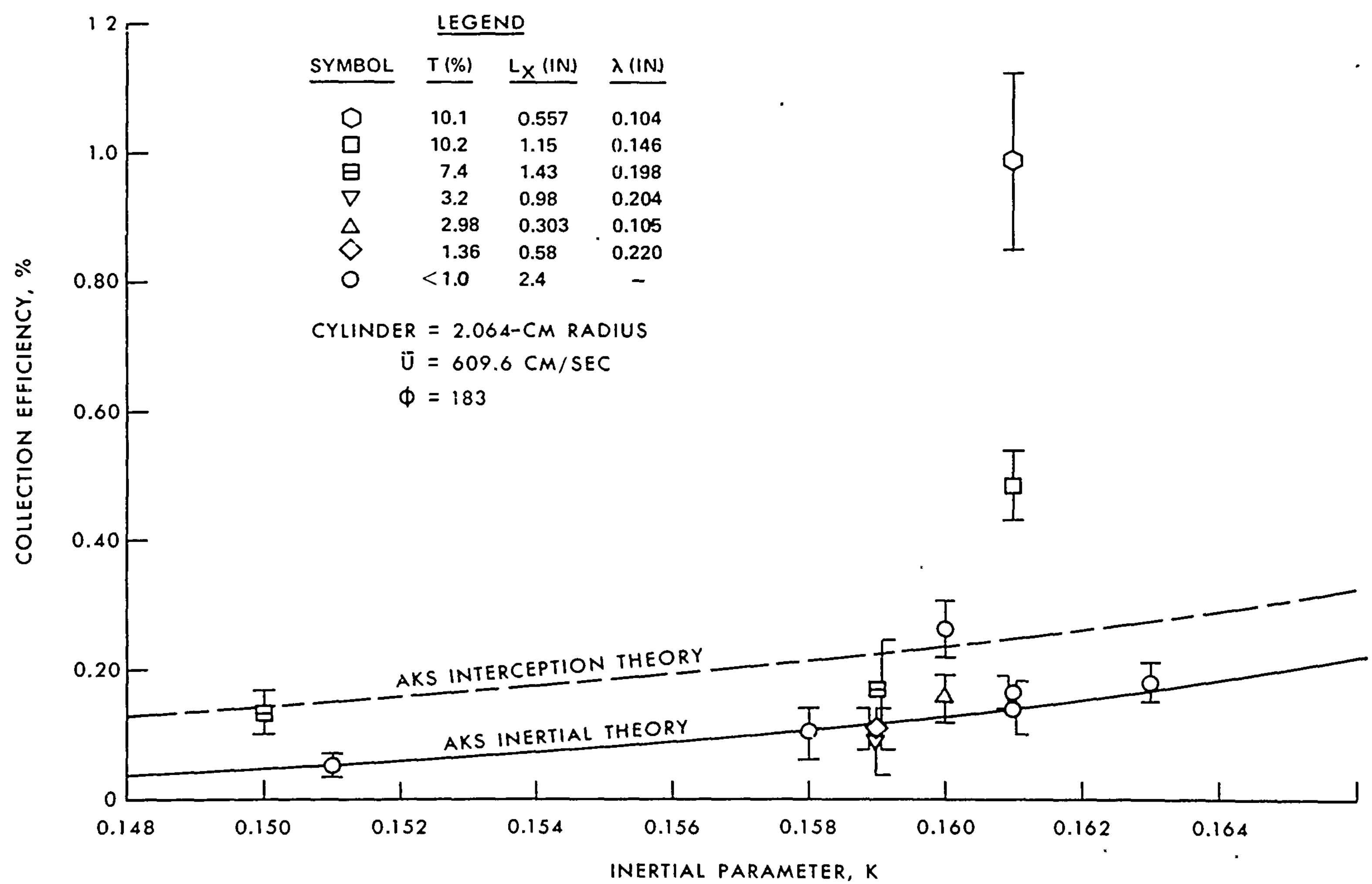

Figure 13. Laminar and Turbulent Flow Collection Efficiency

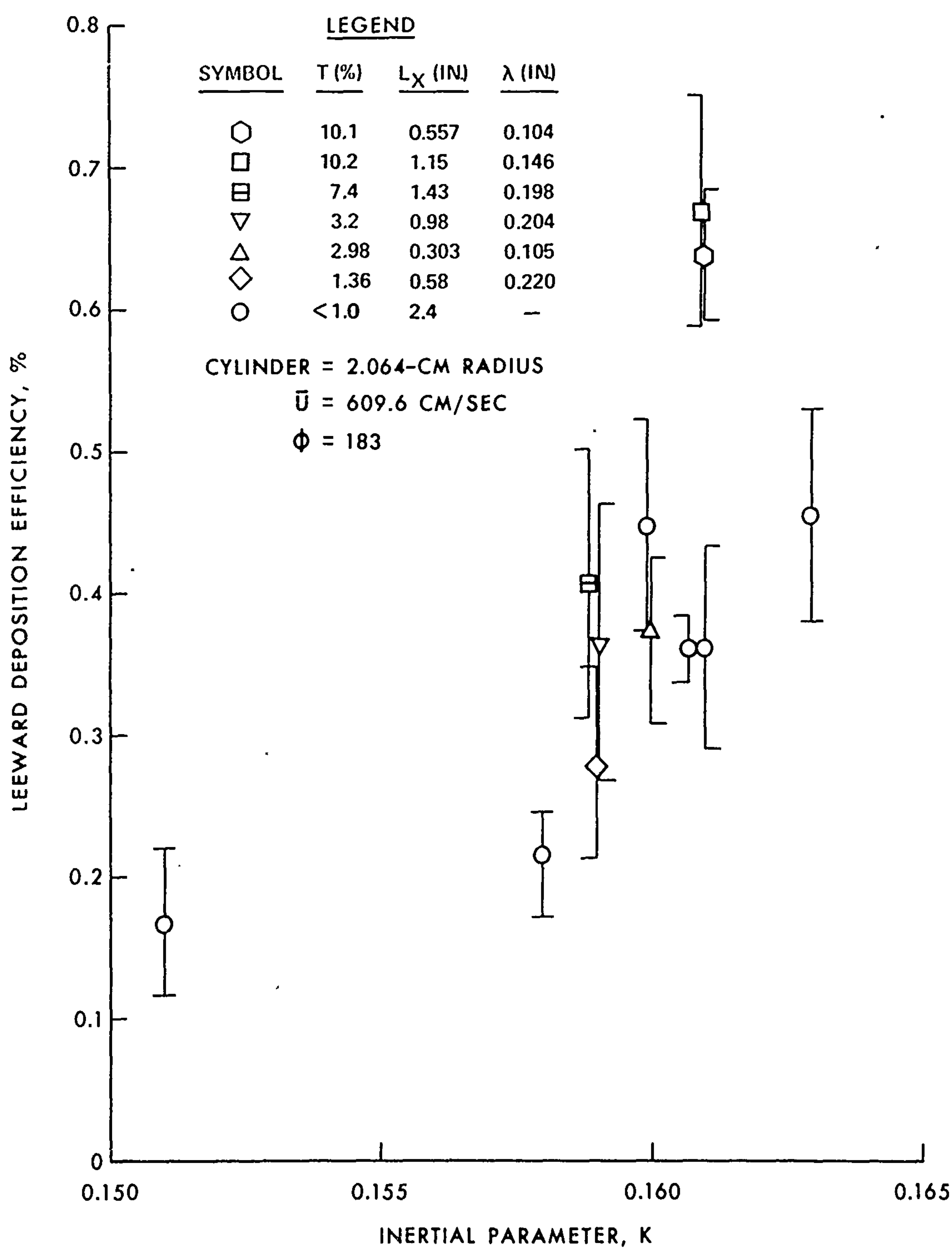

Figure 14. Leeward Deposition Efficiency for Various Turbulence Conditions

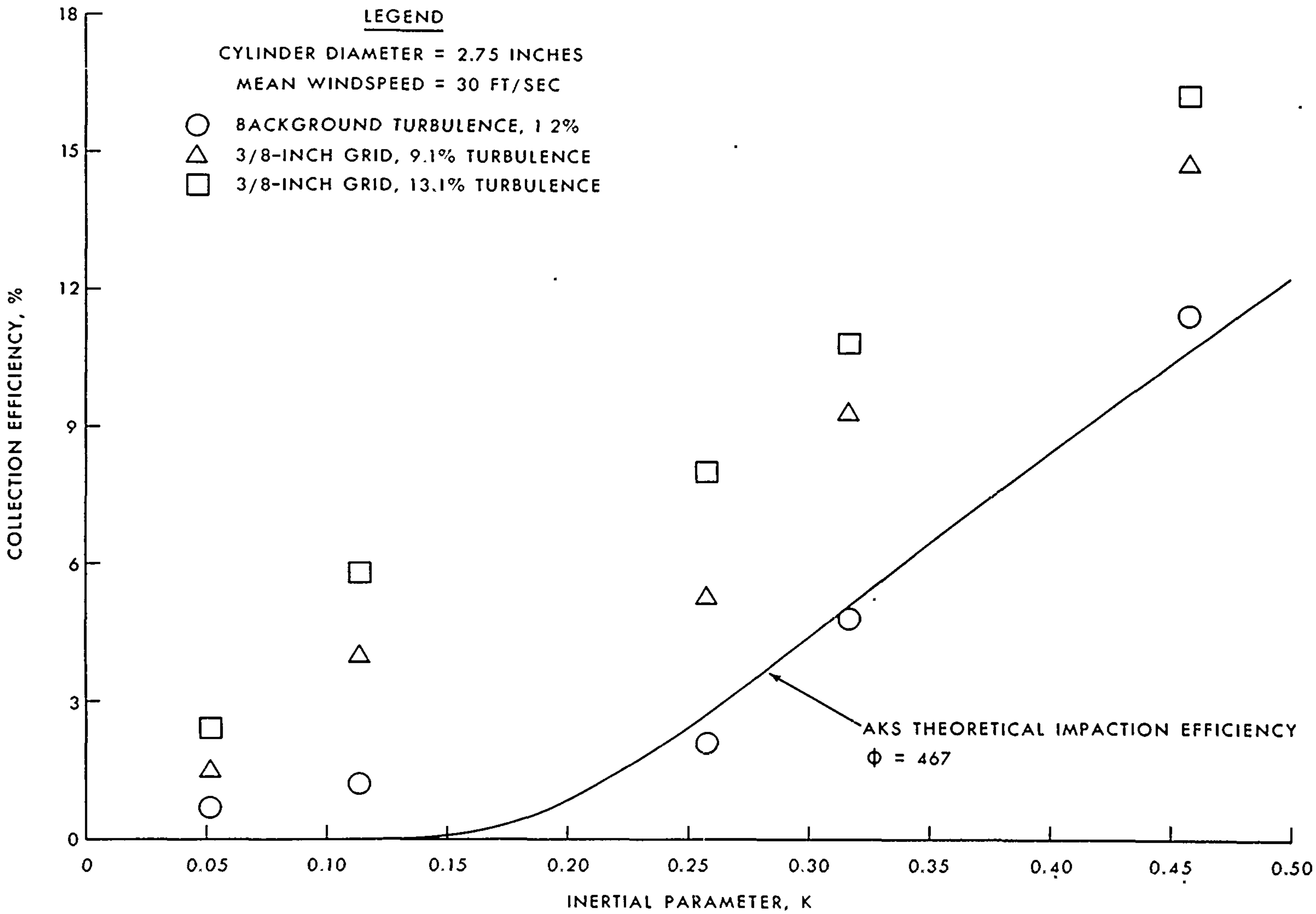

Figure 15. Turbulent Flow Collection Efficiency (Torgeson)

collection efficiency for the small values of inertial parameters being investigated. Unfortunately, a general physical-mathematical model of particle impaction under turbulent flow conditions is presently beyond the state of the art because the mechanisms controlling impaction are not understood. For example, the expected range of theoretical inertial impaction efficiency of a 4.13-cm-diameter cylinder in an ideal flow field when K = 0.161 and ϕ = 183 turns out to be 0.142% up to 0.250% with interception considerations. Experimental collection efficiency measurements for these ideal conditions (laminar flow) from 12 determinations produced an average windward efficiency of 0.155%. However, when the level of turbulence of the flow field was increased to 10.1% with Eulerian macroscales corresponding to 1.15 inches and 0.557 inch, cases 5 and 7, respectively, for the same K and ϕ parameter values, the measured windward collection efficiencies increased to 0.487% and 0.988%, respectively. These measurements are based on 18 determinations for case 5 and 15 determinations for case 7. Evidently, an interaction between relative turbulence intensity and the Eulerian macroscale of the flow field plays an important role to the unknown mechanisms underlying turbulent impaction.

The flow of fluids over a circular cylinder can be generally categorized into three regimes. When the Reynolds number for the cylinder is very small ($\leq$0.5), the resistance to flow is a result of viscous surface friction and the flow over the cylinder is practically laminar. When the Reynolds number increases above the 0.5 level, the drag coefficient for the cylinder decreases but the flow over the forward portion of the cylinder remains laminar. The drag coefficient becomes relatively constant over the Reynolds number range of 10^3 to 10^5. In addition, the boundary layer remains laminar up to the point of separation although a relatively wide turbulent wake now exists behind the cylinder. The third regime of flow begins when a portion of the frontal boundary layer is energized and changes from laminar to turbulent. This is characterized by a sharp decrease of the drag coefficient to about one-half its previous constant value.[16] At transition, the size of the turbulent wake is reduced as the point of separation is displaced toward the downstream side of the cylinder. G. I. Taylor[17] suggested that the onset of the critical flow regime for a sphere should be a function of the magnitude of the relative turbulence intensity and of the ratio of the sphere diameter to the macroscale of the turbulence of the free stream. The Taylor parameter has been used to predict the critical Reynolds number for circular cylinders and to indicate the effect of turbulence on the aerodynamics of cylinders.[18] It is interesting to note that the experimental collection efficiency data acquired in this study can be properly ordered by use of the Taylor parameter defined as the quantity

$$TP = T \left(\frac{D}{L_X} \right)^{0.2} \tag{16}$$

[16] Knudsen, J. G., and Katz, D. L. Fluid Dynamics and Heat Transfer. Chapter 10, McGraw-Hill Book Company, Inc., New York, New York. 1958.

[17] Taylor, G. I. Statistical Theory of Turbulence, V. Proc. Roy. Soc. A156, 307 (1936).

[18] Slurry, D. Institute for Aerospace Studies Report No. 142. The Effect of High Intensity Turbulence on the Aerodynamics of a Rigid Circular Cylinder at Subcritical Reynolds Number. University of Toronto. October 1969. UNCLASSIFIED Report.

where

T = relative turbulence intensity

D = cylinder diameter

L_X = Eulerian macroscale of turbulence

These data are shown in figure 16.

Taylor parameter values can also be obtained for Torgeson's[9] experimental data even though the macroscales of the turbulent fields were not actually measured. The unified analytical treatment of grid turbulence presented by Naudascher and Farell[19] has been used to predict the turbulent flow field characteristics measured in this study and good agreement was achieved in all cases. Application of their proposed methodology to the Torgeson system yields approximate values of the macroscales from the 1-inch by 3/8-inch turbulence-producing grid of 0.49 inch and 0.56 inch for downstream distances of 7.75 inches and 10.75 inches, respectively. The corresponding Taylor parameter values are 0.185 and 0.125 for the turbulence degrees of 13.1% and 9.1% which properly orders the increased collection efficiency data, respectively. Additional experimentation and analytical efforts are required before conclusions regarding the turbulent boundary layer effects on impaction mechanisms can be made.

The leeward deposition efficiencies of the cylinder were found to be greater than the frontal collection efficiencies in most circumstances. These results are in general agreement with the studies made by Amelin and Belyakav[20] on the deposition of transformer oil on cylinders even though the magnitude of their collection efficiencies is unrealistic.[21,22] In particular, these authors indicate that, at inertial parameter values below 0.32 for similar experimental conditions, the leeward deposition efficiencies are always greater than the windward collection efficiencies. The same effect has been observed in this study and future investigations should consider these results.

Qualitative observations made during the course of experimentation indicate that the aerosol was rather uniformly distributed over the leeward portion of the cylinder. The frontal deposition pattern under laminar flow and low turbulence intensities showed a maximum at the stagnation line that rapidly decreased with angular position in accordance with impaction theory. High levels of turbulence intensity caused a broadening of the frontal pattern and significantly increased the aerosol mass deposition. Roughness elements, such as wrinkles in the collection paper, were particularly effective in capturing aerosol that would normally miss a smooth-surfaced cylinder. Electrical grounding of the calibrated wires and cylinders showed no effect in the aerosol challenge or collection efficiency measurements.

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[19] Naudascher, E., and Farell. C. Unified Analysis of Grid Turbulence. J. Eng. Mech. Div., Proc. ASCE 96, No. EM 2, 121 (1970).

[20] Amelin, A. G., and Belyakav, M. I. On the Deposition of Drops from a Flow. Doklady Akad. Nauk SSSR 108, 31 (1956).

[21] Golovin, M. N., and Putnam, A. A. Inertial Impaction on Single Elements. Ind. Eng. Chem. Fundam. 1, 264 (1962).

[22] Fuchs, N. A. The Mechanics of Aerosols. Chapter IV. Pergamon Press Book. The Macmillan Company, New York, New York. 1964.

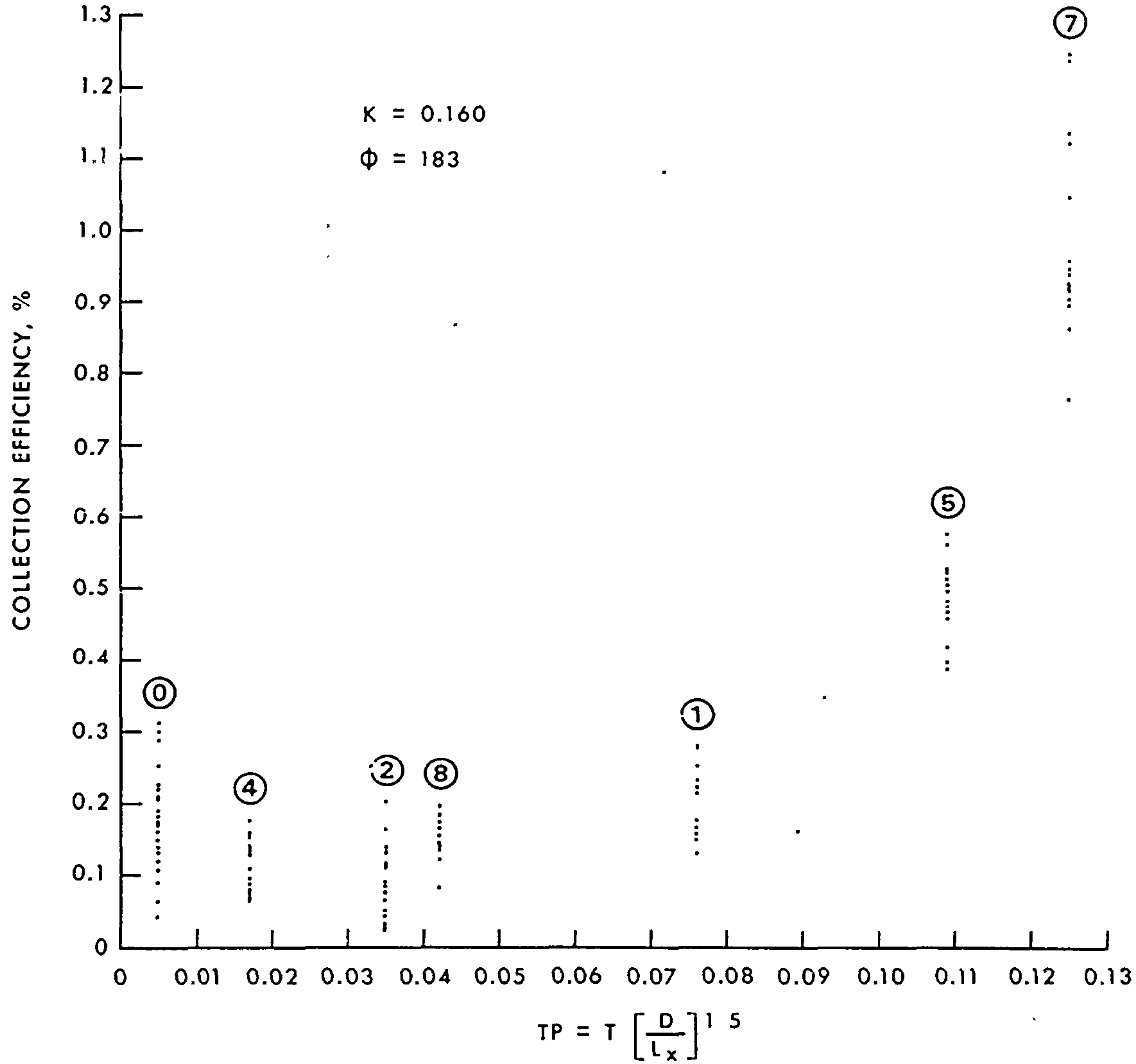

Figure 16. Collection Efficiency Versus Taylor Parameter for Indicated Grid Case Number

Preliminary investigation of the aerosol deposition on glass microscope slides of varying lengths showed that edge effects can be very important and that the collection efficiency of a single slide, 25 mm in width by 75 mm in length, may be substantially higher than the predicted impaction efficiency for an infinitely long ribbon collector. Consequently, estimation of the aerosol challenge and/or size distribution of an aerosol in a flow field with a single microscope slide may lead to highly erroneous results especially for particle sizes less than 20 μm in diameter.

The collection efficiency experiments conducted with the 4.13-cm-diameter cylinders have practical equivalents in accordance with the stylized man-sized target breakdown given in reference 1. Under low levels of turbulence, an impaction efficiency of approximately 0.15% would be expected for each of the following circumstances:

Cylinder diameter cm	Windspeed mph	Particle diameter μm
20 (leg)	3	63
16 (head)	3	56
8 (arm)	6	28

Although the impaction efficiencies of man-sized collectors are low in most cases, an effective dose can still be acquired in practice because the aerosol challenge in any chemical operation is usually very large. Further, the flow field will generally be highly turbulent and, as shown, a manyfold increase in collection efficiency can occur with the small inertial parameter values of interest.

Further experimentation is required under laminar and turbulent flow in the intermediate-size wind tunnel to study collection efficiencies of spread fingers, multiple elements, protuberances on surfaces, and a host of other collector configurations. These studies are required if one is to simulate the collection efficiency of a clothed-man target under field conditions. Additional information and characterization of the microstructure of the turbulent field shed by trees and vehicles under environmental conditions are needed to correlate controlled experimental data with normal operational conditions. Development of the causal relationships could close the knowledge gaps that exist on the impaction of particles on collectors in turbulent flow.

VII. CONCLUSIONS.

1. The collection efficiencies of 4.13-cm-diameter cylinders at low values of the particle inertial parameter have been experimentally determined under laminar and controlled turbulent flow conditions.

2. Impaction efficiencies computed by the inertial impaction theory accurately predict the collection efficiency of cylinders under laminar flow conditions and levels of longitudinal turbulence less than 7.4%.

3. Manyfold increases in the collection efficiency of cylinders at low values of the inertial parameter were observed as a function of relative turbulence intensity and Eulerian longitudinal macroscale of the controlled turbulent flow field.

4. The collection efficiency data for cylinders have been properly ordered by use of the Taylor parameter.

5. The leeward deposition efficiency was greater than the windward collection efficiency for most flow circumstances.

VIII. RECOMMENDATIONS.

1. Experimental studies of the collection efficiency of cylinders and other collector configurations in controlled turbulent flow conditions should be continued. These programs should extend the inertial parameter region of interest and further clarify the mechanisms underlying turbulent impaction of particles on man-sized targets.

2. Characterization of the microstructure of turbulent flow fields generated by trees, bushes, and vehicles should be accomplished to permit correlation of controlled turbulent impaction data with operational conditions.

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. 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.

3. Ranz, W. E., and Wong, J. B. Impaction of Dust and Smoke Particles on Surface and Body Collectors. Ind. Eng. Chem. 44, 1371 (1952).

4. May, K. R., and Clifford, R. The Impaction of Aerosol Particles on Cylinders, Spheres, Ribbons and Discs. Ann. Occup. Hyg. 10, 83 (1967).

5. Householder, M. K., and Goldschmidt, V. W. The Impaction of Spherical Particles on Cylindrical Collectors. J. Colloid Interface Sci. 31, 464 (1969).

6. Asset, G., Kimball, D., and Hoff, M. EATR 4225. Small-Particle Collection Efficiency of Vertical Cylinders in Flows of Low-Intensity Turbulence. January 1969. UNCLASSIFIED Report.

7. Levesque, R. J. Suffield Technical Paper 131. Defence Research Board, Canada. An Experimental Verification of the Theory of Particle Collection on Vertical Cylinders. September 1958. UNCLASSIFIED Report.

8. Kimball, D. V. EATR 4624. Small-Particle Collection Efficiency of Vertical Cylinders in Flows of Medium-Intensity Turbulence. March 1972. UNCLASSIFIED Report.

9. Torgeson, W. L. Applied Science Division, Litton Systems, Inc. Summary Report Phase II. Contract DA-18-035-AMC-340(A). Investigation of Impaction Mechanisms of Particles on Collectors in Turbulent Flow (U). August 1967. CONFIDENTIAL Report.

10. Hinze, J. O. Turbulence. Chapter 1. McGraw-Hill Book Company, Inc., New York, New York. 1959.

11. Brodkey, R. S. The Phenomena of Fluid Motions. Chapter 14. Addison-Wesley Publishing Company, Reading, Massachusetts. 1967.

12. Taylor, G. I. Statistical Theory of Turbulence. Proc. Roy. Soc. A151, 421 (1935).

13. Taylor, G. I. The Spectrum of Turbulence. Proc. Roy. Soc. A164, 476 (1938).

14. Cooper, W. A. EATR 4636. Modifications and Characterization of a Low Speed Open-Circuit Wind Tunnel. April 1972. UNCLASSIFIED Report.

15. Chakko, M. K. Syracuse University Research Institute. Final Report. Contract DA-18-108-AMC-49(A). Measurement of Aerosol Concentration in Turbulent Flows. November 1963. UNCLASSIFIED Report.

16. Knudsen, J. G., and Katz, D. L. Fluid Dynamics and Heat Transfer. Chapter 10, McGraw-Hill Book Company, Inc., New York, New York. 1958.

17. Taylor, G. I. Statistical Theory of Turbulence, V. Proc. Roy. Soc. A156, 307 (1936).

18. Slurry, D. Institute for Aerospace Studies Report No. 142. The Effect of High Intensity Turbulence on the Aerodynamics of a Rigid Circular Cylinder at Subcritical Reynolds Number. University of Toronto. October 1969. UNCLASSIFIED Report.

19. Naudascher, E., and Farell, C. Unified Analysis of Grid Turbulence. J. Eng. Mech. Div., Proc. ASCE 96, No. EM 2, 121 (1970).

20. Amelin, A. G., and Belyakav, M. I. On the Deposition of Drops from a Flow. Doklady Akad. Nauk SSSR 108, 31 (1956).

21. Golovin, M. N., and Putnam, A. A. Inertial Impaction on Single Elements. Ind. Eng. Chem. Fundam. 1, 264 (1962).

22. Fuchs, N. A. The Mechanics of Aerosols. Chapter IV. Pergamon Press Book. The Macmillan Company, New York, New York. 1964.

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Chemical test and assessment technology	

13. ABSTRACT

The collection efficiencies of paper-coated glass cylinders at low values of the particle inertial parameter relevant to chemical operations were determined in a wind tunnel under laminar and controlled turbulent flow conditions. Impaction efficiencies computed by the inertial impaction theory for inertial parameters approaching the theoretical cutoff value accurately predict the collection efficiency of cylinders under laminar flow conditions and levels of turbulence less than 7.4%. Manyfold increases in the collection efficiency of cylinders at low inertial parameter values were observed as a function of relative turbulence intensity and Eulerian longitudinal macroscale of the turbulent flow field. The collection efficiency data for cylinders can be properly ordered by the Taylor parameter. The leeward deposition efficiency was substantial and exceeded the windward collection efficiency for most flow circumstances.

14. KEYWORDS

Droplet	Impaction	Inertial parameter
Aerosols	Efficiency	Particle impaction
Sampling	Turbulence	Impaction efficiency
Particles	Impingement	Collection efficiency
Cylinders	Interception	Deposition efficiency
Collectors	Wind tunnel	Sampling efficiency
Deposition	Inertial impaction	Isokinetic sampling

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