BRL-TR-3005

4

TECHNICAL REPORT BRL-TR-3005

BRL

AD-A210 660

A LASER DOPPLER ANEMOMETRY INVESTIGATION OF SINGLE-PHASE AND PARTICLE-LADEN JET FLOWS

C. K. ZOLTANI
A. F. BICEN

JUNE 1989

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

89

DESTRUCTION NOTICE

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-TR-3005	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USA Ballistic Research Laboratory 6b. OFFICE SYMBOL (If applicable) SLCBR-IB-A	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Aberdeen Proving Ground, MD 21005-5066	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 61102A PROJECT NO.: 1L161102AH43 TASK NO.: 00 WORK UNIT ACCESSION NO.: 00

11. TITLE (Include Security Classification)

A Laser Doppler Anemometry Investigation of Single-Phase and Particle-Laden Jet Flows

12. PERSONAL AUTHOR(S)

Csaba K. Zoltani and Ali F. Bicen

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical Report	FROM Apr 89 TO Apr 89		

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
21	02		Laser Doppler Anemometry
20	04		Two Phase Flow

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An experimental investigation of the near field of an axi-symmetric single-phase and particle laden jets is described. A two-component laser Doppler anemometer was used to measure the turbulent flow characteristics. The second phase consisted of glass beads of 80 μm diameter with a mass loading of 1%. Typical flow Reynolds numbers were 29 000 at the jet exit. The measurements indicate that the particles lag behind the fluid by about 8% near the jet exit but lead the fluid by about 7% at 9 jet diameters downstream. The mean velocity profiles of the particle laden flow are flatter, exhibit lower radial rms velocities than those of the fluid and suggest a smaller spread of the beads in the cross-stream direction. Streamwise velocity fluctuations of the particles were found to be higher than the corresponding fluid fluctuations, especially near the jet exit, which can be attributed to the "fan-spreading" of the particles.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL Csaba K. Zoltani	22b. TELEPHONE (Include Area Code) (301) 278-6108 22c. OFFICE SYMBOL SLCBR-IB-A

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

NOMENCLATURE

D	jet pipe diameter
d_p	particle diameter
r	radial coordinate
S_m	mean Stokes number (t_m / t_p)
S_e	mean Stokes number at jet exit
t_m	time scale of mean flow
t_p	particle time constant
U	streamwise component of fluid mean velocity
U_0	bulk velocity of fluid at exit
U_{om}	centerline velocity of fluid at exit
U_p	streamwise component of particle mean velocity
u	streamwise component of fluid rms velocity
u_p	streamwise component of particle rms velocity
uv	cross-correlation of fluid velocity
$u_p v_p$	cross-correlation of particle velocity
v	radial component of fluid rms velocity
v_p	radial component of particle rms velocity
w	tangential component of fluid rms velocity
z	streamwise coordinate
ν_f	kinematic viscosity of the fluid
ρ_p	particle density
ρ_f	fluid density

I. INTRODUCTION

Interior ballistics, and especially the early phase of the ballistic cycle, is marked by the prevalence of two-phase flows. As yet only limited progress has been demonstrated in the measurement of spatially resolved velocity distributions of the phases which is of interest to those trying to model and understand the intricacies of the interior ballistic phenomena. Specific examples include primer flow characterization, the dynamics of liquid droplets in LP (liquid propellant) gun systems and the effect of particulates on the erosion of gun tube walls.

While in-situ measurements under actual firing conditions with the instrumentation described here are not yet possible, building block type studies can yield considerable insight into the nature of two-phase flows. Here, we report on such an approach, measurements on a two-phase, subsonic jet by means of LDV (Laser Doppler Velocimetry). The mass loading was 1% and the jet exit Reynolds number was 29 000. Velocities of both phases as well as the turbulence quantities were measured at several locations downstream of the nozzle exit and transverse to the bulk flow. This flow geometry is akin to the situation encountered in the study of primer flows in cartridge cases.

The report is divided as follows: Section II presents the salient features of the flow and the parameters used to characterize it. Next, the experimental arrangement and the protocol to obtain the data are described. This is followed by a discussion and interpretation of the results in Section IV. The last section draws conclusions from this study.

II. ANALYTICAL BACKGROUND

Spurred by the emergence of several new diagnostic techniques, including LDV, the study of turbulent, dispersed two-phase flows has witnessed a resurgence in the last few years. Several groups of researchers have attempted two-phase flow velocity measurements in particle laden flows. The most notable of these are summarized in Table I and references 1-19. All of the studied flows are characterized by relatively low density of loading and moderate Reynolds number and narrow range of particle sizes. Only in a few cases was data on the nature, character and magnitude of the turbulence presented. Theoretical approaches are discussed in Ref. 5, 20 and 21.

The theory of steady, subsonic jets is well documented and allows us to verify the experimental technique and the reasonableness of the results. We will concentrate on three important aspects of jet behavior: centerline decay, geometric form of the velocity profile and, with the second phase present, the value of the Stokes number, a measure of the responsiveness of the particles to the flow.

Along the axis of the jet, the velocity decay in the far field can be represented by

$$U/U_0 = 6.57\, D/Z \tag{1}$$

due to Spalding, see Ref. 11. The time scale of the flow can be expressed as

$$t_m = (dU/dZ)^{-1} = (D/U_0)\,(Z/D)^2(1/6.57) \tag{2}$$

where again U is the centerline velocity at the point of observation and U_0 is the exit bulk velocity of the jet. It follows that the time scale at the jet exit is then (D/U_0).

In addition, a particle time constant, t_p has to be introduced. Following Snyder and Lumley, Ref. 21, and where ν_f is the fluid kinematic viscosity,

$$t_p = d_p^{\,2}(1 + 2\,\rho_p/\rho_f)\,/\,36\,\nu_f\,. \tag{3}$$

With these parameters a mean Stokes number, S_m can be defined as follows:

$$S_m = t_m\,/\,t_p = S_e\,(1/6.57)\,(Z/D)^2\,, \tag{4}$$

where S_e is the mean Stokes number at the jet exit,

$$S_e = (D/U_0)\,/\,t_p\,, \tag{5}$$

see Hardalupas et al, Ref. 11.

The presence of particles in the flow has an important effect on the development and character of the velocity distribution. The degree of influence of the second phase can be quantified, and trends predicted, if the value of the Stokes number is known. Generally, if $S_m < 1$, the particles are unresponsive to the flow and a mean slip between the two phases occurs. At $S_m \geq 1$, the particles respond to the flow. In general, the momentum flow rate of the gaseous phase is affected by the particulate phase only if the momentum flow rate of the latter exceeds about 10% that of the carrier phase. In addition, it is expected that particle-to-particle interaction will take place for volume loading of more than 0.3%.

III. THE EXPERIMENTAL SETUP

A schematic of the jet flow rig with the instrumentation used for the measurements is shown in Fig. 1. The jet issues vertically downward from a pipe of 25.4 mm in diameter and 0.56 m in length, giving an L/D ratio of 22, to a plexiglass enclosure which eliminates the effects of room air currents and ensures that the particles are contained and safely exhausted out of the room. The enclosure is relatively large with dimensions of 16D x 16D x 16D so that the jet flow can be considered to be unconfined. The air to the jet was supplied from a fan at a steady rate of 9.01 l/s and monitored by a flowmeter within 1% accuracy. The corresponding Reynolds number at the jet exit was 29 000 based on the bulk velocity of 17.7 m/s. The particles were introduced in a plenum upstream of the jet pipe by means of a rotating brush/piston assembly, TSI model 3410 particle disperser. The particle loading was controlled by the piston driven variable speed motor and supplemented by the air flow through the disperser which was provided by a compressor and controlled by a pressure regulator. For the single phase flow measurements the particle disperser was used to seed the flow with titanium dioxide particles of micron size. For the two-phase flow measurements the disperser delivered glass beads of 80μm nominal mean diameter at a mass loading of 1%. The glass beads had a relatively narrow size range of 60-95μm, so that the effects associated with polydispersed particles were minimized.

The velocity of the fluid and particle flow were measured by a two-component, dual-beam laser-Doppler velocimeter mounted on a computer controlled traversing mechanism that allowed the movement of the measurement volume in three directions. The LDV consists of a high power argon laser source (2W) and optics which forms two measuring volumes. The backscattered light from the two control volumes is collected, color separated and each focussed on the pinhole of a photomultiplier. The Bragg cells were used for frequency shifting to resolve negative velocities in both components. The principal characteristics of the laser Doppler velocimeter are summarized in Table 2. The outputs of the photomultipliers were band-pass filtered, amplified and input to two frequency counters which were interfaced with each other and to a microcomputer so as to allow measurements of the two components of velocity within a coincidence time window of around 100μs. The microcomputer stored the data and at the end of data acquisition performed statistical calculations to yield the mean and rms velocities (U, V, W and u, v, w respectively), and the cross-correlations uv and uw.

Consistency of the data was repeatedly verified by retaking data at selected points. The major sources of error associated with the velocity measurements are due to finite-size statistics and velocity gradient broadening effects, Ref. 22. The overall error in the mean velocity is estimated to be of the order of 3% and around 10% for the rms velocity and cross-correlation. Of course, some variation in the radial distribution was noted, especially near the edge of the jet, due to the changing nature of the flow. The magnitude of these errors is considered to be too small to affect the conclusions drawn on the basis of results presented and discussed in the following section. Due to the sparsity of published two-phase flow data and the choice of flow conditions which differ from ours, a direct comparison with the work of others is not possible.

IV. RESULTS AND DISCUSSION

A. Background

In this section sample results selected to depict salient features of the flow are presented and discussed under two headings. The first is concerned with velocity characteristics of the single-phase flow and the second discusses the results of the flow containing the particles and contrasts these with the single phase results. The velocity results are presented in the form of centerline distributions and radial profiles and are all normalized by the mean exit centerline velocity U_{om} of around 20 m/s. This allows not only a clear description of the jet centerline velocity decay but also gives a better comparison between the particle and single-phase flow velocities.

B. Single-Phase Flow

The centerline velocity distributions of the streamwise mean and rms velocity, the radial rms velocity and some of the streamwise velocity probability density functions, also called pdf's, obtained at various downstream locations are shown in Fig. 2. The mean velocity is constant over a distance of 4 jet diameters and the corresponding rms velocity also remains constant over this distance at a value of around 4% of the mean. Further downstream, the mean velocity decays and the rms velocity gradually increases to around 19% of the local mean at z = 9D. The radial rms velocity also increases and is always less than the streamwise value, as expected, by about 30%. The velocity pdf at z = 3D is near Gaussian with a relatively small standard deviation (rms), but at z = 6D the pdf becomes skewed due to the intermittency of the flow as the shear layers start to merge together at around z = 4D. At farther downstream locations the two shear layers mix more readily and the velocity pdf becomes near Gaussian and is typical of the fully developed turbulent jet flow.

A more detailed description of the flow is given in Fig. 3 which shows the radial profiles of the streamwise mean and rms velocity, radial rms velocity and the corresponding Reynolds shear stress of uv at three downstream locations of z = 1D, 5D and 9D. Fig. 3 is consistent with Fig. 2 and shows that the mean velocity profile close to the pipe exit (z = 1D) is similar to fully developed turbulent pipe flow with corresponding rms levels of around 4% on the centerline increasing to a maximum of around 14% of the centerline velocity in the shear layers. As expected, the radial rms velocities are in general 70% of the streamwise values. The profiles show good symmetry about the centerline at all three downstream locations. The velocities obtained along the orthogonal diameter at z = 5D also indicate an excellent axisymmetry of the flow; the transverse rms velocity in this case corresponds, as discussed above, to the tangential component and is almost identical to the radial rms velocity. The mean velocity profiles become flatter at downstream locations as the jet spreads and turbulence tends towards homogeneity, with streamwise rms velocities of around 20% of the centerline velocity at z = 9D. Parenthetically it should be noted that most of the published data on single phase jets deal with the far field, so direct comparison with the data reported here is problematic. However, the trends, observed by Wygnanski and Fiedler, Ref. 23, for example, on centerline velocity decay and radial and axial rms values were also apparent in these measurements.

C. Two-Phase Flow

The velocity measurements of the particle flow are presented in Fig. 4-6. Here, the corresponding single-phase flow results are reproduced to allow comparison of the two flows. It is assumed for the relatively dilute concentrations considered here that the single-phase flow results closely approximate that of the carried phase, as pointed out in Section II. The results of Ref. 11, for example, show almost identical flow fields for the single and carried phase, particularly in the near field of the jet, with mass loadings of the same particles up to 20%.

The Stokesian time constant of the particles, t_p, Equation 3, is about 50 ms and is much higher than the time constant of the mean flow, t_m, Equation 2, which varies from around 1.4 ms at the exit to about 17 ms at z = 9D; the mean slip between the two phases is expected when $t_m < t_p$, i.e. $S_m < 1$. Fig. 4 shows the centerline distributions of the streamwise mean velocity for the two phases and indicates that the glass beads lag the fluid flow by about 8% near the exit, caught up and led it by around 7% at z = 9D. Fig. 4 also presents the streamwise and radial rms velocities together with the pdf's of particle streamwise velocity at various downstream locations. Although the radial rms velocity of the beads is lower than that of the fluid at the same locations along the centerline indicating a relatively small cross-stream spread of the beads, the streamwise rms values are surprisingly higher, up to 3.5 times at the exit, than the corresponding values of the fluid in the region down to about z = 7D. The velocity pdf's are consistent with this observation in that they broaden toward lower velocities compared to those in Fig. 2. There are two possible explanations for this. The first one may be due to the polydispersed nature of the glass beads, albeit they are in a relatively narrow range of 60-95μm. As a consequence, the bigger particles with the larger time constants slip more and move more slowly than the small ones. The second, and probably more plausible explanation, is that of Ref. 11, and referred to as "fan-spreading". There it is argued that the trajectories of the beads at the exit are virtually straight lines rather than "rand m walks" since in their passage through the pipe leading to the exit, the particles bounce off the wall thereby losing most of their velocity in the radial direction. The angle at which the particles spread, outside of the pipe, can be approximated from the ratio of the rms velocity in the radial direction to the flow mean axial velocity which typically turns out to be around ±3 degrees in deviation from the centerline. In a plane parallel to the exit, but a few diameters downstream, at each location contribution to the particle motion from both high velocity, i.e. particles originally near the centerline, and the slower particles which originated from near the exit wall, can be expected, leading to the "broadening" of the velocity. The streamwise velocity at downstream locations is therefore broadened towards lower velocities by contributions from beads originating near the wall, consequently increasing the rms values as observed in Fig. 4.

Fig. 5 shows the comparison of the streamwise mean velocity profiles for the two phases at three downstream locations. The bead velocity profiles are flatter and, consistent with the lower radial rms values of Fig. 4, indicate a lower rate of cross-stream spread of the beads. The corresponding profiles of the turbulence quantities are shown in Fig. 6. As in Fig. 4, the streamwise rms values at the first two downstream locations are higher than fluid rms velocities near the centerline, and everywhere at z = 9D, the two rms values become comparable and support the explanation of "fan-spreading". The cross-correlation values of the beads ($u_p v_p$) are much lower than the fluid values as was also noted in Ref. 11. Thus the particles at this stage are only subsidiary contributors to the total turbulent state of the mixture.

V. CONCLUSIONS

Measurements in an unconfined, axisymmetric, 80μ particle laden jet were carried out in the Interior Ballistic Flow Diagnostic Lab using LDA techniques. The second phase consisted of glass beads with a density of loading of 1%. For comparison, the jet flow parameters were also measured in the absence of the second phase.

The most important findings of these series of experiments were the following:

- Single phase measurements showed excellent axisymmetry of the jet and were consistent with well accepted results for single phase jets.

- The particles having a Stokesian time constant of around 50 ms were unresponsive to the mean and turbulent flow and lagged the fluid by about 8% near the jet exit but later led it by about 7% at 9 jet diameters downstream.

- The mean velocity profiles of the particles were flatter than those of the fluid and together with the lower values of the radial rms velocity, indicate a relatively small cross-stream spread of the beads.

- Surprisingly, the streamwise velocity fluctuations of the particles near the centerline and exit were much higher, up to 3.5 times at the exit, than the corresponding fluid values in a region of up to 7 jet diameters. This observation is consistent with the findings of other investigators and is mainly attributed to the fan-like spreading of the beads in a straight-line trajectory from the jet exit.

More experiments encompassing variations in jet exit diameters, density of loading and the interaction of particle laden jets are under way and will be reported in the near future.

REFERENCES

1. Hetsroni, G., Sokolov, M., "Distribution of Mass, Velocity, and Intensity of Turbulence in a Two-Phase Turbulent Jet.", J. Appl. Mechanics Vol. 38, 315-327, 1971.

2. Popper, J., Abuaf, N., Hetsroni, G., "Velocity Measurements in a Two-Phase Turbulent Jet", Int. Journal Multiphase Flow Volume 1, pp. 751-757, 1974.

3. Levy, Y., Lockwood, F.C., "Velocity Measurements in a Particle Laden Turbulent Free Jet", Combustion and Flame, Volume 40, pp. 333-339, 1981.

4. Wells, H.R., Stock, D.E., "The Effect of Crossing Trajectories on the Dispersion of the Particles in a Turbulent Flow", Journal of Fluid Mechanics, Volume 136, pp. 31-36, 1983.

5. Shuen, J.S., Solomon, A.S.P, Zhang, Q.F., Faeth, G.M., "A Theoretical and Experimental Study of Turbulent Particle-Laden Jets", NASA-CR-168293, 1983.

6. Modaress, D., Tan, H., Elghobashi, S., "Two-Component LDA Measurement in a Two-Phase Turbulent Jet", AIAA J. Volume 22, pp. 624-30, 1984.

7. Boerner, T., Durst, F., Manero, E., "LDV Measurements of Gas-Particle Confined Jet Flow and Digital Data Processing", Proc. Third Int. Symposium on Applications of Laser Anemometry to Fluid Mechanics, LADOAN, Lisbon, 1986.

8. Nouri, J.M., Whitelaw, J.H., Yianneski, M., "Particle Motion and Turbulence in Dense Two-Phase Flows", Int. Journal Multiphase Flows, Volume 13, pp. 729-739, 1987.

9. Fleckhaus, D., Hishida, K., Maeda, M., "Effect of Laden Solid Particles on the Turbulent Flow Structure of a Round Free Jet", Experiments in Fluids, Volume 5, pp. 323-333, 1987.

10. Vames, J.S., Hanratty, T.J., "Turbulent Dispersion of Droplets for Air Flow in a Pipe", Experiments in Fluids, Volume 6, pp. 94-105, 1988.

11. Hardalupas, Y., Taylor, A.M.K.P., Whitelaw, J.H., "Velocity and Particle-Flux Characteristics of Particle-Laden Jets", Imperial College of Science and Technology Fluids Section, Department of Mechanical Engineering Report FS/87/114, June 1988.

12. Csanady, G.T., "Turbulent Diffusion of Heavy Particles in the Atmosphere", J. Atmos. Science, Volume 20, pp. 201-208, 1963.

13. Snyder, W.H., Lumley, J.L., "Some Measurements of Particle Velocity Autocorrelation Functions in a Turbulent Flow", J. Fluid Mechanics, Volume 48, pp. 41-71, 1971.

14. Goldschmidt, V.W., Householder, M.K., Ahmadi, G., Chuang, S.C., "Turbulent Diffusion of Small Particles Suspended in Turbulent Jets", Progress Heat and Mass Transfer, Volume 6, pp. 487-508, 1972.

15. Calabrese, R.V., Middlemen, S., "The Dispersion of Discrete Particles in a Turbulent Fluid Field", AIChE Journal, Volume 25, pp. 1025-1035, 1979.

16. Tsuji, Y., Morikawa, Y., Tanaka, T., Karimine, K., Nishida, S., "Measurement of an Axisymmetric Jet Laden with Coarse Particles", Int. J. Multiphase Flow, Volume 14, No. 5, pp. 565-574, 1988.

17. Parthasarathy, R.N., Faeth, G.M., "Structure of Particle-Laden Turbulent Water Jets in Still Water", Int. Journal Multiphase Flow, Volume 13, pp. 699-716, 1987.

18. Snyder, W.H., Lumley, J.L., "Some Measurements of Particle Velocity Autocorrelation Function in a Turbulent Flow", J. Fluid Mechanics, Volume 48, pp. 41-71, 1971.

19. Tsuji, Y., Morikawa,Y., "LDV Measurement of an Air-Solid Two-Phase Flow in a Horizontal Pipe", J. Fluid Mechanics, Volume 120, pp. 385-409, 1982.

20. Elghobashi, S., Abou-Arab, T., Rizk, M., Mostafa, A., "Prediction of the Particle-Laden Jet with a Two-Equation Turbulence Model", Int. Journal Multiphase Flow, Volume 10, pp. 697-710, 1984.

21. Faeth, G.M., "Mixing, Transport and Combustion of Sprays", Prog. Energy Comb. Science, Volume 13, pp. 293-345, 1987.

22. Durst, F., Melling, A., Whitelaw, J.H., Principles and Practice of Laser-Doppler Anemometry, 2nd Ed., Academic Press, New York, 1981.

23. Wygnanski, I., Fiedler, H., "Some Measurements in the Self-Preserving Jet", J. Fluid Mechanics, Volume 38, pp. 577-612, 1969.

Table I. REPRESENTATIVE TWO–PHASE FLOW MEASUREMENTS

Reference	Flow Configuration	Particle and Particle Size	Reynolds Number	Particle Mass Fraction
Pepper, Abuaf, Hetsroni (1974)	round jet	oil, 50μ	10 600 49 300	1×10^{-3}
Levy and Lockwood (1981)	round jet $x/D = 20$	sand, $215–1060\mu$	25 000	1.14–3.5
Tsuji, Morikawa (1982)	pipe flow 30 mm i.d.	200μ, 3400μ	5 000	not given
Wells and Stock (1983)	square wind tunnel	glass beads 5μ, 57μ	0.887 (particle)	n.a.
Shuen, Solomon, Zhang, Faeth (1984)	round jet $x/D < 50$	sand, $79–207\mu$	19 000	0.2 – 0.66
Modaress, Tan, Elghobashi (1984)	round jet	glass beads	13 300	0.32, 0.85
Vames, Hanratty (1988)	round jet	water droplets $50–150\mu$	96 000	not given
Tsuji et al (1988)	round jet	polystyrene 170–1400M	32 000	not given
present work (1989)	round jet $x/D = 20$	glass beads, 80μ	29 000	1.0

Table II. CHARACTERISTICS OF THE LASER–DOPPLER ANEMOMETER

Laser wavelength	514.5nm	488 nm
Fringe spacing	4.5 μm	4.3 μm
Length of control volume at $1 / e^2$ intensity	0.97 mm	0.93 mm
Diameter of control volume at $1 / e^2$ intensity	56.0 μm	53 μm
Number of fringes at $1 / e^2$ intensity	12	12
Frequency shift	1–5 MHz	5 MHz

Table III. FLOW CONDITIONS AT JET EXIT, Z = 1 D

Jet diameter	2.54 cm
Carrier phase exit velocity (peak)	20.0 m/s
Carrier phase exit velocity (bulk)	17.7 m/s
Turbulence intensity	1.4 %

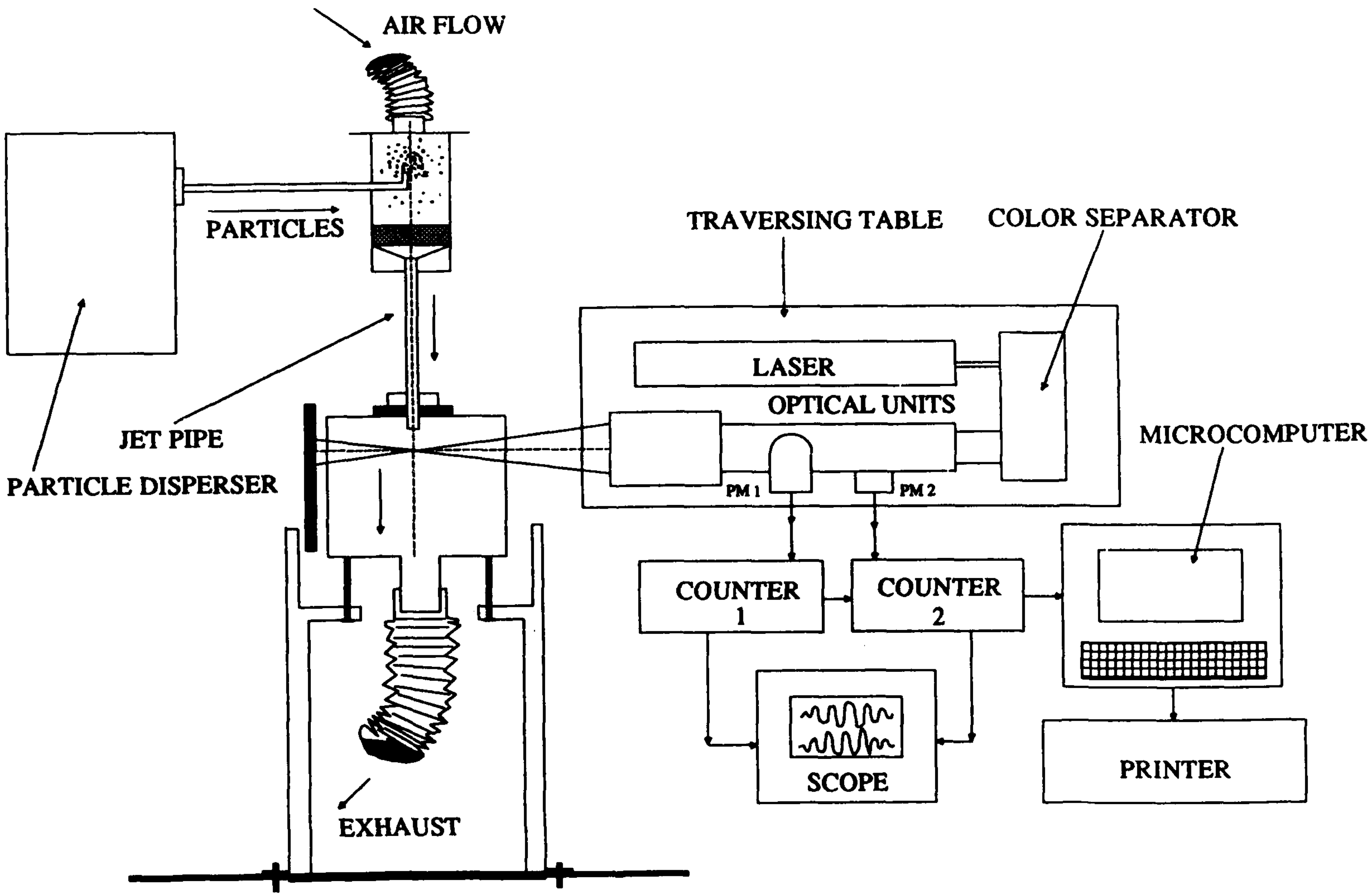

FIGURE 1. LAYOUT OF THE EXPERIMENTAL APPARATUS

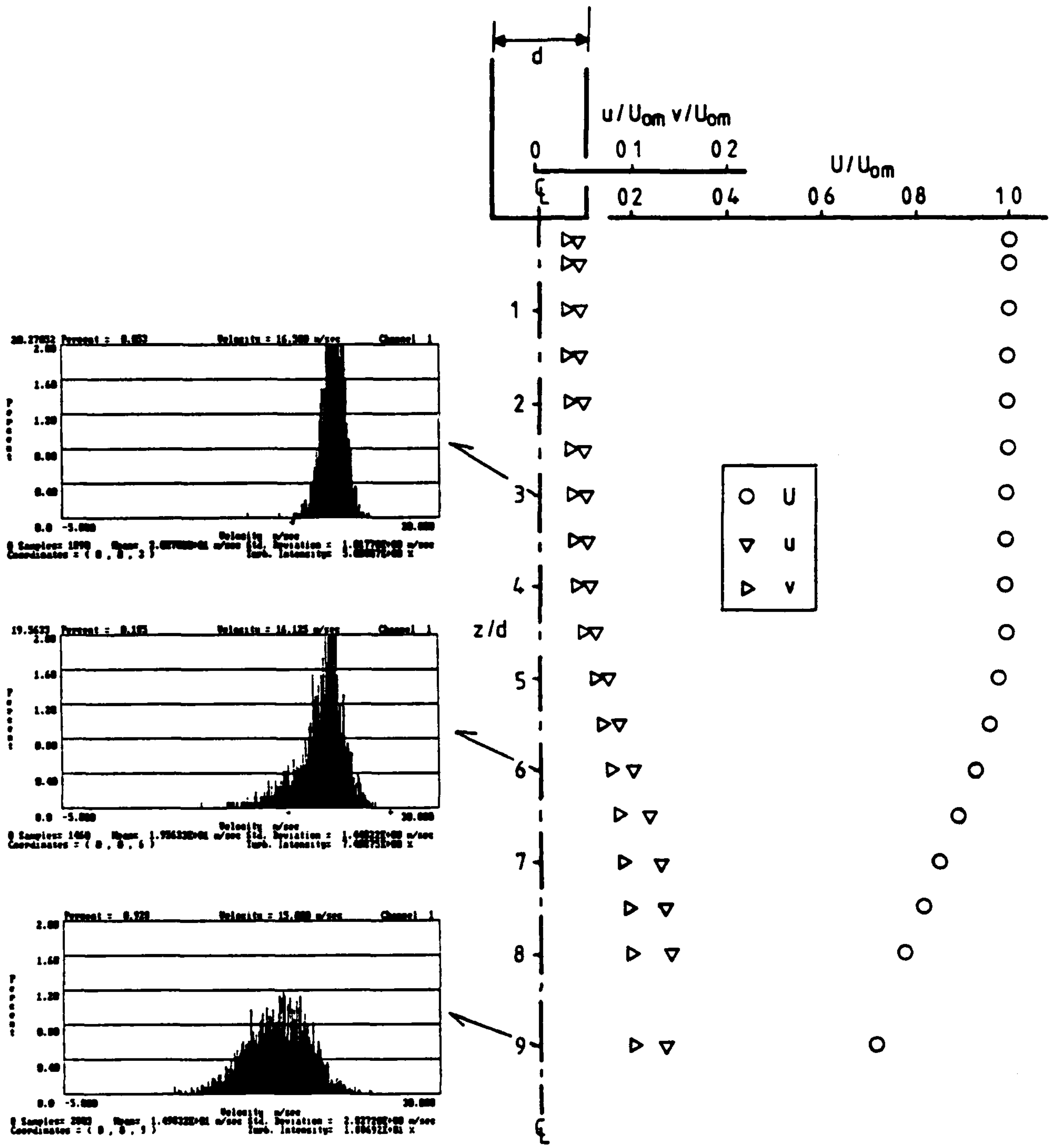

Figure 2. Centerline distribution of mean and rms velocities in single–phase flow.

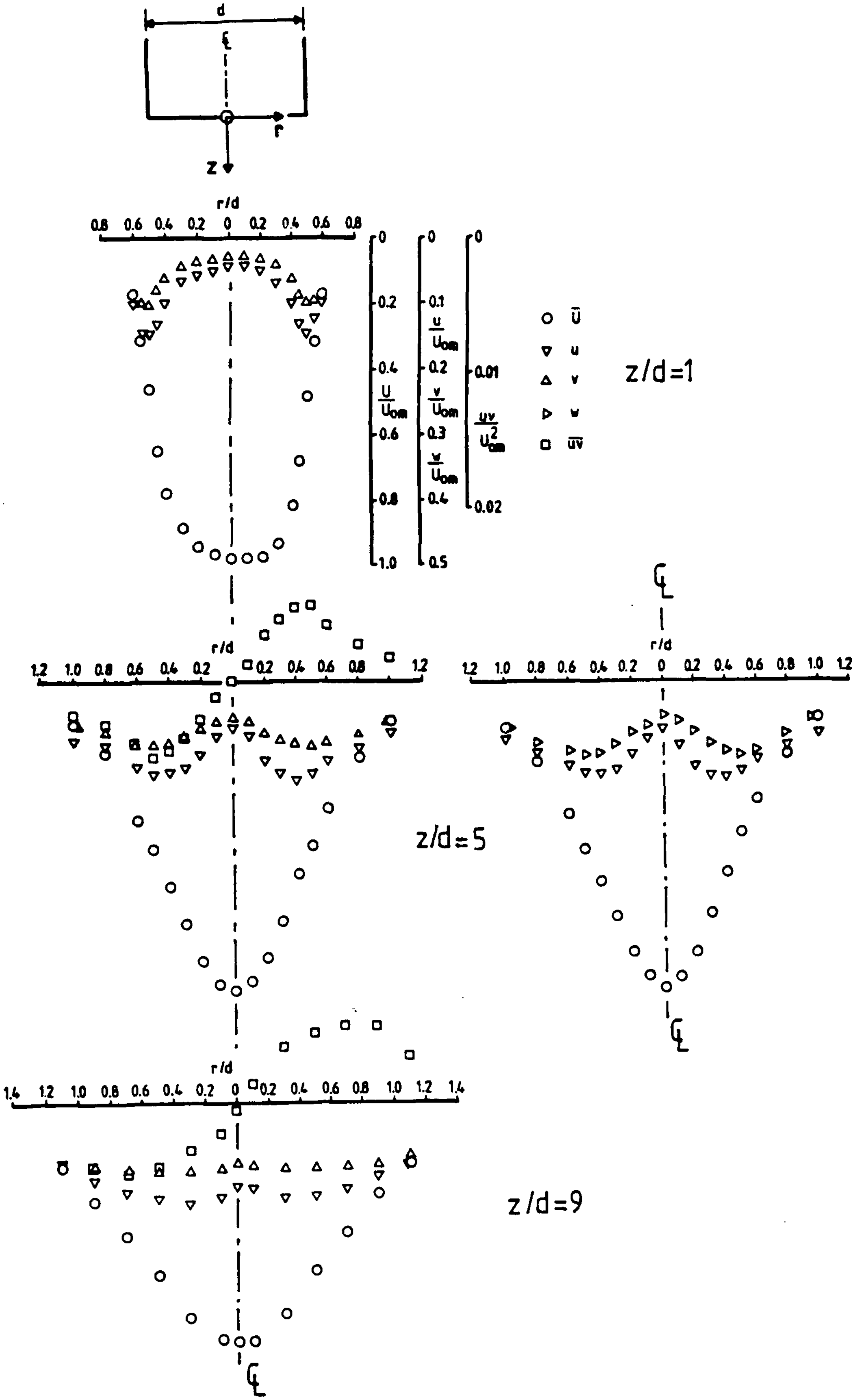

Figure 3. Radial distributions of streamwise mean and rms velocities, radial and tangential rms velocity and cross–correlation of single–phase flow.

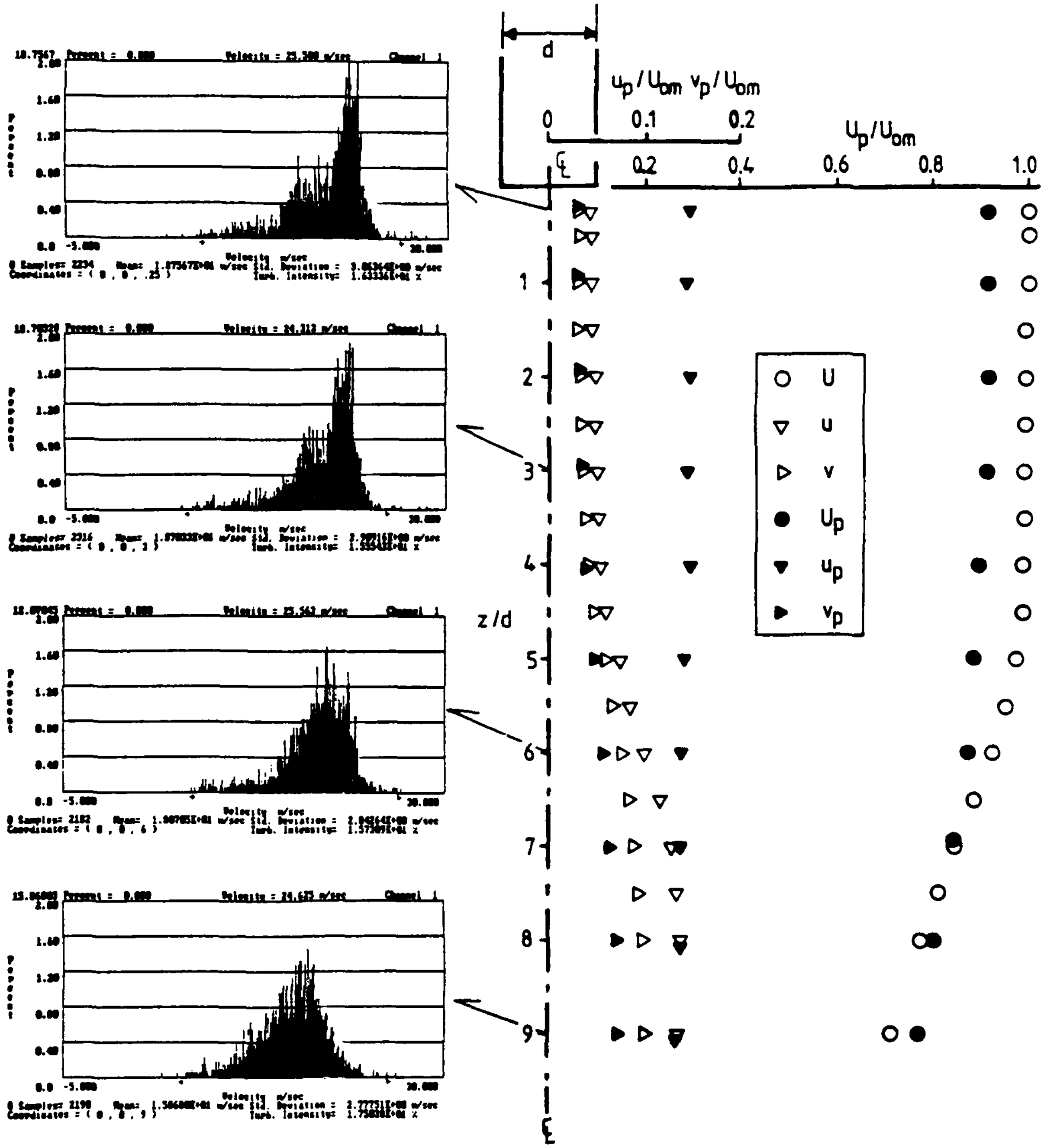

Figure 4. Centerline distributions of streamwise mean and rms velocity and rms velocity of particle flow.

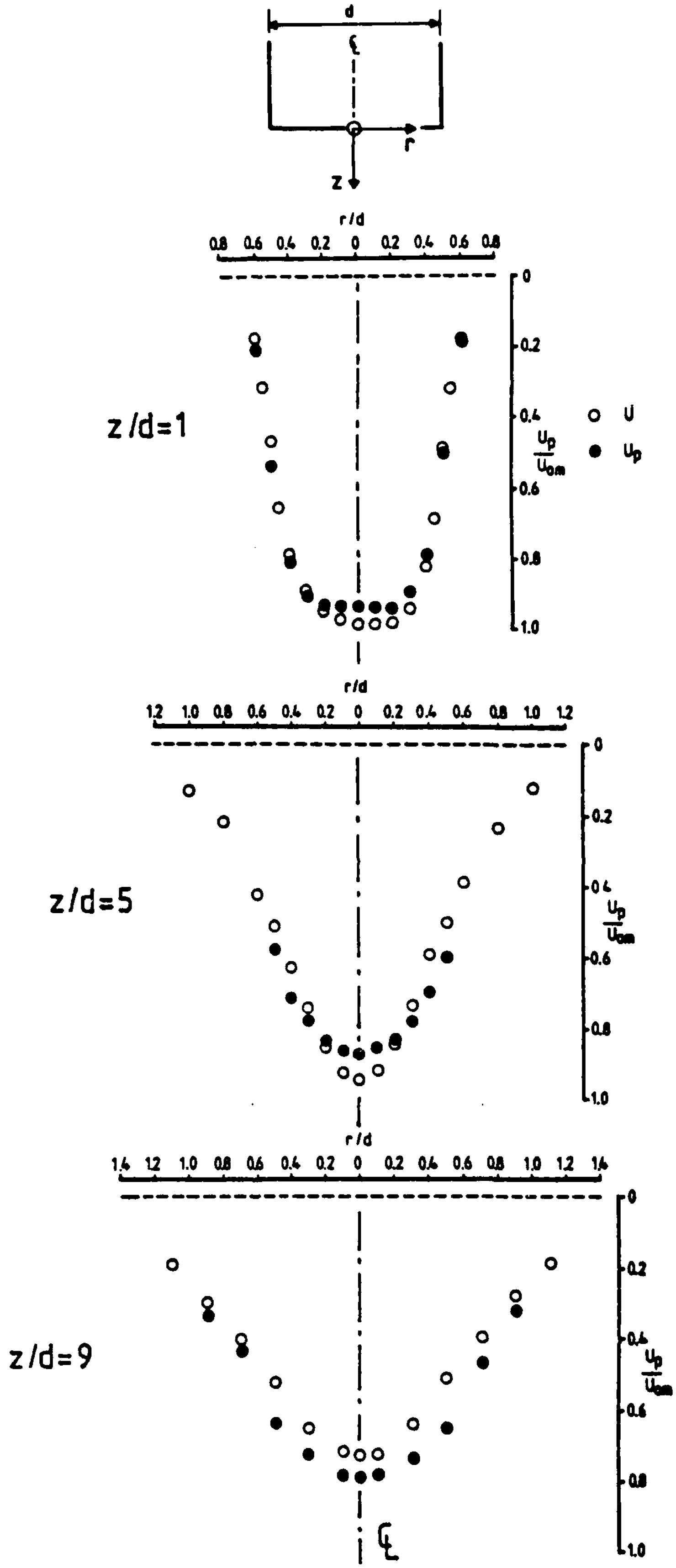

Figure 5. Radial distributions of streamwise mean velocity of particle flow.

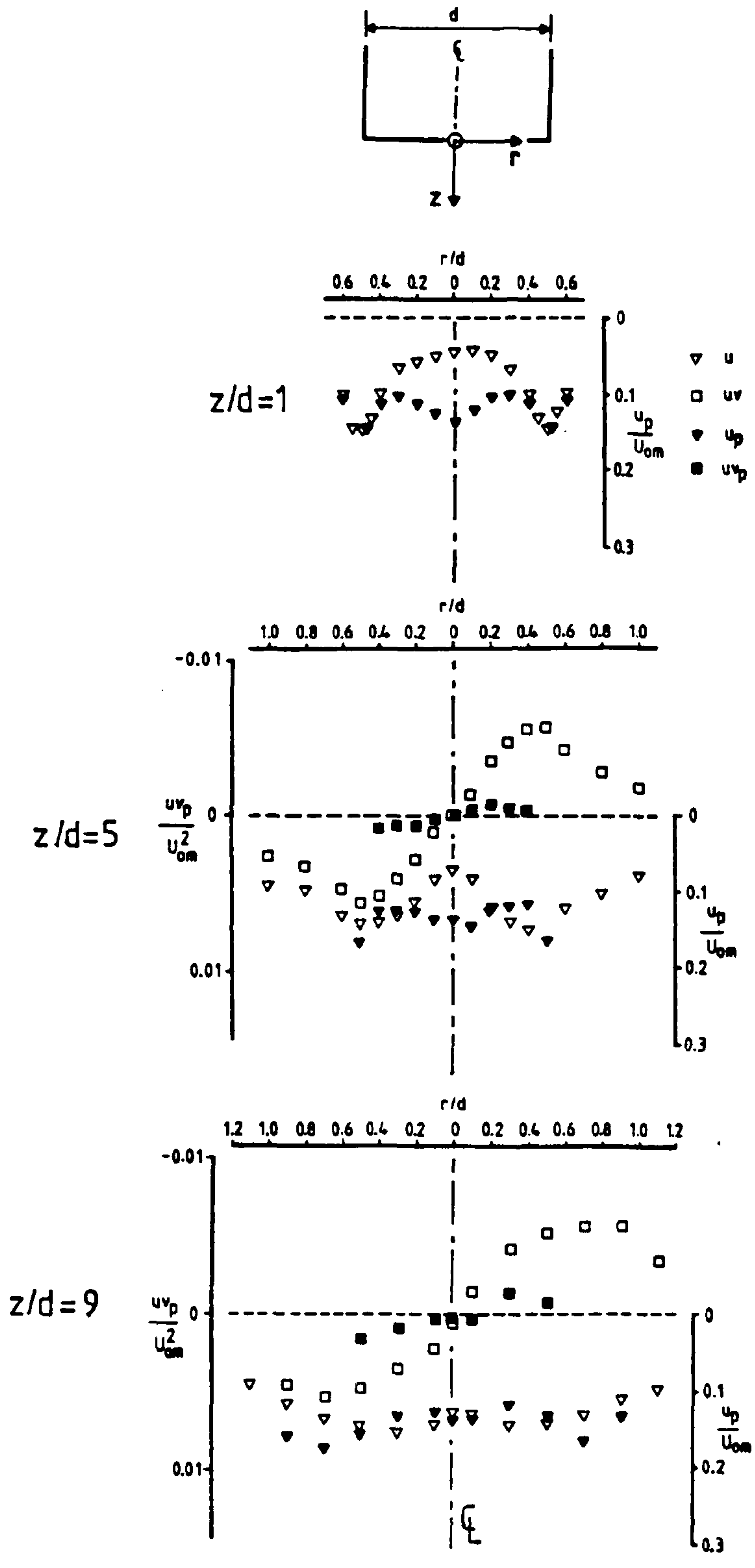

Figure 6. Radial distributions of streamwise rms velocity and cross–correlation of particle flow.

DISTRIBUTION LIST

No. of Copies	Organization
12	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	Commander USA Concepts Analysis Agency ATTN: D. Hardison 8120 Woodmont Avenue Bethesda, MD 20014-2797
1	HQDA/DAMA-ZA Washington, DC 20310-2500
1	HQDA (SARD-TR) Washington, DC 20310-0001
1	HQDA/DAMA-CSM Washington, DC 20310-2500
1	C.I.A. 01R/DB/Standard GE47 HQ Washington, DC 20505
1	Commander US Army War College ATTN: Library-FF229 Carlisle Barracks, PA 17013
1	US Army Ballistic Missile Defense Systems Command Advanced Technology Center P.O. Box 1500 Huntsville, AL 35807-3801
1	Chairman DOD Explosives Safety Board Room 856-C Hoffman Bldg. 1 2461 Eisenhower Avenue Alexandria, VA 22331-9999
1	Commander US Army Materiel Command ATTN: AMCPM-GCM-WF 5001 Eisenhower Avenue Alexandria, VA 22333-5001

No. of Copies	Organization
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-5001
1	Commander US Army Materiel Command ATTN: AMCDE-DW 5001 Eisenhower Avenue Alexandria, VA 22333-5001
5	Project Manager Cannon Artillery Weapons Systems, ARDEC AMCCOM ATTN: AMCPM-CW AMCPM-CWW AMCPM-CWS/M. Fisette AMCPM-CWA/H. Haussman AMCPM-CWA-S/ R. DeKleine Picatinny Arsenal, NJ 07806-5000
2	Project Manager Munitions Production Base Modernization and Expansion ATTN: AMCPM-PBM/A. Siklosi AMCPM-PBM-E/L. Laibson Picatinny Arsenal, NJ 07806-5000
3	Project Manager Tank Main Armament System ATTN: AMCPM-TMA/K. Russell AMCPM-TMA-105 AMCPM-TMA-120 Picatinny Arsenal, NJ 07806-5000
1	Commander US Army Watervliet Arsenal ATTN: SARWV-RD/R. Thierry Watervliet, NY 12189-5001
1	Commander Armament RD&E Center US Army AMCCOM ATTN: SMCAR-MSI Picatinny Arsenal, NJ 07806-5000

DISTRIBUTION LIST

No. of Copies	Organization
1	Commander US Army ARDEC ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
4	Commander US Army Armament Munitions and Chemical Command ATTN: SMCAR-ESP-L Rock Island, IL 61299-5300
1	HQDA DAMA-ART-M Washington, DC 20310-2500
1	Commander US Army AMCCOM ARDEC CCAC ATTN: SMCAR-LCB-TL Benet Weapons Laboratory Watervliet, NY 12189-4050
2	Commander US Army ARDEC ATTN: SMCAR-TDC SMCAR-LC/ LTC N. Barron Picatinny Arsenal, NJ 07806-5000
7	Commander US Army ARDEC ATTN: SMCAR-LCA/ A. Beardell D. Downs S. Einstein S. Westley S. Bernstein C. Roller J. Rutkowski Picatinny Arsenal, NJ 07806-5000
3	Commander US Army ARDEC ATTN: SMCAR-LCB-I/ D. Spring SMCAR-LCE SMCAR-LCM-E/ S. Kaplowitz Picatinny Arsenal, NJ 07806-5000
4	Commander US Army ARDEC ATTN: SMCAR-LCS SMCAR-LCU-CT/ E. Barrieres R. Davitt SMCAR-LCU-CV/ C. Mandala Picatinny Arsenal, NJ 07806-5000
3	Commander US Army ARDEC ATTN: SMCAR-LCW-A/ M. Salsbury SMCAR-SCA/ L. Stiefel B. Brodman Picatinny Arsenal, NJ 07806-5000
2	Commander US Army Aviation Systems Command ATTN: AMSAV-ES AMSAV-DADCL 4300 Goodfellow Blvd. St. Louis, MO 63120-1798
1	Director US Army Aviation Research and Technology Activity Ames Research Center Moffett Field, CA 04035-1099
1	AFWL/SUL Kirtland AFB,NM 87117-5800
1	Commander CECOM R&D Technical Library ATTN: AMSEL-M-L (Report Section) B. 2700 Fort Monmouth, NJ 07703-5000
1	Commander US Army Harry Diamond Laboratory ATTN: DELHD-TA-L 2800 Powder Mill Rd. Adelphi, MD 20783-1145

DISTRIBUTION LIST

No. of Copies	Organization	No. of Copies	Organization
1	Commander US Army Laboratory Command ATTN: AMSLC-DL Adelphi, MD 20783-1145	1	Project Manager M-60 Tank Development ATTN: AMCPM-M60TD Warren, MI 48092-2498
1	Commander US Army Missile and Space Intelligence Center ATTN: AMSMI-AS Redstone Arsenal, AL 35898-5500	2	Director US Army TRADOC Systems Analysis Activity ATTN: ATOR-TSL ATAA-SL White Sands Missile Range, NM 88002-5502
1	Commandant US Army Aviation School ATTN: Aviation Agency Fort Rucker, AL 36360	1	Commander US Army Training & Doctrine Command ATTN: ATCD-MA/MAJ Williams Fort Monroe, VA 23651
2	Commander US Army Tank Automotive Command ATTN: AMSTA-TSL AMSTA-CG Warren, MI 48397-5000	2	Commander US Army Materials and Mechanics Research Center ATTN: AMXMR-ATL Watertown, MA 02172
1	Project Manager US Army Tank Automotive Command Improved TOW Vehicle ATTN: AMCPM-ITV Warren, MI 48397-5000	1	Commander US Army Research Office ATTN: Tech Library P.O. Box 12211 Research Triangle Park, NC 27709-2211
2	Program Manager M1 Abrams Tank System ATTN: AMCPM-GMC-SA/ T. Dean Warren, MI 48092-2498	1	Commander US Army Belvoir Research and Development Center ATTN: STRBE-WC Fort Belvoir, VA 22060-5606
1	Project Manager Fighting Vehicle Systems ATTN: AMCPM-FVS Warren, MI 48092-2498	1	Commander US Army Logistics Mgmt Ctr Defense Logistics Studies Fort Lee, VA 23801
1	President US Army Armor & Engineer Board ATTN: ATZK-AD-S Fort Knox, KY 40121-5200	1	Commandant US Army Infantry School ATTN: ATSH-CD-CS0-OR Fort Benning, GA 31905-5660

DISTRIBUTION LIST

No. of Copies	Organization
1	Commandant US Army Command and General Staff College Fort Leavenworth, KS 66027
1	Commandant US Army Special Warfare School ATTN: Rev & Tng Lit Div Fort Bragg, NC 28307
3	Commander Radford Army Ammunition Plant ATTN: SMCAR-QA/HI LIB Radford, VA 24141-0298
1	Commander US Army Foreign Science & Technology Center ATTN: AMXST-MC-3 220 Seventh Street, NE Charlottesville, VA 22901-5396
2	Commander Naval Sea Systems Command ATTN: SEA 62R SEA 64 Washington, DC 20362-5101
1	Commander Naval Air Systems Command ATTN: AIR-954-Tech Lib Washington, DC 20360
1	Assistant Secretary of the Navy (R, E, and S) ATTN: R. Reichenbach Room 5E787 Pentagon Bldg. Washington, DC 20375
1	Naval Research Laboratory Tech Library Washington, DC 20375
2	Commandant US Army Field Artillery Center & School ATTN: ATSF-CO-MW/B. Willis Ft. Sill, OK 73503-5600
1	Commander US Army Development and Employment Agency ATTN: MODE-ORO Fort Lewis, WA 98433-5099
1	Office of Naval Research ATTN: Code 473, R.S. Miller 800 N. Quincy Street Arlington, VA 22217-9999
3	Commandant US Army Armor School ATTN: ATZK-CD-MS/ M. Falkovitch Armor Agency Fort Knox, KY 40121-5215
2	Commander US Naval Surface Weapons Center ATTN: J.P. Consaga C. Gotzmer Indian Head, MD 20640-5000
4	Commander Naval Surface Weapons Center ATTN: Code 240/S. Jacobs Code 730 Code R-13/K. Kim R. Bernecker Silver Spring, MD 20903-5000
2	Commanding Officer Naval Underwater Systems Center Energy Conversion Dept. ATTN: Code 5B331/R.S. Lazar Tech Lib Newport, RI 02840

DISTRIBUTION LIST

No. of Copies	Organization
5	Commander Naval Surface Weapons Center ATTN: Code G33/J.L. East W. Burrell J. Johndrow Code G23/D. McClure Code DX-21 Tech Lib Dahlgren, VA 22448-5000
5	Commander Naval Weapons Center ATTN: Code 388/R.L. Derr C.F. Price T. Boggs T. Parr Info Sci Div China Lake, CA 93555-6001
2	Superintendent Naval Postgraduate School Dept. of Mech. Engineering Monterey, CA 93943-5100
1	Program Manager AFOSR Directorate of Aerospace Sciences ATTN: L.H. Caveny Bolling AFB, DC 20332-0001
6	Commander Naval Ordnance Station ATTN: P.L. Stang L. Torreyson T.C. Smith D. Brooks W. Vienna Tech Library Indian Head, MD 20640-5000
1	AFSC/SDOA Andrews AFB, MD 20334
3	AFRPL/DY, Stop 24 ATTN: J. Levine/DYCR R. Corley/DYC D. Williams/DYCC Edwards AFB, CA 93523-5000
1	AF Astronautics Laboratory AFAL/TSTL (Technical Library) Edwards AFB, CA 93523-5000
1	AFATL/DLYV Eglin AFB, FL 32542-5000
1	AFATL/DLXP Eglin AFB, FL 32542-5000
1	AFATL/DLJE Eglin AFB, FL 32542-5000
1	Air Force Armament Laboratory AFATL/DLODL ATTN: Tech Info Center Eglin AFB, FL 32542-5000
1	NASA/Lyndon B. Johnson Space Center ATTN: NHS-22 Library Section Houston, TX 77054
1	AFELM, The Rand Corporation ATTN: Library D 1700 Main Street Santa Monica, CA 90401-3297
3	AAI Corporation ATTN: J. Herbert J. Frankle D. Cleveland P.O. Box 126 Hunt Valley, MD 21030-0126
1	Aerojet Ordnance Company ATTN: D. Thatcher 2521 Michelle Drive Tustin, CA 92680-7014
1	Aerojet Solid Propulsion Co. ATTN: P. Micheli Sacramento, CA 95813
1	Atlantic Research Corporation ATTN: M.K. King 5390 Cheorokee Avenue Alexandria, VA 22312-2302

DISTRIBUTION LIST

No. of Copies	Organization
1	AVCO Everett Rsch Lab ATTN: D. Stickler 2385 Revere Beach Parkway Everett, MA 02149-5936
2	Calspan Corporation ATTN: C. Murphy P.O. Box 400 Buffalo, NY 14225-0400
1	General Electric Company Armament Systems Dept. ATTN: M.J. Bulman 128 Lakeside Avenue Burlington, VT 05401-4985
1	IITRI ATTN: M.J. Klein 10 W. 35th Street Chicago, IL 60616-3799
1	Hercules Inc. Allegheny Ballistics Laboratory ATTN: R.B. Miller P.O. Box 210 Cumberland, MD 21501-0210
1	Hercules Inc. Bacchus Works ATTN: K.P. McCarty P.O. Box 98 Magna, UT 84044-0098
1	Hercules Inc. Radford Army Ammunition Plant ATTN: J. Pierce Radford, VA 24141-0299
2	Lawrence Livermore National Laboratory ATTN: L-355/ A. Buckingham M. Finger P.O. Box 808 Livermore, CA 94550-0622

No. of Copies	Organization
1	Lawrence Livermore National Laboratory ATTN: L-324/M. Constantino P.O. Box 808 Livermore, CA 94550-0622
1	Olin Corporation Badger Army Ammunition Plant Baraboo, WI 53913
1	Olin Corporation Smokeless Powder Operations ATTN: D.C. Mann P.O. Box 222 St. Marks, FL 32355-0222
1	Paul Gough Associates, Inc. ATTN: P.S. Gough P.O. Box 1614 1048 South St. Portsmouth, NH 03801-1614
1	Physics International Company ATTN: Library/H. Wayne Wampler 2700 Merced Street San Leandro, CA 94577-5602
1	Princeton Combustion Research Lab., Inc. ATTN: M. Summerfield 475 US Highway One Monmouth Junction, NJ 08852-9650
2	Rockwell International Rocketdyne Division ATTN: BA08/J.E. Flanagan J. Gray 6633 Canoga Avenue Canoga Park, CA 91303-2703
1	Science Applications, Inc. ATTN: R.B. Edelman 23146 Cumorah Crest Drive Woodland Hills, CA 91364-3710

DISTRIBUTION LIST

No. of Copies	Organization
3	Thiokol Corporation Huntsville Division ATTN: D. Flanigan R. Glick Tech Library Huntsville, AL 35807
2	Thiokol Corporation Elkton Division ATTN: R. Biddle Tech Library P.O. Box 241 Elkton, MD 21921-0241
1	Veritay Technology, Inc. ATTN: E. Fisher 4845 Millersport Hwy. P.O. Box 305 East Amherst, NY 14501-0305
1	Universal Propulsion Company ATTN: H.J. McSpadden Black Canyon Stage 1 Box 1140 Phoenix, AZ 85029
1	Battelle Memorial Institute ATTN: Tech Library 505 King Avenue Columbus, OH 43201-2693
1	Brigham Young University Dept. of Chemical Engineering ATTN: M. Beckstead Provo, UT 84601
1	California Institute of Tech 204 Karman Lab Main Stop 301-46 ATTN: F.E.C. Culick 1201 E. California Street Pasadena, CA 91109
1	California Institute of Tech Jet Propulsion Laboratory ATTN: L.D. Strand 4800 Oak Grove Drive Pasadena, CA 91109-8099

No. of Copies	Organization
1	University of Illinois Dept of Mech/Indust Engr ATTN: H. Krier 144 MEB; 1206 N. Green St. Urbana, IL 61801-2978
1	University of Massachusetts Dept of Mech Engineering ATTN: K. Jakus Amherst, MA 01002-0014
1	University of Minnesota Dept of Mech Engineering ATTN: E. Fletcher Minneapolis, MN 55414-3368
1	Case Western Reserve University Division of Aerospace Sciences ATTN: J. Tien Cleveland, OH 44135
3	Georgia Institute of Tech School of Aerospace Eng ATTN: B.T. Zinn E. Price W.C. Strahle Atlanta, GA 30332
1	Institute of Gas Technology ATTN: D. Gidaspow 3424 S. State Street Chicago, IL 60616-3896
1	Johns Hopkins University Applied Physics Laboratory Chemical Propulsion Information Agency ATTN: T. Christian Johns Hopkins Road Laurel, MD 20707-0690
1	Massachusetts Institute of Technology Dept of Mechanical Engineering ATTN: T. Toong 77 Massachusetts Avenue Cambridge, MA 02139-4307

DISTRIBUTION LIST

No. of Copies	Organization
1	Pennsylvania State University Applied Research Laboratory ATTN: G.M. Faeth University Park, PA 16802-7501
1	Pennsylvania State University Dept of Mech Engineering ATTN: K. Kuo University Park, PA 16802-7501
1	Purdue University School of Mechanical Engineering ATTN: J.R. Osborn TSPC Chaffee Hall West Lafayette, IN 47907-1199
1	SRI International Propulsion Sciences Division ATTN: Tech Library 333 Ravenswood Avenue Menlo Park, CA 94025-3493
1	Rensselaer Polytechnic Inst. Department of Mathematics Troy, NY 12181
2	Director Los Alamos Scientific Lab ATTN: T3/D. Butler M. Division/B. Craig P.O. Box 1663 Los Alamos, NM 87544
1	Stevens Institute of Technology Davidson Laboratory ATTN: R. McAlevy, III Castle Point Station Hoboken, NJ 07030-5907
1	Rutgers University Dept of Mechanical and Aerospace Engineering ATTN: S. Temkin University Heights Campus New Brunswick, NJ 08903
1	University of Southern California Mechanical Engineering Dept. ATTN: 0HE200/M. Gerstein Los Angeles, CA 90089-5199
2	University of Utah Dept. of Chemical Engineering ATTN: A. Baer G. Flandro Salt Lake City, UT 84112-1194
1	Washington State University Dept of Mech Engineering ATTN: C.T. Crowe Pullman, WA 99163-5201
1	Honeywell Inc. ATTN: R.E. Tompkins MN38-3300 10400 Yellow Circle Drive Minnetonka, MN 55343

DISTRIBUTION LIST

Aberdeen Proving Ground

Dir, USAMSAA
    ATTN: AMXSY-D
              AMXSY-MP/H. Cohen

Cdr, USATECOM
    ATTN: AMSTE-SI-F
              AMSTE-CM-F/L. Nealley
              AMSTE-TO-F

Cdr, CSTA
    ATTN: STECS-AS-H/R. Hendricksen

Cdr, CRDEC, AMCCOM
    ATTN: SMCCR-RSP-A
              SMCCR-MU
              SMCCR-MSI

USER EVALUATION SHEET/CHANGE OF ADDRESS

This laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers below will aid us in our efforts.

1. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______________________________

2. How, specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______________________________

3. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______________________________

4. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______________________________

BRL Report Number ____________ Division Symbol ____________

Check here if desire to be removed from distribution list. ____

Check here for address change. ____

Current address: Organization ____________

Address ____________

------------------------------FOLD AND TAPE CLOSED------------------------------

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T(NEI)
Aberdeen Proving Ground, MD 21005-5066

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

BUSINESS REPLY LABEL

FIRST CLASS PERMIT NO 12062 WASHINGTON D.C.

POSTAGE WILL BE PAID BY DEPARTMENT OF THE ARMY

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T(NEI)
Aberdeen Proving Ground, MD 21005-9989