DOE/ER/13838--4

DE92 003671

Progress Report

DOE Project DE-FG05-88ER13838-A005

LAGRANGIAN ANALYSIS OF CONTAMINANT DISPERSAL IN BOUNDED TURBULENT SHEAR FLOWS

P. S. Bernard, J. M. Wallace, J.-L. Balint

February 1, 1991 - December 31, 1991.

1. February 1 - June 30, 1991.

a. A program implementing a pseudo-spectral solution to the scalar transport equation in fully developed channel flow was written. This solves the Navier-Stokes equations simultaneously with the non-dimensionalized passive scalar equation

$$\frac{\partial C}{\partial t} + U_i \frac{\partial C}{\partial x_i} = \frac{1}{R\ Sc} \nabla^2 C + Q \tag{1}$$

where Q is an arbitrary source term, R is the Reynolds number and Sc is the Schmidt number. The code has been written to accept the imposition of either Dirichlet or Neumann boundary conditions for the contaminant concentration C. Note that the numerical solutions are equally valid for the case of thermal diffusion, i.e., writing C as the temperature T and replacing Sc by the Prandtl number Pr. The flexibility in boundary conditions allows the treatment of a useful range of physical situations for either heat or mass transport.

b. Comparisons of the transient numerical solutions with exact solutions for transport in the absence of a velocity field were made. Two particular cases were examined, including transport due to a constant source with zero initial condition, and the diffusion from an initial state $C(x, y, z, 0) = \cos(\pi y/2)$ in the absence of a source term. The agreement between the exact and computed solutions was found to be excellent.

2. July 1 - September 30, 1991.

a. Calculations of the numerical solution for the transported scalar field in the case of fully developed turbulent channel flow at Reynolds number $R_\tau = U_\tau h/\nu = 250$ were made. Here, U_τ is the friction velocity and h is the channel width. The numerical solution

domain expressed in wall units, i.e., lengths scaled by ν/U_τ, was $1250 \times 250 \times 625$ in the streamwise, wall-normal and spanwise directions, respectively. The numerical mesh contained $64 \times 65 \times 64$ points in the three coordinate directions. Converged solutions for T were obtained for the case of a uniform source term and $Pr = .1, .71$ and 2.0. These solutions for the mean temperature $\overline{T}$ and mean-square temperature field, $\overline{T'^2}$, agreed well with previous results of Kim and Moin, at Reynolds number $R_\tau = 360$. For example, in the case of $\overline{T'^2}$, the peak value was at the same y^+ position in both calculations.

b. A code was developed and tested for setting up data files of velocity and scalar fields in reverse time order. This procedure is valuable in speeding up the calculation of backward particle paths, which are needed in the Lagrangian transport analysis.

c. A code was written to compute particle paths through the stored sets of velocity fields using a high order Hermite interpolation scheme. At each position of the fluid particles, the velocities, vorticities and scalar fields are computed and stored for later use in evaluating the terms in the Lagrangian expansions of the transport correlations.

d. Calculations have been made of the diffusion from a point source of contaminant released in a turbulent channel flow. The source term in the concentration equation is given a Gaussian form which effectively narrows the release point to a small volume in the flow. From an initial state of zero contaminant, the source is turned on and the time development of the ensuing plumes is calculated. An example of the instantaneous contours computed 500 time steps after initiation of the release is shown in Figure 1. Views from the top and side are given. The center of the release point, which is at the position $y^+ = 25$, is indicated by a small square. It is interesting to observe the presence of a number of local maxima of concentration in the developing plume which reflect the underlying eddy structure of the flow.

e. Digital image processing of flow visualization video sequences, taken simultaneously with vorticity probe measurements in a turbulent boundary layer, were carried out. Smoke particles were injected 3.5 m downstream of the boundary layer leading edge. At this station the Reynolds number based on momentum thickness was $R_\theta = 1000$ and the boundary layer thickness was $\delta = 6.5$cm. The smoke was illuminated by a rotating sheet of light generated by a 5W argon laser reflecting off a 16-face rotating mirror. The passage of the light sheet was synchronized with the image recording and the probe signals. The sequence analyzed was taken at a downstream distance of $X = 30$ cm from the smoke injection slot and with the probe positioned at $y^+ \approx 85$ from the wall. Figure 2 (a) shows a typical case where smoke activity was low and not transported up to the probe measuring volume. The image has been digitally enhanced using a random pseudo-color technique. Figure 2 (b) by contrast, displays a case where the smoke intersects the probe location. The probe tip can be seen at the lower left corner of the pictures. The video images were digitized with a resolution of 512 x 512 pixels. The field of view is about 19.5 cm, thus giving a resolution of 0.40 mm per pixel. Using a calibration method which relates the digital grey levels to relative mass concentration levels, two-dimensional statistical maps of the turbulent concentration field were generated. In addition to long time average statistics, conditional statistics based on events detected by the vorticity probe were also generated. The detection criterion was based on intense Reynolds stress generating (Q2: - u and + v) events with magnitudes 10 times higher than the long time average value $\overline{uv}$

Figure 3 (a) shows the mean concentration field obtained from a sequence of 381 successive frames. The conditional average of 231 images detected on intense Q2 events is shown in Figure 3 (b). For both figures, the mean concentration levels are coded into pseudocolors. The lowest level band on the bar chart is nearly zero concentration and the highest on the bar chart corresponds to 19% of the intial smoke concentration injected at the slot. We notice that the conditional average plume spreads more than the unconditioned one. The same observation is made on Figures 4 (a) and (b) which represents the unconditioned and conditioned rms concentrations, respectively. Here the lowest band on the pseudocolor rms maps also represents nearly zero concentration but the highest band represents 6% of the intial smoke concentration level at the slot. Both mean and rms maps show a thickening of the plume when conditioned by intense Q2 events.

3. Current and Future Research, October 1, 1991 - December, 31 1991.

a. At the present time an ensemble of plumes developing from given point sources at a fixed y^+ distance are being calculated. After averaging, these will give a picture of the mean diffusion from a point source. Initially, the case of $Pr = .71$ is being treated, which can be readily compared with the thermal contaminant data to be obtained from an experiment presently being developed. Data is being computed for five plumes on each wall of the channel, repeated a sufficient number of times until the statistics have converged. By limiting the calculation to five plumes to a plane, it is possible to separate the plumes sufficiently so that they do not interfere with each other over the time period of the simulation. Independent sets of data are calculated by systematically starting the plumes from different points in the flow, as well as from different times of the simulation.

b. Data is also being obtained for the diffusion from a line source. In this case it is possible to compute just one plume at a time from each wall of the channel. Accumulation of the necessary statistics will be made by performing a sufficient number of independent calculations so that converged statistics are achieved. The necessary ensemble of data can be obtained by varying the streamwise position of the line source as well as the time of release.

c. Once the converged data sets are obtained for the point and line sources and compared to the experiments, we will then compute particle paths backward in time so that we can perform a Lagrangian decomposition of the turbulent transport correlation as specified in our proposal.

d. In order to make comparisons with the experimental data of smoke released into the turbulent flow, for which the Schmidt number is very large, we can obtain mean concentration data by tracking the forward time development of large numbers of fluid particles released at fixed points throughout the flow. This data set can be obtained concurrently with the data in points 3a and 3b above.

e. The converged solution for the temperature field due to a uniform source in a channel flow provides a good opportunity to explore the origins of transport in a simplified setting. In particular, the mean temperature profiles are one dimensional, so diffusion in just one direction, normal to the wall, can be examined. The necessary coding to accomplish this has been completed, and the acquisition of the necessary particle paths will soon be forthcoming.

f. The digital image processing of the experimental data will be refined and extended to third and fourth order moments. In addition, long time averaged and conditional correlations of the type $\overline{v_i c}$ or $\overline{\omega_i c}$ (where u_i and ω_i are fluctuating velocity and vorticity components, respectively and c is the relative fluctuating concentration level) will be determined at the various probe locations. These results will be compared to the line source numerical simulations.

g. Experiments utilizing heat as a passive contaminant emanating from point line and uniform sources are being planned and developed to be carried out in the summer of 1992.

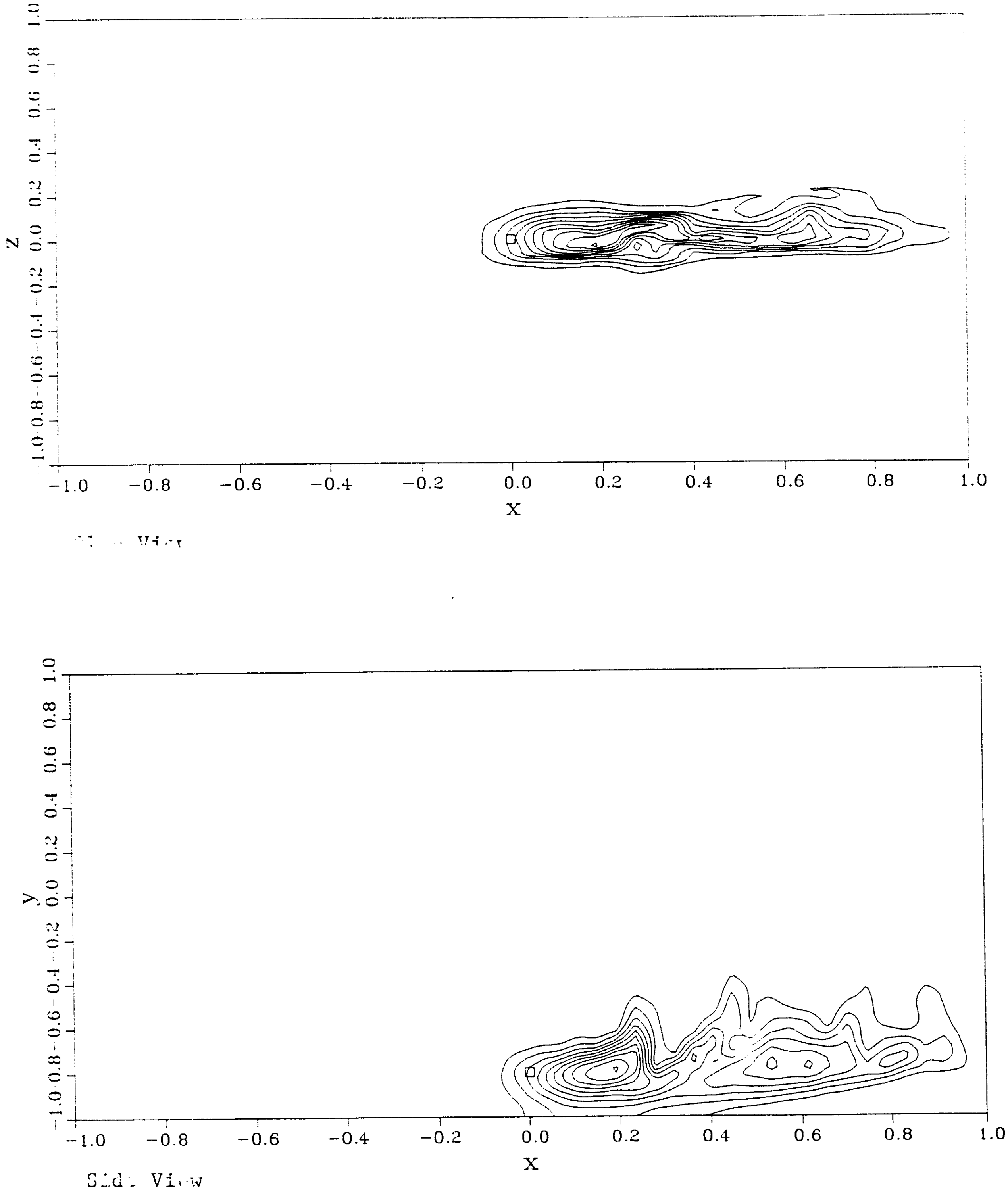

Figure 1. Typical plume calculated in numerically simulated turbulent channel flow.

(a)

(b)

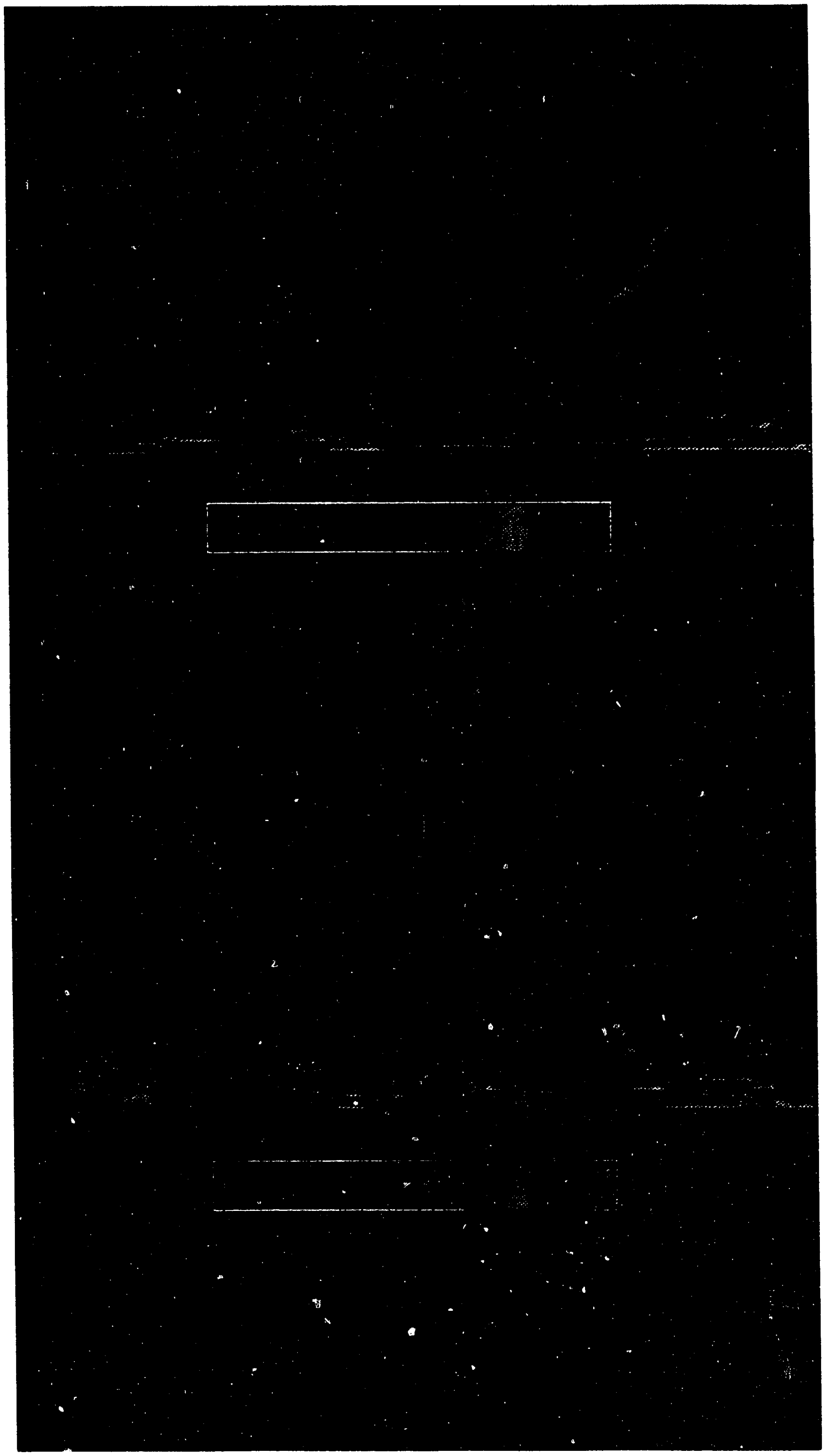

Figure 2

(a)

(b)

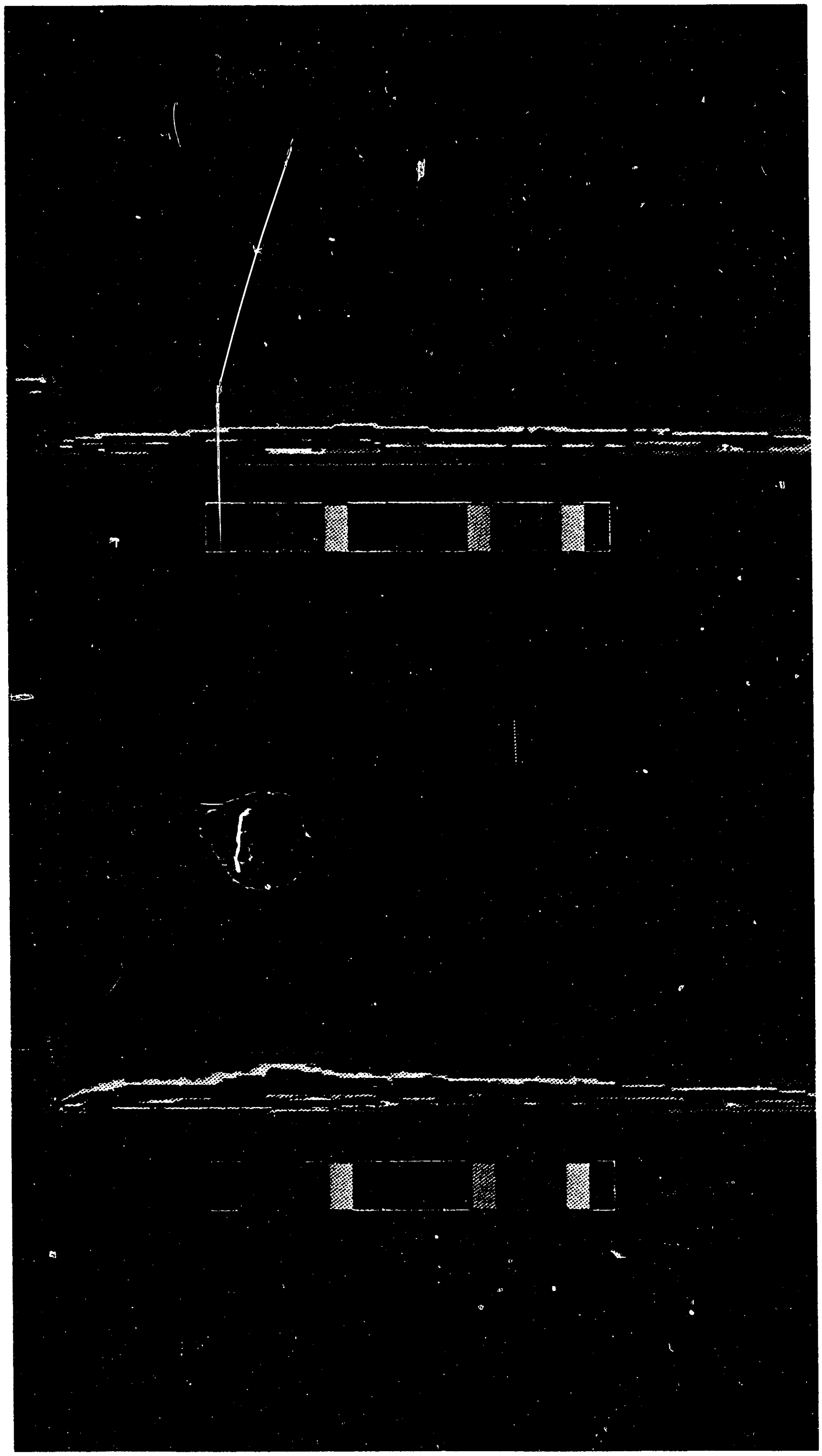

Figure 3

(a)

(b)

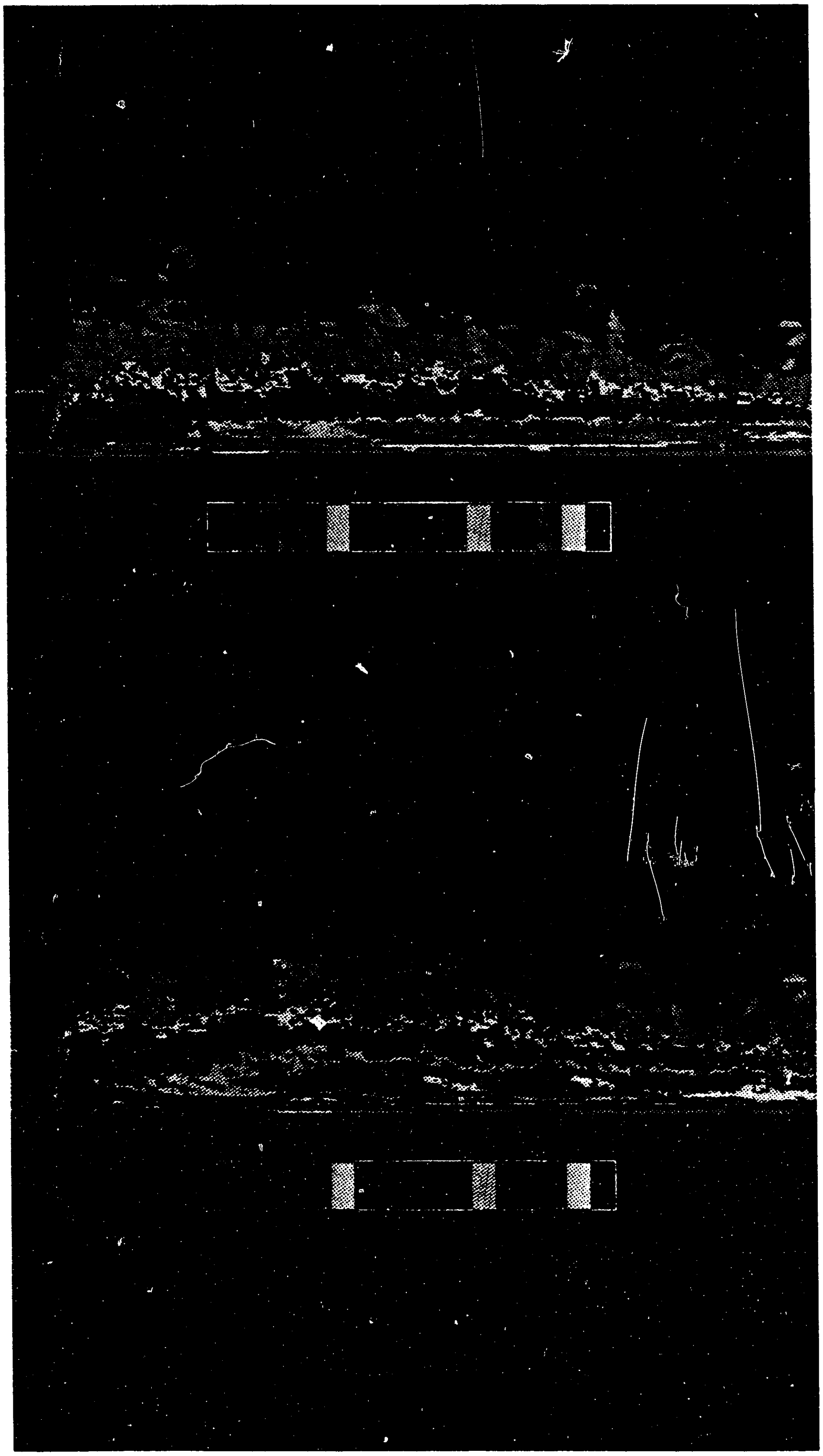

Figure 4

Supplement to Progress Report for

DOE Project DE-FG05-88ER13838-A005

LAGRANGIAN ANALYSIS OF CONTAMINANT DISPERSAL IN BOUNDED TURBULENT SHEAR FLOWS

P. S. Bernard, J. M. Wallace, J.-L. Balint

February 1, 1991 - December 31, 1991.

LIST OF PUBLICATIONS

PAPERS

P. Vukoslavcevic, J. M. Wallace, & J.-L. Balint, "The velocity and vorticity vector fields of a turbulent boundary layer. Part 1. Simultaneous measurement by hot-wire anemometry", J. Fluid Mech. 228, pp.25 - 51.

J.-L. Balint, J. M. Wallace, & P. Vukoslavcevic, "The velocity and vorticity vector fields of a turbulent boundary layer. Part 2. Statistical properties", J. Fluid Mech. 228, pp. 53 - 86.

J. M. Wallace, J.-L. Balint,& L. Ong, "An experimental study of helicity density in turbulent flows", submitted to Physics of Fluids.

R. A. Handler, P. S. Bernard, A. Rovelstad and J. Swearingen, "On the Role of Accelerating Particles in the Generation of Reynolds Stress", submitted to *The Physics of Fluids A*.

CONFERENCE PRESENTATIONS

J. M. Wallace, "Experimentally measured vorticity and helicity properties of turbulent flows", NATO advanced workshop on Topological Fluid Mechanics held at the University of California at Santa Barbara, Nov. 1991.

J.-L. Balint, L. Ong, J. M. Wallace, & F. Ladhari, "Characteristics of sublayer ejections in a turbulent boundary layer", 44th annual meeting of the Div. of Fluid Dynamics of the American Physical Society, Nov. 1991.

L. Ong, J. M. Wallace, & J.-L. Balint, "Joint probability analysis of measured velocity-vorticity components in a turbulent boundary layer", 44th annual meeting of the Div. of Fluid Dynamics of the American Physical Society, Nov. 1991.

P. Vukoslavcevic, J.-L. Balint, & J. M. Wallace, "Statistical properties of a two-stream mixing layer, 44th annual meeting of the Div. of Fluid Dynamics of the American Physical Society, Nov. 1991.

P. S. Bernard, J. M. Thomas and R. A. Handler, "Vortex Dynamics in Near Wall Turbulence", submitted to Second National Fluid Dynamics Congress, Los Angeles, CA, June, 1992.

P. S. Bernard, J. M. Thomas and R. A. Handler, "Time Evolution of Vortical Structures in Numerically Simulated Turbulent Channel Flow", 44th Annual Meeting American Physical Society, Division of Fluid Dynamics, Arizona State University, Scottsdale, AZ, November, 1991.

INVITED SEMINARS

J. M. Wallace, "Properties of vorticity and helicity in turbulent flows", presented at Princeton, Rutgers, Pennsylvania State and Cornell Universities.

P. S. Bernard, "Lagrangian Transport Analysis and the Prediction of Turbulent Flow", presented at Mathematical Sciences Research Institute, U. of California, Berkeley, Meteorology Department, University of Maryland, and Levich Institute, City College of CUNY.

END

DATE FILMED

01/22/92