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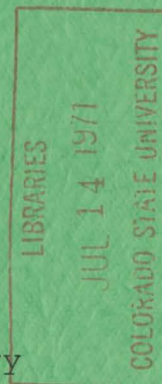
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INTEGRATED ARMY METEOROLOGICAL
WIND-TUNNEL RESEARCH PROGRAM

First Quarterly Progress Report on
Grant DA-AMC-28-043-G20

1 May 1965 -- 31 July 1965

Prepared by the Staff of the
Fluid Dynamics and Diffusion Laboratory
College of Engineering



Colorado State University
Fort Collins, Colorado

CER65JEC-YAS-EJP-GB-30

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INTRODUCTION

This progress report pertains to research outlined in the Proposal for an Integrated Army Meteorological Wind-Tunnel Research Program (CEP65JEC1) dated January 1965. Topics of research are reported on in the same order as outlined in the proposal. Initials of the staff member in charge of a particular effort are given with the title to each appropriate section.

The research under this grant is being conducted in the Fluid Dynamics and Diffusion Laboratory at the Foothills Campus of Colorado State University. Approximately 50 per cent of the effort is accomplished in the Army Meteorological Wind-Tunnel Facility, 30 per cent in Colorado State University's small low-speed wind tunnel and the remaining 20 per cent in the data processing facility assembled under joint Army and National Center for Atmospheric Research sponsorship.

A summary fiscal statement and a personnel statement are included at the end of the report.

I. TURBULENCE STRUCTURE

- A. (Determination of degree of local isotropy in wind-tunnel turbulent boundary layers by measurements of power spectra, intensities and cross correlation of turbulent velocity components. These measurements will be compared with atmospheric data in an effort to determine scaling factors and the extent of atmospheric-laboratory turbulence-structure similarity.)

Effects of Thermal Stratification on Turbulence Structure (HC, JEC)

The effects of thermal stratification on the turbulent intensities and turbulent energy spectra of air flows were studied. The major effort was gathering data of mean-temperature distributions, mean-velocity distributions, the distribution of the vertical component of turbulent velocity, and the turbulent energy spectra at several different elevations in the boundary layer for neutral, stable, and unstable thermal stratifications. The ambient velocity was kept constant for each group of runs at 5, 7, and 10 ft/sec. The data were analyzed and compared with the available atmospheric data. These results were presented by Dr. Cermak at the International Colloquium on Fine-Scale Structure of the Atmosphere in Moscow (USSR).

In order to test the reproducibility of the data, more data have been collected. Signals of each wire of an X-wire anemometer have been measured also. These data are being analyzed.

A paper is under preparation on this work which will appear in the proceedings of the Colloquium referred to in the first paragraph.

- B. (Determination of velocity-disturbance propagation in turbulent boundary layers by measurements of space-time correlations downstream from artificially created disturbances on boundaries of different temperatures relative to the ambient air and different roughness characteristics.)

The Determination of the Structure of Turbulence near a Rough Boundary (EJP)

The problem under investigation concerns the structure of the turbulence near a rough boundary. It was concluded that the decomposition of the turbulence into eddies of different sizes can best be studied by mapping in space the correlation functions for eddies of different frequencies. For this purpose, two hot wires are used. The first wire is embedded into the wall. The prongs extend about 0.01 inches into the boundary-layer flow. The second wire is mounted on a probe positioner. It can be moved freely into different positions. Varied are the lateral forward and vertical distances between the two wires. The turbulence signal from both wires are recorded simultaneously on magnetic tape. They are analyzed by first passing each signal through a filter arrangement and then finding the correlation of the two signals which correspond to the same frequency band. By plotting the space correlation corresponding to different band widths, information can be obtained on the size of turbulent eddies corresponding to the frequency bands considered. The contention is that the major effect of the roughness on the turbulence structure will consist of a change in the eddy structure.

At present, approximately two-thirds of the data have been taken. The mean velocity and turbulent intensity data for two-thirds of the cases have been measured and are analyzed using known techniques of analysis of turbulent boundary layers.

- C. (Determination of mean characteristics of the wind-tunnel boundary layers by measurements of distributions for mean velocity and temperature, turbulent velocity and temperature intensities, turbulence scales, and velocity-temperature fluctuations correlations for heated or cooled and smooth or rough plane boundaries /canopy flows are included in this task/. Studies of mass exchange between a vegetated canopy and the air stream listed in II.C will be made in conjunction with this task.)

Structure over Rough and Smooth Boundaries (Neutral Flow) (VAS)

- a) Mean Velocity Profiles - During the current period the mean velocity profiles from smooth, rough and heated boundary layers have been analyzed.

Clauser, Ref. 1, has demonstrated that the outer 80 per cent of a flat plate turbulent boundary can be treated by an approximate similarity approach. While no exact similarity can exist, the profiles are so close that good engineering approximations can be obtained. Clauser further was able to show a direct correspondence between the outer turbulent boundary layer and a laminar boundary layer. Thus, it is of major interest to analyze the large-scale layers obtained in the Army Wind Tunnel in the light of Clauser's work. Figure 1 is a plot of two boundary layer profiles obtained in the Army Wind Tunnel compared with the similarity concept. One of the profiles is for a smooth surface and the second was taken over coarse gravel. The close agreement between the profiles suggests that the similarity concept may be of great value in correlating boundary layers with widely different surface conditions. Also shown in Figure 1 is the profile for the outer region predicted by Clauser from the laminar boundary layer solution. A second similarity profile obtained by Sandborn, Ref. 2, for Clauser's parameters is shown in Figure 1.

Present analytical and experimental work is directed toward extending the similarity results to the prediction of the shear-stress distribution through the boundary layer. Measurements of the turbulent shear stress have also been made to check the predictions. Current results appear reasonable, however, some inconsistencies in absolute magnitude still must be resolved. The evaluation of the wall shear stress has led to some uncertainty in the overall analysis. The first attempt to employ aerodynamic-type empirical relations for wall shear stress led to incorrect values. The results of Figure 1 were obtained from more direct methods of evaluating the wall shear stress. What appeared at first to be a major difference between the wind-tunnel boundary layers and aerodynamic boundary layers has been attributed mainly to the uncertainty in the wall shear stress.

References:

1. Clauser, Francis H.: The Turbulent Boundary Layer, Vol. IV of Advances in Appl. Mech., Academic Press, Inc., 1956, pp. 1-51.
2. Sandborn, V.A.: An Equation of the Mean Velocity Distribution of Boundary Layers. NASA Memo 2-5-59F, 1959.

b) Turbulence Measurements - During the current period the measurement of the turbulent shear stress and the vertical component of velocity have been made. The evaluation of the total turbulent dissipation was also completed for the smooth and rough surfaces. Figure 2 shows the variation of the turbulent energy dissipation (divided by the longitudinal turbulent velocity squared) for three different surface conditions. The measurements suggest that the dissipation depends mainly on the total turbulent energy and on the location in the vertical direction. Very little effect of longitudinal distance is found after an initial length. The case of the measurements on a smooth plate behind a flexible roughness demonstrates the effect of the initial length effect.

From the turbulent shear stress measurements it will be possible to evaluate the production of turbulence at each location in the boundary layer. From a comparison of the production and dissipation an estimate of the conduction and diffusion of turbulence within the boundary layer will be obtained. This evaluation of the terms in the turbulent energy equation is presently being started. Sufficient data is also available to experimentally evaluate the X-direction equation of motion in the boundary layer.

The Modeling of Thermally-Stratified Flow (EJP)

An extensive investigation had been made of the mean velocity and temperature distribution in a thermally-stratified boundary layer on a smooth plate. The results show that it is possible to model a thermally-stratified boundary layer, and it is found that those equations which give the most satisfactory correlation between theory and field data taken by micrometeorologists are also best to relate laboratory data and theory. The results of this study, which is completed, are being prepared for publication.

- D. (Construct mathematical model for turbulence with plane homogeneity. This turbulence model closely resembles the structure in a well-developed turbulent shear layer; therefore, a working model would

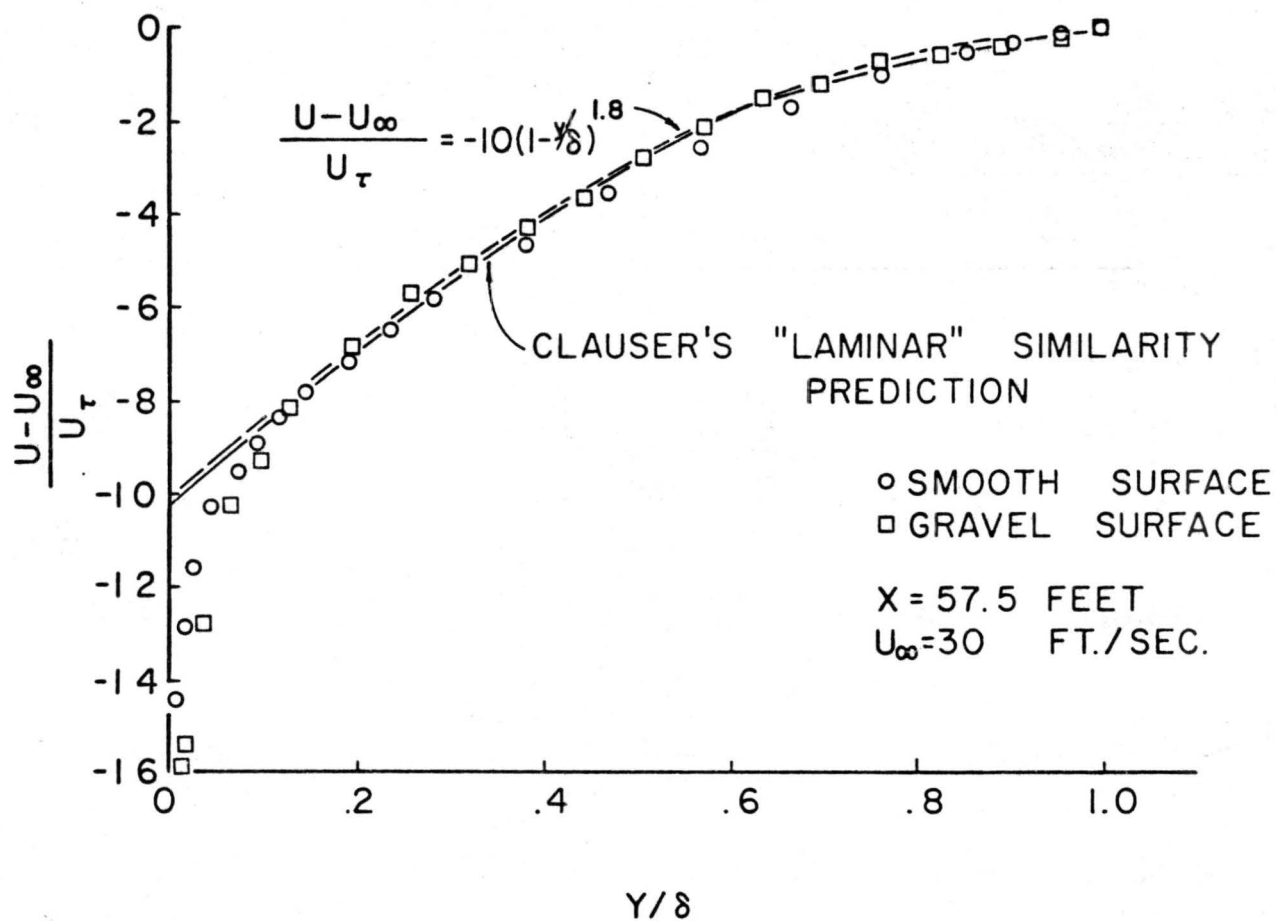


FIGURE 1 SIMILARITY OF TURBULENT VELOCITY PROFILES OVER SMOOTH AND ROUGH SURFACES.

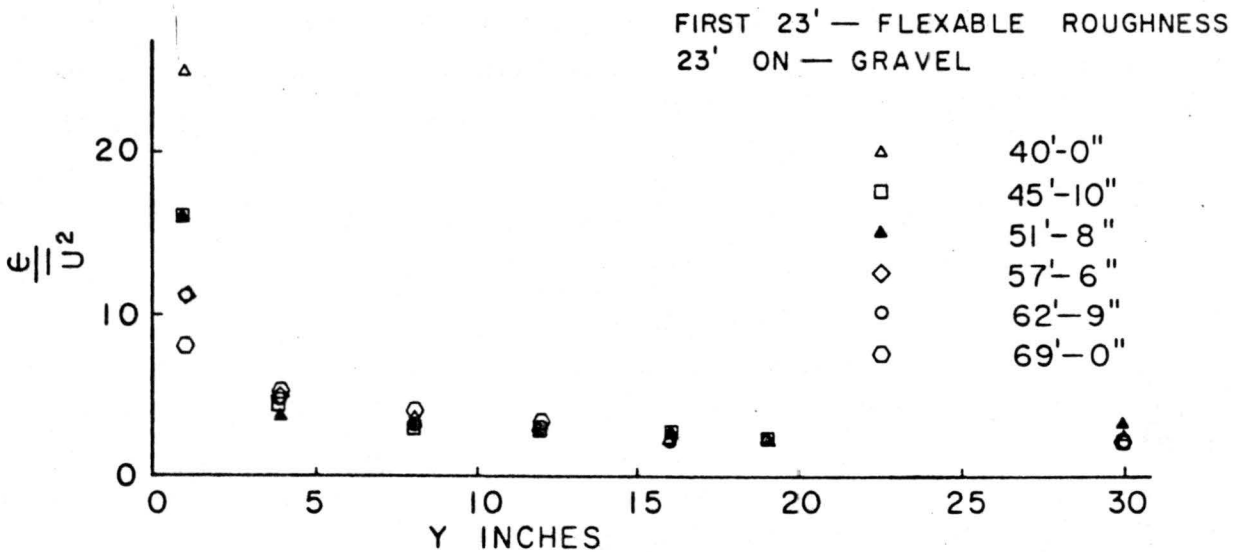
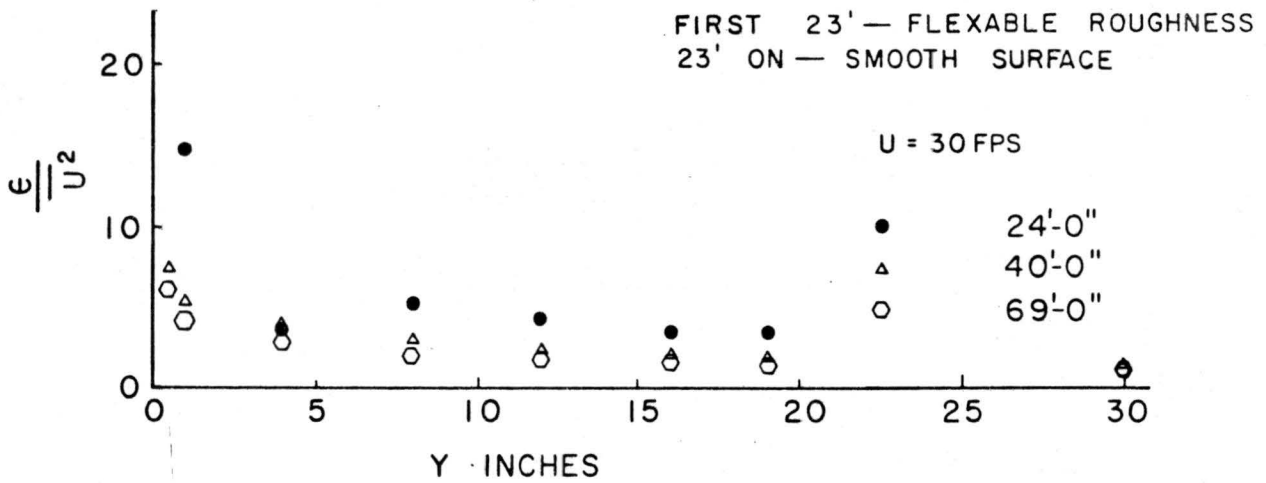
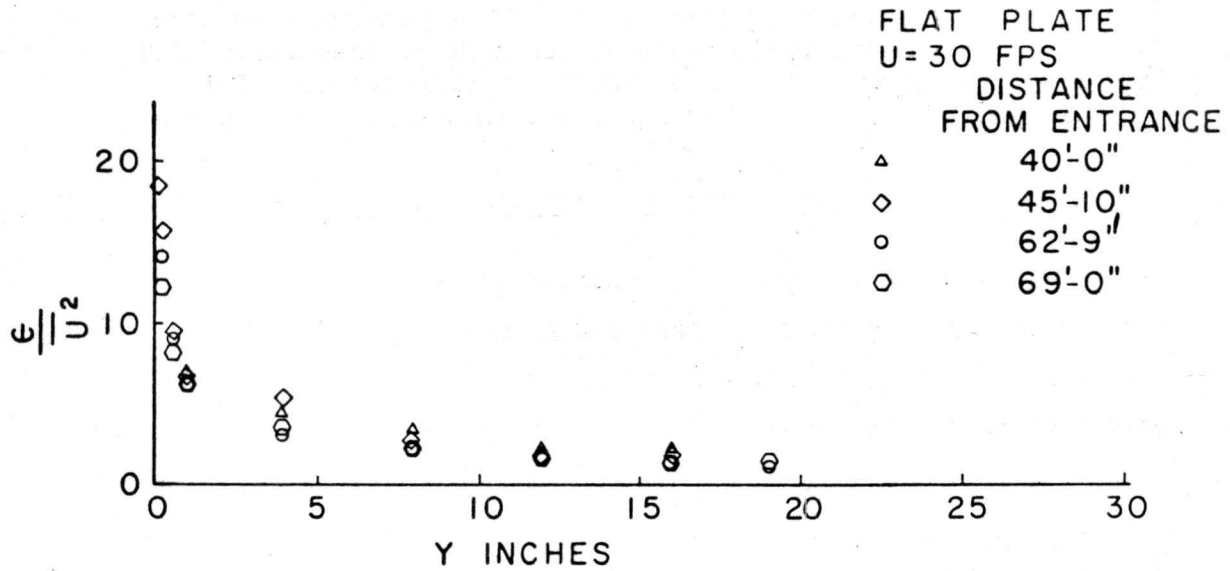


FIGURE 2 TOTAL TURBULENT ENERGY DISSIPATION IN BOUNDARY LAYERS

be useful for predicting structures in the atmospheric surface layer when appropriate boundary conditions are known. A successful development of this model should yield information on how intensities of turbulence, spectra and turbulent velocity correlations vary with distance from the boundary.)

Correlation Functions for Isotropic Planar Turbulence (JEC)

For turbulence which is isotropic and has plane homogeneity, an analysis has been performed to determine the general functional dependence for pressure-velocity, double-velocity and triple-velocity correlations. In the case of an incompressible fluid the general forms are found to depend only upon combinations of particular correlations. The results of this work are being prepared in the form of a Research Memorandum.

II. TURBULENT DIFFUSION

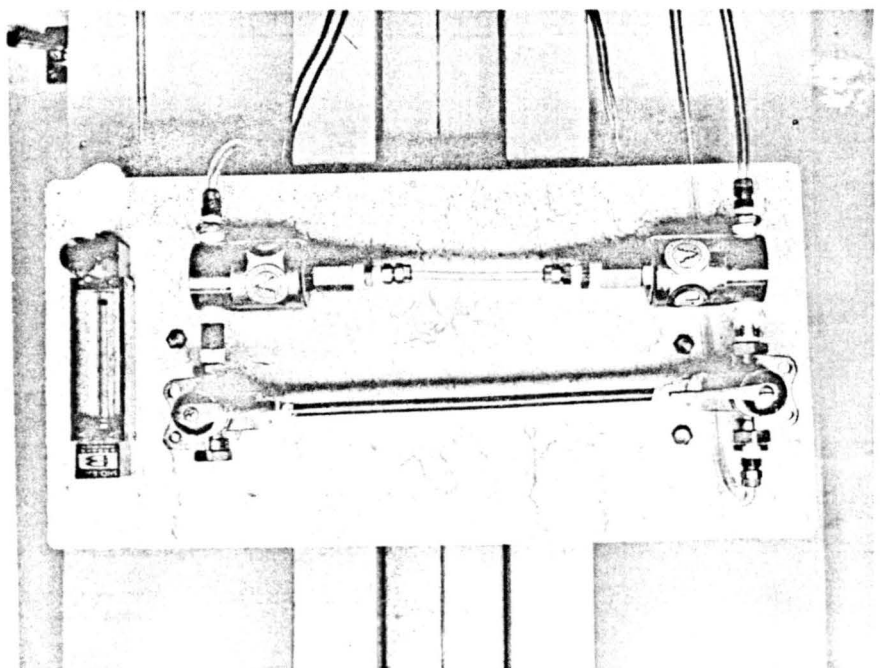
A. (Studies of concentration distributions downstream from release of an instantaneous source.)

Mass Diffusion from an Instantaneous Point Source (EJP)

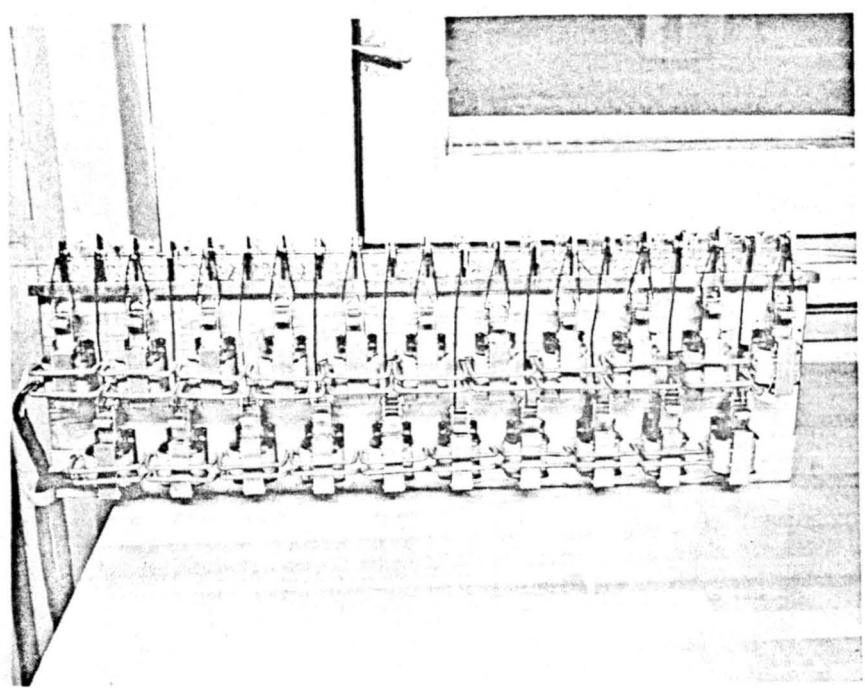
The development of the experimental technique for obtaining measurements of instantaneous concentrations is progressing satisfactorily.

The equipment which is being used is shown in Figure 3. The development of the equipment has been described in a series of progress reports on Grant DA-AMC-28-043-64-G-9.

The work done to date has centered around development of the instantaneous source and the sampling devices. The basic design has been found to yield results of acceptable quality; however, there remain a few problems connected with the reproducibility of the data. The inaccuracies in the timer which sequences the introduction of a gas cloud into the air flow and the irregular closing of the solenoids of the sampler were found to be mostly responsible for the large fluctuations which were observed between successive runs. This problem has been solved to a large extent by acquiring a more reliable timer. Other potential problem sources are being eliminated.



a. THE MASS SOURCE



b. THE SAMPLER

FIGURE 3 . EQUIPMENT FOR INSTANTANECUS MASS SOURCE STUDY

Heat Diffusion from an Instantaneous Point Source (JEC)

Further work has been accomplished with the instantaneous heat source (point). Temperature distribution through the heated cloud of air moving in a turbulent boundary layer have been measured with the resistance thermometer. A typical temperature-time trace for passage of a "heat" cloud is shown by the oscillograph trace in Figure 4.

Exploratory efforts have been made to determine the distribution of mean maximum temperatures experienced at a fixed point downward from the instantaneous source. One hundred source releases were made in the first attempt to determine a significant ensemble average. The results of this effort are very encouraging and the program will continue.

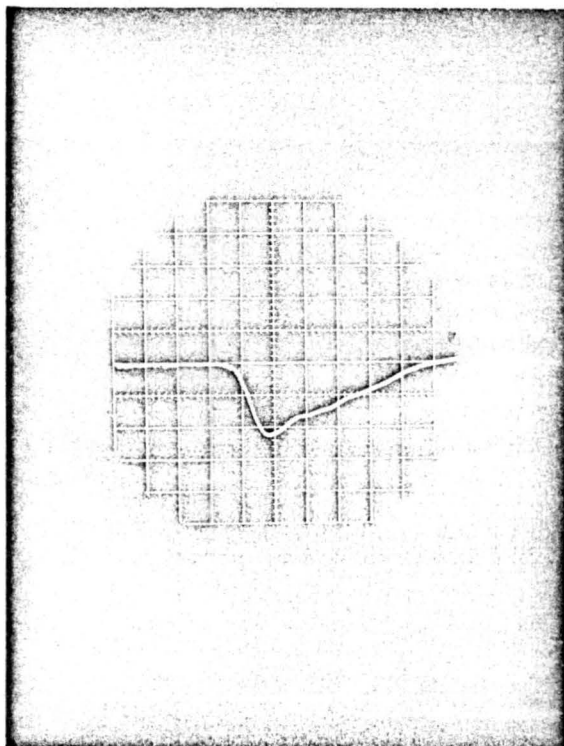
A Schlieren system has been installed across the meteorological wind tunnel test section and an effort will be made to photograph the shape of heated clouds resulting from instantaneous heat source releases.

- B. (Studies of mean concentration downwind from a continuous source located near a two-dimensional hill.)

Diffusion from a Continuous Point Source Downstream from a Two-Dimensional Model Hill (EJP)

Experiments have been completed on the diffusion from a point source into the boundary layer along a smooth flat plate. The boundary layer is disturbed by a two-dimensional model hill with a sinusoidal cross section and the point source located at the crest of the hill. The experimental cases studied are summarized in Table A.

The experiments yielded a most satisfactory set of data, the reproducibility of which was better than ± 10 per cent. The data are presently being analyzed by a similarity analysis, and the results will be summarized in a forthcoming report.



VERTICAL SCALE: GRID LINES 0.5V/CM
HORIZONTAL SCALE: GRID LINES 1 MM/CM

FIGURE 4 . TYPICAL OSCILLOSCOPE TRACE OF
INSTANTANEOUS TEMPERATURE PROFILE.

TABLE A

TEST CASES POINT SOURCE AT CREST OF MODEL HILL

<u>Hill Model</u>	<u>Ua</u>	<u>X(inches from crest)</u>	<u>REMARKS</u>
-	10	24, 48, 72, 96, 180)	Concentrations were taken for one vertical profile and three horizontal profiles.
-	20	")	
4" x 20"	20	")	All hills are sinusoidally shaped. Velocity profiles were taken for vertical sections at center line and at 4" right and left from center line.
2" x 10"	40	")	
"	20	")	
"	10	")	
1" x 10"	20	")	

- C. (Studies of mean concentration downwind of continuous source of mass located in or above canopies formed by flexible or peg-type roughness elements. Existing field data will be analyzed to develop similarity criteria.)

Diffusion over Peg-Type Roughness (JEC)

Analysis of mean velocity and mean temperature and mass concentration distributions has continued during the quarter. Data for the neutral flow and stably-stratified flow are being studied for source heights of 1/16 and 1-3/4 inches located at 0, 15 and 25 ft from the upwind edge of the peg roughness. Figures 5 and 6 illustrate the effect of these variables on the location of maximum concentration downwind of the source.

III. FLOW OVER TOPOGRAPHIC FEATURES AND MAN-MADE STRUCTURES

- A. (Mountain lee-wave studies, both analytical and laboratory simulation, for simple two-dimensional mountain with goal being simulation of lee-wave phenomena over Organ and San Andres Ranges.)

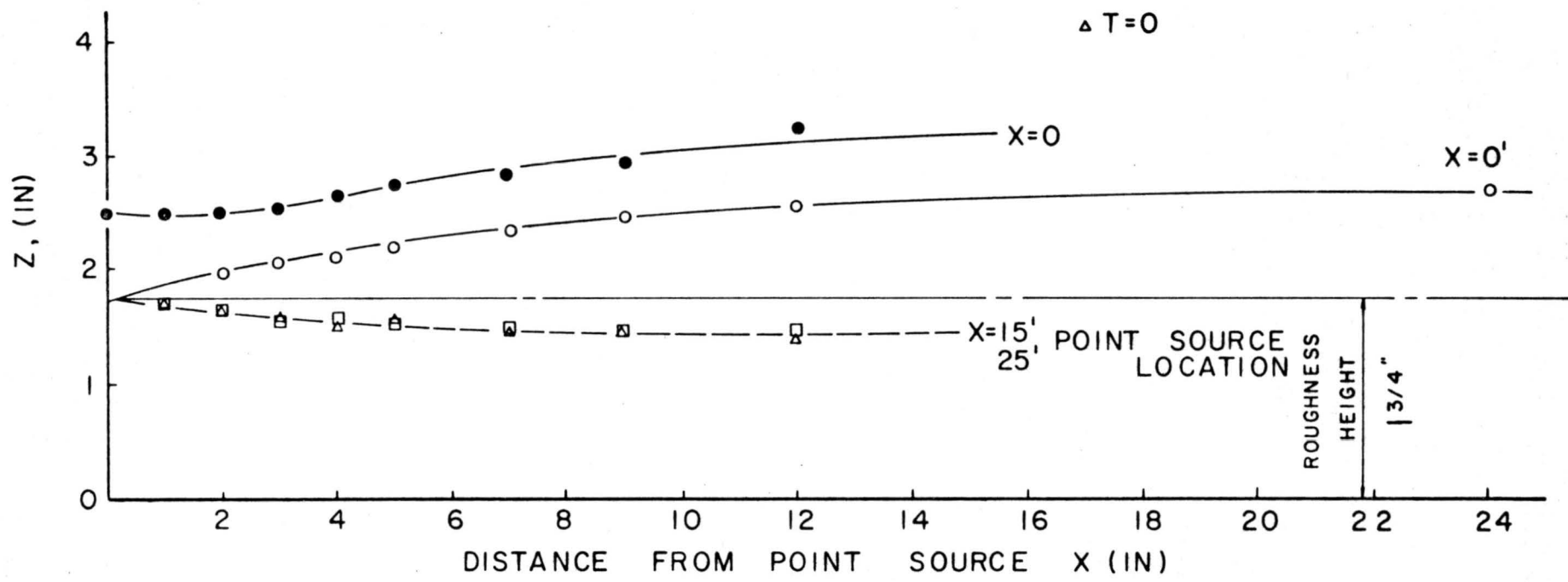


FIGURE 5 N-10 (NEUTRAL) DISTANCE Z OF POINT OF MAXIMUM CONCENTRATION FROM BOUNDARY.

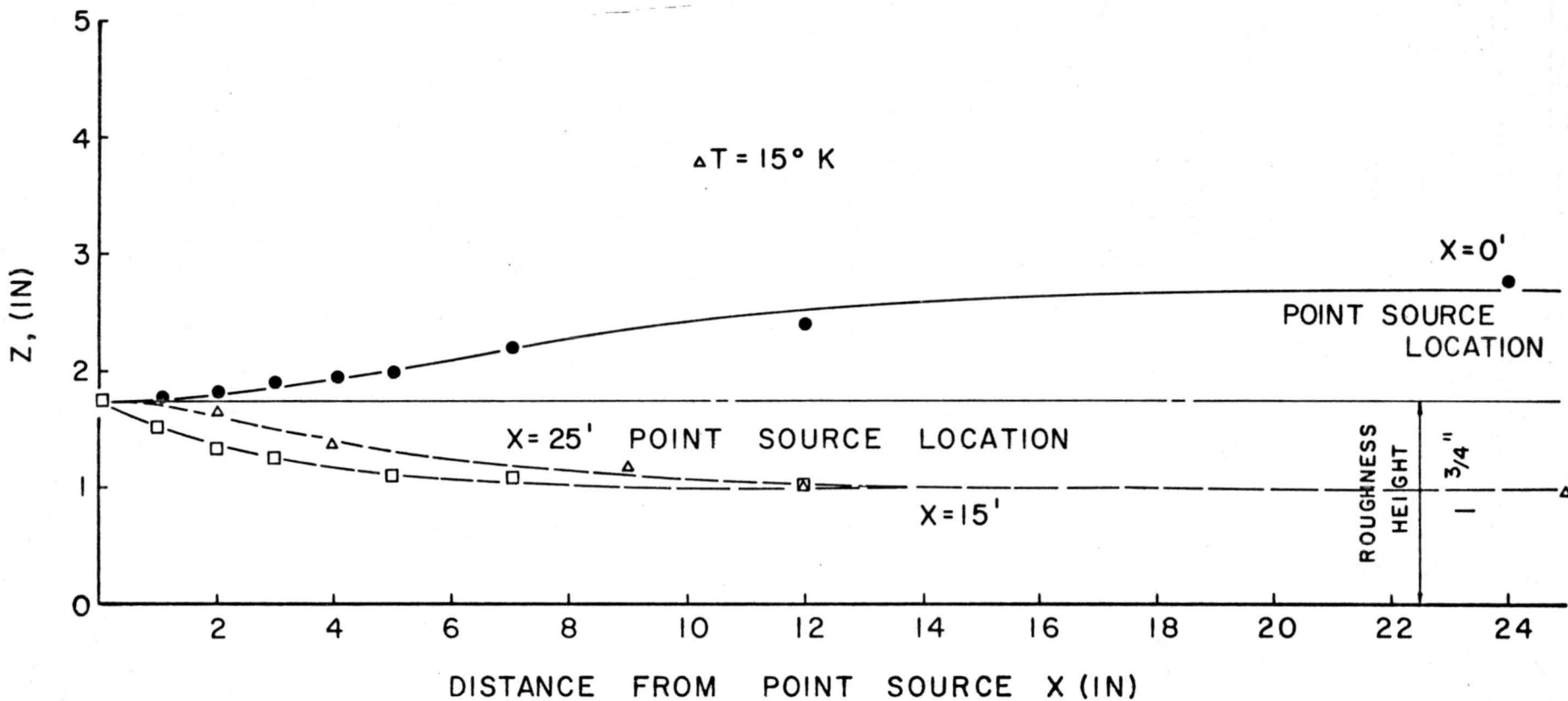


FIGURE 6 C-10 (CODING) TRACES OF MAXIMUM CONCENTRATION POINT.

Wind Tunnel Screens (GJB)

Additional screens designed to produce stable small velocities in the wind tunnel have been mounted on frames, so that they may be easily inserted into or taken out of the tunnel. They permit stable velocities below 1 ft/sec to be maintained in the tunnel.

Hot-Spot Anemometer (GJB)

Much testing has been done on this new instrument required for measuring low mean velocities in studies of mountain lee waves. It has been debugged from noise and 60-cycle pick-up which gave difficulty at the beginning. This effort was very important since the wire output is amplified one million times. Velocities above 1.5 ft/sec measured with the hot-spot anemometer (HSA) compare quite well with those measured with a Pitot-tube.

Thus far the HSA had been used in parallel flow with Line L - perpendicular to both the source and the pick-up wire - parallel to the flow. But since it was to be utilized in the mountain-wave study where the flow is certainly not parallel, it was tested by varying the angle α between line L and velocity V. The experimental results, unfortunately, display a strong dependence on the measured velocity of angle α . For $\alpha = 25^\circ$, the measured velocity may differ by more than 20 per cent from the true velocity, and this discrepancy increases rapidly as α becomes larger.

In addition, this discrepancy is not symmetric with respect to $\alpha = 0$. This is due to the buoyancy force which causes the hot spot to rise. This vertical velocity is estimated to be about 0.7 ft/sec. Unfortunately, this undesirable effect becomes worse as the velocity is further decreased. More testing is being done at the present time at velocities below 1.5 ft/sec to decide upon the use of the HSA in the mountain wave study.

Experiments have also been run with platinum film probes instead of the platinum wire in the HSA, the advantage of the former being greater

mechanical strength. Indeed, the platinum wire for transient temperature measurements is $2/100,000$ inches diameter, and breaks at the slightest mishandling or impact of dust particles. The platinum film is painted on a small glass rod with a diameter of about 0.01 inches. After several unsuccessful attempts, a film probe was obtained which gave signals similar to that of the wire sensor in the HSA.

- B. (Studies of mean-flow variation over the Green River Launch Site by means of a small-scale model centered on the meteorological-tower site. This effort will be accompanied by feasibility studies of modeling wind patterns over selected portions of Dugway Proving Ground by means of a scaled topographical model.)

Model Study of the Green River Launch Site (GJB)

The construction of the model (scale 1:800) is completed. A new technique of model construction was devised. First an enlarged map was glued on the ply-wood support. The contour lines were raised with aluminum strips whose widths were cut to equal the reduced altitudes of the various contours. The space between these contours was then filled with in-place foam rubber and the model was finished with putty.

- C. (Studies of mean flow around idealized or reference structural shapes such as vertical cylinders, hemispheres and parallelepipeds including meteorological instrument support effects on indicated wind speed and direction. Groups of obstacles and groups of buildings will be studied as well as flow around simple structures.)

Flow Round Circular Cylinders Normal to a Plane Boundary (JEC)

An effort has been made to determine the effect of cylinder height relative to boundary-layer thickness and cylinder surface roughness upon the eddy shedding frequency (Strouhal numbers). For the case of a 10"-diameter cylinder spanning the wind tunnel (here the ratio of cylinder height to boundary layer thickness is very large), Figure 7 illustrates the effect of roughness on the Strouhal number. Unfortunately, the Reynolds-number range was insufficiently large to determine the effect of roughness on the critical Reynolds number.

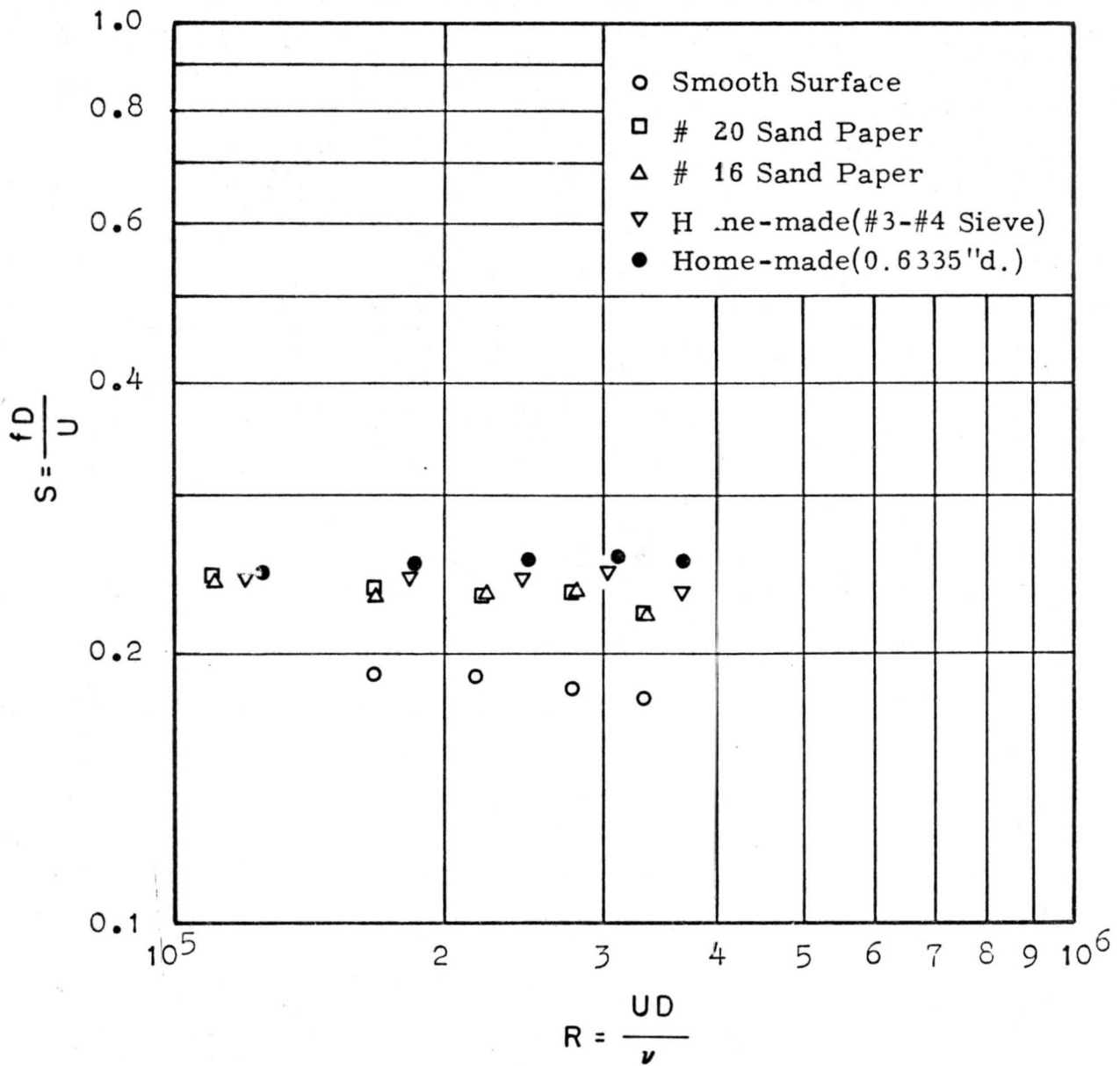


FIGURE 7. THE EFFECT OF SURFACE ROUGHNESS (SAND PAPER) TO THE REYNOLDS NUMBER DEPENDENCE ON STROUHAL NUMBER--SMALL WIND TUNNEL

In a study, performed by a student supported by a National Science Foundation Fellowship, an exploratory examination of effects of cylinder height relative to boundary-layer thickness upon the Strouhal number was made. Figures 8 and 9 illustrate the trend of such effects.

The Velocity Field Downstream from a Model Hill (EJP)

This study is concerned with the velocity field corresponding to the diffusion from a point source in a boundary layer disturbed by a model hill. The analysis progresses along the lines suggested in the Final Report on Grant DA-SIG-36-039-62-G24. In particular it is attempted to obtain a method for calculating the development of the boundary layer if the velocity distribution is known in one vertical section. Different techniques are tested and methods are being explored which will give a more satisfactory correspondence between experimental data and analytical results.

IV. INSTRUMENTATION AND FACILITY DEVELOPMENT

- A. (Upgrade design of existing instruments used to measure mean velocity, mean-flow direction, mean-temperature, turbulent velocities, turbulent temperature, fluid density [optical], tracer gas concentration and boundary shear stress. Development of improved mean-velocity measurement for low-speed flow not sensitive to temperature fluctuations and techniques for flow visualization [primarily smoke].

Wall Shear Stress (VAS)

A thin platinum film-heat transfer gage has been developed to measure the local heat transfer at a surface. Using the relation obtained by Ludwig, Ref. 1, the local heat transfer can be related to the local skin friction. Figure 10 shows a typical calibration plot of the relation

Reference:

1. Ludwig, H.: Instrument for Measuring the Wall Shearing Stress of Turbulent Boundary Layers, NACA TM 1284, 1950.

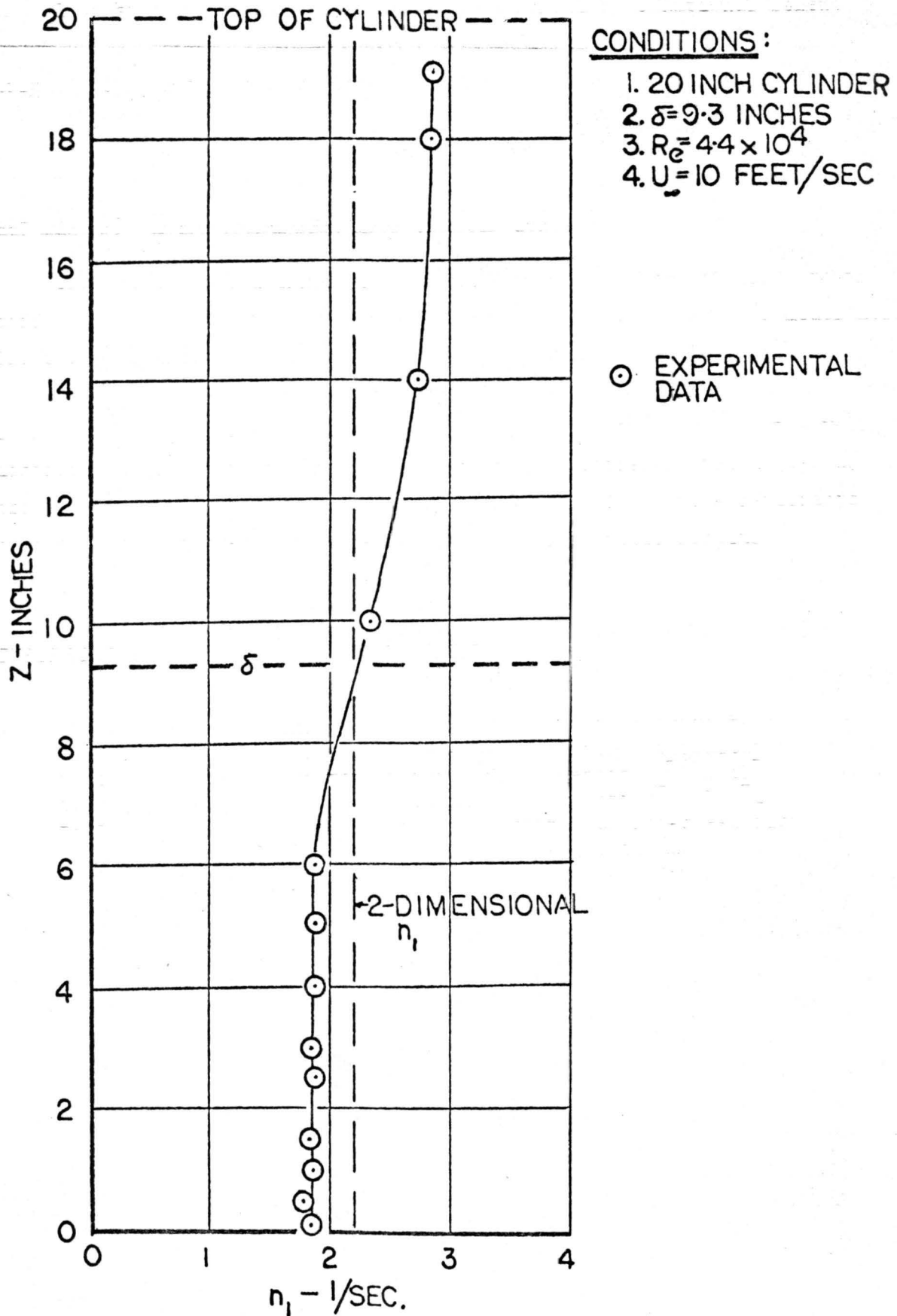


FIG. 8 - VARIATION OF SHEDDING FREQUENCY

CONDITIONS:

1. $3\frac{1}{8}$ INCH CYLINDER
2. $\delta = 9.3$ INCHES
3. $Re = 44 \times 10^4$
4. $U = 10$ FEET/SEC.

○ EXPERIMENTAL DATA

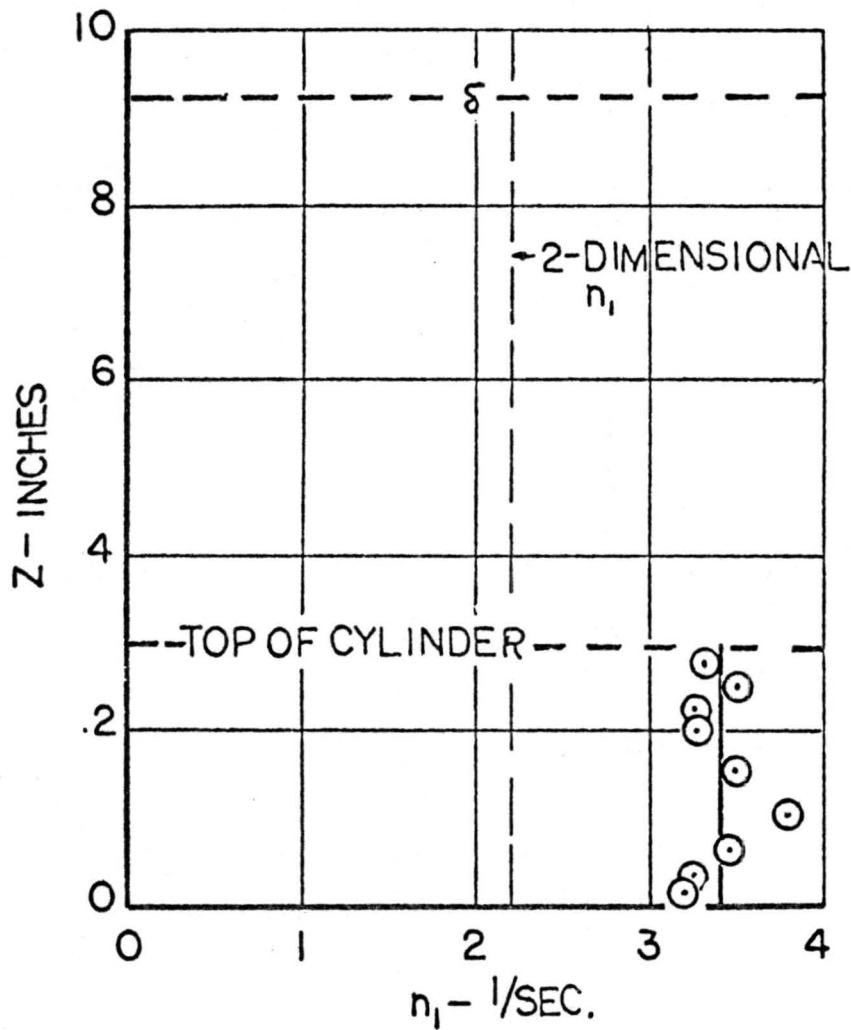


FIG. 9 - VARIATION OF SHEDDING FREQUENCY

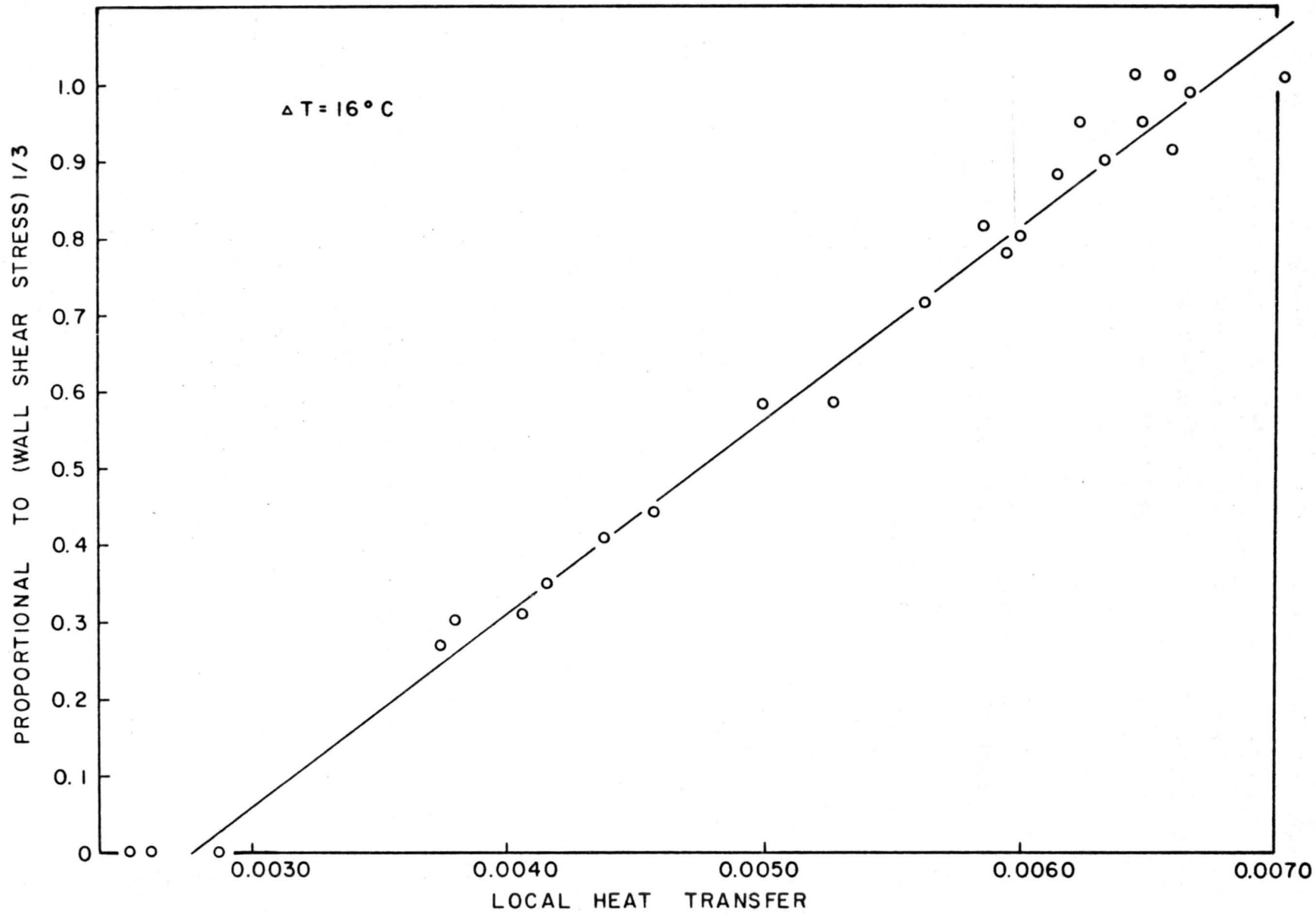


FIGURE 10 FILM HEAT TRANSFER — SHEAR STRESS RELATION.

between the measured heat transfer and the local skin friction for one of the gages. The present gages are made on a piece of mica of the order of 0.003 inches thick. The complete gage can be glued to any surface desired and the local heat transfer measured. The data of Figure 10 was taken with the gage glued to the inside wall of a 5-3/4 inch diameter pipe. The skin friction in the pipe can be evaluated directly from the measured pressure drop down the pipe.

- B. (Development of turbulent velocity instrument using a new concept of transduction -- dynamic-pressure fluctuation by strain-gage measurements.)

No work on this development was performed during the quarter. An additional effort is planned for the future to improve response of the instrument.

- C. (Development of light scattering technique to determine concentration of particulate matter released in turbulent boundary layers.)

Light Scattering System (HC)

Optical (light) scattering system for measuring scattering cross-sections of diffused particles in an air flow was assembled and preliminary tests were carried out with very small lucite spheres (diameters smaller than 0.03 inches) suspended in water in a test tube. A few volts DC deflection could be read at the output of a photomultiplier when the scattered light was focused on the entrance slit of the photomultiplier. Although smoke and chemicals will be used in the study, the preliminary results give much encouragement.

PERSONNEL SUMMARY

<u>Staff</u>	<u>Mo. Reimb. from Grant</u>
JEC	1
VAS	5/6
EJP	1-1/2
GJB	1
HC	3
<u>Grad. Res. Assistants</u>	
MS	21-1/2
PhD	15

FISCAL STATEMENT

Expenditures under the grant as of 31 July 1965 are as follows:

Salaries and labor	\$ 37,255.69
Overhead	8,490.46
Materials and Supplies	7,772.02
Travel	28.00
Other	661.05
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Total Expenditures	\$ 54,207.22
AMOUNT OF GRANT	176,437.50
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	54,207.22
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BALANCE	\$122,230.28

PROGRESS SUMMARY

<u>Task</u>	<u>Estimated % of Effort Completed*</u>
I. A	10
B	30
C	8
D	25
II. A.1	10
A.2	10
A.3	8
A.4.a	0
A.4.b	10
B	90
C	25
III. A	12
B	15
C	10
IV. A	10
B	15
C	10

*On basis of work anticipated over three-year grant period.