FLUID DYNAMICS AND DIFFUSION LABORATORY

Fluid Mechanics Program

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and
DIFFUSION LABORATORY

COLORADO STATE UNIVERSITY
Fort Collins, Colorado

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College of Engineering
Colorado State University
Fort Collins, Colorado

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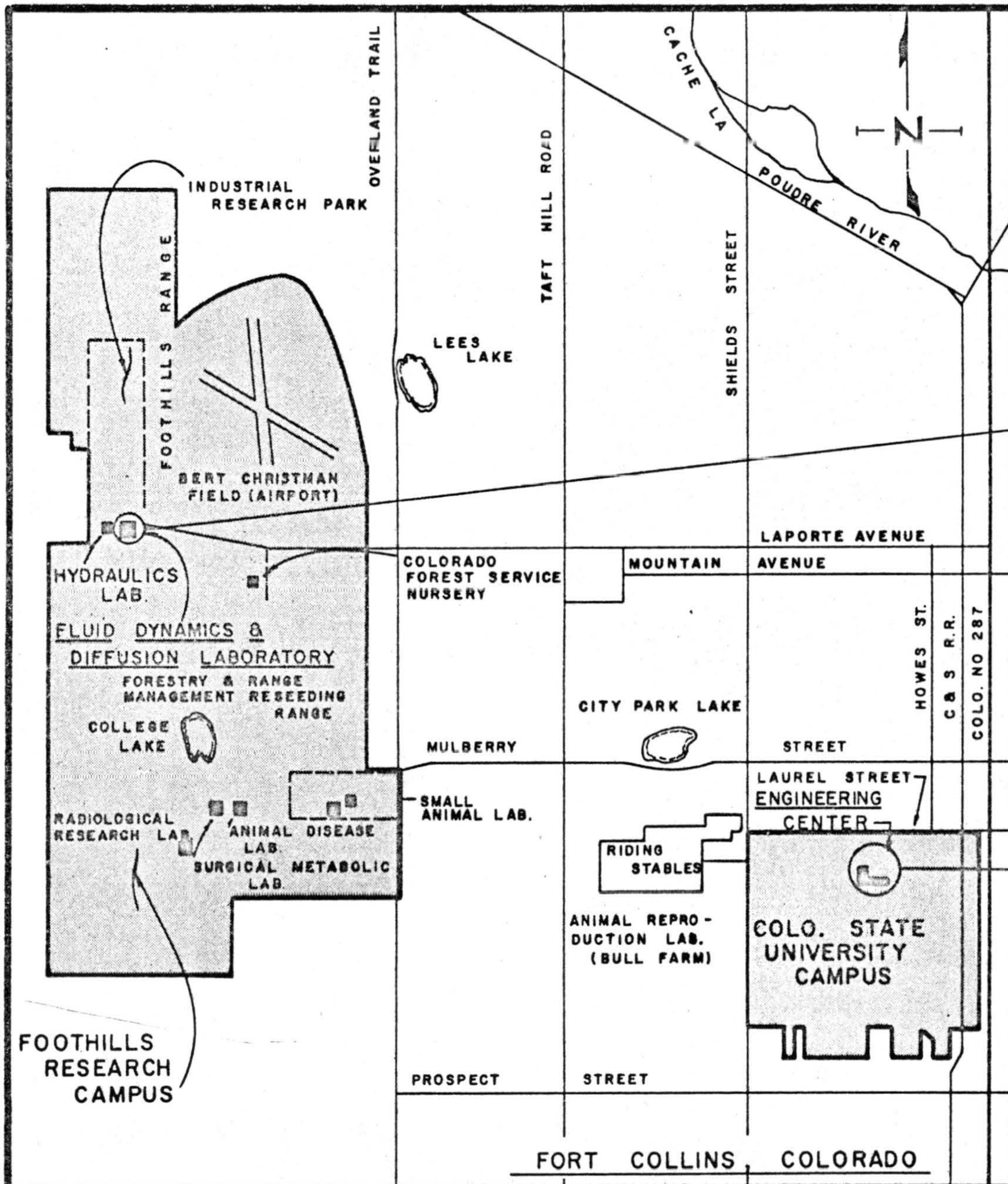

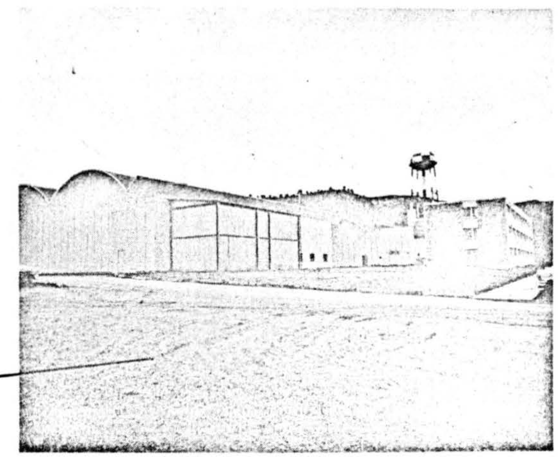

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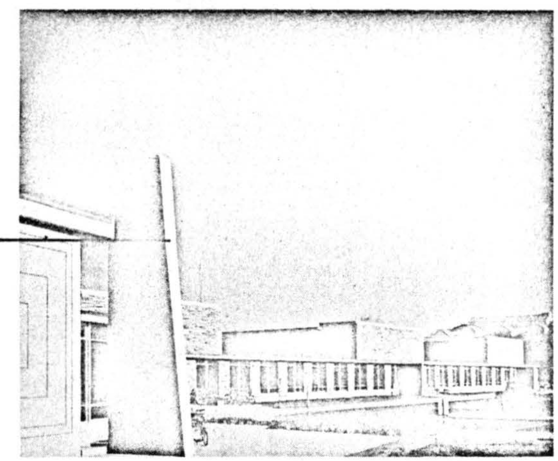

ENGINEERING CENTER

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Introduction

The Fluid Mechanics Program offers academic and research work in fluid mechanics that is coordinated with all engineering departments and the departments of physics, mathematics and atmospheric science. Students working toward an M.S. or Ph.D. are required to take a series of core courses in fluid mechanics, supported by substantial course work in engineering, physics, and/or mathematics, in addition to writing a thesis or dissertation. Research assistants usually work toward a dissertation in the Fluid Dynamics and Diffusion Laboratory on research supported by governmental and private sponsors. The research and study programs are chosen to develop fundamental knowledge in fluid mechanics on which careers in teaching, creative design, or research can be based. Information pertaining to course offerings and degree requirements may be obtained by referring to either the Graduate Bulletin of the Department of Civil Engineering or the Graduate Bulletin of the Graduate School and the Colorado State University General Catalog.

The Fluid Dynamics and Diffusion Laboratory depicted on the frontispiece began operations in 1949 with a low-speed recirculating wind tunnel. During the years that have followed the scope of the laboratory has been expanded to cover subjects related to engineering, physics of fluids, geophysics, and aerospace science. Personnel associated with the laboratory have access to a well-equipped machine shop, wood-working facilities, and an electronics shop. The laboratory is part of a self-sufficient research unit, the Engineering Research Center, which provides efficient and economical expediting of all technical and administrative problems. This brochure is devoted to a description of the facilities, research activities and personnel associated with the laboratory.

Laboratory Facilities and Instrumentation

A schematic diagram locating various facilities of the Fluid Dynamics and Diffusion Laboratory is shown in Fig. 1. This floor plan is presented in conjunction with Fig. 2 which is a photograph of the laboratory interior. The key appearing below Fig. 1 and above Fig. 2 provides a cross reference between the two figures and explanatory information.

The data analysis section is equipped for the statistical analysis of transient data from such transducers as hot-wire anemometers, piezometers, electrokinetic probes, resistance thermometers, or accelerometers. This specialized facility, shown in Fig. 3, employs the latest analog circuits available and is one of the most complete systems of this kind. Primary transducer data are recorded at various locations in the laboratory on magnetic tape which serves as a permanent record of the experimental data as well as the input for the statistical analysis system. This system--which has been assembled through support of the National Center of Atmospheric Research, the Army Materiel Command and the NASA Lewis Research Center--is described in section 8.2 (Data Analysis System).

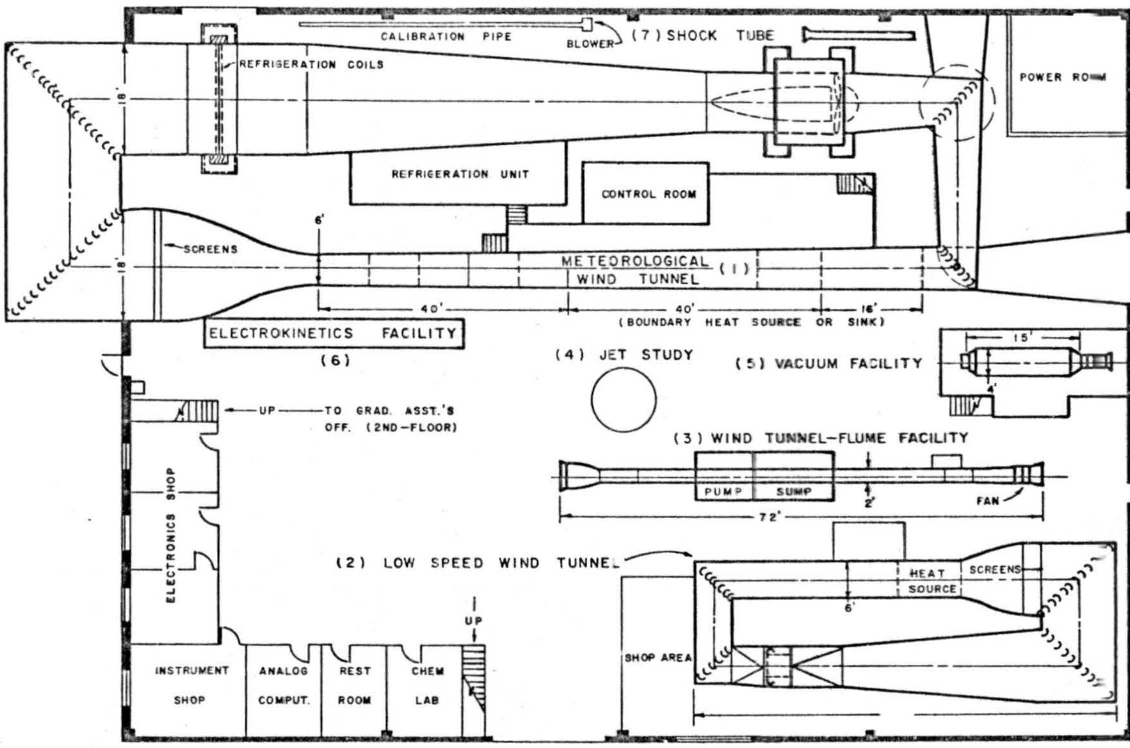

Figure 1. Fluid Dynamics and Diffusion Laboratory (floor plan 160 x 120 ft.)

1. Army Meteorological Wind Tunnel
2. Low Speed Wind Tunnel
3. Wind Tunnel Flume Facility
4. Jet Study Facility
5. Ion Beam Facility
6. Electrokinetics Facility
7. Shock Tube

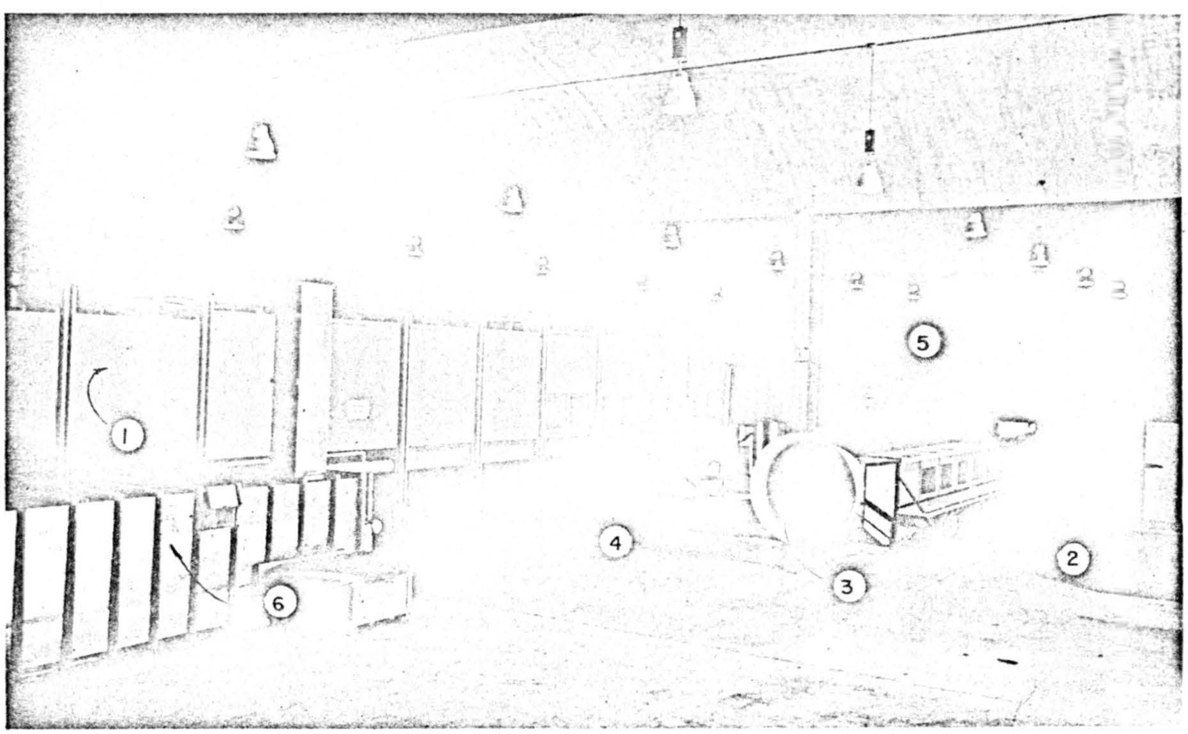

Figure 2. Fluid Dynamics and Diffusion Laboratory

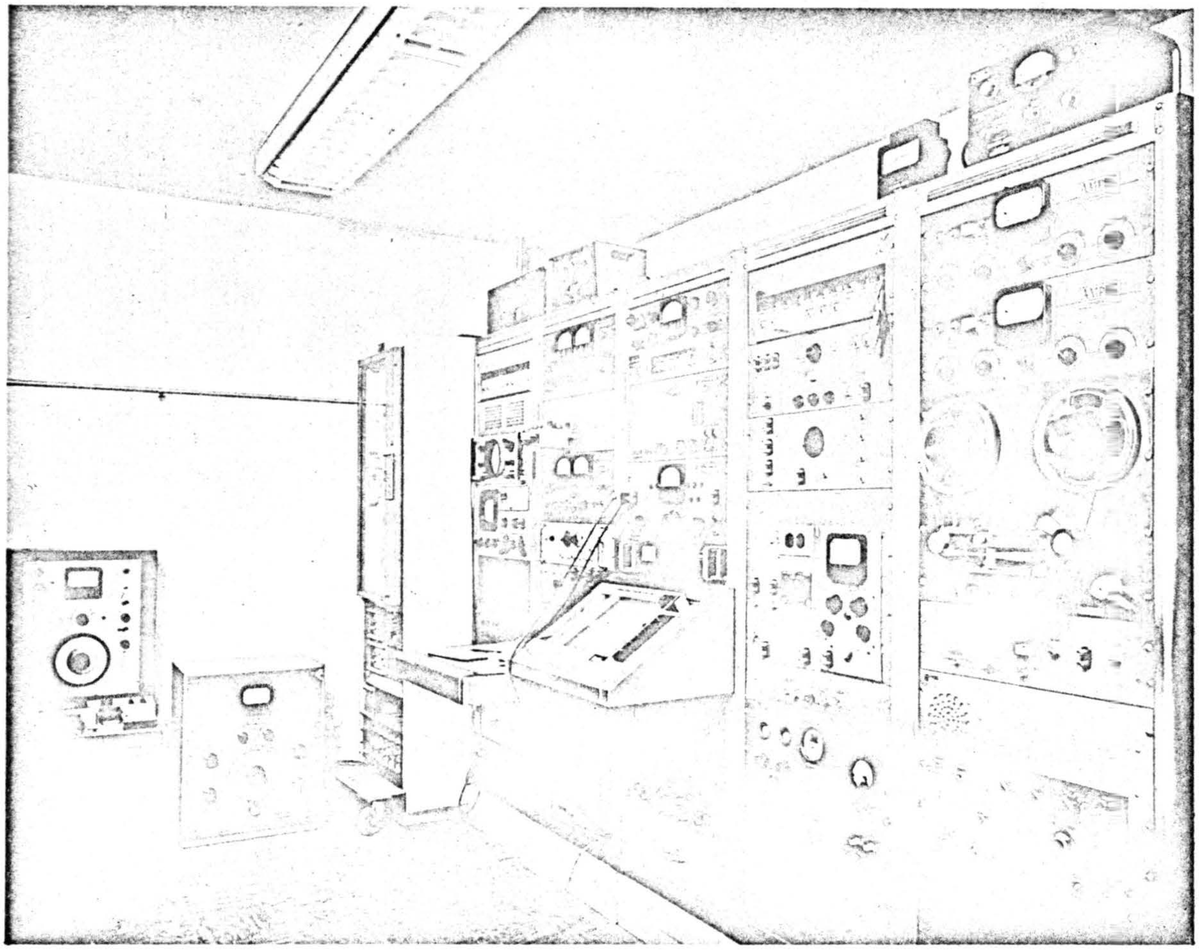

Figure 3. Data Analysis System

1. Army Meteorological Wind Tunnel

The largest and most unique facility in the laboratory is the Army Meteorological Wind Tunnel seen in Fig. 4. An 80-ft. long test section provides unusual opportunity for studying well-developed turbulent boundary layers for different degrees of thermal stratification and surface roughness. The wind tunnel is of the recirculating type; however, it can be converted to open-circuit operation.

For both types of operation the air enters the test section from an 18 ft. x 18 ft. stilling chamber, and passes through a set of four stainless steel screens located in a contraction section where the chamber area is reduced to 6 ft. x 6 ft. Performance characteristics are tabulated in Table 2.

A constant air speed is maintained by keeping the speed of the propeller at a constant value. This speed, achieved by the use of a stabilized DC motor-generator system, is set by either adjusting the rpm of the DC motor or by adjusting the pitch of the propeller. Since no appreciable load changes develop during operation, a constant fan speed virtually assures constant air speeds.

An important property when determining the behavior of boundary-layer flow is the pressure gradient which can be controlled by height adjustment of

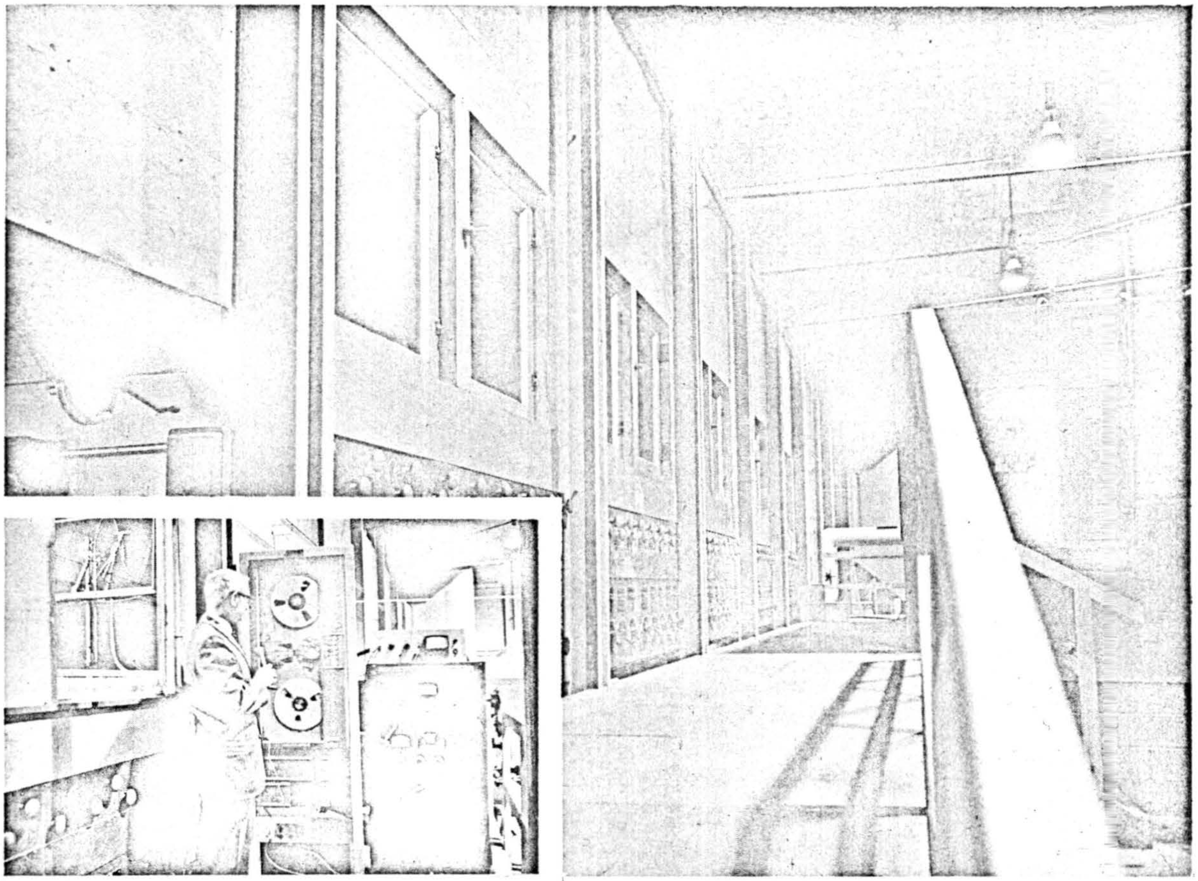

Figure 4. Army Meteorological Wind Tunnel

the test-section ceiling.

A 40-foot long portion of the test-section floor consists of an aluminum plate which can be heated or cooled.

An air conditioned control room, located between the test section and return duct, houses controls for the drive and cooling system, instrument carriage, and the performance recorders.

The instrument carriage, running on tracks located within the wind-tunnel test section, permits remote placement of the instrument probe at any point within the section.

The wind tunnel makes possible the study of micrometeorological phenomena, including stable and unstable atmospheres, under controlled conditions. In a sense the wind tunnel may be considered as an analog computer with the inputs and outputs shown schematically in Table 1.

2. Low-Speed Wind Tunnel

The low-speed wind tunnel is of the recirculating type, with the same cross-sectional test-section area as the Meteorological Wind Tunnel. This wind tunnel, seen in Fig. 5, has a test section 32-feet in length and is powered by a constant-speed, variable-pitch fan rated at 75 hp.

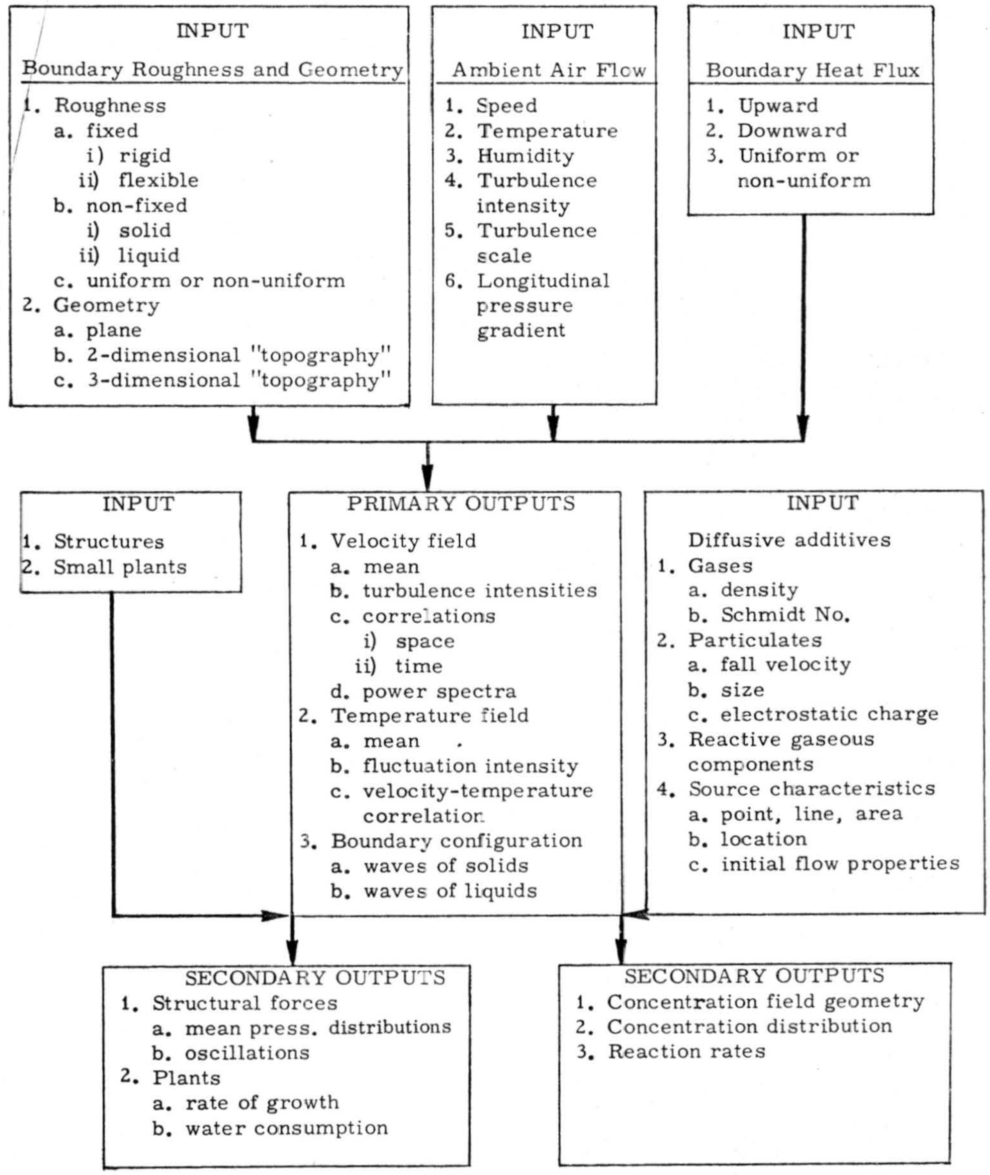

Table 1. Input-Output Scheme

The low-speed tunnel can be converted into an open-circuit tunnel by replacing the southwest corner with a straight duct that funnels discharging air to the out-of-doors. During open-circuit operation the tunnel draws air from inside the building thus assuring a minimum of recirculated exhaust. The controlled boundary of this tunnel is a ten-foot floor section of aluminum plate that can be heated by tubular heaters.

The tunnel is equipped with an instrument carriage whose actuators permit placement of test probes anywhere within a test area of 4 x 2 ft. Tunnel performance characteristics are listed in Table 2.

3. Wind Tunnel-Flume Facility

The wind tunnel-flume facility offers the capability of studying the effects

Characteristic	Army Meteorological Wind Tunnel	Low-Speed Wind Tunnel
1. Dimensions		
Test-section length	88 ft	30 ft
Test-section area	36 ft^2	36 ft^2
Contraction ratio	9:1	9:1
Length of temperature controlled boundary	40 ft	10 ft
2. Wind-tunnel drive		
Total power	400 hp	75 hp
Type of drive	4-blade propeller	16-blade axial fan
Speed control: coarse	Ward-Leonard DC control	single-speed induction motor
Speed control: fine	pitch control	pitch control
3. Temperatures		
Ambient air temperature	40^0 F to 200^0 F	not controlled
Temp. of controlled boundary	40^0 F to 400^0 F	ambient to 200^0 F
4. Velocities		
Mean velocities	approx. 5 fps to 120 fps	approx. 3 fps to 90 fps
Boundary layers	up to 16 inches	up to 8 inches
Turbulence level	low (about 0.1 percent)	low (about 0.5 percent)
5. Pressures	adjustable gradients	not controlled
6. Humidity	controlled from approx. 20% to 80% relative humidity under average ambient conditions	not controlled

Table 2. Performance Characteristics of the Meteorological and Low-Speed Wind Tunnels

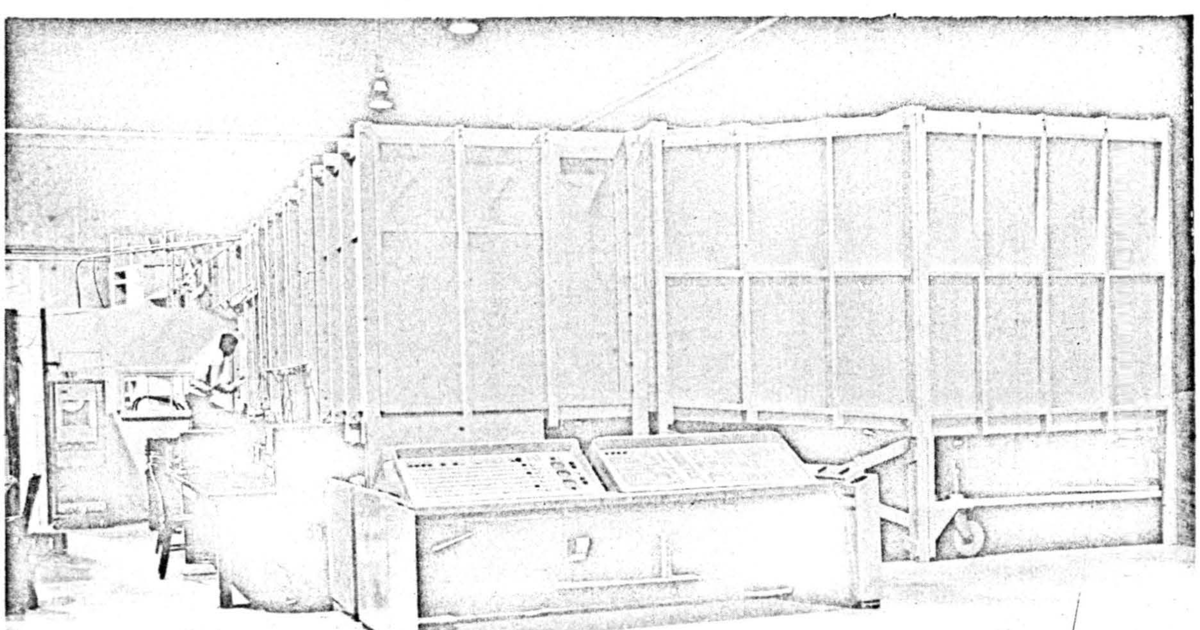

Figure 5. Low-Speed Wind Tunnel

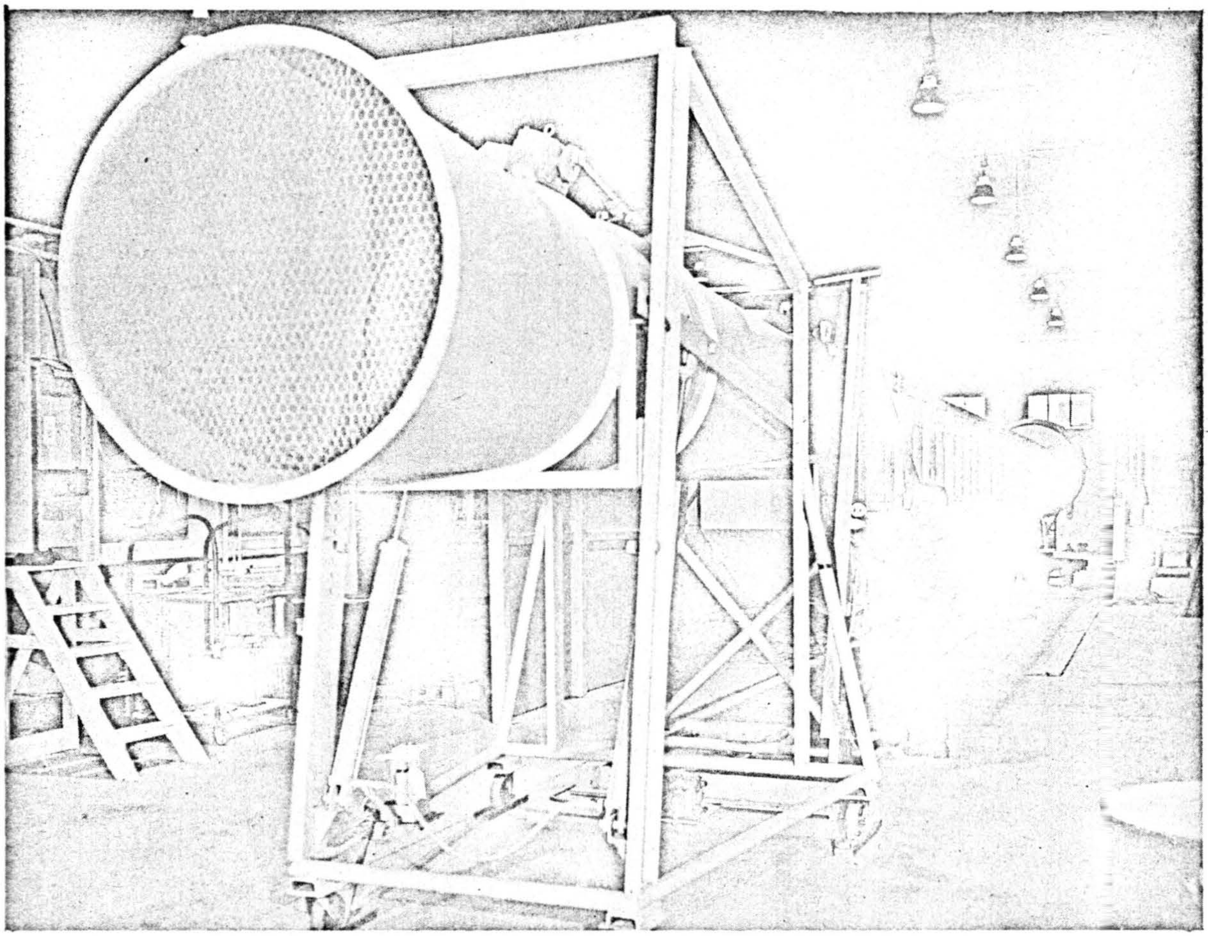

Figure 6. Wind Tunnel-Flume Facility

of wind on water in an open channel. The facility, shown in Fig. 6, is 44 ft. long and is designed so that a uniform depth of 6 in. can be maintained for slopes up to 5 per cent. Uniform channel depth is obtained by tilting the facility on a pivot located one-third of the way under the test section. Water circulation is maintained by an 18 in. diameter horizontal propeller pump equipped with a three-speed 30 hp motor.

Air flow is controlled by a 36 in. fan attached to a 15 hp induction motor which is capable of developing wind speeds of zero to 80 fps.

4. Jet Facility

The jet facility illustrated in Fig. 7 was designed to study jet impingement on a circular plate located perpendicular to the air flow. The air supply for this equipment is developed by a 5 hp centrifugal blower. Screens may be inserted in the settling chamber to assure uniform mixing of air prior to being ejected through a sharp-edge orifice located at the bottom of the chamber. The size of the orifice can be varied according to test configuration. A butterfly valve, located upstream from the centrifugal pump, allows the speed of the jet

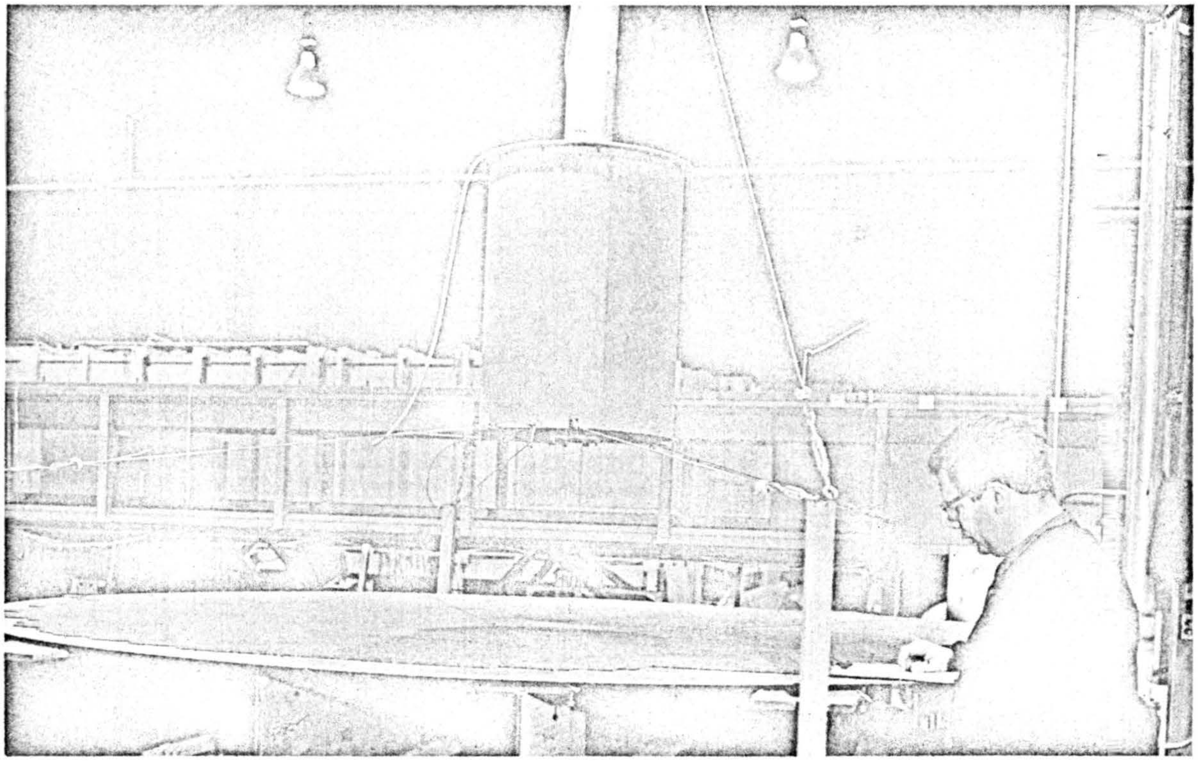

Figure 7. Jet Facility

to be varied from 100 fps to 400 fps. Fine adjustment of the jet speed is accomplished by the use of an auxiliary exhaust outlet.

5. Ion-Beam Facility

The ion-beam facility seen in Fig. 8 is a stainless steel, high vacuum chamber which is 4 ft. in diameter and 15 ft. long. The inner surface of the chamber is maintained at liquid nitrogen temperature for most research applications. Currently the chamber is employed in an experimental study of ambipolar, electrostatically accelerated ion-streams.

A bell jar has been attached to the vacuum tank to facilitate secondary emission experiments. Electrons, whose primary source is a modified cathode ray tube, required for this type of experimental work are collected in a segmented hemisphere.

The chamber is evacuated by a 32-inch diffusion pump which when using Convoi-20 oil can maintain a vacuum in the 10^{-7}mm mercury range. A higher vacuum can be obtained by using a silicon-base oil.

Ion-beam power is measured by hot-wire calorimeter probes. These probes have been designed to eliminate the common problems of inadequate cooling, poor electrical resistance, and large surface exposure to the ion beam. The calorimeters employ a platinum-iridium alloy wire as a sensing element. A special DC feedback amplifier system has been developed to improve the calorimeter frequency response.

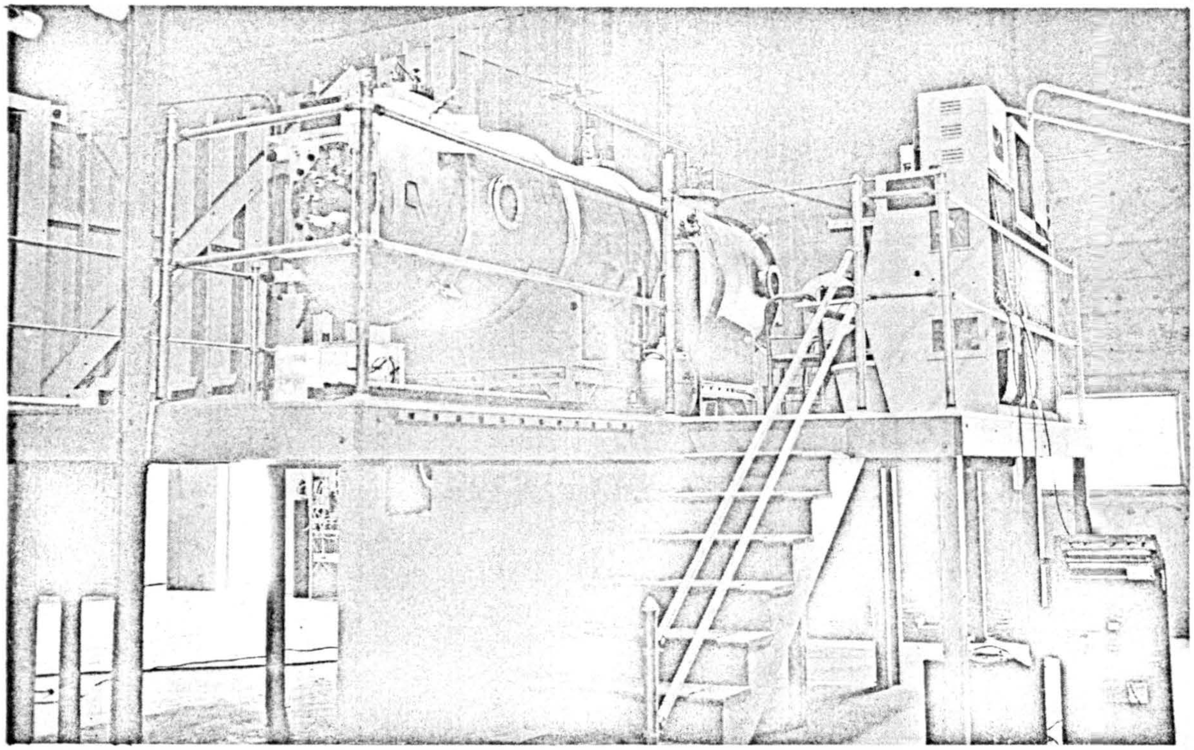

Figure 8. Ion-Beam Facility

Current research employs a hot porous tungsten disk as a contact ion source. Cesium vapor flows from a tiny reservoir at a rate controlled by the thermal dependence of vapor pressure. As the cesium vapor passes through the porous tungsten, the cesium atoms lose an electron and become a positively charged cesium ion at the disk surface. The ions are accelerated electrostatically by a 5000-volt potential difference in a Pierce-type electrode system. An ion beam formed in this manner is neutralized by the injection of electrons downstream of the last electrode. For the ambipolar studies, electrons are introduced within the ion accelerator.

6. Electrokinetic Facility

The electrokinetic facility is designed for experimental studies of phenomena associated with the electrical double layer. Fig. 9 is an interior photograph showing a typical flow system, electrodes, and electronic measurement equipment required by the majority of investigations probing this phenomenon. A basic flow system consists of a 25 ft. long 1 in. diameter glass pipe with a constant head tank for supplying water at a constant flow rate at heads up to 12 ft. Extensive studies on developing probes to measure turbulence in liquids have been made with this system.

7. Shock Tube

A shock tube which will allow the experimental evaluation of real gas

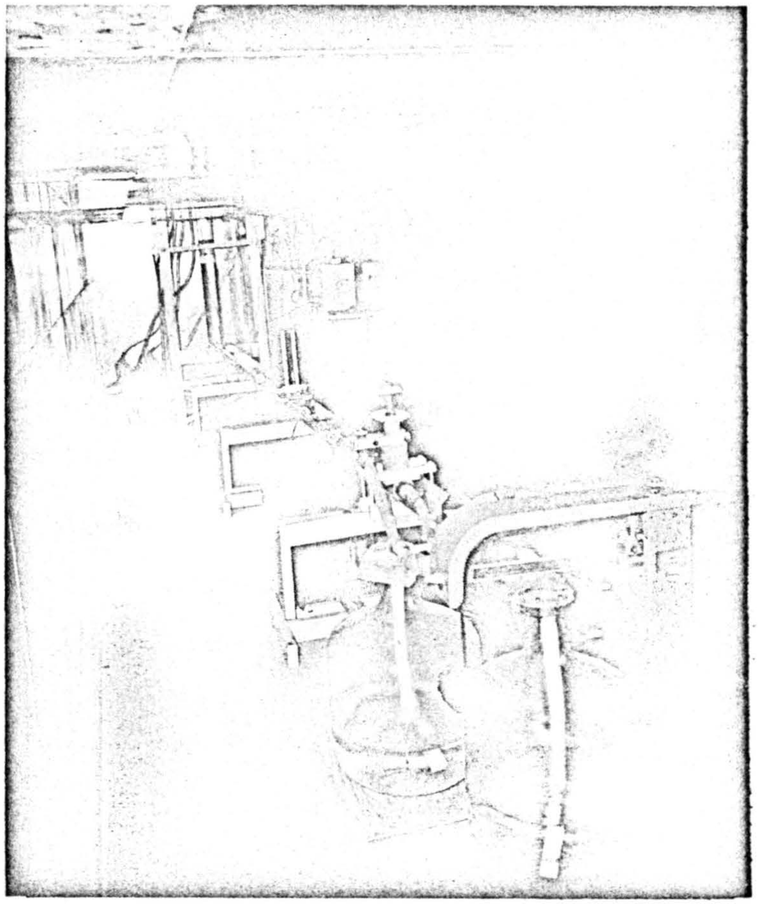

Figure 9. Electrokinetic Facility

properties is shown in Fig. 10. Current plans call for the measurement of two properties: 1) relaxation rates, and 2) ionization effects. Long range plans call for the study of the non-equilibrium "chemi-ionization" known to exist in hydrocarbon gases.

8. Instrumentation

Personnel employed within the Fluid Mechanics Program have assembled a data acquisition system and a data analysis system to provide the means of obtaining and analyzing turbulence data with a completeness almost unequalled in this country.

8.1 Data Acquisition System The data acquisition system shown in Fig. 11 is comprised of a variety of transducers, signal conversion, and data-storage units. This system employs three two-channel hot-wire constant resistance anemometer amplifiers of different designs thus allowing cross checks that improve data reliability.

The system is supported by a number of calibration facilities. Instrument calibration for very low velocities is accomplished by the use of a rotating-arm calibration tank.

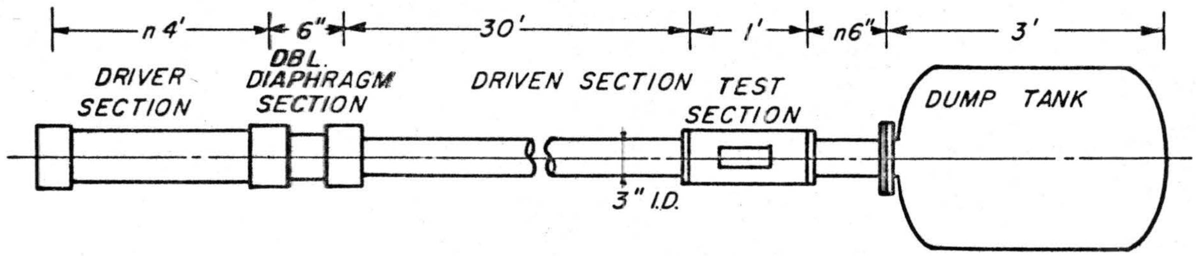

Figure 10. Shock Tube

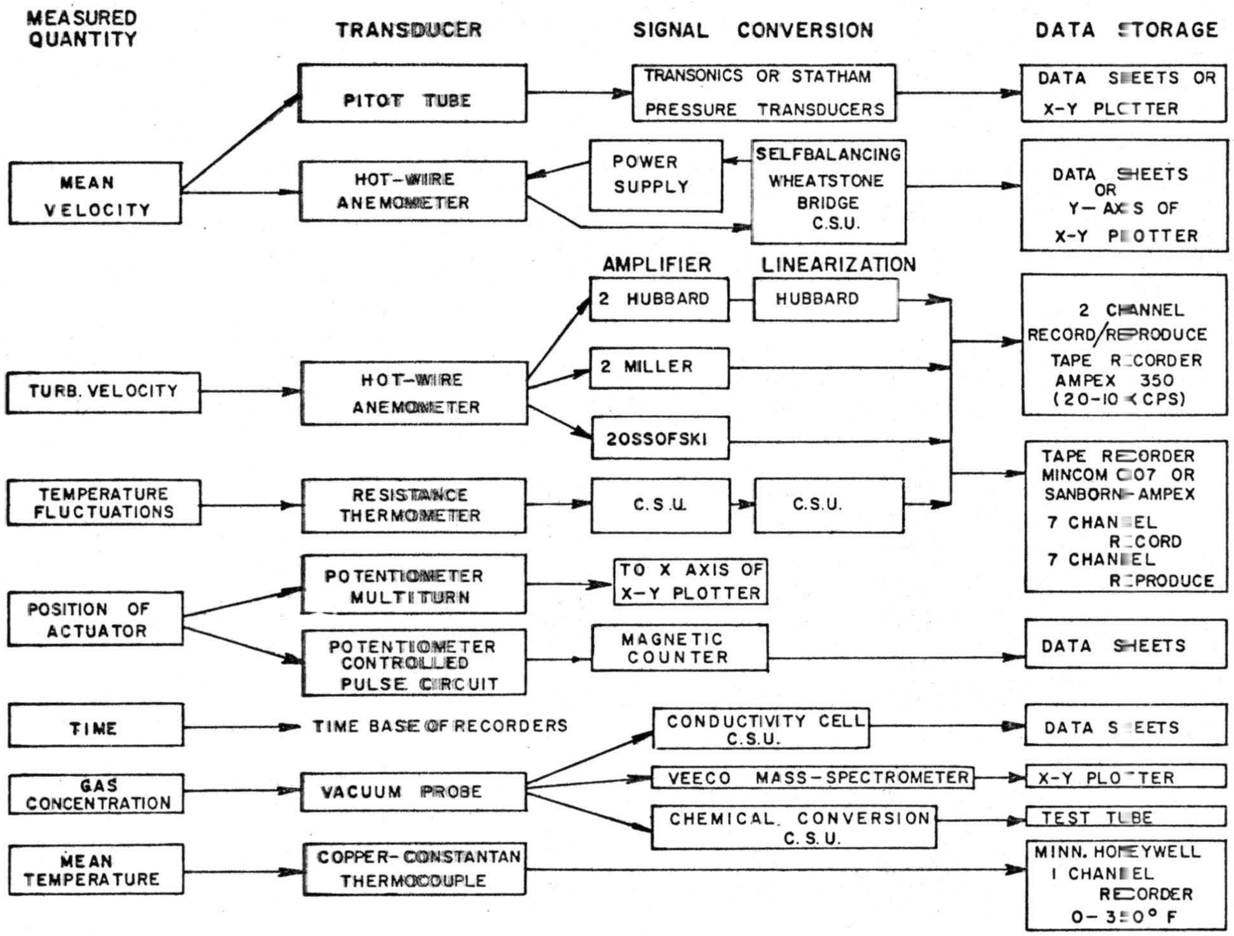

Figure 11. Data Acquisition System

Mean temperature measurement thermocouples are fabricated and calibrated in the laboratory facilities. The system employs resistance thermometers for measuring fluctuating temperatures in a turbulent flow field. Transducer data are recorded on either a standard, FM, seven-channel magnetic tape recorder or a portable magnetic tape recorder which is available for recording data at locations not readily accessible to the standard recorder system.

8.2 Data Analysis System The data analysis system seen in Fig. 12 is com-

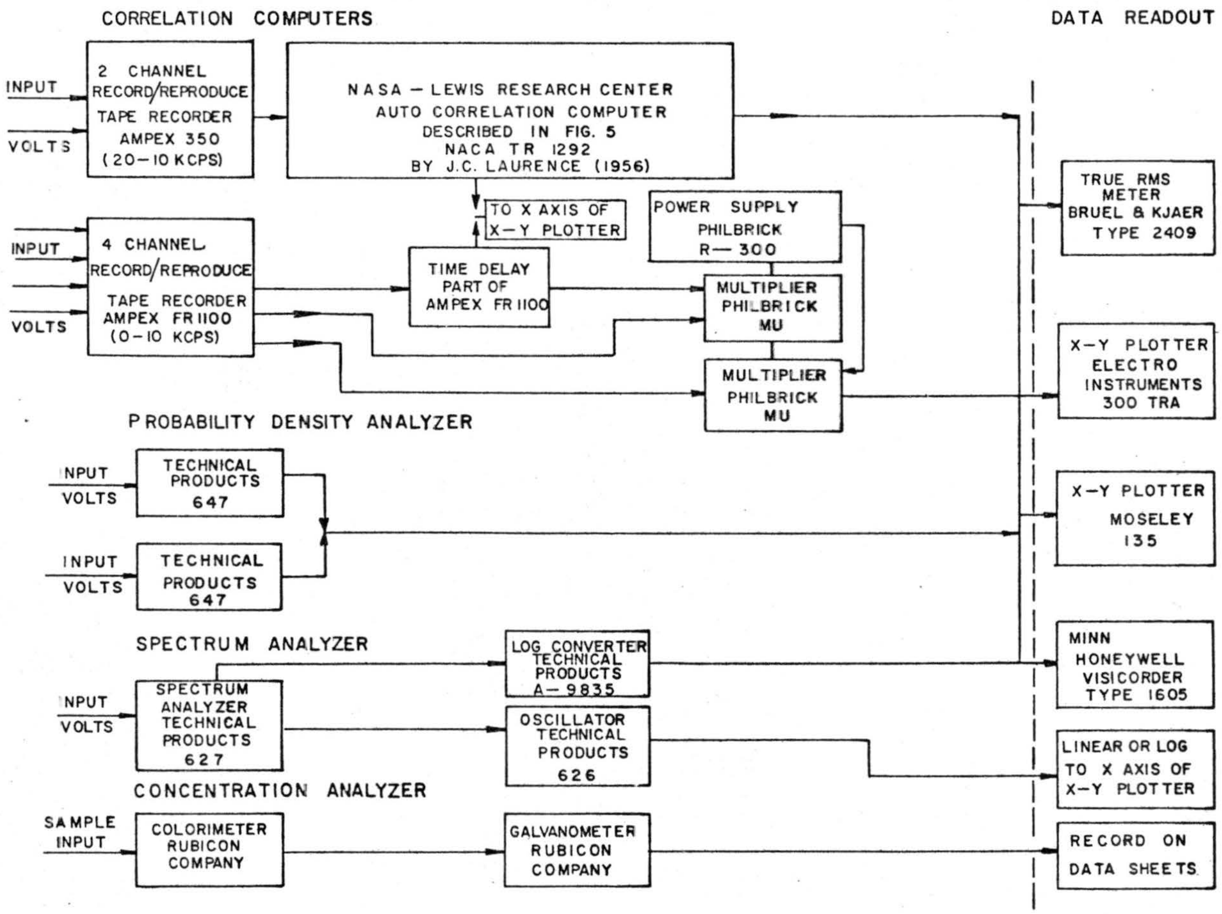

Figure 12. Data Analysis System

prised of components supplied by the University, the Army, and the National Center for Atmospheric Research (NCAR). The system has three major sections: 1) the correlation computers located in the computer section; 2) the spectrum analyzer; and 3) the probability-density-distribution analyzer. All components operate in a frequency range up to 10,000 cps. Even though the spectrum analyzer operates only above 2 cps, this system can accommodate micrometeorological field data that may have frequencies well below 2 cycles per hour by utilizing a second tape recorder to bring data into a frequency range appropriate for analysis.

Autocorrelations are recorded on an X-Y plotter, against the time delay that is expressed by a voltage proportional to the distance between the two reproduce heads. Cross correlations are recorded in the same manner, or are read directly from the rms meter.

The three spectrum analyzers seen in Fig. 12 have either a constant bandwidth or a one-third octave bandwidth. Spectra can be taken either manually, by adjusting the tuning knob of the oscillator and reading frequencies and amplitudes off separate dials, or automatically through the use of a motor drive. Amplitudes and frequencies, or their logarithms, can then be plotted on an X-Y plotter.

Professional Staff

Professional staff members associated with the Fluid Mechanics Program are personally engaged in research and supervise graduate students in investigations leading to theses and dissertations. In addition to laboratory activities, these personnel form the core of the fluid mechanics teaching staff. Staff members engage in teaching at both the undergraduate and graduate levels, not only in the classroom, but in the laboratory as well. Brief biographical information is presented on each staff member of Colorado State University who devotes a major portion of his time to research and teaching in fluid mechanics.

J. E. Cermak, Professor-in-Charge, Fluid Mechanics Program, holds B.S. and M.S. degrees in Civil Engineering from Colorado State University and a Ph.D. in Engineering Mechanics from Cornell University. He has had 16 years experience in teaching and research at Colorado State University. He has served as Chairman of the Fluid Dynamics Committee of the American Society of Civil Engineering, Engineering Mechanics Division, and is an Associate Member of the Fluid Mechanics Committee of the American Society of Mechanical Engineering, Hydraulics Division. Dr. Cermak was the recipient of a North Atlantic Treaty Organization postdoctoral fellowship during 1961-62 at Cambridge University where he was engaged in teaching, study, and research in the field of fluid mechanics. Currently he is Chairman of the Mechanics Division, American Society for Engineering Education. He is a trustee and Vice President of the Colorado State University Research Foundation and a Council Member of the Rocky Mountain Section of the American Institute of Aeronautics and Astronautics. He is a Registered Professional Engineer in Colorado, and also a member of the American Society of Civil Engineers, American Society of Mechanical Engineers, American Geophysical Union, American Meteorological Society, and Sigma Xi.

Lionel V. Baldwin, Dean of Engineering and Professor of Civil Engineering, holds a B.S. degree from the University of Notre Dame, an M.S. degree from Massachusetts Institute of Technology, and a Ph.D. from Case Institute of Technology, with a major in Chemical Engineering and a minor in Physical Chemistry. His experience includes work as an engineering research assistant in the polychemical field for the E. I. DuPont Company, chemical market research for W. R. Grace and Company, and research work over a period of six years with the National Aeronautics and Space Administration at Cleveland, Ohio. Dr. Baldwin has published papers and reports on aerodynamic mixing and turbulent diffusion, heat transfer in rarefied gas flows, ion-beam research, and propulsion-system studies. He co-authored a chapter on the application of a hot-wire probe to low-density, high-energy plasmas (Progress in Astronautics and Rocketry, Vol. 5, Electrostatic Propulsion; Academic Press, 1961). He is a member of Sigma Xi, American Institute of Chemical Engineers, American Society for Engineering Education, and American Society of Mechanical Engineers. He is an associate fellow of the American Institute of Aeronautics and Astronautics, and a Registered Professional Engineer in Colorado.

Gilbert J. Binder, Assistant Civil Engineer, is a graduate of Ecole National des Ponts et Chaussees, Paris, France, and holds a Ph.D. in Engineering from Colorado State University. His principal field of interest is in theoretical and applied fluid mechanics. He is currently engaged in an investigation of turbulence in liquid flows. He is a member of Sigma Xi and the American Society of Engineering Education.

Charles C. Britton, Associate Professor of Electrical Engineering, holds a B.S. degree from Texas Technological College, an M.S. degree from Iowa State University, and has taken part-M.S. work in Electrical Engineering at the University of Colorado. His experience includes one year with the General Electric Company, twelve years teaching at Iowa State and Colorado State Universities. Summers have been spent in instrumentation for a model wave basin, wind tunnel and meteorological studies. He is a senior member of the Instrument Society of America, the Institute of Radio Engineers, and is a Registered Professional Engineer in Colorado.

Hsing Chuang, Assistant Professor and Assistant Civil Engineer, received his B.A. from National Taiwan University, his M.S. degree from the University of Minnesota in Hydromechanics, and obtained his Ph.D. degree in Engineering from Colorado State University. He spent two years at the Engineering Science Laboratory, Harvard University, studying plasma diagnostics by means of a spectrograph. Dr. Chuang is the author of several papers in the area of electrokinetics. He is a member of American Institute of Aeronautics and Astronautics, Sigma Xi, and Phi Kappa Phi.

Calvin L. Finn, Assistant Electronics Engineer, holds a B.S. and an M.S. degree in Electrical Engineering from Colorado State University. His experience includes two years as an electronics engineer with General Dynamics/Astronautics, Space Simulator. Mr. Finn has been associated with the Fluid Dynamics and Diffusion Laboratory for two and one-half years. During this time he has developed electronic circuits for turbulence instrumentation.

Robert D. Haberstroh, Associate Professor, Mechanical Engineering, received a B.S. from Carnegie Institute of Technology, an S.M., a Mechanical Engineering Degree, and a Doctor of Science Degree from MIT. Dr. Haberstroh has taught at Carnegie Institute of Technology, University of Pittsburgh, the Massachusetts Institute of Technology, and Colorado State University. He was an industrial liaison officer with the Research Administration at MIT. He was a George Westinghouse Scholar at Carnegie, 1945-1950, a Ford Doctoral Fellow, MIT 1962-63, and is a Registered Professional Engineer (Massachusetts). Dr. Haberstroh has done research in fluid mechanics and heat transfer with applications to jet engines via Project Meteor. He has conducted a doctoral research program to study flow-regime transition in two phase, gas-liquid flows. Presently he is co-investigator in a project to study nucleate boiling and is doing personal research on analytical means of predicting the heat transfer coefficient for flow of any Newtonian fluid in a circular pipe with constant heat flux. He has also had industrial and business experience as an engineer and sales manager and presently does consulting in heat transfer. Dr.

Haberstroh has published several papers and belongs to the following organizations: Sigma Xi, American Society of Mechanical Engineers, American Society for Engineering Education, National Society for Professional Engineers.

Herman J. Koloseus, Associate Professor of Civil Engineering, holds a B.S. degree in Civil Engineering from Rensselaer Polytechnic Institute, an M.S. degree from Colorado State University, and a Ph.D. degree from the State University of Iowa. He has had nine years experience in teaching and research. His research has been in the fields of fluid mechanics and hydraulics, especially as related to free-surface flow. Dr. Koloseus has published papers on roughness-concentration effects and free-surface instability. He is a Registered Professional Engineer in the State of Iowa and a member of the American Society of Civil Engineers and the American Geophysical Union.

Robert N. Meroney, Assistant Professor of Engineering, holds a B.S. degree from the University of Tennessee, and M.S. and Ph.D. degrees in Mechanical Engineering from the University of California at Berkeley. His experience includes work as an engineer for the Naval Ordnance Laboratory at Silver Springs, Maryland. His primary interests are the effect of mass injection on heat transfer from a partially disassociated gas stream, high heat flux effects on vehicles re-entering the atmosphere at high speeds, and the effects of light gas injection into the boundary layers under the above conditions.

John H. Nath, Associate Professor of Civil Engineering, Colorado State University, has a B.S. degree in Civil Engineering from the University of Colorado and an M.S. degree in Civil Engineering from the Denver Extension Center of the University of Colorado. He is now working for a Ph.D. degree in Civil Engineering at the Massachusetts Institute of Technology. His experience includes four years of teaching as Assistant Professor of Civil Engineering at Colorado State University and he has had many years experience in research and consulting. Mr. Nath served as Director of the Summer Institute in Fluid Mechanics, which was sponsored by the National Science Foundation, during the summer of 1962. He is a member of the American Society of Civil Engineers, and National Society of Professional Engineers.

Maxwell Parshall, Associate Professor of Civil Engineering, Colorado State University, holds a B.S. degree in Chemistry from Massachusetts Institute of Technology and a B.S. degree in Civil Engineering from Colorado State University. He has eight years experience as an analytical chemist and ten years experience in hydraulics and fluid mechanics laboratory work and twenty years in meteorological observations. His experience in the teaching field has been in analytical chemistry, surveying, hydraulics, mechanics, sanitary engineering and meteorology. He is a Registered Professional Engineer and Land Surveyor in Colorado.

Erich J. Plate, Associate Professor, Civil Engineering, Colorado State University, holds an M.S. degree from Colorado State University and a Dipl. Engr. degree from Technical University, Stuttgart, Germany. Prof. Plate has submitted his doctoral dissertation to the Technical University of Stuttgart. He is a native of Germany and came first to the United States under a Fulbright Grant in 1954. He has worked on boundary-layer flows in air and water, on sea interactions and on instrumentation, and has published many reports and papers on these subjects. He is a member of Sigma Xi, American Society of Engineering Education, American Meteorological Society, American Society of Civil Engineers.

Virgil A. Sandborn, Associate Professor of Engineering, holds a B.S. degree in Aeronautical Engineering from the University of Kansas, and an M.S. degree in Aeronautical Engineering from the University of Michigan. He has twelve years experience in fluid mechanics research with the National Aeronautics and Space Administration's Lewis Research Center, and at AVCO, Research and Advanced Development Division. While with AVCO he was a consulting scientist of the Gasdynamics Section. Prof. Sandborn has written numerous scientific reports many of which are on the subject of turbulent boundary layers and hot-wire anemometry. He is a member of Sigma Xi and the American Institute of Aeronautics and Astronautics.

G. L. Smith, Assistant Civil Engineer and Assistant Professor of Civil Engineering, Colorado State University, received his B.S. in Civil Engineering from the University of New Mexico and an M.S. in Irrigation Engineering from Colorado State University. He spent one year at the University of Iowa doing graduate work in hydraulics and fluid mechanics. From 1949-1955 he was employed by the Corps of Engineers at Vicksburg, Mississippi as a hydraulic engineer and as a hydrologist. His experience at Colorado State University has included research in hydraulics, design of hydraulic laboratory equipment for undergraduate and graduate instruction. He is a Registered Professional Engineer.

Hsieh-Wen Shen, Associate Professor of Civil Engineering, holds B.S. and M.S. degrees in Civil Engineering from the University of Michigan, and a Ph.D. degree from the University of California at Berkeley. His experience includes five years as a graduate research engineer participating in several research projects in hydraulics, fluid mechanics, and sedimentation for the Engineering Research Institute of the University of California, Berkeley. Dr. Shen spent over two years with the Harza Engineering Company, Chicago, where he reviewed canal design in West Pakistan. He has had papers published on sedimentation, generation of secondary currents and wave motions. Dr. Shen is the 1965-66 Freeman Fellow from the American Society of Civil Engineers. He is a Registered Professional Engineer in Colorado, and Associate Member of the American Society of Civil Engineers, as well as a member of Sigma Xi.

Hossein Shokouh, Junior Civil Engineer, is a graduate of Valley Junior College (Van Nuys, California), holds B.S. and M.S. degrees in Civil Engineering from Colorado State University. Mr. Shokouh has conducted wind-tunnel research since 1961 at Colorado State University and is now laboratory coordinator for the Fluid Dynamics and Diffusion Laboratory.

The Program is strongly supported in both research and teaching functions through visiting professorships, Faculty Affiliates from agencies of Federal and State Governments and Universities, both domestic and foreign, and Colorado State University Faculty who participate either as advisors or as special course lecturers. Most of these individuals are presented on the following pages. We offer our apologies to those who have taken an active part in the Program but who are not acknowledged here because of our failure to recall all contributors.

Maurice L. Albertson, Professor of Civil Engineering, Colorado State University, holds a B.S. degree in Civil Engineering from Iowa State College, M.S. and Ph.D. degrees in Hydraulic Engineering from the State University of Iowa, and the degree of Doctor of Physical Sciences from the Universite de Grenoble, France. He has had more than twenty years experience in fluid mechanics and water resources research. His experience has been primarily with problems involving design and development of hydraulic structures, alluvial hydraulics, and wind-tunnel studies of boundary layers and evaporation. He is the author of the Applied Hydraulics section of the Encyclopedia Brittanica, 1961, and is co-author of a textbook "Fluid Mechanics for Engineers". Dr. Albertson was awarded the American Society of Civil Engineers Emil Hilgard Prize in 1951 for a paper on diffusion of submerged jets, the J.C. Stevens Award for a discussion of a paper on evaporation, and the J. James R. Croes award for a paper on design of alluvial channels. He is the U.S. Coordinator for the SEATO Graduate School of Engineering in Bangkok, Thailand, and is a Registered Professional Engineer in Colorado. Memberships include American Society of Civil Engineering, American Society for Engineering Education, American Geophysical Union, Sigma Xi, Engineers Joint Council, and the International Commission on Irrigation and Drainage.

Edward R. Benton, Assistant Professor, Department of Astrogeophysics, University of Colorado, holds A.B., A.M. and Ph.D. degrees in Applied Mathematics from Harvard University. His experience includes work on missile aerodynamics with Arthur D. Little, Inc. and research in fluid dynamics at the National Center for Atmospheric Research. Dr. Benton has published papers on the subjects of missile aerodynamics and boundary layer theory. His current research efforts are primarily in the areas of turbulence and geophysical hydrodynamics. He is a member of the American Geophysical Union, American Physical Society and the American Institute for Aeronautics and Astronautics.

A. R. Chamberlain, Vice President for Administration and Professor of Civil Engineering, Colorado State University, holds a B.S. degree from Michigan State University, an M.S. degree from Washington State University, and a Ph.D. in Civil Engineering from Colorado State University. He was a Fulbright Fellow at the Universite de Grenoble, France, where he was engaged in research on fluid mechanics. Vice President Chamberlain has presented and published several technical papers in turbulent transport and open-channel hydraulics. He is Chairman, Special Commission on Weather Modification of the National Science Foundation. He is also a member of Sigma Xi, National Society of Professional Engineers, American Society for Engineering Education, American Society of Civil Engineers, and the American Association for the Advancement of Science.

Ralph R. Goodman, Associate Professor of Physics, Colorado State University, holds B.S.E. (Math), B.S.E. (Physics), M.S. (Physics), and Ph.D. (Physics) degrees, all from the University of Michigan. Dr. Goodman has served as a consultant to the University of Michigan Science Institute and the National Academy of Science committee on Undersea Warfare. He was the senior scientist to NATO SACLANT, ASW Research Center, La Spezia, Italy and has lectured at The Pennsylvania State University. Dr. Goodman's specialties are solid state physics, underwater sound, acoustic scattering, and wave propagation in an elastic media. He is a member of the American Institute of Physics, Acoustical Society of America, and Sigma Xi.

G. M. Hidy, Staff Scientist with the National Center for Atmospheric Research, Boulder, Colorado, holds A.B. and B.S. degrees from Columbia University, an M.S.E. degree from Princeton, and a D. Engr. degree in Chemical Engineering from Johns Hopkins University.

His experience includes work as a Research Engineer at the Tonawanda Laboratories of the Linde Company and at the Miami Valley Laboratories of the Proctor and Gamble Company. Dr. Hidy has spent the last three years with the National Center for Atmospheric Research studying problems in aerosol physics and fluid dynamics. He is the co-editor of the "International Reviews in Aerosol Physics and Chemistry". He is a member of Sigma Xi and the AIChE.

Shozo Ito, Faculty Affiliate (on leave from the Observation Section of the Japan Meteorological Agency, Tokyo) was awarded a scholarship from the Scientific and Technical Agency of the Japanese Government to study in the Fluid Dynamics and Diffusion Laboratory at Colorado State University. Mr. Ito received his B.S. from Tokyo Science College and has studied atmospheric diffusion under Professor J. Sakagami of Ochanomizu University and Dr. Eiichi Inoue of the Division of Meteorology, National Institute of Agricultural Sciences. Mr. Ito has been with the Japan Meteorological Agency since 1941 and is studying atmospheric diffusion in a thermally stratified layer.

Bernard W. Marschner, Head, Department of Mechanical Engineering, Colorado State University, holds a B.S. degree from the University of Minnesota and M.S. and Ph.D. degrees from the California Institute of Technology in Aeronautics and Applied Mathematics. His experience includes seven years as project engineer for the transonic and supersonic wind tunnel at Tullahoma, Tennessee, four years as manager of the Central Inertial Guidance Test Center, two years as Head of Department of Aeronautics and Assistant Dean for Research at the Air Force Academy, and two years as Director of the Science and Technology Program for the Air Force System Command. He is the author of several papers in aeronautics, wind-tunnel design and flight dynamics. He is a member of the Technical Committee on Ground Testing, Fluid Dynamics Panel, AGARD, NATO. Society memberships include the American Institute for Aeronautics and Astronautics, American Society for Engineering Education and the American Society of Mechanical Engineers.

William R. Mickelsen, Professor of Mechanical and Electrical Engineering, Colorado State University, holds a B.S. degree from the University of Wisconsin and an M.S. degree from Case Institute of Technology in Aeronautical Engineering. He has had sixteen years of research experience at the NACA/NASA Lewis Research Center where he was Chief of the Electrostatic Propulsion Branch. In 1958 he was a recipient of the Rockefeller Public Service Award which provided for a year of study at Cavendish Laboratory, University of Cambridge. He has written numerous papers on turbulent diffusion, fluid mechanics of Combustion and electrostatic thrustors. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics, a Fellow of the American Astronautical Society, and a member of Sigma Xi, American Society for Engineering Education, American Society of Mechanical Engineers, American Association for the Advancement of Science.

Elmar R. Reiter, Professor of Atmospheric Science, Colorado State University, holds a Ph.D. degree and the degree Dozent from the University of Innsbruck in meteorology and geophysics. His experience includes an instructorship in meteorology at the University of Chicago; an instructorship in meteorology at the NATO Officers School, Furstenfeldbruck, Germany; lecturer in meteorology at the University of Innsbruck; and guest lecturer in meteorology at the German Weather Service and the Department of Meteorology, University of Melbourne. He is author of the book Meteorologie der Strahlstroeme, Springer 1961 and (English translation) University of Chicago Press 1963. He is a contributor to World Survey of Climatology, vol. 3, and the author of over one-hundred technical papers on atmospheric turbulence, jet streams and general circulation. Dr. Reiter is a member of the American Meteorological Society, Japan Meteorological Society, Royal Meteorological Society, Austrian Meteorological Society, American Geophysical Union, and Sigma Xi.

E. P. Sutton, Lecturer in Engineering and Fellow of Pembroke College, Cambridge University, Cambridge, England, holds B.A. and M.A. degrees from Oxford University, Oxford, England, and an M.A. from Cambridge University. He was Principal Scientific Officer at the Royal Aircraft Establishment, Farnborough and Bedford, England where he was engaged in research on the aerodynamics of wings at high subsonic, transonic and supersonic speeds. Dr. Sutton is a member of advisory committees of the Aeronautical Research Council.

1. Participating Graduate Students

Doctoral candidates from a wide variety of fields participate in the research activities of the Fluid Mechanics Program. While engaged as Research Assistants at a stipend rate up to $4500/year these students are occupied half-time with formal class work and half-time with laboratory or other forms of research. Ordinarily research accomplished under the Research Assistantship leads to a dissertation. The following students are now working toward a Ph.D. degree in the Program as Research Assistants, National Science Foundation Trainees and National Aeronautics and Space Administration Fellows:

Student	Dissertation Topic	Advisor
Bunney, Robert	Plasma physics	V. A. Sandborn
Chandra, Suresh	Turbulent diffusion	E. J. Plate
Chang, Po-cheng	Wind-water interactions	E. J. Plate
Dowdell, Rodger	Three-dimensional boundary layers	J. E. Cermak
Drake, Ronald	Wind-generated waves	E. J. Plate
Galarneau, Andre	Turbulent diffusion	J. E. Cermak
Giorgini, Aldo	Turbulence	J. E. Cermak
Hill, William W., Jr.	Plasma physics	V. A. Sandborn
Hsi, George	Turbulent diffusion	G. J. Binder
Kao, Kai	Turbulent diffusion	J. E. Cermak
Koehler, Stanley B.	Turbulent diffusion	L. V. Baldwin
Lin, C.W.	Thermally stratified flow	G. J. Binder
Liu, Chang-ling	Wind-water interactions	E. J. Plate
Liu, Chang-yu	Turbulent boundary layers	V. A. Sandborn
Marshall, Richard D.	Turbulent boundary layers	J. E. Cermak
Roper, Alan T.	Three-dimensional boundary layers	J. E. Cermak
Tieleman, Henry W.	Turbulent boundary layers	V. A. Sandborn
Yano, Motoaki	Turbulent diffusion	J. E. Cermak
Yeh, Fei-fan	Atmospheric diffusion	E. J. Plate

Graduates of the Fluid Mechanics Program

Perhaps no better indication of what the Fluid Mechanics Program has to offer students by way of future professional activity can be obtained by listing the present professional affiliation of students having graduated from the Program in the last ten years. These graduates are listed on the following pages.

Name	Present Affiliation	Present Position
Bhaduri, Sachindranarayan Ph.D.	Dept. of Mech. Engr. Texas Western College University of Texas El Paso, Texas	Associate Professor

Binder, Gilbert J. Ph.D.	Fluid Mechanics Program Dept. of Civil Engineering College of Engineering Colorado State University Fort Collins, Colorado	Assistant Professor
Chanda, Benoyendra Ph.D.	College of Engineering and Technology, Jadavpur University, Calcutta, India	Assistant Professor
Chao, Junn-Ling Ph.D.	Mechanical Engineering Department, College of Engineering Oklahoma State University Stillwater, Oklahoma	Associate Professor
Chuang, Hsing Ph.D.	Fluid Mechanics Program Dept. of Civil Engineering College of Engineering Colorado State University Fort Collins, Colorado	Assistant Professor
Davar, Kersi Ph.D.	Dept. of Civil Engr. College of Engineering Texas Inst. of Technology Lubbock, Texas	Assistant Professor
Duckstein, Lucien Ph.D.	Systems Engineering Dept. College of Engineering Numerical Analysis Laboratory University of Arizona Tucson, Arizona	Professor
Earle, Edward M.S.	Dept. of Mechanics College of Engineering Cornell University Ithaca, New York	Ph.D. Candidate
Goodwin, Carl R. M.S.	U. S. Geological Survey Palo Alto, California	Research Engineer
Hwang, Neddy Ph.D.	Dept. of Civil Engineering College of Engineering University of Houston Houston, Texas	Assistant Professor
Kemp, Bennett M.S.	Dept. of Aerospace Engr. College of Engineering Indiana Institute of Technology Fort Wayne, Indiana	Associate Professor

Kuo, Yung-huang Ph.D.	Dept. of Civil Engineering College of Engineering University of Louisiana Baton Rouge, Louisiana	Assistant Professor
Lin, Chi-Win M.S.	Department of Engineering Brooklyn Polytechnic Inst. Brooklyn, New York	Ph.D. Candidate
Liu, Henry Ph.D.	Dept. of Civil Engineering College of Engineering University of Missouri Columbia, Missouri	Assistant Professor
Malhotra, Ramesh Ph.D.	Dept. of Civil Engineering College of Engineering Roorkee University New Delhi, India	Assistant Professor
Nagabhushanaiah, Halevoor Ph.D.	Indian Institute of Technology New Delhi, India	Reader
Peterka, Jon A. M.S.	Division of Engineering Brown University Providence, Rhode Island	Ph.D. Candidate
Poreh, Michael Ph.D.	Faculty of Civil Engineering Israel Institute of Technology Haifa, Israel	Assistant Professor
Quraishi, Ali Akhtar Ph.D.	Dept. of Civil Engineering East Pakistan University of Engineering and Technology Dacca, East Pakistan	Assistant Professor
Tan, Huey-Ming M.S.	College of Engineering Northwestern University Chicago, Illinois	Ph.D. Candidate
Tao, Men-Cheh M.S.	Dept. of Mechanics and Hydraulics University of Iowa Iowa City, Iowa	Ph.D. Candidate
Tsuei, Yeong-ging Ph.D.	Dept. of Mathematics College of Engineering University of Cincinnati Cincinnati, Ohio	Associate Professor

Yang, Chi-Sheng M.S.	Dept. of Aeronautical Engineering University of Michigan Ann Arbor, Michigan	Ph.D. Candidate
Yuen, Jack K. M.S.	Dept. of Civil Engineering University of Hawaii Honolulu, T. H.	Associate Professor

Research Studies and Reports

During the past fifteen years research in the Fluid Dynamics and Diffusion Laboratory has been devoted primarily to studies of turbulence and turbulent diffusion. The major deviation from this area of work has been the recent addition of a vacuum facility to study mechanics of cesium ion beams. In the following paragraphs an attempt is made to group the entire past and present research effort into four categories--basic mechanics of fluids, geophysical fluid mechanics, physics of fluids, and instrumentation development. Brief descriptions of the various research projects and reports produced within each category of study are presented.

1. Basic Mechanics of Fluids

1.1 Structure of Turbulent Boundary Layers This subject is part of a long-range program to study the response of low-speed turbulent boundary layers to vertical density stratifications produced by heating or cooling, to various degrees and types of surface roughness and to various types of single surface obstacles. Two-dimensional and axisymmetrical (produced by impingement of a vertical jet on a horizontal surface) boundary layers have been and continue to be studied. Theoretical analysis of non-isotropic turbulence which is homogeneous in planes parallel to a plane solid surface is being undertaken simultaneously with the experimental program. The following reports have been written on this work:

(a) Turbulent Boundary Layer over Heated and Unheated Plane, Rough Surfaces, B. Chanda. Prepared for GRD-AFCRC under Contract AF19(604)-1706, May 1958, CER58BC21.

(b) The Turbulent Boundary Layer at Low Reynolds Numbers with Unstable Density Stratification Produced by Heating, J. E. Cermak Ph.D. dissertation, Cornell University, Ithaca, New York, March 1959.

(c) Mean Velocity Profiles for Flow over a Plane Smooth, Heated Boundary, E. N. Earle, M.S. Thesis, Colorado State University, Fort Collins, Colorado, May 1960.

(d) Separation Flow Downstream of a Plate Set Normal to a Plane Boundary, H. S. Nagabhushanaiah. Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, November 1961.

(e) Axisymmetric Boundary Layer of a Jet Impinging on a Smooth Plate, Y. G. Tsuei. Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, August 1962.

(f) Fundamental Study of a Submerged and Non-submerged Three Dimensional Jet Impinging Upon a Normal Plane, edited by G. L. Smith; report to the National Science Foundation, June 1963, CER63GLS1.

(g) Flow Characteristics of a Circular Submerged Jet Impinging Normally on a Smooth Boundary, M. Poreh and J. E. Cermak. Proceedings 6th Midwestern Mechanics Conference, 1959.

(h) A Resistance Thermometer for Transient Temperature Measurements, J.L. Chao and V. A. Sandborn. Fluid Mechanics Paper No. 1, Colorado State University, Fort Collins, Colorado, January 1964.

(i) The Drag on a Smooth Flat Plate with a Fence, E. J. Plate. Presented at the American Society of Mechanical Engineers Symposium on Fully Separated Flow in Philadelphia, April 1964, CER63EJP66.

(j) Modeling of Velocity Distributions Inside and Above Tall Crops, E. J. Plate and A. A. Quraishi, Journal of Applied Meteorology, Vol. 4, No. 3, June 1965; CER64AAQ-EJP2.

(k) An Experimental Study of Turbulent Boundary Layer Structure, E. J. Plate, V. A. Sandborn, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado. Final Report, Research Grant DA-SIG-36-039-62-G24, December 1964, CER64EJP-VAS37.

(l) Turbulent Momentum Transfer in Three-Dimensional Wall Jet, J. L. Chao, Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, January 1965.

(m) Local Isotropy in Wind Tunnel Turbulence, V. A. Sandborn and R. D. Marshall, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado, Research Memorandum No. 1, Research Grant DA-AMC-28-043-64-G-9, February 1965.

(n) A Three-Dimensional Single Roughness Element in a Turbulent Boundary Layer, H. W. Tieleman, and V. A. Sandborn. Fluid Dynamics and Diffusion Laboratory, Colorado State University, Research Memorandum No. 4, Research Grant DA-AMC-28-043-64-G-9, April 1965, CEM65HT-VAS4.

(o) Evaluation of the Turbulent Energy Dissipation from the Time Derivative Measurements, C. Y. Liu and V. A. Sandborn. Fluid Dynamics and Diffusion Laboratory, Colorado State University. Research Memorandum No. 5, Research Grant DA-AMC-28-043-64-G-9, April 1965, CEM65CYL-VAS5.

(p) Vertical-Velocity Fluctuations in Thermally Stratified Shear Flows, J. E. Cermak and H. Chuang. To be published in Proceedings of International Colloquium on Fine Scale Structure of the Atmosphere, Moscow, USSR, June 1965.

1.2 Diffusion in Shear Layers The diffusion of heat, mass and momentum continues to be a major research area for the laboratory. Most of the basic work done on this subject has been in an effort to learn how different turbulence structures affect the diffusion process and how the information obtained can be applied to diffusion in the atmospheric surface layer. The long working section of the meteorological wind tunnel provides a unique capability for future contributions of the laboratory in this area. The collection of reports written on this research are given in the following list:

(a) Diffusion from a Line Source in Laminar Flow over a Wedge and in Blasius Flow, C. S. Yih, Proceedings, First National Congress of Applied Mechanics, June 1950.

(b) Laminar Heat Convection in Pipes and Ducts, C. S. Yih and J. E. Cermak, prepared for the Office of Naval Research, Contract No. N9 onr 82401, Report No. 5, September 1951.

(c) Laminar Free Convection Due to a Line Source of Heat, C. S. Yih, prepared for the Office of Naval Research, Contract No. N9 onr 82401, Report No. 7, September 1952.

(d) Temperature Distribution in the Boundary Layer of an Airplane Wing with a Line Source of Heat at the Stagnation Edge, Part 1, Symmetric Wind in Symmetric Flow, C. S. Yih, J. E. Cermak, and R. T. Shen, prepared for the Office of Naval Research, Contract No. NOn4-54401, October 1952.

(e) Turbulent Diffusion of Momentum and Heat from a Smooth, Plane Boundary with Zero Pressure Gradient, A. C. Spengos, prepared for Air Force Cambridge Research Center, Contract No. AF-19(604)-421, February 1956.

(f) Heat Transfer by Forced Convection from a Horizontal Flat Plate into a Turbulent Boundary Layer, J. E. Cermak and A. C. Spengos. Proceedings Heat Transfer and Fluid Mechanics Institute, Stanford University, June 1956, CER56JEC21.

(g) Turbulent Diffusion of Momentum and Heat from a Smooth, Plane Boundary with Zero Pressure Gradient, Presentation of Data and Analysis, J. E. Cermak and A. C. Spengos. Prepared for GRD-AFCRC under Contract AF19(604)-421. Part II, Final Report, 1956. CER56JEC22.

(h) Turbulent Diffusion of Momentum and Heat from a Smooth, Plane, Boundary with Zero Pressure Gradient, Experimental Equipment, A. C. Spengos and J. E. Cermak. Prepared for GRD-AFCRC under Contract AF19(604)-421, Final Report, Part I, August 1956, CER56ACS12.

(i) Diffusion from a Point Source within a Turbulent Boundary Layer, K. S. Davar. Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, July 1961.

(j) Diffusion from a Line Source in a Turbulent Boundary Layer, M. Poreh, Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, December 1961.

(k) Diffusion from a Point Source within a Turbulent Boundary Layer with Unstable Density Stratification, R. C. Malhotra, Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, June 1962.

(l) Lagrangian Similarity Hypothesis Applied to Diffusion in Turbulent Shear Flow, J. E. Cermak. Journal of Fluid Mechanics, Vol. 15, Part 1, 1963. CER63JEC50, July 1962.

(m) Mass Diffusion in Neutral and Unstably Stratified Boundary Layer Flows, R. C. Malhotra and J. E. Cermak. International Journal of Heat and Mass Transfer, Vol. 7, June 1963; CER62RCM38.

(n) Wind Tunnel Modeling of Atmospheric Diffusion, R. C. Malhotra and J. E. Cermak. Journal of Geophysical Research, Vol. 68, No. 8, April 1963; CER63JEC49.

(o) Turbulent Diffusion and Anemometer Measurements, L. V. Baldwin and W. R. Mickelsen. American Society of Civil Engineers Paper No. 3507, Vol. 128, 1963, Part I. CER63LVB-WRM20.

(p) Characteristics of Diffusion Plumes from a Point Source within a Turbulent Boundary Layer, K. S. Davar and J. E. Cermak. International Journal of Air and Water Pollution, Vol. 8, pp. 334-354, 30 December 1963, CER62KSD-JEC64.

(q) Study of Diffusion from a Line Source in a Turbulent Boundary Layer, M. Poreh and J. E. Cermak. International Journal of Heat and Mass Transfer, Vol. 7, 410, pp. 1083-1095, October 1964, CER63JEC-MP36.

(r) Diffusion from a Ground Level Line Source into the Disturbed Boundary Layer Far Downstream from a Fence, E. J. Plate. (in preparation)

(s) Diffusion from a Point Source into the Boundary Layer Downstream from a Model Hill. E. J. Plate and C. M. Sheih, 1965. (in preparation)

(t) Laboratory Studies of Mean Velocity Distributions in Thermally Stratified Flows, E. J. Plate. Fluid Mechanics Paper No. 5, Colorado State University, 1965.

(u) Prediction of Turbulent Heat Transfer to Newtonian Fluids of Arbitrary Prandtl Number Flowing in Smooth Circular Tubes, R. D. Haberstroh and L. V. Baldwin, December 1965. (in preparation)

1.3 Turbulent Wakes Axisymmetrical wakes and three-dimensional wakes have been studied in the long test section of the meteorological wind tunnel. This has made data accessible for the period of final decay. Wakes with momentum addition to produce a "momentumless wake" have been investigated. Details of these studies can be obtained from the following reports:

(a) The Formation of Elliptical Wakes, Y.-H. Kuo and L. V. Baldwin, Submitted to Journal of Fluid Mechanics, July 1965. CER65YHK-LVB38.

(b) The Diffusion and Decay of Turbulent Elliptic Wakes, Y.-H. Kuo and L. V. Baldwin, Submitted to AIAA Journal, August 1965. CER65YHK-LVB42.

(c) Three-Dimensional Effects in Viscous Wakes, Y.-H. Kuo and L. V. Baldwin. American Institute of Astronautics and Aeronautics Journal, Vol. 2, No. 6, pp. 1163-4, 1964.

(d) Decay of Turbulence in Axisymmetric Wakes, H. C. Hwang and L. V. Baldwin. Submitted to the American Society of Mechanical Engineering for publication, May 1964, CER64HCH-LVB16.

1.4 Energy Transport at an Air-Water Interface The interaction between air and water is important when developing the theory of two-phase flow, for the influence of the earth's surface on atmospheric circulation, for the prediction of ocean waves and the flow of ocean currents, for the erosion of beaches and sediment transportation in channels, and the design of reservoirs and open channels. Current studies, funded by the National Science Foundation, have three different aims: (1) to provide information that will correct the effect that wind acting on a water surface has on open-channel design parameters, (2) to verify existing wind-wave-generation theories and to extend these results to moving water, and (3) to study the development of wind-generated waves in shallow water as a function of air and water variables. Details and results of investigations can be obtained from the following reports:

(a) A Research Facility with Concurrent Air and Water Flows, E. J. Plate. To be published in La Houille Blanche, France, November 1965. CER64EJP26.

(b) Frequency Spectrum of Wind-generated Waves, E. J. Plate and G. M. Hidy, Physics of Fluids, Vol. 8, pp. 1387-1389.

(c) Wind Action on Water Standing in a Laboratory Channel, E. J. Plate and G. M. Hidy, Paper to be published in Journal of Fluid Mechanics.

(d) The Effect of Wind Drag on Open Channel Flow, C. R. Goodwin, M. S. Thesis, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado, CER65CRG17, March 1965.

(e) Wind Driven Water Currents by W. D. Barnes and D. J. Knapp, Discussion by E. J. Plate, Proc. ASCE, Hydraulics Division, Paper No. 4270, pp. 205-221. Discussion published in Proc. ASCE, Vol. 91, HY5, pp 322-324, September 1965. CER65EJP21.

(f) Laboratory Studies of Wind Action on Water Standing in a Channel, E. J. Plate and G. M. Hidy, Paper presented at the Air-Sea Interaction Conference held at Tallahassee, Florida, February 21-23, 1965. To be published in the Conference Proceedings. CER65GMH-EJP.

(g) The Influence of Wind on Open Channel Flow, E. J. Plate and C. R. Goodwin, Proceedings, ASCE Specialty Conference on Coastal Engineering, Santa Barbara, California, 1965.

(h) Experiments on Wind Generated Waves on the Water Surface of a Laboratory Channel, E. J. Plate and C. S. Yang, Fluid Mechanics Paper No. 4, Colorado State University, Fort Collins, Colorado, 1965. (in preparation)

(i) Air Flow Passing from a Smooth Solid Boundary to a Wavy Water Surface in a Closed Channel, E. J. Plate and G. M. Hidy. Paper presented at the American Met. Society Annual Meeting, Denver, January 1966.

(j) Evaluation of Some Statistics of Random Time Series, E. J. Plate, 1966. (in preparation)

2. Geophysical Fluid Mechanics

<u>2.1 Similarity of Laboratory and Atmospheric Surface-Layer Flows</u> Studies of the turbulence structure and mean flow characteristics developed in laboratory wind tunnels as associated with atmospheric flows derived from available field data have been continuously pursued. The main objective of these studies was the determination of significant criteria for flow similarity in wind tunnel and atmospheric surface-layer flows. Similarity criteria for the effects of vertical density stratification, surface roughness and topographic features on turbulence structure, turbulent diffusion and mean flow characteristics have been of prime interest. In addition to the establishment of similarity criteria for such flows, useful engineering data have also been obtained for the solution of special problems.

The following studies may be grouped together in this classification.

2.1.1 Lake Hefner Studies This investigation was conducted to verify the feasibility of the wind tunnel modeling of wind structures and lake/reservoir evaporation. The project entailed duplicating the topography surrounding Lake Hefner and subjecting this model, seen in Fig. 13, to wind tunnel conditions similar to those found in the atmosphere. Test results were correlated with evaporation conditions known to occur at Lake Hefner. This investigation proved that the wind structure for model and prototype is similar above the viscous sub-layer which existed in the model. A modified Reynolds analogy may be used to correlate evaporation rates when shear velocity rather than the ambient velocity is taken as one of the variables comprising the Reynolds number.

Details and results of this investigation can be obtained from the following reports:

(a) Lake Hefner Model Studies of Wind Structure and Evaporation, Part I, J. E. Cermak and H. J. Koloseus, prepared for the Bureau of Ships, November 1953, CER54JEC20.

(b) Lake Hefner Model Studies of Wind Structure and Evaporation, Part II, J. E. Cermak and H. J. Koloseus, prepared for the Bureau of Ships, July 1954, CER54JEC22.

2.1.2 Point Arguello Flow Investigation A 1:12000 scale model of topography comprising the Point Arguello coastal region was constructed with a sand roughened surface to minimize Reynolds number effects. To study the flow of a stably stratified air mass over the area, as occurs in nature, the model was placed on the cooled floor of the meteorological wind tunnel. With the floor cooled to 120 degrees Fahrenheit below the ambient air temperature significant degrees of thermal stability were obtained. Flow fields, made visible by tracers, were compared with corresponding flow fields measured in the prototype by means of ground-based anemometers, balloon flights and aircraft flights. The model and flow fields can be seen in Fig. 14. General agreement with the field data was found to exist. Reports on this work are under preparation.

2.1.3 San Nicolas Island Flow Investigation This project involves designing and fabricating a wind tunnel model of San Nicolas Island, California. The 1:6000 scale model, shown in Fig. 15, will be used to explore the possibility of improving methods of predicting atmospheric transport and dispersion of toxic and radioactive gases and aerosols in the vicinity of the island. Test data will be compared with field data collected by aerial samplings in the open atmosphere. The comparison should establish the feasibility of using wind-tunnel-model data to predict diffusion in the lower atmosphere under stable conditions.

2.1.4 Candlestick Ballpark Wind Study This study was conducted to map the wind circulation patterns within and surrounding Candlestick Baseball Stadium. Studies entailed subjecting a 1:800 scale model of the stadium and upwind hill, seen in Fig. 16, to several wind directions and wind speeds. Flow patterns were mapped by the use of smoke and streamers. Test data were compared with that gathered at the prototype site. Because of the sharp geometrical

Figure 13. Model of Lake Hefner

Figure 14. Point Arguello Flow Visualization

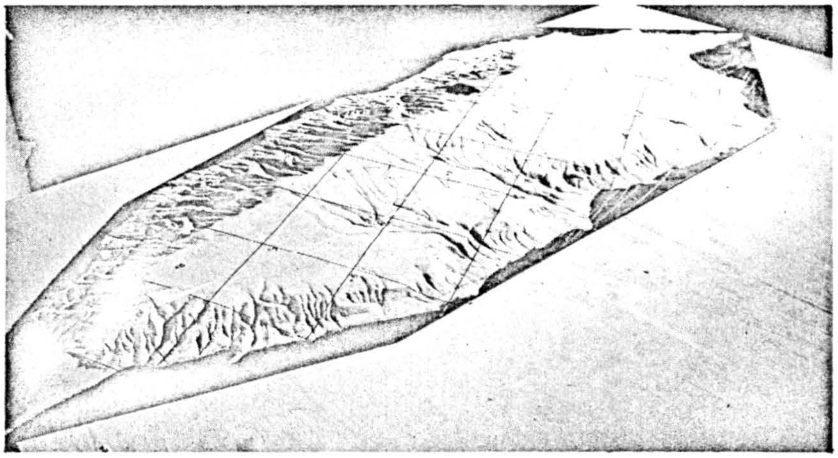

Figure 15. Model of San Nicolas Island

Figure 16. Model of Candlestick Park

features of the stadium and topography, excellent agreement of laboratory and field data were obtained with no significant Reynolds number effects. The results of this project revealed structural and topographic modifications that should eliminate wind problems within the stadium.

Details and results of investigations can be obtained from the following reports and films:

Reports:

(a) Candlestick Park Wind Study Model Investigation, Vol. I, Prototype Wind Studies, Aerosol Laboratory, Metronic Associates, Inc., Palo Alto, California.

(b) Investigation of the Candlestick Park Wind Problem, Vol. II: Wind-Tunnel Model Study, J. E. Cermak, R. C. Malhotra, and E. J. Plate. Fluid Dynamics Diffusion Laboratory, College of Engineering, Fort Collins, Colorado, July 1963, CER63JEC-RCM-EJP27.

(c) Investigations of the Candlestick Park Wind Problem, Vol. III: Conclusions, Recommendations and Summary of Investigation, W. A. Perkins and J. E. Cermak. Prepared for the Department of Public Works, City of San Francisco; Tech. Rep. No. 102, Aerosol Laboratory, Metronics Associates, Inc., Palo Alto, California, August 1963.

Films: (35mm, silent) Investigation of Candlestick Wind Problem

Reel:		Basic Configuration	
1	Correlation Phase	Hill:	Unmodified
		Stadium:	Unmodified
2,3	Modification Phase	Hill:	Unmodified
		Stadium:	Modified
4,5	Modification Phase	Hill:	Removed
		Stadium:	Unmodified and modified
6,7	Modification Phase	Hill:	Modified
		Stadium:	Modified

2.1.5 World Trade Center Towers Flow Investigation This study entails subjecting an aeroelastic 1:500 scale model of the 1400-ft-high World Trade Center Towers in New York City to potentially destructive hurricane winds found in the atmosphere. The objectives of this study, funded by the firm of Worthington, Skilling, Helle, and Jackson, are to determine the dynamic instabilities of single and paired structures, mean pressure distribution, scale of pressure fluctuation areas, mean velocity distribution of air flow downwind from the simulated city, and probability density distributions and intensity of turbulence downwind of a simulated city (in this case the built-up area upwind from the towers as seen in Fig. 17). Measurements of turbulence length scale in both the meteorological wind tunnel and in the atmosphere over New York confirm that these length scales are on the same ratio as that for the roughness length.

Reports and a colored motion picture film are being prepared on this study.

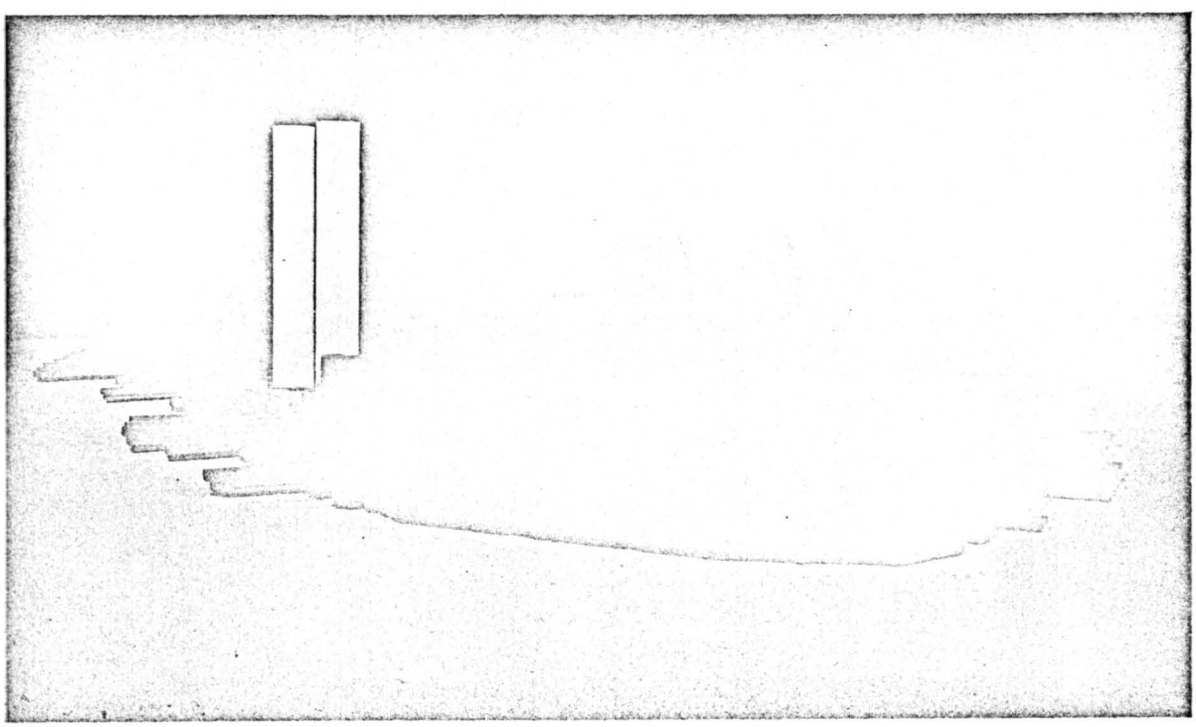

Figure 17. Model of World Trade Center Towers

2.1.6 Flow Near Meteorological Towers The effects of a tower structure on wind speed measurements made by an anemometer attached to a meteorological tower have been studied in the wind tunnel. One particular investigation required the construction of a 1:4 scale model of the White Sands Meteorological Research Tower seen in Fig. 18. Mean velocity measurements were made at potential anemometer locations for all possible orientations relative to the wind directions. These measurements reveal that wind speed deficiencies up to 20 percent may be recorded when the tower is "clean". When the usual rails and other attachments are affixed to the tower the error may be as large as 40 percent. Auxiliary anemometers have been placed in the field to verify the model-prototype similarity.

2.2 Turbulent Diffusion over Topography and Vegetated Areas Turbulent flow over a variety of two-dimensional topography and vegetated surfaces have been simulated in the meteorological wind tunnel. Tracer gases have been released from point and line sources and the concentration field sampled to determine the diffusion characteristics for such flows.

Reports on this phase of work are given in the following list:

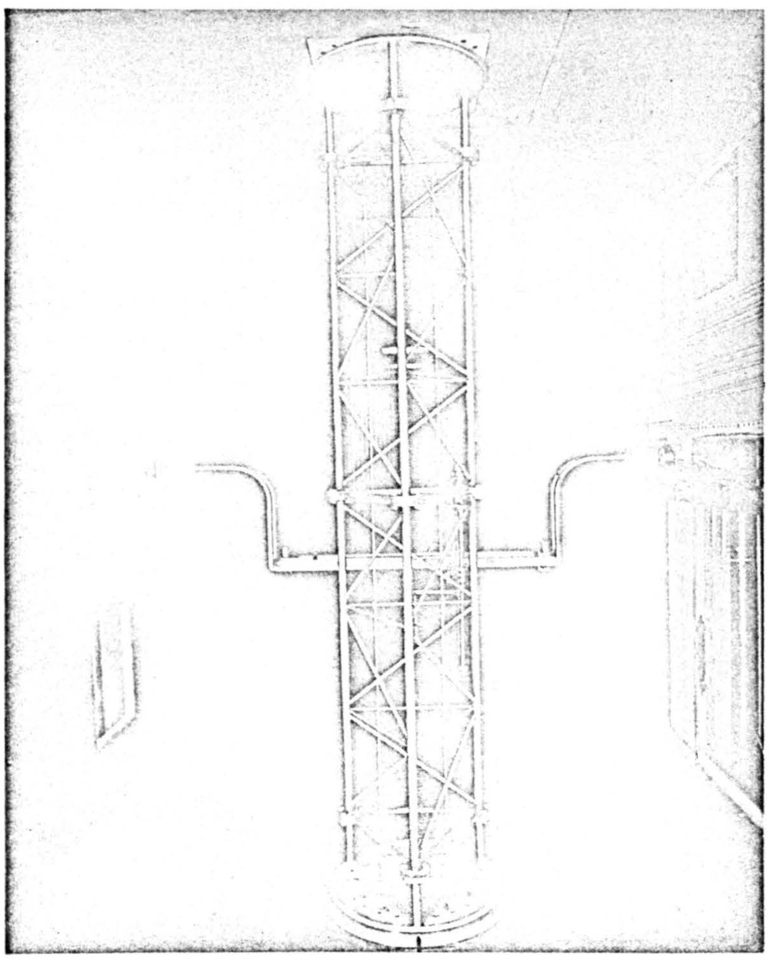

Figure 18. Model of Meteorological Tower

(a) Atmospheric Diffusion from a Point Source, C. S. Yih, prepared for the Office of Naval Research, Contract No. N9 onr 82401, report No. 4, August 1951.

(b) On a Differential Equation of Atmospheric Diffusion, C. S. Yih, Transactions, American Geophysical Union, Vol. 33, No. 1, February 1952.

(c) Atmospheric Diffusion from a Line and Point Source of Mass Above the Ground, C. S. Yih, Colorado State University, April 1952, CER47-52CSY47.

(d) Similarity Solution of a Specialized Diffusion Equation, C. S. Yih, Transactions, American Geophysical Union, Vol. 33, No. 3, June 1952.

(e) On the Asymptotic Behavior of any Fundamental Solution of the Equation of Atmospheric Diffusion and on a Particular Diffusion Problem, C. S. Yih, prepared for the Office of Naval Research, Contract No. N9 onr 82401, Report No. 8, September 1952.

(f) Use of Wind Tunnels in the Study of Atmospheric Phenomenon, J. E. Cermak and M. L. Albertson. Paper presented at the Air Pollution Control Association's Annual Meeting, Paper No. 58-32, May 1958, Philadelphia, Pennsylvania. CER58JEC18.

(g) Investigations to Develop Wind Tunnel Techniques for Measuring Atmospheric Gaseous Diffusion in Model Vegetative Surfaces, E. J. Plate and J. E. Cermak. Report to the United States Department of Agriculture, Agricultural Research Service, July 1963, CER63EJP-JEC28.

(h) Effects of Flexible Roughness Elements on Diffusion in a Turbulent Boundary Layer, A. A. Quraishi and J. E. Cermak. Paper submitted to the International Journal of Air and Water Pollution, January 1964, CER64-AAQ-JEC3.

(i) Ein Beitrag zur Berchnung von Austauschvorgangen im einer durch eine Wand Gestörten Grenzschicht, E. J. Plate, Dr. Ing. dissertation, submitted to the Faculty of Civil Engineering. Technische Hochschule, Stuttgart, Germany, 1965.

(j) The Velocity Field Downstream from a Two-Dimensional Model Hill, Part I, E. J. Plate and C. W. Lin, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Final Report, Research Grant DA-AMC-36-039-63-G7, April 1965. CER65EJP14.

(k) The Velocity Field Downstream from a Two-Dimensional Model Hill, Part II, E. J. Plate and C. W. Lin, Final Report, to U. S. Army Materiel Agency under Contract DA-AMC-36-039-63-G7, 1965. CER65EJP-CWL41.

(i) The Velocity Field Near Reattachment Downstream from a Two-dimensional Boundary Layer Obstruction, E. J. Plate and C. W. Lin, 1965. (paper in preparation)

2.3 Evaporation from Plane Surfaces This experimental program was conducted to study evaporation from a smooth plate boundary. Vapor transport was produced by the forced convection of a turbulent fluid flow parallel to the wind tunnel floor. The major objectives of this study were: 1) to determine the forms of dimensionless parameters best relating to the important variables involved; 2) to determine the effect of dry approach length upon evaporation rates; 3) to determine the effect of lateral diffusion; and 4) to determine the effect of plane boundary shape upon evaporation rate.

Details and results of investigations can be obtained from the following reports:

(a) A Comparative Study of Momentum Transfer, Heat Transfer, and Vapor Transfer, Part I, Forced Convection, Laminar Case, C. S. Yih, prepared for Office of Naval Research, Contract No. 9 onr 82401, Report No. 1, September 1950.

(b) A Comparative Study of Momentum Transfer, Heat Transfer, and Vapor Transfer, Part III, Free Convection, C. S. Yih, prepared for Office of Naval Research, Contract No. N9 onr 82401, Report No. 3, February 1951.

(c) A Comparative Study of Momentum Transfer, Heat Transfer, and Vapor Transfer, Part II, Forced Convection, Turbulent Case, C. S. Yih, prepared for Office of Naval Research, Report No. 2, June 1951, Contract No. N9 onr 82401.

(d) Evaporation from a Plane Boundary, M. L. Albertson, proceedings of Heat Transfer and Fluid Mechanics Institute, Stanford University, California, June 1951.

(e) Application of Model Techniques to Mass Transfer and Evaporation Studies, J. E. Cermak, presented to Centennial of Engineering, Chicago, Illinois, September 1952.

(f) La Mecanique de l'Evaporation, M. L. Albertson, thesis, presented to the Faculte de Sciences de l'Universite de Grenoble, France, 1954.

(g) Vapor Transfer by Forced Convection from a Smooth Plane Boundary, J. E. Cermak and P. N. Lin, prepared for the Office of Naval Research, Colorado State University, Fort Collins, Colorado, January 1955, CER55-JEC1.

(h) The Effect of Boundary Shape on Evaporation Rates, D. F. Nelsón, Master's thesis, Colorado State University, Fort Collins, Colorado, August 1957.

<u>2.4 Mountain Lee-Wave Studies</u> An experimental program to investigate wave motion produced by stratified flow over idealized two-dimensional topography in the meteorological wind tunnel has just commenced. The objective of this effort is to develop the ability to simulate this type of atmospheric flow so that flow downstream from complex mountain ridges may be studied in the future.

3. Physics of Fluids

<u>3.1 Ion-Rocket Thrust Augmentor</u> This project provides systematic experimental and theoretical evaluation of counter-current electron flow of electrostatic accelerators. Preliminary experimental data and theoretical computations have shown that the injection of back-streaming electrons can significantly affect rocket performance. More study is necessary to establish the efficiency characteristics of this counter-current scheme for eliminating Child's Law limitations on electrostatic accelerators. Current research is supplying the basic secondary electron emission data necessary to better understand the effect. Research includes the development of the transient probe technique to study instabilities that occur in the neutralized ion exhaust.

Details and results of investigations can be obtained from the following reports:

(a) Transient and Steady Performance of an Ion Rocket Thrust Augmentor, V. A. Sandborn. Prepared for the National Aeronautics and Space Administration, January 1956, CER65VAS12.

(b) Secondary Electron Emission, R. E. Bunney. Prepared for the National Aeronautics and Space Administration, December 1964, CER65VAS-REB12a.

(c) Effect of Thrustor Characteristics on Electric Spacecraft Missions, W. R. Mickelsen, Presented at 4th AIAA Electric Propulsion Conference, Philadelphia, September 1964.

3.2 Electrokinetic Potentials in Liquid Flows Electrokinetic potentials produced locally by a disturbance of the electrical double layer at a liquid-solid interface through action of turbulence has been systematically studied in pipe flows and jet-induced flows along a plane surface. These basic studies have suggested the possibility of using such phenomena to sense turbulence in liquid flows. Therefore, an effort has been undertaken to develop a turbulence sensing probe. The following reports have been prepared on the basic electrokinetic studies:

(a) Electrokinetic Potential Fluctuations Produced by Turbulence at a Solid-Liquid Interface, G. J. Binder, Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, September 1960.

(b) Electrokinetic Potential Fluctuations Produced by Turbulence in Fully Developed Pipe Flow, H. Chuang, Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, May 1962.

(c) Electrokinetic-Potential Fluctuations Generated by Jet Impingement at a Solid-Liquid Interface, L. Duckstein, Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, May 1962.

(d) Electrokinetic-Potential Fluctuations Generated by Jet Impingement, L. Duckstein and J. E. Cermak. International Journal of Heat and Mass Transfer, Vol. 7, pp. 159-167, June 1962, CER63LD-JEC12.

(e) Electrokinetic Potential Fluctuations Produced by Pipe-Flow Turbulence, H. Chuang and J. E. Cermak. Paper submitted to the American Institute of Chemical Engineering, 1965. CER62HC47.

(f) Streaming-Potential Fluctuations Produced by Turbulence, G. J. Binder and J. E. Cermak. The Physics of Fluids, Vol. 6, No. 8, August 1963. CER63JB-JEC48.

4. Facility and Instrumentation Development

Several reports have been prepared on the design and description of specialized facilities and instrumentation associated with the laboratory. Current efforts in instrumentation which to present have not been described by reports include the following: new type hot-wire anemometer employing an instant current source for major heating power and a variable current source to provide constant temperature operation, airfoil strain-gage transducer for turbulence measurements, and a heat-pulse anemometer for measurement of low-speed air motion.

Details of facility development and various instrument developments are given in the following reports:

(a) Wind Tunnel for the Study of Turbulence in the Atmospheric Surface Layer, J. E. Cermak, Final Report on Contract AF19(604)-1706, Colorado State University, November 1958, CER58JEC42.

(b) A Study of Design and Operation of a Low Speed Precision Wind Instrument Test Facility, E. J. Plate and J. E. Cermak. Report on Contract DA-29-040-0RD-2346, Colorado State University, November 1960, CER60EJP58.

(c) Operation and Maintenance of the Low-Speed Precision Wind Tunnel Test Facility. E. J. Plate. Final Report for Contract DA-29-040-ORD-2346, CER62EJP10.

(d) Electrokinetic Probe Response to Vortex Street Frequency, H. Chuang. Submitted to the American Society of Mechanical Engineering, CER62HC55.

(e) Micrometeorological Wind Tunnel Facility-Description and Characteristics, E. J. Plate and J. E. Cermak. Report to the United States Army Electronic Proving Ground Procurement Office, United States Army Signal Supply Agency, Fort Huachuca, Arizona, February 1963, CER63EJP-JEC9.

(f) Measurement of Turbulence in Water by Electrokinetic Transducers, J. E. Cermak and L. V. Baldwin. Colorado State University Fluid Mechanics Paper No. 2. Paper presented at Fluid Mechanics Symposium, 56th Annual Meeting of American Institute of Chemical Engineers, Houston, Texas, December 1963.

(g) Flow Measurement with a Suspension Wire, B. B. Sharp, Discussion by E. J. Plate. Proceedings appearing in the American Society of Civil Engineers, Vol. 90. Journal Hydraulics Division, p. 34, March 1964, CER64-EJP27.

(h) A Research Facility with Concurrent Air and Water Flows, E. J. Plate. To be published in the L'Houille Blanche, France, 1965. CER64EJP26.

(i) Turbulence Measured by Electrokinetic Transducers, H. Chuang and J. E. Cermak. Submitted to American Society of Civil Engineering, 1964. CER65-HC-JEC5.

Institutes, Conferences and Seminars

The Fluid Mechanics Program attempts to stimulate teaching and research and disseminate knowledge in fluid mechanics through presentation of institutes, conferences and seminars. These efforts are briefly reviewed in the sections which follow.

1. Institutes

Under sponsorship of the National Science Foundation an eight-week Summer Institute in Fluid Mechanics is presented for college teachers at two-year intervals. The main objective of these institutes is to develop a high level of subject matter competence for teachers desiring to start new courses or modify existing courses in fluid mechanics at their institutions.

In 1964 the following courses were given for 30 participants:

- Intermediate Fluid Mechanics (J. E. Cermak)
- Metrology of Fluid Mechanics (V. A. Sandborn and E. J. Plate)
- Turbulent Diffusion (L. V. Baldwin)
- Sediment Transport (D. B. Simons)

The 1966 Institute will offer the following courses:

- Mechanics of Ideal Fluids (J. E. Cermak)
- Metrology of Fluid Mechanics (V. A. Sandborn)
- Turbulence (D. E. Coles)
- Fourier Transform Techniques (D. Macken)
- Water Waves (L. Landweber)

Graduate credit is awarded to NSF-sponsored participants as well as graduate students who register for the courses and complete them successfully.

2. Conferences

In August 1967 the 10th Midwestern Mechanics Conference is to be held at Colorado State University. Technical papers and lectures on dynamics, mechanics of solids and mechanics of fluids will be presented during the three-day conference. Co-chairmen for the conference are J. E. Cermak and J. R. Goodman.

3. Seminars

Throughout the year weekly seminars are presented by visitors and Colorado State University staff and graduate students on a wide range of topics in fluid mechanics. We are particularly grateful to the many illustrious visitors who have provided much stimulation to the Program through their seminars and discussions.

Sponsors

The aggregate of financial support through research contracts and grants from many sources has made possible the development of facilities, the development of instrumentation and the research work described herein. We wish to recognize the key role our sponsors have had in creating the Fluid Dynamics and Diffusion Laboratory and the Fluid Mechanics Program by presenting them in the following list:

- Agricultural Research Service
- Air Force Cambridge Research Center
- Army Materiel Command
- Bureau of Ships, Navy Department
- Colorado State University Research Foundation

David Taylor Model Basin
Martin-Marietta Company
Metronics Associates, Inc.
National Aeronautics and Space Administration
National Bureau of Standards
National Center for Atmospheric Research
National Science Foundation
New York Research Foundation
Office of Naval Research
Public Health Service
U. S. Geological Survey
Worthington, Skilling, Helle, and Jackson

Fluid Mechanics Papers

Fluid Mechanics Papers present significant contributions to the science and application of fluid mechanics. These papers are intended to provide a single source of unabbreviated information on fluid mechanics research emanating from a variety of departments and programs at Colorado State University. The following papers in this series have been printed and can be obtained without charge by writing to Dr. J. E. Cermak, Professor-in-Charge, Fluid Mechanics Program, Colorado State University, Fort Collins, Colorado 80521.

Fluid Mechanics Paper No. 1:	A Resistance Thermometer for Transient Measurements, J. L. Chao and V. A. Sandborn, January 1964.
Fluid Mechanics Paper No. 2:	Measurement of Turbulence in Water by Electrokinetic Transducers, J. E. Cermak and L. V. Baldwin, April 1964.
Fluid Mechanics Paper No. 3:	Instrument for Measuring the Intermittency of Quasi-Steady Signals, C. L. Finn and V. A. Sandborn, October 1964.
Fluid Mechanics Paper No. 4:	Experiments on Wind Generated Waves on the Water Surface of a Laboratory Channel, E. J. Plate and C. S. Yang, February 1966.
Fluid Mechanics Paper No. 5:	Investigations of the Thermally Stratified Boundary Layer, E. J. Plate and C. W. Lin, February 1966.
Fluid Mechanics Paper No. 6:	Atmospheric Diffusion in the Earth's Boundary Layer--Diffusion in the Vertical Direction and Effects of Thermal Stratification, Shozo Ito, February 1966.