FOURTH DECADE OF HYDRAULICS AT THE STATE UNIVERSITY OF IOWA

Edited by

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and

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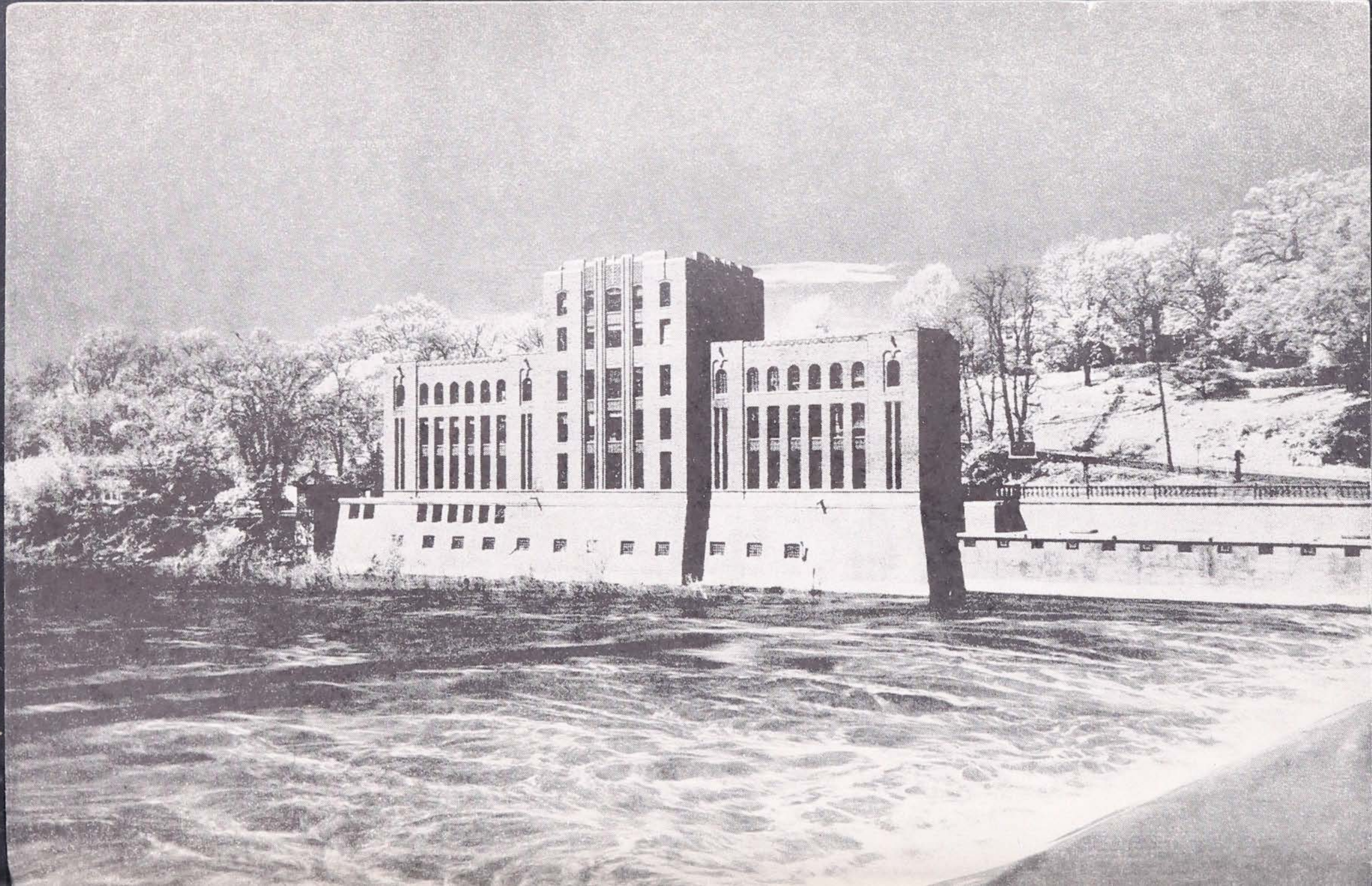

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PREFACE

In order to make available the results of all research conducted at the Iowa Institute of Hydraulic Research, a series of bulletins containing abstracts of graduate theses, reviews of Institute research, and lists of staff publications have been published at irregular intervals. Previous titles in this series, a part of the Iowa Studies in Engineering, have been Bulletin 19, *Two Decades of Hydraulics at the University of Iowa* (1939); Bulletin 26, *Investigations of the Iowa Institute of Hydraulic Research, 1939-1940;* and Bulletin 33, *Third Decade of Hydraulics at the State University of Iowa* (1949). This series is being brought up to date with the present publication. Since Bulletin 33 also contained an extensive description of the Institute itself and of its facilities, this is likewise brought up to date herein. However, only the changes in that description are presented here; hence much of the first part of the present bulletin serves as a complement to Bulletin 33.

THE IOWA INSTITUTE OF HYDRAULIC RESEARCH

Historical Résumé

Earliest provision for a hydraulics laboratory at the State University of Iowa was made in 1904, during construction of a dam on the Iowa River at Burlington Street, when an opening was left at the west end of the dam for an experimental sluiceway. In 1918, with the aid of a legislative grant, construction of a 10-foot channel and a 24x24-foot laboratory building was finished. Ten years later this small building was replaced by a three-story structure which comprises the north wing of the present Hydraulics Laboratory.

The Iowa Institute of Hydraulic Research was formed in 1931 to facilitate the broad study of hydraulics problems without respect to departmental lines. The original organization consisted of a research staff, a board of consultants drawn from many departments of the University, and an advisory committee of prominent practicing engineers. Within a year the existing laboratory space had become inadequate, thereby warranting construction of the tower and south wing of the present Hydraulics Laboratory.

Investigations of the Institute prior to World War II included such fields as model studies of rivers, spillways, and locks; full-scale tests on culverts, embankments, and current-meter rating; development of experimental plots for long-term hydrologic records; and studies of the hydraulics of plumbing systems. Extensive research in the fields

of sediment transportation and fluid turbulence was begun shortly before the war and has been continued to the present time.

With the onset of war in 1941, the Army and the Navy turned to many of the university laboratories for technical assistance. Institute contributions included research on the drag of stationary ships in flowing water; air-tunnel studies of fog dispersal for military airfields, the diffusion of smoke and gas in urban districts, and wind structure over mountainous terrain; water-tunnel investigations of cavitation around undersea bodies; and the development of fire monitors for naval vessels. After the cessation of hostilities, several of the government agencies, realizing the value of fundamental research, continued their support of Institute research.

Almost since its first organization, space in the Institute laboratory has been shared at various times with the Department of Agriculture, the Weather Bureau, the Corps of Engineers, and the U.S. Geological Survey, only the latter of which presently occupies a portion of the building. Space released in 1948 by the departure of the Corps of Engineers, together with that made available the same year by the construction of the Hydraulics Laboratory Annex, permitted both a widespread relocation of existing facilities and the addition of much new equipment. Within a few years, among other projects, the instructional facilities were relocated and considerably enlarged, a small water tunnel for research was replaced by two larger tunnels, a new air tunnel was constructed in the Annex and an existing one rebuilt, and a scour flume and a recirculating sediment-transport flume were constructed. The major physical undertaking of the decade just completed, however, has been the conversion of one of the river channels into a towing tank. This construction, begun in 1954 and completed in 1957, gives the Institute the second of the nation's two inland tanks.

During the 15 years since the end of World War II, investigations have continued in many of the fields in which the Institute had previously been active. Studies have also been initiated or considerably expanded in such fields as investigations of the flow of stratified fluids; studies of the diffusion of jets, the decay of ship wakes, and the characteristics of zero-momentum wakes; development and improvement of electronic methods of instrumentation; analysis of the properties of three-dimensional boundary layers; and theoretical and experimental research in problems of unsteady-state hydrodynamics.

In keeping with the general objectives of a university, the Institute's

policy toward research and teaching has been, and continues to be, directed toward the study of fundamental principles. As a result of these aims, almost all research projects undertaken are those which will lead to a better understanding of some specific or general principle. In addition, teaching facilities are designed to illustrate principles of fluid mechanics rather than merely to establish calibrations of equipment. Thus, the continued research and instructional activities of the Institute are designed to complement each other. The effect of this emphasis is also reflected in the fundamental nature of the majority of the graduate theses.

PRESENT ORGANIZATION

No major changes have been made to the organizational scheme which was set up in 1944. Personnel for the active staff are drawn from the College of Engineering, whereas the Board of Consultants is selected from organizations outside the University. The staff is headed by the director, who is ultimately responsible for all Institute activities, including staff endeavors, laboratory facilities, research procedure, reports, and finances. The director is assisted by the consulting engineers, chosen from the University faculty or from staffs of cooperating agencies permanently located at the Hydraulics Laboratory. The research engineers, most of whom are also staff members of the Department of Mechanics and Hydraulics, supervise the various Institute projects and graduate-student investigations. Research associates and assistants, who conduct the actual tests and evaluate the test results, form the remainder of the technical staff; they are usually graduate students employed on a part- to full-time basis, but also include students holding scholarships from the Graduate College. A nontechnical staff, consisting of secretaries, shop supervisor, machinists, mechanics, carpenters, welders, laboratory assistants, and part-time laborers as needed is maintained. The present staff of the Institute is listed on the next page.

In order to show the names and periods of service of those who have taken a responsible part in the conduct of Institute research, a chronology of the senior staff members, past and present, is presented in Fig. 1. In addition, the lengths of stay of the various government agencies which have been located at the Institute are included

STAFF OF THE IOWA INSTITUTE OF HYDRAULIC RESEARCH

May 1960

DIRECTOR

HUNTER ROUSE
Professor of Fluid Mechanics

CONSULTING ENGINEERS

JOSEPH W. HOWE
Professor and Head
Dept. of Mechanics and Hydraulics

CHESLEY J. POSEY
Professor and Head
Dept. of Civil Engineering

AKE L. ALIN
Professor of Hydraulic Engineering

RESEARCH ENGINEERS

LUCIEN M. BRUSH, JR.
PHILIP G. HUBBARD
LOUIS LANDWEBER
ENZO O. MACAGNO
LAWRENCE R. MACK
ARTHUR TOCH

RESEARCH ASSOCIATES

THOMAS CARMODY
HAU-WONG HO
DONALD E. LAUGHLIN
MATILDE MACAGNO
JACK S. PETERSEN
THEODOR S. STRELKOFF

RESEARCH ASSISTANTS

LEONIDAS DIAMANDIS
RICHARD G. HAJEC
TSE-MIN LEE
JOACHIM K. MALSY
HENRY MAYER
GEORGE H. MITTENDORF
F. S. A. PAVAMANI
MUHAMED RIDJANOVIC
JIN WU
BEN-CHIE YEN

SECRETARIES

FRIEDA SIEVERS
VESTA NEWLIN

SHOP STAFF

DALE C. HARRIS, Shop Supervisor
MERRITT A. EWALT, Carpenter
JOHN R. GLOVER, Lab. Assistant
HOWARD E. KRATTET, Carpenter
DONALD T. MILLER, Mechanic
EUGENE A. NEWMIRE, Mechanic
FRED W. PARKS, Welder
ARTHUR T. PUDGIL, Machinist
ERNEST E. SCHWAB, Machinist
STANLEY E. STUTZMAN, Welder

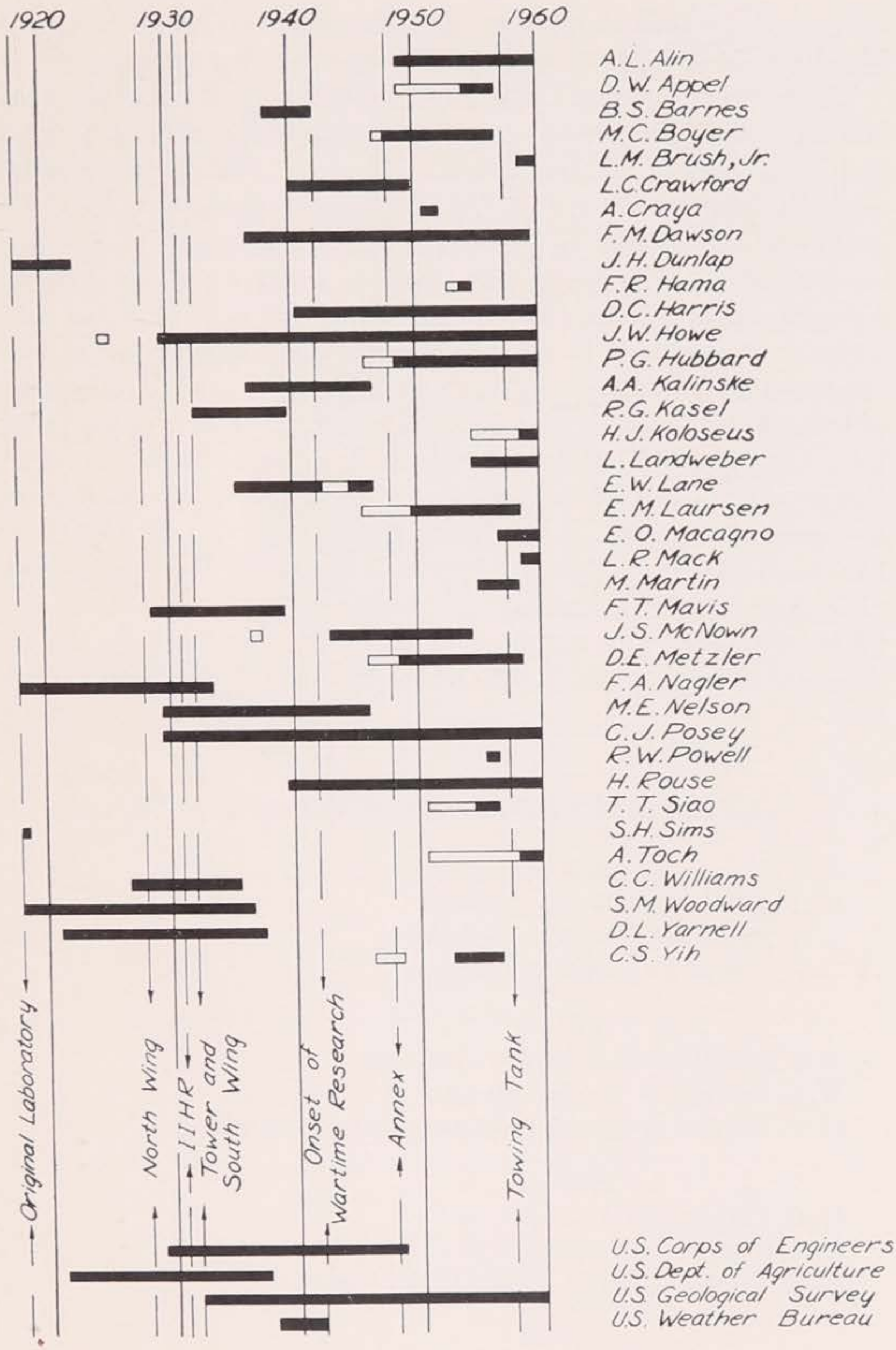

FIG. 1. CHRONOLOGY OF SENIOR PERSONNEL AND RESIDENT AGENCIES.

along with an indication of some of the more important historical high lights of the development and evolution of the Institute.

The Institute Board of Consultants consists of prominent scientists and engineers from various organizations throughout the country who are chosen because of their interest in or direct association with the research activities of the Institute. Each appointment lasts for three years with one-third of the membership changing each year. The primary function of the Board is to advise on matters pertaining to the research program of the Institute and the planning of technical conferences. Professor J. W. Howe, Head of the Department of Mechanics and Hydraulics, now serves as chairman since the retirement of Dean F. M. Dawson, who was also one-time director of the Institute. Altogether 51 appointments have been made to the Board of Consultants since it was organized in 1946. A total of 40 different individuals have served on the Board during this time; five of these have each served two three-year terms, while three others are now in their third terms. All members of the Board, past and present, are listed below, both as a matter of historic interest and to show the diversity of the organizations with which the Institute has been in contact.

MEMBERSHIP OF BOARD OF CONSULTANTS

1946

W. F. DURAND, Stanford University
L. A. JONES, Soil Conservation Service
C. G. ROSSBY, University of Chicago

1946-47

B. A. BAKHMETEFF, Columbia University
W. G. HOYT, U.S. Weather Bureau
H. U. SVERDRUP, Scripps Institution of Oceanography

1946-48

H. O. CROFT, State University of Iowa
G. A. HATHAWAY, Corps of Engineers
H. E. SAUNDERS, David Taylor Model Basin

1947-49

H. L. DRYDEN, National Advisory Committee for Aeronautics
M. E. NELSON, Corps of Engineers
K. E. SCHOENHERR, University of Notre Dame

1948-50

M. L. NICHOLS, Soil Conservation Service
C. G. PAULSEN, U.S. Geological Survey
G. B. SCHUBAUER, National Bureau of Standards

1949-51

B. A. BAKHMETEFF, Columbia University
CARL F. IZZARD, Public Roads Administration
W. H. LEAHY, Office of Naval Research

1950-52

V. R. BENNION, U.S. Geological Survey
MARK MORRIS, Iowa State Highway Commission
J. B. TIFFANY, Waterways Experiment Station

1951-53

PIERRE DANEL, Etablissements NEYRPIC
MINA REES, Office of Naval Research
F. H. TODD, David Taylor Model Basin

1952-54

ADOLPH J. ACKERMAN, Consulting Engineer
PAUL C. BENEDICT, U.S. Geological Survey
RICHARD R. TIPTON, Bureau of Public Roads

1953-55

CARROLL H. DUNN, Waterways Experiment Station
W. E. JONES, Iowa State Highway Commission
G. B. SCHUBAUER, National Bureau of Standards

1954-56

V. R. BENNION, U.S. Geological Survey
PHILLIP EISENBERG, Office of Naval Research
C. J. MCLEAN, Commonwealth Edison Co. of Chicago

1955-57

W. H. LEAHY, Office of Naval Research
MARK MORRIS, Iowa State Highway Commission
GLEN G. POWERS, Iowa State Conservation Commission

1956-58

CARL F. IZZARD, Bureau of Public Roads
C. A. LEE, Kimberly-Clark Corporation
J. B. TIFFANY, Waterways Experiment Station

1957-59

ROLLAND W. CARTER, U.S. Geological Survey
JOHN B. PARKINSON, National Advisory Committee for Aeronautics
E. A. WRIGHT, David Taylor Model Basin

1958-60
V. R. BENNION, U.S. Geological Survey
D. C. BONDURANT, Corps of Engineers
H. M. MARTIN, Bureau of Reclamation

1959-61
PHILLIP EISENBERG, Hydronautics, Inc.
MARK MORRIS, Iowa State Highway Commission
E. S. TURNER, National Research Council of Canada

1960-62
R. D. COOPER, Office of Naval Research
J. B. TIFFANY, Waterways Experiment Station
MELVIN R. WILLIAMS, U.S. Geological Survey

CURRENT RESEARCH ACTIVITIES

The current research program is composed of a wide variety of projects which reflect both the special interests of the various staff members and the needs expressed by the various supporting agencies. Some of these projects represent studies which have continued over a period of years, whereas others are of a short-term nature. In the following paragraphs, a brief description of each of the current research projects is given.

Active interest has been maintained in hydrologic studies of Ralston and Rapid Creeks. These studies represent the longest uninterrupted projects conducted by the Institute and are currently supported by the U.S. Geological Survey, the Soil Conservation Service, the U.S. Weather Bureau, and the Graduate College. Record analyses and data collecting are usually performed by graduate students, many of whom select certain aspects of the hydrologic record for thesis topics. The hydrologic investigations are made under the supervision of Professor Howe, who has served as project director for nearly two decades.

Research in sediment transportation, which has been pursued almost continuously since the Institute was established, is being continued as evidenced by the present studies which involve total-load transport, fall velocity, and sediment diffusion. The investigation of total-load transport, supported by the National Science Foundation, is directed toward determining the effect of the particle-size distribution of the bed material on the volume of total-load transport. The study of sediment diffusion is partially supported by the Gulf Re-

search and Development Company. Projects involving sediment transportation are made under the direction of Professor Brush.

Cavitation investigations, which received considerable attention during and after the war years, generally fell into one of two categories: that involving boundary geometry, and that involving turbulence. The first is currently typified by the rather belated completing of a series of tests on head forms at angles of yaw ranging from 0° to 90°. The second is represented by continued experiments on the pressure fluctuations in a submerged jet, a rather thoroughgoing energy analysis now being conducted of the measured characteristics of both the mean and secondary flows. Since its inception, this work has been under the sponsorship of the Office of Naval Research under the direction of Professor Rouse.

Directly related to at least the latter project has been a long series of investigations of energy transformation in the regions of separation so common in hydraulic structures, particularly in the vicinity of the resulting quasi-stable eddy. Current projects of this nature include the jet directed into a counterflow, the wake of a disk (and its eddy-cavitation counterpart) and of a plate, and abrupt boundary expansions. Of a similar nature is the study that is being made of a zero-momentum-flux wake which is obtained by means of a jet located within the wake created by a disk. Both mean-flow and turbulence characteristics of the wake are being investigated in the proximity of the disk and at considerable distances downstream. Sponsored by the Office of Naval Research, this portion of the research program is under the direction of Professor Rouse and Mr. Toch.

Studies of boundary-layer development continue to be an integral part of the Institute's research program. Supported by the Office of Naval Research, a project is currently under way in the air tunnel located in the Annex on the development of a three-dimensional boundary layer around an ellipsoid with three unequal axes. In addition, a reanalysis of existing data pertaining to boundary layers for zero pressure gradient is being made under the sponsorship of the same agency. These studies are under the direction of Professor Landweber.

In recent years considerable effort has been directed toward problems relating to the motion of ships. The completion of the towing tank in 1957 has greatly augmented the Institute's research activities in this field. A study of the added mass of a vibrating ship and the effect of a free surface on separation represent projects currently be-

ing sponsored by the Society of Naval Architects and Marine Engineers. In addition, other studies such as the separation of viscous drag from wave drag of ships as determined by wake measurements, as well as studies of the mean flow and turbulence characteristics of wakes behind powered vessels, are in progress through the support of the Office of Naval Research. Several other operative projects supported by the ONR on ship motion concern the drag of an oscillating plate for various aspect ratios and the translation of a Russian book *Ship Motions* by Blagoveshchensky. Investigations concerning ship motions are under the direction of Professor Landweber, although, in part, the instrumentation and turbulence measurements are supervised by Professor Hubbard. The Russian translation is being performed by Mr. Strelkoff and edited by Professor Landweber.

Recent interest in so-called ground-effect vehicles has led to the development of a considerable research program in the field of annular jets. A series of related projects, some of which are currently active, have investigated the augmentation of lift due to the pressure build-up beneath the base of an annular jet in close proximity to the ground. Tests have been made examining the lift augmentation over liquid as well as solid surfaces, for different values of geometrical parameters and for various jet strengths. The configuration of a liquid surface beneath the jet and the velocity and pressure distributions in the flow field of an annular jet over land are currently being measured. These projects are sponsored by the Office of Naval Research and are being conducted under the supervision of Professor Mack.

Due to the importance of instrumentation in present-day studies of fluid mechanics, particularly with respect to turbulence measurements, the Institute continues to operate numerous projects aimed at developing new or improving old measuring techniques. Included among studies in this field are the development of electronic units for analyzing and presenting turbulence data in a useful form; continued efforts to improve the instruments for making turbulence measurements, in particular, the hot-wire and hot-film anemometers; and investigations aimed at developing a low-velocity turbulence probe by using minute thermistors as the sensing elements. These projects are sponsored by the Office of Naval Research under the supervision of Professor Hubbard.

At the request of the Rock Island Arsenal of the U.S. Army, a detailed investigation of the characteristics of rapidly accelerated liquids under high pressures, as in recoil systems, has been initiated.

This project will include both analytical and experimental studies of unsteady flow through various transitions. Professor Hubbard and Dr. Macagno are directing the investigation.

During the past decade a series of projects involving stratified flow has been carried out at the Institute. Interest among successive members of the staff has resulted in a continuation of research in this area. The current project is directed at establishing the criteria for the interfacial stability of two fluid layers of slightly different densities. Operating under the sponsorship of the Office of Ordnance Research, the project is led by Dr. Macagno.

In cooperation with the U.S. Geological Survey, a systematic study of the effect of the concentration of roughness elements on the resistance to flow in open channels is being made. The study encompasses both subcritical and supercritical flow and is under the supervision of Dr. H. J. Koloseus, a resident representative of the Survey. A closely related doctoral project under Professor Rouse involves the calculation of the resistance coefficient for various combinations and concentrations of elements, proceeding from the measured drag of a single element in flow with variable velocity gradient.

An analytical investigation of finite-amplitude axisymmetric gravity waves is also in progress. Of particular interest are the division of the total energy into kinetic and potential portions and the differences in their variations with time for a wide range of liquid depths. This study is under the supervision of Professor Mack and is supported, in part, by the Office of Naval Research.

CONFERENCES AND PUBLICATIONS

Continuing its practice, begun in 1939, of holding Hydraulics Conferences at Iowa City at three-year intervals, the Institute has now organized seven such meetings with an average attendance of 200 engineers and scientists from nearly every state in the country, and the papers presented at each have been recorded in separate volumes of *Proceedings*. The *Proceedings of the Fourth Hydraulics Conference,* held just before the appearance of Bulletin 33, *Third Decade of Hydraulics at the State University of Iowa,* was published in 1950 by John Wiley & Sons as the 1,000-page volume *Engineering Hydraulics.* In order to hold the retail price at a reasonable level, the Institute forewent royalties on the first 3,500 copies printed. A second printing was soon necessary, however, and sales at the time of writing had reached the unexpectedly high figure of 6,500 copies—2,800 of these

having been purchased abroad. Although further conferences may still be held, the vast amount of material being published by national organizations and the comparatively limited circulation of the local *Proceedings* make it inadvisable to continue their publication.

As may be judged by the list of bulletins, reprints, and other material at the end of this volume, the Institute has maintained its practice of putting into print all research results of general or specific interest. This is done preferably through internationally available journals, of which 23 different ones are represented on the list of 85 reprints of the past decade. Publications too long for journals are issued in the Studies in Engineering series, as special issues like the *Wind-Tunnel Studies of Pressure Distribution on Elementary Building Forms,* or as bulletins of sponsoring agencies like the Iowa Highway Research Board. Only rarely is a typewritten thesis or report to a contracting organization the final form in which a project is described.

Somewhat more pretentious than the foregoing ventures was the publication by the Institute of its first hard-cover book: *History of Hydraulics* by Rouse and Ince. Initially appearing as a bilingual fold-in supplement of *La Houille Blanche,* the English version was thereafter corrected, amplified, and then reproduced in cloth-bound offset form by Edwards Brothers under the imprint of the Institute. At the time of writing, about 1,050 copies have been sold. Perhaps the most important by-product of this venture has been the investment of income in the purchase of source material for a new history-of-hydraulics collection of the University Library. Some 200 representative volumes in English, French, German, Italian, and Latin, ranging from the middle of the sixteenth century to the end of the nineteenth, already form the nucleus of what should be a steadily growing foundation for future historical research.

An even more extensive undertaking of many years' duration reached its culmination very early in 1959, with the appearance in printed form of the textbook *Advanced Mechanics of Fluids.* A one-semester course of this name had been taught by Professor Rouse ever since coming to Iowa in 1939. In 1948 responsibility for its contents was shared with Professor McNown, and plans were laid for the preparation of a book to serve as text. With McNown's departure in 1954, the authorship of the successive chapters was divided among various members of the staff, and the result was issued in hectograph form for use in a new two-semester course. After several successive editions of the notes had appeared, the revised material was finally published by John Wiley & Sons under the Institute copyright.

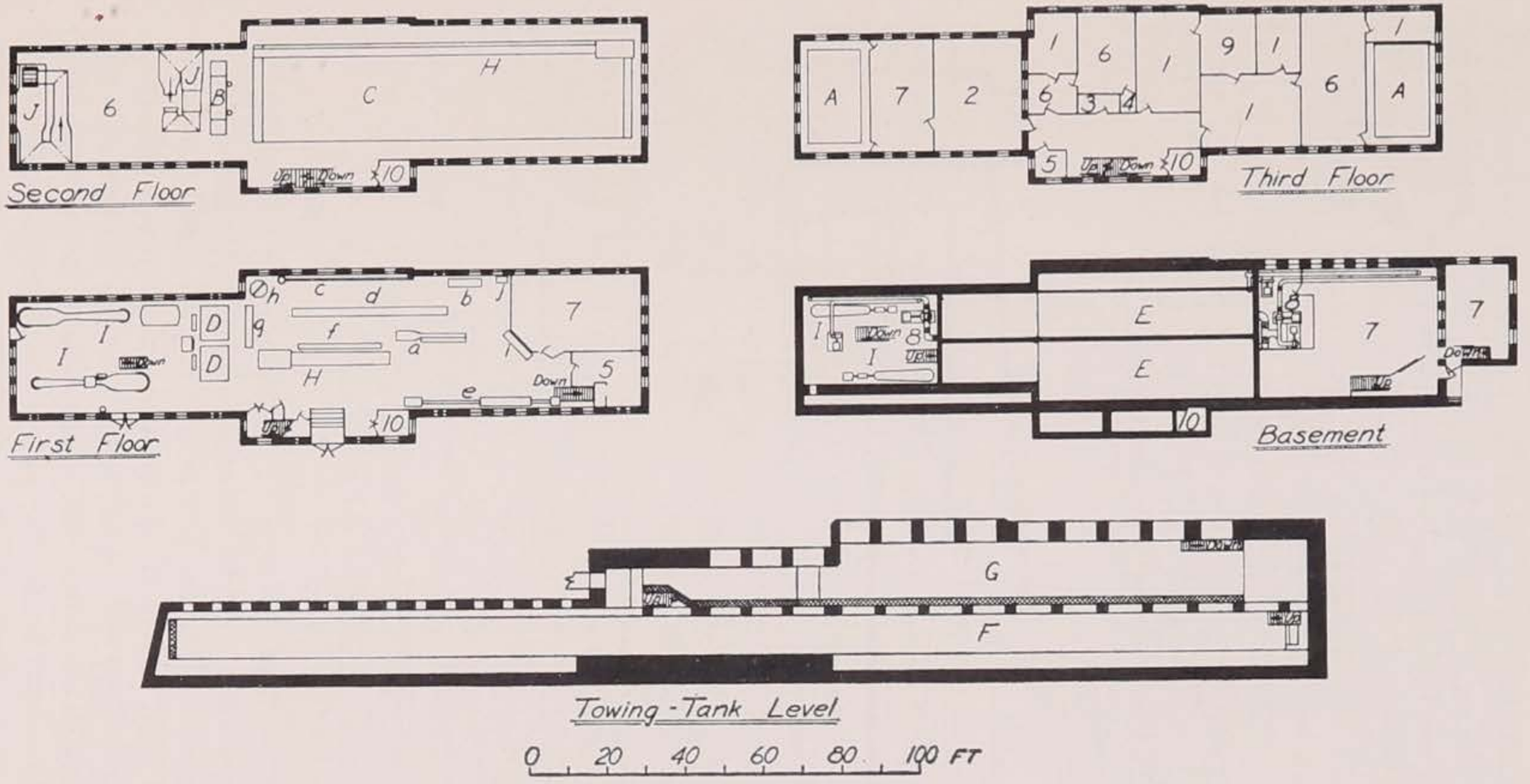

FIG. 2. PLAN VIEWS OF TOWING TANK, BASEMENT, AND FIRST, SECOND, AND THIRD FLOORS.

PHYSICAL PLANT AND BASIC EQUIPMENT

The major physical undertaking of the decade just completed was the enclosure of the river channels beneath the Main Laboratory and the conversion of the 10-foot channel into a towing tank, shown in Fig. 2. This undertaking, begun in 1954 and completed in 1957, gives the Institute the second of the nation's two inland tanks. The channels were bulkheaded, both upstream and down, and completely housed, thus making the entire tank both structurally safe against floods and maintainable at room temperature over its full 300-foot length. At the same time the general quarters in the basement were expanded by a single-story 17x24-foot welding shop constructed over the south end of the 16-foot channel.

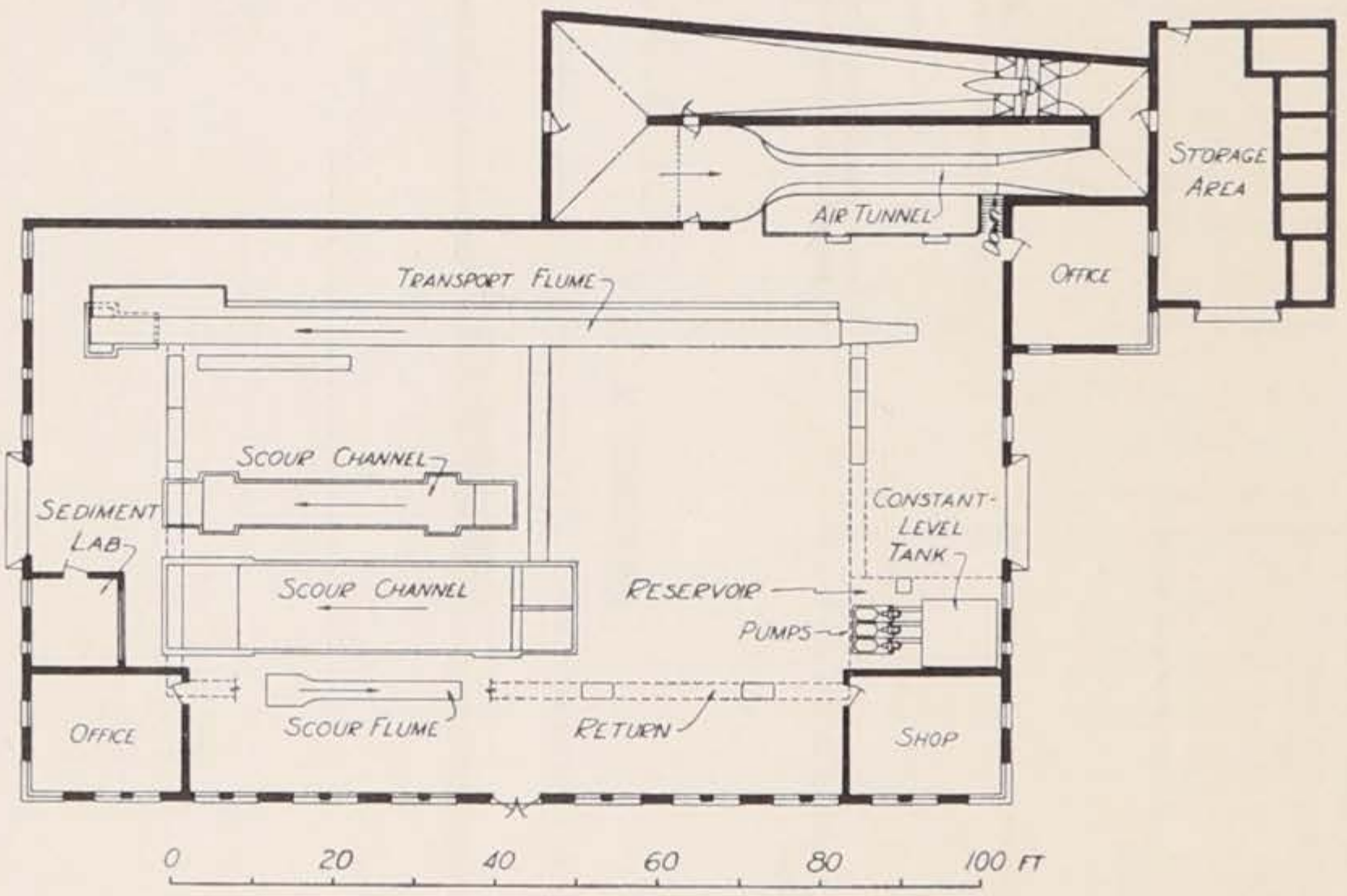

FIG. 3. PLAN VIEW OF LABORATORY ANNEX.

In the Laboratory Annex (Fig. 3), a small sediment laboratory has been set off immediately west of the office in the southeast corner of the building and the floor of the model area in the central portion of the building has been paved. In addition, several sluices connecting with the main sump have been constructed beneath the paving. Outlet sections leading to the sluices have been established to allow efficient utilization of space for simultaneous running of experiments. To the northwest corner of the Annex has been appended a one-story ga-

rage, 22x35 feet, containing a series of concrete bins for the storage of various grades of sand.

In addition to the entire fifth floor of the main building, the district office of the U.S. Geological Survey now occupies two office rooms and the sedimentation laboratory on the third floor. The cableway for stream gaging formerly spanning the Iowa River just downstream from the Main Laboratory has been dismantled.

INSTRUCTIONAL FACILITIES

The instructional facilities of the Institute laboratories are designed to contribute as effectively as possible to the teaching program of the Department of Mechanics and Hydraulics. Accordingly they illustrate primarily the fundamental aspects of fluid motion, as emphasized by the textbooks used in the classroom, rather than simply the empirical calibration of measuring devices. *Basic Mechanics of Fluids* by Rouse and Howe is the textbook now used by all undergraduate classes; to supplement the lectures, three laboratory demonstrations are included as part of the regular course program. First-year graduate students take a two-semester intermediate course for which *Elementary Mechanics of Fluids* by Rouse serves as text. In the laboratory work accompanying these courses the undergraduates perform six selected experiments, whereas the graduates become familiar during the year with all the available instructional equipment by conducting a total of fourteen experiments.

Except for the changes and addition noted below, the equipment for these experiments is for the most part that described in Bulletin 33. Although it is possible to mount various bodies in the test section of the small water tunnel, this unit has been operated only with a Venturi-type constriction for several years. Piezometric openings are so arranged in its test section that the pressure distribution may be evaluated along the center line of the constriction as well as along the boundary. The water-jet unit now has a grid system on a background plate for use in determining the liquid trajectory as well as a spring dynamometer for jet-deflection studies.

For determining the fall velocities of spheres, a set of three cylindrical glass jars, each 8 inches in diameter, has been added to the equipment for graduate instruction. Each of the jars contains a different liquid; to provide a 100-fold range of kinematic viscosities, the liquids used are heavy oil, light oil, and water. The jars are placed within a rectangular water-filled tank to assure a uniform temperature

throughout the jars. The long glass sides of the water bath carry several sets of horizontal wires, which permit the visual timing of the fall of the spheres to be free of both refraction and parallax errors. Lead, glass, lucite, and plastic spheres, ranging in size from less than 1 millimeter to ½ inch in diameter and having over an 11-fold range of specific gravities, are used in the experiment.

RESEARCH FACILITIES

Towing Tank

The 10-foot river channel which formerly passed beneath and extended beyond the Main Laboratory, drawing water from the Iowa River, has been replaced by a completely housed towing tank (Fig. 4) 300 feet long, 10 feet wide, and 9 feet deep, which is normally filled with hydrant water. The conversion from river channel to towing tank

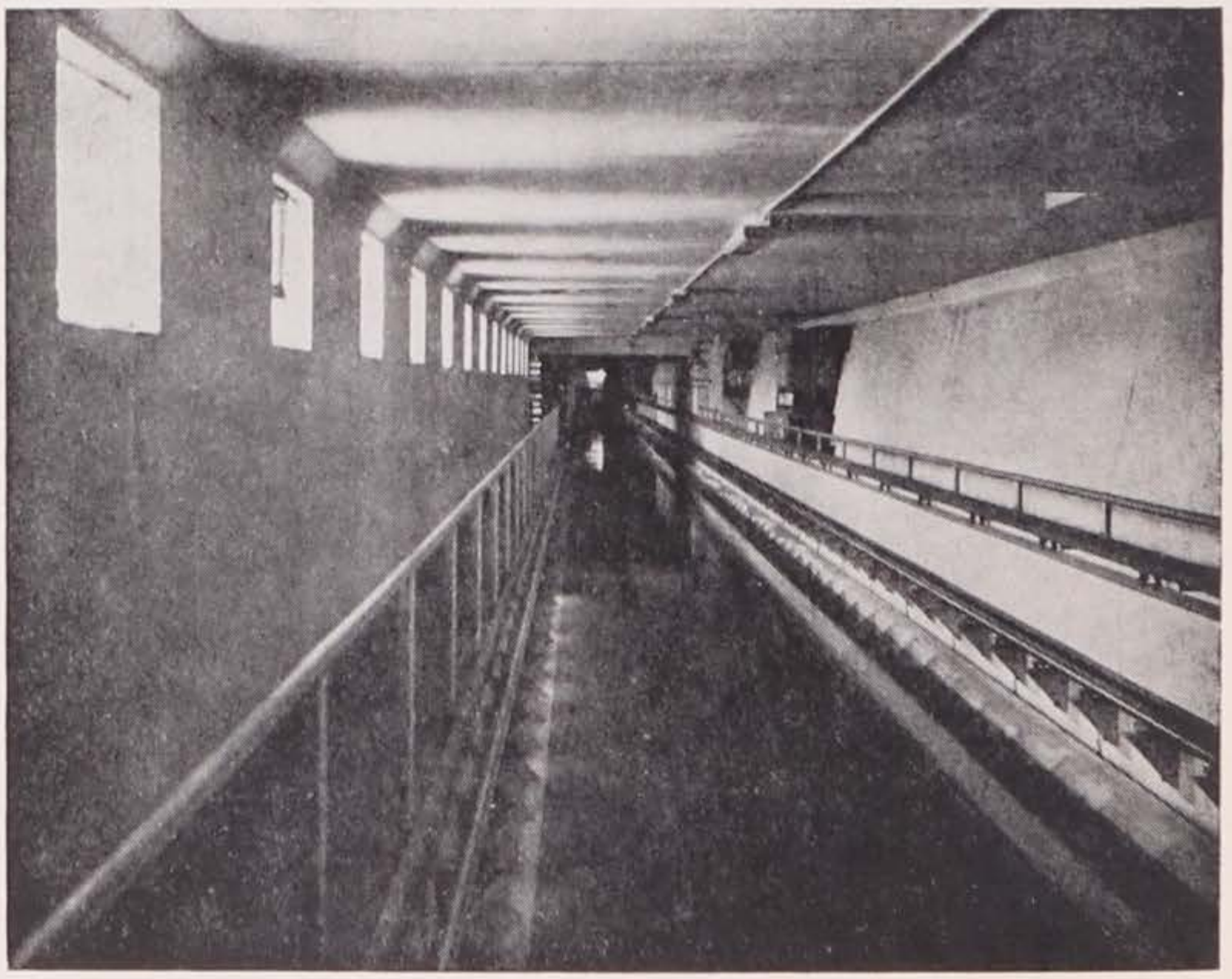

FIG. 4. VIEW OF 300-FOOT TOWING TANK FROM NORTH END.

was begun in 1954 and completed in 1957; it was jointly financed by the Institute and the Office of Naval Research. The tank is spanned by a lightweight carriage which was obtained from the National Research Council of Canada and modified extensively. The rails of

stainless-steel precision-ground shafting on which the carriage rides have been leveled and aligned to within a few thousandths of an inch. The carriage is towed by three endless ½-inch wire-rope cables in parallel, which in turn are driven by a 2-foot-diameter traction sheave anchored at the south end of the tank. A tension of about 1,000 pounds is maintained in each cable by a lever system on the idler sheave at the north end. The traction sheave is driven by a variable-speed hydraulic pump-motor unit which is powered by a constant-speed 25-horsepower induction motor. Continuous variation of speed from ½ to 30 feet per second is possible with this drive. Although lower speeds are possible, it then becomes difficult to maintain a satisfactory degree of constancy. Electrical means for accurately recording the carriage speed are provided. A balance-type dynamometer is being constructed for determining the force acting on a towed model.

Near the middle of the east wall of the tank are four openings, each 6 feet by 3 feet, now closed by bulkheads, which can serve as ports for underwater observations when the need arises. Wave absorbers consisting of 12-inch-wide half-submerged boards are fastened along the walls. At either end of the tank is a sheet-metal parabolic wave absorber. Installation of these wave absorbers reduced the required waiting time between runs by 75 per cent. The water surface is readily skimmed into 10-inch-deep troughs behind the parabolic wave absorbers by raising the water level slightly.

Flumes

The construction of a new flume along the east wall of the second floor of the Main Laboratory for the chief purpose of studying open-channel flow was completed in 1959 with Institute funds. The flume is 2½ feet wide, 10 inches deep, and 85 feet long; both the side and bottom boundaries are of plate glass. An interesting feature of this piece of equipment is that—except for pivots at the head tank—it is hung on four pairs of stainless-steel lead screws from the underside of the third-floor beams as shown in Fig. 5. A motor-driven gear train can be used during operation to adjust the slope to any value between +5 per cent and −0.2 per cent. Supercritical flow at the entrance can be established by means of an inclined headgate; a tailgate at the downstream end is used to control subcritical flow. Stainless-steel rails, running the full length of the flume, support an instrument carriage. A specially designed vibrating-needle point gage is used to measure with precision the level of the water surface and its variation,

if any, with time. A weir, mounted in the head tank, is used to measure discharges up to 6 cubic feet per second.

Water Tunnels

The relatively inexpensive variable-pressure water tunnel installed in 1943 was eventually found to be inadequate for the increasing vol-

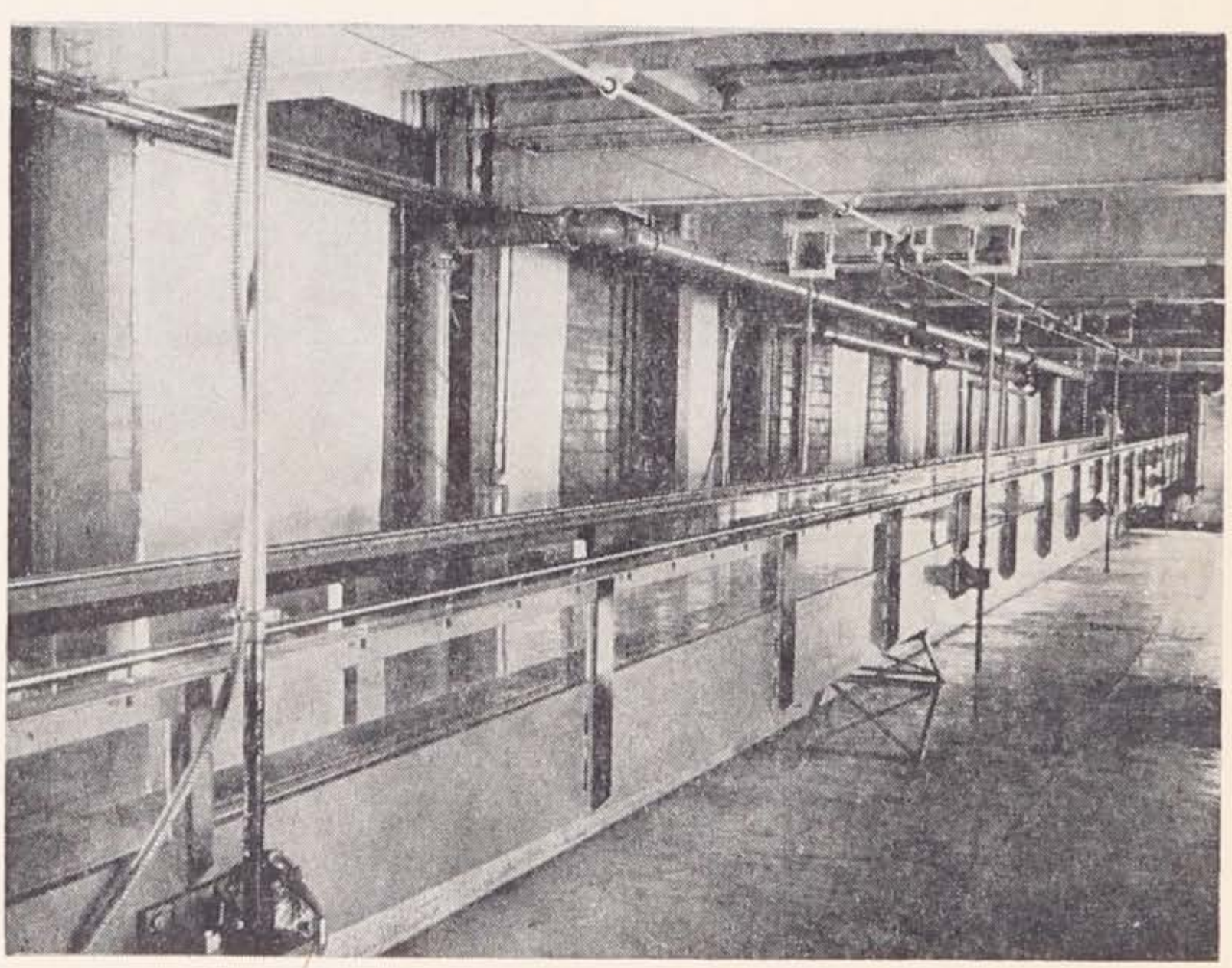

FIG. 5. 85-FOOT TILTING FLUME SHOWING CEILING SUSPENSION.

ume of Institute research. Accordingly it has been replaced by two tunnels of greater circuit length and considerably more refined design. These tunnels, located at the north end of the main building, differ from each other only in the configuration of their interchangeable test sections. The east tunnel, built in 1949 with funds provided by the Office of Naval Research, has a 6x24-inch rectangular cross section for tests on two-dimensional forms; the west tunnel (Fig. 6), constructed in 1951 with Institute funds, has an open-throat test section with the same circular cross-sectional area. The 30-inch axial-flow pump of each tunnel is driven by a 65-horsepower electric motor through a variable-speed hydraulic transmission.

The velocity of flow and the pressure head at each test section can be varied independently within wide limits, velocities of 8 to 35 feet per second being obtainable with pressure heads from +30 to −30

feet of water. Each tunnel is a closed circuit, approximately in the form of a vertical rectangle with vaned turns at each corner, the upper leg containing the test section being on the first floor, and the lower leg comprising the return section and the pumping system being in the basement. The circular cross section of the tunnel varies gradually in diameter from somewhat over 15 inches just beyond the test section to 4 feet in the approach section. All interior surfaces are of stainless steel except for the observation windows, which are of case-hardened glass.

A cylindrical cavitation tank, 5 feet in diameter by 10 feet long, is located near the water tunnels and is connected by a 6-inch line to a centrifugal pump rated at 380 gallons per minute at a 200-foot head. The ambient pressure within the tank can be varied from +15 psi to

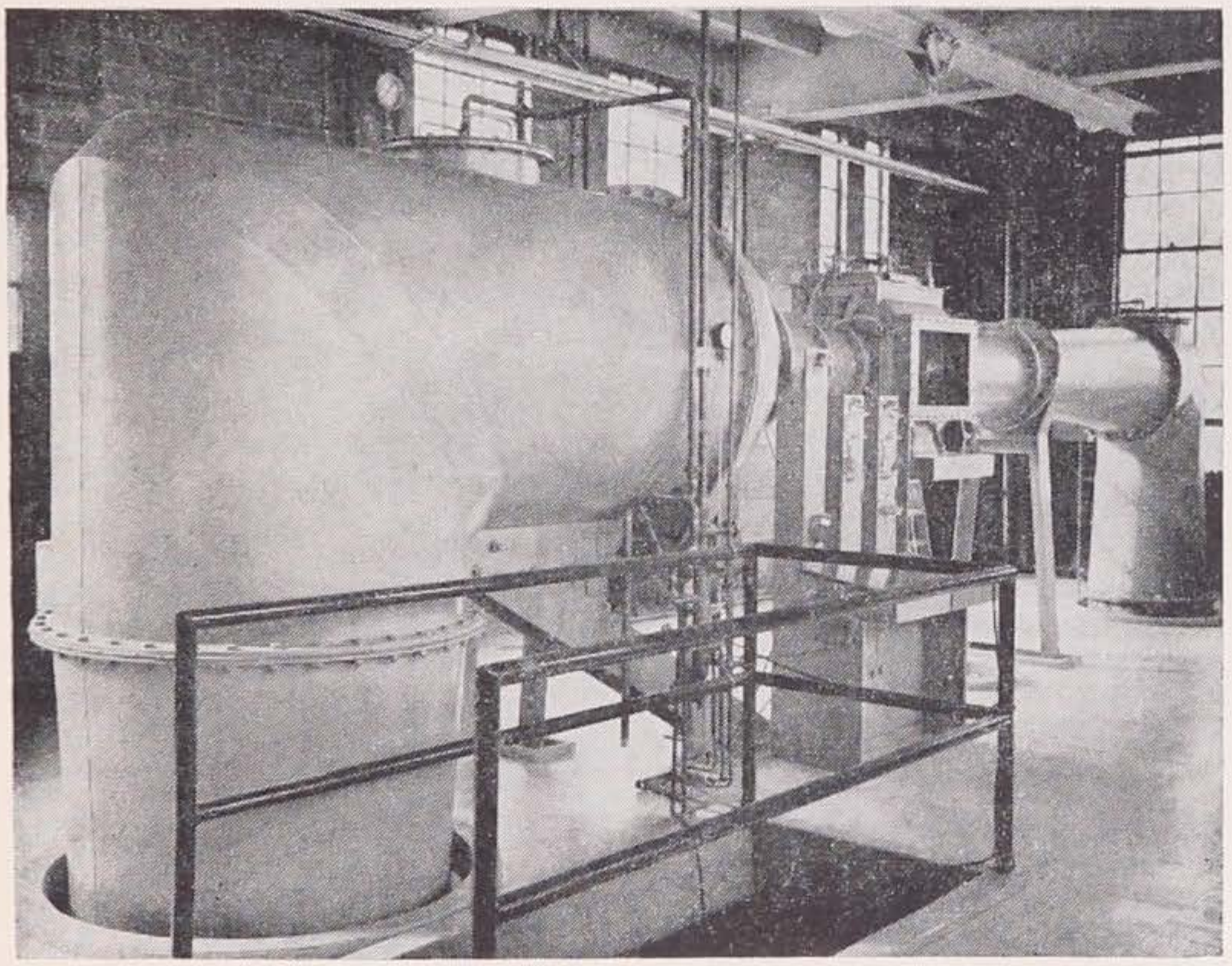

FIG. 6. WATER TUNNEL WITH OPEN-THROAT TEST SECTION.

about −14 psi. This tank is primarily a supplement to the water tunnels for problems involving cavitation characteristics of submerged jets.

Air Tunnels

The low-velocity air tunnel originally built in 1943 was replaced in

1951 by a recirculating tunnel intended primarily for graduate research. This tunnel, located at the north end of the second floor of the Main Laboratory, has a test section 3 feet square by 12 feet long with glass side walls. Its squirrel-cage rotor is driven by a 7½-horsepower variable-speed motor permitting air velocities from 10 to 50 feet per second to be obtained. Adjustable vanes allow further control of the velocity and of its distribution across the test section. Although the tunnel is of the closed-circuit type, in smoke tests the contaminated air can be discharged and fresh air drawn in through windows in the plenum chamber at the north end of the building. Moreover, the closed-throat test section can be removed to provide a set-up of the open-throat type.

Temporary air-tunnel installations are frequently devised for special purposes, one of which is the use of the student shop on the third floor of the Main Laboratory as a combined plenum and test chamber for jet studies. A 1½-horsepower fan has been arranged to exhaust air through the floor at one side of the room, a screened bell inlet at another part of the floor then admitting air to a streamlined nozzle either 12 or 6 inches in diameter. Diffusion measurements can be made over the first seven or fourteen diameters, respectively, of the vertical jet.

Of the three permanent air tunnels now in operation at the Institute, each generally accommodates at least two experimental projects in successive shifts. So useful are these facilities that construction of a fourth tunnel, also to be located at the north end of the second floor, has been started. This new tunnel will have an open-throat test section with a nozzle of octagonal cross section 3½ feet wide. A 20-horsepower motor with Gyrol fluid drive will permit continuous adjustment of test-section air velocity from 0 to 75 feet per second.

Sedimentation Equipment

Research facilities for studying scour and other phases of sediment transportation are located in the Laboratory Annex. Of the four permanent flumes situated there, three are fixed-bed scour flumes while the other is a variable-slope recirculating flume. The 90-foot tilting recirculating flume and the 15-foot glass-walled scour flume have previously been described in Bulletin 33. The other two fixed-bed scour flumes, one 5 feet and the other 10 feet in width, each 2 feet deep and 45 feet long, are equipped with sand-feed elevators and weighing tanks to permit running tests, such as those performed for the Iowa

State Highway Commission and the Bureau of Public Roads, under conditions of equilibrium bed-load transport (see Special Publications).

Facilities are also available for analyzing the physical characteristics of the sediment used in the various experiments. In addition to sieving equipment, a visual-accumulation tube for determining fall diameters of the sediment has been constructed. Other equipment, of a more temporary nature, is constructed, as needed, for precise determination of fall velocity. The Institute has some 12 different grades of sand available in quantity for research purposes.

Instrumentation

The electronic instrumentation equipment has continued to grow in quantity and importance, some projects being primarily for the development of new techniques, others being based on the use of instruments already available. Two 2-channel hot-wire anemometers are in continuous use for studies involving air, and one hot-wire and one hot-film anemometer are available for use in water. The electronic Pitot has been modified to use commercial pressure transducers and microphones, with a consequent increase in reliability and ease of operation. Electrical pressure cells are used not only for detecting the rapid fluctuations in stagnation and local pressures in turbulent flow, but also for detecting and recording velocity head, working-section pressure, and various local pressures in the two-dimensional water tunnel.

Signals from any of these instruments as well as from the water-tunnel dynamometer or towing carriage can be transmitted through a system of conduits to the third floor for recording on an Ampex instrumentation-type magnetic tape recorder or for analysis by root-mean-square or integrating analyzers. The magnetic tape recorder is useful in expanding or compressing the time scale of electrical signals through its capability of operating at different speeds when recording or playing back. In addition, it is possible to take any tape section corresponding to one second or more of a continuous recording and play it back synchronously for spectrum analysis, greater accuracy, or display on a cathode-ray oscillograph.

Scour in the transport flumes can be measured at a boundary such as a pier or an abutment by means of a series of electrodes placed on or near the boundary. Changes in the electrical impedance between adjacent electrodes can be detected and recorded on a continuously

moving chart. Since the relative elevation of the electrodes is known, and since the impedance is quite different for electrodes covered only by water and those covered by the bed, the record provides information on the location of the bed as a function of time.

Additional sensitivity in detecting the level of liquid surfaces has been provided by a vibrating-needle instrument (see Ph.D. dissertation by Koloseus). The vertically vibrating needle is driven by a magnetic circuit and positioned so that it enters and leaves the liquid during each cycle. When the needle is submerged, it completes an electrical circuit, so that the average current during each cycle is a function of the liquid level.

ESTIMATED VALUE OF PLANT AND FACILITIES

All items of physical plant and equipment are carried on the University's books at their original cost. This system accounts neither for depreciation nor for changes in the value of the dollar; it likewise fails to convey any concept of the replacement expense if these facilities were to be duplicated today. As examples of the unrealistic impressions which may be gained from these figures, it is noted that the Annex cost nearly as much as the entire Main Laboratory and that the $82,000 spent in enclosing the 10-foot river channel for conversion into a towing tank nearly equalled the original cost of the entire building. Because the values carried on the University's accounts do not offer meaningful comparisons, it is not considered worthwhile to bring up to date the estimated values of plant and facilities given in Bulletin 33. However, the major equipment expenditures of the past decade may be of interest. In addition to the above-mentioned expense of housing the towing tank, the towing carriage with its rails and supporting structure together with the drive and associated accessories required another $45,000. The water tunnels cost $30,000; the new flume, $25,000; and the rebuilding of the second-floor air tunnel, $6,000. The new air tunnel now under construction is expected to have a value of $7,500.

REVIEW OF INSTITUTE RESEARCH

Boundary-Layer Studies

A continuing program of research on boundary layers was initiated in this decade with studies by Baines (see Ph.D. dissertation) on the turbulent boundary layer on smooth and rough plates. This experimental research became feasible with the acquisition of the new air tunnel, described in Bulletin 33, having a turbulence intensity of about one per cent. It is significant that this renewed interest in the laws of turbulent boundary layers occurred simultaneously in other laboratories, after a lapse of about ten years since the important difference between the turbulent velocity profiles for pipes and plates had been demonstrated. Baines was followed by a succession of investigators—Moore, Hama, Siao, Yu, and Toch—but whereas Baines dealt with the entire problem, both in his dissertation and in a literature-survey report to the Office of Naval Research (see Special Publications), including mean and fluctuating characteristics on both smooth and rough surfaces, the subsequent investigators had much more restricted objectives.

Hama, in a paper in the *Transactions* of the Society of Naval Architects and Marine Engineers (Reprint 136), and Moore (see Ph.D. dissertation) were concerned with the effects of regular roughness. The essential conclusion from this work was to confirm the similarity laws for turbulent boundary layers along rough surfaces which had previously been assumed on the basis of pipe and channel experiments. Hama also developed a theory for the velocity distribution in the turbulent boundary layer near the wall in the range in which the viscous stresses are not yet negligible in comparison with the Reynolds or turbulent stresses (Reprint 124).

The development of a new and simple technique, Preston's method for measuring shear stress at a boundary, encouraged the undertaking of a careful set of new measurements of the boundary-layer velocity distribution on a smooth flat plate in zero pressure gradient, in an attempt to resolve the large discrepancies obtained by various observers in different laboratories. Since it had been shown by Landweber (Reprint 151) that the so-called universal logarithmic law of the turbulent boundary layer was a particular case of a family of possible

laws, an attempt was made to determine the law in best agreement with the flat-plate data. The results, reported by Landweber and Siao (Reprint 156), showed that these data were not sufficiently discriminating between the logarithmic law and an alternative, because of the small range of Reynolds numbers available in the air tunnel. Efforts are being made to obtain more extensive data from towing tests on a long circular cylinder at the David Taylor Model Basin.

The experimental program has continued with a study of the boundary layer on an axially oriented circular cylinder, in which it was shown by Yu (Reprint 161) that, with the inclusion of the ratio of the boundary-layer thickness to the cylinder radius as an additional parameter, the data appeared to be consistent with the same "inner" and "outer" boundary-layer laws, with a logarithmic overlapping range as for the flat plate. At present the three-dimensional boundary layer on an ellipsoid of three unequal axes is being investigated.

CAVITATION

Most of the cavitation studies conducted during the past decade had their origin in wartime tests of the decade before. Three new facilities have been added since then, however, so that the supplementary work was of a considerably more extensive nature. A typical example is the completion of experiments for the Office of Naval Research on pressure distribution and cavitation on a series of torpedo heads. Measurements made in the original water tunnel at zero angle of yaw (see Bulletin 32) have since been supplemented in one of the new tunnels at angles varying from zero to ninety degrees. Preparation of a sequel bulletin describing the study was under way at the time of writing.

Studies of submerged jets made during the previous decade led quite logically to the more recent investigation of cavitation in the eddy zone surrounding such a jet, in connection with the naval problem of jet propulsion. Under the sponsorship of the ONR, tests were conducted on submerged jets in a special cavitation tank, as reported upon by Whitehouse (see M.S. thesis) and by Rouse in a paper presented to the Eighth International Congress of Applied Mechanics at Istanbul (Reprint 116). Subsequently a more detailed investigation of the distribution of cavitation noise along the jet was made by Appel and reported upon to the ONR. As a result of Appel's findings, the entire phenomenon of energy transformation in a diffusing jet has been studied by Carr (see M.S. thesis) and Peng.

The water tunnel with two-dimensional test section has been used for a series of studies of two-dimensional profiles. DeHaven (see M.S. thesis) investigated the drag of a cascade of cylinders of varying relative spacing by means of pressure traverses around the central cylinder. A complementary study, also with ONR support, was conducted by Geist (see M.S. thesis) using the drag indication of a three-component balance. The balance had been designed by Appel under contract with the David Taylor Model Basin for the investigation of the characteristics of a series of hydrofoils, as described by Hug (see Ph.D. dissertation) and Matsuoka (see M.S. thesis). Further details of the hydrofoil study are included under the heading Irrotational Flow.

Hydrology

With the support of the U.S. Geological Survey, the Soil Conservation Service, the U.S. Weather Bureau, and the Graduate College, the long-term records of precipitation, runoff, groundwater levels, and vegetal cover on the Ralston Creek and Rapid Creek watersheds have been continued under the direction of Professor Howe. The hydrologic data for the 3-square-mile Ralston Creek area have been recorded continuously since 1924 and represent those of longest duration for a region of small drainage area in the United States. The similar project on the 24-square-mile Rapid Creek watershed has been continuous since 1941. Various phases of these unique data have been investigated by Song, Dougal, Chang, and Chowdhury (see M.S. theses).

Two bulletins of the Iowa Highway Research Board in the hydrologic field were prepared by members of the Institute staff during the decade. The first, by Howe and Metzler, gave culvert diameters for 5-, 10-, and 25-year runoffs as modified by storage due to various valley shapes upstream from the culvert. Sets of 132 charts for valleys having a range of valley slopes, channel widths, and channel side slopes as well as eight general charts for additional valley configurations were presented. The second bulletin, by Howe and Warnock, is now in press. Rainfall, runoff, and infiltration rates for the Ralston Creek watershed for various time intervals are presented as experienced over a 33-year period in this typical Iowa watershed of small size. (See Special Publications.)

Instrumentation

Electrical measuring and analyzing techniques were developed and

applied extensively during the decade, and most of the major research facilities have been equipped with one or more electrical measuring instruments. The pressure at various points in the two-dimensional water tunnel can be measured by strain-gage-type electrical cells as well as by the usual manometers, and a special dynamometer utilizing differential transformers was designed by Appel to measure lift, drag, and moment on models. The tilting flume on the first floor was equipped by Appel with a bellows-differential-transformer-type cell to measure pressure on the bottom, as well as with parallel-wire and vibrating-needle instruments to measure mean depths or wave profiles. The last instrument was modified by Koloseus (see Ph.D. dissertation).

Bed scour in the sediment-transport flumes was detected and recorded electrically through the impedance between a common ground and each of a series of electrodes embedded in a boundary such as a pier or a special pile. Laursen, Toch, and Hubbard also installed a similar instrument near a bridge pier in the Skunk River to collect data in a larger system (see Special Publications). The possibility of using a very sensitive electrical pressure cell to provide a rapid size-frequency analysis of sediment samples was investigated and a working model was constructed by Appel (see Ph.D. dissertation).

Electrical analogs of potential flow, which had been used near the end of the third decade, were developed and used more extensively during the fourth, with Ling making several refinements. These analogs were of two different forms: a tank containing a liquid electrolyte which can be arranged to represent either a two- or three-dimensional system of fluid flow (Reprint 126), and a resistance network which represents the finite-difference approximation of a two-dimensional system. However, the network analog did not fulfill its promise because of difficulty in obtaining uniform socket connections.

The major effort in the development of electrical techniques was devoted to the detection and analysis of the instantaneous velocity and pressure in fluid systems. Some of the instruments developed, such as the electronic Pitot by Appel (see M.S. thesis) for laboratory use and the shallow-water turbulence meter for large-scale systems, operated upon the fluctuations in total head and local pressure in a small region. Another method, used by Boyer (Reprint 118), depended upon the variation of resistance between a pair of polarized electrodes in flowing water. The most widely employed principle was

that of forced convection of heat from a body placed in the flow. This principle provides the basis of operation of the hot-wire and hot-film anemometers developed by Hubbard and Ling, respectively (see Bulletin 37), which have been used in most of the laboratory equipment employing air as a fluid, as well as in several flumes and the towing tank. Subsequent work on the hot-film anemometer has been carried on by Laughlin.

Instruments for use in analyzing the signals from the various devices were developed concurrently, so that many of the statistical quantities involved in present theories of turbulence were measured. The most recent major item acquired for use in data handling was an Ampex instrumentation-type magnetic tape recorder. With this instrument and an associated electronic integrator developed by Mortley (see M.S. thesis) for use with the recorder, it is possible to compress or expand the time base of fluctuating signals, to play back the signals repetitively, or to integrate for an indefinite period of time. In order to make full use of this versatile system, it has been put within reach of every research facility in the Main Laboratory through a wiring system enclosed in metal conduit.

In addition to such electronic measurement of fluctuating velocities and pressures (see M.S. thesis by Carr), various instruments were made as needed for the indication of mean-flow characteristics. These included Pitot cylinders and direction indicators (see M.S. theses by Arie and Rao), Preston tubes, multiple-tube direction indicators, and suitable manometers. Among the latter, the Institute modification of the two-fluid Wahlen type of gage for the precise indication of small differential pressures has now been converted to a one-fluid gage reading directly by Veeder counter to 0.001 inch of alcohol, as shown in Fig. 7.

IRROTATIONAL-FLOW ANALYSIS

A number of problems of practical interest have been treated on the assumption that the flow is irrotational. These have been solved by various means, such as the electrical analogy, finite differences, and mathematical potential theory.

The extension of the use of the electrolytic tank (Reprint 82) to solve three-dimensional flow problems was an important development, since for such problems, in the absence of an axis of symmetry, a solution by mathematical analysis is extremely difficult. This was accomplished by Hubbard and Ling in 1952 and applied to study the

flow in a transition length from a reservoir to a conduit of square cross section (Reprint 126).

Southwell's method of finite differences, referred to as a relaxation technique, was applied in a paper by McNown, Hsu, and Yih to the

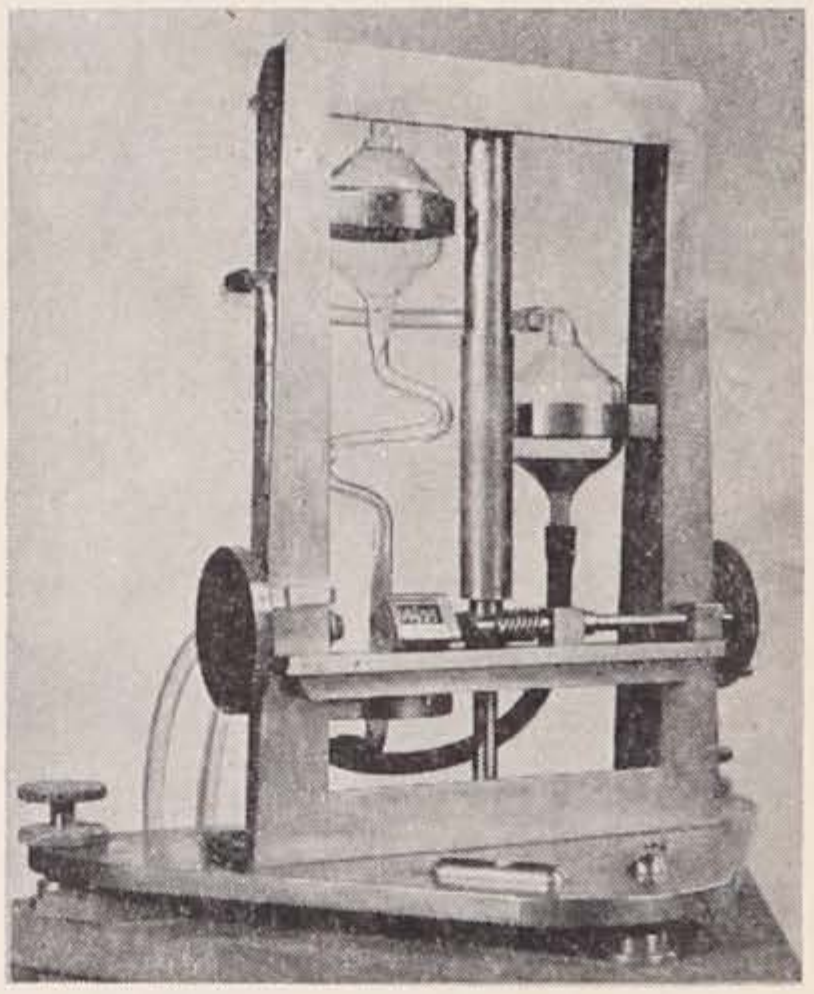

FIG. 7. VIEW OF PRECISION MANOMETER.

solution of Laplace's equation for two-dimensional and axisymmetric flow problems (Reprint 127). Methods of applying the technique to problems with different kinds of boundary conditions were developed. Applications included the flow in a two-dimensional curved inlet, the pressure distribution about a blunt-nosed head form, flow over a weir, flow about a cavitating head form, the impingement of a jet on a flat plate, efflux from a curved nozzle, and seepage through a vertical wall. Both the electrical analogy and the method of relaxation were used by Abul-Fetouh (see Ph.D. dissertation) on orifice flow (Reprint 83), and the relaxation method alone by Huber (see Ph.D. dissertation) on stratified flow.

In strong contrast to the tedious arithmetical operations of the method of relaxation is the elegant mathematical theory available for certain two-dimensional, free-streamline problems. An exposition of the free-streamline theory of Helmholtz-Kirchhoff and its application to several problems are given in a collective work by the Institute staff (Bulletin 35) edited by McNown and Yih. The problems treated include cavitating streamlined struts, inlets, flows about polygonal obstacles, efflux from a manifold, and head losses in miter bends.

New methods for computing the velocity and pressure fields about bodies, and generalizations and extensions of theorems for evaluating the added masses, forces, and moments on bodies moving through a fluid, based on mathematical solutions of Laplace's equation, have been developed by Landweber (Reprint 142). For a body in an arbitrary state of motion (translation and rotation) the boundary-value problem is formulated as a set of Fredholm integral equations of the first kind, which are solved by replacing them by an approximately equivalent set of linear equations. Computing programs for bodies of revolution and symmetric two-dimensional forms, for use with the IBM 650 or 704 automatic computers, are available and are being published in a contract report to the Office of Naval Research.

Often it is the motion of a body rather than the details of the flow about it that is of interest. One must then include in the equations of motion of the body the forces and moments exerted by the fluid. When the flow is steady and irrotational, a theorem due to Blasius expresses the force and moment on a two-dimensional form in terms of the complex potential of the flow, and an analogous theorem due to Lagally expresses the force and moment in terms of the singularities (sources, doublets, and vortices) within the body which may be considered to generate the flow. A third theorem, due to G. I. Taylor, expresses certain of the added masses of a body in terms of the strengths of the internal singularities, in a particularly simple manner. Taylor's theorem has been generalized by Landweber and Yih (Reprint 146) to apply, under broader circumstances, to all the added-mass coefficients, except those due to rotation alone; and the Lagally theorem has been extended to be applicable to unsteady motions of the body in arbitrary unsteady flows. These theorems, in their generalized form, have been applied by Kim (see M.S. thesis) for the motion of two spheres and by Bottaccini (see Ph.D. dissertation) for the added masses of a spheroid near a free surface.

The continuing interest in added mass at the Institute is evidenced by the number of papers and theses produced by the staff on this subject in recent years and the emphasis placed upon it in the new book *Advanced Mechanics of Fluids* and in a chapter of a forthcoming *Handbook of Fluid Mechanics* to be published by McGraw-Hill. Among the Institute contributions are a paper on the added masses of a large family of bodies of revolution (Reprint 159); another presenting a general theoretical procedure for obtaining the added masses of a two-dimensional form moving either horizontally or vertically

in a horizontal free surface (Reprint 155), which has been verified experimentally by Wu (see M.S. thesis); and a third on the added mass of a spheroid, semi-immersed in a free surface and moving transversely in a horizontal plane (Reprint 166).

JETS AND WAKES

Studies of free-turbulence shear flow have been continued most actively during the past several years. Not only was the shear zone of the submerged jet investigated further by Carr (see M.S. thesis) and Peng, but a series of studies of stable eddies formed by various boundary discontinuities was also initiated and carried forward. Among the wakes thus investigated in detail were those occurring at an abrupt expansion (see Ph.D. dissertation by H.-C. Hsu,) behind a normal wall (see M.S. thesis by Arie and Reprint 147), and behind a jet entering the flow at right angles (Reprint 154). Similar in many respects were the studies by Siao (see Ph.D. dissertation) and Nagaratnam (see M.S. thesis) of the hydraulic jump (Reprint 157) and by Rao (see M.S. thesis) of the jet in a counterflow. All these experimental studies were conducted in air, mostly in the second-floor air tunnel, because of the relative simplicity of experimental apparatus and measurement, especially for turbulence; only in the most recently initiated work on wakes with zero momentum flux is water being used in part of the research.

Each of the investigators contributed some facet of knowledge to the growing store of information on free turbulence, but the problem is indeed complex and no one of them could hope to solve it. The latest study, that on zero-momentum wakes under the sponsorship of the Office of Naval Research, is a good example of this difficulty. In order even to attempt an analysis of zero-momentum wakes, some information regarding their geometry and dynamics is required. Thus the experimental work serves the twofold purpose of providing data which might be directly applicable to some prototype problem and which, it is hoped, should also serve to permit an analytical solution of the problem. Part of this study is being conducted in the new towing basin using the hot-wire anemometer (see M.S. thesis by Aron). The primary difference, other than the fluid used, between this part and that run in the air tunnel in the Annex, lies in the means of producing the jet within the wake. A propeller is used in the towing basin, while an air jet emanating from a pipe is employed in the tunnel.

Since the sponsoring agency is particularly interested in conditions far downstream (800 or 1000 diameters) from the body and orifice or propeller, the air-tunnel work will require a jet of about 3/16-inch diameter to keep measurements within the 24-foot-long test section. In the towing basin, on the other hand, any distance can be obtained, limited only by the eventual interference of the basin walls, by returning the carriage and instruments to the appropriate position.

Of the studies concerning free-turbulence shear flow, those on the hydraulic jump might be singled out as especially interesting. They clearly indicated that even certain flows with a free surface could be modeled, and therefore investigated, by means of air flow. The results of this series of tests agreed quite well with subsequent tests conducted in water, which became possible only after the hot-wire anemometer had been adapted to that fluid (see discussion by Hubbard in Reprint 157).

In response to a request of the Office of Naval Research, an investigation of the lifting characteristics of annular jets was begun in 1958 under the direction of Professor Mack. When an annular jet is directed against a nearby surface a high pressure is built up beneath the base of the jet. The total lifting force may hence be considerably larger than that due solely to the momentum flux of the jet. Studies relating this total lift to the geometric and dynamic parameters of the system and to the nature of the nearby surface (i.e., land or water) have been made by Garg and Yen (see M.S. theses) and by Malsy and have led to the presentation of a paper by Mack and Yen at the 1959 Princeton Symposium on Ground Effect Phenomena (Reprint 164).

MODEL STUDIES

Strictly speaking, essentially all experimental research in hydraulics proceeds by means of models, for the subject matter is far too complex to permit many flow principles to be studied without relation to a specific boundary geometry. Sometimes, to be sure, the models are generalized rather than specific, like those of the schematic buildings in the special publication *Wind-Tunnel Studies of Pressure Distribution on Elementary Building Forms*, or the culverts for the Highway Commission-Bureau of Public Roads studies, or the bridge piers, abutments, and embankments in the special bulletins of the Highway Commission (see Bulletin 38 and Special Publications). Just as truly scale models of prototype conditions were those in which air currents were reproduced with saline water (Reprint 137), or in which the

turbulence characteristics of the hydraulic jump were reproduced with air (Reprint 157). However, in hydraulics literature the term "model study" has come to denote the investigation at reduced scale of a particular engineering enterprise. The following are definitely of this category.

An early investigation by Floyd Nagler of the discharge characteristics of the Keokuk spillways on the Mississippi River had its sequel in 1954, when the Institute undertook tests in preparation for maintenance measures on spillways and foundations, for Sverdrup and Parcel, Inc., of St. Louis. Of particular import was the simulation at model scale of the development of dynamic lifting pressures on large slabs of bed rock—a phenomenon also having considerable bearing on the stability of river-bank revetment. For the Houston office of the Ambursen Engineering Corporation the Institute investigated in 1953 various aspects of the San Jacinto Dam, grill-type spillway, and stilling pool; and in 1955 the automatic flashboards of the Wesley E. Seale Dam.

In continuation of the Rio Paraiba investigation mentioned in Bulletin 33, studies were made in the early part of the decade for the Canadian-Brazilian Services, Ltd., of Toronto, on a series of elements of a hydroelectric development in the region between Rio de Janeiro and Sao Paulo. These included, in addition to the sediment diversion already described, extensive tests for the Santa Cecilia Tainter gates, the Sant'Ana spillway, and the Santa Cecilia canal transitions—for the latter of which the use of curved vanes was proposed and incorporated into the design. All parts of the model investigation were described by Laursen in Reprint 89.

For the Stanley Engineering Company of Muscatine and for the State Conservation Commission a number of Iowa spillways—particularly those in the form of high-velocity relief channels—were investigated at small scale to the end of ensuring their safety against overtopping because of standing-wave formation. Of particular interest is the type of arrangement developed with the Conservation Commission, in which the Institute provided the facilities and consulting services and the actual tests were performed in the Institute laboratories by design and field engineers of the Commission staff.

For the Consolidated Edison Company of Chicago various members of the Institute staff investigated at model scale the problem of recirculation of cooling water drawn from and returned to the Chicago Canal by a series of power plants. Through use of cool and

heated water it was possible to obtain certain useful indications as to the advisable spacing and shape of intakes and outlets, although it was impossible to simulate the mixing phenomenon—depending as it does on both Froude and Reynolds numbers—with any degree of certainty. In order that a more general investigation could be made of the characteristics of stratified flow in two dimensions, the contracting company permitted a special test channel to be built for the specific and subsequent generalized tests and certain of its instruments to be retained for this purpose. The results were presented by Bata (see M.S. thesis and Reprint 153).

Note might well be made at this point that—except for service to other state agencies—it is the Institute policy to undertake model studies of a specific nature only if new principles of sufficient interest to warrant their investigation are involved. Although all hydraulics models admittedly have definite instructional value to students (as well as being impressive to the general public), the belief is maintained that the primary role of a university laboratory is pure and applied research.

RESISTANCE

Whereas the resistance of smooth surfaces to both nonuniform boundary-layer flow and uniform conduit flow is relatively well understood, the effect of heterogeneous surface irregularities on either type of flow has been the subject of investigation for very many decades. In the Institute's third decade a resistance diagram was devised (Reprint 36) with the Colebrook-White transition formula as a basis. This, however, uses a single linear factor to describe the roughness magnitude, and it is known that at least one other linear or areal factor must be necessary, if not also standard deviations from both. Roughnesses investigated at the Institute have covered a considerable range of concentrations and shapes.

In the effort to determine experimental relationships for uniform boundary-layer roughness similar to those already available for conduits, Baines (see Ph.D. dissertation) conducted with the support of the Office of Naval Research a series of air-tunnel experiments using commercially available emery cloth as the surface material. This was found to have the twofold drawback of being insufficiently rough and difficult to vary in absolute scale without loss of geometric similarity. For this reason Moore (see Ph.D. dissertation) extended the program through use of the simple transverse-bar form of roughness

previously investigated at Iowa in an open channel by Powell. The two disadvantages of the emery cloth were thus overcome, but the fact remained that such two-dimensional roughness was about as far removed as possible from the desired heterogeneous condition. Soon thereafter it became possible to obtain a series of wire-mesh screens of practically exact geometric similarity over a 30-fold linear range, and these were studied in both the air tunnel and the open channel by Rand, likewise with ONR sponsorship. The results were discussed in detail in a paper by Hama (Reprint 136), as were attempts by Ling to vary both the mean size and the frequency distribution of glass beads cemented to the test surface.

The desirability of controlling the areal distribution as well as the size of roughness element led Koloseus (see Ph.D. dissertation), with the partial support of the U.S. Geological Survey, to investigate the cube as the elementary form. At the time of writing, the elements are limited in size to 3/16 inch, the relative roughness being varied through changes of the water depth in an open channel, and the areal distribution being varied by changing the concentration of cubes by multiples of 4 between the initial and final limits of a smooth surface. With the completion of the original dissertation project, the program has continued under Dr. Koloseus' direction through a cooperative arrangement with the Geological Survey, for which the 85-foot flume described under Research Facilities was specially constructed by the Institute. A noteworthy finding of the dissertation was that the resistance function depended upon the Froude number once the latter exceeded a magnitude of about 1.7.

The rolling motion of a ship is damped because of both viscous effects and wave generation. An unresolved problem in this connection was to account for the unexpectedly high effectiveness of bilge keels as roll dampers. Martin (see Ph.D. dissertation) showed that an oscillating flat plate has drag coefficients which are many times greater than those of a plate in steady flow; on this basis he was able to explain the effectiveness of bilge keels. It was found that roughening the hull along its bilges caused an appreciable reduction in the roll damping of ship models, presumably because of a change from laminar to turbulent separation (Reprint 167). Ursell's theory of the wave making of a rolling ship form was at least qualitatively verified by McLeod (see M.S. thesis), who compared measured amplitudes of the waves generated by different forms with Ursell's predictions. A systematic investigation of ship forms of minimum wave-making resistance, on

the basis of Weinblum's tables of Michel's integral for the wave resistance, led to wasp-shaped forms; this work was described by Martin in a report to the Office of Naval Research.

SEDIMENT STUDIES

Following preliminary tests toward the end of the third decade, a comprehensive experimental program concerning scour at bridge piers and abutments was initiated and carried to completion during the fourth decade. Supported primarily by the Iowa State Highway Commission and the Bureau of Public Roads, the model tests covered the major aspects of scour under equilibrium conditions of bed-load movement for various pier and abutment geometry, spatial configuration, and alignment. The model tests and a prototype verification led to the development of design criteria, as well as suggestions for alleviating scour. (See Reprints 92, 107, 120, 123, and 138 and Special Publications.)

The Iowa State Highway Commission and the Bureau of Public Roads also sponsored an equally important study of storm-drain systems for sediment-transporting flow. Experiments were made to determine both the sediment-transporting capacity for given flow conditions in pipes (see M.S. thesis by Vallentine and Ph.D. dissertations by Ambrose and Craven) as well as the efficiency of short sand traps. These studies were combined to establish design criteria for typical field conditions (see Special Publications and Reprint 121).

As an outgrowth of both the scour and pipe-transport studies, the Institute undertook related projects of scour below a dam for the Ambursen Engineering Corporation of Houston as well as the transport of slag in pipes for the Combustion By-Products Company of Chicago.

In the field of sediment transportation in open channels, a study of the total-load transport under equilibrium conditions was made using fine (0.10- and 0.04-mm) sand. Measurements of both suspended and total load led to the development of an empirical relation for estimating the total load as reported by Laursen (Reprint 165). The project was sponsored by the Office of Naval Research and the experiments were conducted in a 90-foot glass-walled recirculating flume which was originally built with funds from the same sponsor. Using the same experimental flume, a study is presently being made of the effect of various bed-material size gradations on total load, suspended load, and bed configuration for a constant median diameter of 0.38

mm. This work is sponsored by the National Science Foundation.

A continuing interest in the various aspects of fall velocity of spheres and other-shaped particles was in evidence during the fourth decade. Studies were made of the fall velocity of particles both within and beyond the Stokes range, as well as studies of the effect of container geometry and particle concentration on the fall velocity. In addition, investigations were made by Moorman (see Ph.D. dissertation) of the accelerated portion of the free fall of a spherical particle in a stationary fluid and by Carstens (see Ph.D. dissertation) of the flow around spheres within an oscillating fluid. (See Reprints 81, 85, 100, 109, and 130.) Partial support, particularly for the data analysis, was given to several of these projects by the Office of Naval Research. The principles learned from these studies combined with recent electronic advances in pressure-sensitive transducers permitted the development by Appel (see Ph.D. dissertation) of an instrument for making rapid size-frequency analyses of sediment (Reprint 122).

STRATIFIED FLOW

Fluid flow with a nonuniform distribution of density is a common occurrence in many important problems, quite small differences in density often giving rise to substantial changes in the flow pattern. Even if experimental evidence were not at hand in many daily occurrences, a study of the equations of hydrodynamics with variable density would show that new avenues of research are open in the field of stratified flow (see Reprint 152).

The first studies on fluid motion with stratification of density were undertaken at the Institute during the second world war. In the past decade different problems on the subject have been under research as either Institute or contract projects. Several studies were also conducted to investigate the gravitational convection that originates in a fluid when heat is released from boundary sources of different kinds. (See M.S. thesis by Humphreys, and Reprints 110, 114, 115, and 141.)

The stratified flow of two distinct layers without interfacial mixing, or with a small amount of mixing, bears a great resemblance to the well-known flow of water with a free surface, so that terminology and concepts can be borrowed from the field of hydraulics of open channels. The free surface has its counterpart in the interface, and the study of interfacial geometry is akin to the investigation of surface curves. The concept of the critical regime, for instance, is susceptible of being extended to stratified flow, as shown by Craya, who, while

working as a visiting professor, reported on the significance and application of critical regimes to stratified flow (Reprints 93 and 99). The internal hydraulic jump was investigated by Yih and Guha (see M.S. thesis by Guha and Reprint 137). Practical applications of these principles are illustrated under Model Studies in connection with the recirculation of cooling water discharged from thermoelectric plants.

The behavior of a two-layered fluid system, otherwise at rest, when a sink is introduced in the field has been the subject of two investigations: Meyer (see M.S. thesis) studied experimentally the axisymmetric case, and Huber (see Ph.D. dissertation) solved by relaxation methods the case of a two-dimensional stratified flow due to a sink.

Like the free surface, the interface may become unstable, and entrainment of one fluid by the other may assume an important role in the flow. The first step should then be the investigation of the incipient instability; because the free surface corresponds to an extreme case of the interface and because curvilinear flows can be looked upon as having some type of stratification, studies by Yih, with the support of the Office of Ordnance Research, of the stability of parallel flows with a free surface and of curvilinear flow were undertaken as preliminaries to the more difficult investigation of the interfacial stability (Reprints 132, 135, 150).

The diffusion process at the interface, as due to turbulence in one of the layers, was experimentally investigated in a cooperative study with the Fluid Mechanics Laboratory of the University of Grenoble by Rouse and Dodu (Reprint 139). Supported by the Office of Ordnance Research since 1957, an experimental investigation on the interfacial instability and on the subsequent mixing of the fluids is under way. The thickness of the mixing zone and the rate of transfer of mass across the interface are being investigated as the Froude and Reynolds numbers of the flow are varied.

ABSTRACTS OF GRADUATE THESES

Following the granting of the first master's degree in 1922, 352 advanced degrees have been given for studies in fluid mechanics by the Department of Mechanics and Hydraulics. Of this number, nearly 45 per cent have been awarded during the fourth decade, including over 50 per cent of the doctor's degrees. The recipients of these degrees represent some 30 countries, which is approximately double the number represented ten years ago. In addition, nine other countries—Argentina, Costa Rica, Czechoslovakia, Denmark, Mexico, Nicaragua, Norway, Sudan, and Thailand—have been represented by students enrolled for brief periods of time in either the regular program or for special studies. A detailed breakdown of the countries represented and the degrees granted is shown in the accompanying table. It is noteworthy that more than 50 per cent of these students have held assistantships or have been employed by the Institute.

Graduate degrees and countries represented, 1922 to 1960

Country	*M.S.*	*Ph.D.*
Australia	3	
Brazil	4	
Burma	1	
Canada	10	2
Ceylon	2	
China	52	17
Colombia	6	
Ecuador	1	
Egypt	3	2
England	2	
France	1	1
Germany	2	1
Greece	2	
Hungary	1	
India	23	1
Iran	1	
Iraq	1	1
Ireland	1	

Country	*M.S.*	*Ph.D.*
Israel	1	
Japan	2	
Korea	1	
Pakistan	3	
Peru	2	
Philippines	6	
Spain	1	
Turkey	9	3
United States	154	22
Uruguay	1	
Venezuela	5	
Yugoslavia	1	
Total	302	50

CAVITATION

Cavitation and Pressure Distribution at Gate Slots. ARISTOKLI SPENGO. M.S. Thesis, June 1949; Professor McNown, adviser. This thesis presents the results of an experimental investigation of pressure distribution along a boundary in the vicinity of a sluice-gate slot and of the critical cavitation number. Studies were conducted in a variable-pressure water tunnel and in an air tunnel at different scales. The slot shapes were rectangular, with width-depth ratios varying from 0 to 2, while the difference in elevation between the upstream and downstream edges of the slot was varied from negative to positive for each width-depth ratio. It was found that the pressure distribution along the upstream boundary in the case of negative superelevation is a function only of superelevation, while for positive superelevation it is a function of the width of the slot also. The pressure distribution along the downstream boundary in the case of negative superelevation is a function of the width of the slot and the superelevation, whereas in the case of positive superelevation it is a function of the cavitation number also.

An Investigation into the Point of Incipient Cavitation of Submerged Jets. JOHN P. WHITEHOUSE. M.S. Thesis, February 1952; Professor Rouse, adviser. The effect of temperature and nozzle geometry on the magnitude of the incipient cavitation parameter for a submerged liquid jet was investigated experimentally. Measurements were conducted in a 5x10-foot vacuum tank on jets from 1½-inch

nozzles, and a hydrophone and recorder were used to detect cavitation. High-speed photographs showing that cavitation occurs in the zone of maximum turbulence of a submerged jet were obtained. Contrary to previous tests, the absence of temperature effects was clearly demonstrated, whereas the effect of the nozzle shape, although present, was not quantitatively evaluated. A design value of 0.6 for the incipient cavitation parameter of initially parallel jets was recommended. (See Reprint 116.)

Theoretical and Experimental Investigation of Forces on Cavitating Hydrofoils. MICHEL HUG. Ph.D. Dissertation, February 1956; Professor Landweber, adviser. A linearized theory has been derived to compute the forces exerted upon a cavitating hydrofoil. The leading principle of the derivation is the transformation of the deviation flow around the hydrofoil into a deviation flow which can be computed by known methods; the transformed boundary conditions become those of a cambered thin airfoil, the flow around which can easily be computed. An alternative linearized theory had already been derived by M. P. Tulin, who preserved the complex velocity through the transformation rather than the velocity potential, which is kept invariant in the present theory. The two different ways of transforming the problem lead to different types of difficulties. In the present case it was necessary to correct the influence of singularities on the numerical value of the result. A typical computation has been made giving the lift and moment coefficients versus the cavitation index for a bubble of finite length longer than the foil. All of these results are in good agreement with Tulin's results. In the case of a bubble terminating on the foil, a theory derived by A. J. Acosta gives a fairly good check of the results. The experimental part of this work was not completely satisfactory, but a partial check of the linearized theory was obtained by allowing a certain shift of the cavitation index to compensate for the partial air pressure in the cavity.

Water-Tunnel Tests of a Cavitating Hydrofoil. TSUYOSHI MATSUOKA. M.S. Thesis, August 1957; Professor Landweber, adviser. The force and moment characteristics of the NACA 66_1-012 hydrofoil were measured in a two-dimensional water tunnel at various angles of attack and cavitation numbers. It was found that there was considerable discrepancy between vapor and cavity pressures. The latter were used in the specification of the cavitation numbers. Some consideration was given to the correction for the effect of tunnel walls. It was

shown that the limiting cavitation numbers obtained in the tests are in approximate agreement with theoretical values.

The Drag of Cavitating Cylinders Arranged in a Straight Grid. JEAN JACQUES GEIST. M.S. Thesis, February 1959; Professors Rouse and Landweber, advisers. An experimental investigation of the drag of cavitating cylinders arranged in a straight grid is presented with the emphasis on the effect of the cavitation number. This is the logical continuation of DeHaven's thesis on the drag of noncavitating cylinders (see page 78). In the present work direct force measurements were made with the Institute's new hydrodynamic balance. Results of experimental studies are discussed and given in form of a space representation.

The Effect of Cavitation on a Rotating Cylinder. DINSHAW N. CONTRACTOR. M.S. Thesis, February 1960; Professor Landweber, adviser. This experimental investigation of the effect of cavitation on a rotating cylinder was carried out in a two-dimensional water tunnel. The stainless-steel cylinder had piezometric taps around it in the side walls of the test section. The pressure distribution around the cylinder was recorded under both cavitating and noncavitating conditions for different ratios of rotational velocity to free-stream velocity. The pressure distributions around the cylinder were plotted and integrated to obtain the lift and drag coefficients. These parameters were then plotted against the cavitation number. It was found that cavitation reduces both the lift and drag coefficients of the cylinder. Before cavitation begins, the boundary layer around the cylinder can be either laminar or turbulent at the region of highest local Reynolds number. When the boundary layer becomes turbulent, the lift and drag decrease slightly. When cavitation begins, the lift decreases very rapidly. However, with the onset of cavitation the drag first increases by 60 to 80 per cent and then decreases to very low values.

CONDUIT FLOW

Studies of Multiple Laterals in Manifold Flow. ADOLFO YANES. M.S. Thesis, February 1951; Professor McNown, adviser. Earlier studies of flow through multiple laterals were extended to determine: (1) the effect of port spacing of multiple-port manifolds on the variations in pressure and head losses (see M.S. thesis by Escobar, "Studies of Manifold Flow," 1948); (2) the influence of symmetrically placed ports on the pressure increase downstream from the ports; and

(3) practical methods of applying the data on diverging flow in multiple manifolds obtained by Barton (see M.S. thesis, "A Study of Diverging Flow in Pipe Lines," 1946). Measurements were made for flow in 1- and 2-inch pipes, and the observed results were found to depend somewhat on the Reynolds number of the pipe flow. (See Reprint 125.)

An Experimental Study of Energy Dissipators for Culvert Outlets. LEONCIO RODA. M.S. Thesis, August 1953; Professor Metzler, adviser. An investigation of the scour in the bed of a channel downstream from an energy dissipator installed at the outlet of a culvert was conducted. Tests were made of one energy dissipator proposed for use in Iowa, several modifications of this type, and others of entirely different design. Qualitative results of the study are presented.

Effect of Inlet Design on Square Culvert Flow. HENRY MAKSOUD. M.S. Thesis, February 1954; Professor Metzler, adviser. An experimental study of the effect of inlet design on the discharge characteristics of culverts of square cross section was made. For culvert inlets with flaring wingwalls and sharp junctures between the wingwalls, headwall, and barrel, separation from the top slab of the barrel and strong vortex motion in the pool above the inlet were shown to reduce considerably the efficiency when the culvert was operated with the headwater elevation above the crown. Rounding of the sharp corners at the entrance provided only minor improvement in the head-discharge relationship of the culvert. However, proper streamlining of the entrance plus provisions for elimination of the vortex produced a marked increase in the rate of discharge through the culvert for a given depth of headwater. (See Bulletin 38.)

Pressure Conditions at the Outlet of a Pipe. DANIEL RUEDA-BRICENO. M.S. Thesis, February 1954; Professor Howe, adviser. The pressure distribution at various cross-sectional positions and the vertical position of the hydraulic grade line near the outlet of a 3-inch lucite pipe were determined experimentally. The pressure at the top and the upper part of the sides of the pipe near the outlet was found to be negative. The magnitude as well as the extent of the zones of low pressure depended upon the Froude number of the flow. The elevation of the intersection of the hydraulic grade line with the plane of the outlet was also found to depend upon the Froude number. Qualitative, but not quantitative, agreement with both mathematical studies and previous experiments indicated that the shape and rela-

tive roughness of the conduit, as well as the Froude number, affect both the pressure near the outlet and the vertical position of the hydraulic grade line.

Improved Culvert Inlet Design. JOHN E. FLACK. M.S. Thesis, August 1954; Professor McNown, adviser. The discharge characteristics of various culvert-inlet models were determined using a 3-inch-square culvert. Diagrams of the coefficient of discharge as a function of the ratio of headwater depth to barrel height and the slope of the culvert were prepared for the models tested, and the results were compared with the performance of inlets of standard design. Two models that provided better hydraulic properties than the inlets commonly used were developed. The location of the piezometric grade line at the outlet was evaluated experimentally, and the variation of this location with the Froude number of the flow was determined. At Froude numbers less than 1.0, the intersection of the piezometric grade line with the plane of the outlet was significantly above the midpoint of the outlet, and at Froude numbers greater than 1.5 this intersection was found to be located at about the midpoint of the outlet. (See Bulletin 38.)

Measurement of Fluid Resistance in Oscillatory Unsteady Flow in a Smooth Pipe. DON B. JONES. M.S. Thesis, August 1954; Professor McNown, adviser. Direct measurement of fluid resistance in oscillatory unsteady flow in a smooth pipe was accomplished using a system in which bulk acceleration of the fluid did not take place. A vertical tube, open at the top, was given a longitudinal, simple-harmonic motion, and the boundary resistance was measured by recording the fluctuations in pressure on the face of a fixed piston at the base of the liquid column within the tube. Data from exploratory measurements over a limited range of the Reynolds number were obtained and compared with theoretical values. Effects of the amplitude of the stroke were found, as well as expected deviations from theory for large values of the Reynolds number. Data for small values of the Reynolds number, for which the closest correspondence with theory is expected, need refinement in order that a valid comparison with the theory can be made.

Variations of the Kinetic Energy Coefficient at the Outlet of Square Culverts. PETER M. SMITH. M.S. Thesis, February 1956; Professor Metzler, adviser. The purpose of the investigation was to determine the values of the kinetic-energy coefficient at the outlet of square

culverts flowing full and having undefined channels, well-rounded entrances, horizontal barrels, and free outfall. Vertical, horizontal, and diagonal velocity profiles of a test section one barrel width upstream from the outlet of a 3-inch and of a 6-inch model were roughened for two tests. Tests were made with barrel lengths of 10, 20, and 30 barrel widths and with the Froude number ranging from 0.83 to 1.75. For each test velocity contours were plotted and graphically integrated to yield the value of the kinetic-energy coefficient, which was then plotted against Reynolds number and Froude number. The experimental values of the coefficient found one barrel width upstream from the outlet should be slightly smaller than the values at the outlet. At the outlet section the coefficient decreases as the Reynolds number and the Froude number increase and increases as the relative roughness increases. If uniform flow is not established, it increases as the relative length increases. Uniform turbulent flow was essentially established at the length of 20 barrel widths. (See Bulletin 38.)

Pressure Distribution in Two-Dimensional Flow at a Conduit Outlet. YUN-SHENG YU. M.S. Thesis, February 1956; Professor Rouse, adviser. The purpose of this research was to investigate experimentally and analytically the pressure distribution in two-dimensional flow at a conduit outlet and to interpret the resulting flow pattern. Analytically, the phenomenon was considered as a problem of two-dimensional potential flow and was approached by both the relaxation method and the resistor-network method. Experimentally, a rectangular conduit outlet 3 feet long with a cross section of 3 inches by 6 inches made of lucite plates ¼ inch thick was used. Forty-two piezometer orifices were installed at seven different sections along the conduit. The distance from the outlet plane to the various measuring sections ranged from ¼ inch to 2.4 inches. Two setups with width-depth ratios of ½ and 2, each with and without wing walls, were investigated. The range of Froude number investigated was from 1.21 to 4.5 for width-depth ratio of ½ and from 1.0 to 5.0 for width-depth ratio of 2. The results obtained by the analytical and the experimental methods were compared.

Velocity Distribution along a Short, Smooth, Square Culvert. NARAIN R. RIJHWANI. M.S. Thesis, August 1956; Professor Metzler, adviser. The purpose of this investigation was to study the variation of velocity distribution along a short, smooth, square culvert. The results are based on water flowing through a 4-inch-square culvert

with a well-rounded entrance. Two sets of data were taken; during one set the ratio of water depth to culvert depth at the inlet was approximately 1.4 and the conduit was horizontal, and during the other set this ratio was approximately 1.75 and the conduit slope was 4 per cent. The nonuniformity of flow was indicated by coefficients of kinetic energy α, and momentum β, which were evaluated by graphical integration. The Kármán-Prandtl universal law for velocity distribution near smooth boundaries was utilized to evaluate the boundary shear, and hence the Darcy-Weisbach resistance coefficient f. The values of α, β, and f were plotted for various sets of data. An integrated curve showing the change of the average resistance coefficient (for the whole conduit) with the relative length of the conduit was plotted. The length of flow establishment was estimated, and the coefficients α, β, and f were evaluated for the established flow. (See Bulletin 38.)

Inlet Loss in Laminar and Turbulent Flows. I YU. M.S. Thesis, February 1959; Professors Rouse and Landweber, advisers. An experimental investigation of the establishment of uniform flow was conducted in the oil-pipe assembly of the instructional laboratory. The first part supplements existing analyses of laminar boundary-layer development beyond a well-rounded pipe inlet. The second part deals with the turbulent flow produced by four short wires 0.012 inch in diameter inserted radially into the pipe to disturb the boundary layer a short distance beyond the inlet bell.

FALL VELOCITY

Effect of Shape of Particles on Their Settling Velocities—Triaxial Particles. HIMANSU RANJAN PRAMANIK. M.S. Thesis, February 1950; Professor McNown, adviser. In an extension of Malaika's study of the effects of particle shape on fall velocity (see Ph.D. dissertation, "Effect of Shape of Particles on Their Settling Velocity," 1949, and Reprint 85), an investigation was made of particles having the form of rectangular prisms and double pyramids with all three axes unequal. Observations were made for Reynolds numbers (based on the diameter of the sphere having the same volume) between 10^{-4} and 10^{3}, and values were determined for a shape coefficient to be applied to Stokes' equation. It was found that within the Stokes range the value of the shape coefficient for a particle of known axis ratio and orientation can be estimated within 5 per cent from the theoretical

curves for the settling velocity of an ellipsoidal particle. For higher Reynolds numbers, curves are presented which can be used to estimate settling velocities for particles of any shape with an accuracy of 15 per cent. (See Reprint 130.)

Accelerated Motion of a Sphere. MARION ROBERT CARSTENS. Ph.D. Dissertation, June 1950; Professor McNown, adviser. The forces on an oscillating sphere in a fluid medium were studied by experimental means. To facilitate measurements, the mass of the oscillating system was adjusted so as to produce resonance; in this way the inertial effective force and the dissipative (shear) force could be evaluated separately. The sphere motion was assumed to be at least approximately simple harmonic, and the data were compared with the results of the theory given by Stokes for laminar oscillatory motion. Variations of an added-mass coefficient and an equivalent laminar-resistance coefficient were determined for various Reynolds numbers and various relative amplitudes. The experimental results were applied to an allied problem of a stationary sphere in an oscillating fluid. The experimental results, as applied to this problem, were found to correspond closely with the data of an experiment performed earlier in Germany. The analysis was extended to include an approximate indication of the diffusion characteristics of suspended sediment in water. (See *Trans. A.G.U.*, Vol. 33, 1952.)

Mutual Influence of Two Freely Falling Spherical Particles and the Effects of a Plane Vertical Boundary on a Single Spherical Particle. JAGDISH RAJ BAMMI. M.S. Thesis, August 1950; Professor McNown, adviser. A study was made of the effects of a neighboring sphere and of a nearby vertical plane boundary on the settling velocity of a single sphere. It was found that the settling velocity was affected appreciably for horizontal spacings of ten diameters or less. The magnitude and zone of influence of these effects were found to decrease with increasing Reynolds number, becoming negligible for the highest number tested (700) except for very small spacings. For comparatively large spacings the effects of the container were found to be large; for spacings greater than 4 sphere diameters the velocity of the two spheres was less than that of a single sphere in an infinite medium. (See Reprint 100.)

Effect of Spacing and Size Distribution on the Fall Velocity of Sediment. PIN-NAM LIN. Ph.D. Dissertation, August 1951; Professor McNown, adviser. The effects of spacing and size distribution of sedi-

ment in suspension on the fall velocity of the particles were investigated, both theoretically and experimentally, for homogeneous suspensions of uniform particles. The problem was essentially one of evaluating the hydrodynamic interference due to the superposition of velocity fields generated by the falling particles. Expressions for the velocity components induced at an arbitrary point in a suspension were derived on the basis of Oseen's theory of viscous flow around a sphere. A theoretical relationship between the actual and reference fall velocities was then developed from these expressions. Results of this theory were compared with those observed in the laboratory for suspensions of samples of sand and of glass beads, the samples having been carefully prepared so that the fall velocities of all particles in a given sample were the same. Observations were made for concentrations (by immersed weight) between 0.1% and 6%, for which surprisingly large reductions in velocity—10% to 30%—were recorded. The findings have been shown theoretically to be applicable to stratified suspensions of nonuniform particles as well. This indicates the possibility of applying the results obtained to the practical problems of sediment-size analysis. (See Reprint 109.)

Motion of a Spherical Particle in the Accelerated Portion of Free Fall. ROBERT W. MOORMAN. Ph.D. Dissertation, February 1955; Professor McNown, adviser. A systematic study of the physical variables related to the motion of a spherical particle in the accelerated portion of free fall was made. Data were collected photographically over a range of terminal Reynolds numbers from 1 to 2000 for ratios of density of the sphere to density of the liquid between 1.2 and 9. A single equation and one accompanying plot are presented by means of which future occurrences can be predicted. Calculations of the variation of the velocity with time in the zone of acceleration, based on the assumption that the resistance in that zone is directly proportional to the instantaneous velocity, gave results that were in good agreement with the velocity variation determined experimentally. This confirms the findings of Carstens for harmonic motion but is at variance with the assumption of many previous investigators of free fall that the exponents and drag coefficients for uniform motion are applicable.

FLOW MEASUREMENT

The Development of a Turbulence Pitot for Use in Water. DAVID W. APPEL. M.S. Thesis, June 1949; Professor Rouse, adviser. An instru-

ment having the form of a Prandtl Pitot with an elastic diaphragm between the tip and the side piezometer openings was developed. The deflection of the diaphragm is proportional to the differential pressure and is detected electrically through the change in reluctance of a small coil behind the diaphragm. The characteristics of the instrument were determined from measurements in a submerged jet. Its directional and frequency limitations are discussed.

A Direct Optical Method for Measuring Fluid Velocities in Laminar Flow. ELLIS BERTRAM PICKETT. M.S. Thesis, August 1950; Professor Posey, adviser. A method and apparatus for direct optical determination of the fluid velocity in any filament of steady, uniform, laminar flow in a pipe or channel are described in this thesis. The limitations of the method and apparatus are recognized and recommendations are made for their improvement. Observations were made on the ground glass of a camera of the movement of minute aluminum particles, carried in suspension and illuminated in a vertical plane, in comparison with an electrically driven, variable-speed thread in front of the ground glass. Velocities ranging from less than 0.001 foot per second to 0.100 foot per second were accurately observed, less than two minutes being required for each determination. Displacement of the plane of illumination permitted measurements to be made over an entire trapezoidal cross section.

The Study of the Price Current Meter in Low Velocity Flow. WILLIAM G. HALL. M.S. Thesis, February 1953; Professor Boyer, adviser. The purpose of this investigation was to determine the effect of the number of bucket-wheel cups on the low-velocity rating of the Price current meter. Bucket wheels with six, five, four, and three cups were tested for the stalling speed of the meter, for the minimum velocity at a constant number of revolutions per foot of travel, and for the slope of the rating curves. The meter was towed in a glass-walled flume at velocities from 2 feet per second down to the stalling speed of the meter. The meter was also placed in an air tunnel and run at air speeds from 22 feet per second to 60 feet per second. The present six-cup bucket wheel was found to be the best of those tested.

Constant-Temperature Hot-Wire Anemometry with Application to Measurements in Water. PHILIP G. HUBBARD. Ph.D. Dissertation, June 1954; Professor Rouse, adviser. In order to fill the critical need for an instrument to measure the turbulent characteristics of flowing water under laboratory conditions, the hot-wire anemometer—widely

used for measurements in air—was tested and adapted for use in water. Special attention was given to those properties of water (ambient temperature and pressure, sediment content, and electrochemical effects) which complicate the problem and have prevented a general application of the method. Means of cancelling the effects of each of these extraneous variables were devised and tested, and a working model was built. As a part of the dissertation, the theory of constant-temperature operation of a hot wire is presented, and the practical design procedure is described in detail. The metering circuits and computational procedures necessary to derive the desired statistical quantities from the indications of the electrical apparatus are also included so that all of the information needed to design, construct, calibrate, and use an instrument is made available. Finally, a comparison was made between results of measurements with similar instruments operating in water and in air. (See Bulletin 37.)

Measurement of Flow Characteristics by the Hot-Film Technique. SUNG-CHING LING. Ph.D. Dissertation, June 1955; Professor Yih, adviser. A project to develop a dependable technique for measuring turbulence in water culminated in the production of a hot-film sensing element which was also applied to high-temperature and high-velocity flows of gases. This element possesses many desirable characteristics, such as high mechanical strength, good dynamic response, long life, high signal sensitivity, and high temperature stability. The dynamic and static heat-transfer characteristics of the hot film were investigated, both analytically and experimentally. A complete instrument which operates this sensing element on the constant-temperature principle was built. Theories of equipment design, operational procedures, and computational steps to obtain the various flow characteristics are explained. Finally, some sample measurements are described to demonstrate the art of hot-film anemometry. (See Bulletin 37 and Reprint 145.)

(The following abstracts are of theses written by students of the Department of Electrical Engineering. They are included here because their subject matter is related to instrumentation problems of interest to the Institute and because the studies were prepared using the facilities located at the Hydraulics Laboratory.)

An AC-Bridge Hot-Wire Anemometer with Constant Temperature Operation. PETER L. BERNTSEN. M.S. Thesis, August 1950; Professor Lonsdale, adviser. A hot-wire anemometer for use in air was designed to take advantage of the freedom from drift of AC amplifiers, as com-

pared to their DC counterparts. The heating-current frequency was 30 kilocycles, and satisfactory response to modulation frequencies up to 2500 cycles was obtained. Stability was noticeably improved over that of the DC type of instrument.

Analogue Computer for Multiplication. JOHN J. STAFFORD. M.S. Thesis, August 1952; Professor Lonsdale, adviser. This thesis describes an instrument developed under Institute sponsorship for use in analyzing random fluctuations in the output voltage of various electrical transducers for measurement of turbulent velocities and pressures. It is based on the use of selected vacuum tubes which are rich in harmonics. The fundamental and odd-order harmonics are eliminated by a parallel arrangement of two tubes, so that the dominant component in the output is the second harmonic. This characteristic was used in a quarter-square circuit to make a function multiplier capable of operating from very low frequencies to beyond 20 kilocycles.

Application of a Magnetic Tape Recorder to the Analysis of Continuous Random Signals. JACK L. MORTLEY, M.S. Thesis, August 1959; Professor Ware, adviser. An electronic integration instrument for use with continuous random signals was designed and constructed under sponsorship of the Institute. Its operation is based on use with the Ampex 1104FM tape recorder, so that expansion or compression of the time scale can be arranged simultaneously with digital readout. Time of integration extends from the period of ordinary d'Arsonval meters to several hours. Tests showed an over-all error of less than 0.5 per cent.

HYDROLOGY

Influence of the Location of Storm Runoff on Shape of the Unit Hydrograph. YU-CHEH SOONG. M.S. Thesis, February 1950; Professor Howe, adviser. A study was made of the relationships between the shape of the unit hydrograph and the rainfall in the Iowa River Basin, which is characterized by a very large length-width ratio. The parameters used were the mean-time and standard-deviation characteristics of the unit hydrograph and the weighted mean distance and weighted concentration coefficient, which define the rainfall-excess distribution over this basin. Relationships between mean time and weighted mean distance and between the standard deviation and a combination of basin characteristics were obtained.

Minimum Expected Yield from Small Watersheds Using Synthetic Meteorological Years. CHARLES E. LEWALD. M.S. Thesis, June 1950; Professor Howe, adviser. A method was developed for deriving a short synthetic meteorological period from Weather Bureau records for use in estimating the minimum yield of small watersheds. For use in conjunction with this synthetic meteorological period, a concept is proposed which eliminates the necessity for construction of a mass curve of monthly net yields. Advantages claimed are the following: (1) critical dry periods can be anticipated; (2) minimum yield expected can be predicted with regard to frequency of occurrence; (3) determination of net yield may be restricted to three synthetic meteorological years; and (4) for small watersheds the necessity of estimating monthly net yield and of constructing a mass curve has been eliminated.

A Study of the Relationship between Watershed Characteristics and Distribution Graph Properties. RICHARD G. WARNOCK. M.S. Thesis, February 1952; Professor Howe, adviser. In this investigation the properties of the distribution graph, including the time to peak, the time base, and the peak percentage of discharge were correlated with the watershed characteristics, size of the area, the land slope, and the shape of the basin. The data were taken from 33 Illinois drainage basins, ranging in size from 10.1 square miles to 1,364 square miles. The land slope was found to be an important factor in the correlations for areas smaller than 200 square miles. Inclusion of the shape, expressed as a compactness coefficient or a form factor, improved most of the correlations. Curves for the derivations of the distribution-graph properties from the watershed characteristics are given.

Evaluation of the Storage Factor for Flood Routing in Natural Channels. ALBERTO VAL. M.S. Thesis, June 1954; Professor Boyer, adviser. Valley storage along two reaches of the Des Moines River in Iowa was studied. The storage is presented as a function of the outflow from each reach and methods of utilizing channel storage in flood routing are discussed.

Frequency of Infiltration Intensities on Rapid Creek Watershed. CHIEH-SHYANG SONG. M.S. Thesis, February 1956; Professor Howe, adviser. Average infiltration rates for 48 storms occurring in the years 1943 through 1953 were computed by four different methods. Frequency relations, in the form of duration curves, were drawn for each method of analysis. The relation between the stream flow immedi-

ately before the rainfall, the infiltration capacity of the soil, and the time of excess rainfall were also studied. It was found that the area factor is more important than the time factor in computing infiltration rates.

Synthetic Unit Hydrographs Based on Triangular Inflow. JAMES C. I. DOOGE. M.S. Thesis, June 1956; Professor Howe, adviser. This study is concerned with the problem of synthetic unit hydrographs, that is, the prediction of surface runoff on the basis of only such information as is available from a topographic map of the catchment area. A theory of the unit hydrograph is presented which links the unit-hydrograph principle with the presence of linear storage in the catchment area. The nature of the runoff process and the morphology of natural catchments are discussed in order to provide a basis for a synthetic method. It is argued that the instantaneous unit hydrograph can be produced by routing a triangular inflow through a single element of linear reservoir storage, and hydrographs derived in this way are shown to give excellent agreement with both the dimensions and shape of unit hydrographs derived by other means. In the final chapter a practical procedure is outlined and two examples presented.

A Method for the Synthesis of Unit Hydrographs for Small Watersheds. ALBERTO M. VILLARES. M.S. Thesis, June 1956; Professor Howe, adviser. A procedure for producing a synthetic hydrograph was developed for 20 small watersheds ranging in area from 22.5 to 199 square miles. The time-to-peak and unit-peak values were obtained in terms of the basin characteristics. An expression was derived for the entire unit hydrograph. The results were compared with those of other investigators and are believed to be applicable to small watersheds which are physiographically similar. The synthetically developed hydrographs should be useful in determining the size of spillways required for reservoirs on small watersheds.

Investigation of Storage Effects of Reservoirs Subjected to Superfloods. STEVEN DOLA. M.S. Thesis, February 1957; Professor Posey, adviser. This thesis studies the effect of reservoir type, spillway length, spillway-crest elevation, outlet-conduit size, and hydrograph time base on reduction of peak inflows of superfloods by reservoirs. These physical characteristics describing the reservoir, dam, and flood hydrograph are combined and expressed as a dimensionless parameter which, when plotted as the third variable on a dimensionless plot, permits the quantitative evaluation—sufficiently accurate for

preliminary purposes—of the reduction in the peak inflow of a superflood by a reservoir. The relative effectiveness of reservoirs in reducing peak inflows of superfloods may be compared simply by evaluating the above dimensionless parameter.

Hydrologic Safety Standards for Spillway Capacity. OLAF M. ERICKSON. M.S. Thesis, August 1957; Professor Posey, adviser. The three approaches for estimating a spillway design flood—flood formula, frequency analysis, and the unit-hydrograph method—have been examined and an attempt has been made to point out the limitations and merits of each. A standard procedure is suggested for estimating a spillway design flood by classifying dams, and classifying the design storm and infiltration estimate to be used in classifying the dam. A standard flood could then be derived by the unit-hydrograph method of analysis.

A Study of the Factors Which Affect Infiltration Rates on the Ralston Creek Watershed. MERWIN D. DOUGAL. M.S. Thesis, February 1958; Professor Howe, adviser. The intensity and duration of rainfall, the antecedent precipitation index for a measure of soil moisture, and the season of the year were investigated to determine their relation to the infiltration index. A three-quadrant graphical correlation was developed for computing the infiltration index for observed values of each factor. Observed values of infiltration index varied between 0.09 and 2.35 inches per hour for the 258 storms studied.

Investigation of Storage Effects of Reservoirs Subjected to Superfloods. YUAN-PO KOU. M.S. Thesis, February 1958; Professor Posey, adviser. This thesis is a continuation of the investigation of Dola. His results were extended to a wider range of the depth-capacity exponent, m, which is one of the most important factors affecting the storage effect of a reservoir. This thesis also offers a method of comparing the storage effects of reservoirs if the values of m and the maximum spillway surcharge are available.

Relation of Soil Moisture Content and Rainfall Intensity to Infiltration Rates on Rapid Creek. JYUH-SHENG CHANG. M.S. Thesis, June 1958; Professor Howe, adviser. Data from 48 storms occurring in the years 1943 through 1953 were used to determine the relationships between rainfall intensity, soil moisture content, and infiltration rates on the Rapid Creek watershed. The correlation of these factors was studied graphically with the infiltration rate as the dependent vari-

able and the rainfall intensity, soil moisture content, season, and duration as independent variables.

Prediction of Runoff Frequency from Precipitation and Infiltration Frequencies. MANZUR AHMED CHOWDHURY. M.S. Thesis, August 1958; Professor Howe, adviser. The purpose of this investigation was to determine the runoff frequency from precipitation and infiltration frequencies. The analysis was made with the available data for three watersheds—Ralston Creek, Rapid Creek, and the Piscataquis River—which range in size from 3 to 460 square miles. Infiltration and precipitation frequencies, determined from the recorded data, were used to compute the runoff frequency, which was then compared to the observed magnitude.

IRROTATIONAL FLOW

Characteristics of Irrotational Flow from Axially Symmetric Orifices. ABDEL-HADI ABUL-FETOUH. Ph.D. Dissertation, August 1949; Professor Rouse, adviser. Although an exact analytical solution of the orifice problem has not yet proved feasible, use of the method of relaxation has permitted a numerical determination of the flow characteristics to be made with sufficient precision for the problem to be considered solved. The coefficient of contraction is found to be practically identical with that evaluated by von Mises for two-dimensional flow from slots over the entire range of area ratio, and reasonable agreement is shown to exist between measurement and computation. Coordinates of the jet profiles are presented in tabular and graphic form, and are found to differ appreciably from those previously adapted from the two-dimensional case. A composite dimensionless chart is also provided showing the distribution of pressure along the boundary and center line and across the efflux section for the various area ratios. (See Reprint 83.)

Approximate Analyses Interrelating Pressure Distribution and Axisymmetric Body Form. EN-YUN HSU. Ph.D. Dissertation, February 1950; Professor McNown, adviser. Methods are presented for mathematically defining body forms with preassigned pressure or velocity distribution. Approximate solutions were obtained by means of (a) numerical methods and (b) a simplified analytical approach. In either case, the solutions are applicable to real flows only if the Reynolds number is large and the body well streamlined, so that the flow is essentially irrotational. The relaxation procedure, a numerical

or finite-difference method for the solving of the appropriate differential equations of motion, was applied in finding the cavitation-pocket form around a hemispherical head with parallel afterbody. As an expedient, a solution to the Laplacian equation in elliptical coordinates was obtained in a mathematical analysis based on the assumption that the body profile is slender. Two series of profiles, one symmetrical fore and aft and the other unsymmetrical, were evaluated for various specified pressure and velocity variations and for various ratios of maximum diameter to length. It can be concluded that the problem of defining, with good approximation, a body form with an assumed pressure distribution can be solved by the latter method. The solution is significant, in that form drag can be reduced and cavitation-free body forms can be obtained for known conditions of flow. (See Reprints 95 and 127.)

An Exploratory Study of Vortex Rings. ARTHUR K. JOHNSTON. M.S. Thesis, June 1953; Professor McNown, adviser. An experimental investigation was made to determine the properties of vortex rings and to compare these properties with those derived from theoretical analysis. Vortex rings were generated in air, using a piston and cylinder with a sharp-edged orifice in the end. The vortex rings produced were observed visually using smoke, and measurements of their velocities were made with a hot-wire anemometer and an oscilloscope. The major finding of the investigation was that freshly generated vortex rings may be classified by three parameters: (1) the ratio of the ring diameter to the core diameter, (2) the ratio of the product of the ring diameter and the speed of translation to the circulation, and (3) the ratio of the center velocity to the speed of translation. Only the first two of these ratios are implicit in the existing mathematical theory of vortex rings, but the experimental results showed that it is also necessary to consider the third. Although the theory also assumes that the motion is irrotational, a rotational core was found in all rings tested.

Path of a Spherical Particle in the Flow Field about a Sphere. WOOK DONG KIM. M.S. Thesis, February 1956; Professor Landweber, adviser. The arbitrary motion of two spheres in an infinite, inviscid, irrotational fluid was analytically studied by using the method of successive images and a theorem relating added masses and doublet strengths. The kinetic energy of the given dynamic system and the differential equation of motion have been determined. A numerical solution for the motion of a small sphere along the line of centers for

the case in which a large sphere moves with uniform velocity is presented.

The Added Masses of Prolate Spheroids Accelerating under a Free Surface. M. R. BOTTACCINI. Ph.D. Dissertation, June 1958; Professor Landweber, adviser. The motion of a submerged body under accelerative forces may be divided into two components: a steady part, dependent only on velocities; and an unsteady part, dependent on accelerations as well as velocities. The steady part has been investigated thoroughly. The unsteady part is known only for an infinite three-dimensional fluid. This dissertation presents the theory of accelerated motion of a spheroid moving in a heavy nonviscous fluid in the neighborhood of a free surface. Use is made of the general Lagally theorem. The general form of the solution is given and special cases are described.

Experimental Investigation of the Added Mass of Cylinders Oscillating Horizontally in a Free Surface. CHOU-CHEN WU. M.S. Thesis, August 1959; Professor Landweber, adviser. The cylinders involved in this study were of ogival section. The free-vibration method was used for determining their natural frequencies in air and water. From the difference of these two natural frequencies, the added-mass coefficients were obtained. Experimentally it was found that: (1) the added-mass coefficient for horizontal vibration is a complicated function of the Froude frequency number; (2) the results obtained from the flush ogive-shaped sections are more reliable than those from the circular cylinder at small and intermediate frequencies; and (3) at high frequencies the trend of both sets of data is toward the theoretical asymptotic values.

JETS

Pressure and Velocity Fluctuations in a Submerged Jet. S. REX CARR. M.S. Thesis, February 1958; Professor Rouse, adviser. An experimental investigation of the turbulence characteristics in the zone of flow establishment of an axisymmetrical jet of air is described. Both pressure and velocity characteristics of the turbulence were measured and their correlation studied. In addition to the hot-wire anemometer, a mechano-electronic pressure probe was used, and several head forms were checked for suitability as pressure-sensing devices.

Investigation of the Penetration of a Jet into a Counterflow. T. R. KRISHNA RAO. M.S. Thesis, February 1958; Professor Rouse, adviser.

A study of a high-velocity jet from a nozzle of small diameter directed upstream against a uniform flow was conducted in the 3x3x10-foot test section of an air tunnel. Measurements were made of the mean velocity through use of a Pitot cylinder, and of the turbulence through use of a hot-wire anemometer. A nondimensional plot of the mean-flow pattern, including the jet envelope, was obtained through use of the momentum flux from the nozzle as the sole jet parameter.

Studies of an Annular Jet in Proximity to the Ground with Ambient Velocity. SATYA PRAKASH GARG. M.S. Thesis, August 1959; Professor Mack, adviser. Experiments were conducted on an axisymmetric annular jet directed against a ground plate in a 3x3-foot air tunnel. The augmentation of lift (that is, the ratio of total lift on the nozzle to the momentum flux of the jet) was seen to increase with decreasing distance of the jet from the plate. The effect of ambient wind velocity was to cause a reduction in the augmentation. An analytical treatment of the effect of ambient wind was made and the experimental results were seen to follow the trend indicated by the analysis. The effect of jet mixing was also studied theoretically. (See Reprint 164.)

An Annular Jet Directed against a Nearby Water Surface. BEN-CHIE YEN. M.S. Thesis, August 1959; Professor Mack, adviser. The proximity of an annular air jet to a surface causes a rise in the pressure on the base of the nozzle and hence produces a lift force greater than that due to the jet momentum flux alone. When the nearby surface is liquid, this augmentation of lift is shown to depend on the momentum flux of the jet as well as on the relative altitude above the surface. Theoretical studies for both two-dimensional and axisymmetric cases are presented. Lift augmentations, base-pressure distributions, and water-surface configurations obtained experimentally for an axisymmetric nozzle are also discussed. (See Reprint 164.)

The Effect of a Free Surface upon the Velocity Distribution of a Submerged Jet. JAMES JOSEPH MROSS. M.S. Thesis, February 1960; Professor Hubbard, adviser. The velocity distribution was determined for free surfaces from 1.4 to 12 diameters above the jet center line, and was found to be generally described by the normal probability curve. Although the velocity profiles varied for low free surfaces, the kinetic-energy flux, the momentum flux, and the volume flux were found to be closely approximated by the equations derived by Dai (Reprint 88).

MODEL STUDIES

A Study of Flow from a Submerged Sluice Gate. HAROLD ROBERT HENRY. M.S. Thesis, February 1950; Professor Rouse, adviser. An investigation was undertaken at model scale to obtain the mean-flow and turbulence characteristics of a sharp-edged sluice gate operating at various degrees of submergence. A generalized diagram for the discharge coefficient as a function of opening and submergence ratios was prepared from the results of the experiments and was compared with impulse-momentum requirements. Measurements of the intensity of turbulence by means of the Appel tube were used to evaluate the energy changes from section to section. (See discussion by Henry in Reprint 88.)

Pressure Distribution on the Downstream Face of a Submerged Weir. MICHAEL BAR SHANY. M.S. Thesis, June 1950; Professor Alin, adviser. A determination was made of the pressure variation along the downstream face of a model of a low spillway operating under various degrees of submergence, in order to evaluate the magnitude of its contribution to the stability of the spillway structure. As a secondary aspect, discharge coefficients for various degrees of submergence were determined.

Modification of Pressure Distribution around Buildings due to Parapets. PHILIP S. NACY. M.S. Thesis, June 1951; Professor Howe, adviser. Flat-roofed building models with parapets of different heights were tested in an air tunnel, pressures being measured at various points on their surfaces in a continuation of a previous thesis by Chien, Feng, and Wang ("Pressure Distribution on Models of Three-Dimensional Buildings Exposed to Moving Air," 1948). The results were compared with those of the previous thesis by means of pressure-distribution contour maps. A large decrease in the intensity of negative pressure on the roof occurred as the result of the addition of a parapet, while only a slight effect was noted on the walls.

The Effect of Lip Angle upon Flow under a Tainter Gate. ARTHUR TOCH. M.S. Thesis, February 1952; Professor Metzler, adviser. Observations of various parameters of flow were made on a model Tainter gate of 1-foot radius r at various magnitudes of the gate opening b, trunnion height a, headwater elevation h, and tailwater elevation t. The experiments were conducted in a glass-walled flume, 1 foot wide, 2 feet deep, and 10 feet long. All measurements were re-

duced to three dimensionless diagrams showing the discharge coefficient C as a function of h/r, t/r, b/r, and a/r for both free and submerged efflux. (See *Trans. A.S.C.E.*, Vol. 120, 1955.)

Discharge Characteristics of a Tainter Gate on a Spillway. ZYNOWIJ M. GLOWIAK. M.S. Thesis, February 1955; Professor Metzler, adviser. The discharge coefficient and the pressure distribution along the spillway of a Tainter gate on a curved spillway for low dams were determined. The gate opening was held constant while the headwater depth, tailwater depth, trunnion height, and position of the lip of the gate relative to the spillway crest were varied. The discharge coefficient is presented graphically as a function of boundary geometry. A method of determining the discharge coefficient using the principles of continuity and conservation of energy along with simplifying assumptions is presented.

Relative Efficiency of Draft Tube Forms. BENOYENDRA CHANDA. M.S. Thesis, August 1955; Professor Howe, adviser. The relative efficiencies of conical and Prasil types of water-turbine draft tubes were compared experimentally. The performance was compared for radial inflow (0° whirl) at the entrance with the deflection plate at a distance equal to the inlet diameter of the tube. For both draft tubes it was found that the performance improved with decrease in the angle of flare. For short lengths, it was found that the Prasil tube was superior to the conical tube, but this superiority decreased as the length was increased and, finally, for the maximum length tested the Prasil tube was slightly inferior to the conical. The distance of the deflection plate from the end of a conical draft tube was found to have no influence on the efficiency for distances equal to or greater than the inlet diameter of the tube, but the efficiency decreased when the deflection-plate distance was reduced to less than the inlet diameter.

Pressure Distribution on Flashboards. ERNESTO D. BACCI. M.S. Thesis, February 1956; Professor Howe, adviser. The distribution of pressure on both sides of a flashboard was determined for different conditions of head over the spillway crest, height of flashboard, tailwater elevation, and downstream-apron inclination. The tests were run in a channel 25 feet long and 1 foot wide. The model was located 11¾ feet downstream from the stilling tank. It consisted of a flashboard made of brass 4 inches high, 1 foot wide, and ¼ inch thick, supported on a spillway with a movable downstream apron. Pressures on the flashboard were measured with seven piezometers on each

face. The spillway model was 8 inches high; the upstream part of the crest profile had the form of a quarter ellipse. The downstream face was hinged to the high point of the ellipse, so that inclinations of 60°, 45°, 30°, and 0° with the horizontal were obtained. Heads over the spillway crest of 1.5, 2, 2.5, 3, and 4 times the flashboard height were tested. The results are shown in graphs, the net moment on the flashboard being plotted against the submergence ratio for different heads on the spillway crest for each of the four apron inclinations. The net moment on a flashboard depends upon the head, the tailwater depth, and the downstream-apron inclination. The moment is maximum when there is no tailwater influence and decreases with increasing submergence.

Discharge Characteristics of Low Weirs and Sills. P. K. KANDASWAMY. M.S. Thesis, February 1957; Professor Rouse, adviser. The discharge coefficient and the nappe profiles were determined experimentally for relatively low weir heights. The data of the present investigation together with those obtained by Rouse at M.I.T. are presented to define the discharge coefficient and the surface profiles for the entire range from zero to infinity of the ratio of head to weir height. (See Reprint 160.)

Comparison of Efficiencies of Axial Flow Draft Tubes. SHIEH-WEN MAO. M.S. Thesis, February 1957; Professor Howe, adviser. This investigation, a continuation of the work of Chanda, compares the relative efficiencies of four types of axial-flow draft tubes, namely, conical, Prasil, White, and Moody, under an identical experimental setup with similar flow conditions at the entrance, identical surface roughness, and the same ratio of inlet and outlet areas for all the tubes. Three lengths of each type of tube were tested without model runner, and the whirl into the draft tube was introduced by movable guide vanes. The relative performances of axial-flow draft tubes were compared for various lengths as well as various whirls.

The Effect of Relative Height of Model Buildings upon Wind Pressure Distribution. WILLIAM S. HARTLEY. M.S. Thesis, August 1958; Professor Howe, adviser. Tests were made on models of buildings in which the cross section was held constant and the height was varied. Pressures using the dimensionless parameter $\Delta p/(\rho V^2/2)$ were referred to an ambient velocity at a section in line with the front face of the model. Angles of attack of 0° and 45° were used on models with square cross section and height-to-depth ratios ranging from 1 to 6.

An angle of attack of 0° was used on models with a width of twice the depth and the height-to-depth ratio ranging from 1 to 6.

Effects of Eaves on Pressure Distribution around Model Buildings. J. V. NAGARAJA. M.S. Thesis, June 1959; Professor Howe, adviser. The problem of the evaluation of pressure distribution around model buildings with eaves is analyzed with geometrically similar angular models on the assumption that dynamic similarity exists when the flow pattern around the buildings is reproduced in the experiments. The dimensionless parameter $\Delta p/(\rho V^2/2)$ at various piezometer points on the surface of the building models was evaluated with reference to a predetermined piezometer location on the floor of the air tunnel. Pressure-intensity analysis was conducted for two types of models, one with flat roof and the other with a gable roof at an angle of 45°. The ratio between the eave width and the height of the model varied from zero to ¼ in steps of 1/12. The isopiestics for angles of attack of 0°, 45°, and 90° indicate that the eaves reduce the negative pressure intensity on the leeward wall and increase the negative pressure on the roof.

Moments on a Flashboard. ALAN H. SCHULTZ. M.S. Thesis, August 1959; Professor Howe, adviser. This investigation was performed as an independent check of the results of an earlier thesis by Bacci. The net moment on a flashboard was measured with a balance scale for various conditions of head, tailwater depth, and downstream-apron inclination. The results, as graphically represented, indicate that the maximum moment on a flashboard will occur when the tailwater is low, the downstream apron is steeply inclined, and the head on the flashboard is a maximum. This investigation arrives at a means of designing flashboards to meet operational requirements.

OPEN-CHANNEL FLOW

A Study of Meanders. CEZAR P. NUGUID. M.S. Thesis, August 1950; Professor Posey, adviser. Field measurements were made of meandering streams in the vicinity of Iowa City, Iowa. A length-measuring device was developed which served very well for the measurement of the talweg of the streams, readings being taken during the winter when the streams were ice covered and easily accessible. From qualitative observations an attempt was made to evaluate the variables numerically. Among others, the following conclusions were drawn: (1) that a stream tends to maintain an equilibrium slope

within its system, resulting in meandering; (2) that true meandering streams may be considered as graded streams for practical engineering purposes; (3) that irregularities in meander patterns are due to local changes in alignment caused by nonuniform bank conditions; and (4) that it is possible to obtain a quantitative relation between discharge, size of bed material, and slope.

Effect of the Submergence of the Stilling Basin Sidewalls on the Hydraulic Jump. STAVROS NICOLAOU. M.S. Thesis, August 1951; Professors Howe and Alin, advisers. An experimental investigation of the effects of submergence of the sidewalls of a stilling basin on the downstream elevation of the hydraulic jump was made in a rectangular flume 2.5 feet wide. Three different channel widths and several wall heights were tested. It was found that flow returning over the sidewalls along their upstream length appreciably decreased the downstream depth of the hydraulic jump, and quantitative values were determined for the range of variables studied.

Effect of the Reduction of Stilling Basin Sidewalls on Tailwater Elevations in the Basin. JOHN R. SHEPPARD. M.S. Thesis, June 1953; Professors Alin and Howe, advisers. As a continuation of the work of Nicolaou, an experimental study to determine the feasibility of reducing both the height of the sidewalls and the depth of excavation for the bottom of a stilling basin was made. Such reductions were found to be possible because of the effect of the overflow from the sidewalls onto the jump in reducing the downstream depth of the jump. Results of both this and the previous investigation were plotted as a composite figure which shows the effect of four dimensionless parameters of the stilling basin on the hydraulic jump under conditions of backflow over the top of the sidewalls.

Oscillatory Gravity Waves in Flowing Water. TURGUT SARPKAYA. Ph.D. Dissertation, June 1954; Professor Yih, adviser. The conditions of stability of progressive oscillatory gravity waves in flowing water were investigated, and an evaluation of the influence of various characteristics of flowing water on the velocity of propagation of stable waves was effected by making a comparison of the experimental results with those obtained from the available theories, particularly those of Stokes and Struik. The following conclusions were reached: (1) for a given flow, there is only one neutrally stable wave; (2) the celerity of a stable ascendant wave in flowing water is smaller than that obtained from the theories of Stokes and Struik, and the

celerity decreases slightly with increasing wave steepness; (3) the deviation of the measured wave velocity from that obtained from potential theory increases with increasing Froude numbers and decreases with increasing Reynolds numbers; and (4) for a channel with an artificially roughened bottom the deviation is greater than the corresponding one in a channel with a smooth bottom.

Lowering of Channel Entrance Grade Line to Increase Discharge. CHUAN-CHUNG CHANG. M.S. Thesis, February 1957; Professor Posey, adviser. A study was made of the increase of discharge delivered into a channel leading from a reservoir as a result of deepening the entrance reach to form a transition of uniform gradient. By use of numerical calculations, it was found that the horizontally excavated transition provides the maximum increase of discharge for a given amount of excavation. The relation of the increase of discharge to the geometry of the deepened transition was determined, and the effect of channel condition on the increased flow ascertained. Charts which will facilitate the solution of practical problems, together with a numerical example, are presented.

Study of Backwater Curves in a Triangular Channel. KRISHAN PIARA SINGH. M.S. Thesis, August 1958; Professor Posey, adviser. Use is made of data from experiments conducted on the right-angled-triangular flume at Rocky Mountain Hydraulic Laboratory for the purpose of investigating friction losses in open channels, using different artificial roughnesses. The equation of gradually varied flow for the triangular channel has been derived and tables compiled for evaluating the required integral function. A brief discussion of the various existing methods for computing backwater curves is also included. The value of Manning's roughness factor, as obtained for the normal flow for a particular discharge and bottom slope, has been used for all the backwater curves for the same discharge and bottom slope. It has been assumed that the energy loss through friction, at a given section, is the same in nonuniform flow as it would be for uniform flow at the depth of flow existing at that section. The computed water-surface profiles for *M1*, *M2*, *M3*, *S1*, *S2*, and *S3* curves fit the observed profiles very well, thus supporting the validity of the assumptions made.

Optimum Shape of a 90° Bend in a Rectangular Channel. CARL E. DENZLER. M.S. Thesis, February 1960; Professor Howe, adviser. An effective method of reducing head loss in 90° bends in rectangular channels is to widen the inside of the bend by increasing the inside

radius. For a particular bend having a center-line radius-to-width ratio of 4.5, the bend having minimum head loss had a maximum-width-to-entrance-width ratio of 1.38. The experimental channel was 6 inches wide and had a total length of 66 feet.

SEDIMENTATION

An Investigation of the Effect of Bridge-Pier Shape on the Relative Depth of Scour. DOUGLAS E. SCHNEIBLE. M.S. Thesis, June 1951; Professor Rouse, adviser. Results of tests made on various shapes of pier and on various scour arresters used as adjuncts to the pier are discussed as part of an experimental investigation on the bridge-scour problem conducted for the Iowa State Highway Commission and the U.S. Bureau of Public Roads. Reductions obtained in relative depth of scour, referred to a basic pier, were as great as 25 per cent for a pier with an elongated right section and 50 per cent for a scour arrester properly located on the basic pier. (See Reprints 107 and 120.)

Protection of Earth Embankments by Riprap of Uniform Size. JOSE O. DE ABREU LIMA and WILLIAM B. MORGAN. M.S. Thesis, August 1951; Professors Posey and Metzler, advisers. The effects of shape, size, and thickness of riprap of a uniform size on the protection of a horizontal sand bed against horizontal flow were investigated, with a view toward extension to the protection of embankments. Two shapes of riprap, two sizes for each shape, and four thicknesses for each size were studied. Results indicate that the shape has no noticeable effect, the size determining the protective quality for a given thickness. The results also indicate that riprap of uniform size would not be practicable, since only a small increase in the velocity requires a large increase in thickness of riprap to prevent failure.

The Effect of Sand-Trap Proportions on the Efficiency of Operation. ALY BALIGH. M.S. Thesis, August 1951; Professor Rouse, adviser. An experimental investigation of a two-dimensional model of a sand trap showed that the efficiency of two-dimensional traps is dependent upon the ratio of the length of the trap to the depth of the oncoming flow and the ratio of the fall velocity of the sediment particles to the velocity of the oncoming flow. Results were plotted as dimensionless curves, relating the trap efficiency to the length and velocity ratios, the length ratios investigated being ¼, 1, and 4, and the velocity ratios ranging from 0.12 to 20. (See Special Publications.)

A Study of the Transportation of Sand in Pipes. JOHN PINNA CRAVEN. Ph.D. Dissertation, August 1951; Professor Rouse, adviser. An experimental investigation was conducted to determine the parameters and functional relationships which describe the movement of sediment in pipes flowing full. A mathematical expression for the piezometric gradient was derived from an examination of existing bed-load equations. Introduction of the Darcy-Weisbach equation furnished a functional relationship for the ratio of the volume of sediment in the pipe to the volume of the pipe. Analysis of the mechanics of movement provided additional relationships for the limiting values of the piezometric gradient and the obstructed-volume ratio. The experimental program was planned so that these relationships could be determined. The experimental results indicate that the transport phenomenon can be divided into three regimes: that for which the piezometric gradient is governed by the transport-discharge ratio; a transition region; and that for which the piezometric gradient is independent of the transport-discharge ratio and dependent on the properties of flow, the roughness of the boundary, and the critical shear of the sand bed. (See Reprint 121.)

The Transportation of Uniform Sand in a Smooth Pipe. HARRY H. AMBROSE. Ph.D. Dissertation, June 1952; Professor Rouse, adviser. The purpose of this study was to identify the parameters which govern the transport of sand in pipes and to determine their functional relationship. As an extension of the dissertation by Craven, tests were performed in a single plastic pipe of variable slope with three sizes of sediment ranging from fine to very coarse sand. The rates of sand and water discharge, slope, and geometry of the bed and flow were measured by specially designed equipment. Investigation was made of conditions for full-pipe flow and for free-surface discharge, both with and without an inert sand bed. The results were reduced to three generalized functions of practical use in designing drainage systems. (See Reprint 121.)

Tests of Graded Riprap for Protection of Erosible Material. HENRY DE SILVA MANAMPERI. M.S. Thesis, June 1952; Professor Posey, adviser. Investigations were made to determine (1) the velocities of overflow at which a sand bed would be disturbed when protected by various thicknesses of uniformly graded round gravel, the flow approaching the test section over both a smooth and a rough channel bottom, and (2) the protective qualities of crushed-stone layers sat-

isfying the Terzaghi-Vicksburg criteria for effective filter blankets. Results indicate that the velocities of failure are higher with a rough bottom than with a smooth bottom and that a properly graded blanket material gives satisfactory protection to a sand bed subject to overflow or to a combination of overflow and upward flow through the blanket.

Efficiency of Short Sand Traps. RASIN Z. ETIMAN. M.S. Thesis, February 1953; Professor McNown, adviser. The purpose of this study was to determine the effect of trap dimensions and of flow characteristics on the efficiency of operation of short sand traps. Flow under pressure was adopted to eliminate the effects of a free surface. Two- and three-dimensional traps with sand of a uniform size and sand of a nonuniform size were investigated. The approach conditions were found to have a significant effect on the efficiency of the trap, and recommendations for improvement of the approach are made. The variables affecting the flow are expressed in the form of dimensionless parameters, and performance curves are presented for direct use. (See Special Publications.)

Initial Bed-Load Movement Caused by a System of Periodic Standing Waves. JOHN M. F. ROGERS. M.S. Thesis, February 1953; Professor McNown, adviser. An introductory study of the initial movement of sand in flow free from turbulence was made using a system of periodic standing waves established in a rectangular tank of water. Four different sand types were used as the bed load to determine the effects of particle spacing, grain size, and shape on the velocity required to initiate movement. The following conclusions, based on arbitrary definitions of both initial movement and characteristic flow velocity, were reached: (1) the velocity required to initiate movement in a given sand is between 60 and 74 per cent of the mean fall velocity; (2) particle shape is an important factor governing the movement of isolated grains; (3) there is a possibility that the particle characteristics of grain size, shape, and spacing can be considered together in a function to describe the velocity at which movement is initiated; and (4) an analysis of the forces causing the movement of a typical particle on a smooth surface shows that viscosity is the dominant fluid property.

Transportation of Sand in a Pipe. H. RUPERT VALLENTINE. M.S. Thesis, June 1953; Professor McNown, adviser. The objectives of this thesis—the third of a series of studies of bed-load transportation in

a circular conduit—were to extend the previous investigations in order to determine: (1) for free-surface flow in a smooth pipe, the effect upon the flow of the presence of bed loads of uniform sands at such low relative transport rates that deposition does not occur; and (2) whether nonuniform sands yielded head-loss and blockage relationships comparable with those previously found for uniform sands. Tests results indicate, at least within the range of the experiments, that the presence of bed load in such small quantities that deposition does not take place will have negligible effects on the hydraulic design of a piping system, and that the phenomena associated with the bed-load transportation of nonuniform sands are similar to those previously observed with uniform sands. (See Reprint 121.)

An Instrument for Rapid Size-Frequency Analysis of Sediment. DAVID W. APPEL. Ph.D. Dissertation, August 1953; Professor McNown, adviser. A rapid method for obtaining a size-frequency distribution was developed by using a sensitive pressure transducer and an automatic recorder. Changes in concentration of a stratified sediment sample falling in suspension cause minute pressure differences which upon conversion, by means of a transducer, to an electric signal are amplified and transmitted to a pen recorder. By this method, size-frequency curves may be obtained automatically, thereby reducing the time necessary for tabulating the percentage finer for particular sediment sizes. When a traversing sensing element is used the time required for making an analysis is further reduced. The results of this method are compared to those obtained by the bottom-withdrawal method. (See Reprint 122.)

Exploratory Study of the Measurement of the Suspended Sediment Characteristics by Sonic Means. CAY G. WEINEL, JR. M.S. Thesis, August 1953; Professor McNown, adviser. A study was made to determine whether characteristics of suspended sediment could be evaluated by the measurement of the attenuation of sound waves passing through the suspension, and the various existing theoretical analyses of the problem were collected and compared. In a laboratory experiment using glass beads, the effects on the sound attenuation of variation of the sound frequency and the concentration, size, and size distribution of the sediment were studied. Although this investigation showed that the individual characteristics of a sediment suspension can be evaluated qualitatively by a simultaneous solution of measurements made at three sound frequencies, further refinements in the

equipment will be required before quantitative measurements can be made.

The Total Sediment Load of Streams. EMMETT M. LAURSEN. Ph.D. Dissertation, February 1958; Professor Rouse, adviser. Although a rigorous analysis of the general problem of sediment transportation is not yet possible, by means of a descriptive analysis the various factors involved were isolated and the relationships among them qualitatively indicated. Parameters linking the hydraulic characteristics of the flow and the characteristics of the bed material were then formed through the use of appropriate approximations. The relationships between these parameters, however, could only be defined empirically. The experimental data which were used for this purpose included original experiments conducted at the Iowa Institute of Hydraulic Research and published data from other sources. Empirical curves were drawn for the total, suspended, and bed loads, and a computation procedure devised to consider the nonuniformity of the bed material. The correlation of laboratory data which was finally achieved was good considering the probable errors of the measurements. The proposed relationships were also used to predict the sediment-transporting characteristics of three natural streams with encouraging results. (See Reprint 165.)

Riprap Protection against Scour around Bridge Piers. NELSON LUIZ DE SOUSA PINTO. M.S. Thesis, August 1959; Professor Posey, adviser. Riprap protection against erosion around a 0.3-foot-diameter circular pier was studied. Horizontal circular layers of riprap having "filter" grading with respect to the sand bed were used as the protective device. Different diameters of layers and levels of emplacement were tested and a correlation was obtained between the necessary size of the protection and the dimensions of the unprotected scour hole. An exploratory study of possible modifications on the design of the protective layer was undertaken. Comment on model-prototype conformity for the rock size tested is also presented. (See Sousa Pinto, N. L., Sybert, J. H., and Posey, C. J., "Model Tests of Riprap Scour Protection," Rocky Mountain Hydraulic Laboratory Publication No. 23, 1959.)

Scour at Relief Bridges. ROBERT C. STIEFEL. M.S. Thesis, August 1959; Professor Brush, adviser. A laboratory study of the final or equilibrium depth of scour expected at a bridge abutment for the case of clear-water scour was made. Qualitative results showing the effects

of velocity, geometry, and particle size are presented. The results are compared to conditions where scour occurs while sediment is being supplied to the scour hole and a measure of the increased depth of scour due to clear-water conditions is made. No field verification is included.

STRATIFIED FLOW

Simultaneous Flows of Air and Water in a Closed Flume. TEMEL H. ORGA. Ph.D. Dissertation, June 1953; Professor McNown, adviser. Various theoretical studies of the formation and propagation of waves by wind were reviewed, and laboratory tests were made to verify, if possible, the theories. The variables that affect the characteristics of waves generated by wind action on both still and flowing water were studied, and an evaluation was made of the mutual interaction of surface waves and surface drag, and of the dependence of these on parameters or characteristics of the flow and the fluids. The effects of an oil film on waves and the stability of gravel breakwaters under the action of both gravity and wind-generated waves were also investigated.

Internal Hydraulic Jump in a Two-Layer Fluid System. CHITTA R. GUHA. M.S. Thesis, February 1954; Professor Yih, adviser. The purpose of this investigation was to determine experimentally the physical characteristics of flow of a two-layer fluid system with one layer moving and the other at rest. Whereas an analysis based on the continuity and momentum relationships—neglecting the effect of shear—indicates that the ratio of downstream and upstream depths of the moving layer depends upon a modified Froude number alone, the results from systematic tests showed that this ratio depends on not only a Froude number, but also on the density ratio explicitly. Deviation of the experimental depth ratio from its theoretical value was found to increase with increasing density ratio for the same modified Froude number within the experimental range. This deviation was shown to be due mainly to interfacial shear. (See Reprint 137.)

An Investigation of Recirculation in Stratified Flows. GEZA L. BATA. M.S. Thesis, August 1956; Professor Yih, adviser. The momentum balance of stratified flows, including the effect of interfacial shear, is analyzed theoretically and the results are compared with two-dimensional experiments. To simulate the flow near a thermoelectric plant, a portion of the water flowing in a concrete flume of

rectangular cross section was removed at the bottom by means of a slot. The same amount of water, after being heated with steam, was returned to the canal farther downstream. The resulting characteristics of flow, including the amount of recirculation, were measured and shown to agree satisfactorily with predicted values. (See Reprint 153.)

Flow toward a Pipe in a Stratified Fluid. CHARLES O. MEYER. M.S. Thesis, February 1958; Professor Rouse, adviser. This is an experimental investigation of the relationships of the variables pertaining to flow toward a pipe in a two-layered stratified fluid (fresh and salt water). The ratio of the lower-stratum flow to the total flow is shown to depend upon five parameters: the Froude number, and four ratios of outlet dimensions. Pipe sizes tested ranged from ⅛ inch to 1½ inches in diameter. The results are extrapolated to obtain a solution for a point sink in a stratified fluid. An existing method is used to obtain a theoretical solution for the point sink; the solution is in agreement with the experimental result.

Irrotational Motion of Two Fluid Strata towards a Line Sink. DAVID GRANT HUBER. Ph.D. Dissertation, August 1958; Professor Rouse, adviser. The irrotational motion of two fluid strata of equal depth towards a line sink located in the lower corner of a rectangular configuration extending to infinity in the upstream direction is shown to be governed by a unique relationship between the Froude numbers for the two strata. These Froude numbers are calculated at infinity and include in the denominator the ratio of the difference in densities to the density in the appropriate stratum. A numerical value for the critical Froude number in the lower stratum at which the upper fluid either begins or ceases to flow is obtained and it is shown that the Froude numbers approach each other in value as the rates of flow become large and inertial effects predominate. The angle of the interface at the sink and the streamline pattern are shown to be dependent on the value of the Froude number in the upper stratum. The points which were plotted to give the pertinent relationships were obtained by a relaxation process.

SURFACE AND FORM RESISTANCE

Effect of a Cylindrical Boundary on the Drag of Spheres. JOHN TERHUNE NEWLIN. M.S. Thesis, August 1950; Professor McNown, adviser. In an experimental investigation conducted with air flowing

past spheres fixed on the axes of cylindrical tubes, the coefficient of drag for the spheres was determined from measurements of the distribution of pressure around the spheres. Sphere-to-cylinder diameter ratios from zero to 0.9 were investigated for Reynolds numbers between 10^4 and 10^5. An approximate theoretical expression gave results which coincided with those observed for values of the diameter ratio greater than 0.75. These results extended those obtained in previous experiments using falling spheres. (See Reprints 81 and 113.)

Drag Coefficients of Multiple Plates as a Function of Solidity Ratio. TIEN-TO SIAO. M.S. Thesis, August 1950; Professor Rouse, adviser. Tests of composite plates of three series—squares, rings, and screens—were conducted in the low-speed air tunnel of the Institute. Drag forces were measured directly by means of an external beam balance. While each of the composite plates was symmetrical, for each series they were varied by changing the solidity ratio S and the number n of the constituent parts. A third geometric parameter b/s (the ratio of the width to the center-to-center spacing of the constituent parts), which is dependent on S and n, was also used. The test results of each series were plotted in curves giving at once the relation of the drag coefficient and the three geometric parameters. It was found, moreover, that some surfaces of constant solid area produced a greater drag when subdivided than when intact. (See discussion by Siao in Reprint 94, and Reprint 134.)

An Experimental Investigation of the Boundary-Layer Development along a Rough Surface. WALTER L. MOORE. Ph.D. Dissertation, August 1951; Professor Rouse, adviser. As a continuation of the initial boundary-layer study by Baines (see Special Publications), experiments were performed in the air tunnel on a flat surface roughened with transverse bars under conditions of zero pressure gradient. The same geometric form was produced at three different scales, covering a 12-fold variation in absolute size. Velocity profiles were taken and compared with those obtained by other investigators. The values of the surface-resistance coefficient determined from measurement were compared with those predicted analytically. The velocity distribution for the boundary layer along the three surfaces was found to differ significantly from that for a conduit, though expressible in terms of similar parameters. The surface-resistance coefficient was in poor agreement with that predicted by the von Kármán relation, but approximated that predicted by the Schlichting equation; however, a

significant deviation, depending on the absolute size of the roughness, was apparent. (See Reprint 124.)

Drag Tests on Cylinders Arranged in a Straight Grid. CLARK G. DEHAVEN. M.S. Thesis, June 1953; Professor McNown, adviser. An experimental and analytical study was made of the pressure distribution about evenly spaced cylinders in two-dimensional flow. The experiments were confined to Reynolds numbers above the upper critical zone, and an eightfold variation in spacing ratios was covered. Dimensionless curves of the drag coefficients—obtained by graphical integration of measured pressure distributions—are presented.

Flow Past a Normal Plate in Contact with a Boundary. MIKIO ARIE. M.S. Thesis, August 1955; Professor Rouse, adviser. Measurements of the velocity, pressure, and turbulence behind a series of normal plates in the uniform test section of an air tunnel are described, the oscillation of the wake being prevented in all but one test through use of symmetrically located tail plates. By a combination of experimental and computational techniques, details of the pattern of flow over a wall on a plane boundary in an infinite fluid are closely approximated. A significant difference is indicated between the mean characteristics of such a flow and those of the flow past an isolated plate with oscillating wake. (See Reprint 147.)

The Effect of Free-Surface Instability on Channel Resistance. HERMAN J. KOLOSEUS. Ph.D. Dissertation, August 1958; Professor Rouse, adviser. Most previous investigations of open-channel resistance were based on experiments with either subcritical flow or flow for which the Froude number was equal to or slightly greater than one; they show the relationships between the pertinent parameters to be similar to those for pipes as found by Nikuradse. To investigate the possibility that pipe and channel flow may also be dissimilar under certain circumstances because of the imminent instability due to the presence of the free surface in open channels is the purpose of the present study of supercritical flow in a rough flume. Following the procedure of Jeffreys, a stability criterion for turbulent gradually varied unsteady open-channel flow was formulated. For all practical purposes the flow could be regarded as stable when the Froude number was less than 1.6 and unstable when it was greater. A tiltable flume, 2 feet wide and 30 feet long, was used for the experimental work; brass cubes, 3/16 inch on a side, were employed as the roughness

elements. The depth was measured by means of a specially designed vibrating-needle point gage. The experimental data indicated that the resistance coefficient was independent of the Froude number when the flow was stable, depending only upon the relative roughness and the roughness concentration. The form of the law of resistance was identical with that found by Nikuradse for rough pipes and agreed with the expression advocated by Keulegan for two-dimensional open-channel flow. When the flow was unstable, the resistance coefficient was a function of not only the channel and roughness geometry but also the Froude number; specifically, it varied as the ratio of the relative roughness to the Froude number.

Roll Damping due to Bilge Keels. MILTON MARTIN. Ph.D. Dissertation, June 1959; Professor Landweber, adviser. The high degree of effectiveness of bilge keels in damping the roll of ships at zero and low speeds is shown to be due to the exceptionally high values of drag coefficients resulting from the oscillatory motion. Measurements of the mean drag coefficient of oscillating flat plates of infinite length-width ratio show that this coefficient varies considerably with the dimensionless oscillation amplitude X_0/b, where X_0 is the amplitude of oscillation and b is the half width of the plate, from 13 at $X_0/b=0.2$ to 3.4 at $X_0/b=9$ and presumably must approach the steady value of 1.9 at very large values of X_0/b. The high drag coefficients at small values of oscillation amplitude are attributed to that part of the low pressures associated with the initial growth of vortices at the plate edges in phase with the plate velocity. Photographs showing the vortices becoming detached and moving laterally away from the edges of the oscillating plate presumably depict the manner in which the damping energy is transmitted from the plate to the fluid. In order to explain the effectiveness of bilge keels on roll damping underway, the bilge keel is treated as a wing of very low aspect ratio. An expression, derived for the nonlinear part of the lift curve for wings of very low aspect ratio, is shown to agree well with existing data. Application of this expression to the prediction of roll damping underway due to bilge keels yields extinction curves somewhat lower than measurements. The results of computations of the relative contributions to roll damping from frictional resistance, eddy making, and wave making for twenty ship models are also presented.

Experimental Investigation of Ursell's Theory of Wave Making by a Rolling Ship. W. CURTIS MCLEOD. M.S. Thesis, June 1959; Pro-

fessor Landweber, adviser. Measurements were made of the surface waves produced by two different cross sections of ship hulls and comparisons made to the analytical predictions of Ursell. The experimental equipment consisted of two 9-foot-long constant-cross-section models which were rolled about a fixed axis in the waterplane by means of a mechanical oscillator. The oscillator permitted constancy of the roll angle during the time of wave measurements at any desired angle between 0 and 17 degrees. Roll angles and model periods were obtained by using a gyro-transmitter; wave measurements were taken by means of a vibrating needle. The most significant conclusion was that by varying the hull cross section the ratio of wave energy to total model energy lost per cycle could be appreciably changed. The energy-ratio variation with roll angle is given for both models studied.

TURBULENCE

(The following thesis was inadvertently omitted from Bulletin 33, *Third Decade of Hydraulics at the State University of Iowa,* 1949.)

Diffusion Characteristics of Turbulence in an Open Channel. JAMES M. ROBERTSON. M.S. Thesis, January 1940; Professor Kalinske, adviser. Measurements were made of the diffusive power of turbulence by direct experimental means, using motion-picture photography of particles suspended in the flow. The diffusion coefficient was found to vary from zero at the channel bottom, through a maximum at about half depth, returning to zero at the surface. The variation through the vertical of the root-mean-square values of two of the three fluctuating velocity components was determined, as was the variation in the length scale of the turbulence. Some studies also were made of the transverse horizontal diffusion near the surface of the water. (See Reprint 26.)

Characteristics of Mean Flow and Turbulence at an Abrupt Two-Dimensional Expansion. HSIEH-CHING HSU. Ph.D. Dissertation, February 1950; Professor Rouse, adviser. This study was undertaken for the purpose of tracing the energy changes at an abrupt two-dimensional flow expansion. The experiments were made just beyond the bell inlet of a rectangular air tunnel. Pressure intensities were measured by means of wall piezometers, the longitudinal component of the mean velocity with a Pitot tube, and the components of turbulence with a hot-wire anemometer. The energy equation for the mean and the secondary motion was integrated to indicate the change of the

various terms in the longitudinal direction. It was found that the viscous dissipation of the mean motion and the energy transferred to turbulence are small, in comparison with the total loss, except near the boundaries and in the initial section of the expansion. The rate at which energy is supplied by the mean motion is high near the initial section, drops rather rapidly, rises a little near the section where the stable eddy ends, and approaches a constant value thereafter. The dissipation rate, following a different trend, is small at the beginning, reaches a maximum near the mid-length of the eddy, and gradually drops toward a constant limit.

Gravitational Convection from Line Sources. HAROLD W. HUMPHREYS. M.S. Thesis, February 1950; Professor Rouse, adviser. The distributions of mean velocity and temperature were measured in the zone of turbulent convection above single and parallel line sources of heat located on a horizontal boundary. All data were reduced to a dimensionless form satisfying the basic momentum equation and the hypothesis of similarity. The results obtained are directly applicable to the problem of fog dispersal over airfields and may also be of value in such widely varied fields as meteorology, chemical engineering, and oceanography. (See Reprint 110.)

An Exploratory Investigation of Boundary-Layer Development on Smooth and Rough Surfaces. WILLIAM DOUGLAS BAINES. Ph.D. Dissertation, August 1950; Professor Rouse, adviser. The object of this study was to conduct and evaluate the results of preliminary tests on turbulent flow along smooth and rough boundaries, for use in planning long-range investigations of this subject in connection with resistance of ship hulls. The measurements involved the determination of velocity and turbulence distribution in the boundary layer along a plane surface suspended in an air tunnel. The most important characteristic of the flow, the drag of the surface, was computed from the velocity measurements through use of the momentum equation. One size of granular roughness was used in the rough-surface experiments and the relative roughness was varied by changing the velocity of the flow and the effective length of the surface. (See Special Publications.)

The Development of the Turbulent Boundary Layer on Steep Slopes. WILLIAM JOHN BAUER. Ph.D. Dissertation, August 1951; Professor Rouse, adviser. Development of the boundary layer on steep slopes controls not only the loss of head but also the onset of air

entrainment; the ability to predict its rate of growth is therefore essential to proper spillway design. This dissertation describes a laboratory investigation of the variation in velocity distribution on smooth and rough channel beds for a series of slopes and rates of discharge. The boundary-layer thickness, the coefficient of local resistance, and the parametric shape of the velocity profile are analyzed as functions of the Reynolds number and the relative roughness. These functions are shown to be in accordance with general boundary-layer theory, and essentially independent of both slope and discharge. A practical method is then proposed for computing the limit of boundary-layer development on concrete spillways. (See *Trans. A.S.C.E.*, Vol. 119, 1954.)

Characteristics of Turbulence in an Air-Flow Model of the Hydraulic Jump. TIEN-TO SIAO. Ph.D. Dissertation, June 1954; Professor Rouse, adviser. Because of the difficulties of measuring the characteristics of turbulence in the water of an actual hydraulic jump, an air duct with an adjustable boundary was constructed to simulate a hydraulic jump in a rectangular channel, and the pertinent measurements were made with air as the fluid medium. Through use of a symmetrical two-legged stagnation tube, the mean values of the fluctuating velocities were measured in both the actual hydraulic jump and its air-flow model for a Froude number of 4. The mean-flow patterns of the actual and the simulated jump at this Froude number were nearly identical, thus indicating that the details of the phenomenon could be studied with good approximation in an air duct. Measurements of pertinent turbulence characteristics were then carried out in the air duct with the hot-wire anemometer. Finally, the momentum balance, the mean-energy balance, and the turbulent-energy balance over the entire length of the model jump were evaluated. (See Reprint 157.)

Diffusion of Turbulence from Piers and Abutments of Spillways. LUIS FERNANDEZ-RENAU. M.S. Thesis, August 1954; Professor Rouse, adviser. The object of this investigation was to determine the manner in which turbulence diffuses from piers and abutments of spillways in order to locate zones of possible air entrainment. The turbulent boundary layer developing from spray walls and turbulent wakes behind spillway piers and rods projecting from the channel bottom were delineated by following the oscillations of the mercury in an open manometer connected to a stagnation tube. Additional

qualitative information concerning the afore-mentioned zones of turbulent flow is presented.

The Mechanism of Energy Dissipation in the Hydraulic Jump. S. NAGARATNAM. M.S. Thesis, June 1957; Professor Rouse, adviser. As a supplement to Siao's dissertation, the diffusion of turbulence and the energy dissipation due to turbulence were investigated in an air-duct model of the hydraulic jump for Froude numbers of 2 and 6. It was found as before that the production of turbulent energy is concentrated along the interface between the expanding jet and the roller; and the major portion of the production and dissipation of the turbulent energy occurs before the end of the roller. Trends of the various characteristics with Froude number are presented. (See Reprint 157.)

Decay of Turbulent Wakes behind a Propeller. GERT ARON. M.S. Thesis, February 1960; Professor Hubbard, adviser. The rates of decay of mean and turbulent velocities, dissipation of mean-flow energy, and radial expansion of the wake with respect to downstream distances from the propeller were investigated in a towing tank. Dimensionless parameters were used in the graphical presentation of experimental data and results.

UNCLASSIFIED

Evaluation of Unconfined Flow to Multiple Wells by the Membrane Analogy. VAUGHN E. HANSEN. Ph.D. Dissertation, June 1949; Professor Rouse, adviser. Tests were conducted on single and multiple wells, using unconfined sand models, to obtain information on the shape of the free surface of the water table near the well. After the free surface was corrected for the effects of capillary rise by use of flow-net principles, it was found that the surface could be approximated by a linear logarithmic function similar to that for confined flow. From these data dimensionless plots of boundary conditions in the vicinity of the well were made. With the boundary conditions at the well thus defined and the free surface near the well following a straight-line logarithmic function, a study was made of a thin rubber membrane to ascertain its feasibility as a model to solve complicated problems of multiple-well flow. When allowance was made for the limitations imposed by gravity and surface tension, the membrane gave the piezometric surface for confined flow and the free surface for unconfined flow from the zone of departure from the Dupuit

curve to the well. Ease of construction, the variety of problems which may be solved, and the visual demonstration of the piezometric surface—all make this method of considerable practical value. (See *Trans. A.S.C.E.*, Vol. 118, 1953.)

Experimental Investigation of the Discharge Coefficient for a Rectangular Side Weir. RUSSELL JORDAN KENNEDY. M.S. Thesis, August 1949; Professor McNown, adviser. Variation of the discharge coefficient of a side weir was investigated for various channel and weir geometries and for Froude numbers between 0.1 and 0.7. A flume of rectangular cross section and a level side weir set into one wall were used throughout the laboratory investigation. The geometries selected for testing corresponded more closely to those found in water-supply and sewage systems than to those sometimes used for spillway sections in large dams. The tests were restricted to sharp-edged weirs. A significant variation in discharge coefficient was observed for the range of Froude numbers between 0.3 and 0.7, and for still higher values an unstable and partial hydraulic jump was observed in the immediate vicinity of the weir. Data were reduced to dimensionless parameters, the coefficient of discharge being presented in both tabular and graphical form as a function of the Froude number and ratios of length dimensions.

Entrainment of Air by Liquid Jets. ROBERT W. SHIRLEY. M.S. Thesis, August 1950; Professor Rouse, adviser. The object of this experimental investigation was to determine the characteristics of air entrainment by a water jet plunging through the free surface of water in a tank. Data were collected for jets entering at angles varying from 45° to 67° and extrapolated to represent conditions of vertical entry. The rate of entrainment was evaluated as a function of the Froude number; further experiments with other liquids will be necessary to determine the extent of capillary and viscous influences.

Experimental Investigation of the Discharge Coefficient for a Rectangular Side Weir. CARLOS ACOSTA-SIERRA. M.S. Thesis, February 1951; Professor McNown, adviser. The variation of the discharge coefficient for a rectangular side weir was determined for two limiting conditions not covered in previous investigations: (a) zero sill height above the floor of the channel, and (b) channels effectively very wide. The discharge coefficient was evaluated as a function of the Froude number and of the geometrical characteristics of the channel and of the weir.

A History of Hydraulics to the End of the Eighteenth Century. SIMON S. INCE. Ph.D. Dissertation, August 1952; Professor Rouse, adviser. An attempt was made to trace the growth of some fundamental ideas and the formulation of the elementary principles upon which present-day hydraulics is based. Although it was sometimes necessary to consider engineering works in order to gain an insight into the knowledge existing at any given period and at other times to consider the influence of new modes of thought on mechanics, and consequently on hydraulics, the primary emphasis was laid upon the development of hydraulic knowledge itself. (See Special Publications.)

Aeration Demand of a Sharp Crested Weir. GO CHEAN SHIEH and ARTURO OBADIA. M.S. Thesis, June 1954; Professor Howe, adviser. A study was made of the rate of flow of air required to maintain atmospheric pressure under the nappe of a vertical sharp-crested weir. The air demand was determined as a function of the weir height, the head on the weir, and the size of the air pocket beneath the nappe. (See *Civil Eng.*, Vol. 25, 1955.)

STUDIES IN ENGINEERING

Bulletin 1. "The Flow of Water through Culverts," by D. L. Yarnell, F. A. Nagler, and S. M. Woodward, 1926. 128 pages, 26 figures, 23 plates. Out of print.

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