THE

IOWA INSTITUTE

OF

HYDRAULIC RESEARCH

University of Iowa Studies in Engineering
Bulletin No. 30
1946

No. 414

PUBLISHED BY THE STATE UNIVERSITY OF IOWA, IOWA CITY

THE

IOWA INSTITUTE

OF

HYDRAULIC RESEARCH

Published by the University
Iowa City, Iowa
1946

TABLE OF CONTENTS

FOREWORD

Despite a twenty-five-year background of continuous activity, no magazine articles or technical papers have described the Iowa Institute of Hydraulic Research with sufficient completeness to answer the frequent inquiries which are received regarding its facilities, research policies, and publications. Preparation of the present bulletin was therefore begun in 1944, with practically every member of the staff taking an active part in writing or assembling illustrations.

At the same time, unfortunately for the progress of the manuscript, the work of the Institute continued to expand, with the result that some portions of the text became obsolete shortly after being drafted. In fact, plans now in preparation for enlargement of the laboratory structure to meet increasing need for space should make a supplement to this bulletin necessary within a very few years. Publication in the spring of 1946 was nevertheless decided upon, in view of the transition from war to peacetime endeavors and the completion of arrangements for the Third Hydraulics Conference.

It is believed that the present account of Institute activities will prove of interest to its many past and prospective graduate students and staff members, to other organizations engaged in similar fields of endeavor, and to the numerous private firms and government agencies which the Institute has been asked to serve in a research capacity.

THE IOWA INSTITUTE OF HYDRAULIC RESEARCH

THE IOWA INSTITUTE OF HYDRAULIC RESEARCH

INTRODUCTION

History

Construction of a grist mill on the Iowa River above Iowa City, about 1840, was the first link in a chain of events which led to the formation, nearly a century later, of the Iowa Institute of Hydraulic Research. The mill was busy and prosperous through the last decades of the nineteenth century, but declining revenues and disastrous floods so discouraged the owner, Euclid Sanders, that he deeded his water rights to the College of Applied Science of the State University of Iowa in the fall of 1903. A grant from the Legislature in 1904 made possible the construction of a 10-foot dam two years later. The new dam was built a mile below that of the grist mill, to take advantage of a better location and to provide more head. Although power was again the chief object, the possibility of hydraulic experimentation was foreseen, and a 10-foot opening was left at the west end of the dam to provide an entrance to an experimental channel.

In 1914 the construction of a concrete bridge at Burlington Street, 50 feet upstream from the new dam, was begun. In order to stabilize the west abutment, a heavy concrete retaining wall was deemed necessary, and the newly created Mechanics and Hydraulics Department was asked to locate this wall in such a way as to provide room for a hydraulics laboratory. Plans were made by Professor S. H. Sims for the wall, as well as for a 10-foot channel and a small laboratory building. A legislative grant made the proposal feasible, and the project was completed in 1918 under the direction of Professor J. H. Dunlap. The original laboratory, shown in Fig. 1, was but 22 feet square in plan, and was placed 130 feet from the head of the channel. A small pump was provided for unwatering the channel at moderate and high river stages, but no experimental equipment was placed in the building. All hydraulic tests were conducted in the flume, and the building served mainly

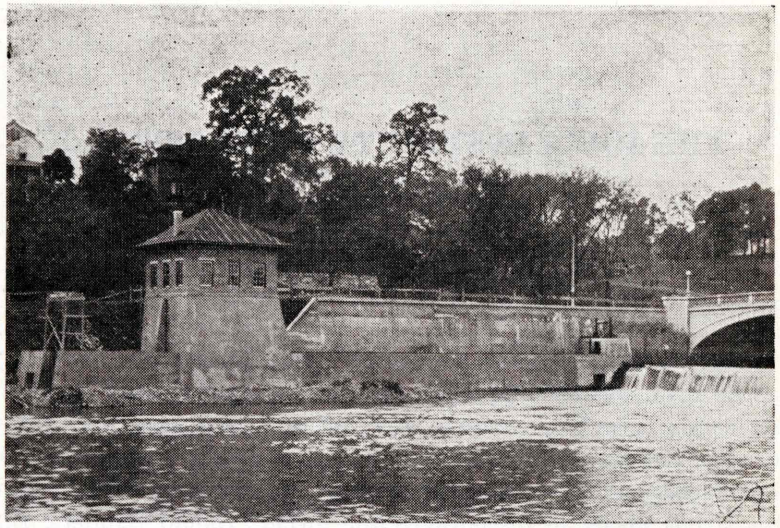

FIG. 1. PHOTOGRAPH TAKEN IN 1919 OF THE ORIGINAL LABORATORY AND RIVER CHANNEL.

as a shop. Oddly enough, the hydraulics laboratory for student instruction was developed in the materials-testing laboratory, where an elevated constant-level tank and two weighing tanks of 18,000-pound capacity permitted instruction and research to be carried on.

The channel and other facilities, though somewhat meager, were nevertheless better for large-scale hydraulic experiments than practically any in the country. However, before an extensive research program could be developed, Professor Dunlap left Iowa City to become Secretary of the American Society of Civil Engineers. At that time the head of the Mechanics and Hydraulics Department was Professor Sherman M. Woodward, a member of the University staff who had become nationally known for his hydraulic studies for the Miami Conservancy District project. Professor Woodward replaced Professor Dunlap with a young doctor of philosophy just out of the army meteorological service, Floyd A. Nagler, who assumed charge of the laboratory in 1920.

Professor Nagler possessed a rare combination of energy, enthusiasm, and technical ability, and it is safe to say that the tremendous impetus given to hydraulic development at Iowa can be credited largely to his dynamic personality. He simply decided that this was to be an important center of hydraulic research and, with the understanding cooperation of Professor Woodward, pro-

ceeded to make it so. His original expectation was that the laboratory would undertake an extensive program of turbine testing, since the only existing facilities for such tests were in Massachusetts. Provisions for handling turbines therefore received first priority as new equipment was added. On the other hand, the publicity which Professor Nagler had given to this new undertaking soon resulted in a connection with the Department of Agriculture which was destined to play an important part in the growth of the laboratory. In 1921 this Department sent David L. Yarnell to the University for the specific purpose of conducting full-scale tests on culverts. Mr. Yarnell caught Professor Nagler's enthusiasm and threw his influence squarely behind all plans to increase the laboratory facilities. He continued an active program of research on various Department of Agriculture projects and supported a number of graduate students in hydraulics through employment as engineering assistants.

Before long the need for more space became apparent, and in 1927 plans for a larger laboratory were announced. A three-story structure, approximately 30 feet by 60 feet in plan, was completed in 1928 (see Fig. 2), and the large scales and other equipment previously used for instruction were moved to the new building.

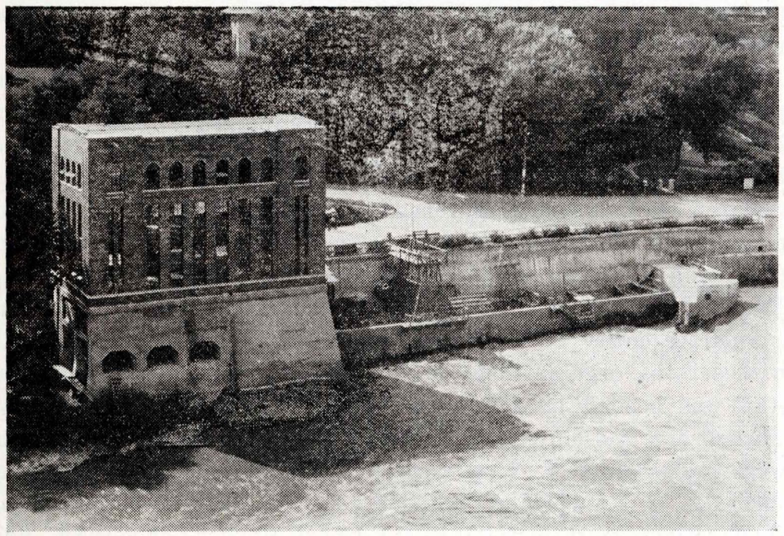

FIG. 2. NORTH WING OF THE HYDRAULICS LABORATORY SHORTLY AFTER COMPLETION IN 1928.

Three years later a 48-inch steel penstock was extended southward from the dam to supply a second channel 16 feet wide. A large constant-level tank and a circulating water system permitted experimentation on all floors of the building.

A flood study on a model of a portion of the Des Moines River valley at Ottumwa, Iowa, and a model-prototype comparison of the Keokuk spillways soon brought national attention to the work being done at the University; indeed, the latter work ultimately won for Professor Nagler and his collaborator, Albion Davis, the 1931 Norman medal of the A.S.C.E., because of its importance in establishing in the minds of American engineers the dependability of model studies.

The Army Engineer Corps was at that time beginning a canalization program on the Mississippi River and wished to check the adequacy of the spillways at the navigation dam at Hastings, Minnesota. A visit to the Iowa laboratory convinced them that model studies could prevent many costly mistakes and lead to economies in design. In 1929 the Engineer Corps accordingly established a sub-office in Iowa City under the able direction of Martin E. Nelson, and began an extensive program of model studies on dams, spillways, locks, and navigation problems. In fact, the Army program so quickly filled the newly provided space that it soon became necessary to use the upper floor of an old shop building across the river as a laboratory annex.

The desirability of bringing to bear upon intricate hydraulics problems the full scientific power of the University, without respect to departmental lines, led in 1931 to the formation of the Iowa Institute of Hydraulic Research, an organization consisting of a research staff, a board of consultants drawn from other departments of the University, and an advisory committee of prominent practicing hydraulic engineers. Although an integral part of the Engineering College, the Institute at the same time functioned as a separate entity in the negotiation of agreements and contracts with persons, organizations, or governmental agencies. The original staff was headed by Professor Nagler as Director, and Messrs. Yarnell and Nelson as Associate Directors. University Consultants were Professors S. M. Woodward, hydraulics; B. J. Lambert, structures; A. C. Trowbridge, sedimentology; G. W. Stewart, physics; H. L. Rietz, mathematics; and Edward Bartow, chemistry. The original Advisory Committee consisted of the following well known

engineers: Dean Clement C. Williams (Chairman), Nathan C. Grover, LeRoy E. Harza, Robert E. Horton, Ivan E. Houk, Samuel H. McCrory, Arthur E. Morgan, and George R. Spalding. R. G. Kasel became an Associate Director in 1932 following the establishment of a U.S.G.S. District Office at the Institute laboratory.

The volume of work being done by the Institute necessitated a further expansion of its laboratory facilities a year after its organization. A five-story central tower section 45 feet square and a 35 x 60-foot south wing of three stories were added in 1932 to the existing structure, with the result shown in Fig. 3. The river chan-

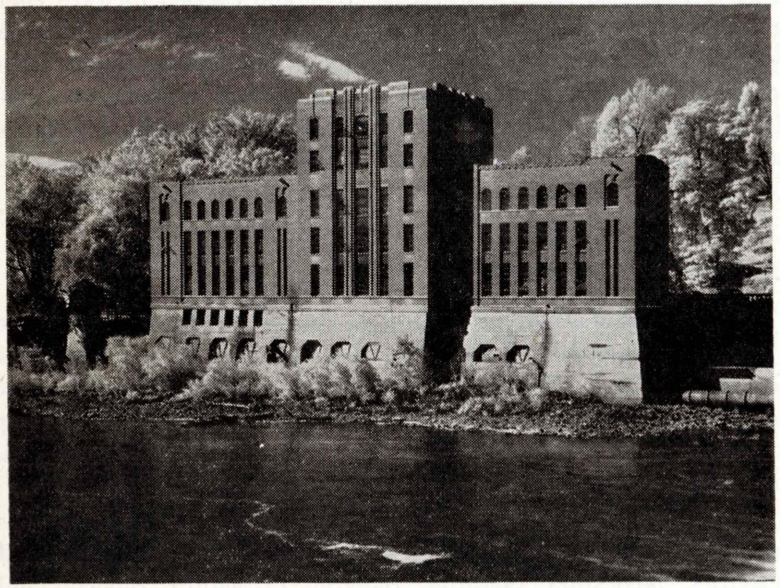

FIG. 3. LABORATORY OF THE IOWA INSTITUTE OF HYDRAULIC RESEARCH IN THE SUMMER OF 1945.

nels were enlarged to 311 x 10 feet and 120 x 16 feet, respectively, and additional pumping and storage facilities were provided. A lusty development of specific research by means of model studies then went forward.

Following the untimely death of Professor Nagler in 1933, Dean Williams assumed the directorship of the Institute and made Professor F. T. Mavis Associate Director in charge of the laboratory. Under Professor Mavis there came about a great increase in graduate work, and the problem of sediment transportation began to receive attention. Dean F. M. Dawson replaced Dean Williams as Dean of the Engineering College and Director of the Institute in 1936, and the following year Professor E. W. Lane became Associate Director in charge, Professor Mavis having decided to devote all his time to the Mechanics and Hydraulics Department. Following Dean Dawson's arrival the Institute was named the National Laboratory for the Master Plumber's Association. Under Professor Lane's guidance an intensification of sediment studies occurred, culminating in a project carried on cooperatively with six government agencies. Pioneer investigations of liquid turbulence were begun by Professor A. A. Kalinske in 1936 and carried forward energetically during the following eight years. The addition of Professor Hunter Rouse to the Institute staff in 1939 led to the extension of research interests into related fields of fluid motion. Professor Lane was granted a two-year leave of absence in 1942, and Professors Rouse and Kalinske were appointed Associate Directors, the former being placed in charge of Institute activities.

Present Organization

In 1944 Dean Dawson resigned as Director of the Institute and Professor Rouse was appointed to that position. At the same time the original plan of organization of the Institute was modified to consist of the active staff, drawn from the College of Engineering, and a single board of consultants chosen primarily from organizations outside the University.

The present technical staff is headed by the Director, who is ultimately responsible for all Institute endeavors, including staff activities, laboratory facilities, research procedure, reports, and finances. He is assisted by one or more Associate Directors, who are chosen from the Institute staff and from the staffs of cooperating agencies permanently located at the Hydraulics Laboratory. Research Engineers, selected largely from the staff of the Department of Mechanics and Hydraulics, directly supervise the various Institute projects and student investigations. The remaining members of the technical staff are the Research Associates and Assistants, who conduct the actual tests and evaluate the test results; the Research Assistants usually include several advanced students on part-time scholarships from the Graduate College. A non-technical staff, consisting of secretaries, machinists, mechanics, assis-

tants, and part-time laborers as needed, is maintained. At the time of writing, the staff of the Institute was as follows:

DIRECTOR

Hunter Rouse
Professor of Fluid Mechanics

ASSOCIATE DIRECTORS

Emory W. Lane
Professor of Hydraulic Engineering

Lawrence C. Crawford
District Engineer
U. S. Geological Survey

Martin E. Nelson
Senior Engineer
Corps of Engineers

RESEARCH ENGINEERS

Joseph W. Howe
Professor and Head,
Dept. of Mechanics and Hydraulics

Chesley J. Posey
Associate Professor,
Hydraulic and Structural Engineering

John S. McNown
Assistant Professor,
Mechanics and Hydraulics

RESEARCH ASSOCIATES

Maurice L. Albertson
En-Yun Hsu
Donald E. Metzler
Conrad F. Schadt
Randolph A. Jensen

RESEARCH ASSISTANTS

James R. Barton
John W. Forster
Philip G. Hubbard
Charles A. Lamb
Emmett M. Laursen
Kai Lei

SECRETARIES

Leona M. Amelon
Alice A. Edwards

MACHINISTS

Dale C. Harris
Dave E. Chadwick

MECHANICS

Merritt A. Ewalt
Fred W. Parks

LABORATORY ASSISTANTS

Merrill F. Andrews
Lester P. Harris
Leslie F. Harris

The Board of Consultants is composed of prominent engineers and scientists from various parts of the country who are chosen because of their interest in or direct association with the research activities of the Institute. The terms of service of members of the Board are so arranged that one-third of the membership will change each year. The functions of the Board are purely advisory, being directed primarily toward suggestions for productive lines of research and the development of desirable conference programs. The Dean of the Engineering College acts as Chairman of the Board. At the time of writing, the Board consisted of the following members:

BOARD OF CONSULTANTS

Chairman, F. M. Dawson
Dean of Engineering
State University of Iowa

B. A. Bakhmeteff (1947)
Professor of Hydraulic Engineering
Columbia University

H. O. Croft (1948)
Head, Dept. of Mechanical Eng.
State University of Iowa

W. F. Durand (1946)
Professor Emeritus
Stanford University

G. A. Hathaway (1948)
Special Assistant to the
Chief of Engineers, U. S. Army

W. G. Hoyt (1947)
Exec. Officer, Water Resources Com.
Dept. of the Interior

L. A. Jones (1946)
Chief, Division of Drainage
Soil Conservation Service

C.-G. Rossby (1946)
Professor of Meteorology
University of Chicago

H. E. Saunders (1948)
Tech. Director, Taylor Model Basin
Bureau of Ships, U. S. Navy

H. U. Sverdrup (1947)
Director, Scripps Institution of Oceanography

Research Policy

The Institute policy regarding research and testing has developed along two general lines. In the case of investigations to determine the solution of specific problems, contracts are entered into with the agency concerned, the financial arrangements varying with the degree of participation required of the Institute staff. Such participation ranges from a minimum in the case of projects brought in and conducted by engineers of the outside agency, to full responsibility for planning and carrying projects to completion. In accepting specific research problems, priority is given to those considered most productive of useful information, while routine testing is undertaken only when men and facilities are not needed in research programs.

The Institute has also had a strong and continuing interest in fundamental research, and has manifested this interest either by contributing staff time and facilities or by sharing expenses with outside agencies interested in such work. An excellent opportunity for studies of this nature arises from the participation of the Institute in student instruction, since students doing graduate research in fluid motion are advised by staff members, and since it is thus possible to have related phases of a particular problem investigated by different students in successive years. Research assistantships granted by the Graduate College also provide part-time employment of graduate students for Institute projects. In addition the Institute itself has frequently employed students for staff projects, and the same procedure has on several occasions been adopted by cooperating agencies. Thus, the service of able, technically trained men is continuously at hand for a broad research program.

Institute Activities

The major activity of the Institute is its research and testing program, the bulk of its equipment and the major portion of the time of its staff being devoted to such work. As indicated in the foregoing paragraph, a considerable amount of fundamental research is conducted on a long-term basis with graduate student help. Important research programs have also been carried on for such agencies as the U. S. Army, the U. S. Navy, the National Defense Research Committee, the American Society of Civil Engineers, the National Association of Master Plumbers, and the State Conservation Commission; in general, these agencies desired to have particular problems studied by the Institute staff. Cooperative arrangements of somewhat different nature have been made by the U. S. Department of Agriculture, the U. S. Engineer Department, the U. S. Geological Survey, the Soil Conservation Service, and the U. S. Weather Bureau, such agencies furnishing men and materials and paying for services on various projects of joint interest to the Institute and the agency concerned. Testing work of a commercial nature has also been carried on when facilities of the required type were not readily available elsewhere. Activities of this nature are more fully described in later sections of the bulletin.

Important among the more general activities of the Institute are its Hydraulics Conferences. The first, held in 1939, brought together nearly 250 hydraulic engineers in a four-day meeting devoted to a résumé of current knowledge in the fields of turbulence, hydrology, model study, hydraulic structures, transportation of sediment, and open-channel flow. Some twenty papers were read by authorities on these subjects and later published as *Proceedings* *of Hydraulic Conference*, Bulletin 20, Iowa Studies in Engineering. The second conference was held in 1942. This meeting, handicapped by wartime conditions, suffered somewhat in attendance but by no means in excellence. Papers showing the applications of fluid mechanics in many different fields were read by eminent engineers and scientists. The subjects of fluid resistance, methods of research, cavitation, wave motion, turbulence, and sediment transportation were treated from the standpoints of men in many different fields; the resistance problem, for example, was discussed by specialists in hydraulic, chemical, aeronautical, and petroleum engineering. The twenty-four papers presented were published as *Proceedings of the Second Hydraulics Conference*, Bulletin 27, Iowa Studies in Engineering. At the time of writing, the Third Hydraulics Conference is being planned for 1946.

Although much of the research conducted by the Institute, the Mechanics and Hydraulics Department, and the several cooperating agencies comes to the attention of the profession through published articles and discussions, there remains a considerable amount of such work which does not lend itself to publication in ordinary channels. With a view to making all research results available, the Institute has initiated a series of bulletins containing abstracts of all graduate theses, staff publications, and reports of associated agencies. Bulletin 19, *Two Decades of Hydraulics at the University of Iowa* (1939), was the first of this series; the second was Bulletin 26, *Investigations of the Iowa Institute of Hydraulic Research, 1939-1940*, the latter containing in addition four original papers by staff members. The Institute has also cooperated in the publication of Water Supply Bulletins of the State of Iowa.

Occasional seminar meetings of the Institute staff and graduate students are held, the time being used for discussion of a current research project by a staff member or graduate student. The entire personnel is, in this way, kept abreast of current research work. Considerable attention is also given to the more routine phases of instruction. Noteworthy is the student laboratory, designed by the staff and described later in the bulletin, wherein excellent facilities for undergraduate and graduate instruction are provided. The preparation of educational motion pictures on various aspects of fluid motion and the organization of advanced summer courses for practicing engineers are indicative of the Institute's general interest in instructional work.

PHYSICAL PLANT AND BASIC EQUIPMENT

Laboratory Structure

The Hydraulics Laboratory of the Iowa Institute of Hydraulic Research is located on the west bank of the Iowa River immediately downstream from the University dam. The completion of the present building in 1933 came as a natural step in the evolution of the Institute, as the increased demands on space in the laboratory prior to that time emphasized the need for considerable expansion. Plans were drawn which utilized the 1928 construction as the north wing of a building with a central tower and symmetrical north and south wings as shown in Fig. 4. The design was carried out through the cooperation of several members of the staff under the supervision of Professor F. A. Nagler, Director of the Institute at that

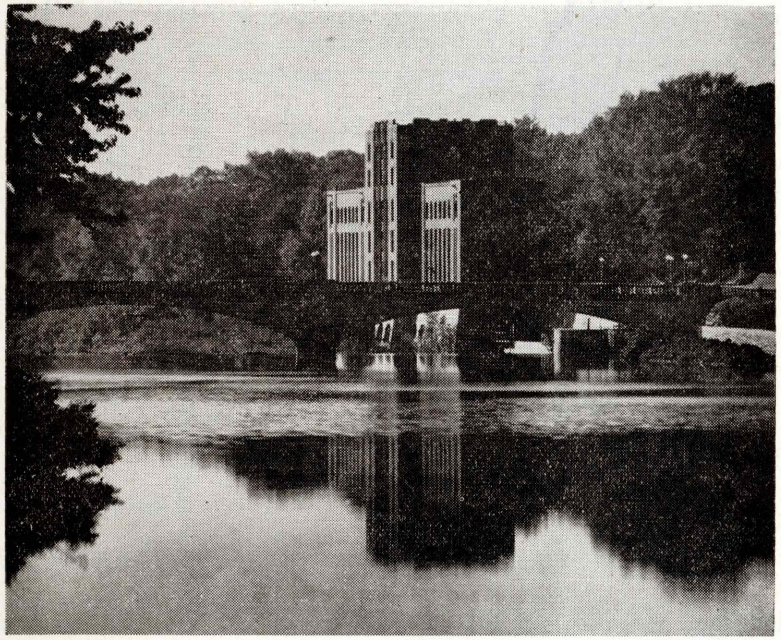

Fig. 4. View of the Hydraulics Laboratory over the pool formed by the University Dam.

time. The contract, let in June, 1932, was divided among several contracting firms, and in February of 1933 the building was ready for occupancy. This addition brought the total investment in the plant and basic equipment to well over $100,000 (refer to page 33). The brick and concrete building is rectangular in plan, 164 feet

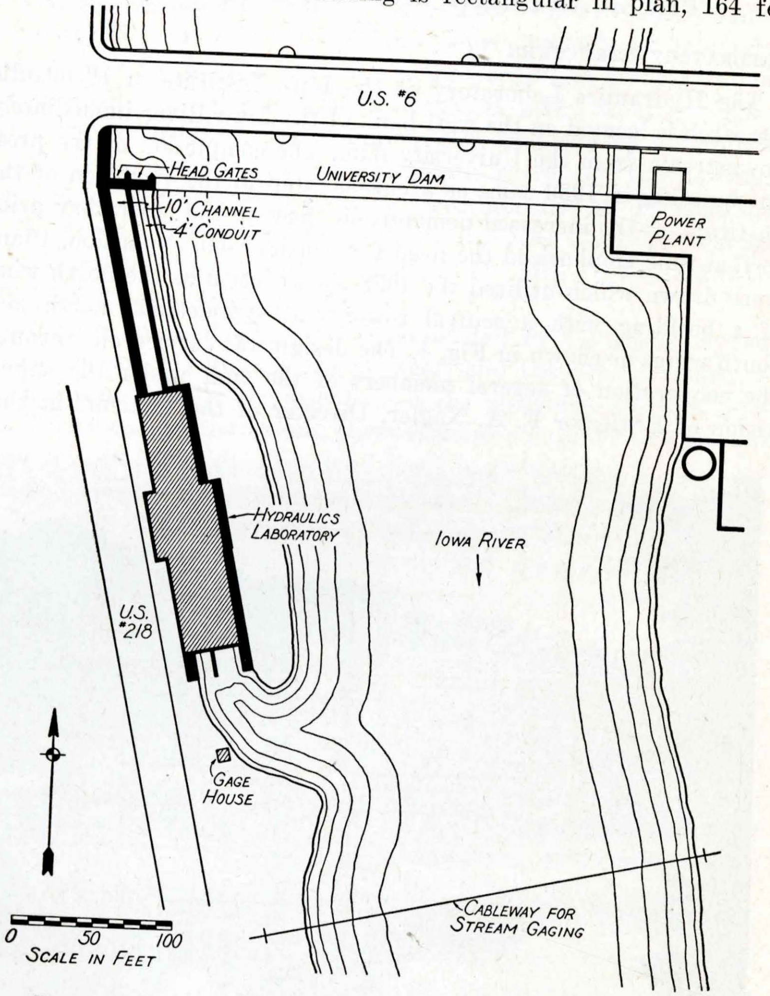

FIG. 5. MAP SHOWING LOCATION OF LABORATORY, DAM, AND RIVER CHANNEL.

long and ranging in width from 30 to 45 feet, with the river on one of the long sides and state highway No. 218 on the other, as may be seen from Fig. 5. The overall height is 90 feet at the central

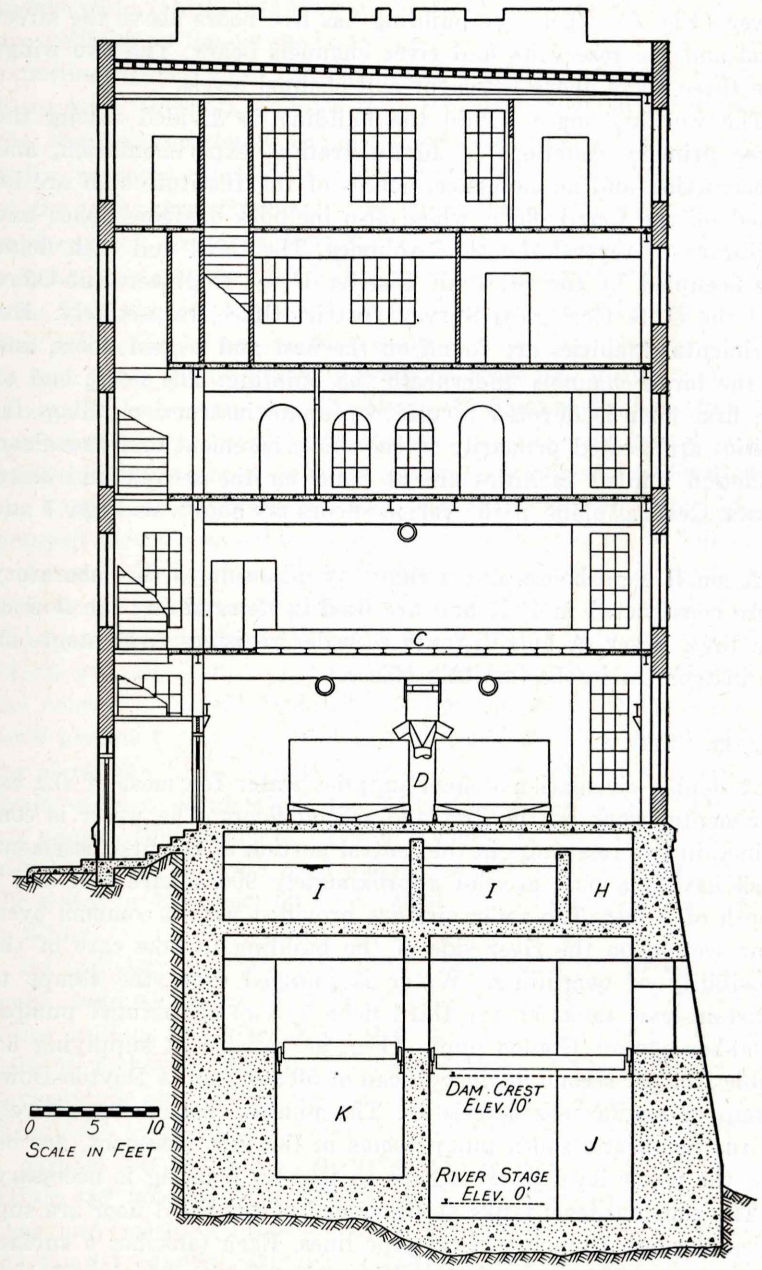

FIG. 6. VERTICAL SECTION THROUGH CENTRAL TOWER OF LABORATORY.

tower (Fig. 6), where the building has five floors above the street level and the reservoirs and river channels below. The two wings rise three floors above basement and channel levels.

The working space within the building is divided among the three primary functions of administration, experimentation, and construction and maintenance. Offices of the Institute staff are located on the fourth floor, which also includes drafting space and a library of several thousand volumes. The third and fifth floors are occupied by the St. Paul District U. S. Engineer Sub-Office and the U. S. Geological Survey District Office, respectively. Experimental facilities are found on the first and second floors, and in the large channels underneath the building. The north end of the first floor is devoted to undergraduate instruction. Shop facilities are located primarily in the south basement and first floor, although limited facilities are at hand on the second and third floors. General plans of the various floors are shown in Figs. 7 and 8.

A small gage house and a cableway adjacent to the laboratory were constructed in 1921 and are used in determining the flow of the Iowa River. A long-distance recorder registers river stages on an instrument in the Institute offices.

Water Supply

A double circulation system supplies water for most of the experimental work on the first and second floors. The water is contained in two reservoirs in the central portion of the first basement, each having a plan area of approximately 900 square feet and a depth of 6 feet. The reservoirs are provided with a common overflow section on the river side of the building to take care of the possibility of overfilling. Water is pumped from the sumps to constant-level tanks on the third floor by two centrifugal pumps: a 50-horsepower Goulds pump (Fig. 9) capable of supplying 6.7 cubic feet per second against a head of 50 feet, and a Dayton-Dowd pump of similar characteristics. The pumps, located respectively in the north and south pump rooms in the first basement, are below the water level in the sumps so that no priming is necessary.

The constant-level tanks at either end of the third floor are supplied through 10-inch vertical pipe lines. Each tank has a surface area of some 350 square feet and is equipped with a series of skimming weirs having a total crest length of about 700 feet. Numerous

independent take-off connections, 12 inches in diameter and smaller, are available in the bottom of the tanks for pipe lines to the various experimental projects. The portion of the water which is not used flows over the weirs, collects in a separate basin, and returns to the reservoirs through 12-inch pipes. Because of the skimming weirs, a considerable discrepancy between flow into and flow out of the tanks does not materially affect the elevation of the water surface, and the tanks thus serve as two independent sources of water under constant head. An interconnecting 10-inch pipe line runs from the constant-level tanks along the ceilings of both the first and second floors, so that water may be supplied from either or both tanks for tests at any point on these two floors. A number of smaller lines connected directly to the tanks makes simultaneous operation of several projects possible, provided the combined demands do not exceed the available supply. A 10-inch line by-passing the north tank has been installed so that, if desired, water can be pumped directly at heads up to the shut-off value of 74 feet.

Accurate determination of the rate of discharge is made possible by the two large weighing tanks (Fig. 9) on the first floor. The Toledo scales on which the tanks are mounted have a capacity of 18,000 pounds each, and their load may be quickly determined to the nearest 5 pounds from the reading on a dial which indicates 4000 pounds for each revolution of the pointer. A swinging deflector above the tanks permits diversion of flow into either tank. The drain valves through which the water returns directly to the sump are operated by means of hydraulic controls. Continuous measurement of flows as great as 5 cubic feet per second is possible, as the water in one tank can be weighed and drained while the other is filling.

By utilizing the water from the river above the dam, the two main channels permit large-scale tests which otherwise would require prohibitively expensive pumping equipment. One of the channels, 10 feet wide and 10 feet deep, extends from the dam to the downstream end of the laboratory, a distance of about 300 feet. Headgates at the dam control the flow into this channel and into a parallel conduit 4 feet in diameter. A second channel wholly within the laboratory is 100 feet long, 16 feet wide, and 13 feet deep, and is supplied through the 4-foot pipe and by diversion from the smaller channel. Hinged tailgates at the downstream ends of the channels, used in conjunction with remote-control adjustment

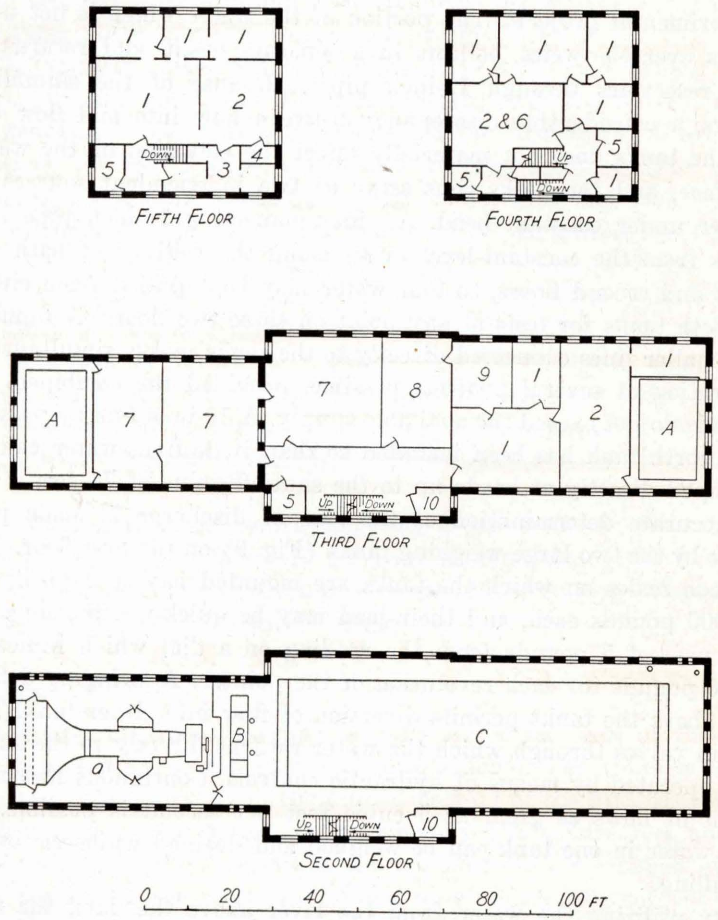

FIG. 7. PLAN VIEWS OF SECOND, THIRD, FOURTH, AND FIFTH FLOORS.

Legend

1 — Offices	7 — Shops	A — Constant-level tanks
2 — Drafting rooms	8 — Classroom	B — Weighing-tank hopper
3 — Janitor's quarters	9 — Silt laboratory	C — River-model flume
4 — Supplies	10 — Elevator shaft	D — Weighing tanks
5 — Lavatories	11 — South pump room	E — Pumps
6 — Library	12 — North pump room	F — Motor generator

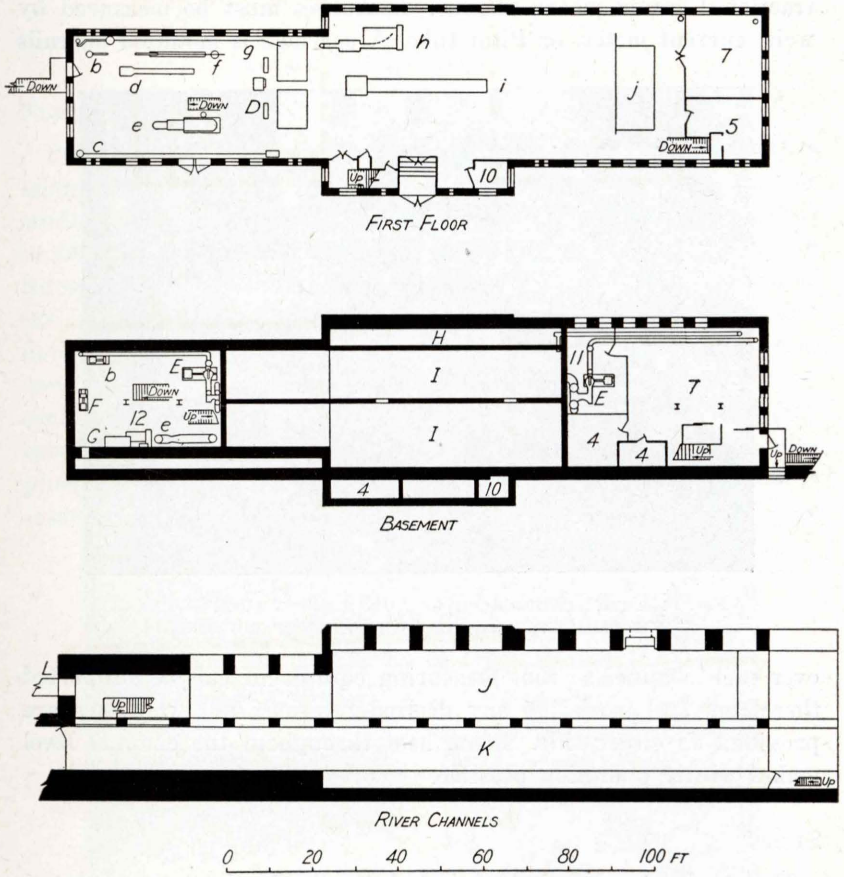

FIG. 8. PLAN VIEWS OF RIVER CHANNELS, BASEMENT, AND FIRST FLOOR.

Legend

G — Power tunnel	a — Air tunnel	f — Oil-flow unit
H — Overflow	b — Cavitation unit	g — Pipe assembly
I — Reservoirs	c — Pipe assembly	h — High-velocity table
J — 16-foot channel	d — Glass-walled flume	i — Department of Agriculture flume
K — 10-foot channel	e — Variable-pressure water tunnel	j — Plumbing demonstration
L — Penstock		

of the headgates, provide the necessary flow regulation. Except for the water supplied by the 4-foot pipe, which contains a side-contraction Venturi meter, channel discharges must be measured by weir, current meter, or Pitot tube. A carriage is mounted on rails

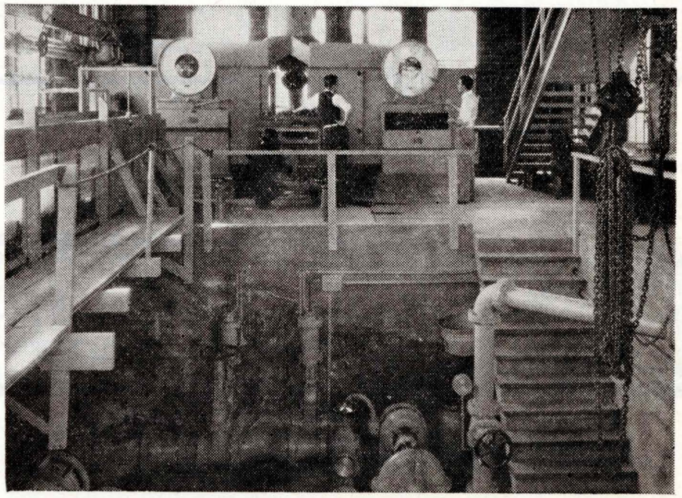

FIG. 9. EARLY PHOTOGRAPH OF PUMPS AND WEIGHING TANKS IN NORTH WING BEFORE COMPLETION OF BUILDING.

over each channel so that measuring equipment can be supported therefrom and moved to any desired position, and walkways are provided on either side. Steam heat throughout the channel level makes winter operation possible.

SHOPS

Except for large units fabricated for the Institute on contract, the major portion of the experimental apparatus is constructed in the laboratory shops, and facilities are at hand for the maintenance of all equipment. Since test requirements may involve precision turning or milling, welding, plumbing, carpentry, sheet-metal work, plastic forming, and masonry, it has been necessary to accumulate the machines and tools, the materials, and the skills for all such phases of construction. The extent of the equipment available may be judged from the approximate evaluation on page 34.

RESEARCH FACILITIES

FLUMES

Probably the most useful research equipment of a hydraulics laboratory consists of its channels and flumes, for in these may be studied the various phenomena of flow with a free surface peculiar to the general field of hydraulic structures. As described in the foregoing section on basic equipment, the two largest channels of the Iowa Institute of Hydraulic Research are of sufficient size and flow capacity to permit full-scale study of many engineering problems. However, early realization of the fact that visibility of flow conditions below the water surface is often of paramount importance led in 1935 to the construction of a glass-walled flume supplied with clear water by the laboratory pumping system. This is customarily known as the Department of Agriculture flume, since

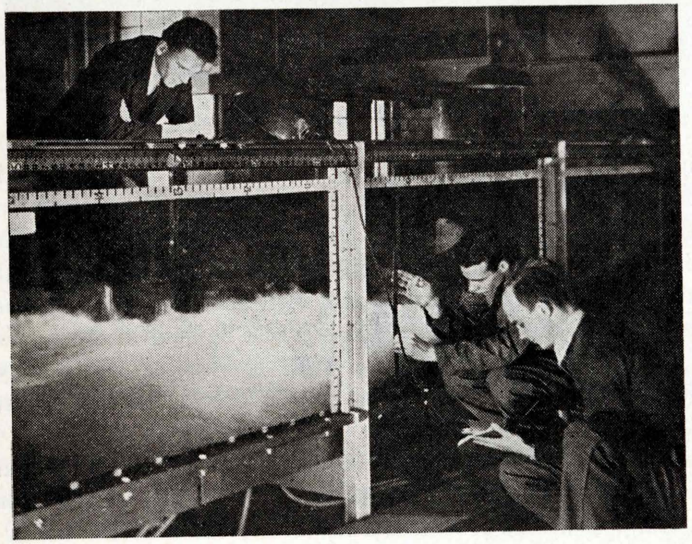

FIG. 10. EXPERIMENT ON THE HYDRAULIC JUMP IN THE DEPARTMENT OF AGRICULTURE FLUME.

it was built under the direction of Mr. Yarnell with government funds and hence is Federal property; it nevertheless forms an integral part of the available equipment (see Fig. 10) and is in frequent use on both government and student projects. The flume itself is 26 feet long, $2\frac{1}{2}$ feet wide, and 3 feet deep, and has 4 panels of $\frac{3}{4}$-inch glass on each side. The rate of inflow is measured by a 30-inch weir in the elevated supply tank at the head end, and a

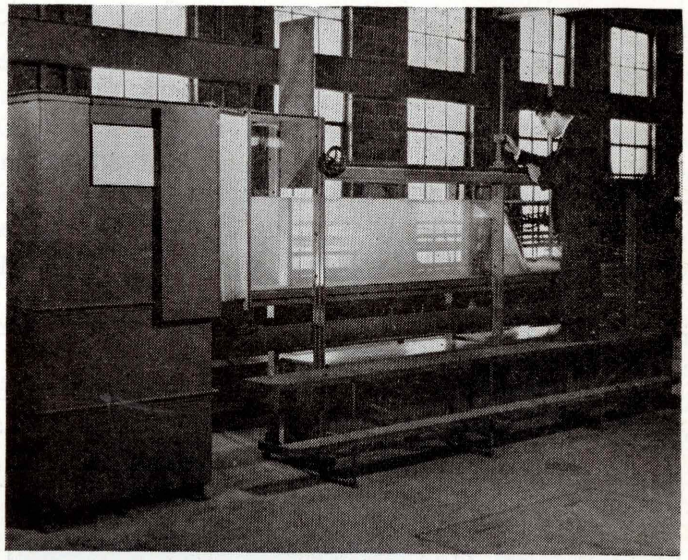

FIG. 11. GLASS-WALLED FLUME USED FOR STUDENT INSTRUCTION.

maximum discharge of 7 cubic feet per second may be attained. As shown on the building plans, it is permanently installed near the center of the first floor of the laboratory. A smaller flume, which may readily be moved to any desired point in the laboratory, has a length of 15 feet, a depth of 2 feet, and a width of 11 inches, and contains a single panel of glass 6 feet in length. Owing to the steel construction of one entire wall, piezometer inlets may be placed at any desired point. The rate of flow is usually measured by weir at the downstream end.

After considerable experience in the design of such equipment, it was possible to incorporate in the newest glass-walled flume a great many desirable features. This unit, located at the north end of the first floor and shown in Fig. 11, is designed structurally to permit a maximum of visibility. On each side at the upstream end is a panel of $\frac{5}{8}$-inch glass 3 feet high and $1\frac{1}{2}$ feet long, followed by two panels 5 feet long and 2 feet high. The width of this portion is only 1 foot, for the flume was specifically intended for problems

of two-dimensional flow. The floor is surfaced with brass plate containing 22 piezometers spaced from 1 to 6 inches apart, and at three points a section of the floor is removable for the insertion of ventilation pipes or additional piezometer leads. A manometer panel containing 13 tubes is mounted at the head end. Between the glass panels are vertical, stainless-steel slots for the insertion of gates or weirs; a removable sluice gate in the upstream slot is controlled by a rack-and-pinion drive, as is a hinged gage at the exit. Both the sluice gate and the removable sharp-crested weir used in this flume have a series of piezometers distributed over the upstream face. Level rails of 1-inch precision shafting carry a gage carriage above the flume. Water is supplied to the head end of the flume through a 6-inch pipe, which contains a calibrated elbow meter for flow measurement. The 3 x 3 x 6-foot head tank is so arranged as to provide maximum stilling in a relatively short distance.

Somewhat different from the usual laboratory channel is the Lucite air-water flume constructed through a grant from the Engineering Foundation and the Committee on Hydraulic Research of the American Society of Civil Engineers. This flume has a fully enclosed cross section 8 inches wide and 15 inches deep with panels of transparent plastic on both sides throughout a length of 50 feet; its slope may be varied from 0° to 10°. Water is supplied to the flume at its head end, the discharge being measured by a 6 x 3-inch orifice meter; a maximum rate of flow of 2.0 cubic feet per second may be attained. Simultaneous with the water flow, air may be passed through the covered flume in either direction by means of a 5-horsepower blower and a two-

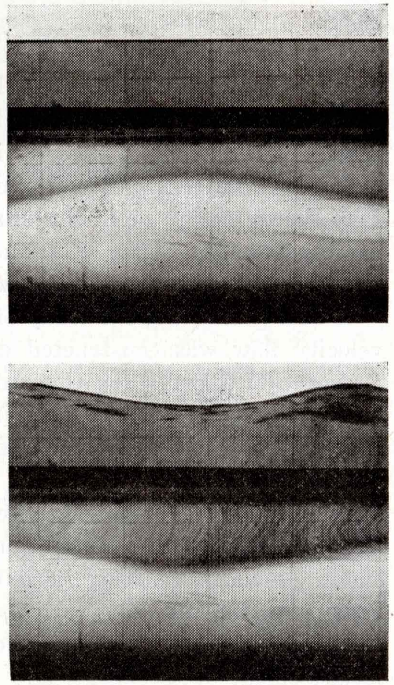

FIG. 12. SURFACE AND SUBSURFACE WAVES IN A LIQUID WITH DENSITY STRATIFICATION.

directional duct containing a diaphragm orifice for flow measurement. The ratio of water and air velocities is controllable over a wide range of positive and negative values, so that wave effects of any desired nature may be produced (Fig. 12).

For the specific purpose of sediment investigation, the Institute constructed at its laboratory annex a recirculating system for silt and sand consisting of a 10-horsepower pump and mixing tank, 80 feet of rectangular flume $2\frac{1}{2}$ feet wide and 1 foot deep, and an equivalent length of trapezoidal flume as a return. Both portions are of light steel construction, with several glass panels in the rectangular test section, and are mounted on screw jacks to permit slope variation from 0° to 5°. Velocities as high as 3.0 feet per second may be attained, and mean sediment concentrations as high as 11 percent by weight.

In order to demonstrate and photograph eddy phenomena produced by the relative motion between a fluid and an angular boundary, a small towing tank was constructed of wood and sheet metal for the undergraduate laboratory. This flume has a maximum depth of 1 foot, a width of two feet, and an overall length of 15 feet. A carriage travels smoothly on ball-bearing wheels over rails of precision steel shafting extending the length of the channel, making possible the towing of such bodies as plates and cylinders or even channel constrictions. Aluminum flitter scattered on the water surface shows, under high illumination, the flow pattern around the moving boundary (Fig. 13), and a still- or motion-picture camera may be mounted upon the carriage for recording the flow sequence.

A unit permitting the study of open-channel transitions for high-velocity flow was constructed on a grant from The Engineering Foundation through the Committee on Hydraulic Research of the American Society of Civil Engineers. This unit consists of a pressure tank 3 feet in diameter and 5 feet long, three rectangular outlets of different width-depth ratios, and a plane 5 x 7-foot floor on which channel walls of different forms may be installed; the floor may be varied in slope from 0° to 10°. A gage carriage mounted on precision shafting permits the movement of a point gage, Pitot tube, or direction indicator to any point in the test zone. Calibrated elbow meters in 4-inch and 8-inch supply pipes permit measurement of discharge, and efflux velocities as high as 20 feet per second may be produced.

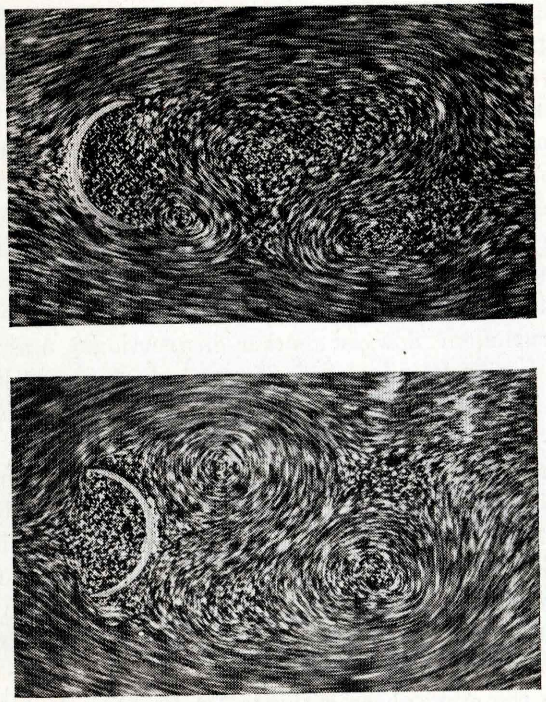

FIG. 13. FLOW PATTERNS PRODUCED BY A HALF CYLINDER WITH CONVEX SIDE UPSTREAM AND DOWNSTREAM.

PIPE INSTALLATIONS

Owing to their ready assembly, the majority of piping systems used by the Institute for specific tests are constructed as the need arises, and then torn down at the end of the tests to make room for other projects. As described in the preceding section, the basic supply lines of the laboratory are arranged to make such a method extremely practicable, since water may conveniently be obtained from the mains and either wasted or led to the weighing tanks from almost any part of the first or second floor. Certain phases of instruction and test routine, on the other hand, make the following items of permanent equipment of considerable value.

A Reynolds demonstration unit for showing the distinction between laminar and turbulent flow is mounted on the west wall of the undergraduate laboratory. It consists, in sequence downstream, of an 18-inch head tank with skimming weir, 15 feet of 6-inch pipe for stilling, a $4\frac{1}{2}$ foot section of 6-inch transparent Lucite pipe containing a dye jet and a coaxial length of 1-inch glass tube with bell inlet, and finally a control valve on the waste line. The unit thus differs from the customary tank of still water in that the duration of the demonstration is not limited by the tank capacity. While the unit was designed for purely visual observation of the diffusion of the dye filament, means have since been provided for measuring the rate of flow in order that quantitative results may be obtained.

Perhaps even more demonstrative of the difference between laminar and turbulent flow is another instructional unit, which involves the recirculation of a light oil through a $\frac{3}{4}$-inch horizontal brass pipe. About 60 gallons of oil are stored in an elongated tank below the pipe, from which it is fed by a $\frac{1}{4}$-horsepower centrifugal pump to a 6-inch pipe. The entrance to the $\frac{3}{4}$-inch pipe within the 6-inch approach section has the form of a well rounded bell 3 inches in diameter, in front of which is pivoted a semicircular strip of brass to provide an optional source of eddies. Along the 15 feet of pipe are 9 piezometers at successively greater intervals, copper leads running to a manifold connected directly to a 10-foot open glass piezometer column with Vernier gage. The pipe discharges freely into the atmosphere within a Lucite box which permits the jet form to be observed. After passage into a weighing tank with quick-acting valve, the oil is returned to the sump tank. Reynolds numbers from 100 to about 8000 may be obtained with a mineral oil some 10 times as viscous as water, the symmetry of the entrance being such that laminar motion persists at the maximum value of **R** unless a disturbance is produced artificially by turning the semicircular strip across the bell inlet. Aside from the very close correlation of measured results on head loss with the standard resistance equations (see Fig. 21 on page 37), the equipment yields a very striking picture of the change in jet characteristics as the flow changes from laminar to turbulent. Means are also at hand of evaluating the resistance function versus the Reynolds number in the zone of flow establishment beyond the pipe entrance. In addition to such tests, the equipment has proved useful in investigating the behavior of pipe fittings at low to moderate Reynolds numbers.

Standard tests on pipe resistance are conducted on a unit which is now supplied with water from the constant-head tanks of the laboratory, and which will eventually also be connected with a

centrifugal fan to permit alternative tests with air. The inlet and outlet connections are such as to accommodate in parallel three 30-foot sections of pipe of any diameter from $\frac{1}{8}$ inch to 3 inches (Fig. 14). At present a length each of 2-inch brass and galvanized steel pipes are in place, both having a series of piezometer con-

FIG. 14. TESTS ON THE RESISTANCE OF SMOOTH AND ROUGH PIPE OF VARIOUS DIAMETERS.

nections with leads to a gage manifold. Changes in head are measured on a single gage which reads by Vernier to 0.001 foot of either mercury or water. At the outlets of two of the pipes are Pitot-tube housings permitting velocity traverses to be made from wall to wall with fine hypodermic needles. The flow passes directly into one of the large-capacity weighing tanks near the end of the unit. A somewhat similar unit on the west wall at the north end of the first floor contains a series of pipe transitions (abrupt inlet, enlargement, contraction, Venturi, orifice, elbow, tee, valve, and submerged and free outlets) with some 30 piezometer connections leading to a manifold and Vernier gage similar to that on the east wall. While these units were constructed primarily for undergraduate instruction and graduate research, they are available for other test purposes.

Somewhat out of the ordinary is the frequent use by the Institute of Lucite pipe to permit either photographic or visual observation of the flow pattern within closed conduits. In most instances the path lines within the fluid must be made visible through use of smoke, dye (Fig. 15), or finely dispersed droplets of oil, but in the case of pipes flowing only partly full of water it is the form of the free surface — such as that in Fig. 25 — which is of primary importance. The Institute has at hand a considerable supply of transparent pipe for this purpose, in flanged lengths of 5 feet and varying in diameter from 1½ to 6 inches. Of particular note are two 34-foot units of 4-inch and 6-inch diameter which may be

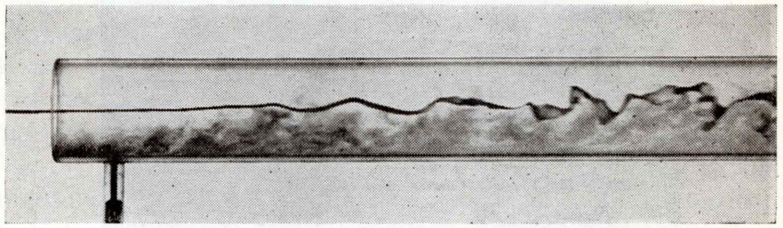

FIG. 15. DIFFUSION OF EDDIES PRODUCED BY SEPARATION AT THE INLET OF A REËNTRANT TUBE.

mounted interchangeably on a continuous 5-inch I-beam which may be varied in slope from 0° to 30°; these were provided through the J. Waldo Smith Fellowship of the American Society of Civil Engineers. Such supplementary Lucite fittings as tees, elbows, and long-radius bends are either taken from stock or specially constructed for specific needs.

Considerable piping of a semi-permanent nature is located at the south end of the first floor in the laboratory section devoted to plumbing research and demonstration. This consists of a system of supply lines interconnected with a 3-horsepower vacuum pump, so that plumbing facilities may readily be tested under a wide range of flow and pressure conditions. Extending along the west wall of the first floor is a 105-foot length of 1¾-inch line with pressure tank and quick-acting valves, which permits tests to be made on plumbing equipment under severe conditions of water hammer.

VARIABLE-PRESSURE WATER TUNNELS

In the spring of 1941, the Institute constructed with ESMDT funds a small cavitation unit to be used in a special training course the following summer. In order to permit independent variation of pressure head and rate of flow, the unit was connected to the constant-level tank of the laboratory by a small pressure line, the flow itself being produced by a 3-inch 15-horsepower Worthington

centrifugal pump located in the north basement. A closed tank 6½ feet high and 18 inches in diameter serves as a stilling chamber for the pump discharge. The test section, leading at eye level from the stilling tank, consists of a passage 6 inches high, ¾ inch wide, and 18 inches long, the sides of which are made of ⅜-inch Lucite panels set in frames for ready removal. The outlet of the test section is connected by pipe to the suction inlet of the pump. Profiles of any desired two-dimensional form may be mounted between the Lucite panels for observation. A fine stagnation tube and wall piezometer, connected to a mercury differential gage, permit measurement of the entrance velocity head, and piezometer leads from the test section to a manifold and compound Bourdon gage make possible the investigation of the pressure distribution around any boundary profile under study. Control of a valve on the pressure line to the constant-level tank yields positive heads up to 30 feet,

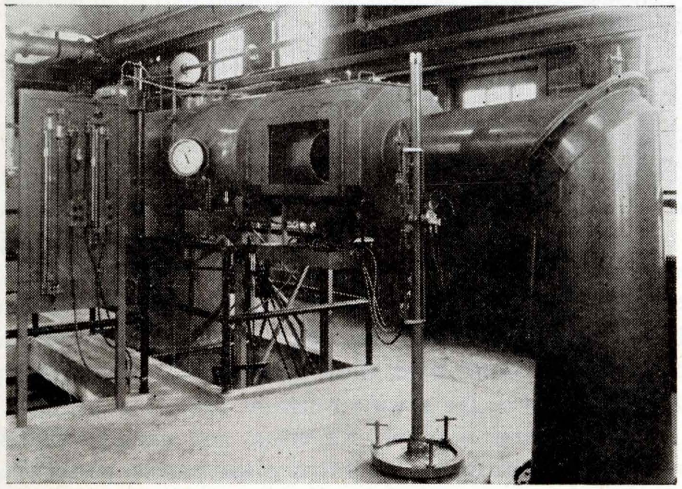

FIG. 16. VIEW OF VARIABLE-PRESSURE WATER TUNNEL WITH OPEN-JET TEST SECTION.

while a similar line leading to the basement channels will produce negative heads of the same magnitude. With a maximum velocity head of 15 feet, conditions of mild to severe cavitation may be produced (see Fig. 20 on page 35) for a wide range of two-dimensional forms.

Since this initial unit was somewhat limited in size, flow capacity, and adaptability to research of a precise nature, in the fall of 1943 the Institute undertook the construction of a larger water tunnel (Fig. 16) with funds granted by the University for this purpose. In order to provide flexibility in speed control, a 24-inch Fairbanks-Morse axial-flow pump delivering from 8 to 35 cubic feet of water per second is powered by an 80-horsepower Continental gasoline engine. Two interchangeable test sections with $\frac{3}{4}$-inch tempered plate-glass windows make it possible to investigate the flow around bodies in either an open-throat stream of circular cross section or a confined stream of square cross section. Since the cross-sectional area of each throat is 1 square foot, maximum test velocities of 35 feet per second may be obtained. A sensitive pressure control, consisting of a vacuum pump and a small centrifugal pump with suitable valves and leads, makes it possible to vary the pressure head of the jet between the limits of +30 and —30 feet of water. Bodies of the required form, mounted in either test section, may thus be subjected to practically any desired degree of cavitation, piezometer openings at pertinent locations in the body permitting a study of the variation in pressure distribution and drag over a wide range of flow conditions.

Low-Velocity Air Tunnels

In keeping with the present policy of the Institute to be equipped for research in many related fields of fluid motion, the addition in 1943 of two low-velocity air tunnels to its experimental facilities represented a logical extension of its previous work in fluid turbulence. Although constructed for the specific purpose of conducting diffusion tests for the Armed Services through the National Defense Research Committee, these tunnels are so designed as to provide test facilities for a wide range of peacetime projects. The small portable tunnel is purely for visual and photographic study of flow in two dimensions, 2 x 3-foot glass panels permitting by means of smoke filaments observation of the pattern of motion around any body or boundary profile which is introduced. The large tunnel, on the other hand, occupies the entire north end of the second floor of the laboratory. Air is admitted through grids at the four north windows, passing through stilling devices and an entrance bell into a hardboard duct having a length of 20 feet, a width of 6 feet, and a height of 4 feet (Fig. 17). This duct leads to the inlet of a Clarage centrifugal fan exhausting through windows on both the east and west sides of the laboratory. Driven by a $7\frac{1}{2}$-horsepower electric motor, the fan produces a maximum air

speed of 25 feet per second at the test section of the tunnel; adjustable louvers at the fan inlet permit a fine control from 1 foot per second to the maximum. A gage carriage traveling on leveled rails at the tunnel ceiling provides motion of instruments to practically any point in the tunnel. The construction of the tunnel itself is

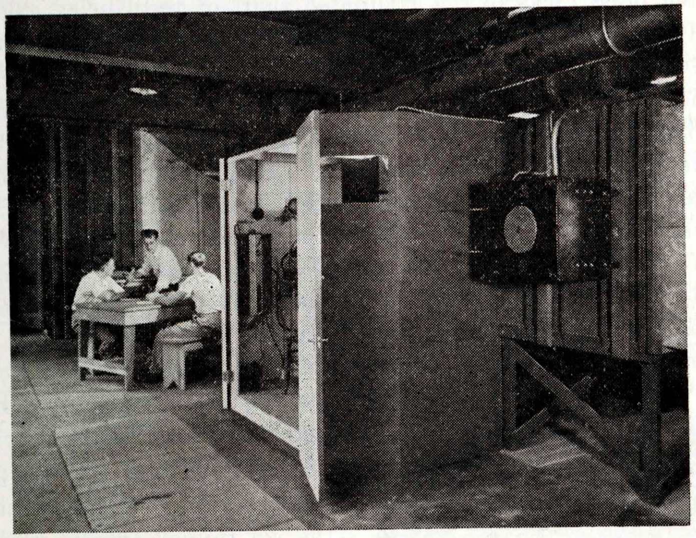

Fig. 17. View of low-velocity air tunnel, observation chamber in foreground and bell entrance in background.

such as to provide a great deal of flexibility in the introduction of model structures and in the photography or measurement of essential characteristics of the resulting flow pattern.

Instruments

Since much of the test procedure involved in the research work of the Institute requires special instrumentation, a considerable portion of the measuring equipment used in the laboratory is constructed for specific purposes in the Institute shop. Certain general details which have proved successful are, of course, repeated wherever feasible. In addition to such special devices, the Institute has at hand a wide assortment of standard flow meters, gages, and other observational equipment. All instruments read in foot-pound-second units.

Measurement of the free-surface level in stilling pots is usually accomplished by means of standard Gurley hook gages. In the case of curvilinear flow with a free surface, wherein the gage must cover conveniently a considerable range of depth, it is found that a friction or rack-and-pinion drive is more satisfactory. Of the former type the Stevens gage has been used very successfully, while the latter type has been constructed in the laboratory shops by adding brass racks to the graduated shaft of the Gurley gage. In such instances the gage carriage is generally arranged to move on longitudinal and lateral rails to any point in the test section.

Liquid manometers, which are essential for accurate measurement of fluid pressure, range from simple banks of open glass tubes backed with a 0.01-foot grid system, through mercury-water differential gages, to a direct-reading zero-displacement gage (Fig. 18) developed by the Institute for use with either mercury or water. This involves in brief a pot and graduated bar moved vertically with either rack-and-pinion or friction drive, the meniscus in the opposite leg of a flexible U being brought to a fixed position in a stationary glass tube — thus obviating the necessity of a double reading and subsequent subtraction. These gages are read by vernier to 0.001 foot. For purposes of measuring very small heads in the air tunnels, use is made of the Wahlen principle, which yields results which are accurate to 0.001 inch of alcohol. Simple and compound Bourdon gages of various capacities are at hand for pressure tests not requiring the precision of the liquid manometer; accurate Baldwin-Southwark gages with 12-inch dial have proved particularly useful.

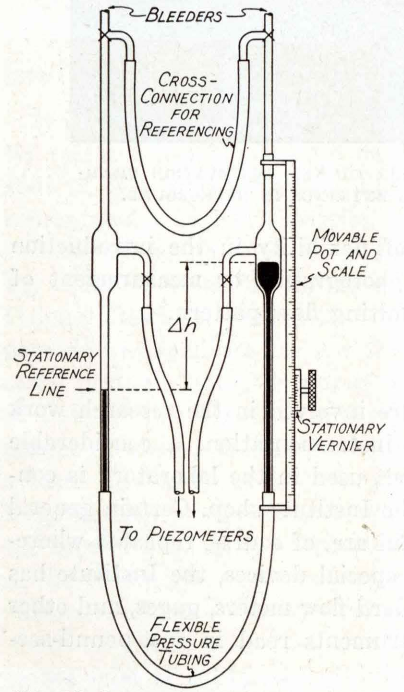

FIG. 18. SCHEMATIC DRAWING OF ZERO-DISPLACEMENT DIFFERENTIAL MANOMETER.

Pitot tubes are generally of the Prandtl type, which has been found to possess a coefficient only slightly smaller than unity and to be relatively insensitive to slight errors in directional setting. Directional measurements are made in several ways:

Rough indications are obtained visually by means of dye, smoke, or simple pivoted vanes. A more precise result ($\pm 1^\circ$) is obtainable through use of a small vane mounted on a shaft with pointer and protractor, a fine stagnation tube on either side of the vane near the leading edge producing a sizeable reading on a differential gage unless the plate is parallel to the local flow. A three-dimensional water-velocity indicator used successfully by the Institute consists of a round-nosed stagnation tube with four additional openings around a circle at approximately 45° from the tip. The orientation of the tube is varied in the horizontal and vertical planes until a zero differential head is obtained for the two pairs of 45° openings; the differential head between the stagnation opening and the 45° openings then yields a fixed multiple of the velocity head. A similar instrument (Fig. 19) has been developed for use in the air tunnel.

The Institute possesses a number of Price and Ott current meters of various forms for velocity measurement in the large channels and in the nearby river. Midget current meters have proved successful in certain model studies involving low water velocities, and their counterpart is found in a very small anemometer developed at the Institute for use in the air tunnels. The need for a current meter or anemometer yielding instantaneous velocity readings has been of continuing interest to the Institute, with some success in preliminary models.

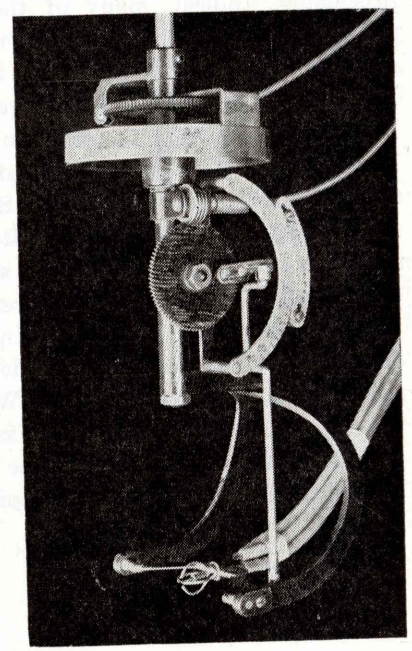

FIG. 19. INSTRUMENT FOR MEASURING MAGNITUDE AND DIRECTION OF AIR VELOCITY.

Owing to the laboratory facilities for ready calibration of any type of metering device, it has been the Institute practice to depart to a considerable degree from so-called standard flow meters. To avoid expense, meters of the Venturi type are generally constructed of available pipe fittings welded together to form the desired section. In temporary installations simple diaphragm orifices are introduced when the available head permits, but use of a convenient conduit bend as a flow meter is found more desirable in most instances; some six or eight pipe elbows of different sizes have been calibrated for this purpose. For many model tests requiring small to moderate rates of flow, recourse is had to a number of portable tanks containing a calibrated V-notch weir and vernier hook gage.

Equipment for visual and photographic observation of flow phenomena includes a number of high-intensity light sources, one of which yields a flash of 1/20,000-second duration, together with a stroboscopic light (Strobotac) for determining the frequency of such periodic occurrences as cavitation and eddy formation. The Institute possesses both still and moving picture cameras and projectors, including a unit arranged for projecting motion-picture film frame by frame to obtain the velocity distribution from streak lines of dispersed particles. Although the laboratory was once equipped with darkroom facilities, the University photographic service has proved so satisfactory that most films are sent there for processing. Indeed, many of the moving-picture sequences prepared by the Institute for instructional purposes, as well as the majority of the photographs in this bulletin, have been taken by Mr. F. W. Kent, who is in charge of this service.

In connection with the sediment investigations conducted by the Institute, a well equipped silt laboratory is maintained on the third floor of the laboratory proper. Standard apparatus for size and fall-velocity analysis includes a Ro-tap with 8-inch U. S. Standard sieves, a set of small-diameter sieves for hand use, a precision Chainomatic balance, a drying oven, and incidental stirring devices, burettes, and other glassware. In addition, a new form of device developed at the Institute for determining the size frequency of sediment samples (the Bottom Withdrawal Tube) is in frequent use for tests in this range. The same laboratory is used for other purposes such as analyses of the salinity of water samples taken downstream from an injection point in turbulence studies.

ESTIMATED VALUE OF PLANT AND FACILITIES

Building and Appurtenances		
Channel and Headgates (1918)	$13,000	
Gage house and cableway (1921)	3,000	
North wing and penstock (1928)	37,000	
Tower and south wing (1932)	58,000	
		$111,000
Basic Equipment		
Pumps	3,500	
Constant-level tanks	4,000	
Weighing tanks and scales	1,500	
Piping	7,500	
		16,500
Instructional Equipment		
Glass-walled flume	2,250	
Cavitation unit	475	
Oil-flow unit	575	
Fall-velocity tank	120	
Surface-resistance piping	700	
Form-resistance piping	630	
Turbines	400	
Demonstration units	775	
Classroom appurtenances	350	
		6,275
Research Equipment		
Flumes	3,200	
Water tunnel	5,500	
Air tunnel	1,800	
Plumbing stand	750	
Tanks and scales	1,300	
Blowers, pumps, motors	2,300	
Miscellaneous piping	1,700	
		16,550

Instruments		
Flow meters and gages	3,500	
Electrical apparatus	1,600	
Photographic apparatus	750	
Sediment laboratory	500	
Timing devices	150	
Surveying equipment	300	
		6,800
Shops and Stock		
Machine	9,000	
Instrument	3,000	
Carpentry	600	
Plumbing	700	
Welding	550	
Plastic	800	
		14,650
Office Equipment		
Furniture	3,300	
Machines	650	
Drafting	325	
Supplies	250	
Books and reprints	1,500	
		6,025
	Total	$177,800

STUDENT INSTRUCTION

Undergraduate Laboratory

In order that students in the Engineering College may become familiar with general phenomena of fluid motion, a basic course in the mechanics of fluids is given by the Department of Mechanics and Hydraulics in the junior year. *Elementary Mechanics of Fluids* by Professor Rouse is used as the text. This course stresses the fundamental laws of flow, the essential similarity of liquid and gaseous motion being driven home by problems from all engineering professions dealing with fluid motion. Emphasis is upon principles and their application rather than the empirical study of hydraulic equipment.

The corresponding undergraduate laboratory instruction therefore departs considerably from the traditional practice of simply calibrating various flow meters and conduits. While the fluid-me-

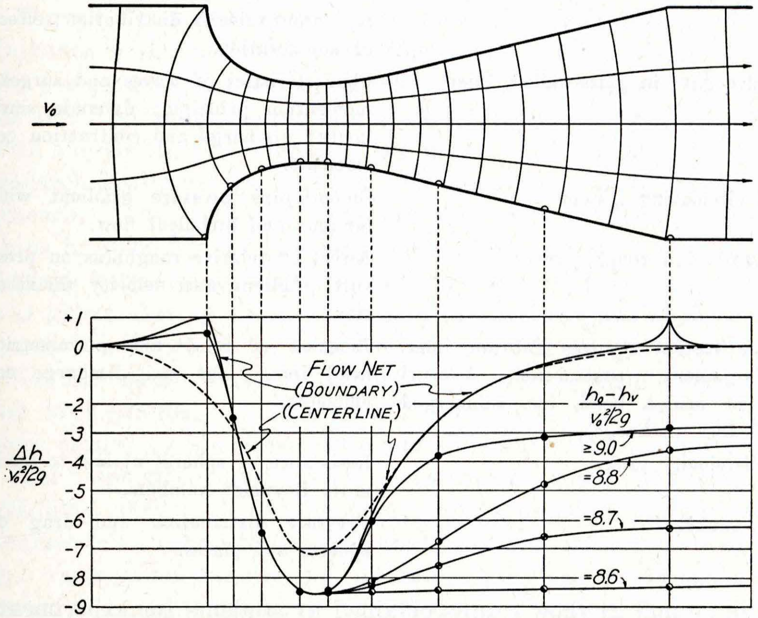

Fig. 20. Distribution of pressure in a two-dimensional Venturi passage at various stages of cavitation.

chanics laboratory contains several pieces of apparatus not unlike those found in conventional laboratories, the experiments differ markedly from the usual type. In general, each experiment requires a rather complete and detailed study of fluid behavior under the influence of particular fluid properties. For example, the experiment on a sharp-crested weir involves the dependence of pressure and velocity distribution in the free nappe upon gravitational acceleration, while the pipe experiments illustrate the effect of viscosity upon the same flow characteristics. The student thus learns through measurement the correlation of classroom principles with actual flow phenomena.

The present fluid-mechanics laboratory apparatus has been described in the previous section. The undergraduate laboratory course contains the following experiments:

Apparatus	*Object of Experiment*
Cavitation unit	Pressure-velocity relations in confined flow through or around various boundary forms.
Weir in glass-walled flume	Shape of nappe; distribution of pressure and velocity; evaluation of flow rate from velocity distribution; effect of non-aeration.
Sluice gate in glass-walled flume	Characteristics of waves and surges; momentum principle; dynamic similarity; discharge and contraction coefficients.
Oil circulating system	Smooth-pipe pressure gradient with laminar and turbulent flow.
Smooth and rough pipes	Effect of relative roughness on pressure gradient and velocity distribution.
Pipe section changes (abrupt inlet, enlargement, contraction, Venturi meter, orifice, bend, tee, submerged and free discharge)	Relation of total- and piezometric-head lines; loss and discharge coefficients.
Fall-velocity tank	Resistance of spheres at low to moderate Reynolds numbers.
Air tunnel	Pressure distribution and drag of spheres and plates.

Figs. 20 and 21 show results obtained by students for experiments on cavitation and pipe resistance.

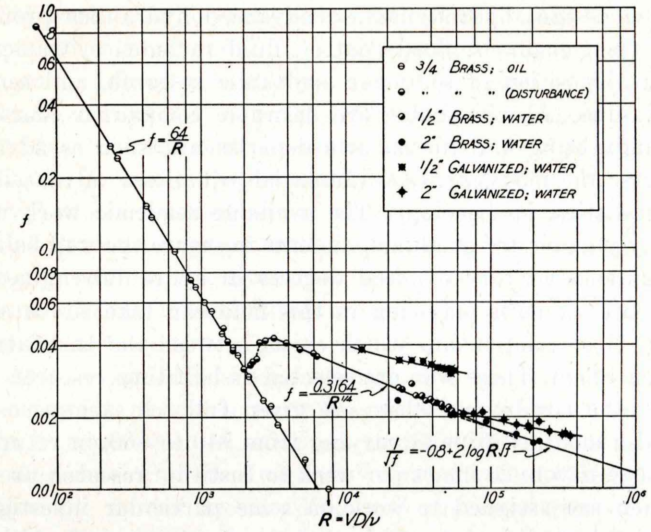

FIG. 21. RESULTS OF STUDENT MEASUREMENTS ON PIPE RESISTANCE VERSUS THE REYNOLDS NUMBER.

GRADUATE RESEARCH

During the development of the Hydraulics Laboratory and the Institute of Hydraulic Research, there was a comparable growth in the postgraduate academic program of the Department of Mechanics and Hydraulics. In the fall of 1921, Professor Nagler arranged with the Graduate College for the granting of two departmental research assistantships. The first master's degrees in hydraulic engineering were conferred upon the recipients of these assistantships in 1922. In the following decade an average of four M. S. degrees were granted each year and in the same period one Ph.D. was given. During the next decade, the average was about eight master's and two doctor's degrees per year. In the period 1922 to 1944, 122 master's and 19 doctor's degrees in hydraulic engineering were granted — a total of 141. Of this number, 25 per cent were earned by students from eight different foreign countries.

The Department now offers a comprehensive curriculum of postgraduate work in hydraulic engineering, the following graduate courses being currently listed in the University catalogue: hydrology, water-power engineering, hydraulic turbines, measurement of water, advanced hydraulics, irrigation and drainage, advanced hydraulics laboratory, hydraulic structures, advanced fluid mechanics, hydraulic design, hydrodynamics, advanced hydraulics problems, flow in open channels, flood control, fluid turbulence, transportation and deposition of sediment, hydraulic research, and seminar in hydraulics. Also available are desirable companion courses in other engineering and liberal arts departments, such as advanced structures, thermodynamics, differential equations, advanced calculus, statistics, and geology. The available academic work makes it readily possible for graduate students to secure the well balanced training required for advanced degrees in hydraulic engineering.

Graduate students majoring in this field can take advantage of the very close relationship which exists between the Institute and the Department. Those who are selected as half-time research assistants by the Graduate College are given full fee exemptions and are paid a monthly stipend varying from $40 to $60, in return for which they devote 20 hours per week to Institute research projects. Such men are assigned to work on some particular investigation under the direction of a member of the Institute staff. Although a research assistant devotes half of each day to such work, he is nevertheless permitted to carry 10 credit hours of work (a two-thirds schedule), and may thus earn the 30 credit hours required for the M. S. degree in two semesters and a summer term.

Students who do not hold research assistantships from the Graduate College may be employed directly by the Institute, the hours and rate of pay depending upon the type of work to be performed. Reduced registration in the Graduate College is then mandatory, since, if the number of work hours per week is high, it has been found advisable to curtail the amount of study. Such positions are also open to qualified undergraduates in related departments. It is thus possible for a student to earn a good share of his expenses, and at the same time to gain valuable experience in hydraulic experimentation. Opportunity to learn about current investigations is provided by occasional meetings of graduate students and staff members at which research findings are discussed.

In general, the research work done by candidates for the master's degree is limited in scope and may not always involve the discovery of new relationships. It is designed principally to benefit the student by confronting him with a specific problem requiring a study of the field, the planning of a research procedure, the organization and analysis of data, and the writing of a comprehensive report. When such a piece of research appears to be valuable to

the profession, it is generally published separately or in combination with other investigations of similar nature. The doctor's dissertation, on the other hand, requires nearly an academic year to complete and is expected to be a definite contribution to technical knowledge. Practically all dissertations are published as articles in technical journals. Experimental thesis investigations by graduate students are carried out in the Hydraulics Laboratory, allocation of space and equipment being made by the Institute. If existing apparatus in the laboratory will not suffice, necessary purchases of additional equipment are made by the Mechanics and Hydraulics Department.

Graduate research has been devoted to a great many subjects, most numerous of which have been investigations of turbulence and the transportation of sediment, model studies of various structures, the behavior of the hydraulic jump, characteristics of rivers, flow through porous media, discharge characteristics of tainter gates and weirs, hydrologic problems, flood-control problems, situations involving the flow of air and water, and problems in open-channel and pipe flow. Copies of all theses and dissertations are preserved in the Institute library and the Engineering College library. Loan copies of theses submitted since 1938 are available at the Institute, and abstracts are included in the Institute bulletins summarizing its researches.

INSTITUTE RESEARCH

General Field of Investigation

The primary purpose of the Institute is the organization and conduct of research projects in various phases of fluid motion, ranging from very practical problems of applied hydraulics to fundamental studies of general fluid behavior. Although most of its investigations are concerned with the flow of water, in recent years extensive experiments have been made with air as the flowing medium, and specific tests have required the use of many other liquids and gases. As is evidenced by the description of laboratory facilities and instructional policy in the foregoing portions of this bulletin, the broad experience and interests of the Institute make it uniquely suited for the study of a wide variety of flow problems.

Such breadth of endeavor is due to the fact that the research program of the Institute has long involved a healthy combination of staff projects of a continuing nature and projects conducted under contract for government and private agencies. While the majority of the staff projects have been of fundamental character, the results are often immediately applicable to engineering practice. Similarly, although contract projects usually deal with the solution of specific problems, in frequent instances the resulting data provide valuable basic information on fluid behavior. Since the ultimate objective of the Institute is to supply the engineering profession with useful facts and methods, the solution of problems submitted by the profession is evidently the most direct means of accomplishing this objective; fundamental research without immediate application in view is nevertheless at least as important a means, for it has repeatedly been proved that such research provides the background information necessary for the solution of even the most practical problems of the future.

In order to indicate the extensive scope of past and present Institute research, the following pages give a general résumé of its activities in certain typical phases of fluid motion. These are arranged, for purposes of coherence, in a series of general categories, only those projects being enumerated which pertain in some way to the particular category in question. Many of the individual top-

ics will be seen to involve a series of graduate theses correlated by a staff supervisor as a continuing project of fundamental nature; these have been partially financed by the Graduate College, the Department of Mechanics and Hydraulics, and professional societies, and the results are on file in the Institute library. Other projects have been conducted by the staff members themselves, often with student help, and financed wholly by the Institute; such results, together with digests of the continuing projects, are almost all available in published form, as either bulletins or reprints designated in the text by number and listed at the end of the present volume. Contract investigations are generally completely financed by the sponsoring agency, and reports are submitted to the agency in question; wherever possible, however, findings of general interest have been made public in printed form as indicated.

Open-Channel Hydraulics

Quite a number of experimental investigations have been concerned with the hydraulic jump, mainly in open channels. An early thesis study by C. M. Stanley classified the various types of stilling-basin action according to the length of basin and the degree of submergence of the normal jump depth; a paper by Mr. Stanley based upon this thesis won the 1935 Collingwood Prize of the American Society of Civil Engineers. Following the Yarnell-

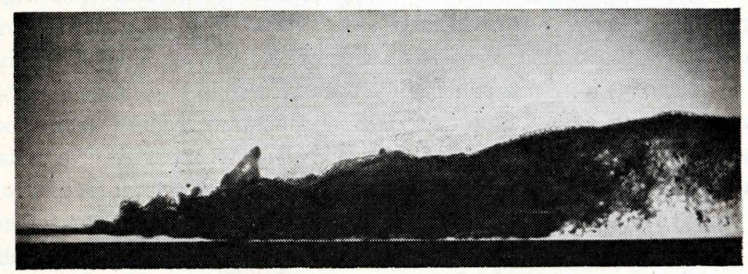

Fig. 22. Silhouette of the hydraulic jump at a Froude number of approximately seven.

Kindsvater project for the Department of Agriculture on the hydraulic jump in a sloping conduit, Professor Lane and Mr. Kindsvater investigated the formation of the jump in a pipe (Reprint No. 8). Later Professor Posey and Pei-Su Hsing studied the jump in trapezoidal channels of various side slopes, devising a formula for the jump length (Reprint No. 8). Further experiments involved the effect of viscosity and surface tension upon the jump at small scale, the characteristics of the traveling jump or surge, and the use of the jump to control the flow beyond a level apron without end sills. In 1945 Mr. Kindsvater was awarded the Collingwood prize for a paper based upon his earlier studies of the jump under Mr. Yarnell.

Under the direction of Professor Lane tests were conducted upon the characteristics of high-velocity flow emerging from a channel upon a level floor, followed by experiments relative to the design of open-channel transitions in such flow. In view of the fact that supercritical flow of this nature is subject to analysis according to the principles of wave mechanics, a continuing project entitled "Supercritical Flow in Open-Channel Transitions" was then organized under the sponsorship of The Engineering Foundation and the Committee on Hydraulic Research of the A.S.C.E. Hydraulics Division, with Professor Rouse as the Institute representative; several graduate theses have provided material for the first and second reports.

An extensive series of tests on the resistance of artificially roughened channels was conducted in the 50-foot Lucite flume of the Institute by Ralph W. Powell in the summer of 1940, the results forming the basis of a paper in the A.S.C.E. *Proceedings* of December, 1944.

Analytical investigations of the problem of the inflow-storage-outflow relationship of gradually varied flow have been carried out under the direction of Professor Posey. Following a comparative study of existing flood-routing methods, a special slide rule was developed for computing the outflow pattern from a level-pool reservoir with fixed outlets for any known pattern of inflow. Later studies (see Woodward and Posey's *Hydraulics of Steady Flow in Open Channels*) extended this technique to include the effects of variable stage-discharge relationships and storage under the backwater curve. The slide-rule method was finally extended to provide an approximate solution of the general case of unsteady flow (Bulletin 27). The inverse problem — that of determining the amount of storage necessary in a fixed-outlet reservoir to accomplish a given amount of flood control — was investigated in a thesis by Fu-Te I, who generalized Woodward's five-sixths rule to an extent that permitted approximation of data from 250 reservoir sites in the United States, England, and China. An adaptation of this method by Professor Posey and Dr. I (Bulletin 26) takes into account any type of stage-discharge relationship that can be approximated by a monomial exponential function.

Model Studies

An early Iowa laboratory project was a series of model tests made in 1929 to determine the benefits from a proposed cut-off of the Des Moines River at Ottumwa, Iowa. The model, representing 9.32 miles of river channel, was constructed to a scale of 1:800 horizontal and 1:100 vertical. The fixed mortar bed was roughened until model profiles corresponded to field observations for the conditions then existing, after which various proposed improvements were tested in the model. This was ". . . . . . probably the first attempt in the United States to determine in advance of actual field construction, by means of models, the benefits to be derived from straightening rivers" (*Trans.* A.S.C.E., Vol. 103, 1938, p. 1923).

Spillway discharge tests on the Keokuk Dam, previously referred to, were made in 1924 by Professor Nagler and Albion Davis. Current-meter measurements of the discharge over the spillway gates

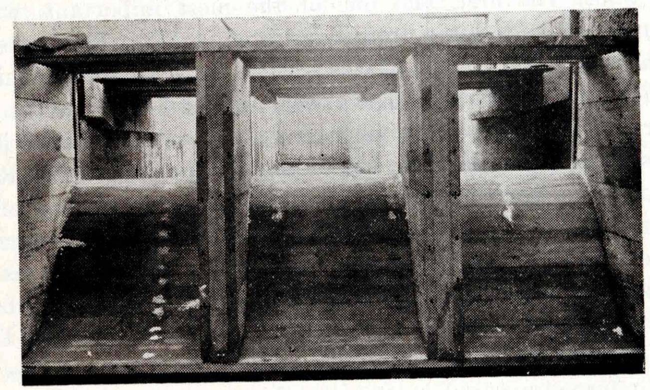

Fig. 23. One of the earliest Iowa models — the Keokuk spillway.

were made for various arrangements of adjacent gates open, but all at nearly constant head. A 1:11 model of three adjacent spillways was tested at the Iowa Hydraulics Laboratory. The model and prototype coefficients agreed within the accuracy of the measurements. For their paper describing this work (*Trans.* A.S.C.E., Vol.

94, 1930), the authors were awarded the 1931 Norman Medal by the American Society of Civil Engineers.

The latter measurements had much influence in convincing American engineers of the value of model tests, and this project was followed by a flood of model studies, both at Iowa and elsewhere. The series of investigations made at the Iowa laboratory by the Department of Agriculture and the Engineer Corps are described elsewhere. Those conducted directly under Institute supervision included two plans for the control of floods on Mill Creek, Milan, Illinois; a comparison of 1:20 and 1:8 model data with corresponding data from the Ralston Creek control structure; and a model-prototype study of the University Dam adjacent to the Hydraulics Laboratory. At present, Institute model techniques are well established in such varied fields as cavitation, thermal convection, ship drag, and wind structure over buildings, as well as the more familiar phases of hydraulic engineering.

Hydrologic Investigations

A number of studies pertaining to hydrologic and hydraulic problems peculiar to the State of Iowa have been made by the Institute staff. The first, and one of the most important, was the Ralston Creek hydrologic project initiated in 1924. This watershed, lying at the eastern edge of Iowa City, is three square miles in area. Five standard rain gages, twelve ground-water wells, and a discharge control and stage recorder have been maintained in continuous operation during the intervening years, making the Ralston Creek record the longest in the country for a watershed of comparable size. In 1941 the Soil Conservation Service contributed five recording rain gages, and records from these stations have since been included with the hydrologic network data published by the Weather Bureau. The runoff record is made by the United States Geological Survey and published in its *Water Supply Papers*. An annual report is written by the research assistant assigned by the Institute to the project. A summary of the data accumulated in the period 1924-35 was published as Bulletin 9 in the Engineering Series. This project is significant as an example of cooperation between various agencies. The Soil Conservation Service pays the rain-gage observers, the U. S. Geological Survey provides the runoff record, the Graduate College of the University supports a half-time student assistant to make field observations and prepare

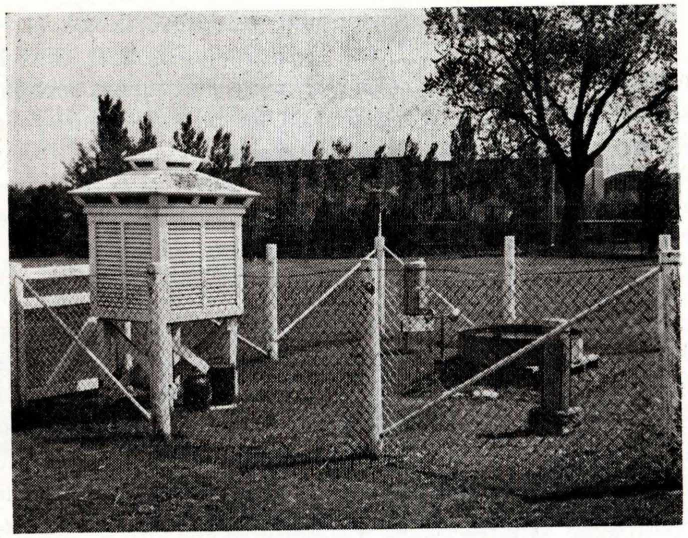

Fig. 24. The Institute evaporation station for hydrologic records.

the annual report, and the Institute provides general supervision.

A related project was begun on the Rapid Creek watershed in 1938. This area lies just north of the Ralston watershed, but has an area above the control of 25 square miles. Observations were begun with the purpose of using this typical area as an index basin in the flood-forecasting work then being initiated by the Weather Bureau. This agency had one recording rain gage in the area and the U. S. Geological Survey maintained two ground-water stage recorders and a stage recorder at the control. In 1941 the Institute interested the Weather Bureau in establishing three additional rain-gage stations in the watershed. Records on runoff and rainfall on this area are included in the data published by the U.S.G.S. and the Weather Bureau, respectively.

In addition to these continuing projects, various studies have been made on the runoff from rivers and small watersheds in Iowa (Reprint 4), on drouths (Extension Bulletin 266), on the variability of precipitation (Reprint 15), and on the relation of ground-water level to the low-water flow of a stream. Numerous other papers of a similar nature have been written by the staff. The most extensive of such studies, reports covering navigation, flood control, power development, and irrigation in the Iowa, Des Moines, and Skunk River valleys (the so-called "308 Reports"), were written by Professor Nagler and submitted to the 71st and 72nd Congresses (H.D. 71-2-134, H.D. 71-3-682, H.D. 72-1-170). These reports provided the data for many subsequent navigation, flood-control, and power proposals and served as a model for similar reports written by the Army Engineers.

Pipe and Conduit Studies

One of the first large experimental projects undertaken at the Iowa Hydraulics Laboratory was the series of tests on the flow of water through culverts conducted cooperatively by the Bureau of Public Roads of the U. S. Department of Agriculture and the State University of Iowa. As described by D. L. Yarnell, F. A. Nagler, and S. M. Woodward in Bulletin 1, more than 3000 tests were made on short pipe culverts of different materials from 12 to 30 inches in diameter and box culverts from 2 to 4 feet square (including intermediate rectangular shapes), with different standard ends and under a variety of flow conditions. Working formulas for the discharge were derived for many commonly encountered conditions.

Typical of the fundamental studies conducted more recently by the Institute staff was an extensive project on the conversion of kinetic to potential energy in flow expansions, sponsored by The Engineering Foundation and the Committee on Hydraulic Research of the A.S.C.E. Hydraulics Division. This project involved the measurement and analysis of the distribution of pressure, velocity, and turbulence along conical expansions of various angles; extending as it did over a period of about eight years (1935-1943), it occupied the time of a large number of graduate students and assistants. Although the project was begun by Professor Mavis, then head of the M & H Department, the major portion of the testing and evaluation of results was performed under the direction of Professor Kalinske, using experimental techniques described in the following section on Turbulence. The complete project was reported upon in the A.S.C.E. *Proceedings* for December 1944.

A study dealing with the simultaneous flow of air and water in a closed conduit was organized in 1941 under the direction of Dean Dawson and also sponsored by The Engineering Foundation and the A.S.C.E. Committee on Hydraulic Research. Experimental work on this project was carried on by Professor Kalinske, with the assistance of graduate students, over a four-year period. The 50-foot Lucite flume described elsewhere was constructed for this

purpose, and observations were made both visually and photographically on resistance and wave phenomena at different relative velocities of water and air.

The Institute has also been honored in receiving the J. Waldo Smith Fellowship of the A.S.C.E. for two successive years, the student recipients being J. M. Robertson and P. H. Bliss in the years 1940 and 1941, respectively. The project these men studied was concerned with the removal of air from pipe lines, and was carried on under Professor Kalinske's direction. A detailed study

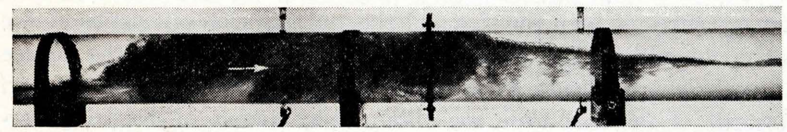

Fig. 25. Formation of the hydraulic jump in a closed conduit.

was made of the air-entrainment characteristics of a hydraulic jump in a closed conduit, since it was found that the breaking front of a jump in a partially filled sloping pipe was the primary means by which air was removed. Data were obtained which related the pipe slope, pipe size, and water velocity to the rate of air removal. The results of this project are published in two A.S.C.E. papers (Reprints 40 and 56).

In addition to such experimental investigations, analytical studies by the staff and graduate students have appreciably advanced present-day understanding of conduit resistance. Papers on the resistance of smooth and rough pipes have been published by Professor Kalinske (Reprint 10), and Professor Rouse devised a general resistance diagram applicable to many commercial boundary materials (Reprint 36).

Turbulence Investigations

An early approach to the turbulence problem was made in a cooperative project of the Bureau of Public Roads and the State University of Iowa, reported upon in an A.S.C.E. paper of 1931, "Effect of Turbulence on the Registration of Current Meters"; this paper won the James R. Cross medal for its authors, D. L. Yarnell and Floyd Nagler. In the course of the investigation tests were made on a number of different types of current meters held stationary in a stream of water of controlled turbulence, the results showing primarily that cup meters overregister in turbulent water, while propeller meters underregister. These experiments were conducted, it must be noted, some time before turbulence characteristics were broken down into independent length and time scales, the study of which has formed a major part of more recent research conducted by the Institute.

Two essentially different methods of analysis have come to form the basis of turbulence measurement. The first consists of recording the temporal variation of the velocity at various points in the flow under study, statistical evaluation of such time records yielding measures of both the size and the velocity characteristics of the turbulent eddies. The second involves determination of the degree of turbulent diffusion existing at various points in a given flow. Records of the first type are obtained by means of sensitive current meters or anemometers or by photographing with a movie

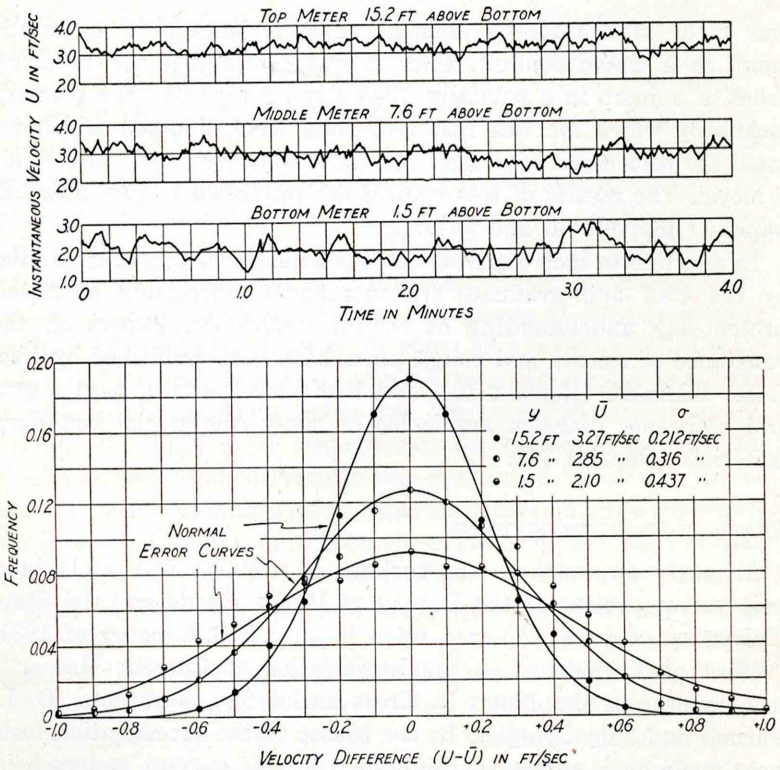

Fig. 26. Statistical analysis of velocity fluctuations in the Mississippi River.

camera the paths of finely dispersed liquid or solid particles suspended within the moving fluid. Diffusion measurements are made through use of dye or saline solution injected into flowing water or gas injected into moving air, with either visual or electrical methods of determining angularity or concentration gradients. Since data of this nature are significant only after painstaking statistical analysis, the great amount of time involved in evaluating the results of tests is obvious.

Institute research on turbulence during the past eight years has provided material for a series of student theses, and a number of papers have been published on the subject by Professor Kalinske, under whom the work was conducted (Reprints 20, 24, 26, 37). The background of fundamental knowledge acquired by the Institute in this manner has also been applied to the investigation of many practical problems, such as suspended-material transport, air entrainment by flowing water, fluid drag on various bodies, the separation of grease from water, and mixing phenomena involved in the operation of hydraulic equipment. Such knowledge proved particularly useful in contributions by the Institute to methods of sediment analysis and in war research for the armed services.

Research on Sediment

In the control of the rivers of the United States, problems resulting from the erosion, transportation, and deposition of sediment are continuously increasing in importance. The Iowa Institute has had an especially active part in seeking the solution of these problems, particularly in two specific fields of study. One is the investigation of laws governing the transportation of sediment by flowing water, and the other is the improvement of methods used in the measurement and analysis of sediment loads of rivers. Investigations in the first of these fields have been carried on largely as student theses and as projects of the Institute staff. Work in the second field has been conducted as a cooperative project with various Government agencies which are interested in the sediment problems of this country; the latter phase of the research is described in another part of the bulletin.

The Institute studies to formulate the laws of sediment transportation may further be subdivided as follows: (1) those concerned with the movement of coarse material near the stream bed, and (2) those dealing with the movement of sediment carried in suspension. The work with coarse material has formed the basis of some five thesis investigations since 1933, largely under the direction of Professor Mavis. The experiments involved the measurement of the quantity of material moved in a uniform flume under various conditions of velocity and depth of water, the major portion of the results being summarized in Bulletins 5 and 11. More recently W. C. Krumbein, under a special Guggenheim Fellowship, made a laboratory study at the Institute of the behavior in flowing water of coarse, non-uniform particles as a function of form and fall velocity; these tests are described in the American Geophysical Union *Transactions* for 1942.

Theoretical and experimental studies of suspended load at the Institute have been principally under the direction of Professors Lane and Kalinske. Perhaps the most important contribution of these writers was the determination of a relationship between the amount of material in suspension, the turbulence of the stream, and the bed composition (Reprint 28). Experimental studies on some of the fundamental aspects of turbulence and suspended-material transport in open channels have formed the basis of several doctoral dissertations under Professor Kalinske (Bulletin 29 and Reprint 27), and a general résumé of the theory of sediment suspension has been prepared by Professor Rouse (Reprint 21).

Correlation of the theoretical and experimental investigations with field measurements has also been stressed in the Institute program. For example, field data have been obtained and analyzed for the Mississippi and other sediment-laden streams, and the Institute conducted an extensive laboratory investigation of a specific sediment transport problem for the Loup River Public Power Authority of Nebraska. Despite the practical nature of these studies, they have invariably thrown considerable light on the theories being developed. Thus the analytical and the applied aspects of the problem have progressed hand in hand in this important phase of Institute activity.

Intermediate between the phenomena of sediment transportation by water and the percolation of water through sediment is the problem of uplift under conditions of vertical seepage. The theory of this phenomenon was developed and checked experimentally in a graduate thesis under Professor Rouse (Bulletin 26 and Reprint 47), the study being carried to the extreme degree

of complete sediment suspension in the upward flow. Other theses conducted under Professor Mavis were concerned with the permeability of sand, capillary flow through sand dams, and groundwater profiles, as functions of the type, grading, and porosity of the pervious material and the temperature of the water (Bulletins 7 and 18).

Fishways

In 1937 studies were undertaken by the Iowa Institute, at the request and with the financial support of the Iowa State Conservation Commission, to develop forms of fishways which would waste a minimum amount of water and yet would permit fish to pass dams as freely as possible. The project consisted of a thorough review of the world's literature on fishways, experiments on fishway models both without and with small fish, and finally tests of actual structures.

The review of the literature was largely the work of Dr. Paul Nemenyi, and an extensive bibliography was made available in Bulletin 23. This publication gives brief summaries of articles on the subject from all known sources. The following experiments on models — some 45 in all — were made to check the performance of known fishway designs, and to seek improvement of construction and efficiency. While such studies at model scale were undertaken with full confidence in the accuracy of prototype indications, it was not known whether the behavior of small fish could likewise be extrapolated. A number of species supplied by the Conservation Commission could nevertheless readily be induced to ascend the

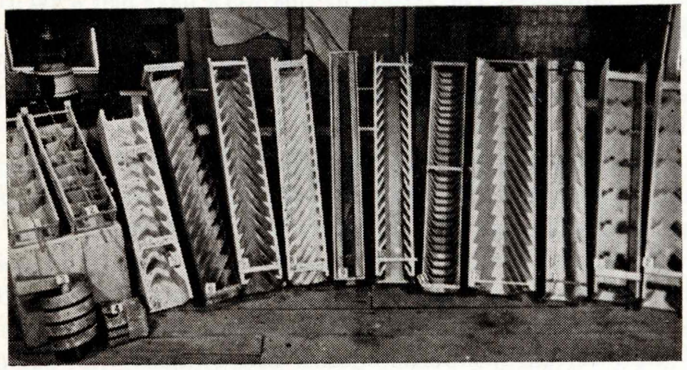

Fig. 27. Typical fishways studied by the Institute.

channels, and their action shed considerable light on the relative desirability of the various types of construction.

Tests of full-size fishways were conducted in the 10-foot channel leading directly from the Iowa River Dam to the laboratory, some 11,000 fish of 15 different species being trapped and classified after passage. Many of the structures used were modifications of a type developed by Denil in Belgium; ladders using his principle of design proved superior to the others tested, but appeared too fragile for American conditions of operation. A very simple and rugged Denil-type fishway was finally devised which used very little water.

In addition to showing the relative advantages of the various existing types of fishway and improvements thereon, these experiments yielded considerable information on the migrating habits of native fish. Careful records of the weather conditions, water temperature, and related factors which might affect the movement of fish indicated (1) that little action could be expected below a temperature of 65°, (2) that the period of greatest activity occurred between May 15 and July 15, and (3) that flow conditions at the foot of the fishway played a major role in attracting fish. The experimental phases of the investigation were under the direction of A. M. McLeod, and are described in Bulletin 24.

Plumbing Research

For the past seven years the National Association of Master Plumbers has financed research work at the Institute on various hydraulics problems relating to the water-supply and drainage systems of buildings. The results of this work have had a far-reaching influence on plumbing codes throughout the country. The work has provided the basis for sounder government regulations and has indicated the importance of good plumbing in its relation to public health.

One of the most significant investigations conducted under this program was concerned with back-siphonage through plumbing fixtures with the consequent possibility of polluting the water supply in buildings. Extensive studies were made relating to the hydraulic conditions producing vacuums in piping systems. Tests were made on numerous plumbing fixtures and methods were developed for certain protection against back-siphonage. A summary of all this work was published in 1938 by the N.A.M.P. as Technical Bulletin No. 1, entitled *Plumbing Cross-Connections and Back-Siphonage Research*, by Dean Dawson and Professor Kalinske.

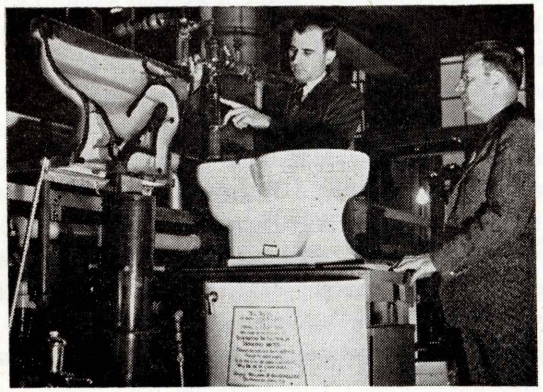

Fig. 28. Plumbing units used in demonstrating back-siphonage.

Another very extensive investigation was concerned with the hydraulics and pneumatics of the plumbing drainage system. The flow of mixtures of air and water in the sloping and vertical plumbing drains is a complex phenomenon about which practically no definite information existed. The results of this investigation were published in 1939 by the N.A.M.P. as Technical Bulletin No. 2, under the authorship of Dean Dawson and Professor Kalinske. This bulletin provided data for use in setting up tables for drainstack and vent sizes in plumbing codes, and it has been widely used by those concerned with developing and revising plumbing codes.

The water-supply side of the plumbing system, so far as code regulations are concerned, has been grossly neglected. To assist in correcting this deficiency the Institute gathered together existing data relating to design of piping systems in buildings and, where necessary, augmented it with further research. This material was published in 1942 as Bulletin No. 3 by the N.A.M.P. under the authorship of Dean Dawson and Professor Kalinske.

Ship-Model Tests

Models of ships and other surface craft have always been tested by towing in a basin of still water. Models and parts of airplanes tested in wind tunnels, on the other hand, are held stationary in a moving stream of air. Theoretically, such flow phenomena depend only on the relative motion between the body and the fluid, and therefore it should be immaterial whether the body or the fluid moves. It has been realized for some time that certain phases of the hydrodynamics of surface craft could be studied more conveniently if the model were stationary and the water moved past it. However, it was also realized that there would be certain difficulties in using a moving stream of water with a free surface — for instance, surface oscillation, surface slope, non-uniform velocity distribution in the channel cross-section, and turbulence. The David Taylor Model Basin of the U. S. Navy nevertheless decided to construct, as part of its experimental equipment, a recirculating water channel in which models of surface craft could be held stationary for tests of any desired duration. Such a channel has now been built at the Model Basin, the test section being 22 feet wide and 10 feet

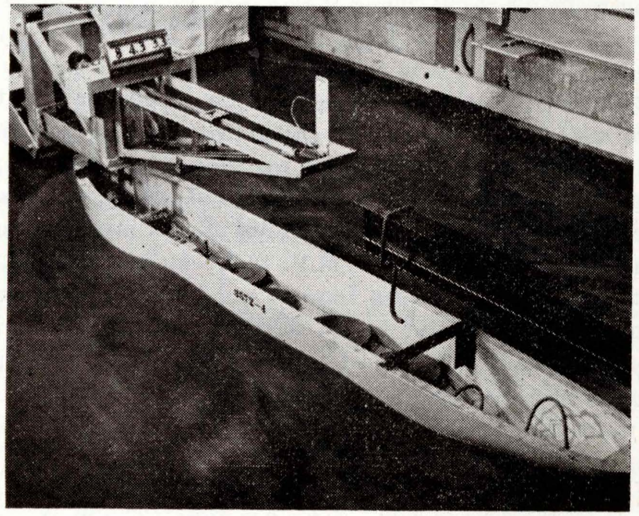

FIG. 29. RESISTANCE TESTS ON A MODEL FREIGHTER IN THE 10-FOOT CHANNEL.

deep and the pumps being capable of producing a maximum velocity of 15 feet per second in the test section. So far as is known, this is the largest equipment of its kind in the world.

In order that the Navy engineers might have a preview of some of the problems that would be encountered in using stationary ship models and moving water, in 1942 a project was arranged under Professor Kalinske in which the two large channels of the Institute

laboratory, which are supplied with water from the pool above the dam, would be used for fundamental studies of flow around stationary ship models. For about two years, while the recirculating channel of the Navy was under construction, the Institute tested several sizes of a particular ship model at various depths of water in channels varying in width from 10 to 16 feet. Measurements were made of surface slope, velocity distribution, drag, pressure at various points on hull, sinkage, and wave profile for comparison with data obtained on the models when towed in still water. In a doctoral thesis, W. S. Hamilton also measured the velocity distribution (both magnitude and direction) completely around one of the model hulls. This is the first time such data have ever been secured for a stationary ship model in moving water.

Studies were later made to determine the influence of the turbulence present in the flowing water on the drag measurements of ship models, submerged spheres, and a catamaran friction plane. These bodies were located at varying distances behind screens of different mesh sizes placed in the test section of a channel 11 feet wide with 4.5-foot water depth. The studies were planned to provide fundamental data relating to the control of turbulence in the recirculating channel of the Model Basin.

WAR RESEARCH

While the ship-model tests conducted by the Institute for the David Taylor Model Basin were undoubtedly prompted by the imminence of war, the entry of the United States into armed conflict brought further indication of the role that could be played by a hydraulics laboratory as a war-research organization. It is of considerable significance, so far as the breadth of interest of the Institute staff is concerned, that early in 1943 arrangements were made through Division 10 of the National Defense Research Committee for construction in the Institute laboratory of a low-velocity air tunnel to be used in the investigation of atmospheric diffusion problems for the Chemical Warfare Service, under the direction of Professor Rouse. Before this project was well under way, a higher-priority model study of heat requirements for fog dispersal over airplane runways was undertaken in the air tunnel for the Bureau of Aeronautics of the Navy, and tests on the burner and wind-curtain methods of eliminating fog continued throughout 1944. In 1945 the CWS project was resumed under Professor Kalinske, together with preliminary measurements on atmospheric diffusion over mountainous terrain for the Army Air Forces. With the termination of the war and of the NDRC contract, a direct contract

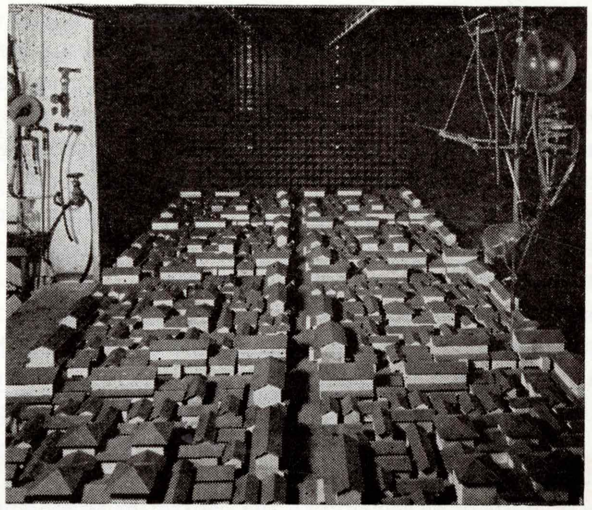

FIG. 30. MODEL OF AN URBAN DISTRICT USED IN AIR-TUNNEL STUDIES OF GAS DIFFUSION.

was arranged with the Army Air Forces for continuation of the meteorological investigations. The research techniques developed in these projects, as well as the air-tunnel facilities themselves, should find broad post-war use in such fields as evaporation, wind pressure, and smoke abatement.

In the early summer of 1944, use of the Institute's new variable-pressure water tunnel was requested by the David Taylor Model Basin through Division 12 of the NDRC, and Professor McNown began tests on the pressure distribution around a systematic series of body forms under various stages of cavitation. This contract was eventually transferred to Division 6 of the NDRC, and the project was finally made an integral part of an extensive program under direct contract with the Bureau of Ships of the Navy. Although these water-tunnel tests were conducted specifically for military purposes, the experience gained in operation of the tunnel and in evaluating cavitation measurements will have considerable bearing upon the peacetime study of similar problems in the design and operation of hydraulic structures and machinery.

The direct contract with the Bureau of Ships, originally written in March, 1945, for the continuance of the water-tunnel tests, rapidly expanded to include a number of other investigations for the Navy. Principal among these was an extensive series of developmental studies of fire monitors for the Coast Guard. Existing 3-inch and 6-inch monitors were believed to be relatively inefficient instruments for concentrating a fire stream upon a target a hundred or more feet away, and the Institute was requested both to investigate the characteristics of present monitors and nozzles and to devise improved forms. A battery of 8 engine-driven fire pumps was mounted on a platform at the south end of the building, the 10-foot channel was converted into an enclosed 100-foot test gallery, and a special sampler, profilometer, and Pitot tube were constructed for determining the jet characteristics at successive sections. Following thorough calibration of the monitors, and of the nozzles themselves through independent mounting, both the monitor and the nozzle were improved to such an extent, through elimination of all

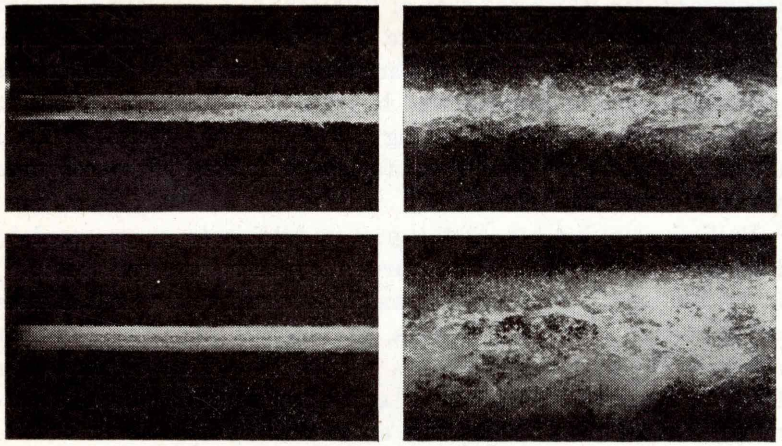

FIG. 31. HIGH-SPEED PHOTOGRAPHS OF $1\frac{1}{2}$-INCH FIRE STREAMS: LEFT, AT NOZZLE; RIGHT, 25 FEET DOWNSTREAM; TOP, IOWA MONITOR; BOTTOM, COAST GUARD MONITOR.

possible sources of turbulence, as to produce a 900% increase in the maximum concentration of the jet at 90 feet.

The Bureau of Ships contract also included the following projects: (1) The completion of the drag tests in the 16-foot channel, using the sphere method of evaluating the degree of turbulence to which the ship models were subjected during the tests; spheres of

10-inch, 14-inch, and 18-inch diameters were used, the differential pressure between front and rear piezometers being determined as a function of the Reynolds number. (2) The development of apparatus for application of the electrical analogy in three dimensions to problems of velocity and pressure distribution around streamlined bodies of various forms. (3) The evaluation of the characteristics of flow through a systematic series of screens, including the loss of head, the adjustment of asymmetrical velocity distribution, and the degree of induced turbulence and its decay with distance downstream; the latter measurements were conducted in the air tunnel, with supplementary checks in the 16-foot water channel.

Laboratory Design

In the fall of 1944 the National University of Colombia, at Bogotá, sent Professor L. E. Orduz to the United States to arrange for the design and construction of equipment for a new hydraulics laboratory, for which the sum of $100,000 had been appropriated. The extensiveness of the Institute facilities, and the fact that much of the equipment — in particular the new units for student instruction — had been duplicated by other laboratories in this country, eventually led to the signing of a contract between the Institute and the National University for the complete design and supervision of construction.

Preliminary sketches of the proposed laboratory, prepared by Professor Rouse, called for a three-story structure approximately 50 by 100 feet in plan. The basement contained reservoir and measuring basins, pumps and blowers, and a small shop. The first floor, arranged for student instruction, provided for small air and water tunnels, a glass-walled flume, a small towing tank, water-jet and air-jet units, turbine and pump stands, a Reynolds demonstration tank, pipe systems for resistance studies of air and oil as well as water, a reversible-flow filter, a water-hammer unit, and a section for demonstrating and testing plumbing equipment. The second floor, intended for hydraulic-model studies, included a large model basin, a current-meter towing tank, a glass-walled channel, and a percolation tank, with considerable space for temporary model installations. The third floor provided space for offices, a lecture hall, library, and a constant-level tank.

After approval of the preliminary design, the Institute staff prepared in the winter of 1945-46 complete details and specifications for all experimental equipment. Since the contract included the securing of bids and inspection of equipment, at the time the present bulletin went to press the Institute was beginning negotiations for the construction of the various items involved in the final plans. Arrangements were also being considered for the employment of a member of the Institute staff by the National University to supervise the installation and initial testing of equipment in the new laboratory. With the completion of this project, the facilities of the Bogotá laboratory, although less extensive, will be far more modern than those of the Institute itself. In view of the proposed expansion of the Institute, the further experience thus gained in the design of research equipment should result in noteworthy additions to its present plant.

COMMERCIAL TESTING

Though the Institute is not interested in undertaking routine testing of the kind which can readily be handled by commercial laboratories, it does do testing work of a specialized type for which its facilities and staff are particularly suited. The Institute is especially desirous of conducting work of this nature for which it has developed a background of knowledge through previous research. Such commercial testing is considered a valuable part of the Institute's activities, since it brings the staff in contact with practical problems, and permits direct application of the fundamental investigations which the Institute is carrying on in the broad field of fluid mechanics. A few examples of test projects handled by the Institute are described below.

The program of studies conducted by the Institute on the problem of back-siphonage and water pollution in the plumbing system resulted in the arrangement of Institute tests on a large number of protective devices known as vacuum-breakers and backflow-preventors. Boards of health and plumbing inspectors throughout the country relied on the Institute's findings in determining whether or not such devices would be permitted. The tests made were far from being routine, since considerable background knowledge relating to the back-siphonage problem was necessary in order that the test results could be properly interpreted.

The Institute has for many years been engaged in research and testing relating to grease interceptors as used on kitchen and restaurant sinks and dish-washers, and has been instrumental in developing testing standards and methods of rating for such interceptors. During the war large numbers of grease interceptors were required in the kitchens of army cantonments and similar establishments. With the cooperation of the construction branch of the Army Engineers and the interceptor manufacturers, a standard test method was developed. Any type of interceptor, before it could be installed in an Army camp kitchen, had to have a rating certificate from the Institute. A hundred or more makes of interceptors were tested under this program, and the Institute assisted many of the manufacturers in revising their designs to yield more efficient performance.

In 1943 the Dow Chemical Company of Midland, Michigan, was interested in having tests made on their plastic (Saran) tubing and fittings in regard to their use for water-supply piping in buildings. The Institute tested the tubing and fittings under various conditions existing in water-piping systems. Strength tests over a wide range of water temperature were made; water-hammer tests indicated the strength of the joints under shock; and friction-loss measurements revealed the smoothness of the tubing. Because of certain failures that occurred under the water-hammer tests, suggestions were made and accepted for improvements in the fitting design.

The Thompson Products Co., of Cleveland, Ohio, developed a special type of joint closure permitting oil and gasoline lines in airplanes to be quickly disconnected. An extensive series of tests was conducted at the Institute to determine quite accurately the losses in various sizes of these fittings as functions of the Reynolds number.

In addition to these examples, the Institute has conducted many other tests of a similar nature on new forms of pipe fittings, automatic valves, and flow meters. Aside from such tests, the Institute has, in several instances, undertaken special development work for commercial concerns on problems and products which were of special interest. Charges are generally based upon actual cost of time and materials plus a fixed percentage of such cost for overhead.

COOPERATING AGENCIES

Various Forms of Cooperative Agreements

In addition to the various research projects conducted by the Institute staff under contract with Federal agencies, a considerable amount of research, testing, and systematic gathering of hydraulic data is performed on Institute premises by representatives of the agencies themselves. Federal representation of this nature has ranged from single employees sent by certain agencies for temporary participation in specific projects, to as many as forty full-time staff members of a sub-office established at the laboratory for a continuous program of experimentation.

So far as the Institute is concerned, such direct contact with many different phases of applied hydraulics has provided a very desirable counterpart to the more fundamental aspects of its own staff endeavors. In many instances, indeed, the problems brought to the Institute by these agencies have either provided a stimulus for further basic research or put to use principles determined through previous studies. Although, as a general rule, the projects brought to the Institute by the various agencies are handled by their own staff members, there is usually a considerable interchange of ideas, and reports and data are always made mutually available. In the case of joint projects among several agencies, moreover, the Institute frequently serves as the coordinating organization.

Cooperative arrangements of this nature vary somewhat in form, depending in part upon the nature of the Federal agency and the role which it plays in local or state activities, and in part upon the extent to which the facilities of the Institute are involved. Under some circumstances the Institute is considered to represent the State of Iowa as a contributor of funds and services to be matched by the Federal Government in hydraulic engineering work which will benefit the State. Under other circumstances, laboratory facilities are rented on a contract basis to the Federal Government for experimental purposes. Finally, the Institute itself has frequently contributed both facilities and staff time to cooperative projects of a general scientific nature.

U. S. Department of Agriculture

The first Federal agency to use the hydraulics facilities at the University of Iowa was the Department of Agriculture, a project organized in 1921 under the direction of Mr. Yarnell continuing until his death in 1937. As the branch of this agency originally involved was the Bureau of Public Roads, a great many of the problems which it studied were concerned with highways and bridges. When the work first began, the staff of the Institute was drawn upon heavily for technical advice, but as time passed the Federal group became self-sufficient, and eventually had to its credit a series of well known publications describing its accomplishments.

One of the earliest investigations undertaken in the Iowa laboratory by the Bureau of Public Roads was a study of the hydraulics of road culverts, to improve the design of these structures in order that they might discharge a maximum quantity of water at minimum cost. The experimental program included an evaluation of roughness effects, an investigation of the influence of headwall and inlet form, and a determination of the losses in box culverts. The results were published by Messrs. Yarnell, Nagler, and Woodward as Bulletin No. 1 of the Iowa Studies in Engineering, the supply of which has long since been exhausted except for several much-used loan copies.

Another study made in cooperation with the Bureau of Public Roads dealt with the flow of water over railway and highway embankments. A full-scale embankment section was installed in the channel of the laboratory, and discharge tests were made with both single- and double-track rails; further tests with rails removed simulated flow over highway embankments. From the flow relationships thus determined it was possible to estimate rates of discharge which had occurred in several controversial cases of flood overflow. The results of these studies were published by Mr. Yarnell in the "Flow of Flood Water over Railway and Highway Embankments," *Public Roads*, April, 1930. The Bureau also carried on extensive tests to determine the obstruction effects of bridge piers and pile trestles on the flow in streams and rivers. Tests on both full-scale structures and models were conducted in the 10-foot channel and smaller flumes. These experiments were described by Mr. Yarnell in the U. S. Department of Agriculture Technical Bulletins 412 and 429, *Bridge Piers as Channel Obstructions* and *Pile Trestles as Channel Obstructions*.

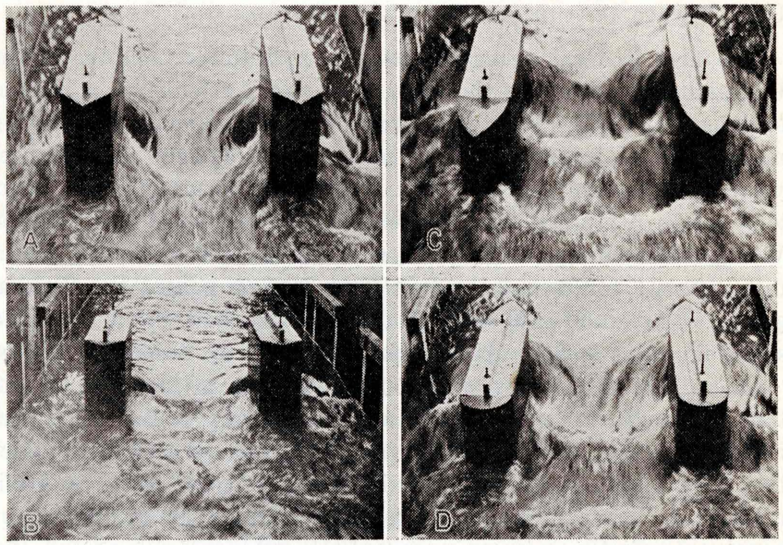

FIG. 32. REPRODUCTION FROM YARNELL REPORT ON FLOW OBSTRUCTION CAUSED BY BRIDGE PIERS.

Following the change from the Bureau of Public Roads to the Bureau of Agricultural Engineering as the Department of Agriculture agency at the Iowa Institute, a cooperative project was conducted on the flow of water in conduit bends. Experiments were made in transparent conduits and pipes to determine the nature of the secondary currents, and particular attention was paid to the flow resistance in its relation to the distribution of velocity in the approach section. These tests were described by Messrs. Yarnell and Nagler in the *Transactions* of the A.S.C.E., Vol. 100, 1935, and by Messrs. Yarnell and Woodward in U. S. Department of Agriculture Technical Bulletin 526, *Flow of Water around 180-Degree Bends.* Perhaps the best-known paper prepared by Mr. Yarnell for the Bureau of Agricultural Engineering is that dealing with the intensity-frequency of rainfall of short duration. The records of some 28,000 storms from all parts of the United States were analyzed, and the data were reduced to a series of tables and charts indicating such useful information as expected maximum precipitations for 2- to 100-year intervals and for various rainfall durations from 5 to 120 minutes, most severe rainfalls at each recording station in the country, and probable excessive storms in various sections for each month of the year. The paper appeared

as U. S. Department of Agriculture Misc. Pub. No. 204, 1935.

Following the death of Mr. Yarnell in 1937, representation of the Department of Agriculture at the Institute was continued through the Soil Conservation Service, the staff member in charge of the Institute acting as Collaborator. Aside from such cooperative projects as the sediment investigation described under a separate section, the Service maintains a certain amount of equipment at the laboratory and supports the continuous hydrologic project at Ralston Creek.

U. S. WEATHER BUREAU

From 1938 to 1942 a branch office of the flood-prediction service of the U. S. Weather Bureau was maintained in the Institute laboratory under the direction of Mr. B. S. Barnes. This organization was engaged primarily in developing more scientific methods of flood prediction, but cooperated to a considerable degree in the Institute program of hydraulic research.

U. S. GEOLOGICAL SURVEY

Through the joint efforts of Professor Nagler and Mr. N. C. Grover, then Chief Hydraulic Engineer of the U. S. Geological Survey, cooperation was inaugurated in 1932 between the Institute and the Water Resources Branch of the Survey, and a district office of the Surface Water Division was established at the Institute laboratory under Mr. R. G. Kasel as District Engineer. The primary function of this office is the measurement of the stage and flow of Iowa streams in collaboration with the Iowa Geological Survey and other interested agencies. However, extensive participation in the Institute program of hydrologic research was arranged by Messrs. Nagler and Kasel, and further expansion of this program has been accomplished by Mr. L. C. Crawford, who succeeded Mr. Kasel in 1940.

As a result of such close relationship between the Survey and the Institute, some five thousand dollars of municipal and state funds are made available annually through the Institute to be matched equally by the Federal Government for the maintenance of stream-gaging stations through the State of Iowa. Perhaps the most immediate benefit to the State of such cooperation is indicated by the fact that inquiries as to stream stage and flow from all parts of the State are received and answered daily by the Survey staff;

similar service is rendered through the publication of a series of Iowa Geological Survey Water Supply Papers based upon data determined and analyzed by the Federal office at the Institute laboratory. Due to the close participation of this office in the co-

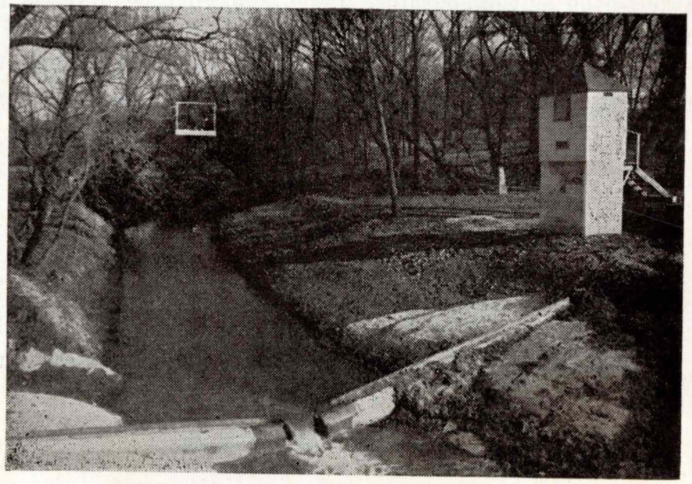

FIG. 33. ARTIFICIAL CONTROL, GAGE HOUSE, AND CABLEWAY ON RAPID CREEK.

operative sediment project later described, routine measurement of the sediment load as well as the discharge of Iowa streams is also being made.

Of particular importance to the educational aspects of such cooperation with a Federal agency is the fact that one of the graduate assistantships provided by the University involves part-time work in the Survey office in the evaluation of Ralston and Rapid Creek runoff records. The annual reports on this experimental project, prepared by the graduate assistants, are of considerable interest to the Geological Survey and the Soil Conservation Service, which cooperate in the project sponsorship, since the discharge and ground-water records cover a longer period than those of any comparable watershed in the country.

U. S. ENGINEER DEPARTMENT

By far the most extensive cooperative arrangement between the Iowa Institute and a Federal agency has been that inaugurated by the U. S. Engineer Department in 1929 and continued thereafter without interruption. Mr. Martin E. Nelson was the initial super-

visor of this program, remaining in residence as Engineer-in-Charge of the Iowa City Sub-Office until 1942; at that time he was transferred to the St. Paul District Office, but has maintained general direction of the laboratory work through regular inspection trips.

Because hydraulic-model testing was in its infancy at the time the cooperative agreement was first made, the early work conducted under this arrangement was of general scientific interest, and very close collaboration between the Institute staff and that of the Engineer Department was essential to the rapid progress which was made in developing experimental techniques. As the various test procedures became perfected, the work of the Sub-Office developed largely into the solution of specific engineering problems from the St. Paul and neighboring districts. A staff of considerable size and ability was gradually formed, and many who thus served their ap-

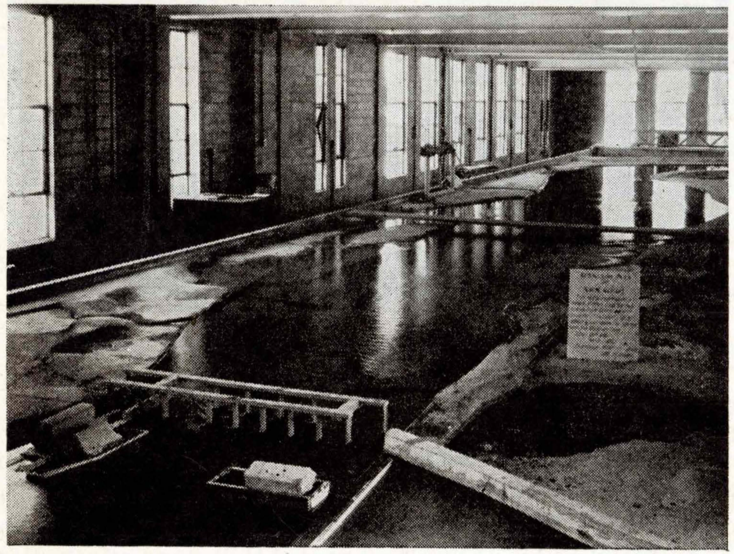

FIG. 34. MODEL OF THE MISSISSIPPI RIVER AT ALTON, ILLINOIS.

prenticeship at Iowa City are now in charge of similar projects in various parts of the country. In addition, a number of new instruments developed for local use have also found application in other government and university laboratories.

Owing to the nature of the hydraulics problems in this portion of the country, practically all of the model investigations conducted by the Engineer Department in the laboratory of the Iowa Institute have dealt with the improvement of rivers for navigation, with particular emphasis upon the design of locks. Models for fifteen localities on the Mississippi between St. Paul and St. Louis have been tested, as well as others on the Ohio, Monongahela, Kiskiminitas, Kanawa, Clinch, Illinois, St. Marys, and Tennessee Rivers. Some of these have involved general model studies over considerable reaches of the rivers in question, others have been restricted

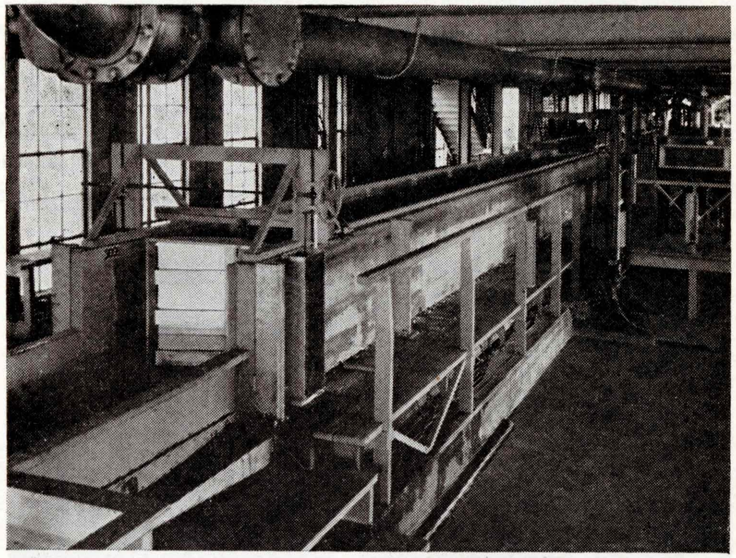

FIG. 35. MODEL OF THE MACARTHUR LOCK, SAULT STE. MARIE.

to the investigation of specific dam profiles and the elimination of scour downstream, and many have involved the detailed analysis of the filling and emptying systems of navigation locks. In addition to the laboratory studies, tests were also made on prototype locks on the Ohio and Tennessee Rivers to correlate model and field data. The apparatus used in the performance of these tests was developed by the Iowa City Sub-Office.

Fifty-one extensive reports have been prepared for the War Department on the results of these model experiments, some of which involved information which could not be given general circulation owing to wartime restrictions. However, the findings of the investigation on the Hastings Dam were prepared for publication (Bulletin 2) by Mr. Nelson, who also discussed the manifold problem in

its bearing upon lock design in the *Proceedings* of the First Hydraulics Conference (Bulletin 20).

COOPERATIVE SEDIMENT STUDIES

Six governmental agencies — namely, the Office of Indian Affairs, the Bureau of Reclamation, the Tennessee Valley Authority, the Corps of Engineers, the Geological Survey, and the Department of Agriculture — in collaboration with the Iowa Institute began in 1940 a rather extensive study on methods to be used in determining the quantity and size distribution of sediment carried by American streams. The program, as conducted over a period of more than six years, was divided into the following phases of endeavor: (1) An exhaustive study of methods already in use throughout the world. (2) The critical examination of such methods in the light of recent developments in fluid mechanics. (3) The development of more dependable measuring apparatus and techniques. (4) Thorough field testing of the methods developed, with the aim of further refinement.

Under the direction of Professor Lane, several years of activity in the Institute laboratory on the part of representatives of the six agencies resulted in the preparation of the following reports under the general heading "A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams":

Report No. 1. Field Practice and Equipment Used in Sampling Suspended Sediment.
Report No. 2. Equipment Used for Sampling Bed-Load and Bed Material.
Report No. 3. Analytical Study of Methods of Sampling Suspended Material.
Report No. 4. Methods of Analyzing Sediment Samples.
Report No. 5. Laboratory Investigation of Suspended Sediment Samplers.
Report No. 6. The Design of Improved Types of Suspended Sediment Samplers.
Report No. 7. A Study of New Methods of Size Analysis of Suspended Sediment Samples.
Report No. 8. Measurement of the Sediment Discharge of Streams.
Report No. 9. Density of Sediments Deposited in Reservoirs.

These reports were published by the St. Paul U. S. Engineer District Sub-Office at the Hydraulics Laboratory of the Institute and are available at cost.

Three instruments developed in the course of these studies are worthy of mention. The first is the Depth-Integrating Sampler, which is designed to withdraw from the stream as it is lowered from surface to bottom a continuous sample of the sediment-water mixture at a rate which is proportional to the local stream velocity. The second is the Point-Integrating Sampler, which may be controlled to withdraw a continuous sample at a given level over a specified time interval. The third is the Bottom-Withdrawal Tube, which permits an accurate size-frequency analysis of sediment samples to be made over a considerably greater range of size and concentration than was formerly possible.

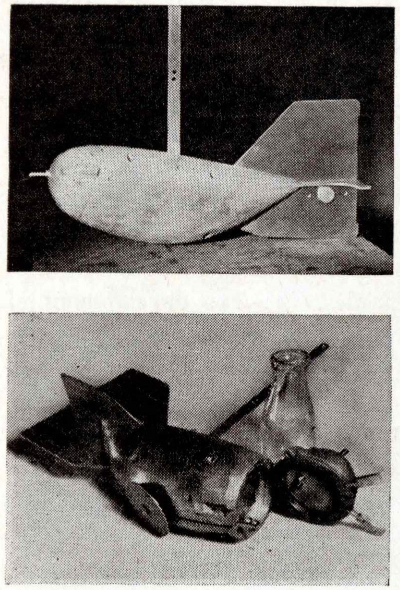

Fig. 36. Depth-integrating sediment samplers.

The two forms of sampler based upon and originally described in the foregoing reports have already seen extensive service in various parts of the country, and a number of improvements on their construction and operation have been made. Although only one sampler of the mechanically operated point-integrating type was initially tested in the field, a second model with electrical control was completed early in 1946. On the other hand, 10 depth-integrating samplers were made for the cooperating agencies in 1942, and the Geological Survey purchased 16 additional units for field use in 1944 and another 35 in 1946. It is hoped that this combination of laboratory and field study will eventually lead to the same routine measurement of sediment load throughout the country as now prevails for stream discharge.

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.

Bulletin 2. Laboratory Tests on Hydraulic Models of the Hastings Dam, by Martin E. Nelson, 1932. 72 pages, 40 figures. Out of print.

Bulletin 3. Tests of Anchorages for Reinforcing Bars, by Chesley J. Posey, 1933. 32 pages, 18 figures, price $0.50.

Bulletin 4. The Physical and Anti-Knock Properties of Gasoline Blends, by Theodore R. Thoren, 1934. 32 pages, 13 figures, price $0.35.

Bulletin 5. The Transportation of Detritus by Flowing Water—I, by F. T. Mavis, Chitty Ho, and Yun-Cheng Tu, 1935. 56 pages, 15 figures, price $0.50.

Bulletin 6. An Investigation of Some Hand Motions Used in Factory Work, by Ralph M. Barnes, 1936. 60 pages, 22 figures. Out of print.

Bulletin 7. A Study of the Permeability of Sand, by F. T. Mavis and Edward F. Wilsey, 1936. 32 pages, 12 figures, price $0.35.

Bulletin 8. Radiation Intensities and Heat-Transfer in Boiler Furnaces, by Huber O. Croft and C. F. Schmarje, 1936. 32 pages, 17 figures, price $0.35.

Bulletin 9. A Summary of Hydrologic Data, Ralston Creek Watershed, 1924-35, by F. T. Mavis and Edward Soucek, 1936. 72 pages, 25 figures, price $0.50.

Bulletin 10. Report on Hydraulics and Pneumatics of Plumbing Drainage Systems—I, by F. M. Dawson and A. A. Kalinske, 1937. 32 pages, 5 figures, price $0.35.

Bulletin 11. The Transportation of Detritus by Flowing Water—II, by F. T. Mavis, Te-Yun Liu, and Edward Soucek, 1937. 32 pages, 8 figures, price $0.35.

Bulletin 12. Studies of Hand Motions and Rhythm Appearing in Factory Work, by Ralph M. Barnes and Marvin E. Mundel, 1938. 64 pages, 24 figures. Out of print.

Bulletin 13. Hydraulic Tests of Small Diffusers, by F. T. Mavis, Andreas Luksch, and Hsi-Hou Chang, 1938. 32 pages, 16 figures, price $0.25.

Bulletin 14. A Study in Flood Waves, by Elmer E. Moots, 1938. 32 pages, 7 figures, price $0.25.

Bulletin 15. The Road Map of Hydraulic Engineering in Iowa, by E. W. Lane and Edward Soucek, 1938. 16 pages, 4 figures, price $0.25.

Bulletin 16. A Study of Hand Motions Used in Small Assembly Work, by Ralph M. Barnes and Marvin E. Mundel, 1939. 68 pages, 33 figures, price $0.50.

Bulletin 17. A Study of Simultaneous Symmetrical Hand Motions, by Ralph M. Barnes and Marvin E. Mundel, 1939. 40 pages, 15 figures, price $0.40.

Bulletin 18. Percolation and Capillary Movements of Water Through Sand Prisms, by F. T. Mavis and Tsung-Pei Tsui, 1939. 32 pages, 13 figures, price $0.25.

Bulletin 19. Two Decades of Hydraulics at the University of Iowa, Abstracts of Theses, Publications, and Research Reports, 1919-1938, edited by F. T. Mavis, 1939. 84 pages, price $0.50.

Bulletin 20. Proceedings of Hydraulics Conference, edited by J. W. Howe, 1940. 260 pages, 84 figures. Out of print.

Bulletin 21. Studies of One- and Two-Handed Work, by Ralph M. Barnes, Marvin E. Mundel, and John M. MacKenzie, 1940. 68 pages, 31 figures, price $0.50.

Bulletin 22. The Study of the Effect of Practice on the Elements of a Factory Operation, by Ralph M. Barnes and James S. Perkins with the assistance and collaboration of J. M. Juran, 1940. 96 pages, 34 figures, price $0.75.

Bulletin 23. An Annotated Bibliography of Fishways, by Paul Nemenyi, 1941. 72 pages, 12 figures, price $0.50.

Bulletin 24. An Investigation of Fishways, by A. M. McLeod and Paul Nemenyi, 1941. 64 pages, 15 figures, 6 plates, price $0.50.

Bulletin 25. The Electrostatic Effect and the Heat Transmission of a Tube, by Melvin R. Wahlert and Huber O. Croft, 1941. 40 pages, 10 figures, price $0.40.

Bulletin 26. Investigations of the Iowa Institute of Hydraulic Research, 1939-1940, edited by J. W. Howe, 1941. 64 pages, 15 figures, price $0.40.

Bulletin 27. Proceedings of the Second Hydraulics Conference, edited by J. W. Howe and Hunter Rouse, 1943. 352 pages, 167 figures, price $1.65.

Bulletin 28. The Preparation of Stoker Coals from Iowa Screenings, by H. L. Olin, 1942. 64 pages, 22 figures, price $0.50.

Bulletin 29. Study of Transportation of Fine Sediments by Flowing Water, by A. A. Kalinske and C. H. Hsia, 1945. 40 pages, 18 figures, price $0.40.

Bulletin 30. The Iowa Institute of Hydraulic Research. 80 pages, 36 figures, price $0.50.

REPRINTS

Reprint No. 1. Flow Characteristics in Elbow Draft Tubes, by C. A. Mockmore, 1937. 36 pages, 19 figures. Reprinted from Proceedings of the American Society of Civil Engineers, Feb., 1937, pp. 251-286. Price $0.25.

Reprint No. 2. Vacuum-Breaker Development for Back-Siphonage Prevention, by F. M. Dawson and A. A. Kalinske, 1937. 15 pages, 3 figures. Reprinted from Journal of the American Water Works Association, Vol. 29, No. 3, March, 1937, pp. 307-321. Price $0.15.

Reprint No. 3. Flow of Water Around 180-Degree Bends, by David L. Yarnell and Sherman M. Woodward, 1937. 64 pages, 48 figures. A reprint of Technical Bulletin No. 526, United States Department of Agriculture, Washington, D. C., Oct., 1936. Price $0.10.

Reprint No. 4. *Miscellaneous Papers in Hydraulic Engineering.*—1. Price $0.35.

An Analysis of Unusual Precipitation Records in Iowa, by F. T. Mavis and J. W. Howe. Reprinted from Journal of the American Water Works Association, Vol. 27, No. 2, Feb., 1935.

The Frequency of Intense Rainfall in Iowa, by F. T. Mavis and D. L. Yarnell. Reprinted from the Bulletin of the Associated State Engineering Societies, Oct., 1935.

Fundamental Hydrologic Considerations for the Design of Impounding Reservoirs in the Middle West, by E. L. Waterman, F. T. Mavis, and Edward Soucek. Reprinted from Journal of the American Water Works Association, Vol. 28, No. 2, Feb., 1936.

Reprint No. 5. *Miscellaneous Papers in Hydraulic Engineering.*—2. Price $0.35.

Research Notes, Hydraulic Research at Iowa University, by F. T. Mavis. Reprinted from Engineering News-Record, Sept. 26, 1935.

Capacity of Creosoted-Wood Culverts Studied, by F. T. Mavis. Reprinted from Engineering News-Record, Oct. 18, 1934.

Slide Rule for Routing Floods Through Storage Reservoirs or Lakes, by Chesley J. Posey. Reprinted from Engineering News-Record, Apr. 25, 1935.

Flush Wave Velocities in Sewers, by E. W. Lane and O. J. Baldwin. Reprinted from Engineering News-Record, June 11, 1936.

Sutro Weir Investigations Furnish Discharge Coefficients, by Edward Soucek, H. E. Howe, and F. T. Mavis. Reprinted from Engineering News-Record, Nov. 12, 1936.

Predicting Stages for the Lower Mississippi, by E. W. Lane. Reprinted from Civil Engineering, Feb., 1937.

Reprint No. 6. Sewage Treatment at Iowa City, Iowa, by Earle L. Waterman and Royal E. Rostenbach. Reprinted from Sewage Works Journal, Vol. 10, No. 1, pp. 106-114, Jan., 1937. Price $0.15.

Reprint No. 7. *Miscellaneous Papers on Management.*

A Plan for Job Evaluation, by Ralph H. Landes. Presented at Management Conference in Iowa City, April 8, 1938. Supply exhausted.

References to Papers by the other Conference Speakers.

Practical Applications of Motion-Study Research, Ralph M. Barnes. Reprinted from Mechanical Engineering, May, 1938. Price $0.10.

Reprint No. 8. *Two Papers on the Hydraulic Jump.* Price $0.10.

Hydraulic Jump in Trapezoidal Channels, by C. J. Posey and P. S. Hsing. Reprinted from Engineering News-Record, Dec. 22, 1938.

Hydraulic Jump in Closed Conduits, by E. W. Lane and C. E. Kindsvater. Reprinted from Engineering News-Record, Dec. 29, 1938.

Reprint No. 9. *Two Papers on Structural Problems.* Price $0.10.

Handling Corners in Rigid Frames, by B. J. Lambert and C. J. Posey. Reprinted from Engineering News-Record, Aug. 4, 1939.

Diagrams for Designing Reinforced Concrete Columns, by F. T. Mavis and O. J. Baldwin. Reprinted from Civil Engineering, June, 1935.

Reprint No. 10. *Two Papers on Pipe Flow.* Price $0.10.

Solving Pipe Flow Problems With Dimensionless Numbers, by A. A. Kalinske. Reprinted from Engineering News-Record, Vol. 123, No. 1, p. 55, July 6, 1939.

A New Method of Presenting Data on Fluid Flow in Pipes, by A. A. Kalinske. Reprinted from Civil Engineering, Vol. 9, No. 5, p. 313, May, 1939.

Reprint No. 11. Methods of Calculating Water-Hammer Pressures, by F. M. Dawson and A. A. Kalinske. Reprinted from Journal of American Water Works Association, Vol. 31, No. 11, November, 1939. Price $0.10.

Reprint No. 12. Application of Statistical Theory of Turbulence to Hydraulic Problems, by A. A. Kalinske and E. R. VanDriest. Reprinted from the Proceedings of the Fifth International Congress of Applied Mechanics, 1938. Price $0.05.

Reprint No. 13. *Studies in Sediment Transportation and Deposition.* Price $0.35.

Stable Channels in Erodible Material, by E. W. Lane. Discussions by R. C. Johnson, E. S. Lindley, J. C. Stevens, C. R. Pettis, Harry F. Blaney, Sigurd Eliassen, R. E. Ballester, Gerald Lacey, V. V. Tchikoff, W. M. Griffith, and E. W. Lane. Reprinted from Trans. American Society of Civil Engineers, Vol. 102, p. 123, 1937.

Engineering Aspects of Sediment Transportation and Deposition, by E. W. Lane. Reprinted from Bulletin of Associated State Engineering Societies, Oct., 1939.

Collection of Data on the Solids Load of Flowing Streams, by E. W. Lane. Reprinted from Journal of the Association of Chinese and American Engineers, Vol. XIX, No. 3, May-June, 1938.

The Relation of Suspended to Bed Material in Rivers, by E. W. Lane and A. A. Kalinske. Reprinted from Trans. of the American Geophysical Union, 1939.

Reprint No. 14. *Miscellaneous Papers on Plumbing.* Price $0.25.

Cross-Connections in Air-Conditioning Equipment, by F. M. Dawson and A. A. Kalinske. Reprinted from Journal of American Water Works Association, Vol. 29, No. 11, Nov., 1937.

Control of Water Piping From Main To Consumer, by F. M. Dawson and A. A. Kalinske. Reprinted from Journal of American Water Works Association, Vol. 30, No. 3, March, 1938.

The Hydraulics and Pneumatics of the Plumbing Drainage System, by A. A. Kalinske. Reprinted from Bulletin of Associated State Engineering Societies, Oct., 1938.

The National Plumbing Laboratory, by F. M. Dawson and A. A. Kalinske. Reprinted from American Journal of Public Health, Vol. 30, No. 1, Jan., 1940.

Plumbing Free From Pollution, by F. M. Dawson. Reprinted from The Nation's Schools, Vol. 23, No. 5, May, 1939.

The Prevention of Back-Siphonage, by F. M. Dawson and A. A. Kalinske. Reprinted from Plumbing and Heating Business, Sept., 1939.

Water Hammer—Cause and Cure, by F. M. Dawson and A. A. Kalinske. Reprinted from Plumbing and Heating Business, Oct., 1939.

Pollution in the Plumbing, by F. M. Dawson. Reprinted from The Modern Hospital, Vol. 53, No. 6, Dec., 1939.

The Design, Operation, and Testing of Grease Interceptors, by F. M. Dawson and A. A. Kalinske. Reprinted from Plumbing and Heating Business, Nov. and Dec., 1939.

Grease Interceptors in Practical Use, by F. M. Dawson and A. A. Kalinske. Reprinted from Plumbing and Heating Business, Jan., 1940.

Reprint No. 15. *Miscellaneous Papers in Hydraulic Engineering.* Price $0.35.

Entrainment of Air in Swiftly Flowing Water, by E. W. Lane. Reprinted from Civil Engineering, Feb., 1939.

Dams—Ancient and Modern, by E. W. Lane. Reprinted from Journal of Association of Chinese and American Engineers, Vol. XIX, No. 6, Nov.-Dec., 1938.

Routing of Floods Through Reservoirs with Especial Attention to Determination of Spillway Capacity for Small Reservoirs, by C. J. Posey. Reprinted from Bulletin of Associated State Engineering Societies, Oct., 1938.

A Study of Variability of Precipitation, by Edward Soucek and J. W. Howe. Reprinted from Transactions of the American Geophysical Union, 1938.

An Analysis of Stream-flow Data for Iowa, by F. T. Mavis and Edward Soucek. Reprinted from Transactions of the American Geophysical Union, 1937.

Reprint No. 16. Transformer Current and Power Inrushes Under Load, by E. B. Kurtz. Reprinted from Electrical Engineering, August, 1937. Price $0.05.

Reprint No. 17. A Low-Frequency Alternator, by E. B. Kurtz and M. J. Larsen. Reprinted from Proceedings of the Institute of Radio Engineers, Vol. 27, No. 2, Feb., 1939. Price $0.05.

Reprint No. 18. Water Level Indicator, by L. A. Ware. Reprinted from Electronics, March, 1940. Price $0.10.

Reprint No. 19. *Miscellaneous Papers on Sediment Transportation and Deposition.* Price $0.25.

Notes on the Formation of Sand, by E. W. Lane. Reprinted from Transactions of the American Geophysical Union, Nineteenth Annual Meeting, 1938.

Notes on Limit of Sediment Concentration, by E. W. Lane. Reprinted from the Journal of Sedimentary Petrology, Vol. 10, No. 2, Aug., 1940.

The Different Approaches to the Study of Propulsion of Granular Materials and the Value of their Coördination, by Paul Nemenyi. Reprinted in U. S. A. from Transactions of the American Geophysical Union, 1940.

A Study of Sedimentation in a Miami Conservancy District Reservoir, by E. W. Lane and J. C. Kennedy. Reprinted in U. S. A. from Transactions of the American Geophysical Union, 1940.

Suspended-Material Transportation Under Non-Equilibrium Conditions, by A. A. Kalinske. Reprinted in U. S. A. from Transactions of the American Geophysical Union, 1940.

Reprint No. 20. Relation of the Statistical Theory of Turbulence to Hydraulics, by A. A. Kalinske. Reprinted from Transactions of American Society of Civil Engineers, Vol. 105, 1940. Price $0.25.

Reprint No. 21. Laws of Transportation of Sediment by Streams: Suspended Load, by Hunter Rouse. Duplicated by the Iowa Institute of Hydraulic Research. Price $0.15.

Reprint No. 22. Functional Design of Flood Control Reservoirs, by C. J. Posey and Fu-Te I. Reprinted from Transactions of American Society of Civil Engineers, Vol. 105, 1940. Price $0.25.

Reprint No. 23. An Electronic Method for Determining Distribution Curves, by L. A. Ware. Reprinted from Electronics, October, 1940. Price $0.10.

Reprint No. 24. Turbulence and Energy Dissipation, by A. A. Kalinske. Reprinted from Trans. American Society of Mechanical Engineers, Jan., 1941. Price $0.20.

Reprint No. 25. On the Four Regimes of Open-Channel Flow, by J. M. Robertson and Hunter Rouse. Reprinted from Civil Engineering, March, 1941. Price $0.20.

Reprint No. 26. Turbulence in Open-Channel Flow, by A. A. Kalinske and J. M. Robertson. Reprinted from Engineering News-Record, April 10, 1941. Price $0.20.

Reprint No. 27. Investigations of Liquid Turbulence and Suspended Material Transportation, by A. A. Kalinske. Reprinted from University of Pennsylvania Bicentennial Conference Proceedings, 1941. Price $0.20.

Reprint No. 28. Engineering Calculations of Suspended Sediment, by E. W. Lane and A. A. Kalinske. Reprinted from Transactions of the American Geophysical Union, 1941. Price $0.15.

Reprint No. 29. Some Recent Flood-Flow Determinations in Iowa, by L. C. Crawford and G. L. Whitaker. Reprinted from the Iowa Transit, Vol. 17, No. 1, Oct., 1942. Price $0.10.

Reprint No. 30. Dynamic Characteristics of a Single-Phase Induction Motor, by E. B. Kurtz. Reprinted from Transactions of the American Institute of Electrical Engineers, Vol. 59, 1940. Price $0.10.

Reprint No. 31. Operation of a Thyratron as a Rectifier, by L. A. Ware. Reprinted from Proceedings of the I. R. E., Vol. 30, No. 11, Nov., 1942. Price $0.10.

Reprint No. 32. Ultrahigh-Frequency Transmission in Wave Guides, by L. A. Ware. Reprinted from Electrical Engineering, Dec., 1942. Price $0.10.

Reprint No. 33. Criteria For Determining Sand-Transport by Surface-Creep and Saltation, by A. A. Kalinske. Reprinted in U. S. A., from Transactions of the American Geophysical Union, 1942. Price $0.10.

Reprint No. 34. Power-angle Indicator and Record for Synchronous Machines, by E. B. Kurtz. Reprinted from General Electric Review, Vol. 43, No. 10, Oct., 1940. Price $0.10.

Reprint No. 35. Turbulence and Transport of Sand and Silt by Wind, by A. A. Kalinske. Reprinted from Annals of New York Academy of Sciences, Vol. 44, p. 41, May, 1943. Price $0.20.

Reprint No. 36. Evaluation of Boundary Roughness, by Hunter Rouse. Reprinted from Proceedings of the Second Hydraulics Conference, Bulletin 27, 1943. Price $0.10.

Reprint No. 37. Role of Turbulence in River Hydraulics, by A. A. Kalinske. Reprinted from Proceedings of the Second Hydraulics Conference, Bulletin 27, 1943. Price $0.10.

Reprint No. 38. Measurement of Sediment Transportation, by E. W. Lane. Reprinted from Proceedings of the Second Hydraulics Conference, Bulletin 27, 1943. Price $0.10.

Reprint No. 39. Studies Relating to Use of Saran for Water Pipes in Buildings, by F. M. Dawson and A. A. Kalinske. Reprinted from Journal of American Water Works Association, Vol. 35, p. 1058, Aug., 1943. Price $0.10.

Reprint No. 40. Air Entrainment in Closed Conduit Flow, by A. A. Kalinske and J. M. Robertson. Reprinted from Transactions of American Society of Civil Engineers, Vol. 108, p. 1393, 1943. Price $0.50.

Reprint No. 41. Computations for Influence Lines Simplified by Semi-Graphical Method, by C. J. Posey. Reprinted from Engineering News-Record, Vol. 131, Dec., 1943. Price $0.10.

Reprint No. 42. Eddy Diffusion, by A. A. Kalinske and C. L. Pien. Reprinted from Industrial and Engineering Chemistry, Vol. 36, p. 220, March, 1944. Price $0.10.

Reprint No. 43. Experiments on Eddy Diffusion and Suspended-Material Transportation, by A. A. Kalinske and C. L. Pien. Reprinted from Transactions of the American Geophysical Union, 1943. Price $0.10.

Reprint No. 44. The Design of a 1540 Foot Three Span Continuous Tied Arch Truss, by Ned L. Ashton. Reprinted from Iowa Transit, Vol. XLVIII, No. 7, April, 1944. Price $0.20.

Reprint No. 45. Hydraulics of Vertical Drain and Overflow Pipes, by A. A. Kalinske. Reprinted from Investigations of the Iowa Institute of Hydraulic Research, 1939-1940, Bulletin 26, Dec., 1941. Price $0.10.

Reprint No. 46. Table of Fixed-End Moments, by C. J. Posey. Reprinted from Engineering News-Record, Vol. 127, Nov., 1941. Price $0.05.

Reprint No. 47. Suspension of Sediment in Upward Flow, by Hunter Rouse. Reprinted from Investigations of the Iowa Institute of Hydraulic Research, Bulletin 26, Dec., 1941. Price $0.10.

Reprint No. 48. Effects of Channel Shape on Losses in a Canal Bend, by C. H. Yen and J. W. Howe. Reprinted from Civil Engineering, Vol. 12, No. 1, Jan., 1942. Price $0.10.

Reprint No. 49. Flood-Wave Characteristics as Related to Flood Routing, by C. J. Posey. Reprinted from Proceedings of the Second Hydraulics Conference, Bulletin 27, 1943. Price $0.10.

Reprint No. 50. Sedimentation of Sewage, by R. E. Rostenbach and E. L. Waterman. Reprinted from Sewage Works Journal, Vol. 15, No. 3, May, 1943. Out of print.

Reprint No. 51. Physics and Rapid Airplane Development, by E. C. Lundquist. Reprinted from American Journal of Physics, Vol. 11, No. 4, Aug., 1943. Out of print.

Reprint No. 52. Design and Operation of Grease Interceptors, by F. M. Dawson and A. A. Kalinske. Reprinted from Sewage Works Journal, May, 1944. Price $0.10.

Reprint No. 53. Non-Linearity in Transformers, by Reed. Published by the Kuhlman Electric Co., Bay City, Mich., Vol. 20, No. 1, 1944.

Reprint No. 54. Symposium on Grease Removal; Design and Operation of Grease Interceptors, by F. M. Dawson and A. A. Kalinske, Reprinted from Sewage Works Journal, Vol. XVI, No. 3, May, 1944. Price $0.10.

Reprint No. 55. Quarter-Wavelength Insulators, by L. A. Ware, Reprinted from Nov., 1944 Communications.

Reprint No. 56. Removal of Air from Pipe Lines by Flowing Water, by A. A. Kalinske and P. H. Bliss. Reprinted from Civil Engineering, October, 1943. Price $0.10.

Reprint No. 57. A General Stability Index for Flowing Near Plane Boundaries, by Hunter Rouse. Reprinted from the Journal of The Aeronautical Sciences, Vol. 12, No. 4, October, 1945. Price $0.10.

Reprint No. 58. A New Method of Sediment-Transportation, by E. W. Lane. Reprinted from Transactions of 1944 of the American Geophysical Union. Price $0.10.

Reprint No. 59. Application of Statistical Theory to Velocity and Suspended Sediment Measurements in Rivers, by A. A. Kalinske. Reprinted from Transactions of 1945 of the American Geophysical Union, Vol. 26, October, 1945. Price $0.10.