THIRD INSTALLMENT

# HYDRAULICS IN THE UNITED STATES 1776 - 1976

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# CHAPTER VI

## THE RISE OF FLUID MECHANICS

When John R. Freeman began to promote the modeling of rivers in the laboratory at greatly reduced scale, it was still an essentially unknown procedure in the United States. In Europe, however, the first movable-bed model had been built by Fargue as early as 1875, and further tests were conducted by Reynolds, Vernon-Harcourt, and Engels well before the turn of the century. Small-scale testing as such was even older, of course, for Smeaton had experimented with model water wheels, and d'Alembert, Condorcet and Bossut (not to mention Benjamin Franklin), with model ships more than a century before; yet it was not till the time of Reech and Froude in the third quarter of the 19th century that the principle of gravitational similarity received its initial formulation. Since then Rehbock and his 20th-century contemporaries greatly improved the various experimental techniques but scarcely extended the rules of similitude. (Judging by German lectures paraphrased in the Freeman book, in fact, the hydraulician's understanding of dimensional analysis was years behind rather than ahead of Buckingham's 1915 article.) On the whole, the civil-engineering branch of hydraulics simply continued its testing program with little further innovation. Unfortunately, whereas adoption of the practice of river modeling at reduced scale represented for American engineers a great step forward, with this practice they inherited as well the tendency toward continued cut-and-try design that had beset the civil-engineering hydraulicians of Europe.

Civil engineers had long since developed an essentially empirical sort of hydraulics, as exemplified by the many tabulations of coefficients in the textbooks reviewed in Chapter IV. At the other end of the spectrum, mathematical physicists had refined a subject known as classical hydrodynamics, best exemplified by Horace Lamb's *Hydrodynamics*, first published (in Great Britain) in 1879 under the title *A Treatise on the Mathematical Theory of the Motion of Fluids* and well into its 5th edition at the time of Freeman's major influence. Neither subject, however, was of much use in the new profession of aeronautics. On the one hand, the theoretical approach had little direct contact with reality; on the other hand, pure empiricism did not lend itself to application beyond the conditions of observation. What was needed was a combination of the good points of each subject, without its weaknesses. Just such a hybrid approach was provided early in the century by Ludwig Prandtl of Gottingen, Germany, and his many followers, nearly all of whom were mechanical engineers. Proceeding from Prandtl's boundary-layer hypothesis of 1904 (that a state of flow can be approximated by a wall zone of viscous influence and an outer zone of irrotational motion), these men developed a quasi-analytical approach now known as fluid mechanics, in which the mathematics was simplified to the greatest possible extent still in accord with experimental indications. Aided by his student Heinrich Blasius, Prandtl further developed his boundary-layer theory and its application to immersed bodies. In friendly competition with his former student Theodor von Kármán and with the Cambridge meteorologist Geoffrey Taylor, and assisted by his students Johann Nikuradse and Hermann Schlichting, Prandtl greatly advanced the theory of turbulent resistance. His colleague Albert Betz specialized in the mathematical process of conformal mapping and the development of flow instrumentation. His student Adolf Busemann established in large measure the theory of compressible-fluid motion. And his contemporary Richard von Mises, also a mechanical engineer, not only formed his own school at Berlin but edited a journal on applied mechanics in which much of the new work appeared. All of those just named published papers that have become classics.

In parallel with European developments, the U. S. Congress established on 3 March 1915 the Advisory Committee for Aeronautics as a rider to a naval appropriations bill, with an allocation of $5000 annually over a five-year period. The word National was soon added to its title, and it became popularly known as the NACA. W. F. Durand, then a Stanford professor, was one of the twelve original appointees to the Committee, and in 1916 he was elected chairman; that same year Langley Field was founded north of Hampton, Virginia, as the Committee's primary research establishment. A year thereafter the NACA was ruled independent of the Navy Department. Its primary purpose was the coordination of all aeronautical research in the United States, and it gradually developed a prodigious output of excellent research reports, including translations of foreign literature of significance. Thus, NACA Report 116 of 1921 was a paper by Prandtl on "Applications of Modern Hydrodynamics to Aeronautics," and in 1929 Prandtl's original boundary-layer paper was published in English as NACA Technical Memorandum No. 452. The NACA publications were to have a salutary effect not only on aeronautics but also on such other fields as came to be related through the new science of fluid mechanics.

In keeping with the traditional independence of civil and mechanical engineers, most of the advancement in fluid mechanics on the part of the mechanical (and aeronautical) engineers took place without attracting the attention of the civils. One of the MIT Fellows, Hunter Rouse (1906-. . . .), an Ohioan who spent two years with Rehbock, does not recall having heard the name Prandtl the whole time he was in

Karlsruhe. In fact, not till just before his departure did he hear the name of the mechanical-engineering professor of hydraulic machinery on the same campus, Wilhelm Spannhake (1881-1959), who was of course thoroughly aware of the new contributions and had himself participated in them. Apparently only one of the Freeman Scholars—Victor Lyle Streeter (1909-. . . .)—spent any appreciable amount of time on the Gottingen and Aachen campuses, though at least two—Clifford Kittredge and the Canadian George Ross Lord (1906-. . . .)—studied at the hydraulic-machinery institutes of Munich and Karlsruhe, and Robert Knapp surely visited these and similar institutes during his travels. It is hence the more to Freeman's credit—civil engineer and traditional hydraulician that he was—to have seen that Prandtl, Thoma, and eventually Spannhake all lectured at MIT.

Though a civil engineer by education, Morrough O'Brien taught mechanical engineering when he went to Berkeley in 1928 and became head of that department in 1934. This possibly explains the fact that of all the early Freeman Scholars he was the one most receptive to the new concepts, as reflected in many of his technical writings. A noteworthy example was his 1933 "Review of the Theory of Turbulent Flow and its Relation to Sediment Transportation," which applied Wilhelm Schmidt's theory of the turbulent diffusion of atmospheric dust to the suspension of sediment by flowing water. Hunter Rouse, also educated as a civil engineer, spent much of his time with Rehbock trying to understand the hydromechanics of the free overfall, and he continued experiments on flow over sharp-crested weirs of various relative heights after his return to MIT in 1931. During the next two years, on the other hand, he served as unofficial assistant to Spannhake, who was then visiting professor in mechanical engineering. Rouse attended Spannhake's lectures the first year and transcribed those on hydrodynamics for student use the second. During the summer between, after taking the doctoral examination at Karlsruhe, he had the opportunity of visiting both Prandtl and von Mises, with whose work he had become acquainted through Spannhake's lectures. In addition to lecturing on hydrodynamics in general and conformal mapping in particular (especially with respect to hydraulic machinery), Spannhake himself spent much of his time at MIT in the design and operation of a cavitation stand, in which the basic nature of cavitation damage at a simple Venturi throat was studied. The work was supported by at least one hydroelectric company, and considerable interest was aroused in the search for materials with high resistance to pitting.

Quite independently of Freeman's influence, at least one other European had come to the United States well before Spannhake, and his effect upon American hydraulics was to be still greater—in large part because he became a permanent resident of the country. This was Boris

Alexandrovitch Bakhmeteff (1880-1951), a native of Tiflis, Georgia, who had studied at the St. Petersburg Polytechnic Institute and then taught civil engineering there and developed a private consulting practice. In 1912 he published a dissertation on open-channel hydraulics which first made use of the energy and momentum diagrams and refined the French methods of handling the backwater equation. This book continued to be reprinted by the Soviets for a number of decades, and their revised introduction lauded Bakhmeteff's stature as a hydraulician but made no mention of what had become of him. As a matter of fact, he had come to the United States as ambassador under the Kerensky regime, remained in America after the Revolution, and acquired wealth and prestige as one of a group of White Russians manufacturing paper book matches.

In 1932 an enlarged version of Bakhmeteff's Russian dissertation was published in English as an Engineering Societies Monograph under the title *Hydraulics of Open Channels,* and about the same time he became a part-time professor at Columbia University. There he began the construction of a modest facility for studying the hydraulic jump, similar to one that he had built at St. Petersburg, and developed successive sets of lecture notes for use by his undergraduate students. Reproduced by offset from typewritten copy in 1932 and 1933, his two-part *Mechanics of Fluids Compendium* thus became the first in a growing stream of such writings to leave the American press. Published by the ASCE in 1934 with the coauthorship of Arthur Edward Matzke (1908-1962), a Columbia graduate who had made the painstaking measurements, his paper on the hydraulic jump stressed the geometric characteristics of the profile in a nondimensional manner, and it might fruitfully be compared with the previous papers of Karl Kennison and Sherman Woodward. Woodward, in fact, submitted a brief discussion that disparaged Bakhmeteff's attempt at generalization. It is a mark of the latter's diplomatic charm that, when the two first met some time thereafter, it was not long before their arms were around each other's shoulders!

Another immigrant to whom the profession owes very much was Theodor von Kármán (1881-1963), a mechanical-engineering graduate of the Royal Polytechnic Institute of Budapest before becoming one of Prandtl's early doctoral students. In 1912 he was appointed professor and director of the newly established aeronautical laboratory at the Polytechnic Institute of Aachen. Following the advent of the Nazi movement, a similar post was created for him at the California Institute of Technology in 1930. His interests, like those of Prandtl, extended into practically every field of mechanics. So far as the present treatment is concerned, special mention should be made of his work on the pendulating wakes of immersed bodies, surface resistance to turbulent flow, and the analogy between sound and gravity waves.

With the appearance in Europe of books on the new approach to the study of fluid motion, it would have been surprising if no translations had been released in the English language. The first of these consisted of Prandtl's lectures which had been transcribed and published in German by his student Oskar Tietjens, the translations of which appeared in the United States in 1934 as *Fundamentals of Hydro- and Aeromechanics* and *Applied Hydro- and Aeromechanics* in the Engineering Societies Monograph Series. Hunter Rouse, then building a small laboratory under Bakhmeteff at Columbia, published in the ASCE *Proceedings* of January 1936 a review of the Prandtl-Kármán-Nikuradse contributions to pipe-resistance analysis under the title "Modern Conceptions of the Mechnics of Fluid Turbulence," which was to receive the Society's Norman Medal. Bakhmeteff's lectures at Princeton on the same subject were reproduced in book form as *The Mechanics of Turbulent Flow* later in the year. The first full-fledged undergraduate textbooks on the subject to appear in the States were by Dodge and Thompson and by O'Brien and Hickox. Though the titles were somewhat similar—*Fluid Mechanics* and *Applied Fluid Mechanics,* respectively—the publisher was the same and the preface dates (April 1937) were identical. Russell Alger Dodge (1893-1972) and Milton John Thompson (1904-. . . .) were Michiganders by birth and education. Dodge, however, was a civil engineer teaching engineering mechanics at the university, whereas Thompson was an aeronautical engineer who had recently spent a year as Guggenheim Fellow studying aerodynamics at the Warsaw Polytechnic Institute in Poland. Their book was obviously a combination of traditional hydraulics and modern fluid mechanics without full correlation between the two. Nevertheless, it followed Bakhmeteff's lead in introducing into the undergraduate curriculum concepts of flow analysis that had not been there before. Morrough O'Brien has already been mentioned as the Freeman Scholar first interested in the broad approach, and George Hickox as the first director of the TVA laboratory. Theirs was a slightly smaller volume than Dodge and Thompson's, dedicated to Freeman and placing more emphasis on the liquid aspect in accord with the prefatory remark, "These notes are a gradual development from what was originally a course in hydraulics."

Though a mechanical engineer from start to finish, Robert Knapp at first showed a passive rather than an active interest in fluid mechanics at Caltech, but he did place a very high value on von Kármán's presence there and sought his advice in all his undertakings. His first graduate student was Richard Gilman Folsom (1907-. . . .), an assistant who taught Knapp's classes while the latter was in Germany (1929-30); his doctoral dissertation on ultra-rough surfaces was reviewed by Knapp and von Kármán together in 1932, and the following year Folsom moved to Berkeley under O'Brien. A researcher rather than a teacher, Knapp had a keen sense of what problems were important and how they might be solved. At times, however, his primary abilities seemed to be those of research initiation and gadgetry. So highly mechanized were his investigations that members of the staff amusedly coined the slogan "It's automatic, but it won't work!" And so able did he rapidly become in attracting financial support that his steadily growing staff had difficulty in carrying out all his contract projects. These began in 1932 with a model study of a cooling-water intake for the local power company, of which the principal investigator was Vito August Vanoni (1904-. . . .), a Californian of Italian background who had just completed his second Caltech degree. Vanoni was thus the first of a series of young men from all parts of the country who were supported at Caltech by Knapp's activities and thereby exposed to the stimulus of proximity to von Kármán.

In 1933 Knapp contracted with the Metropolitan Water District of Los Angeles to conduct a fundamental study of pumps for the Colorado Aqueduct, Robert Daugherty joining von Kármán as consultant. As described in the ASME *Transactions* for 1936, the resulting laboratory seemed like a gadgeteer's dream, remote control permitting discharge, head, speed, and power to be measured with a reproducibility—if not absolute accuracy—of 99.9%. Not only were performance tests run on manufacturer's models, but considerable research was done on transient flows; of particular interest was a 1934 study of pump characteristics in all four quadrants, prompted by Freeman Scholar Clifford Kittredge's dissertation in Thoma's Munich laboratory. Most of this—well ahead of its time—has since become standard practice. Five successive doctoral students were in turn active in this laboratory: Frank Leslie Wattendorf (1906-. . . .), a Bostonian who had studied previously at Harvard, MIT, and Gottingen and was to have a varied career in aeronautics, the field in which he took his degree; Ralph Mayhew Watson (1905-. . . .) of Pasadena, who was to go with the Worthington Pump and Machinery Corporation before completing the doctorate; George Friederich Wislicenus (1903-. . . .), who had come from Germany to take his three degrees at Caltech, whereafter he also went to Worthington; Raymond Charles Binder (1907-. . . .) of Chicago, who had previously studied at MIT and was later to join the staff at Purdue; and James Wallace Daily (1913-. . . .), a Missourian and Stanford graduate who remained with Knapp through the War. Freeman Scholar Donald Barnes, who had studied civil rather than mechanical engineering there, was later to be in residence at Pasadena as representative of the Bureau of Reclamation during pump tests.

Arthur Thomas Ippen (1907-1974), born in London of German parents and educated at Aachen, had come to Iowa City in 1932 to study with Floyd Nagler. Left high and dry on Nagler's death in 1933, Ippen then joined Knapp's staff at Pasadena. Knapp had recently become acquainted with Walter Clay Lowdermilk (1888-. . . .) during the latter's move from the U. S. Forest Service, through the Soil Erosion Service of the Interior Department, to become director of research of Agriculture's new Soil Conservation Service, and between them a sediment laboratory was planned for Caltech. It was to have a veritable mushroom growth. Vito Vanoni was project supervisor, and two early members of his staff were Nephi Albert Christensen (1903-. . . .) of Utah and Merit Penniman White (1908-. . . .) of Massachusetts, both doctoral candidates at the Institute. Ippen was an intended member of the SCS staff, and at von Kármán's suggestion he undertook the solution of O'Brien's sediment-suspension equation through use of Krey's logarithmic velocity-distribution formula for open channels. However, when it was found that he could not be employed by the SCS because of his foreign citizenship, Ippen was shifted to a project which Knapp had just arranged with the Los Angeles County Flood Control District, to investigate the superelevation of the water surface at bends in high-velocity flood-relief channels. A tilting flume of rectangular cross section with several bends of different radii was built, numerous tests were run, and a first report was under way when von Kármán drew Knapp and Ippen's attention to the analogy between gravity waves and sound waves in supercritical flow, the latter already being subject to analysis; Ippen's dissertation in 1936, as well as subsequent papers, made much of the analogy in solving the superelevation problem. He continued to study the phenomenon in trapezoidal channels until his departure for a teaching position at Lehigh University in 1938.

At the beginning of 1936 Hunter Rouse joined the SCS staff at Caltech, at the invitation of Knapp, whom he had known in Germany, but attracted in no small measure by the presence there of von Kármán, whom he had met as Bakhmeteff's guest at Columbia. At Pasadena Rouse first devised a series of "turbulence-jar" experiments to verify the hypothesized interrelationship of turbulence, fall velocity, and distribution of sediment concentration predicted by O'Brien from Schmidt's theory of atmospheric mixing. Then, without knowledge of Ippen's previous work, Rouse independently performed a similar combination of the sediment-suspension and the velocity-distribution equations, using von Kármán's form for the latter instead of Krey's; the results were published in the 1937 closure to the discussion of his ASCE turbulence paper. In the evenings of his second year at Caltech, Rouse completed the manuscript of *Fluid Mechanics for Hydraulic Engineers,* a book begun at Columbia and intended to correlate the analytical and experimental aspects of the subject in a manner that would be significant to the practicing hydraulician. Reflecting the teachings of Rehbock (flow patterns), Spannhake (conformal processes), Bakhmeteff (viscosity and drag), and von Kármán (turbulence and wave motion), the book was published as an Engineering Societies Monograph in 1938.

While engaged in his sediment studies, Rouse chanced upon a 1936 Berlin dissertation by one A. Shields in which a relationship was shown to exist between roughness effects on the laminar sublayer and the beginning of sediment movement. Because of its obvious excellence, Rouse not only made available an English translation of the dissertation but publicized it in his own writings. Not till after the Fifth International Congress for Applied Mechanics in 1938 at MIT, which each attended without knowledge of the other, did Rouse learn that—far from being German—Albert Frank Shields (1908-1974) was also a native Ohioan, who had graduated from Stevens Institute of Technology, gone to Berlin in 1933 on an exchange scholarship, and conducted an original bed-load study at the Prussian Experiment Station for Hydraulic and Marine Engineering as a temporary employee. From subsequent correspondence Rouse learned that Shields had never received the printed copies of his dissertation, which apparently became lost in the mails, nor had his early hope to find employment in the fluids field at either Vicksburg or Caltech been successful. He hence returned to the paper-manufacturing business, where he had previously done design work and in which he eventually obtained some 200 patents. What a loss to the fluids profession!

The 1938 Congress at MIT also saw the arrival in the States of Paul Felix Neményi (1895-1952), a Hungarian migrant who had published *Wasserbauliche Stromungslehre* while Privatdozent at Berlin. Except for a 1914 text by Richard von Mises (1883-1953), this book was probably the one most slanted toward the new approach of all those on hydraulics that had appeared in the German press. Unfortunately, neither it nor the von Mises volume was translated into English, but the establishment of residence in America on the part of both (von Mises later came to Harvard from Berlin via Istanbul) had a somewhat comparable effect. Before crossing the ocean, Neményi had spent time at Copenhagen and London, and following the Congress he devoted several years to fishway investigations at Iowa. His knowledge of the fluids literature was encyclopedic, and he gradually veered in the direction of mathematical hydrodynamics.

Not all sediment studies were conducted on the west coast by any means, but before other parts of the country are considered, four additional projects warrant mention. One was a 1934 paper by O'Brien and his student B. D. Rindlaub on bed-load transportation, still susceptible only to the empirical approach. Another was a 1937 booklet published by O'Brien and Folsom, "The Transportation of Sand in Pipe

Lines''; this contained a good review of the theory of both turbulent flow in pipes and sediment movement in flowing water, and an analysis of extensive experiments with a wide range of grain sizes in a special pumping rig, including the effect of the sediment load on pump performance. (Though obviously not involving sediment, the 1939 O'Brien-Folsom paper on the design of pumps and fans must be mentioned in passing.) Still another sediment investigation was a series of tests on localized scour by Rouse (1939), which indicated that the excavation of uniform material tended to progress as an inverse logarithmic function of time and hence to be without apparent limit. The fourth was a continuing study by Vanoni on the transportation of uniform material in suspension; his 1941 AGU paper, ''Some Experiments on the Transportation of Suspended Load,'' contained measurements in good accord with the analyses by Ippen and by Rouse.

On the east coast, the third of the MIT Fellows, Cedric Hugh MacDougall (1901-. . . .) of Canada took over a graduate student's inconclusive bed-load study, converted it into a significant piece of work (albeit purely empirical), and presented it at the same meeting of the AGU at which O'Brien gave Schmidt's theory of suspension. (After his release from MIT because of the Depression, MacDougall took a post at a preparatory school—much as Blasius had done a decade before—and never returned to hydraulics.) At Iowa, in the years following his return from Europe, Theodore Mavis directed the thesis endeavors of a series of Chinese graduate students in the investigation of bed-load transportation. Emory Lane, who had consulted on the improvement of the Grand Canal and neighboring Chinese rivers, also wrote extensively on the subject of sediment movement, his approach remaining wholly empirical till the beginning of his collaboration in 1936 with Anton Adam Kalinske (1911-. . . .). The latter, born and educated in Wisconsin and one of those brought to Iowa by Dean Dawson, at first assisted Dawson in studies (such as the prevention of back-siphonage) for the National Association of Master Plumbers. However, Kalinske was a voracious reader of the technical literature—particularly in the field of turbulence, though from the Taylor point of view rather than that of Prandtl; he not only supplied the theoretical understanding to balance Lane's practical approach, but supervised graduate students in turbulence and sediment projects and published extensively in his own right and with various graduate students. One of these students was Edward Reginald Van Driest (1913-. . . .) of Cleveland and Case Institute, who—after completing doctoral requirements at both Caltech and Zurich—was to specialize in the thermal phases of fluid mechanics. Two other men who had been on the Iowa staff almost as long as Mavis will be mentioned repeatedly in later pages: Joseph Warner Howe (1902-. . . .), an Iowan by birth and education, who was beginning to specialize in hydrology; and Chesley Johnston Posey (1906-. . . .), a Minnesotan with a Kansas education, who was beginning to develop his Rocky Mountain Hydraulic Laboratory at Allenspark, Colorado, for summer use.

Though even less in the direction of fluid mechanics than some of the other sediment projects, note must surely be taken at this point of Lane's organization in 1939 of an Interdepartmental Sedimentation Committee, which under various names continued its activity for several decades and did much practical good. The agencies involved were the Geological Survey, the Indian Service, and the Bureau of Reclamation of the U. S. Department of the Interior; the Flood Control Coordinating Committee of the Department of Agriculture; the U. S. Engineers of the War Department; and the Tennessee Valley Authority. Representatives of these organizations were stationed at the Iowa Institute of Hydraulic Research, where, under Lane's direction, they prepared a series of reports on various aspects of the sediment problem: primarily means of measuring the suspended load and bed load in natural streams and of interpreting the results; several widely used instruments for both sampling and size-frequency determination were devised. Eight reports on the initial findings were published in 1940 by the U. S. Engineer Suboffice at Iowa City under the general title *A Study of Methods Used in Measurement and Analysis of Sediment Loads in Streams*. The Committee shifted its headquarters to the St. Anthony Falls Laboratory at Minneapolis in 1948, with personnel from both the Corps and the USGS. Subsequent decades saw the participation of six additional agencies and the publication of five more numbered reports, plus a long series of lettered ones including a summary of the work up to 1963.

Most decidedly in the direction of fluid mechanics was the research done in the Thirties at the National Hydraulic Laboratory by two or three members of the staff, though it is ironic that practically none of this research required the enormous establishment in which they were housed. Garbis Keulegan was the guiding force; a mathematical physicist by background, it is only logical that the major part of his work should have been analytical by nature. He thought very highly of Boussinesq, moreover, and much of his writing stemmed from what he knew by heart to exist in the tome *Essai sur la théorie des eaux courantes*. The first of his investigations, albeit an experimental one, was done in collaboration with Hilding Beij on the resistance to laminar flow in curved pipes. Next he discussed at length the free-surface counterpart of the Prandtl-Kármán pipe-resistance analyses in the paper "Laws of Turbulent Flow in Open Channels." At much the same time he undertook some simple but original tests on the stability of the interface between fresh- and salt-water layers, introducing what he called the "densimetric" (i.e. gravimetric) Froude number ($v/\sqrt{d\Delta\gamma/\rho}$) as similarity parameter, not to mention the misnomer "density current" for what is actually a gravitational phenomenon; both terms are firmly embedded in the literature. Finally, on becoming interested in open-channel wave motion, he set out on a series of noteworthy analyses, some of which were in collaboration with other members of the staff but most were his alone. Essentially all were published in the Bureau's *Journal of Research,* although—despite his retiring nature—he was eventually persuaded to take actual part in national congresses.

At several points in this chapter mention has been made of the Fifth International Congress for Applied Mechanics. The first one of the series to be held in the United States, it was to have a considerable effect upon American fluid mechanics. The series had grown out of a meeting called in Innsbruck, Austria, by Theodor von Kármán to bring together once again specialists from many countries who had become separated by World War I. The first formal congress had been convened in Delft, Holland, in 1924; this was followed by those in Zurich in 1926; Stockholm in 1930; and Cambridge (England) in 1934. Many of the more recent accomplishments in fluid (as well as solid) mechanics were described in the proceedings of these meetings, particularly in the field of turbulence. The 1938 congress was held in Cambridge, Massachusetts, with Harvard and MIT as the official hosts. As Karl Taylor Compton, President of both MIT and the Fifth Congress, said in his opening address,

> To this Congress have come over three hundred delegates from more than a dozen countries. While not large in membership, compared with some scientific bodies, this Congress is distinctive in that it deals with the most difficult problems in the most fundamental of all branches of applied science, and in that its members are scientists and engineers of the highest degree of distinction in this difficult field.

Among the more than 400 who actually attended the sessions were at least 20 American hydraulicians, many of whom have already been mentioned in the foregoing pages, and seven of whom presented papers (Bakhmeteff and Feodoroff, Kalinske and Van Driest, Knapp and Ippen, and Rouse). As in previous congresses, the fluids half of the program stressed the turbulence phenomenon, and American hydraulicians were among the contributors. Interestingly enough, the hydraulics problem of pipe resistance again was the subject of papers by aerodynamicists from various countries, in one of which von Kármán's Caltech colleague, Clark Blanchard Millikan (1903-1966), theoretically derived the logarithmic form of the velocity-distribution function. Another of the papers on turbulence was presented by the MIT mathematician Norbert

Wiener (1894-1964), with emphasis on his theory of chaos; von Kármán, who chaired that session, thanked Wiener and (himself no mean mathematician) said he was only sorry that he could not understand the mathematics involved. Before the end of the Congress it was decided that the next one would be held at Paris in 1942. By then, of course, the world was engaged in its second great war, and 1938 represented for many of the participants their last international professional gathering.

Although the Hydraulic Division of the ASME had sponsored sessions in the annual meetings of the organization since its establishment in 1926, the ASCE depended upon the Irrigation and Waterways Divisions for the sponsorship of hydraulics papers. Then in 1938 the ASCE Board of Direction, at the instigation of Fred Scobey, Boris Bakhmeteff, and others—authorized the formation of a Hydraulics Division, with Scobey as its first chairman. Probably the most active of its original committees was that on Hydraulic Research, under the chairmanship of John Cyprian Stevens (1876-1970), a consulting hydraulic engineer and instrument manufacturer of Oregon. The AGU Hydrology Section, of course, had existed since 1931, and many papers by Freeman Scholars appeared in its *Transactions*. The first national conference purely for hydraulicians was that organized by Theodore Mavis at the State University of Iowa in June of 1939, the year that he left for Pennsylvania State College and was replaced by Hunter Rouse. Some two hundred hydraulicians—including representatives of the Corps of Engineers, the Geological Survey, the Bureau of Reclamation, and the Department of Agriculture—from all parts of the country attended the four-day June meetings. One of the eight half-day sessions was devoted to an open house at the Institute of Hydraulic Research, and the remaining seven involved the presentation of 20 invited papers. As was to be expected, these ran the gamut between the old and the new, the trite and the imaginative. With reference to the foregoing pages, mention should be made of papers on the mechanics of bed movement by Straub, similarity and scour by Rouse, and suspended-load control by Lane; liquid turbulence, by Kalinske; and—of particular note—the propagation of flood waves, by Harold Allen Thomas (1885-1973), a native of Michigan and professor at the Carnegie Institute of Technology; his paper combined a mathematical analysis of the roll-wave phenomenon with experiments in which the roll waves were brought to rest on a moving belt. So well-received was this gathering that it became the forerunner of six additional Iowa conferences, an indefinite series of annual conferences later sponsored by the new Hydraulics Division of the ASCE, and many other meetings under the auspices of various organizations dealing with the mechanics of fluids.

The accomplishments of this period were perceptively reviewed by

Arthur Ippen in his address during the 1965 dedication of the Straub Memorial Library at Minnesota:

> Thus, a unique and most fertile new age dawned in the American hydraulic world, leading to the present eminent position of American hydraulic research . . . . This position has been achieved as the result not only of the earlier injection of massive doses of hydrodynamic theory and of largely empirical model and experimental techniques into United States hydraulics over a generation ago, but by the gradual pragmatic blending of the entire spectrum of hydraulic knowledge into a sound system of purposeful action. This philosophy of simultaneous promotion of knowledge through theory, experiment, and field observation has come to form the basis of our profession . . .

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# CHAPTER VII

## THE WAR YEARS AND THEIR AFTERMATH

War invariably produces a change in nearly every phase of civilized life, and World War II had as much effect on hydraulics as on most other professions. The change in the Forties, however, displayed several unexpected aspects. To be sure, some hydraulicians enlisted in the Armed Forces, and some were drafted; in view of the decreasing university enrollments, some teachers decided that they could be more effective in industry than in education; some researchers even closed their laboratories; but a few became so deeply involved in experimental studies for the war effort that their professional lives were never the same again. Because of America's initial isolationism, the effect of World War II became apparent only slowly. The Depression was still strong in people's memories, and had it not been for the resumption of industrial output as the result of Lend-Lease demands, the lean years would probably have continued much longer. At the same time, however, the Draft began its inroads on university activities, and a gradual variation in pedagogical emphasis took place.

At Iowa, for example, Lane at first continued his endeavors in the field of sediment, as did Kalinske in that of turbulence. Rouse, newly arrived, joined the two in the hydraulics laboratory. Mavis's position as head of Mechanics and Hydraulics was taken over by Joseph Howe, who thereafter played father-confessor to the 400 or more graduate students who were to study hydraulics at Iowa prior to his retirement. Chesley Posey had chosen to be an understudy of Sherman Woodward well before the latter's departure for the TVA; not only did he then continue Woodward's deliberate style of teaching potential-flow theory, but he combined the latter's lectures based on his Miami Conservancy findings with his own work on backwater analysis in the form of a book that was published jointly in 1941 under the title *Hydraulics of Steady Flow in Open Channels*. During the summer of 1940 Rouse taught a graduate class in fluid mechanics at Colorado State at the invitation of Dean Nephi Christensen; unsponsored, this was to be followed by many sponsored summer classes in future years. In the course of his second year at Iowa he prepared notes for an undergraduate text on the mechanics of fluids, and Howe and Kalinske taught the course with him. Then in 1941 Kalinske obtained summer employment in a new laboratory of the Navy at Washington DC, and a relationship that was to prove of lasting value to the Iowa Institute was established.

During the century or more that has elapsed since William Froude built his first towing tank at Torquay, Devonshire, essentially every country engaged in shipping has followed suit. The U. S. Navy's Experimental Model Basin at Washington was established in 1899 after designs by Rear Admiral David Watson Taylor (1864-1940), who directed its operations for the next fifteen years. The need for expansion became apparent in the late Twenties, but limitations on space at the Navy Yard made it desirable to seek a suitable location outside the city. In 1936 Congress authorized a new establishment at Carderock, Maryland, some 10 miles northwest of Washington, and the following year it was named the David W. Taylor Model Basin. Most of the design had proceeded under Commander Harold Eugene Saunders (1890-1961), who had been assigned to the Experimental Model Basin in 1929 as senior assistant to the officer in charge; he eventually became director of the EMB and then of the new TMB as he was promoted to the captaincy. In addition to the very extensive model shops, the principal features of the establishment were its three towing tanks: a shallow one, 303x51x10 feet in size; a deep one, 963x51x22 feet; and one for high speed, 1168x21x10 feet; the second and third were so long that their tracks were not linear but curved with the earth's surface. In 1940 the 12-inch and the 27-inch water tunnels for propeller testing, built at the EMB in 1930 and 1937, respectively, were moved to the new establishment. Next plans were begun for a huge recirculating channel that would permit models to be held stationary in flowing water, and Kalinske brought several problems connected with its use back to Iowa City for investigation under contract.

Primary among these problems was the effect of free-surface slope on the measurement of model drag and possible means of minimizing this error. Both the 10-foot and the 16-foot river channels of the Iowa laboratory were adapted in 1942 to simulate the proposed facility. The gravitational component was shown to be a very real factor in the case of a sloping or undulating surface, but it was also found that proper manipulation of discharge, depth, and bed slope could produce a level surface in the vicinity of the model. The effect of turbulence on the drag was also investigated. Many of the tests were conducted by Wallis Sylvester Hamilton (1911-. . . .), a graduate staff member from New Jersey who had studied at Carnegie and there assisted Professor Harold Thomas. Hamilton's doctoral project involved the measurement of the detailed velocity distribution around a model hull in flowing water and the calculation therefrom of the surface drag for comparison with the measured total drag. The prototype channel which was put into operation at Carderock in 1944 had a test section that was 60 feet long, 22 feet wide, and 9 feet deep, with a maximum water velocity of 17 feet per second. It was initially under the supervision of Lieutenant Clyde Warren Hubbard (1903-1971), one of "Prof" Allen's former students at Worcester; he was assisted by Charles Allen Lee (1915-. . . .), a

Montanan who had been Arthur Ippen's first graduate student at Lehigh and was later to serve in uniform with the Navy's Construction Battalion before returning to the Model Basin. Probably as a result of this contact, one of Kalinske's doctoral students, James Mueller Robertson (1916-. . . .) of Illinois, was to join the TMB staff on completion of his dissertation on air entrainment in pipes.

In the course of a 1941 trip by car to a conference at the Waterways Experiment Station, Dawson, Lane, Robertson, and Rouse had decided that a Second Hydraulics Conference should be held at Iowa City in 1942 to maintain the momentum acquired in 1939. Howe, Kalinske, and Rouse arranged a program to emphasize the "astonishing similarity of principles utilized by the wide variety of professions dealing with fluid motion." Twenty-four speakers (including Bakhmeteff and von Kármán) were invited from such varied fields as aeronautical, chemical, civil, marine, and mechanical engineering, and geology, meteorology, and oceanography—with particular heed to those who could call attention to knowledge of fluid behavior which might benefit the war effort. The Conference was attended by 150 engineers and scientists from thirty different States; though because of wartime conflicts the attendance was smaller than before, the subsequent volume of *Proceedings* was completely sold out.

Not long after the Conference, Lane decided that he could do more for the country with the Tennessee Valley Authority, and he was granted a two-year leave of absence by the University. Rouse and Kalinske were appointed associate directors in his stead, the former being placed in responsible charge. On returning from one of his visits to the Taylor Model Basin, Kalinske presented a seminar talk comparing the characteristics of water tunnels and air tunnels, in many respects to the advantage of the former. Funds were then sought from the University for the construction of a small water tunnel for contract research. John Stephenson McNown (1916-. . . .), a Kansan who had obtained higher degrees from Iowa and Minnesota, was brought back to Iowa City from the Navy's Radio and Sound Laboratory near San Diego to design the new facility. With a water velocity of 35 feet per second at a test section 1 square foot in cross-sectional area, surplus pump, and a gasoline-engine drive, the tunnel was used for the next five years (whereafter it was sold to the Waterways Experiment Station) to study the pressure distribution around torpedo heads of various forms at different stages of cavitation, under a contract administered by the Model Basin. The measurements and supplementary analyses were the work of McNown and En-Yun Hsu (1915-. . . .), a Chinese doctoral student who later went to Stanford by way of Caltech, various naval laboratories, and Lockheed.

At about the same time that the water tunnel was being constructed, a contract was signed by Rouse with the National Defense Research Committee, for the construction of a low-velocity air tunnel to study atmospheric-diffusion problems for the Chemical Warfare Service. The tunnel had a 4x6-foot cross section with an air speed of only 25 feet per second, and was under the direct supervision of Maurice Lee Albertson (1918-. . . .), a Kansan with degrees from Iowa State and Iowa who had been brought back from the TVA to serve as a wartime staff member. Before this project was well under way, however, a higher-priority study of heat requirements for fog dispersal over airport runways was undertaken in the air tunnel for the Navy's Bureau of Aeronautics; the diffusion of heat downwind from a line of gas burners was shown to be a gravitational phenomenon depending upon Garbis Keulegan's modified Froude number as similitude parameter. After this interlude, Albertson and several colleagues conducted experiments on the diffusion of smoke and gas over urban regions, as well as on the generation of large-scale turbulence over mountainous terrain. Kalinske was able to correlate analytically the diffusion expected from point bursts and observed from continuous point sources. A training film prepared in the air tunnel for CWS personnel proved to be the forerunner of a series of subsequent educational films on the mechanics of fluids. In fact, the air tunnel itself was proclaimed by Rouse to be as valuable a tool for hydraulic research as any in the laboratory. In 1940 Alexander Kolin (1910-. . . .), a Russian immigrant, moved to Iowa from Columbia University, where he had developed under Bakhmeteff what he called an electromagnetic velometer for measuring the velocity of flowing liquids. Because tenure at Iowa could not be guaranteed, Kolin soon left for Chicago, and his place was taken by Philip Gamaliel Hubbard (1921-. . . .), a Missourian educated at Iowa, under whom electronic instrumentation flourished—particularly the constant-temperature hot-wire anemometer.

The Third Hydraulics Conference of the Iowa Institute had to be postponed from 1945 to 1946 because of wartime exigencies, but then it purposefully emphasized the peacetime utilization of war experience. Some 325 people attended the sessions, and 18 invited papers were presented. The theses of this and the preceding conference were aptly summarized by Rouse in his discussion of still another paper on research by Commander E. A. Wright, then deputy technical director of the TMB, from which the following excerpt is taken:

> So forceful and inclusive a case for research has been presented by the author of this paper that the writer can do little more than attest to a wholehearted agreement with each and every point. Such agreement is particularly significant due to the fact that the author and the writer differ considerably in professional background and immediate endeavors, however close their indirect interests may be. The author is by training a naval architect, the

writer a civil engineer; the author, as an officer of the Navy, is directly engaged in the strengthening of American protective power, whereas the writer, as a university professor, is concerned primarily with the discovery and propagation of scientific information. Professions with even closer mutual interests than these have long made their independent ways with little mutual assistance. However, as indicated by the author's entire paper, one of the few great blessings of the recent war has been the lesson which it has taught of the value of close collaboration among all professional groups having the slightest common ground of endeavor.

Two of the several research needs stressed by Commander Wright are identical with certain aims of any large technical school: the training of men to do creative work in research laboratories, and the gathering of fundamental knowledge in science and engineering. It goes without saying that the interest of men so trained will vary directly with the eventual demand for their services, and that the amount of fundamental knowledge so acquired will depend to a great extent upon the availability of research funds. If all Federal agencies followed the pattern thus set by the Navy for sponsoring university training and research, the ultimate benefit to the technical strength of the country could not be overestimated.

Of particular importance to the writer, who is engaged in research in general fluid mechanics, is that portion of Commander Wright's paper which deals with fluid motion. Quite apparent from the illustrative matter accompanying his arguments is the fact that ship resistance is by no means the only phenomenon involved in the research program which he has envisaged, nor is ocean water the only fluid with which he is concerned. The writer, in turn, must emphasize the fact that problems of naval architecture are by no means the only ones with which he would wish to deal, nor is he particularly interested in seeking principles which are restricted to a narrow field of application. Fortunately for both the success of the author's program and the satisfaction of the writer in assisting with a small phase of it, technological development has at last reached a stage at which no single branch of science is sufficient for its further progress, while science itself has so broadened in scope that its same basic principles are applicable to a thousand and one different fields of practice. The author, for example, cites the use by naval architects of boundary-layer theories of aerodynamics, sound-wave theories of ballistics, and open-channel theories of hydraulics; and the writer, at the moment, is occupied with studies (sponsored by the author's organization) which are applicable at one and the same time to meteorology, river control, and sanitary engineering, as well as naval architecture. Indeed, all branches of technology are fast becoming so closely interlaced that progress in any one branch in some manner or other invariably advances the rest.

While the wartime research of the Iowa Institute was probably the most varied among American hydraulics laboratories, and hence the best illustration of this point of view, it was by no means on the grandest scale. Instead, the program masterminded by Knapp at Caltech was surely the most extensive and elaborate investigation of a particular subject—the interaction between projectiles and the air or water through which they travel. To quote his final report to the NDRC:

> During the four-year period from the fall of 1941 to the fall of 1945, the Hydrodynamics Laboratory of the California Institute of Technology devoted its entire resources to the prosecution of a war research program for the Office of Scientific Research and Development under the direction of Division 6 of the National Defense Research Committee. The general assignment was to observe and analyze the hydrodynamic forces acting on bodies moving through fluid media, and to develop shapes for these bodies that would result in the specific performance characteristics desired. With very few exceptions, the bodies studied were projectiles. The larger part of the time and energy available was used in studying the behavior of projectiles whose trajectories were either partly or wholly under water. However, a very significant part of the laboratory activities was given over to work on airflight projectiles operating at velocities enough lower than the velocity of sound so that the air could be considered incompressible. Much consideration was also given to the water entry problems associated with air-launched underwater projectiles such as aircraft torpedoes and antisubmarine rockets.

In the late summer of 1941, work was begun by Knapp and his assistants on what was to become the primary piece of equipment of the new facility: a high-velocity water tunnel having a test section 14 inches in diameter and 6 feet long, with pressure controls and water speeds as high as 75 feet per second. Much of the equipment in the hydraulic-machinery laboratory was incorporated into the system, but additional instrumentation—particularly a recording three-component dynamometer—had to be designed, an operation in which Knapp was in his element. The personnel was rapidly augmented, three members of the prewar staffs forming the nucleus: Vito Vanoni, again general manager and buffer between Knapp and those under him; James Daily, primarily responsible for operation of the tunnel; and Hugh Stevens Bell

(1899-. . . .), a natural-science teacher from Ohio who had come to the SCS by way of a career as free-lance writer and photographer in the American Southwest; at his hands, unsurpassed photographic studies of the cavitation process were to be produced. Mention should also be made of the Palestine-born Joseph Levy (1906-1972), a Caltech graduate who was to contribute to various phases of the laboratory program. Above all, however, note must be taken of the superb group of machinists assembled by Knapp for fabricating the projectile models, none of which was greater than 2 inches in diameter and some highly detailed in form.

Within barely a year after the water tunnel had begun operation, space in the former hydraulic-machinery laboratory became inadequate for future needs, and in 1944 a new building was completed next to the old (which in turn, had formed an integral part of von Kármán's Guggenheim Aeronautical Laboratory). In addition to offices and shops (and the water tunnel, which was eventually moved), this was to house two new units. One was a controlled-atmosphere launching tank, 13 feet in diameter and 29 feet long, with a centrifugal mechanism for projecting torpedo models through air of controlled density into carefully filtered water, and windows to permit photographing their complete trajectories. The other unit was a free-surface water tunnel, having a test section to accommodate a stream 20 inches square over a length of 8 feet, and windows permitting observation both above and below the free surface; in addition to studying free-surface phenomena, the necessary deaeration system beyond the test section also made possible the use of models discharging air for propulsion purposes. These units were not ready for operation till after the end of hostilities.

Fully as important as the three major pieces of equipment were supplementary items of instrumentation which could be used on each one. Principal among these was the lighting system to permit high-intensity short-duration (5-microsecond) flashes for still photography of cavitation. As the launching tank came into use toward the close of the war, observation by high-speed motion pictures became necessary, which required not only as many as 3000 flashes per second with synchronized batteries of lights, but also cameras with continuously moving loops of film. (Fully 20,000 frames per second were ultimately realized in the old water tunnel.) Since cavitation noise was an essential element of study, means of focusing microphones on definite underwater points of observation had to be devised. Finally, analysis of countless successive movie frames to determine projectile trajectories and their kinematic characteristics required a whole new system of instruments and techniques.

While the launching facility was not activated in time to be of any use in World War II, tests of projectile trajectories were conducted well into the Korean War to provide general information to the Navy. The free-surface water tunnel continued in operation for another quarter of a century, and by no means exclusively for military purposes (for instance, studies of fish propulsion). The original high-speed water tunnel, on the other hand, was completely rebuilt by 1947 in order to accommodate a novel 4-pass resorber system; this extended 85 feet below the test section and thus insured that all gases released by pressure reduction at the test section would be redissolved. The revised unit became the primary piece of research equipment for the study of cavitation. High-speed motion pictures, also utilized for launching studies, were specially adapted for these investigations, the film again moving continuously and the flashing lights determining the position of the image on the film. The result, of course, could not be projected in the usual manner, because the images were not properly spaced. In the mistaken belief that Knapp would not approve such an expenditure of effort, Bell spent many an hour of his own time clandestinely rephotographing the individual frames to provide a film that could be shown with a standard projector to reveal in slow motion the details of cavitation-bubble formation and collapse—and subsequent rebound. A letter from Vanoni to the author sheds further light on the accomplishment:

> I have talked to Hugh Bell about his work on the development of high-speed motion pictures of cavitation. This work started with the use of an Edgerton camera which takes standard 35-mm frames at 2000 per second. It soon became clear that this was not fast enough, so the frame was cut in half and the pictures taken at twice the speed or 4000 per second. Now the problem was to make a projectable motion picture out of this. This was done, first by making enlargements of each frame and copying them, but later by actually photographing each picture on the negative itself, using a milling-machine bed to advance and register the film. These pictures would be taken by registering each picture according to some fixed point on the tunnel, in which case the cavitation bubbles moved, or by focusing on a bubble and watching its development as it stood still in the picture.
>
> Higher-speed pictures were taken by further reduction of the size of the picture taken. These pictures were always of standard width but reduced in height to as little as one millimeter. To take these higher-speed pictures, the flash lamps were driven independently of the camera with an electronic circuit. With this scheme, pictures were taken at the rate of as high as 30,000 per second. These motion pictures were taken on 100-foot strips of 35-mm film. Total exposure time was 1/10th of a second, which exposed only part of the 100-foot strip. The heat generated by the

lamps was extremely intense and would have melted the lamps if the exposure time had exceeded this short duration. Hugh admits that all of this activity kept him up nights.

Shortly before the onset of war, Hans ("My friends call me 'Albert' ") Einstein had moved from the Greenville office of the SCS to Caltech, where the staff gradually shifted their activities from sediment to problems more closely associated with military endeavors. Einstein engaged in a number of such projects, principally the operation of a ripple tank to simulate supercritical flow of either a gas or a liquid with a free surface—the Kármán-Knapp-Ippen wave analogy in reverse, so to speak. Sediment was still Einstein's primary love, however, and over the years he had developed an empirical means of bed-load evaluation, which he published in the ASCE *Transactions* of 1942. This departed from customary procedures in ignoring the concept of initial movement and introducing a statistical notion of successive particle steps of constant average magnitude, the rate of transport varying with the frequency of the steps. In 1947 Einstein left the SCS for an associate professorship at Berkeley, there joining Joe Johnson, who had already made the change in 1942 and was by then a specialist in coastal problems (the O'Brien-Folsom influence was reflected in the fact that both were placed in mechanical rather than civil engineering). At California Einstein was able—at least to his own satisfaction—to convert his empirical transport formula into an analytical one, which he published in 1950. In later years, moreover, he sought to combine his analysis of bed load movement with those of Ippen and Rouse for the distribution of suspended load, by using the former to define a particular value of the latter, but this was not too successful. At best a very complex function, the Einstein bed-load formula was probably fully understood only by its creator, although he trained a number of graduate students who regarded his work highly and published jointly with him. Prominent among these were Robert Blackburn Banks (1922-. . . .), of Kansas and Northwestern, and Ning Chien, a Chinese graduate student from Iowa who later returned to the People's Republic. While a consultant in the Corps of Engineers, he collaborated with Nicholas Leonard Barbarossa (1915-. . . .) of the Missouri River Division. Einstein probably suffered as much as he profited from his family name; in any event, he seldom mentioned his father to friends or acquaintances. As a consultant his advice was practical, sound, and widely sought. But his intuitive grasp of a sediment problem was not easy to inculcate in others.

During the decade between the founding of the Waterways Experiment Station and the onset of World War II, considerable headway had been made in the development of a steadily growing experimental program. Joseph Tiffany, who had been responsible for establishing much of the test and report procedure (and had himself conducted an extensive investigation of bed-load transport), became the first Chief of the Hydraulics Division in 1938, Technical Director in 1940, and Acting Director during two of the war years. Eugene Fortson succeeded Tiffany as Chief of the Hydraulics Division, though while he was on active duty his place was taken by Bradford Fenwick. The latter had already laid the foundation of his expertise on river hydraulics, as had Robert Hudson his on waves and breakwaters. Three staff members of note were added during the decade: Frank Bixby Campbell, who came to the Corps in 1938 by way of the USGS, the USBR, and the SCS; Freeman Scholar Haywood Dewey, who reached the Experiment Station in 1942 after six years with the Bureau of Reclamation; and Henry Brown Simmons (1915-. . . .) of Mississippi, who began as an engineering aid in 1940 and was eventually (in 1971) to succeed Fortson as Chief of the Hydraulics Division. The War diverted much of the WES attention to such defense matters as model studies for dry-dock improvements, the design of pontoons and pneumatic floats, breakwaters at naval air stations, and the development of harbors used in transoceanic shipping. At the end of hostilities, work was resumed on the accumulated backlog of model tests for the thirty-odd District Offices of the Corps. Civil works projects of this nature ran the gamut of tests on spillways, sluices, fuse-plug levees, penstocks, diversion works, stilling basins, prevention of shoaling, salt-water intrusion, dredges, cavitation-free baffle piers, and floodway structures.

In 1946 a group of consultants were appointed to advise the WES staff on its various projects on an intermittent (usually annual) basis. The original group consisted of Boris Bakhmeteff, Arthur Ippen, Robert Knapp, Morrough O'Brien, Hunter Rouse, and Lorenz Straub. Among the repeated items of advice given by the group over its quarter century of existence were the upgrading of the staff by continuing education both internal and external, and the upgrading of its product by the conduct of research as well as development. Two years later the Corps established its Committee on Tidal Hydraulics, whose task was to advise on research related to estuarial analysis; this body—the first report of which was issued in 1950—consisted of a dozen or more of the Corps' own civilian personnel, plus half a dozen external consultants. Though most of the members have already been mentioned, note should be taken of Jacob Henrick Douma (1912-. . . .) of California, a long-time member of the Chief's Office; since practically all hydraulic designs were eventually to pass through his hands, Douma was involved as well in most of the planning for the Corps, model tests included, not to mention considerable private consulting.

Freeman Scholar Martin Mason transferred in 1940 from the Bureau of Standards laboratory to the Beach Erosion Board. The following year the Board began the publication of a series of technical reports. Number 1, by Mason, was "A Study of Progressive Oscillatory Waves in Water," and this was followed the same year by "A Summary of the Theory of Oscillatory Waves" by Morrough O'Brien and Mason together. As the War progressed, the Board undertook an intensive study of potential landing operations on the African and European coasts. Garbis Keulegan, already a specialist in wave studies, was borrowed from the Bureau of Standards, and William Christian Krumbein (1902-. . . .) moved to Washington from the University of Chicago for the same purpose; a geologist with interest in water-borne sediment, Krumbein had just completed a Guggenheim year at Iowa and California. Though the entire wartime staff of the BEB never exceeded 35, they produced more than 50 highly valuable reports on beach intelligence.

At the end of the War, in 1945, the 79th Congress formally established research and development as legal activities of the BEB. The latter's shore-protection counterpart was then abolished and its functions absorbed by the BEB, and the following year Congress authorized federal participation in the cost of protecting publicly owned shores. The first research contracts with non-federal organizations were written in 1948: with the Scripps Institution of Oceanography, the University of California (under O'Brien and Joe Johnson), and New York University (under Thorndike Saville). In 1943 Joseph Caldwell, who had been with the Waterways Experiment Station for ten years, transferred to the Board and was thereafter the designer of the new 635x15x20-foot wave tank that was installed in 1949-50; because of the Korean War, the tank was not activated till 1955. Another unit constructed during this period was the 300x150x3-foot Shore Processes Test Basin, with 10 movable wave generators. 1949 also saw the addition to the staff of Thorndike Saville Jr, Maryland-born and educated at Harvard and California, who ably carried on the professional interests of his father. When Mason left the Board in 1951 to become dean at George Washington University, he was succeeded as chief engineer by Caldwell. During Boris Bakhmeteff's membership on the board of the Engineering Foundation in 1950, a Council on Wave Research was formed, with O'Brien as chairman and Johnson as secretary. That year an Institute of Coastal Engineering was held at Long Beach, California, followed in later years by many more in various cities of the world. The year 1954 saw the appearance of the BEB's Technical Report No. 4, the 390-page volume *Shore Protection Planning and Design,* in its first of several editions.

The widely varied program of research begun at Iowa even before the War did not end, of course, when the War did—or even many years thereafter. For example, the low-velocity air tunnel was used by Maurice Albertson for his doctoral investigation of the relationship between boundary layers and evaporation layers, and he promoted similar studies in air at Colorado State College after moving there in 1947. The necessary generation of turbulence in the diffusion studies culminated in a paper on the velocity and scale of eddies downwind from coarse grids. The work on submerged jets involved in the fog-dispersal project appeared as several graduate theses and a paper on the diffusion of jets from slots and orifices. Not too remote from the submerged-jet study was a project on the improvement of fire monitors and nozzles for the Coast Guard, reminiscent of the earlier tests by John R. Freeman for his fire-insurance companies; but whereas Freeman made no mention of turbulence in his prize-winning papers, the Iowa studies sought to produce a design that would yield minimum initial turbulence—and hence maximum throw—of the free jet (a criterion which continues to be ignored by the fire-fighting world). Similarly, when it was proposed by the Navy to reduce propeller noise and cavitation by locating the propeller in an enlarged duct within the ship and using a high-velocity jet at the stern for propulsion, it was pointed out by Rouse that noise might still result from the cavitation of eddies generated by the diffusing jet. Navy-sponsored tests were then begun at Iowa on the mechanism of submerged-jet cavitation, to which John Peter Whitehouse, a master's-degree student from England, and David Woodhull Appel (1924-. . . .) and Sung-Ching Ling (1925-. . . .), doctoral students from Washington DC and China, respectively, strongly contributed. Individually, the latter two also produced independently a number of instruments for the measurement of sediment and others for that of turbulence—in particular Ling's hot-film anemometer—under the guidance of Philip Hubbard.

Two other series of investigations at Iowa were also the outgrowth of the wartime research. One had to do with the diffusion of heat from point and line sources. Measurement of the temperature distribution over a point source, its analytical evaluation for laminar conditions, and the empirical establishment of the critical Reynolds number (using a cigarette as the heat source) comprised the doctoral project of Chia-Shun Yih (1918-. . . .), a Chinese graduate assistant who then continued to distinguish himself at Colorado State, Iowa, and Michigan. The temperature distribution over single and parallel line sources was the work of Harold Wesley Humphreys (1921-. . . .) of North Carolina. William Douglas Baines (1926-. . . .) of Canada assisted in the completion of measurements for the resulting papers of 1952 and 1953. The other series of studies was concerned with surface resistance. At the Second Hydraulics Conference, in 1942, Rouse had presented a resistance diagram incorporating the British Colebrook-White smooth-to-rough transition function. The parameters $1/\sqrt{f}$ and $\mathbf{R}\sqrt{f}$ were used instead of the customary $f$ and $\mathbf{R}$, because of the generality that this would yield; *f* and **R** were available, however, on supplementary scales. After the Conference, Lewis Moody of Princeton suggested using the latter variables as primary rather than supplementary, as in the past, but Rouse resisted the temptation because he felt that to do so would be a step backward. So Moody himself published such a plot, and it is known around the world as the Moody diagram! Baines' doctoral dissertation involved measurements of the velocity distribution in the boundary layer along a smooth plate, and he later (1951) prepared an Institute report on all that was then known about boundary layers. Subsequently, studies were conducted on the effects of sand, screen, and bar roughness in channels and boundary layers by Baines, Walter Rand (1914-. . . .) of Estonia, and Walter Leon Moore (1916-. . . .), a doctoral student from California, respectively. The results were analyzed in a 1954 paper by Francis Ryosuke Hama (1917-. . . .) of Japan, like Rand a post-doctoral research associate of the Iowa Institute for several years.

In the late summer of 1946 Rouse went to Europe under TMB sponsorship with a triple purpose: to assess the postwar laboratory situation in the various countries; to inspect water tunnels in preparation for a new one to be built at Iowa; and to present a paper on Iowa's wartime fog-dispersal studies at the Sixth International Congress for Applied Mechanics held at Paris after a four-year postponement. The German hydraulics laboratories were at a standstill, some having been partially destroyed. Prandtl was visited at Gottingen (the city was intact) and Spannhake at Karlsruhe (the city was in ruins), and the latter was then invited to Washington for work with the TMB. Three laboratories in other countries (those at Zurich, Grenoble, and London) impressed Rouse with their activity, however, and he recommended them through a letter in *Civil Engineering* to prospective Freeman Scholars. At least at Grenoble, where Martin Mason had been attracted by Pierre Danel before the War, the recommendation had a long-time effect. As recounted by Rouse in a subsequent memoir honoring Danel:

> The second Freeman Scholar, George S. Dixon, Jr., of the Corps of Engineers, actually arrived in Grenoble that fall and had received the engineering doctorate by 1949. My enthusiasm next led my colleague, John S. McNown, to spend his year as Fulbright Research Scholar with Danel in 1950-51; there he wrote a comprehensive paper on fall velocity, did research on seiche, and passed the examination for a doctorate in sciences. During McNown's absence from the Iowa Institute of Hydraulic Research, his chair was filled for a year by Antoine Craya of Grenoble, who later returned to the States to teach at Columbia after the death of Boris A. Bakhmeteff. McNown was followed immediately at Grenoble by Charles W. Thomas, of the Bureau of

Reclamation, also a Fulbrighter, as was I in 1952-53. At Grenoble I met Enzo O. Macagno, of Argentina, who was studying there for the doctorate, and in 1956 he moved from La Plata to Iowa City as a member of the Institute staff. My Fulbright successor at Grenoble was Maurice L. Albertson, of Colorado State College, who was the fourth to receive the local doctorate. Ira A. Hunt, of the Corps of Engineers, was the third Freeman Scholar, in 1953-54, and the fifth doctor. [A. R. Chamberlain, Albertson's first doctoral student at Fort Collins, was a Fulbright Scholar at Grenoble in 1955-56.] The fourth Freeman Scholar, in 1961-62, was Jacques W. Delleur, of Purdue University (and previously one of Craya's students at Columbia). Several other Americans were there a month or more, and literally hundreds must have visited Neyrpic, and more recently SOGREAH, at one time or another.

In view of the attention that has been given to the subject of pipe resistance, a pertinent story might well be told at this point. Benjamin Miller (1904-. . . .), a New York consulting engineer to the oil and gas industries, while checking some of Nikuradse's experimental results shortly after the War, discovered that the published raw and computed velocity-distribution data differed by a constant additive factor. During an ASME meeting Miller happened to tell Rouse about the discrepancy, and the latter, recently returned from his visit to Gottingen, offered to transmit a letter of inquiry from Miller to Prandtl; this was soon done. Nikuradse was then back in Gottingen from Breslau, but Prandtl, who was no longer on speaking terms with him, asked his associate Reichardt to question him instead. The eventual response was that Nikuradse had added the constant factor (which had an appreciable effect on the semi-logarithmic expression only in the wall vicinity) because his measured values would otherwise not be compatible with the laminar-film theory; Prandtl added his own opinion that the correction was hence justifiable, whereas the author's failure to mention it in the text was not. Though Miller interpreted the subterfuge as evidence against the existence of the laminar film, subsequent measurements by the Hungarian-born aerodynamicist John Laufer (1921-. . . .), of Caltech and the Bureau of Standards, verified Nikuradse's assumed function. [It has recently been pointed out by Landweber at Iowa that the discrepancy in measurement resulted from Nikuradse's having placed his stagnation tube in the free-shear zone somewhat beyond the end of the pipe rather than within the pipe itself.]

Little mention was made of the St. Anthony Falls Hydraulic Laboratory in the foregoing chapter on fluid mechanics, because the limited amount of work that was done before the War was confined to Lorenz Straub's studies of sediment and river control involved in his growing consulting practice. As soon as the War was under way, moreover, Straub was among those who decided that they should contribute more to the defense effort than was possible at home, and he spent the years 1942-45 with the National Defense Research Committee in its Divisions of Rocket Ordnance and Subsurface Warfare at New York; for essentially half a year (while the bombs were falling) he was in London on a related mission. During Straub's absence from his laboratory, the work of the cooperating federal agencies was continued with their own reduced staffs. Practically the only laboratory projects that remained active were on the aeration of high-velocity flow on steep slopes, which was studied as a doctoral project by Warren William DeLapp (1912-. . . .), an instructor from Colorado by way of Iowa, who was to return to Colorado in 1947; and on soil conservation structures by Fred William Blaisdell (1911-. . . .) of New Hampshire and MIT, who had been with the SCS since 1936, first at the Bureau of Standards and then at Minnesota. At the close of the War Straub surrounded himself with Minnesotans who had been active in the country's defense: Edward Silberman (1914-. . . .), who had served 5 years with the Army, was to take a strong part in teaching and research in the mechanics of fluids; Alvin Anderson, already mentioned in connection with the SCS, had been several years with the NDRC at New York, and thereafter continued his studies of sediment transport at Minneapolis; John Frederick Ripken (1914-. . . .), who had participated in the design of the Minnesota laboratory before the War, spent four years in naval research at Columbia University and one with the Taylor Model Basin before returning to pursue his special interests in instrumentation and cavitation. In the postwar period the St. Anthony Falls Laboratory not only initiated an active program of model investigations, but through their wartime naval connections the staff also developed strong research programs on cavitation, wave motion, underwater acoustics, hydrofoils, and polymer additives.

Two other hydraulicians who did wartime work at the Model Basin before returning to nonmilitary research have already been mentioned—James Robertson and Charles Lee. As a matter of fact, during the War the TMB played much the same catalytic role as Caltech had done a few years earlier. Charles Edward Bowers (1919-. . . .) of Wyoming was there from 1942 to 1945, and upon Lee's return from the South Pacific, he worked under the latter's direction on experimental studies for a sea-level canal in Panama; their joint paper on the investigation received the ASCE Collingwood Prize; thereafter, Lee went into research with the paper industry, and Bowers—after graduate study at Minnesota—spent two years with the Bureau of Reclamation and then joined Straub's staff. Freeman Scholar Victor Streeter, who had been a hydraulic engineer with the Bureau of Reclamation and the International Boundary Commission before going to the Illinois Institute of Technology, spent the summer of 1942 at the Basin reducing Lamb's *Hydrodynamics*, as the saying went, "from words of five syllables to words of four"; the eventual outcome was a series of advanced and elementary textbooks on fluid mechanics which went into many editions; Streeter was to remain with the Armour Research Foundation—originally a part of IIT—till his return to Michigan in 1954. Phillip Eisenberg (1919-. . . .) of Michigan did graduate work at Iowa and Caltech before joining the TMB staff in 1942, remaining there in cavitation analysis till going to the Mechanics Branch of the Office of Naval Research in 1953 for contract administration. A latecomer to the TMB because of his youth, Marshall Peter Tulin (1926-. . . .) of Connecticut, after study at MIT and Brown and service with the National Advisory Committee for Aeronautics, went to the TMB in 1950 and then followed Eisenberg to the ONR in 1953. Eisenberg and Tulin together were to found the private research firm Hydronautics in 1959, where they were joined the following year by Virgil Evans Johnson (1927-. . . .) of Florida, Georgia Tech, and MIT, whose experience had included (instead of the TMB) the WES, the MIT Hydrodynamics Laboratory, and the NACA.

Boris Bakhmeteff succeeded Fred Scobey as chairman of the ASCE Hydraulics Division in 1943. Among his early innovations was the appointment of Committees on Hydraulic Data and Facts and on the State of Art and Science of Hydraulics. The latter was short-lived, giving way in 1946 to a Committee on Fluid Mechanics, with Hunter Rouse as its first chairman (the ASME Hydraulic Division soon following suit in both respects). One of the initial committee activities was the listing of available motion pictures on fluid-flow phenomena. Another was the sponsorship of a symposium on high-velocity flow in open channels. Four papers on the subject were written (basic principles, by Ippen; flow in bends, by Knapp; flow at contractions, by Ippen and Dawson; and flow at expansions, by Rouse, Bhoota, and Hsu), and these were presented at an annual meeting of the Society. The symposium was published in the 1951 *Transactions,* and Ippen received the Hilgard Prize for his initial paper. By the end of the four-year terms of Scobey and Bakhmeteff, the Division had gathered considerable momentum, and one-year chairmanships were instituted. Most of the people named in these pages served on its Executive Committee at one time or another, and the Division has remained one of the most active in the ASCE.

While completing at Lehigh a noteworthy study of the influence of viscosity on the performance of centrifugal pumps, Arthur Ippen was invited by MIT in 1945 to replace KC Reynolds, who had left for Cooper Union the year before. The hydraulics faculty then consisted of George Russell, already mentioned in Chapter IV, and Allan Thurston

Gifford (1906-. . . .), an MIT graduate who had had several years of hydrologic experience with the TVA. Donald Robert Fergusson Harleman (1922-. . . .) of Pennsylvania, who by chance had arrived in Cambridge the very same day as Ippen, became Ippen's first graduate assistant, and attention was given to reestablishing Reynolds' original laboratory, which had lain idle during the War. The same period saw the initial post-war influx of officers from the Corps of Engineers as graduate students, and this continued at a rather high level (about 15) for the next five years. When Russell retired in 1946, his place was taken by Ippen's close friend at Caltech, James Daily, and that year the second graduate assistant was employed: Henry Martyn Paynter (1923-. . . .) of Illinois, who had received his undergraduate degree two years earlier. With the support of the US Air Force, Harleman completed his doctoral research in 1950 on the validity of the hydraulic analogy to supersonic flow; Paynter at the same time worked on the application of analog and digital computers to surge-tank transients, receiving his degree in 1951. The hydraulics faculty then consisted of Ippen, Daily, Gifford, Harleman, and Paynter, and the number of research assistants had grown to 13.

The War years also saw the beginning of the tremendous upsurge that was to follow in the publication of textbooks on fluid mechanics. The first of these was written by John King Vennard (1909-1969) of New Hampshire, who had assisted Spannhake at MIT before joining the teaching staff at New York University and then at Stanford; published in 1940, his *Elementary Fluid Mechanics* was to go through many editions prior to his untimely death. The second was published by Raymond Binder in 1943, a few years after he went to Purdue from Caltech; somewhat simpler and slanted toward the mechanical engineer's interest, his *Fluid Mechanics* also came out in many successive editions. The notes prepared by Rouse finally appeared as *Elementary Mechanics of Fluids* in 1946; though limited to a single edition, it was translated into several languages, including mainland Chinese! In 1947 a noteworthy volume, *Fluid Mechanics of Turbomachinery,* was published by George Wislicenus; begun while he was at Caltech and written during his ten years with Worthington, it reflected the new approach to a considerable degree. While on the subject of publications, it should be remarked that the *Proceedings* of the Fourth Hydraulics Conference, held at Iowa City in 1949, took the form of a 1000-page reference book, *Engineering Hydraulics.* All thirteen invited chapters were preprinted for discussion at the Conference, and the fluid-mechanics viewpoint was strongly evidenced in each one: fundamental principles, by Rouse, the editor; hydraulic similitude, by J. E. Warnock of the Bureau of Reclamation; flow measurement, by J. W. Howe; hydrology, by G. R. Williams of Knappen Tippetts Abbett

Engineering Company; ground water, by C. E. Jacob of the University of Utah; steady flow in conduits, by V. L. Streeter; water hammer, by J. S. McNown; channel transitions, by A. T. Ippen; gradually varied flow, by C. J. Posey; flood routing, by B. R. Gilcrest of the Corps of Engineers; wave motion, by G. H. Keulegan; sediment transportation, by C. B. Brown of the SCS; and hydraulic machinery, by J. W. Daily. Some 425 attended the Conference, and the group photograph appears as the frontispiece of this book. The volume itself, which appeared in 1950, was dedicated to Boris Bakhmeteff, who had originally advised against the venture because of its difficulty of accomplishment! The following year the Engineering Societies Monograph *Hydraulic Transients* was published by George Rollo Rich (1896-. . . .) of Massachusetts and Worcester, a consulting engineer with various private firms, the TVA, and the Corps of Engineers, and guest lecturer and adviser to several universities.

Emphasis has already been laid upon the accelerative effect of war requirements on certain types of research, and upon the catalytic action of the Office of Scientific Research and Development in this regard. Much of its success, it should be noted, had stemmed from its authority to select individuals and teams for particular projects without requiring competitive bidding. At the close of hostilities, the OSRD properly terminated its activities. But one of the few salutary results of the war had been its demonstration of the importance of federal sponsorship of research on a broad basis. To provide continuity, Congress authorized in 1946 the establishment of the Office of Naval Research, the scope of which ranged surprisingly far beyond purely military interests. Competitive bidding on announced programs was still not required, competition taking the far more effective form of excellence of staff and proposals. The ONR's effectiveness was vouched for by no less an authority than Vannevar Bush, who had led the OSRD throughout the war:

> The Navy . . . has done a magnificent piece of work in this regard (sponsored research). It understands scientific and university-service relationships . . . .

Thanks to the efforts of Bush and his colleagues, in 1950 Congress finally authorized formation of the National Science Foundation, to take over the non-military activities of the ONR, including the support of education as well as research in science and engineering. In the words of the first NSF director, Alan Waterman,

> During the five years after the war, a considerable evolution took place. Academic institutions learned that Federal aid to research was possible without Federal control. Agencies with practical

missions found that even basic research done by academic professors could prove useful to them.

In the years to follow, both ONR and NSF support was to be of primary importance in hydraulic research.

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