NATIONAL ACADEMY OF SCIENCES

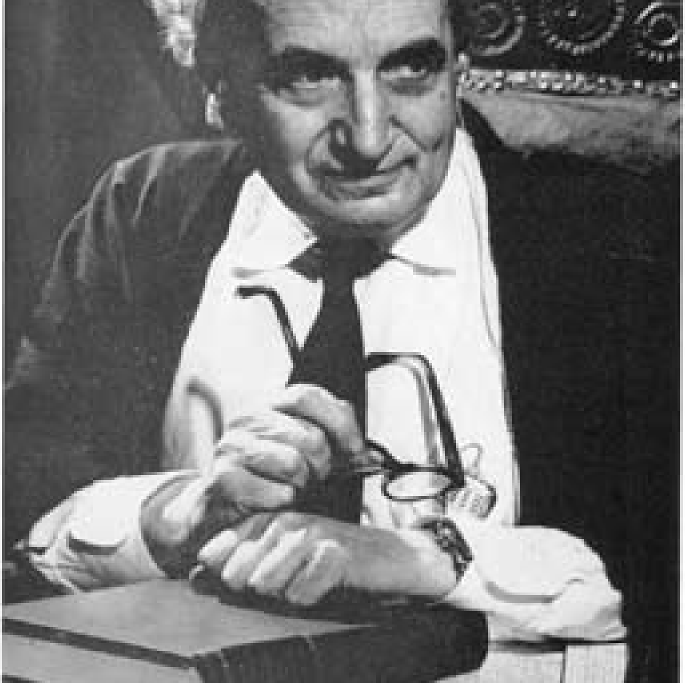
THEODORE VON KÁRMÁN

1881—1963

A Biographical Memoir by

HUGH L. DRYDEN

Biographical Memoir



Theodore v. Kármán

THEODORE VON KÁRMÁN

May 11, 1881–May 7, 1963

BY HUGH L. DRYDEN

THEODORE VON KÁRMÁN, distinguished aeronautical engineer and teacher, elected to the National Academy of Sciences in 1938, died in Aachen, Germany, on May 7, 1963, four days before his eighty-second birthday. He was a person of unusual genius and vision. He made outstanding contributions to modern engineering, particularly to aeronautical engineering and to other engineering fields based on solid and fluid mechanics. Von Kármán himself attributed the origin of modern applied mechanics to Felix Klein, his professor at the University of Göttingen. Klein had visited the United States in 1893. As a result, in von Kármán's words, "What Klein recognized and what has since become commonplace is the fact that alongside the massive resources of American technology a European industry could exist only if it held a superiority with respect to efficiency and saving of material. This appeared to be possible only if one could increase as much as possible the accuracy of the knowledge of technical processes and the accuracy of prior computation with the aid of chemistry, physics, mechanics, and mathematics."

Von Kármán devoted his whole professional life to bridging the gap which had developed between theoretical workers who were content with general theorems and selected simple examples and engineers who were frustrated by the failures of theory and therefore resorted to pure empiricism and rule of thumb. He insisted not only that a rational theory should be logically correct but also that it should approximate reality and be confirmed by suitable experiments. His unique contributions have been described by his associate, Clark B. Millikan, as follows:

"(a) The discovery and presentation of a new conception of some phenomenon which had hitherto remained quite unexplained and mysterious, in other words creative scientific conception at its highest level.

"(b) The clarifying and reducing to clear and transparent form of material which had before been confused and hence only imperfectly comprehended. This is often associated with the finding of a mathematically elegant and hence essentially simple framework with reference to which very complex phenomena can be understood.

"(c) The finding of the essential physical elements in complicated engineering problems so that rational and simple approximate solutions can be obtained, which solutions can then be improved by methods of successive approximation."

Von Kármán was born in Budapest on May 11, 1881. His father was Maurice von Kármán, distinguished philosopher and educator, who was active in the foundation of the state school system under Emperor Franz Joseph. His mother was Helene Konn. The family was devoted to intellectual and cultural pursuits. It is reported that von Kármán had been diverted by his father from development as a mathematics prodigy early in childhood without discouraging his natural curiosity and mental agility.

He graduated in 1902 from the Royal Technical University of Budapest with highest honors as a mechanical engineer. His thesis was a workmanlike analysis of the motion of a heavy rod supported on its rounded end by a horizontal plane. In more familiar terms, this is the theory of the common children's toy with weighted spherical bottom which returns to the vertical position when upset.

From his graduation until 1906, he taught at his alma mater and conducted theoretical research for Ganz and Co., a machinery manufacturer, except for an interruption of one year for the required military service. During this period he published his second paper, on the theory of buckling and compression tests on long slender columns, common structural elements in machinery, buildings, bridges, and airplanes. We do not know whether the stimulation for this paper came from the engineering work for Ganz and Co. or solely from the published experiments of Tetmajer which he reanalyzed in the paper. We see here the beginnings of the concepts of the double-modulus theory of column behavior which was to make him famous. He introduced in this paper the idea that the modulus to be used in the theory was that corresponding to the computed stress at failure.

Von Kármán left Budapest in 1906 to study at the University of Göttingen. Here were to be found not only Felix Klein, already mentioned, but also Ludwig Prandtl, the foremost investigator in the field of fluid mechanics, and David Hilbert, outstanding mathematician. Visits were made to London and Paris. In Paris in 1907 he went to Issy-les-Moulineaux, reportedly at 5 A.M., to see his first airplane flight, that of Henri Farman over a circular one-kilometer course. One by-product of his Paris trip was a report to his colleagues in Hungary on the very lightweight aero-engines of Antoinette and others that he had seen in Paris.

Von Kármán received his Ph.D. from the University of Göttingen in 1908. His dissertation continued his interest in the buckling strength of straight columns. He either personally conducted experiments or, more probably, as was the custom then in Germany, supervised their conduct by technical assistants. Although he was always interested in and familiar with experimental results and stimulated others to conduct many experiments, he was primarily interested in theory and analysis. W. Duncan Rannie, one of his associates, notes: "In spite of his insight and understanding of experiments, von Kármán showed little talent for experiment himself. This failing, his sole deficiency in the scientific field, was of course a constant source of amusement and innumerable stories among his associates. When he visited a laboratory there was always a danger that he might turn a knob or pull a lever, to see what would happen, and cause a minor catastrophe. He was an atrocious automobile driver; his friends were greatly relieved when he finally agreed to have a chauffeur." I myself recall when, as he was sitting in the cockpit of an amphibian airplane on the desert at Edwards Air Force Base, he pulled a lever and the flotation gear inflated, greatly to his own embarrassment as the crew labored in the hot sun to stow the gear in its containers.

In his dissertation von Kármán made a masterful presentation of the double-modulus theory of column behavior and the confirming experimental data. He introduced the concept of a modulus averaged over the cross section, each fiber being assigned the "tangent" modulus corresponding to the fiber stress. He noted that Prandtl had informed him of the work of Engesser, who used the modulus of the fibers on the compression side only, and of Considère, who called attention to Engesser's error.

Von Kármán was appointed Privat-docent at Göttingen following his graduation and remained at Göttingen until 1912. During this period, as he himself tells in his book *Aerodynamics: Selected Topics in the Light of Their Historical Development*, each morning on his way to the laboratory he passed the water tank in which a doctoral candidate, Karl Hiemenz, was trying to achieve symmetrical flow of the water around a circular cylinder. To his daily question about the progress of the experiment, the reply was always the same, "It always oscillates." Von Kármán was thus incited to compute the stability of the vortex arrangements and showed that only the unsymmetrical arrangement was stable. Though others had described and made studies of the vortex patterns before von Kármán, his quantitative theoretical analysis led to the naming of this arrangement ever since as the Kármán vortex street. The exciting forces from such a Kármán vortex street are responsible for the vibration of electrical transmission lines, chimneys, and suspension bridges, as exemplified in the destruction of the Tacoma-Narrows Bridge which von Kármán analyzed late in his career.

Von Kármán's interests at Göttingen were broad. He collaborated with Max Born in papers on the vibrations of crystal lattices, theory of specific heat, and related problems. He did further work on buckling strength of columns, deformation of thin-walled tubes, strength of corrugated tubes, stress distribution in plastic and granular media, turbulent skin friction, and strength experiments on materials under isotropic pressure. He contributed a section to the Teubner *Encyklopädie der mathematischen Wissenschaften* on Strength Problems in Machine Construction and with L. Föppl a section on the Physical Foundations of Strength Theory. He also contributed sections on Elasticity, Strength, Equilibrium, and Hardness and Hardness Testing to G. Fischer's *Handwörterbuch der Naturwissenschaften*. During this period von Kármán attained a productivity of a new paper or book approximately every 4½ months, a rate which he continued until very late in life.

Von Kármán was invited to organize an aerodynamics institute at the Technical University of Aachen. In 1912 he became Professor of Aerodynamics and Mechanics and Director of the Aerodynamics Institute where he developed a friendly rivalry with his former colleagues at Göttingen. His interests turned almost completely to fluid mechanics. The period from 1912 to 1921 was one of organization and build-up interrupted by his return to Hungary during World War I, 1914-1918. In the war period he served as Director of Research of the Austro-Hungarian Aviation Corps, working on problems of synchronization of guns with propellers, protection of fuel tanks, etc. During this period he designed a helicopter which is associated with his name. He often related that his war experience taught him the art of "getting along" with generals and admirals, a talent which he exercised throughout his entire career.

At Aachen, both von Kármán and the Aerodynamics Institute grew to eminence and attained a world-wide reputation. He traveled and lectured widely and attracted students from all over the world. His mastery of many languages was a great asset, for he spoke fluently Hungarian, German, French, Italian, Yiddish, and what he always described as the international language, "bad English."

At Aachen von Kármán and his colleagues contributed to a much better understanding of the problem of the frictional resistance of fluids. Major papers developed the Kármán momentum relation by integration of the boundary layer equations and applied it in the Kármán-Pohlhausen solution. Other papers presented an analysis of the stability of laminar flow, the origin of turbulence, and a theory of fully developed turbulence. In this work one can detect his initial groping toward the statistical theory of turbulence which he formulated later. Other papers in fluid mechanics described the Kármán-Trefftz method of computing potential flow about given wing sections, interpreted Reynolds number in terms of gas properties, outlined a method of computing pressure distribution on airship hulls, and analyzed the effect of spatial variations of airstream velocity on the lift of wings.

Although von Kármán's major interest at Aachen was fluid mechanics, he published a few papers on problems of solid mechanics. Perhaps the most notable is the paper entitled "Die mittragende Breite," a term which he introduced and for which we use the less meaningful term "effective width." The effective width is that width of the sheet material in a floor, tank, airplane wing or fuselage with longitudinal stiffeners which can be regarded as carrying the same stress as the stiffener. The concept was well known at the time but von Kármán gave it its present name and illustrated its application to the case of a beam on infinitely many supports.

Von Kármán first came to the United States in 1926 on invitation of Robert Millikan, President of the California Institute of Technology, and of Harry Guggenheim, President of the Daniel Guggenheim Fund for the Promotion of Aeronautics. In the previous year Daniel Guggenheim had donated $500,000 to establish a School of Aeronautics at New York University. On January 16, 1926, he formally established the Daniel Guggenheim Fund for the Promotion of Aeronautics to speed the development of civil aviation. During 1926 additional grants were made to establish Daniel Guggenheim Schools of Aeronautics at the Massachusetts Institute of Technology, Stanford University, California Institute of Technology, and the University of Michigan. Millikan had met von Kármán at an international physics congress in Europe in 1924 and had been impressed by the accomplishments and ability of the forty-three-year-old director of the Aerodynamics Insitute.

Von Kármán was invited to serve as consultant to the California Institute of Technology on the establishment of the aeronautical courses and on the design of wind tunnel equipment and to lecture at the other universities where schools were to be established. He arrived in New York on September 26, 1926, in company with his sister Josephine (usually called Pipö), fulfilled his advisory and lecture commitments, and visited Dayton (to see Orville Wright) and Washington.

Millikan pressed von Kármán to emigrate to the United

States to head the Daniel Guggenheim Aeronautical Laboratory at the California Institute of Technology. After lecturing in Japan and India during 1927, von Kármán in 1928 agreed to research associate status, dividing his time between Aachen and Pasadena. In 1930 he accepted Millikan's offer of the directorship and settled permanently in the United States, becoming a U. S. citizen in 1936.

Von Kármán was fond of telling many stories about his introduction to the strange new country. When he arrived in Boston late in November, he was told that there would be a dinner of thanksgiving the next day. He was surprised at such recognition of his visit and prepared for the occasion by having his hair cut. "To my chagrin," he said, "I learned that Americans have this day of Thanksgiving every year." In Washington, he attended a nearby church to improve his knowledge of English. He was attracted by the excellent enunciation of the Negro preacher and the friendliness of the congregation who hailed him as brother.

During the period of transition between Aachen and Pasadena von Kármán introduced new concepts in turbulent skin friction in two papers with identical titles, "Mechanical Similarity and Turbulence." He retained the Prandtl mixing-length concept but introduced the concept of similarity of the turbulent velocity fluctuations at every point. The scale or mixing length was then shown by dimensional considerations to be proportional to the ratio of the first derivative of the mean velocity; with respect to the direction normal to the flow, to the second derivative. There resulted the Kármán logarithmic formula for turbulent skin friction which has withstood the test of time except for minor improvements.

This paper was the outcome of a race between Prandtl and von Kármán to produce a valid engineering formula for turbulent skin friction in time for the Third Congress of Applied

Mechanics at Stockholm in 1930. Here is the story as told to me by Frank Wattendorf, then one of von Kármán's students at Aachen. Aachen is near the Dutch border and von Kármán lived in the Dutch town of Walz, just over the border, the two cities being connected by a streetcar line. Von Kármán worked at his best in the evening and Wattendorf frequently worked with him at his home. The last streetcar left at midnight and von Kármán escorted his collaborator to the carline, continuing the discussion en route. On this particular evening a new idea occurred just as the streetcar arrived. Von Kármán began writing equations on the side of the streetcar. The writing and discussion continued. At first the conductor waited patiently, then he coughed gently, and finally became insistent that the car must leave. It moved away just as the solution was finished. Unfortunately Wattendorf could not remember the steps and could not see the writing by leaning out of the window. So at each stop Wattendorf dashed to the street, copied a few lines, and jumped on as the car left. Fortunately there were enough stops to get it all copied before arrival at Aachen.

In the nineteen years of his association with the California Institute of Technology as Director of the Guggenheim Aeronautical Laboratory, von Kármán published some fifty papers, alone and with his students. Many of them dealt with his first love, buckling problems. A major contribution was his analysis of the physical nature of the buckling of spherical shells and the development of a nonlinear theory which accounted for the great discrepancies between the experimental results and those obtained from linear elastic theory. The fundamental ideas were found applicable to the buckling failure of curved sheets in general. The new phenomenon is that commonly known as "oil canning" from the observed snapping of the bottom of an oil can between two stable positions, the diaphragm being unstable at intermediate positions. This phenomenon occurs when the bending stiffness of the sheet is small. Its presence gives rise to buckling loads at failure much smaller than those obtained from the classical linear theory.

Other buckling papers dealt with the strength of thin plates in compression, influence of curvature on the buckling characteristics of structures, buckling of thin cylindrical shells under axial compression, and methods of analysis for torsion with variable twist.

Three papers interpreting applied mathematics for engineers have had a wide influence. They are "Some Remarks on Mathematics from the Engineer's Viewpoint," "The Engineer Grapples with Nonlinear Problems," and "Tooling up Mathematics for Engineering." His book with M. A. Biot, *Mathematical Methods in Engineering,* has been translated into Spanish, French, Italian, Portuguese, Russian, Turkish, and Japanese.

Von Kármán early acquired an interest in the theory of fluid flow at high subsonic, transonic, and supersonic speeds. His first published paper on supersonic flow, with Norton B. Moore, set forth the Kármán-Moore slender body theory for bodies of revolution in which the flow was linearized by assuming the body so slender as to produce only small perturbations and the effect of the body was represented by a source distribution. Other papers dealt with the boundary layer in compressible fluids and compressibility effects in aerodynamics generally. His 1935 Volta Congress paper treated the problem of drag in compressible fluids and the Kármán ogive with minimum wave drag was developed. By 1941 aircraft represented the dominant application of compressible flow theory. In his paper on compressibility effects in aerodynamics von Kármán notes that "the aeronautical engineer is pounding hard on the closed door leading into the field of supersonic motion," an interesting commentary on the "sonic barrier" as seen at that time. Other notable papers on compressible flow are the Tenth Wright Brothers Lecture on "Supersonic Aerodynamics—Principles and Applications" and the paper which describes the von Kármán similarity law of transonic flow. The Wright Brothers Lecture was an ingenious review of the physical principles and applications of supersonic aerodynamics. By the use of such novel concepts as "forbidden signals," "zones of action and zones of silence," and "rule of concentrated action" he contributed greatly to that "knowledge of supersonic aerodynamics [which] should be considered by the aeronautical engineer as a necessary prerequisite to his art."

A number of papers during the Pasadena period presented the developing ideas of von Kármán with respect to a statistical theory of turbulence. The fundamentals of the theory were developed in cooperation with L. Howarth. The statistical properties of isotropic turbulence were described in terms of a correlation tensor, which can be written in terms of two correlation coefficients between two components of the velocity because of spherical symmetry. By virtue of the continuity equation the tensor is fully determined by a single scalar function. The equations of motion were used to derive an equation for the change of the correlation with time, thus obtaining the rate of decay of the turbulence. In the first analysis the triple correlations were incorrectly assumed to be zero. This error was corrected in the later definitive paper by von Kármán and Howarth published in the Proceedings of the Royal Society in 1938.

Throughout his career, von Kármán engaged in many consulting activities with industry and government. An example is his paper on the analogy between the two-dimensional flow of a gas and two-dimensional flow of water in an open channel applied to the practical problems of the Metropolitan Water District of Southern California on flow in curved open channels. Most of the results of his consultations for industry remain in the closed files of the industrial firms involved.

Von Kármán was an active leader and guiding hand in the early activities in rocket research in the United States. One of his students, Frank Malina, describes how William Bollay reviewed the rocket motor experiments carried out by E. Sänger in Vienna at one of von Kármán's seminars early in 1936. A newspaper account brought to the laboratory two rocket enthusiasts, John W. Parsons and E. S. Forman, looking for someone with whom they might work. Malina, with von Kármán's permission, formed a group to build high-altitude sounding rockets. In 1938, von Kármán, as a member of a committee of the National Academy of Sciences advisory to the U.S. Air Corps, offered his services and those of the group to make experiments on the use of rockets for assisted take-off of airplanes. The group later became the Jet Propulsion Laboratory.

Having failed to interest industry to enter the field of rocketry, von Kármán with a few friends and co-workers organized a new company, the Aerojet Engineering Corporation, the first U.S. firm specifically engaged in rocket development. Incidentally, the reputed $1,250 investment of each of the founders grew over the years into small fortunes as rocket developments became essential to the new military weapons, ballistic missiles.

In 1944 von Kármán's career entered a new phase when General H. H. Arnold asked him to organize and chair a Scientific Advisory Group to study the use of science in warfare by the European nations and to interpret the significance of the new developments in rockets, guided missiles, and jet propulsion for the future of the U.S. Air Force. Thus began a series of leaves of absence for extended periods until he resigned as Director of the Guggenheim Laboratory in 1949 to accept emeritus status. Although he retained his home in Pasadena until his death, his headquarters were mainly in Washington until 1951, then mainly in Paris, but with frequent travels between Pasadena, Washington, and the capital cities of Europe.

The Scientific Advisory Group prepared one report entitled

"Where We Stand," with many appendices, which contained the results obtained by the group in Europe on the technical status of various fields. A second report, "Toward New Horizons," also with many appendices, dealt with the future, setting forth the impact of the new developments on future air warfare and recommending in effect the future technical policy of the U.S. Air Force. The group was succeeded by the U.S. Air Force Scientific Advisory Board, of which von Kármán was Chairman until 1954 and Chairman Emeritus until his death.

Von Kármán continued to publish papers at a slightly decreased rate during the Washington period, a number on the statistical theory of turbulence, others on such new interests as aerothermodynamics and propagation of plastic deformation in solids, and a provocative paper with G. Gabrielli on "What Price Speed?"

In 1951 von Kármán enlisted the cooperation of the U.S. Air Force and the Military Standing Group of the North Atlantic Treaty Organization to hold a meeting of the directors of aeronautical research of the NATO countries to discuss measures which might be taken to strengthen the common defense by interchange of information about modern developments in aeronautics and increased activity in aeronautical research in the several countries. The conference recommended and the NATO authorities approved the organization of the NATO Advisory Group for Aeronautical Research and Development with a major responsibility for advising NATO on questions in this field. Paris was selected as the location, and von Kármán was elected as chairman, a position which he held until his death. AGARD revived aeronautical research in Europe and improved its quality by extensive interchange of information. Panels for special topics were organized to hold technical symposia and publish their proceedings, as well as special technical reports and manuals, and to provide consulting service. Von

Kármán gave generously of his time and made Paris the major center of his activities, personally participating in the organization of the panels and the planning of their programs. He himself presented papers from time to time, including several on aerothermochemistry, the name he gave to the science underlying combustion phenomena, which was a major interest in his latter years. Many U.S. scientists and engineers invited to participate in AGARD activities were at first skeptical of the value of the effort but became enthusiastic supporters after observing the quality of the programs and the impact on our NATO allies.

AGARD was the high point of von Kármán's leadership of international cooperation in science which he began early in life. The seeds were evident in his early days at Göttingen, for in his early papers we can discern his eagerness to report to his colleagues in Hungary the scientific developments he saw in progress at Göttingen and in Paris. In Aachen after World War I he became concerned about the lack of contacts between scientists in various countries. In 1922 the time seemed appropriate for initiative. Von Kármán as a personal enterprise invited the leading workers in hydro- and aerodynamics to meet at Innsbruck to discuss progress of the last decade. The meeting was informal. Von Kármán's sister, Dr. Josephine de Kármán, affectionately known as Pipö, was secretary and general manager as well as hostess. At this meeting it was proposed to organize similar meetings of somewhat extended scope at regular intervals. The First International Congress of Applied Mechanics was held in Delft in 1924. Later congresses took place in 1926 (Zurich), 1930 (Stockholm), 1934 (Cambridge, England), 1938 (Cambridge, Massachusetts), 1946 (Paris), 1948 (London), 1952 (Istanbul), 1956 (Brussels), 1960 (Stresa, Italy), and the Eleventh Congress is scheduled for Munich in 1964. The congresses are informal, planned by a continuing International

Congress Committee, which determines its own membership. At each congress the Committee accepts an invitation from one of its members, to whom authority for the organization of the next congress is delegated, subject to certain policies established by the Committee. Von Kármán was a member of the Committee from the beginning.

At the Paris Congress in 1946, the first held after World War II, many members proposed the formation of a more formal organization, an International Union of Theoretical and Applied Mechanics (IUTAM) under the International Council of Scientific Unions. This was agreed to and von Kármán became Honorary President. On his advice the organization of the congresses remained with the International Committee, IUTAM undertaking encouragement and financial support. Congress Committee members became individual members of the General Assembly of the Union.

In 1958 von Kármán was instrumental in the organization of the International Council of the Aeronautical Sciences, with membership open to all nations, its function being to sponsor International Congresses of the Aeronautical Sciences. The first congress was held in 1958 (Madrid), the second in 1960 (Zurich), the third in 1962 (Stockholm), and the fourth is scheduled for 1964 (Paris). Von Kármán served as Honorary President until his death.

Finally, von Kármán established the International Academy of Astronautics within the framework of the International Astronautical Federation. The program consists of highly technical discussions at the time of the Federation meetings and symposia at other times on special scientific and engineering problems of space flight. Von Kármán was Director of the Academy from its inception.

Von Kármán's greatest contribution to international friendship and cooperation resulted from his frequent travels around the world and the innumerable personal friendships he established with people everywhere. He developed a world-wide community of scholars and friends. He never forgot anyone who came within his circle of friendship, and even after years of separation he could take up the relationship and the conversation as if there had been no interruption.

In the Paris period von Kármán published several review papers on aerodynamics and aeronautics, including one, "On the Foundations of High Speed Aerodynamics," which was an abridged version of his contribution to Volume VI A of the Princeton Series on High Speed Aerodynamics and Jet Propulsion, to which he had added a section on aerothermodynamic problems. Other review papers were the paper on solved and unsolved problems of high speed aerodynamics before the 1955 Conference on High Speed Aeronautics at the Polytechnic Institute of Brooklyn and the First Daniel and Florence Guggenheim Lecture before the First International Congress of the Aeronautical Sciences in Madrid in 1958. His new scientific interests during this period were aerothermochemistry, magnetofluid-dynamics, and operations research.

Von Kármán was devoted to his family. His father died in 1915 while von Kármán was in Hungary with the Austro-Hungarian Aviation Corps. In 1923 his mother and sister joined him in Aachen, his brother, a banker, remaining in Budapest until after World War II, when von Kármán succeeded in obtaining permission for his emigration to Switzerland. Von Kármán never married. Mother and sister made a happy home for him in Aachen and later in Pasadena, the sister, Pipö, taking over after the mother's death in 1941 and accompanying him on his travels. His tribute to her was that "her devoted companionship secured for me the peace of mind necessary for scientific thinking."

Von Kármán received wide recognition in many countries in the form of honors and awards. He was Honorary Fellow, Honorary Member, or Fellow of approximately forty national professional societies in eleven countries. These included membership in the National Academy of Sciences, American Philosophical Society, Royal Society of London, Académie de Science de l'Institut de France, Accademia dei Lincei, and Royal Academy of Sciences (Madrid).

He received more than sixty honorary degrees or special awards in recognition of his scientific contributions from institutions in thirteen countries. Among the special awards are U.S. Medal for Merit (1946), John Fritz Medal (1948), Franklin Gold Medal (1948), Lord Kelvin Gold Medal (1950), Gold Medal of the Royal Aeronautical Society (1952), Wright Brothers Memorial Trophy (1954), Daniel Guggenheim Gold Medal (1955), U.S. Air Force Exceptional Civilian Service Award (1955), U.S. Medal of Freedom (1956), Ludwig Prandtl Ring Award (1956), Goddard Gold Medal (1960), and U.S. National Science Medal (1963). In addition to honorary degrees from many institutions in other countries, honorary degrees were received from the following U.S. institutions: Princeton, Columbia, Illinois Institute of Technology, Yale, Northwestern, University of Southern California, New York, Brown, California, Wayne State. A more complete list of honors and awards is given in an appendix.

Among his colleagues and friends, von Kármán's wit is as famous as his scientific contributions. He loved to tell stories. For example, he told of a meeting with the famous British aviatrix, Amy Johnson, at a *conversazione* of the Royal Aeronautical Society, where the problem of the spin of airplanes was discussed by British and American engineers and scientists. The aviatrix asked von Kármán, "Can you tell me in a few words what causes spin and what is the mechanism of the thing?" He replied, "Young lady, a spin is like a love affair. You don't notice how you get into it, and it is very hard to get out of."

He defined an aerodynamicist as a man who is willing to assume everything except responsibility, an expert as any engineer who lives 300 miles away from the home office, a practical engineer as one who perpetuates the errors of his predecessors, and a Hungarian as a man who goes into a revolving door behind you and comes out ahead of you.

Von Kármán's publications are the record of a remarkable scientist and engineer. Though he was never an experimentalist or project engineer, he made many unique contributions to the success of the experiments and projects of others. His generosity to his colleagues makes it difficult to comprehend the full extent of his contributions, which are far greater than the many described in his publications. Many others are hidden in his own correspondence files and those of his colleagues and of the firms for which he was consultant. Many were lost on tablecloths, on backs of old letters, on odd pieces of paper, and on blackboards as ideas flowed freely from his mind in conversations with students and colleagues. He was filled with enthusiasm and an exciting sense of discovery in science and engineering. Yet he was modest, tactful, and considerate. As one of his colleagues (Si Ramo) wrote on his seventy-fifth birthday, "Von Kármán, despite who he is, talks with any one of us, another and lesser man, as though that man were von Kármán, and he, von Kármán, the one learning from the master."

In summary, Theodore von Kármán was an inspiring leader in research in solid and fluid mechanics, creator of new concepts, analyzer of complex phenomena into understandable basic principles. He was a great teacher, infecting generations of students with his enthusiasm for science. His catalytic influence on the new engineering technologies of our time is without parallel. He was one of the few men among us recognized as unusually talented. His place will not soon be filled.

CHRONOLOGY

1881	Born in Budapest on May 11
1902	Graduated with highest honors as mechanical engineer from the Budapest Royal Technical University
1902-1906	Taught at alma mater; military service; research engineer for Ganz and Co.
1907	Study at Göttingen with brief periods in Paris and London
1908	Received Ph.D. degree from University of Göttingen
1908-1912	Teaching fellow at Göttingen
1912	Became Professor of Aerodynamics and Mechanics and Director of the newly organized Aerodynamics Institute at Aachen
1914-1918	Returned to Hungary for duty as Director of Research of the Austro-Hungarian Aviation Corps
1915	Von Kármán's father died
1918	Returned to Aachen
1922	Organized Innsbruck meeting, predecessor to International Congresses of Applied Mechanics
1923	Mother and sister joined him in Aachen
1926	Visited United States to give Guggenheim Lectures and consult on education in aerodynamics and wind tunnel design
1927	Travel around the world, lecturing in Japan and India
1928	Arranged to divide time between Aachen and Pasadena (California Institute of Technology)
1930	Left Aachen to become Director of the Guggenheim Aeronautical Laboratory of the California Institute of Technology and Director of the Daniel Guggenheim Airship Institute at Akron
1936	Became U.S. citizen
1936	Authorized work at California Institute of Technology on rockets
1938	Began work on rockets for assisted take-off of airplanes as Director of the Jet Propulsion Laboratory of Caltech
1938	Elected to membership in the National Academy of Sciences

1941	Von Kármán's mother died
1942	With a few friends, founded Aerojet Engineering Corporation
1944	Organized Scientific Advisory Group for General H. H. Arnold, Commander, U.S. Army Air Corps
1945	Reported on "Where We Stand" and "Toward New Horizons." Became Chairman, Scientific Advisory Board, U.S. Air Force, a continuing group
1949	Became Professor Emeritus, California Institute of Technology
1951	Became Honorary President of the International Union of Theoretical and Applied Mechanics
1951	Called meeting of NATO directors of aeronautical research, leading to formation of AGARD. Kármán became Chairman of AGARD
1951	Von Kármán's sister died
1954	Became Chairman Emeritus, USAF Scientific Advisory Board
1958	Organized International Council of the Aeronautical Sciences to organize international congresses. Became Honorary President
1963	Died in Aachen, May 7

HONORS

SOCIETY MEMBERSHIPS

Academia de Bellas Artes de Santa Isabel de Hungria, Seville
Accademia Nazionale dei Lincei, Rome
Académie des Sciences de l'Institut de France, Paris
American Academy of Arts and Sciences
American Association for the Advancement of Science
American Association of University Professors
American Astronautical Society
American Geophysical Society
American Hungarian Institute
American Mathematical Society
American Meteorological Society
American Ordnance Association
American Philosophical Society
American Physical Society
American Rocket Society
American Society of Civil Engineers
American Society of Mechanical Engineers
American Society of the French Legion of Honor
Association Française des Ingenieurs et Techniciens de l'Aéronautique, Paris
Association des Ingenieurs-Docteurs de France, Paris
Association des Ingenieurs sortis de Ecole de Liége, Belgium
Association of Hungarian Students in North America
Associazione Italiana di Aerotecnica, Rome
Associazione Tecnica dell l'Automobile, Turin
Calcutta Mathematical Society
Canadian Institute of Aeronautics and Space
Franklin Institute
Indian Academy of Sciences, Bangalore
Institute of the Aerospace Sciences
International Mark Twain Society
National Academy of Sciences
Pontifical Academy of Sciences
Royal Academy of Sciences, Madrid
Royal Academy of Sciences, Turin

Royal Aeronautical Society, London
Royal Society of London
Schweizerische Astronautische Arbeitsgemeinschaft, Baden
Societa Adriatica de Elettricita, Venice
Society of Civil Engineers of France, Paris
Spanish Institute, New York
Weizmann Institute of Science, Rehovoth

LECTURESHIPS

Twenty-fifth Wilbur Wright Memorial Lecture, 1937
Josiah Willard Gibbs Lecture, 1939
Joseph Henry Lecture, 1944
Tenth Wright Brothers Lecture, 1946
Robert Henry Thurston Lecture, 1950
Vanderbilt University 75th Anniversary Lecture, 1950
Messenger Lectures, 1953
Chaire Franqui, University Libre, Brussels, 1955
Howard Hughes Lecture Series, 1957
Florence Guggenheim Memorial Lecture, 1958
Seventh Thomas A. Edison Memorial Lecture, 1960

and probably many others

HONORARY DEGREES

Doctor of Engineering
- Technische Hochschule, Berlin, 1929
- University of Liége, Liége, 1940
- Princeton University, 1947
- Columbia University, 1948
- Technische Hochschule, Aachen, 1953
- Technische Universität Berlin-Charlottenburg, 1953
- Die Eidgenossische Technische Hochschule, Zurich, 1955
- Illinois Institute of Technology, 1959

Doctor of Science
- Yale University, 1951
- University of Istanbul, 1952
- Technical University of Istanbul, 1952

Hebrew Institute of Technology, Haifa, 1954
Northwestern University, 1956
University of Southern California, 1958
New York University, 1960
Brown University, 1961

Doctor of Law
University of California, 1943
Wayne State University, 1959

Doctor of Philosophy
University of Berne, 1961

Doctor Honoris Causa
Université Libre de Bruxelles, 1937
Université de Liége, 1947
Université d'Aix-Marseilles, 1949
Université de Lille, 1953
Technische Hogeschool, Delft, 1956
Université de Paris, 1957
University of Seville, 1958
Politecnico di Torino, 1960
University of Athens, 1961

DECORATIONS AND AWARDS

University of Liége Gold Medal, 1937
ASME Gold Medal, 1941
Army Air Force Commendation for Meritorious Civilian Service, 1945
U.S. Medal for Merit, 1946
Grand Médaille d'Honneur, Association des Ingénieurs-Docteurs, de France, 1946
Officier de la Legion d'Honneur, France, 1947
Sylvanus Albert Reed Award, Institute of the Aeronautical Sciences, 1948
John Fritz Medal, 1948
Franklin Gold Medal, 1948
Lord Kelvin Gold Medal, 1950
Royal Aeronautical Society Gold Medal, 1952
Grand Officer of the Order "al Merito della Repubblica" of the Italian Government, 1953

Trasenster Medal and Diploma, Association des Ingenieurs de Liége, 1954
American Rocket Society Astronautics Award, 1954
Wright Brothers Memorial Trophy, 1954
Daniel Guggenheim Gold Medal, 1955
Grand Cross of Merit for Aeronautics, Madrid, Spain, 1955
Commander de la Legion d'Honneur, France, 1956
Grand Officer of the Order of Orange-Nassau, Netherlands, 1956
Federal Grand Cross for Merit with Star, West Germany, 1956
USAF Exceptional Civilian Service Award, 1956
U.S. Medal of Freedom, 1956
Ludwig Prandtl Ring of the Wissenschaftliche Gesellschaft für Luftfahrt, 1956
Vincent Bendix Gold Medal, 1957
Timoshenko Medal, 1958
Benjamin Garver Lammé Gold Medal, 1960
Robert H. Goddard Memorial Gold Medal, 1960
Karl Friedrich Gauss Medal, 1960
Christopher Columbus Gold Medal, Genoa, 1960
American Hungarian Institute George Washington Award, 1961
U.S. National Medal of Science, 1963

BIBLIOGRAPHY

KEY TO ABBREVIATIONS

Aachen Abh. = Abhandlungen aus dem Aerodynamischen Institut an der technischen Hochschule, Aachen

Aachen Vortr. = Vorträge aus dem Gebiete der Aerodynamik und verwandter Gebiete, Aachen (Berlin, Julius Springer, 1929)

Advan. Appl. Mech. = *Advances in Applied Mechanics,* ed. by R. von Mises and Th. von Kármán (New York, Academic Press, 1951)

AGARD Colloq. = Colloquium, North Atlantic Treaty Organization Advisory Group on Aeronautical Research and Development, held at Cambridge Univ., England, Dec. 7-11, 1953. Published in *Selected Combustion Problems—Fundamentals and Aeronautical Applications* (London, Butterworths Scientific Publications, 1954)

AGARD Gen. Ass. = Proc. 3d General Assembly, London, 1953. Advisory Group for Aeronautical Research and Development AG6-P3

Ann. Matem. pur. e. appl. = Annali di Matematica Pura e Applicata, Serie IV

Arch. Elektrotech. = Archiv für Elektrotechnik

Atti Congr. internaz. matem. Bologna = Atti del Congresso Internazionale dei Matematici, editore, Nichola Zanichelli (Bologna, 1928)

Beitr. techn. Mech. = Beitrage zur technischen Mechanik

Biezeno Anniv. Vol. = Anniversary Volume on Applied Mechanics Dedicated to C. B. Biezeno (Haarlem, H. Starn, 1953)

Bull. Am. Math. Soc. = Bulletin of the American Mathematical Society

Bull. Univ. Wash. Eng. Exp. Sta. = Bulletin of the University of Washington Engineering Experiment Station

CW 26 = Paper no. 26 in *Collected Works of Theodore von Kármán* (London, Butterworths Scientific Publications, 1956)

Comptes Rendus = Comptes Rendus des Séances de l'Académie des Sciences, Paris

Conf. High Speed Aeron. Brooklyn = Proceedings of the Confer-

ence on High-Speed Aeronautics, Polytechnic Institute of Brooklyn, January 20-22, 1955 (Brooklyn, Polytechnic Institute of Brooklyn, 1955)

Dan. Guggenh. Airship Inst. = Publication no. 1 of the Daniel Guggenheim Airship Institute, Akron, 1933

Encyk. Math. Wiss. = Encyklopädie der mathematischen Wissenschaften (Leipzig, B. G. Teubner, 1910)

Fifth Volta Congr. Rome = Quinto Convegno "Volta," Rome, 1935. Reale Accademia d'Italia, Classe delli Scienze Fisiche, Mathematiche e Naturali

Gött. Nachr. = Nachrichten der königlichen Gesellschaft der Wissenschaften zu Göttingen. Mathematisch-physikalische Klasse

Handbuch Naturw. = Handwörterbuch der Naturwissenschaften (Jena, Gustav Fischer, 1913)

Innsbruck Vortr. = Vorträge aus dem Gebiete der Hydro- und Aerodynamik, Innsbruck, 1922. Ed. by Th. von Kármán and T. Levi-Civita (Berlin, Julius Springer, 1924)

J. Aeron. = Journées Techniques Internationales de l'Aéronautique, 1932 (Paris, Chambre Syndicale des Industries Aéronautiques, 1933)

J. Aeron. Res. Inst. Tokyo = Journal of the Aeronautical Research Institute, Tokyo

J. Aeron. Sci. = Journal of the Aeronautical Sciences

J. Appl. Mech. = Journal of Applied Mechanics

J. Appl. Phys. = Journal of Applied Physics

J. Franklin Inst. = Journal of the Franklin Institute

J. Marine Res. = Journal of Marine Research

J. Math. Phys. = Journal of Mathematics and Physics

JPL Memo. = Memorandum of the Jet Propulsion Laboratory of the California Institute of Technology

JPL Rept. = Report of the Jet Propulsion Laboratory of the California Institute of Technology

J. Roy. Aeron. Soc. = Journal of the Royal Aeronautical Society (London)

J. Wash. Acad. Sci. = Journal of the Washington Academy of Sciences

Jahrb. W. G. L. = Jahrbuch der Wissenschaftlichen Gesellschaft für Luftfahrt (Berlin, Julius Springer)

Konfer. Schiffsantrieb = Aus dem Buchwerk der Konferenz über Hydromechanische Probleme des Schiffsantriebes, Hamburg, 1932

Magyar Mérn. Épít.-Egyl. Héti-Értes. = Magyar Mérnök-És Építész-Egylet Héti-Értesitöje, Budapest (Weekly Bulletin of the Society of Hungarian Engineers and Architects)

Magyar Mérn. Épít.-Egyl. Közl. = Magyar Mérnök-És Építész-Egylet Közlönye, Budapest (Journal of the Society of Hungarian Engineers and Architects)

Math. Phys. Lapok = Mathematikai és Physikai Lapok, A Magyar Tudományos Akadémia, Mathematikai és Physikai Tarsulat, Budapest

Mech. Eng. = Mechanical Engineering

Mem. Soc. Ing. Civ. France = Mémoires de la Société des Ingenieurs Civils de France

Mitt. V.D.I. = Mitteilungen über Forschungsarbeiten, herausgegeben vom Verein Deutscher Ingenieure

NACA Tech. Memo. = Technical Memorandum of the National Advisory Committee for Aeronautics

NACA Tech. Note = Technical Note of the National Advisory Committee for Aeronautics

NACA Tech. Rept. = Technical Report of the National Advisory Committee for Aeronautics

Naturw. = Die Naturwissenschaften

Phys. Z. = Physikalische Zeitschrift

Pop. Educator = Popular Educator (New York, National Alliance, Inc., 1938)

Prob. Cosmic. Aerodyn. = Symposium of the International Union of Theoretical and Applied Mechanics, *Problems of Cosmical Aerodynamics,* Central Air Documents Office, U.S. Air Force, 1951

Proc. First U.S. Nat. Congr. Appl. Mech. = Proceedings of the First U.S. National Congress on Applied Mechanics, Illinois Institute of Technology, June 11-16, 1951 (New York, American Society of Mechanical Engineers, 1952)

Proc. ______ Internat. Congr. Appl. Mech. = Proceedings of the ______ International Congress of Applied Mechanics

Proc. Joint Aeron. Conf. = Proceedings of the Joint Aeronautical Conference convened by the Royal Aeronautical Society and the Institute of the Aeronautical Sciences, September, 1947 (London, Royal Aeronautical Society, 1948)

Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences

Proc. Roy. Soc. = Proceedings of the Royal Society of London, Series A

Proc. Second Hydraulics Conf. Iowa = Proceedings of the Second Hydraulics Conference, Bulletin 27, Iowa Studies in Engineering, 1943

Quart. Appl. Math. = Quarterly of Applied Mathematics

Reissner Anniv. Vol. = *Reissner Anniversary Volume. Contributions to Applied Mechanics* (Ann Arbor, Mich., J. W. Edwards, 1949)

Revs. Mod. Phys. = Reviews of Modern Physics

Scripta Univ. = Scripta Universitatis atque Bibliothecae Hierosolymitanarum, 1923

Timoshenko Anniv. Vol. = Contribution to the Mechanics of Solids. Stephen Timoshenko 60th Anniversary Volume (New York, Macmillan Co., 1938)

Trans. A.S.M.E. = Transactions of the American Society of Mechanical Engineers

Univ. of Penna. Bicentenn. Conf. = *Fluid Mechanics and Statistical Methods in Engineering.* University of Pennsylvania Bicentennial Conference 1941 (Philadelphia, University of Pennsylvania Press, 1941)

Werft, Reed., Haf. = Werft, Reederei, Hafen

Z. angew. Math. Mech. = Zeitschrift für angewandte Mathematik und Mechanik

Z. Flugt. Motorl. = Zeitschrift für Flugtechnik und Motorluftschiffahrt

Z. Flugwiss. = Zeitschrift für Flugwissenschaften

Z. techn. Phys. = Zeitschrift für technische Physik

Z. V.D.I. = Zeitschrift des Vereins Deutscher Ingenieure

1902

Gömbölyü végével vízszintes lapra támaszkodó súlyos pálcza mozgása (The motion of a heavy rod supported on its rounded end by a horizontal plate). Math. Phys. Lapok, 11:34-41; 69-78; 134-40. CW 1.

1906

A kihajlás elmélete és a hosszú rudakon végzett nyomás-kisérletek (The theory of buckling and compression tests on long slender columns). Magyar Mérn. Épít.-Egyl. Közl., 40:329-34. CW 2.

1907

Über stationäre Wellen in Gasstrahlen. Phys. Z., 8:209-11. CW 3.

1908

A gözök és gázok áramlasi jelenségeire vonatkozó újabb vizsgálatok (Recent investigations regarding the flow phenomena of vapors and gases). Magyar Mérn. Épít-Egyl. Közl., 42:103-10. CW 4.

Igen könnyü mótoro król (Very light-weight engines). Magyar Mérn. Épít.-Egyl. Héti-Értes., 27:248-51. CW 5.

Die Knickfestigkeit gerader Stäbe. Phys. Z., 9:136-40. CW 6.

1909

With Alfred Haar. Zur Theorie der Spannungszustände in plastischen und sandartigen Medien. Gött. Nachr., pp. 204-18. CW 7.

Hullámos tüzcsövek szilárdsága (The strength of corrugated fire tubes). Magyar Mérn. Épít.-Egyl. Héti-Értes., 28:302-5. CW 8.

1910

Mitöl függ az anyag igénybevétele? (What determines the stress-strain behavior of matter?) Magyar Mérn. Épít.-Egyl. Közl., 44:212-26.

Untersuchungen über die Bedingungen des Bruches und der plastischen Deformation, insbesondere bei quasi-isotropen Körpern. Habilitationschrift, Göttingen.

Untersuchungen über Knickfestigkeit. Mitt. V.D.I., p. 81. CW 9.

Festigkeitsprobleme im Maschinenbau. Encyk. Math. Wiss., 4:311-85. CW 10.

With L. Föppl. Physikalische Grundlagen der Festigkeitslehre. Encyk. Math. Wiss., 4:675-770. CW 11.

1911

Festigkeitsversuche unter allseitigem Druck. Z. V.D.I., 55:1749-57. CW 12.

Über die Formänderung dünnwandiger Rohre, insbesondere federnder Ausgleichrohre. Z. V.D.I., 55:1889-94. CW 13.

Über die Turbulenzreibung verschiedener Flüssigkeiten. Phys. Z., 12:283-84. CW 14.

Über den Mechanismus des Widerstandes, den ein bewegter Körper in einer Flüssigkeit erfährt—1.Teil. Gött. Nachr., pp. 509-17. CW 15.

1912

Über den Mechanismus des Widerstandes, den ein bewegter Körper in einer Flüssigkeit erfährt—2.Teil. Gött. Nachr., pp. 547-56. CW 16.

With H. Rubach. Über den Mechanismus des Flüssigkeits- und Luftwiderstandes. Phys. Z., 13:49-59. CW 17.

With M. Born. Über Schwingungen in Raumgittern. Phys. Z., 13:297-309. CW 18.

1913

With M. Born. Zur Theorie des spezifische Wärme fester Körper. Phys. Z., 14:15-19. CW 19.

With M. Born. Über die Verteilung der Eigenschwingungen von Punktgittern. Phys. Z., 14:65-71. CW 20.

Näherungslösungen von Problemen der Elastizitätstheorie. Phys. Z., 14:253-54. CW 21.

With H. Bolza and M. Born. Molekularströmung und Temperatursprung. Gött. Nachr., pp. 221-35. CW 22.

Elastizität. Handbuch Naturw., 3:165-93. CW 23.

Festigkeit. Handbuch Naturw., 3:1014-30. CW 24.

Gleichgewicht. Handbuch Naturw., 4:245-61. CW 25.

Härte und Härteprüfung. Handbuch Naturw., 5:198-202. CW 26.

1914

With E. Trefftz. Über Längsstabilität und Längsschwingungen von Flugzeugen. Jahrb. W. G. L., 3:116-38. CW 27.

1915

Vizsgalatok a rugalmassagi hatar és a törés feltételeiröl (Research on the conditions of elastic limit and rupture). Mat. es természlttudomanyi értessitö.

1916

Das Gedächtnis der Materie. Naturw., 4:489-94. CW 28.

1918

With E. Trefftz. Potentialströmung um gegebene Tragflächenquerschnitte. Z. Flugt. Motorl., 9:111-16. CW 29.

Lynkeus als Ingenieur und Naturwissenschaftler. Naturw., 6:457-63. CW 30.

1921

Die Bedeutung der Mechanik für das Studium der technischen Physiker. Z. techn. Phys., 2:127-30. CW 31.

Über laminare und turbulente Reibung. Z. angew. Math. Mech., 1:233-52. CW 32.

Mechanische Modelle zum Segelflug. Z. Flugt. Motorl., 12:220-23. CW 33.

Theoretische Bemerkungen zur Frage des Schraubenfliegers. Z. Flugt. Motorl., 12:345-54. CW 34.

1922

Bemerkung zu der Frage der Strömungsform um Widerstandskörper bei grossen Reynoldsschen Kennzahlen. Innsbruck Vortr., pp. 136-38. CW 35.

Über den motorlosen Flug. Naturw., 10:121-33.

Standardization in aerodynamics. Aerial Age Weekly, 14:392.

Über die Oberflächenreibung von Flüssigkeiten. Innsbruck Vortr., pp. 146-67. CW 36.

1923

Über die Grundlagen der Balkentheorie. Scripta Univ. Also republished Aachen Abh. 7 (1927). CW 37.

Gastheoretische Deutung der Reynoldsschen Kennzahl. Z. angew. Math. Mech., 3:395-96. CW 38.

1924

Über das thermisch-elektrische Gleichgewicht in festen Isolatoren. Arch. Elektrotech., 13:174-80. CW 39.

Die mittragende Breite. Beitr. techn. Mech., pp. 114-27. CW 40.

With Th. Bienen. Zur Theorie der Luftschrauben. Z. V.D.I., 68:1237-42, 1315-18. CW 41.

Über die Stabilität der Laminarströmung und die Theorie der Turbulenz. Proc. First Internat. Congr. Appl. Mech., Delft. CW 42.

1925

Beitrag zur Theorie des Walzvorganges. Z. angew. Math. Mech., 5:139-41. CW 43.

1926

Über elastische Grenzzustände. Proc. Second Internat. Congr. Appl. Mech., Zurich. CW 44.

1927

Berechnung der Druckverteilung an Luftschiffkörpern. Aachen Abh., No. 6, pp. 3-17. CW 45.

Selected problems in aeronautics (in Japanese). J. Aeron. Res. Inst. Tokyo, 37:353-410.

Ideale Flüssigkeiten. In: *Differentialgleichungen,* ed. by Ph. Frank and R. von Mises, 2. Vieweg und Sohn, Braunschweig.

1928

Die Schleppversuche mit langen Versuchsflächen und das Ähnlichkeitsgesetz der Oberflächenreibungen. Werft, Reed., Haf., p. 9. CW 46.

Mathematische Probleme der modernen Aerodynamik. Atti Congr. internaz. matem. Bologna. CW 47.

1929

Beitrag zur Theorie des Auftriebes. Aachen Vortr., pp. 95-100. CW 48.

With K. Friedrichs. Zur Berechnung freitragender Flügel. Z. angew. Math. Mech., 9:261-69. CW 49.

The impact on seaplane floats during landing. NACA Tech. Note 321. CW 50.

1930

Mathematik und technische Wissenschaften. Naturw., 18:12-16. CW 51.

Mechanische Ähnlichkeit und Turbulenz. Gött. Nachr., pp. 58-76. CW 52.

Mechanische Ähnlichkeit und Turbulenz. Proc. Third Internat. Congr. Appl. Mech., Stockholm, 1:85-93. P. A. Norsted and Söner, Stockholm, 1931. CW 53.

1931

Die Seitenwege der Luftfahrt. Z. Flugt. Motorl., 22:481-87. CW 54.

1932

With E. E. Sechler and L. H. Donnell. The strength of thin plates in compression. Trans. A.S.M.E., 54:53-57. CW 55.

With N. B. Moore. Resistance of slender bodies moving with supersonic velocities, with special reference to projectiles. Trans. A.S.M.E., 54:303-10. CW 56.

Theorie des Reibungswiderstandes. Konfer. Schiffsantrieb. CW 57.

Quelques problèmes actuels de l'aérodynamique. J. Aeron., pp. 1-26. CW 58.

1933

Some aerodynamic problems of airships. Dan. Guggenh. Airship Inst., Publication No. 1, pp. 45-52. CW 59.

Analysis of some typical thin-walled structures. ASME Aeronautical Engineering, 5:155-58. CW 60.

1934

Turbulence and skin friction. J. Aeron. Sci., 1:1-20. CW 61.

Turbolenza e attrito superficiale. L'Aerotecnica 14:1156-84.

With Clark B. Millikan. The use of the wind tunnel in connection with aircraft design problems. Trans. A.S.M.E., 56:151-66. CW 62.

With Clark B. Millikan. On the theory of laminar boundary layers involving separation. NACA Tech. Rept. 504. CW 63.

Some aspects of the turbulence problem. Proc. Fourth Internat. Congr. Appl. Mech., Cambridge, England, pp. 54-91. Cambridge, University Press, 1935. CW 64.

1935

With J. M. Burgers. General aerodynamic theory. Perfect fluids. In: *Aerodynamic Theory,* ed. by W. F. Durand, p. 2. Berlin, Julius Springer.

With Clark B. Millikan. A theoretical investigation of the maximum-lift coefficient. J. Appl. Mech., 2:21-27. CW 65.

Neue Darstellung der Tragflügeltheorie. Z. angew. Math. Mech., 15:56-61. CW 66.

The problem of resistance in compressible fluids. Fifth Volta Congr. Rome. CW 67.

1937

On the statistical theory of turbulence. Proc. Nat. Acad. Sci., 23:98-105. CW 68.

The fundamentals of the statistical theory of turbulence. J. Aeron. Sci., 4:131-38. CW 69. Italian version, L'Aerotecnica 17.

Turbulence. J. Roy. Aeron. Soc., 41:1108-41. CW 70.

1938

With Leslie Howarth. On the statistical theory of isotropic turbulence. Proc. Roy. Soc., 164:192-215. CW 71.

Eine praktische Anwendung der Analogie zwischen Überschallströmung in Gasen und überkritischer Strömung in offenen Gerinnen. Z. angew. Math. Mech., 18:49-56. CW 72.

With H. S. Tsien. Boundary layer in compressible fluids. J. Aeron. Sci., 5:227-32. CW 73.

With W. R. Sears. Airfoil theory for non-uniform motion. J. Aeron. Sci., 5:379-90. CW 74.

Some remarks on the statistical theory of turbulence. Proc. Fifth. Internat. Congr. Appl. Mech., Cambridge, Massachusetts, pp. 347-51. New York, John Wiley, 1939. CW 75.

Use of orthogonal functions in structural problems. Timoshenko Anniv. Vol. CW 78.

With F. J. Malina. A series of lectures on aeronautics. Pop. Educator, No. 2:93-96 and scattered numbers. (Titles vary.)

1939

The analogy between fluid friction and heat transfer. Trans. A.S.M.E., 61:705-10. CW 76.

With H. S. Tsien. The buckling of spherical shells by external pressure. J. Aeron. Sci., 7:43-50. CW 77.

1940

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Some remarks on mathematics from the engineer's viewpoint. Mech. Eng., 62:308-10. CW 79.

With L. G. Dunn and H. S. Tsien. The influence of curvature on the buckling characteristics of structures. J. Aeron. Sci., 7: 276-89. CW 80.

The engineer grapples with nonlinear problems. Bull. Am. Math. Soc., 46:615-83. CW 81.

With F. J. Malina. Characteristics of the ideal solid propellant rocket motor. JPL Rept. No. 1-4. CW 82.

1941

With H. S. Tsien. The buckling of thin cylindrical shells under axial compression. J. Aeron. Sci., 8:303-12. CW 83.

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Problems of flow in compressible fluids. Univ. of Penna. Bicentenn. Conf., pp. 15-39. CW 85.

1942

Isaac Newton and aerodynamics. J. Aeron. Sci., 9:521-22 and 548. CW 86.

1943

Tooling up mathematics for engineering. Quart. Appl. Math., 1:2-6. CW 87.

The role of fluid mechanics in modern warfare. Proc. Second Hydraulics Conf. Iowa, pp. 15-30. CW 88.

With H. S. Tsien and F. J. Malina. Summary of the possibilities of long-range rocket projectiles. JPL Memo., No. 1, Nov. 20, 1943. CW 89.

1944

With F. J. Malina, M. Summerfield, and H. S. Tsien. Summary of comparative study of jet propulsion systems as applied to missiles and transonic aircraft. JPL Memo., No. 2, March 28, 1944. CW 90.

With N. B. Christensen. Methods of analysis for torsion with variable twist. J. Aeron. Sci., 11:110-24. CW 91.

1945

With H. S. Tsien. Lifting-line theory for a wing in non-uniform flow. Quart. Appl. Math., 3:1-11. CW 92.

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Faster than sound. J. Wash. Acad. Sci., 35:144-55.

1946

With Wei-zang Chien. Torsion with variable twist. J. Aeron. Sci., 13:503-10. CW 94.

On laminar and turbulent friction. NACA Tech. Memo. 1092.

1947

Supersonic aerodynamics—principles and applications. J. Aeron. Sci., 14:373-409. CW 95.

The similarity law of transonic flow. J. Math. Phys., 26:182-90. CW 96.

Theoretical considerations on stability and control at high speeds. Proc. Joint Aeron. Conf., pp. 19-36. CW 97.

Sand ripples in the desert. Technion Yearbook, pp. 52-54. CW 98.

1948

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Progress in the statistical theory of turbulence. Proc. Nat. Acad. Sci., 34:530-39. CW 101. See also J. Marine Res., 7:252-64 and Cience y Tecnica, 116:43-52 (1951).

L'aérodynamique dans l'art de l'ingénieur. Mem. Soc. Ing. Civ. France, pp. 155-78. CW 102.

Progress in aviation. J. Franklin Inst., 246:451-52. CW 103.

1949

With C. C. Lin. On the concept of similarity in the theory of isotropic turbulence. Revs. Mod. Phys., 21:516-19.

On the theory of thrust augmentation. Reissner Anniv. Vol., pp. 461-68.

Accelerated flow of an incompressible fluid with wake formation. Ann. Matem. pur. e. appl., 29:247-49. CW 104.

1950

With G. Gabrielli. What price speed? Specific power required for propulsion of vehicles. Mech. Eng., 72:775-81. CW 105.

With Pol Duwez. The propagation of plastic deformation in solids. J. Appl. Phys., 21:987-94. CW 106.

With Jean Fabri. Écoulement transsonique à deux dimensions le long d'une paroi ondulée. Comptes Rendus, 231:1271-74. CW 107.

1951

With C. C. Lin. On the statistical theory of isotropic turbulence. Advan. Appl. Mech., 2:1-19. CW 108.

Introductory remarks on turbulence. Prob. Cosmic. Aerodyn., Chapter 19. CW 109.

The theory of shock waves and the second law of thermodynamics. Termotecnica, 31:82-83. CW 110.

1952

With F. B. Farquaharson and L. G. Dunn. Aerodynamic stability of suspension bridges. Part IV. The investigation of models of the original Tacoma Narrows Bridge under the action of the wind. Bull. Univ. Wash. Eng. Exp. Sta., No. 116, part III.

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On the foundation of high speed aerodynamics. Proc. First U.S. Nat. Congr. Appl. Mech., pp. 673-85.

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