Ann. Rev. Fluid Mech. 1979. 11: 1–10

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William R. Sears and Mabel R. Sears

Theodore von Kármán (left) and Clark B. Millikan in the Guggenheim Laboratory, about 1934.

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William R. Sears
University of Arizona, Tucson, Arizona 85721

Mabel R. Sears
6560 Skyway Road, Tucson, Arizona 85718

Theodore von Kármán directed the Guggenheim Aeronautics Laboratory at the California Institute of Technology from its founding in the late 1920s until 1942. During that relatively short span of years, GALCIT achieved an international reputation as a research center and training ground, especially in fluid mechanics. The world's most distinguished fluid mechanicists were attracted to it as short- and long-term visitors, its publications and communications almost dominated the literature of the field, and its students went out to become outstanding engineers, scholars, and captains of industry in many countries. The influence of GALCIT was remarkable.

It is not only a pleasant exercise to reminisce about those "Kármán Years"; it is also a worthwhile project to try to discover some of the elements that led to the success of that rather small institution during the fourteen-year period of Kármán's involvement.

Fluid mechanics at Caltech did not begin with Kármán's arrival, of course—nor, in fact, did the Institute's activities in aeronautics. The great English-born mathematician and fluid-mechanicist, Harry Bateman, was Professor of Aeronautical Research and Mathematical Physics in the Throop College of Technology even before that institution became the California Institute of Technology. Albert A. Merrill, a pioneer in American aviation, was Research Assistant and was largely responsible for the design and construction of an "N.P.L.-type" (open-return) wind tunnel.

Professor Bateman was already, in the mid 1920s, offering his remarkable, challenging courses in theoretical hydrodynamics, and Merrill was carrying out wind-tunnel experiments. Fortunately, these activities

0066-4189/79/0115-0001$01.00

attracted the attention of an able and enthusiastic graduate student, Clark B. Millikan, a physics graduate of Yale University. Millikan was fascinated by the exciting young field of aerodynamics. He did his Ph.D. research on viscous-flow theory under Bateman's direction, worked in the wind tunnel with Merrill, and learned to fly. Merrill had novel ideas about airplane design, and a project actually to construct and fly one of his designs was undertaken. But the veteran aviator and the enthusiastic, air-minded physics graduate needed much assistance with the detail design of structure and controls and enlisted the services of a recent Caltech Ph.D., Arthur L. Klein. An experimental physicist, Klein was a Research Associate and had also been attracted by the wind tunnel. Having a natural talent for design, instrumentation, and controls, he translated Merrill's ideas into hardware.

The "Merrill plane" was built and flown. The project itself had little impact on aeronautics, but a team—Merrill, Bateman, Millikan, and Klein—had been drawn together at a most propitious time, for the Daniel Guggenheim Fund for the Promotion of Aeronautics had been founded and was accepting proposals for financial grants to universities. The team convinced Clark Millikan's distinguished father, Dr. Robert A. Millikan, Chairman of Caltech's Executive Council, of the importance, especially in Southern California, of aeronautics. In 1926, Caltech's proposal for a graduate school and laboratory of aeronautics, largely prepared by this team, was approved by the Guggenheim Fund.

A feature of Caltech's plan was to bring to Pasadena an outstanding Director. The nomination of Kármán, Hungarian-born and Göttingen-educated, who was then Director of the Aerodynamics Institute in Aachen, was the suggestion of Paul S. Epstein, Professor of Physics at Caltech; the choice of Director was made and stands as one of a long list of illustrious appointments made by Robert Millikan during his leadership of Caltech.[1]

Kármán first visited Caltech in 1926. Part of Caltech's proposal to the Guggenheim Fund was a large open-return wind tunnel. Kármán recommended that it be redesigned as a closed-return ("Göttingen-type") tunnel. The new design, with a circular, closed working section 10 feet in diameter, forms the core of the Guggenheim Building, around which offices and laboratories—but only minimal corridors and stairways!—are clustered. The original open-return design of Millikan and Klein would have required much more total volume and an appropriately larger building.

[1] On display at GALCIT today is Millikan's letter to Harry F. Guggenheim, mentioning Kármán, Ludwig Prandtl, and Geoffrey I. Taylor as possible choices for the directorship of GALCIT and naming Kármán as the Institute's first choice.

From the start, GALCIT was conceived as a small institution, involving no more than five faculty members. The Guggenheim Building therefore provided a minimum of office space and only one relatively small classroom.

GALCIT began its active existence in 1928. In October 1929, Kármán agreed to become its Director, having already consulted with the Caltech people about their wind tunnel. In December 1929, he moved to Pasadena with his mother and sister. He continued to hold the position of Director in Aachen and divided his time between the two institutions until 1933, when he resigned the Aachen position.

It is clear that Kármán brought to the new institution two characteristics that established its spirit and its atmosphere. The first of these was emphasis on original research and publication—a natural carry-over from his background in Prandtl's institute in Göttingen, but not, in the late 1920s and early'30s, a common characteristic of American engineering schools. The second quality was informality; this seems to have been an inherent trait of the Director himself—hardly typical of old-world university groups—and it was well received and easily encouraged by the Caltech atmosphere and the proclivities of the Director's American colleagues. We recall that there was some apprehension in the junior ranks in the Guggenheim Building as the time of Kármán's arrival approached, lest a Herr Professor from a German university should turn out to be a stern and formal taskmaster. At least, it was easy for young staff members to worry a still younger secretary (M.R.S.) with warnings of "Teutonic" strictness to be coped with. To say that the problem did not materialize is an understatement.

A most important feature of GALCIT's program from the time of Kármán's arrival was the weekly Research Conference. It was held without fail, always chaired by Kármán when he was in Pasadena and by Clark Millikan otherwise. The name "Research Conference" has different meanings in different institutions; under Kármán it was an occasion for short progress (or lack-of-progress) reports by essentially everyone in GALCIT. All professors, visiting scholars, post-doctorate personnel, and students engaged in research reported regularly; each was called on at least biweekly for a progress statement. M.R.S. was present as the department's secretary, and the chairman closed each individual's report by dictating to her a one-sentence summary, which was read back to the conference as that individual was called upon for his report one or two weeks later.

It was a meeting at which progress was reported, plans were made, equipment and shop-time were allocated, publication schedules were set, and the advice or assistance of all present was offered to each investigator.

Clearly, the success of such conferences depended, first of all, on the breadth of interests, experience, and judgment of the chairman and his colleagues. An obvious spirit of open inquiry and willingness to expose one's errors before one's teachers and colleagues were also necessary. The chairman's objectivity and the friendly, informal atmosphere of the meeting made these things possible.

These Research Conferences were indeed pleasant occasions. There was great enthusiasm for the ongoing investigations, and the obstacles encountered therein were treated as necessary, challenging features of good research. Projects usually received short, sometimes pithy nicknames: we recall the "mayonnaise" and "termite" problems.... Kármán's happiness and amazement were infectious when, for example, it turned out that the description of some complex fluid-flow problem could be expressed in elegant mathematical form: "...a la Whittaker-Watson!", he quipped. "Maj" Klein was equally overjoyed when, as often happened, he could solve someone's problem of instrumentation or laboratory modelling by ingenious use of off-the-shelf items from local hardware stores or drugstores.

What would have been called a "colloquium" in many universities was the weekly Aeronautics Seminar. For many years, it was planned and scheduled by Clark Millikan. Although the talk was sometimes given by a visitor from an aircraft plant or elsewhere, we recall that Caltech personnel were more frequently the speakers. The GALCIT faculty attended all seminars without fail, occupied the front-row seats, and seemed never to miss a word. Engineers from the aircraft factories were always present.

Every year some of the world's leading solid- and fluid-mechanicists, attracted by the prospect of working with Kármán, came to GALCIT for more-or-less extended stays. They naturally provided an ideal pool of talent for the Aeronautical Seminar and for other, extra-curricular lecture series more accurately described by the name "seminar." It was one of the delightful and inspiring features of student life there to find oneself rubbing elbows and even sharing an office with Walter Tollmien, Leslie Howarth, Sydney Goldstein, Carl-Gustav Rossby, Tony Biot, K. D. Wood, or Charles Sadron.

Howarth's stay (1936–1937) came in the days of Kármán's greatest activity in turbulence theory. The statistical theories of Prandtl, Taylor, and Kármán were new and developing rapidly. Kármán told us, "I will get Leslie to teach me tensor theory!" He did, and a result was their famous joint paper of 1938. The next year, Howarth's distinguished mentor, Sydney Goldstein, succeeded him at GALCIT, finished correcting the page proofs of *Modern Developments*..., and gave us lectures on isotropic tensors. The result of Tony Biot's stay at GALCIT was, of course, the remarkable textbook *Mathematical Methods in Engineering* (1940). Sometimes it was not the famous themselves who made the pilgrimage to Pasadena but their protégés: Richard von Mises wrote from Istanbul to recommend a promising youngster, Hans-Wolfgang Liepmann, who came to GALCIT in 1939, remained, and is now himself the Director of GALCIT.

As we reminisce about those busy days, we recall how easy it apparently was for Kármán to arrange the financial aspects of such visits. On several occasions we heard Clark Millikan tell him that someone was available to spend a year at GALCIT. The key consideration, clearly, was what he would contribute to the program. If that was favorably agreed upon, the question of funding the stay was considered, and Kármán invariably had the answer. Although he had the reputation, not entirely unearned, for absentmindedness, he obviously carried a clear, up-to-date picture of GALCIT's budget in his head.

Moreover, the budget must have been remarkably generous, compared with what we are used to in today's academic world. The arrangements for the year-long residence of a visiting scholar, described above, were typically carried out in the corridor at the head of Guggenheim's stairway and involved no proposal-writing. We recall, as well, an occasion when the Director came to W.R.S., who was then Assistant Professor, and asked, "What will you do this summer?" His answer was that he hoped to continue his research at GALCIT through the summer. That was agreeable to the Director; there were no other formalities, and W.R.S.'s salary continued through the summer. Professor Ernest E. Sechler says that Kármán's answer was always "Go and buy it. I'll find the money," when he was asked for funds for equipment.

One explanation of this happy situation seems to be that the 10-foot wind tunnel provided income that was generally available to the Director of GALCIT for such important activities as we have mentioned here: visitors' salaries, staff summer salaries, travel, and equipment. The tunnel was in continual demand by the aircraft companies in the United States; they paid an hourly occupancy charge and reimbursed Caltech for the services of model-shop personnel. This income provided a modest margin that went into a fund for Aeronautics Equipment, but apparently the definition of what this fund covered was broad enough to include some salaries, travel, etc.

Kármán's travels often took him away from GALCIT for weeks at a time; travel, especially transatlantic, took more time in those days. Once, he was absent so long that a research project in solid mechanics led successfully to conclusions that were promptly reported in a journal, during his absence. That journal's "Letters" page soon carried gleeful messages from readers who pointed out that Kármán had reached and published the same conclusions years before. "Doesn't anyone at GALCIT remember von Kármán?" asked one writer.

All of the GALCIT faculty were great travelers—possibly excepting Klein, who disliked travel but spent several days each week in wide-ranging work in the Southern California aircraft plants. Not surprisingly, GALCIT's research programs benefitted enormously from all this contact with the world of aeronautics and research. We were kept up-to-date on practical engineering problems and plans and the latest discoveries or speculations of research workers everywhere. Our studies of unsteady-airfoil theory, for example, were begun after Kármán had visited Göttingen and been informed of radical conclusions about nonequivalence of moving airfoils and airfoils in moving fluids. (We succeeded in proving these conclusions wrong.) He brought us news, very early, of European developments in transonic and supersonic aerodynamics, wind tunnels, laboratory techniques, and other matters. The first Research Conference following each January meeting of the Institute of the Aeronautical Sciences in New York was devoted to a report by the faculty on what they had heard there that seemed exciting.

Kármán, with temporary collaboration of Howarth and Goldstein, as mentioned earlier, was deeply involved in the new field of statistical turbulence theory, which he helped found. He also made his very successful attack on the problems of turbulent skin-friction and heat transfer; his definitive paper appeared on the first page of the first issue (1934) of the new *Journal of the Aeronautical Sciences*. He gave new treatments and new insight into lifting-surface theory and unsteady-airfoil theory. With N. B. Moore, he began the long history of slender-body approximations in supersonic flow and, with H. S. Tsien, their well-known approximate treatment of subsonic flow. Toward the end of the period we are discussing, he discovered the similitude laws of transonic flow and thus the nonlinear small-perturbation equation that still occupies the attention of so many aerodynamicists.

The complexities of transonic flow occupied much of GALCIT's collective attention in those days. We recall the day that Kármán returned from Europe with news of the paper by Tollmien's student, Ringleb, which first pointed out the "limit lines." Kármán was chagrined, because we at GALCIT had missed this mathematical phenomenon, which, he suspected, must be related to the appearance of shock waves. He encouraged Liepmann to build the wind tunnel and carry out the experiments that clarified a number of transonic phenomena, including shock-wave boundary-layer interaction.

GALCIT's close relations with industry seem remarkable, viewed from the 1970s. The burgeoning aircraft industry was penetrating new speed regimes with new power plants and new kinds of aeronautical structures. Its engineers came frequently to Kármán and GALCIT for advice and assistance. As we look back, we realize that all of GALCIT's professors welcomed these contacts and almost invariably responded with enthusiasm and vigor, and GALCIT's research programs, across the board, were greatly influenced. "Purity" in research was not the rule, and many of the most profound and lasting of GALCIT's contributions stemmed from this willingness to attack the pressing practical problems of the day.

Clark Millikan continued, throughout his long career at GALCIT, his interest in viscous flows. With Kármán he constructed a two-layer theory of separating laminar boundary layers. Millikan and Klein devoted much attention to theoretical and experimental studies of maximum lift coefficients, with both laminar and turbulent separation and with artificial stream turbulence introduced into the 10-foot tunnel airstream. In a remarkable 1938 paper, Millikan showed that essentially all the results of years of theoretical modelling of turbulent shear flows can be recaptured from dimensional analysis. But he also wrote extensively on airfoil aerodynamics, the vortex theory of biplanes, and wind-tunnel boundary effects.

H. J. Stewart was also concerned with problems of wind-tunnel interference and with theories of thin wings. Caltech had a vigorous program in meteorology in those days, under I. P. Krick's direction. This was housed in the Guggenheim Building, and Kármán took a great deal of interest in it. This led to the year-long residence of Rossby in GALCIT and to Stewart's studies of meteorological flows; he published a number of mathematical papers concerning the large-scale features of the earth's atmosphere.

In retrospect, we can see that our expectations of what the new statistical theories of turbulence could accomplish were overly optimistic. We were also naive about the meaning of the limit lines, but our optimism about isentropic transonic flow is now seen to have been well-founded, although that subject has endured an interim period of rejection. On the other hand, GALCIT's contributions to such rapidly developing fields as boundary layers, wing theory, and slender-body aerodynamics had immediate practical impact. It was a period during which the transformation of aerodynamics from empiricism to a highly mathematical branch of fluid mechanics, begun at Göttingen, was still under way and was progressing rapidly.

In spite of the workload of industrial testing, the 10-foot wind tunnel was involved in a considerable amount of fluid-mechanics research. Besides the maximum-lift-coefficient experiments mentioned above, we carried out series of tests of an airplane model with running propeller, an early investigation of ground effect on airplane pitching moments, and tests of boundary-layer removal from a wing. Using a Northrop model, Klein made a study of wing-fuselage interaction and first showed, by wake surveys, the efficacy of a wing-fuselage fillet that expands greatly in radius from front to rear. Klein's invention was quickly adopted in the aircraft industry around the world, because Kármán used it as an example of GALCIT's wind-tunnel research in a major lecture in France and presented the data. It seems that, in French-speaking countries, these expanding wing-fuselage fillets are still called "karmans."

Although Kármán was himself a theoretician, he insisted that theoretical studies be carried out in contact with and guided by experimental observations. Theoretical conclusions had to be tested against experimental results, and numerical constants needed in theoretical analyses had to be provided by experiments. In this sense, experimental research seemed to be, in his philosophy, an adjunct to theoretical research, rather than the reverse. But Kármán had uncanny ability to provide new theories and new mathematical models when agreement with experiment was lacking, and when the experiments disclosed new phenomena. When Liepmann began his transonic experiments, mentioned above, the philosophy of research was more that of an experimental physicist: the experiments were designed to disclose new phenomena in an area where there was no theoretical model.

Robert Millikan told Goldstein, in 1939, that experimental research is the only real research, and Liepmann told us that he believes Albert Einstein said the same about theoretical research.

Although we are writing here about fluid mechanics, it must be mentioned that GALCIT's contribution to the field of solid mechanics, under Kármán, was of the same magnitude. Problems posed by the introduction of stiffened, stressed-skin structures in aircraft were attacked both experimentally and theoretically at GALCIT, especially by Kármán, L. H. Donnell, Sechler, and their students. He and Tsien made major contributions to the theories of nonlinear buckling.

We have mentioned the informality of GALCIT as one of its striking characteristics. There was not only informality of dress; it also characterized the relationships between students and faculty, and among the faculty. Attendance was never taken in classes, tardiness was tolerated, and professors encouraged interruptions—at least reasonably intelligent interruptions—of their lectures.

Kármán often gave his final examinations in oral form before an audience that included most of the faculty, attracted principally by the ingenuity of the questions posed. This caused great stage fright among new students (such as W.R.S.), who did not yet appreciate the objectivity and friendliness of the group.

Kármán's manner of giving course grades was extremely forgiving, in any case; we recall that the grades for a course jointly taught by him and Sechler were first calculated by Sechler, using a rational algorithm. Kármán then simply raised each student's term grade by one letter, to everyone's delight. His consistent principles of objectivity and high scientific standards, he explained to us, did not include fear lest a weak student might "get by." Even so, his mother insisted he was too hard on his students.

Caltech, in those days, offered some famous, difficult courses in mathematics and physics. Besides Bateman's, already mentioned, we recall the challenging courses taught by W. R. Smythe, Fritz Zwicky, E. T. Bell, and Morgan Ward. GALCIT's students were expected to take these and to uphold GALCIT's reputation by doing well in them. We remember an occasion when William Bollay and W.R.S. were struggling together, at a blackboard, with one of Ward's difficult homework problems: proof that a certain infinite integral existed. Kármán came into the office and asked, as always, "What are you doing?" When we explained, he proceeded to prove the existence in a typical, ingenious way, not using any of the powerful theorems of Ward's course. He explained, "I have to use these simple methods because I never studied this kind of mathematics myself." Ward was delighted by the ingenious proof handed in by Mr. Bollay and Mr. Sears, and had us present it to the class.

Sharing the Guggenheim Building with GALCIT was Caltech's Hydraulics Laboratory. We knew it familiarly as "the pump lab," since much important development work on the hydraulic equipment of the Metropolitan Water District was carried out there. It was directed by Professors Robert T. Knapp and Robert L. Daugherty. An important fluid-mechanical contribution of their laboratory was early work on high-velocity open-channel water flow. The principles of design of open flumes for supercritical flow were discovered and exploited, with Kármán's collaboration; it was a case of the open-channel analogy to gas dynamics being used in reverse. One of the practical results was the design of catch basins for Southern California's flood-control system, significantly smaller and more effective than had previously been used.

Another endeavor that involved rather far-out fluid mechanics was GALCIT's Rocket Research Project. This was started in the late 1930s by Frank J. Malina, Tsien, and other rocket enthusiasts. At first it was housed in the Guggenheim building; later it required larger and more isolated quarters, and was moved to the Arroyo Seco, north of Pasadena. Ultimately, it grew into Caltech's famous Jet Propulsion Laboratory. Essentially the same personnel, with encouragement and support of Kármán and Clark Millikan, founded the Aerojet company, which grew into a giant corporation and has been a leader in development of rocket engines for missiles and space vehicles.

Kármán played a vital part in all of this rocket development. Malina and Tsien were his students and, after receiving their doctorates, his assistants. From the beginning of their modest experiments and calculations, he was convinced of the importance of rocket propulsion. He provided funds and space for their research, and helped them sell the idea of jet-assisted take-off to the Air Force and Navy. Unlike the work of some other early enthusiasts, that of the GALCIT Project contributed directly to today's rocket technology and had great influence upon it.

Faculty meetings of GALCIT's professors were never held, at least in any formal sense. When a consensus was needed, Millikan or Sechler rounded up the professors, and in one of our offices the question was presented. We recall that at least once Kármán polled the group; it was a vote on course requirements for a certain Ph.D. candidate. Our vote was unanimously against waiving certain published requirements, until Kármán overruled us with a grin: "I see you are unanimous, but I am the Director and vote the other way. So he does not need to take the courses!" No one was disturbed; we appreciated our benevolent dictator.

The principles and the qualities of Kármán's GALCIT have been carried over into many sister institutions, especially because so many of GALCIT's graduates have themselves become influential professors. The heritage of that remarkable Director and his colleagues has had profound effects throughout the world of engineering and applied sciences.

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