Von Kármán: Fluid dynamics and other things

He was one of the pioneers of aerodynamics, contributing the concepts of vortex streets and explaining the sand ripples in the desert, and he practically invented consulting.

William R. Sears

It is a pleasure to write about Theodore von Kármán. I am somewhat concerned, however, as I consider the audience for this article, many of whom are also fluid dynamicists: I can imagine quite a few old friends who knew von Kármán—perhaps as well as I—saying, "Oh, that isn't the way it really was." Well, I can only say that what I am going to write about is the way I remember it. (There must be some kind of "statute of limitations" that says that when you get to a certain age—and I suppose I have—you're entitled to tell it the way you remember it, and let the chips fall where they may.)

It is very fitting that we claim von Kármán as a part of our fluid-dynamics heritage—and a very colorful part indeed. "Colorful" is the right adjective for him all right. *Time* magazine used it once when they described him, and I think it pleased him. He asked me, "Am I colorful?" I told him, "Yes, I think that might be right!"

However, such a colorful person attracts stories, so there is a pitfall in talking about a man like von Kármán: There is a danger that when you quote his clever remarks and describe his personality you will end up making him look like an eccentric or a clown. His memory has already started attracting all the best and most famous absent-minded-professor stories, even those that have been told for a hundred years—with equal justice about equally colorful people, no doubt—and bear no resemblance to him.

He was an engineer, physicist, applied mathematician and solid-mechanicist, an administrator and consultant, adviser to governments and military services, author, editor, organizer of international science, *bon vivant* and much else, but reference to the five volumes of his *Collected Works* will confirm that his greatest published output was in fluid mechanics.

He is memorialized by buildings, laboratories, wind tunnels, lectureships, medals, fellowships, even an international research college, all named after him. Seventeen years after his death, meetings and symposia were held in his memory in Washington, Aachen, Pasadena, Long Beach (at the meeting of the American Institute of Aeronautics and Astronautics) and probably elsewhere. That was at the time of his 100th anniversary. (APS apparently preferred to celebrate his 103rd birthday. I'm not sure whether 103 has a special significance, but it is, for one thing, a prime number.)

It is appropriate to ask, especially on behalf of our younger colleagues, who may wonder if they too may be so remembered: Who was von Kármán? What did he do? What, in fact, is the legacy that he left?

Martians

First of all, he was a Hungarian! He was born and raised in Buda, which is the part of Budapest on one side of the Danube, with Pest on the other. There is a theory, proposed by the distinguished physicist, my friend Philip Morrison, that Buda was infiltrated by a colony of Martians! It is the only logical explanation of the unearthly language of the people there, the unearthly beauty of their women (the Gabor sisters), their music (Bartók), and their superhuman intelligence—the quite unreasonable impact the Hungarians have had in science and the arts!

As evidence, Morrison offered the following: Besides von Kármán, John von Neumann, Edward Teller, Leo Szilard and Eugene Wigner all came from Buda, and all, I believe, went to the same high school! The list, no doubt, includes others of comparable fame whom I've forgotten; it also includes my colleagues in fluid dynamics Nicholas Rott and Nicholas Hoff, and probably Les Kovásznay. That high school had a prize, given to the senior who showed the greatest mathematical talent, and I think all those I've listed won that prize.

I had the incredible pleasure of bringing Morrison and von Kármán together one day in Ithaca, and hearing Morrison tell von Kármán of his discovery—that he had blown the Martians' cover. They had never met before, but obviously charmed each other at first sight, there in the Statler Club. I said, "Dr. von Kármán, Phil has made a discovery about you Hungarians that I want you to hear." So Morrison proceeded to present the evidence and the conclusion—

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Theodore von Kármán in 1961, at the International Academy of Astronautics in Paris.

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which he had arrived at while working with Teller at Los Alamos. As Morrison talked, von Kármán walked back and forth in the room chuckling and saying, "Funniest thing I've heard!" Then he turned to me and said, "Mind you, I do not deny!"

From a brilliant start as a student in Hungary, von Kármán went to Göttingen as a graduate student under the great Ludwig Prandtl. That was in the greatest days of the Prandtl school. Prandtl had just "discovered" inviscid fluid mechanics. Not literally, of course, but he had revolutionized fluid mechanics by discovering that classical, mathematical fluid mechanics and practical, engineering fluid mechanics could be brought together by the radical concepts of the boundary layer and the inclusion in the flow of the "inviscid" fluid of such features as circulation and vortices, which dominate the behavior of the fluid and whose existence depends on viscosity.

Prandtl didn't *discover* the boundary layer either—you can already find it in William Froude's work, for example—but it was Prandtl who tamed it, who recognized it as a singular perturbation and thus made the whole subject of inviscid irrotational flow meaningful. We now say, in fancy language, that he invented matched asymptotic expansions, but Prandtl was not a mathematician (nor was von Kármán, as I'll point out later), and what he did was not the formal mathematics of matched asymptotic expansions. He left that to his successors.

What a school Prandtl built at Göttingen! His students included Albert Betz, Jakob Ackeret, Max M. Munk, Adolph Busemann and Theodore von Kármán. All of practical fluid mechanics seemed to be yielding to Prandtl's wonderful ideas at the time von Kármán went there: the aerodynamics of monoplanes and multiplanes, induced drag and the slope of the lift curve, the ground effect, wind-tunnel boundary interference, propellers, windmills and much more besides.

Von Kármán's first big success in fluid mechanics, in 1910, was in the same spirit, but so novel that it could not be called a mere application of Prandtl's ideas; in fact Prandtl was so surprised and impressed by it that he told his young student: "You've got something there! Write it up and I'll present it to the Academy."

Theodore von Kármán (1881–1963)

Theodore von Kármán, who always identified himself as an engineer, became renowned not only in that profession but also as an applied mathematician and physicist. He was world-famous as a teacher, research worker, author, consultant and raconteur.

Born in Budapest, he received his education there before proceeding to Göttingen for graduate studies under the great Ludwig Prandtl. He became director of the Aerodynamics Institute at Aachen, then emigrated in 1928 to Pasadena, where he was made director of Caltech's Guggenheim Aeronautics Laboratory (GALCIT). He became an American citizen in 1936.

Von Kármán's earliest scientific work was in solid mechanics: He developed a theory for the effects of plastic deformation in the case of a buckling column. In later life, he returned to problems of stability and buckling of structures, including buckling of shells. He collaborated with Max Born on a famous paper on the molecular structure of solids and specific heat. His publication list is also peppered with purely mathematical papers and book chapters. But he is probably best remembered for his many contributions to fluid mechanics.

He was a pioneer in the statistical treatment of turbulence and turbulent flows, especially the turbulent boundary layer. He was also a pioneer in the theories of transonic and supersonic flows—flows involving speeds near and exceeding the speed of sound, respectively.

Von Kármán was a great teacher. His influence upon the character and quality of engineering education in America was profound. His books, including *Aerodynamics: Selected Topics in the Light of Their Historical Development* (Cornell U. P., Ithaca, N. Y., 1954) and *Mathematical Methods in Engineering* (McGraw-Hill, New York, 1940), are considered to be classics. There is a five-volume collection of his published works.

In his later years, he was devoted to the subjects of international science and cooperation. He was founder of NATO's Advisory Group for Aeronautical Research & Development. The list of the honors he received is long and impressive: He was elected to academies and received awards and honorary degrees in many nations; he was also selected in 1963 to be the first recipient of the National Medal of Science of the United States.

Vortex streets

What had happened was this: Prandtl was intrigued and bothered (as many workers in fluid dynamics still are) by the drag of bluff bodies—the phenomenon of oscillatory separation and vortex production. He asked Karl Hiemenz, a doctoral candidate, to build a water channel and a precisely circular cylinder so they could study the basic, symmetrical flow. Hiemenz worked with great precision, but when von Kármán asked him, every morning, "How goes it?" the answer was, sadly, "It always oscillates." Von Kármán thought about it and had the really startling idea that maybe only the asymmetrical, oscillating flow configuration was stable. Again it was modeled as an inviscid irrotational flow, but with an infinite train of ideal vortex filaments—later called the "Kármán vortex street."

Actually, von Kármán's earliest scientific triumph was not in fluid mechanics but in structures: the theory of inelastic buckling, that is, the behavior of columns whose buckling is accompanied by plastic deformation. This work originated a whole branch of structures research that is still going on (as is the subject of bluff-body drag, because the details are so complex).

Later, he and G. I. Taylor more or less founded the whole subject of statistical turbulence. They defined the averaging, identified the important statistical quantities, employed tensor techniques and drew many conclusions from what they found. They made just about all the enticing mistakes—wrong guesses—about the array of correlations that crop up, saving their successors a lot of trouble. Their cooperation, as well as their work with Sydney Goldstein and others, is in delightful contrast with the well-publicized story of the search for the DNA structure.

But surely von Kármán's greatest legacy to us is not inelastic buckling, the vortex street or the statistical theory of turbulence. It is the legacy of a lifetime, the accumulation of a hundred timely, ingenious attacks on a hundred real, intransigent problems, in each of which he provided remarkable, original insight. Some of the problems in fluid dynamics he wrote on are:

- skin friction, both laminar and turbulent
- theory of helicopters
- vortex theory of propellers
- resistance of supersonic projectiles
- the rolling of metals such as steel
- sand ripples in the desert
- stalling and the maximum lift coefficient
- open-channel water flow and the gas-dynamic analogy
- detonation and deflagration waves.

I think von Kármán believed that any problem in engineering (and perhaps in a much broader category) could profitably be attacked mathematically.

Family portrait. From left to right: von Kármán, his mother Helene, his sister Josephine and an unidentified visitor at the von Kármán home in Pasadena, around 1934.

He asked: What are the dominant phenomena? How can they be modeled most simply? (Often this meant linearly, but if not, how? At best, it would be with a *differential* model!) His ability to use the principle of similitude—that is, the principles of sophisticated dimensional analysis—was incredible. Some of this magic was obviously learned by his students Clark Millikan, Francis Clauser and H. W. Liepmann, and passed along by them to Don Coles and to their students.

One of my fellow students at Caltech's Guggenheim Aeronautics Laboratory (generally referred to as GALCIT) told me: "The old man is hooked on approximations. I think he'd rather have an approximation than an exact solution." I resented the remark at the time, but now I think it might have been true. The beautiful, simple formula, embodying only the really important effects, was certainly what fascinated him. He was willing to let others carry out the details. How many PhD dissertations at GALCIT were the results of competent carrying out of the beautiful ideas jotted by von Kármán, often on the back of a menu or concert program, and left on his student's desk!

Von Kármán didn't believe you had even qualitative understanding of an observed phenomenon until you could write at least the equations of its first approximation! (I guess an intelligent layman won't understand that sentence; he'll say "qualitative" and "equations" are contradictory.)

This, I believe, is his legacy: the conviction that a mathematical description—the simpler the better—is *necessary* in good engineering. He used to quote (I know not from whom), "There is nothing more practical than a good theory."

This was radical in the 1930s and 1940s. It was not how engineering was taught or practiced, either in the US or in the United Kingdom. A great transformation was accomplished between the 1930s and the 1960s, and I think von Kármán led it.

How he did it

How did he do it? Well, first of all, he had the credentials—the papers and books written, the honors received. Second, he was a great teacher, not only in the classroom, but also in the offices of generals, admirals and industrialists and in the meetings of engineering societies. Some of his papers and books are pedagogical masterpieces: *Mathematical Methods in Engineering*, which he wrote with Maurice Biot; *Aerodynamic Theory* (Volume II of the Durand series), "The engineer grapples with nonlinear problems" (*Bulletin of the American Mathematical Society* **46**, 615, 1940); and a real classic: *Aerodynamics: Selected Topics in the Light of Their Historical Development*. (An indication of the force of von Kármán's personality is the fact that *Mathematical Methods in Engineering* is always referred to as "*Kar*man–*Bi*ot," pronounced BEEoh, because that is how any Hungarian pronounces the distinguished coauthor's distinguished Belgian name. The same happens with "*Kar*man–*Tsi*en," where the coauthor's distinguished Chinese name also became Hungarian. Von Kármán once went to a ticket window to buy a ticket to Schenectady, but returned to tell me, "Bill, I asked the fellow for one-way *Schen*ectady, and he gives me a one-way ticket to Kansas City.")

I urge our young colleagues who haven't read these marvelous books and papers to do so. They might also enjoy von Kármán's "Atomic engineering?" (*Mechanical Engineering* **67**, 672, 1945), a paper not really devoted to that subject but to engineering education in general; he deplores the fact that engineering students are not given more intellectual challenge. It includes the remark, "At the institution where I have been teaching in the last fifteen years . . . [the atmosphere for engineering students is one] in which the beam on three supports is considered a most

Last-minute calculations, on 23 August 1941, just before a test of the rocket-powered plane on whose wing von Kármán is writing. The flight was one of a series that demonstrated the potential of jet-assisted takeoff. From left to right: Clark Millikan, Martin Summerfield, von Kármán, Frank J. Molina and Homer A. Boushey, the pilot. (From T. von Kármán, L. Edson, *The Wind and Beyond*, Little, Brown, Boston, 1967; reproduced with permission of the Caltech Archives.)

difficult problem."

There are two papers in von Kármán's bibliography that cast important light on his attitude toward mathematics: "Some remarks on mathematics from the engineer's viewpoint" and "Tooling up mathematics for engineering." The latter was the first paper of the *Quarterly of Applied Mathematics*, and has the form (learned from Galileo) of a dialog between two speakers, of whom one does and the other doesn't believe in applied mathematics. It's a technique used by writers who are not, themselves, sure which side they are on. Actually, von Kármán was not very well trained in mathematics; his mathematical skill was mostly intuitive. I know, from writing papers with him, that he didn't approve(!) of analytic continuation, and thought it a huge joke when the solutions for mixed transonic flow in the hodograph plane came out in terms of what he called "confluent hypergeometric functions á la Whittaker-Watson!"

Third, he had infinite energy. He always taught classes, carried on original research, masterfully directed GALCIT, consulted with industry, served on governmental boards and committees, attended scientific meetings and lived an active social life. One of the unfounded legends now told about von Kármán is that he was an absent-minded administrator. On the contrary, he was a very able administrator. Many times I stood with Mabel Rhodes, the departmental secretary, in her little office on the second floor of GALCIT, and overheard conversations in which Clark Millikan told von Kármán that some distinguished person—Carl-Gustaf Rossby, Leslie Howarth or whoever—proposed to come to GALCIT for a period. When von Kármán agreed that it was desirable, Millikan would ask what we would use for funds. After a moment's thought, the director would always know how much was available and where it was coming from. Sometime each spring he would ask us younger staff members what we planned to do in the coming summer; if we said we'd like to continue our research (and salary) right there, he'd say OK. No proposal, no contract—those were the good old days!

In his work and in his social life he was at all times "assisted" by his beloved sister Josephine. (He said "assisted," but to some of us it seemed the word should be "harassed.") She is in part responsible for what is likely to be a puzzle for many generations of librarians and bibliographers: One lone paper among von Kármán's is by "Theodore de Kármán and Leslie Howarth." Josephine didn't like Germany or anything German, and was unhappy about Theodore's use of the Germanic "von"; she was always "Josephine de Kármán." Both "von" and "de," of course, are translations of some Hungarian honorific that reflected the honor bestowed upon their father. When her brother and Leslie Howarth were writing up their fine paper on isotropic turbulence in 1937, she seems to have badgered him into changing his professional name from the German to the French form. Obviously the change didn't last beyond that one paper—it wasn't a very practical idea. In the *Collected Works*, which were assembled in 1956, the Kármán–Howarth paper is presented with the "de" changed back to "von."

Finally, he had the advantage of a charming, winning, colorful, Hungarian personality. Let me use the rest of my space on the personal side of this man; it was an important part of his impact in his field.

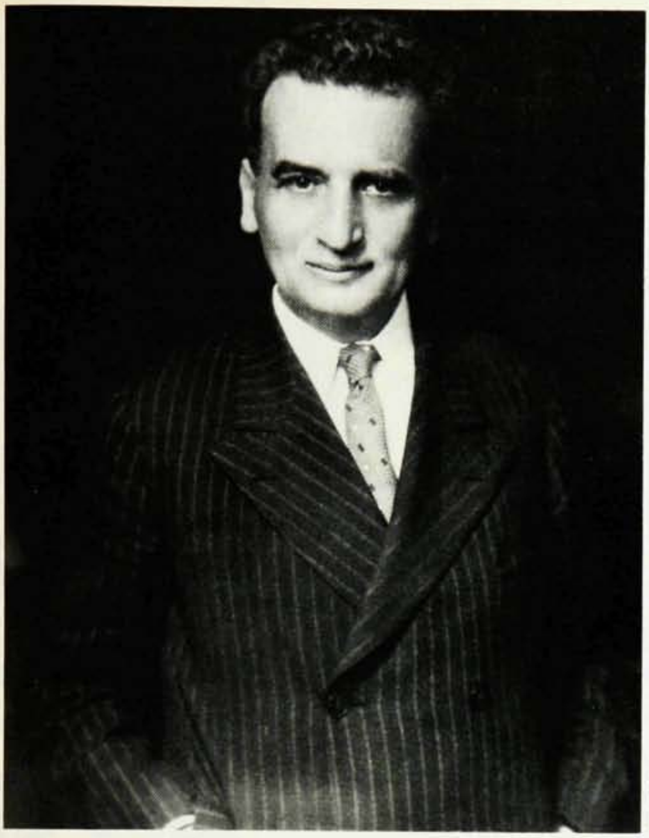
He loved people. Wherever he went, he struck up conversations with taxi drivers, waiters and waitresses, and chambermaids. He found out where their accents or surnames came from and tried to converse in their native languages or discuss their major fields of college study—because he was sincerely interested. He also loved parties, drinks, girls, jokes, the *bon mot*. All his life he played the part of the dangerous Hungarian bachelor. He succeeded in shocking some of the young wives (and their husbands), but charmed many more. He told us: "I have decided how I want to die. At the age of 85 I want to be shot by a jealous husband."

He had a story for every occasion, an apropos joke to take the edge off any unpleasant episode. Whenever he met an Air Force general whose name he didn't know, he would greet him as "General Anderson," whereupon the general would explain: "Oh, I'm not General Anderson, Doctor, I'm General —." Von Kármán's reply was, "Oh, of course. You see, I know three General Andersons, so when I meet an Air Force general whose name I've forgotten, I call him General Anderson to maximize the probability."

He was a great admirer of the legendary Sam Goldwyn and loved to emphasize points in meetings by quoting such Goldwynisms as "OK, but include me out," "Wait a minute, I've got a wonderful idea, but I don't think much of it" and "I can give you my opinion in two simple words: Im Possible!"

Biting wit

He could, however, be bitterly sarcastic, especially when he encountered sham or scientific fakery. I remember when a fellow "generalized" the famous Kármán–Tsien linear approximation to the adiabatic gas law by using an exponent whose value depended on which family of NACA airfoil profiles was under consideration. Von Kármán's comment at an Institute of Aeronautical Sciences national meeting was: "This speaker reminds me of my boyhood in Hungary; we always



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Von Kármán in 1928, shortly after moving to the United States.

had gypsy magicians who did tricks. The difference is that the gypsies only *pretended* to violate the laws of physics!"

A Czech scholar annoyed von Kármán by saying, constantly, that the Czechs had been oppressed by the Austro-Hungarian Empire. Von Kármán's father was an important official in the Empire's educational system—he was knighted for his work—and von Kármán always retained a sentimental attachment to it. He pinned the scholar down at a cocktail party: "Now, Dr —, tell us how you were oppressed?" All that the gentleman could come up with was, "For ten years I was assistant professor, and never promoted." Von Kármán turned to the other guests, saying, with great sarcasm, "Oh, that was terrible oppression indeed, but hardly worth fighting a World War over!"

He often encountered engineers who said, "Well, professor, I don't follow all of your fancy mathematics. I am a practical engineer." To which von Kármán's reply was: "Yes. You know what a practical engineer is? He's one who perpetuates the mistakes of his predecessors!"

Unfortunately, his clever remarks and analogies were not always understood by his hearers. I came across the memoirs of Stanislaw Ulam, the mathematical physicist, and looked in the index to see if von Kármán was mentioned. (Actually, of course, I looked first to see if I was mentioned. I wasn't. Von Kármán had already taught me that one always looks up oneself first and that the greatest number of references is invariably to the author himself.) I found three mentions of von Kármán. One is a delightful story: Ulam saw von Kármán at a party and asked John von Neumann who that little old guy was. "What, you don't know Theodore von Kármán?" said von Neumann. "Why, he invented consulting!"

But Ulam didn't quit there. He went on to say that von Kármán was one of the earliest European airplane pilots and held one of the oldest pilot's licenses. (He never flew an airplane.) And then quoted von Kármán as defining an *engineer* as one who perpetuates the mistakes of his predecessors. Surely that is blasphemy!

I hope that by now you have had a glimpse of von Kármán's personality. Let me close by telling you something about his character. He was absolutely committed to personal and intellectual honesty and to the highest ethical standards in both the academic and business worlds. I was with him once when an ethical matter arose in connection with the consulting activities of one of my contemporaries. It involved reneging on a consulting commitment because the activity had led the consultant to some very promising results, which he now wished to keep for himself, and, after all, he hadn't yet been paid any fee for the work. Von Kármán was shocked, and let my friend know it in no uncertain terms. But he was not nearly as angry as he had been once at Caltech when a graduate student suggested that he should have some special favor "because we Central Europeans should stick together."

There was only one category in which he was not, I'm afraid, strictly reliable: the recommendations he wrote for us, his students, were much too kind. I think they must have originated in Hungarian, where *nem* (no) often comes out sounding like *igen* (yes). Duncan Rannie traveled with von Kármán through Western Europe in 1946. He says that wherever they stopped, von Kármán was given the keys to the city and offered a directorship in the local university. Duncan says, "As far as I could make out, he accepted them all."

I don't know whether I should describe von Kármán as modest. He came from a 19th century European tradition that valued scholarship, science and college professors. He surely knew that in those terms he was something special, but he didn't expect to receive special privileges as a result. Within the academic world, on the other hand, he believed in special privileges (and responsibilities) for professors, but that meant all professors and not special favors for himself.

I remember when he was visited in Pasadena by the son of one of his former students, who said: "I am going to study engineering, Professor. If I can be half as great an engineer as you, I will be happy." Von Kármán told me this, in private, and added, with a twinkle in his eye: "Now, Bill, what do you think? Fifty percent is a modest wish?"

Theodore von Kármán was too big, too complex, too many-sided to describe in 700 lines! I apologize for all that I've left out.

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This article is adapted from an invited lecture delivered at the annual meeting of the APS division of fluid dynamics on 17 November 1984 at Brown University. □