AIAA JOURNAL
Vol. 39, No. 5, May 2001

History of High-Speed Flight and Its Technical Development

John D. Anderson Jr.*
National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560-0312

If you define a great scientist as a man with great ideas, then you will have to rate Einstein first. He had four great ideas. In the history of science perhaps Sir Issac Newton is ahead of Einstein because he had five or six ideas. All the other major scientists of our age are associated with just one, or at the most two, great ideas. In my case I have had three great ideas. Maybe more. Yes, perhaps three and a half great ideas.

Theodore von Kármán, from
The Wind and Beyond, by T. von Kármán
with Lee Edson, Little, Brown, and Co.,
Boston, 1967.

Theodore von Kármán lived for 82 years. During his lifetime he witnessed, and to some degree participated in, the technical development of high-speed flight, from the regime of subsonic flight near the speed of sound to transonic, supersonic, and hypersonic flight. What a remarkable time to have lived. This paper is a brief summary of the historical and technical evolution of flight, as witnessed by von Kármán.

Note

Material for this paper is liberally taken from the author's recent book *A History of Aerodynamics and Its Impact on Flying Machines*[1] and from his paper "Research in Supersonic Flight and the Breaking of the Sound Barrier,"[2] which should be consulted for more details.

Introduction

BECAUSE this paper is one in the annual series of AIAA von Kármán Lectureships in Astronautics, and because by good fortune I have the honor to present the first von Kármán Lecture that will begin the period of the 2000s, I am motivated to make this a special commemorative to its namesake. The main thrust of this paper is to survey the historical evolution of high-speed flight and its technology. Theodore von Kármán (1881–1963) witnessed much of this evolution over his lifetime of 82 years and indeed participated in part of it (see Fig. 1). Therefore, this is going to be a discussion of the history of high-speed flight, but with a twist. We are going to look at this history as von Kármán witnessed it, and we are going to marble into our discussion some of the history of von Kármán himself: his observations and thoughts. Indeed, to highlight the various "von Kármánisms" as they appear in parallel with the history of high-speed flight, they will be printed in italics to set them apart from the rest of the text.

The Beginnings

Speed of Sound

Most golfers know the following rule of thumb: When you see a flash of lightning in the distance, start counting at a normal rate, one, two, three, etc. For every count of five before you hear the thunder, the lightning bolt struck a mile away. Clearly, sound travels through air at a definite speed, much slower than the speed of light. The standard sea level speed of sound is 1117 ft/s; in 5 s a sound wave will travel 5585 ft, slightly more than a mile. This is the basis for the golfer's "count of five" rule of thumb.

The speed of sound is the demarcation between subsonic and supersonic flow, two flows whose physics are as different as day and night. The evolution of our intellectual understanding of the characteristics of high-speed flight begins with the speed of sound.

Knowledge of the speed of sound is not a product of 20th century science. Precisely 260 years before the first supersonic flight of the Bell X-1, Isaac Newton published the first calculation of the speed of sound in air.[3] At that time it was clearly appreciated that sound propagates through air at some finite velocity. Newton knew that artillery tests had already indicated that the speed of sound was approximately 1140 ft/s. The 17th century artillery men were preceding the modern golfer's experience; the tests were performed by standing a known large distance away from a cannon and noting the time delay between the light flash from the muzzle and the sound of the discharge. In Proposition 50, Book II of his *Principia* (1687), Newton calculated a value of 979 ft/s for the speed of sound in air, 15% lower than the existing artillery data. Undaunted, Newton followed a now familiar ploy of theoreticians; he proceeded to explain away the difference by the existence of solid dust particles and water vapor in the atmosphere. However, in reality Newton had made the incorrect assumption in his analysis that the air temperature inside a sound wave was constant (an isothermal process), which caused him to underpredict the speed of sound. This misconception was corrected more than a century later by the famous French mathematician, Pierre Simon Marquis de Laplace, who properly assumed that a sound wave is adiabatic (no heat loss), not isothermal.[4] Therefore, by the time of the demise of Napoleon, the process and equation for the speed of sound in a gas was fully understood.

Theodore von Kármán was born in Budapest, Hungary, on May 11, 1881. His father, Maurice, received a Ph.D. in philosophy from the Pazmany Peter University of Budapest and later held a professorship at the Pazmany. Maurice drafted a plan for modern, secondary school education in Hungary and later was able to put his reforms into effect as Secretary General of the Austro–Hungarian Ministry of Education. Theodore always credited his father for nurturing "a general humanistic interest," one of the many qualities that was to distinguish von Kármán during his career in the 20th century. His mother was Helen Konn, a descendent of a long line of scholars back to a great 16th century mathematician at the Imperial Court of Prague. It is obvious why von Kármán as a child developed a love of intellectual thought and learning. At the time of von Kármán's birth, proper understanding and calculation of the speed of sound in air had been in effect for 65 years.

Shock Waves

Shock waves are omnipresent in the flowfields around transonic and supersonic vehicles. As in the case of the speed of sound,

Presented as Paper 2000-0002 at the AIAA 38th Aerospace Sciences Meeting, Reno, NV, 10–13 January 2000; received 16 June 2000; revision received 7 October 2000; accepted for publication 18 October 2000.

*Curator for Aerodynamics; also Professor Emeritus, Department of Aerospace Engineering, University of Maryland, College Park, MD 20742. Fellow AIAA.

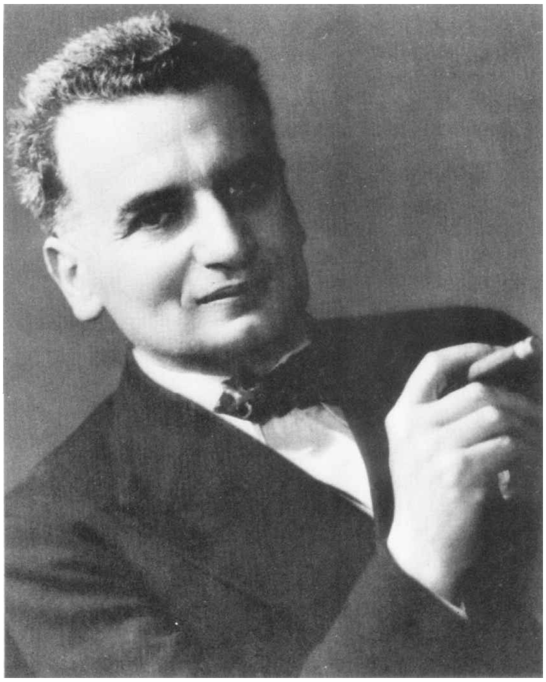

Fig. 1 Theodore von Kármán, at the time he became Director of GALCIT in 1930.

knowledge of shock waves is not unique to the 20th century; their existence was recognized in the early 19th century. The German mathematician, G. F. Bernhard Riemann, first attempted to calculate shock properties in 1858, but he neglected an essential physical feature and, hence, obtained incorrect results. (A shock wave is, in thermodynamic language, an irreversible process, caused by viscosity and thermal conduction effects inside the shock wave. A measure of the amount of irreversibility is the entropy, which from the second law of thermodynamics always increases in any process involving such irreversibilities. The entropy of a gas always increases as it passes through a shock wave. Unfortunately, Riemann made the incorrect assumption that the entropy remained constant across a shock.) Twelve years later, William John Rankine, a noted engineering professor at the University of Glasgow, derived the equations for the change in flow properties across a normal shock wave. In 1870, two years before his death, Rankine, in a paper in the *Philosophical Transactions of the Royal Society*, correctly presented for the first time the proper normal-shock equations for continuity, momentum, and energy in much the same form as studied today by students in a compressible flow class. Rankine correctly assumed that the internal structure of a shock wave was not isentropic; rather, it was a region of dissipation. He was thinking about thermal conduction, not the companion effect of viscosity. Nevertheless, he was able to derive the correct relationships for the thermodynamic changes across the shock.

The equations obtained by Rankine were subsequently rediscovered by the French ballistician Pierre Henry Hugoniot. Not aware of Rankine's work, in 1887 Hugoniot published a paper in the *Journal de l'Ecole Polytechnique* in which the correct equations for normal-shock thermodynamic properties were presented. As a result of the pioneering work by Hugoniot and by Rankine before him, all equations dealing with shock waves are known as Rankine–Hugoniot relations, a label that appears frequently in modern gasdynamics literature.

However, the work of Rankine and Hugoniot did not establish the direction of changes across a shock wave. Noted in both works was the mathematical possibility of either compression shocks (pressure increases across the shock) or rarefaction shocks (pressure decreases across the shock). It was not until 1910 that the ambiguity was resolved. In two almost simultaneous and independent papers, first Lord Rayleigh and then G. I. Taylor invoked the second law of thermodynamics to show that only compression shocks are physically possible. (For more historical details on this story, see Refs. 1 and 5.)

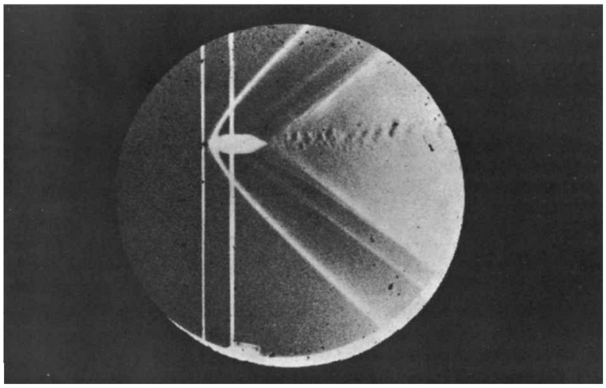

Fig. 2 First photograph of a shock wave from a body (a bullet) moving at supersonic speeds. The photograph was taken by Ernst Mach in 1887.

The first person to observe and record the nature of shock waves in a supersonic flow in the laboratory was Ernst Mach, the famous 19th-century physicist and philosopher. In a paper entitled "Photographische Fixierung der durch Projektile in der Luft eingeleiten Vorgange" presented before the Academy of Sciences in Vienna in 1887, Mach showed the first photograph of shock waves (Fig. 2). They are produced by a bullet moving at supersonic speed. Also visible are weaker waves at the rear of the projectile and the structure of the turbulent wake downstream of the base region. The two vertical lines were made by trip wires designed to time the photographic light source (a spark) with the passing of the projectile. Mach was a precise and careful experimentalist; the quality of the photograph and the fact that he was able to make the shock waves visible in the first place (he used an innovative technique called the shadowgraph, a common optical system in experimental aerodynamics today) attest to his exceptional experimental abilities. Note that Mach was able to carry out such experiments involving split-second timing without the benefit of electronics; indeed, the vacuum tube had not yet been invented.

Mach was the first researcher to understand the basic physical characteristics of a supersonic flow, and to point out the importance of the flow velocity V relative to the speed of sound a and to note the discontinuous and marked changes in a flowfield as the ratio V/a changed from below 1 to above 1. He did not, however, call that ratio the Mach number, as we do today. The term Mach number was introduced in 1929 by the Swiss engineer Jakob Ackeret during a lecture in Zurich and did not reach the English literature until the late 1930s.

Rankine published his normal shock equations and Mach showed the first photograph of shock waves in the same year—1887. In that year, von Kármán was six years old. He was already something of a prodigy. At the age of six he had a phenomenal ability to multiply numbers in his head. At gatherings of family and friends, he would be asked to demonstrate this ability as almost a game. Von Kármán remembered such an instance as follows: "The procedure was always the same. One of my uncles called for silence and shouted 'All right, Todor. Multiply these two numbers in your head: 144567 by 19765.' A hush then fell on the room while all eyes turned expectantly toward me. And like a performer on-stage, (so my mother told me), I hesitated just a moment and then announced the results while somebody checked with pen and paper and declared my answers were correct. I repeated the performance several times. I never quite understood how I could figure these numbers, but everybody usually clapped and laughed and seemed somewhat astounded." But not his father, who was concerned about problems associated with "wonder children." Taking von Kármán aside, his father made him promise not to think about mathematics again. He thought it was abnormal to be able to mentally multiply by long numbers. His father's influence kept von Kármán away from mathematics for a decade. When he was much older, von Kármán could add and subtract in German, English, French, and Spanish, but he could multiply only in Hungarian, and by his own admission, slowly at that. He had completely lost the extraordinary visual memory necessary for the mental mathematical tricks he performed at the age of six.

Supersonic Flow in the Laboratory

Today, supersonic wind tunnels are commonplace in all major government, industrial, and university aerodynamic laboratories. The lineage of these tunnels can be traced to Carl Gustaf Patrik de Laval, who was the first to employ a convergent–divergent supersonic nozzle in a mechanical device, namely, to drive a turbine.

Carl Gustaf Patrick de Laval was born at Blasenborg, Sweden, 9 May 1845. The son of a Swedish army captain, de Laval showed an early interest in mechanical mechanisms, disassembling and then reassembling such devices as watches and gun locks. His parents encouraged his development along these lines, and at the age of 18 de Laval entered the University of Uppsala, graduating in 1866 with high honors in engineering. He was then employed by a Swedish mining company, the Stora Kopparberg, where he quickly realized that he needed more education. (This is a phenomenon which has affected young engineers through the ages.) Therefore, he returned to Uppsala, where he studied chemistry, physics, and mathematics, and graduated with a Ph.D. in 1872. From there, he returned to the Stora Company for three years, and then joined the Kloster Iron Works in Germany in 1875. By this time, his inventive genius was beginning to surface: He developed a sieve for improving the distribution of air in Bessemer converters and a new apparatus for galvanizing processes. Also, during his time with Kloster, de Laval was experimenting with centrifugal machines for the separation of cream in milk. Unable to convince Kloster to manufacture his cream separator, de Laval resigned in 1877, moved to Stockholm, and started his own company. Within 30 years, he had sold more than a million de Laval cream separators, and to the present day he is better known in Europe for cream separators then for steam turbines.

However, it was with his steam turbine designs that de Laval made a lasting contribution to the advancement of compressible flow. In 1882, he constructed his first steam turbine using rather conventional nozzles. Such nozzles were convergent shapes, indeed nothing more than orifices in some designs of that day. In turn, the kinetic energy of the steam entering the rotor blades was low, resulting in low rotational turbine speeds. The cause of this deficiency was recognized: The pressure ratio across such nozzles was never less than one-half. Today, we know that such nozzles were choked and that the flow exhausted from the nozzle exit at a velocity that was not greater than sonic. However, in 1882, engineers did not fully understand such phenomena. Finally, in 1888, de Laval hit on the system of further expanding the gas by adding a divergent section to the original convergent shape. Suddenly, his steam turbines began to operate at incredible rotational speeds, over 30,000 rpm. Overcoming the many mechanical problems introduced by such an improvement in rotational speed, de Laval developed his turbine business into a large corporation in Stockholm, and quickly obtained a number of international affiliates, in France, Germany, England, the Netherlands, Austria–Hungary, Russia, and the United States. Subsequently, his design was demonstrated at the World Columbian Exposition in Chicago in 1893.

In addition to his successes as an engineer and businessman, de Laval was also adroit in his social relations. He was respected and liked by his social peers and employees. He held national office, being elected to the Swedish Parliament from 1888 to 1890 and later becoming a member of the Senate. He was awarded numerous honors and decorations and was a member of the Swedish Royal Academy of Science.

After a full and productive life, Carl G. P. de Laval died in Stockholm in 1912 at the age of 67. However, his influence and his company have lasted to the present day.

It is interesting to note that, on a technical basis, de Laval and other contemporary engineers in 1888 were not quite certain that supersonic flow actually existed in the "Laval nozzle." This was a point of contention that was not properly resolved until the experiments of Stodola in 1903, as discussed next.

The innovative steam turbine nozzle design by de Laval sparked interest in the fluid mechanics of flow through convergent–divergent nozzles at the turn of the century. Leading this interest was Hungarian-born engineer by the name of Aurel Boleslav Stodola, who was to eventually become the leading expert in Europe on steam turbines. However, whereas de Laval was an idea and design man, Stodola was a scholarly professor, who tied up the loose scientific and technical strings associated with Laval nozzles. Stodola is a major figure in the advancement of compressible flow, thermodynamics, and steam turbines. Let us see why and, at the same time, take a look at the man himself.

A Hungarian like von Kármán, Stodola was born 10 May 1859, in Liptovsky Mikulas, Hungary, a small Slovakian town at the foot of the High Tatra mountains. The second son of a leather manufacturer, he attended the Budapest Technical University for one year in 1876. He was an exceptional student, and in 1877 he shifted to the University of Zurich in Switzerland, and then to the Eidgenossische Technische Hockschule in 1878, also in Zurich. Here, he graduated in 1880 with a mechanical engineering degree. Subsequently, he served a brief time with Ruston and Company in Prague, where he was responsible for the design of several different types of steam engines. However, his superb performance as a student soon earned him a "Chair for Thermal Machinery" back at the Eidgenossische Technische Hockschule in Zurich, a position he held until his retirement in 1929.

There, Stodola established a glowing academic career, which included teaching, industrial consultation, and engineering design. However, his main contributions were in applied research. Stodola had a synergetic combination of high mathematical competence and an intense devotion to practical applications. Moreover, he understood the importance of engineering research at a time when it was virtually nonexistent throughout the world. In 1903 (the same year as the Wright brothers' first powered airplane flight), Stodola wrote[6]:

> We engineers of course know that machine building, through widely extended practical experimenting, has solved problems, with the utmost ease, which baffled scientific investigation for years. But this "cut and try method", as engineers ironically term it, is often extremely costly; and one of the most important questions of all technical activity, that of efficiency, should lead us not to underestimate the results of scientific technical work.

This commentary on the role of basic scientific research was aimed primarily at the design of steam turbines. But it was prophetic of the massive and varied research programs to come during the latter half of the 20th century.

The importance of Stodola in high-speed aerodynamics lies in his pioneering work on the flow of steam through Laval nozzles. As mentioned earlier, the possibility of supersonic flow in such nozzles, although theoretically established, had not been experimentally verified and, therefore, was a matter of controversy. To study this problem, Stodola constructed a convergent–divergent nozzle with the shape illustrated at the top of Fig. 3. He could vary the backpressure over any desired range by closing a valve downstream of the nozzle exit. With pressure taps in a long, thin tube extended through the nozzle along its centerline (also shown in Fig. 3), Stodola measured the axial pressure distributions associated with different backpressures. These data are shown below the nozzle configuration in Fig. 3. Figure 3 is taken directly from Stodola's original publication, a book entitled *Steam Turbines*, first published in 1904. Here, for the first time in history, the characteristics of the flow through a supersonic nozzle were experimentally confirmed. In Fig. 3, the lowest curve corresponds to a complete isentropic expansion. The curves D–L in Fig. 3 correspond to a shock wave inside a nozzle, induced by higher backpressures. The curves A, B, and C correspond to completely subsonic flow induced by high backpressures. With regard to the large jumps in pressure shown by some of the data in Fig. 3, Stodola comments:

> I see in these extraordinary heavy increases of pressure a realization of the "compression shock" theoretically derived by von Riemann; because steam particles possessed of great velocity strike against a slower moving steam mass and are therefore compressed to a higher degree.

(In the preceding quotation, Stodola is referring to F. G. Bernhard Riemann mentioned earlier; however, he would be historically more correct to refer instead to Rankine and Hugoniot.) Stodola's nozzle experiments as described earlier, and his original data shown in Fig. 3, represented a quantum jump in the understanding of supersonic nozzle flows. Taken in conjunction with de Laval's

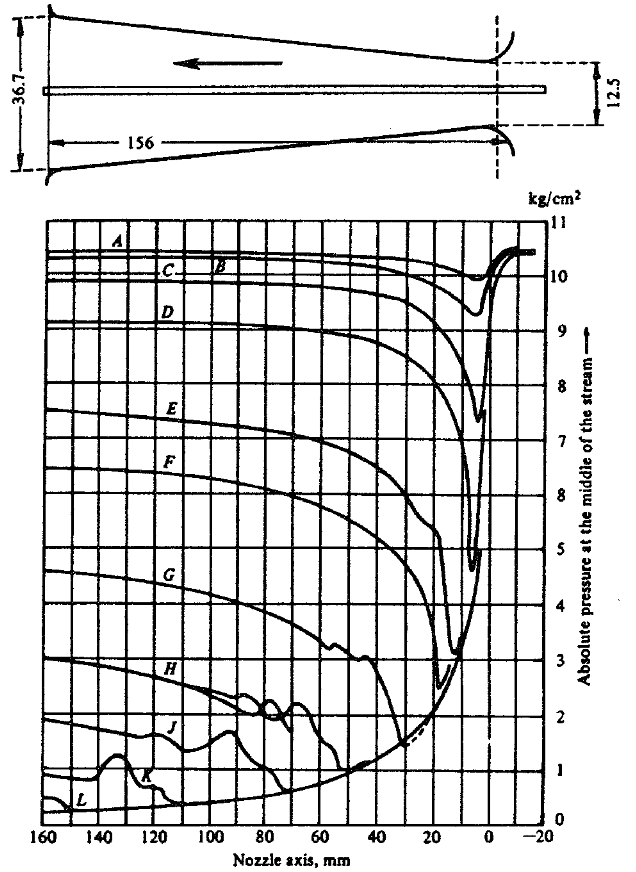

Fig. 3 Pressure distributions through a supersonic nozzle measured by Stodola, 1904 (from Ref. 6)

contributions, Stodola's work represents the original historical foundation for the design of supersonic nozzles.

Stodola died in Zurich in 1942 at the age of 83. He had become the world's leading authority on steam turbines, and his students were found throughout the Swiss companies that made steam turbines, the international leaders in that field. He had exceptional personal charm, and his students composed an almost disciplelike group during his long life in Zurich. Clearly, Stodola left a permanent mark in the history of high-speed flow.

The final important figure in the early history of high-speed aerodynamics was the ubiquitous Ludwig Prandtl. Prandtl's creative influence dominates 20th-century aerodynamics: boundary-layer theory, low-speed airfoil theory, and finite-wing lifting-line theory, to name only a few. It is not our purpose here to give a long exposition on Prandtl. But it is not widely recognized by many students of aerodynamics that Prandtl made major contributions to the theory and understanding of high-speed flows. In 1905, he built a small Mach-1.5 supersonic nozzle to study steam-turbine flows and the movement of sawdust in sawmills. For the next three years he continued to study the flow patterns associated with such supersonic nozzles. Figure 4 shows some striking photographs made in Prandtl's laboratory during that period that clearly illustrate a progression of expansion and oblique shock waves emanating from the exit of a supersonic nozzle. The dramatic contrast is that Prandtl was learning about *supersonic* flow at the same time that the Wright brothers were just introducing practical powered airplane flight to the world, with maximum velocities no larger than 40 mph.

The observation of such shock and expansion waves naturally prompted Prandtl to explore their theoretical properties. Consequently, Theodor Meyer, one of Prandtl's students at Gottingen, presented his doctoral dissertation in 1908 entitled "Ueber Zweidimensionale Bewegungsvorgange in einem Gas, das mit Ueberschallgeschwindigkeit Stromt" ("On the Two-Dimensional Flow Processes in a Gas Flowing at Supersonic Velocities"). In this dissertation, Meyer presented the first practical theoretical development of the relations for both expansion waves and *oblique* shock waves.

The work of Prandtl and Meyer on the physical understanding and calculation of oblique waves in supersonic flows brings to a close this discussion of the "beginnings" of high-speed flight. It is remarkable that such a sound, fundamental basis of the understanding of supersonic flows existed prior to the beginning of World War I, at a time when aerodynamics was being applied to airplanes that could barely fly faster than 100 mph. This work, both theoretical and experimental, was carried out by basic researchers, who (with the possible exception of de Laval) were interested in the subject on an academic basis only. The true practical value of this work did not come to fruition until the advent of supersonic flight in the 1940s. However, this is an excellent example of the value of basic research on problems that appear only purely academic at the time. In the 1940s, when basic supersonic flow theory and fundamental understanding of shock waves were suddenly needed due to the advent of high-speed airplanes and rockets, it was there, quietly residing and sleeping in a few dusty books and archive journal articles in the library.

At the time that de Laval was developing the convergent–divergent nozzle, von Kármán entered, at the age of nine, the Minta, or Model Gymnasium. This school embodied the best of his father's educational theories, and it became the model for all Hungarian high schools. The Minta became famous in Hungary, but little known in the west. Von Kármán once recalled that a writer for the London Observer called the Minta a "nursery for the elite," and compared it with Eton in Britain.[7] For von Kármán, the Minta was a great educational experience. It was here that, breaking away from the earlier promise to his father, he began to study mathematics eagerly. Von Kármán excelled in school. In 1898, he enrolled in the Royal Joseph University of Polytechnics and Economics, where he studied science, mathematics, and engineering. Von Kármán could have easily gone to a more prestigious foreign university, but a year earlier his father suffered a nervous breakdown and was institutionalized for the next four years. Von Kármán had to stick close to home. He graduated in 1902 with distinction and, like most young Hungarian males at that time, was immediately drafted into the Hungarian army. He served a year in the artillery.

Returning to his alma mater as an assistant professor, von Kármán also became involved as a consultant to Ganz and Company, Budapest's largest engine and generator company. For the next three years he was immersed in the working world of machines as well as the intellectual work of mechanics. In 1906, under a two-year fellowship from the Hungarian Academy, von Kármán arrived on Ludwig Prandtl's doorstep at Göttingen University. His life would never be the same thereafter.

At Göttingen, von Kármán carried out research on the theory of structures, with supporting experiments on the buckling of structures. By 1908, von Kármán completed his Ph.D.; it had been accomplished at the most prestigious university in Germany with the most prestigious mechanics professor, Prandtl, as his advisor.

During this time, von Kármán expressed little interest in fluid mechanics, and no interest in the fledgling area of flying machines. Although I can find no proof of it, he must have been aware of the technical work of de Laval, and especially the pioneering supersonic nozzle experiments of Stodola, simply because von Kármán lived in the technical world of mechanics and most likely would have seen the contemporary literature on steam turbines. Also, he was physically present at Prandtl's laboratory at the time of the supersonic nozzle experiments reflected by Fig. 4. However, aerodynamics, especially high-speed aerodynamics, simply was not on his primary radar screen at that time.

On 13 January 1908, the French aviator Henri Farman flew his delicately constructed Voisin–Farman I-bis biplane over a course extending to 1 km out and the same back. He was in the air for 1 min and 28 s, the longest flight in Europe to that date. For this, among the cheers of the crowd that had gathered for the occasion, Farman was awarded the Grand Prix d'Aviation. In the crowd early that morning was Theodore von Kármán, on vacation in Paris; he was accompanied by an attractive female companion, who had instigated their attendance at the flight, over von Kármán's disinterest and lack of enthusiasm of being out on the field at 5 a.m. However, this was von Kármán's first major contact with the world of flying

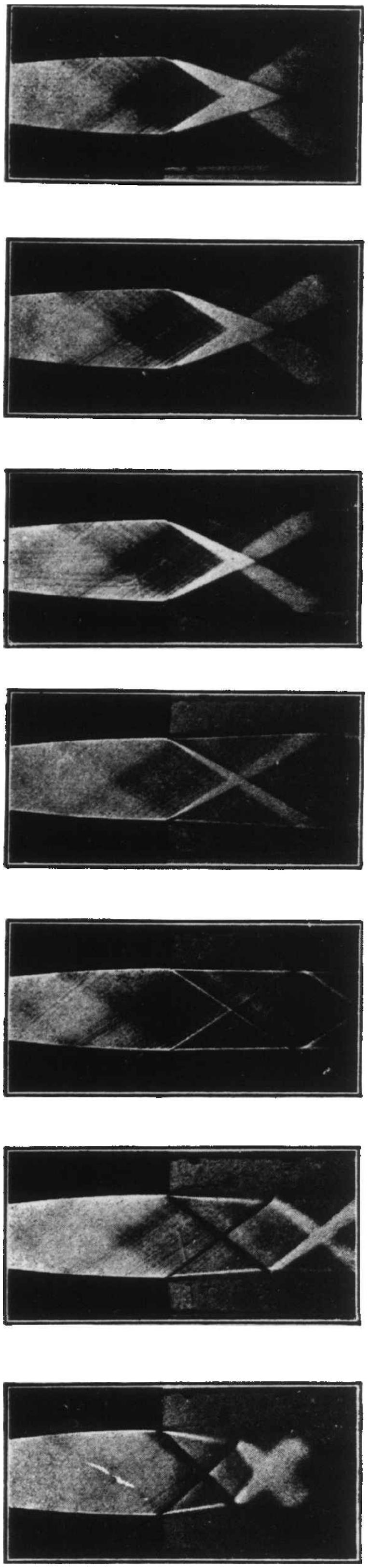

Fig. 4 Various wave patterns in a supersonic nozzle, photographed by Prandtl, 1904.

machines, and it sparked his interest. Quite by coincidence, when von Kármán returned to Gottingen in the capacity of privat docent, the lowest rung on the faculty ladder, Prandtl had a new project waiting for him. It involved the construction of a large new wind tunnel and setting up the first applied aerodynamic experiments at Gottingen, sponsored by Count Ferdinand von Zeppelin, who was in the airship business. Von Kármán's career in aerodynamics had begun.

Sneaking up on Mach 1

Airplane aerodynamics, from the time of the Wright Flyer to the beginning of World War II, assumed that changes in air density were negligible as the air flowed over the airplane. This assumption, called *incompressible flow*, was reasonable for the 350 mph or slower flight speeds of airplanes during that era. Theoretically, it was a tremendous advantage to assume constant density, and physically the slow-speed aerodynamic flows usually exhibited smooth variations with no sudden changes or surprises. All of this changed when flight speeds began to sneak up close to the speed of sound. Aerodynamic theory had to account for changes in the air density in the flowfield around the airplane, and physically the flowfield sometimes acted erratically and frequently surprised and greatly challenged aerodynamicists. Aerodynamicists in the 1930s simply threw these phenomena into one pot and called them generically "compressibility problems."

Ironically, the first inklings of compressibility problems occurred during the age of the strut-and-wing biplanes, with flight velocities about as far away from the speed of sound as you can get. It had to do with an airplane part, namely, the propeller. Although typical flight speeds of World War I airplanes were less than 125 mph, the tip speeds of propellers, because of their combined rotational and translational motion through the air, were quite large, sometimes exceeding the speed of sound. This fact was appreciated by aeronautical engineers at the time. This drove Frank Caldwell and Elisha Fales of the propeller branch of the U.S. Army Air Service Engineering Division at McCook Field in Dayton, Ohio, to design and build in 1918 the first high-speed wind tunnel in the United States, purely to investigate the problems associated with propellers. The tunnel velocity range was from 25 to a stunning 465 mph. It had a length of almost 19 ft, and the test section was 14 in. diam. This was a big and powerful machine for its day. Six different airfoils, with thickness ratios (ratio of maximum thickness to the chord length) from 0.08 to 0.2, were tested. At the higher speeds, the results showed "a decreased lift coefficient and an increased drag coefficient, so that the lift-drag ratio is enormously decreased." Moreover, the airspeed at which these dramatic departures took place was noted as the "critical speed." Because of its historical significance, some of their data are shown in Fig. 5, reproduced directly from the NACA TR 83 (Ref. 8). Here, the lift coefficient for the airfoil at 8-deg angle of attack is plotted vs airstream velocity. Note the dramatic drop in lift coefficient at the "critical speed" of 350 mph, the compressibility effect. This plot and ones like it for other angles of attack that were published in NACA TR 83 are the first published data in the history of aerodynamics to show the adverse effects of compressibility on airfoils. Caldwell and Fales made an error in the reduction of their data (an understandable error associated with the inexperience of dealing with compressible flow conditions at the early date of 1919), which caused their reported lift and drag coefficients to be about 10% too low at the higher speeds (see Ref. 1 for a detailed analysis of this error). This did not compromise the dramatic and important discovery of the large increase in drag and decrease in lift when the airfoil sections were tested above the "critical speed." Moreover, they were the first to show that the "critical speed" for thin airfoils was higher than that for thick airfoils and, hence, by making the airfoil section thinner, the adverse compressibility effects can be delayed to higher Mach numbers. This was an important finding, and one which would have a lasting impact on high-speed vehicle design.†

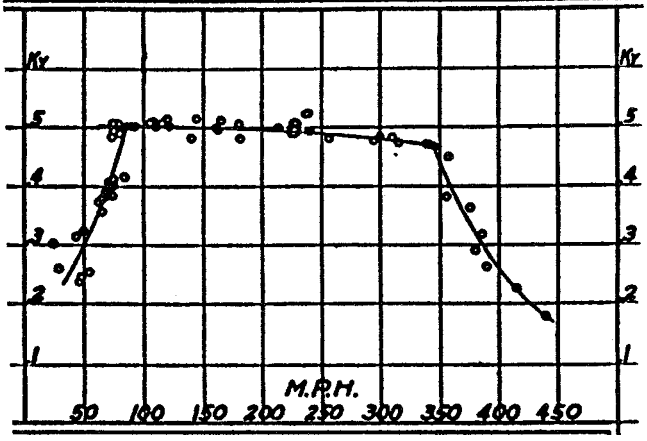

Fig. 5 First data to show the adverse compressibilty effects of high-speed flow over an airfoil, by Caldwell and Fales.[8] The definition used for *Ky* at that time differed from the modern definition of lift coefficient C_L, by a factor of two, that is, $C_L = 2Ky$.

In 1911, von Kármán developed the mathematical theory describing the alternately shed vortices behind a bluff body: the Kármán vortex street it was later called. This brought von Kármán to the attention of the fluid dynamics community. Anxious to branch out, and to somewhat get out from the dominance of Prandtl, von Kármán accepted the chair of aeronautics at the Technische Hochschule in Aachen. He was to stay at Aachen for the next 16 years.

Also at Aachen was Professor Hugo Junkers, who was pioneering the design and construction of the first all metal airplanes; interaction with Junkers further expanded von Kármán's interest in aeronautics. Immediately on his arrival at Aachen, he built a large wind tunnel patterned after the one at Göttingen. Unfortunately, his efforts were interrupted by World War I; von Kármán was called back to serve in the Hungarian Army, which consumed five years of his life. He returned to Aachen in November of 1919 and began a teaching and research program in aeronautics that propelled Aachen to world-class status in that area by the mid-1920s. It was there that he developed the integral approach to the solution of boundary layers, what has become known as the Kármán–Polhausen approximation. He also developed turbulence models for the approximate analysis of turbulent boundary layers, pioneering the velocity defect law for the velocity distribution in turbulent boundary layers.

In 1926, von Kármán paid his first visit to America, in response to an invitation by the famous physicist and Nobel Prize winner, Robert Millikan, then the head of the California Institute of Technology. Millikan had an ulterior motive; he was looking for just the right person to direct California Institute of Technology's new aeronautics program and to run the newly established Guggenheim Aeronautical Laboratory at the California Institute of Technology (GALCIT). Von Kármán's visit would take him to Cal Tech, and later to the University of Michigan, New York University, Massachusetts Institute of Technology, and Washington, D.C. However, von Kármán considered that the "peak-event" was a visit with Orville Wright at Dayton. He also visited Wright Field, where he talked with Frank Caldwell and Elisha Fales; he was shown the high-speed wind tunnel in which the measurements shown in Fig. 5 were taken. Up to this time, von Kármán had shown only a moderate interest in high-speed aerodynamics; he wrote an article on shock waves in 1908, published by the Society of Hungarian Engineers, and at Aachen he laid the groundwork for a supersonic laboratory (which came to fruition after he left).

On a second visit to Cal Tech in the fall of 1928, Millikan popped the question to von Kármán: Would he become the director of GALCIT? A new, large subsonic wind tunnel had just been finished at Cal Tech, and the offer was tempting. However, von Kármán did not immediately accept. Back at Aachen, von Kármán found Germany in a deteriorating political atmosphere, with antisemitic feelings on the rise, along with the strength of the Nazi Party. This, combined with Millikan's unrelenting recruitment efforts, led to von Kármán accepting the position. Theodore von Kármán arrived at Cal Tech in April of 1930, where he was to spend the rest of his professional career.

Following the work of Caldwell and Fales, NACA continued a program on high-speed compressibility effects during the 1920s and 1930s. Caldwell and Fales had identified the adverse effects of the "critical speed" on airfoils, namely, a loss of lift and a dramatic increase in drag. But nobody knew why these effects occurred. A piece of the puzzle fell into place in 1926 when L. J. Briggs and Hugh Dryden, working at the National Bureau of Standards under NACA sponsorship, measured pressure distributions over the surface of airfoils at and beyond the critical speed.[9] At the U.S.

†The critical Mach number is precisely defined as that freestream Mach number at which sonic flow is first encountered on the surface of a body. The large drag rise due to compressibility effects normally occurs at a freestream Mach number slightly above the critical Mach number; this is called the drag-divergence Mach number. In reality, Caldwell and Fales had reached and exceeded the drag-divergence Mach number in their experiments. But their introduction of the word "critical" in conjunction with this speed was eventually the inspiration for its use in later coining the term "critical Mach number."

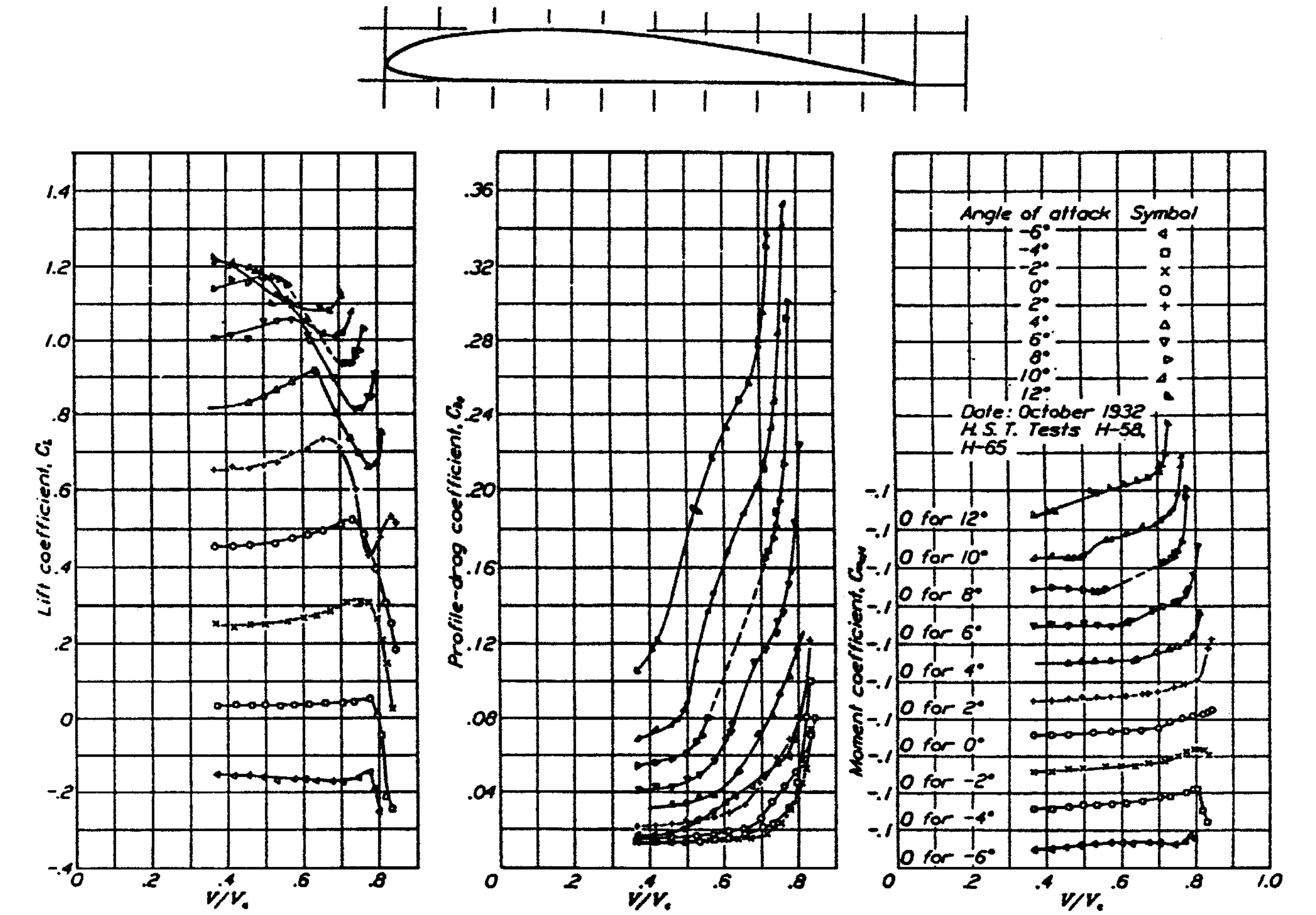

Fig. 6 Compressibility data from NACA TR 463 by John Stack. The three graphs are, from left to right, the variations of lift, drag, and moment coefficients, respectively, vs the ratio of the freestream velocity to the speed of sound (Mach number).

Army's Edgewood Arsenal, they constructed a small high-speed wind tunnel with an airstream only 2 in. in diameter. However, by careful design of the small airfoil models, two pressure taps could be placed on each model. Seven identical models were used, each one with different locations of the pressure taps. A total of 13 pressure tap locations, 7 on the upper surface and 6 on the lower surface, were employed. (For the reader who is counting, the seventh model had only one tap.)

With this technique, Briggs and Dryden measured the pressure distributions over the airfoil at Mach numbers from 0.5 to 1.08. The results were dramatic. Beyond the critical speed, the pressure distributions over the top of the airfoil exhibited a sudden pressure jump at about from one-third to one-half the distance from the leading edge, followed by a rather long plateau toward the trailing edge. Such a pressure plateau was familiar: It was very similar to that which exists over the top surface of an airfoil in low-speed flow when the airfoil stalls at high angle of attack. And it was well known that airfoil stall was caused by the separation of the flow off the top surface of the airfoil. Briggs and Dryden put two-and-two together and concluded that the adverse effects of compressibility were caused by flow separation over the top surface, even though the airfoil was at low (even zero) angle of attack. To substantiate this, they conducted oil-flow tests, wherein a visible, pigmented oil was painted on the model surface, and the model was placed in the high-speed airstream. During the tests, the tell-tale flow separation line formed on the oil pattern. Clearly, beyond the critical speed, flow separation was occurring on the top surface of the airfoil. The next question was: Why? What was causing the flow to separate? The answer to this question still lay eight years in the future.

By 1932, a closed-throat, high-speed wind tunnel with a test section diameter of 11 in. was operating at the NACA Langley Memorial Laboratory in Hampton, Virginia. Also by this time, the top speed of airplanes was getting high enough that compressibility effects on the airframe itself began to be of concern, not just on the propeller. The British Supermarine S.6B had just set the world's speed record of 401.5 mph in 1931. The study of high-speed compressibility effects took on renewed importance within NACA. In 1933, using data measured in the high-speed tunnel, John Stack, soon to become a famous NACA aeronautical engineer, reported the most detailed data to date on the adverse compressibility effects on airfoils.[10] These data, reproduced in Fig. 6, show very clearly the precipitous decrease in lift coefficient and the dramatic increase in drag coefficient as the Mach number is increased above the critical value. Of course, it was now known that these adverse effects were due to the flow separation over the airfoil. But what was causing the flow separation?

John Stack and the NACA were responsible for the answer to this question, a breakthrough that occurred in 1934. By this time, Stack had a new instrument with which to work, a schlieren photographic system, an optical arrangement that made density gradients in the flow visible. One of nature's mechanisms for producing very strong density gradients is a shock wave; hence, a shock wave ought to be visible in a schlieren photograph. Stack's boss, Eastman Jacobs, was familiar with such optical systems through his hobby of astronomy; it was in keeping with Jacob's innovative mind to suggest to Stack that the use of a schlieren system might make visible some of the unknown features of the compressible flowfield over an airfoil and might shed some light on the nature of the compressibility burble. It did just that, and more.

With the 11-in. tunnel running above the critical speed for an NACA 0012 symmetric airfoil mounted in the test section, and with the aid of the schlieren system, Stack and Jacobs observed for the first time in the history of aerodynamics a shock wave in the flow over the top and bottom surfaces of the airfoil. It became immediately clear to these two experimentalists that the separated flow over the top surface of the airfoil, and the resulting compressibility

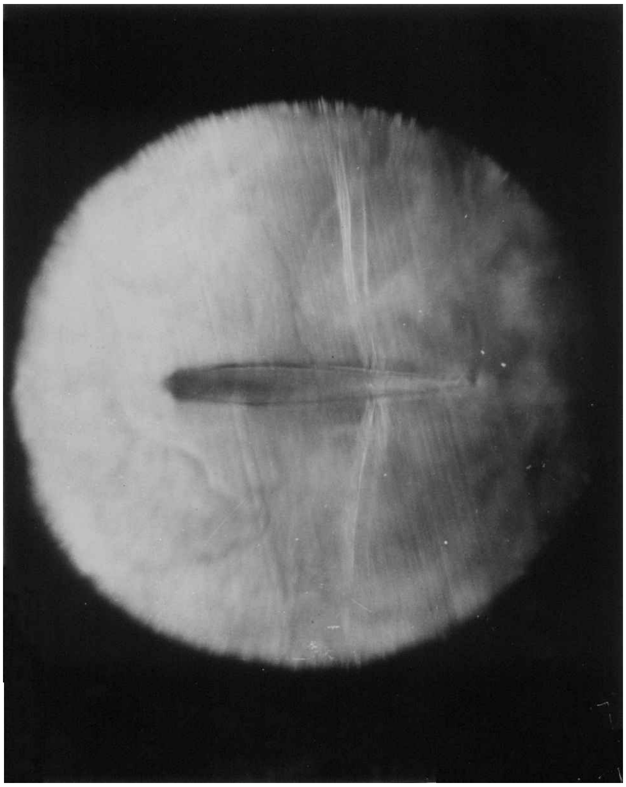

Fig. 7 Schlieren photograph taken by John Stack in 1934 of the shock pattern on an NACA 0012 airfoil in a freestream above the critical speed.

burble with all its adverse consequences, was caused by the presence of a shock wave. One of the pioneering schlieren pictures of the flow over the NACA 0012 airfoil taken by Stack in 1934 is shown in Fig. 7. The quality is poor by present-day standards, but it is certainly sufficient for identifying the phenomenon. This is a historic photograph in the annals of the history of aerodynamics, one which led to the final understanding of the physical nature of the compressibility burble. This was a breakthrough of enormous intellectual and practical importance. And it was totally due to the work of two innovative and highly intelligent aerodynamicists at the NACA Langley Laboratory, John Stack and Eastman Jacobs.

An interesting confluence of events occurred in 1935 that allowed the NACA in a timely fashion to inform the international research community of this intellectual breakthrough in understanding compressibility effects and the compressibility burble. One was the existence of the data itself, fresh, exciting, and revolutionary. The other was the scheduling of the fifth Volta conference in Italy. Since 1931, the Royal Academy of Science in Rome had been conducting a series of important conferences sponsored by the Alessandro Volta Foundation. The first conference dealt with nuclear physics and then rotated between the sciences and the humanities on alternate years. The second Volta conference had the title "Europe," and in 1933 the third conference was on the subject of immunology.

This was followed by the subject "The Dramatic Theater" in 1934. During this period, the influence of Italian aeronautics was gaining momentum, led by General Arturo Crocco, an aeronautical engineer who had become interested in ramjet engines in 1931, and, therefore, was well aware of the potential impact of compressible flow theory and experiment on future aviation. This led to the choice of the topic of the fifth Volta conference, "High Velocities in Aviation." Participation was by invitation only, and the select list included all of the leading aerodynamicists at that time. Because of his reputation in the design and testing of the famous NACA four-digit airfoil series, and the fact that he was the Section Head of the NACA Variable Density Tunnel, which had put the NACA on the international aerodynamic map in the 1920s, Eastman Jacobs received an invitation. He took the opportunity to present a paper on the new NACA compressibility research. Hence, during the period between 20 September and 6 October 1935, the major figures in the development of high-speed aerodynamics of the 1930s (with the exception of John Stack) gathered inside an impressive Renaissance building in Rome that served as the city hall during the Holy Roman Empire and discussed flight at high subsonic, supersonic, and even hypersonic speeds. The fifth Volta Conference was to become the springboard for new thought on the development of high-speed flight.

In the midst of all of this discussion was Eastman Jacobs representing NACA. Jacobs' paper, entitled "Methods Employed in America for the Experimental Investigation of Aerodynamic Phenomena at High Speeds," was both tutorial and informative. He took the opportunity to derive and present the basic equations for compressible flow assuming no friction and no thermal conduction. Then he described the NACA high-speed tunnel, the schlieren system, and the airfoil experiments carried out in the tunnel. Then came the blockbuster. He showed, for the first time in a technical meeting, some of the schlieren pictures taken at Langley Memorial Laboratory. One of these was the photograph shown in Fig. 7. Conscious of the NACA's penchant for perfection, especially in its publications, Jacobs apologizes for the quality of the photographs, a very modest gesture considering their technical (and historical) importance: "Unfortunately the photographs were injured by the presence of bent celluloid windows forming the tunnel walls through which the light passed. The pictures nevertheless give fundamental information in regard to the nature of the flow associated with the compressibility burble." With this, the NACA high-speed research program was not only on the map, it was leading the pack.

Also attending the Volta Conference was von Kármán. In the five years since joining Cal Tech, he had guided the development of GALCIT into arguably the most advanced aeronautical laboratory in any American university. Moreover, von Kármán brought with him the Göttingen and Aachen philosophy of combining science with engineering, making the Cal Tech program the most advanced mathematically and theoretically. However, at the same time, von Kármán appreciated the advantages of interaction with industry, applying theoretical research to practical problems. In this period, the high-performance low-speed wind tunnel at GALCIT attracted work from the major aircraft companies such as Douglas, Lockheed, Consolidated–Vultee, and Boeing. The Douglas DC-1, DC-2, and DC-3 series were tested in this wind tunnel, playing a major role in the excellent performance of these airplanes. (For a case history of the design of the DC-3, and the role played by the GALCIT wind tunnel, see Chapter 8 of Ref. 11.)

In 1931 von Kármán began a theoretical study of the supersonic flow over a projectile, which led to the famous Kármán–Moore minimum drag body shape,[12] published in 1932. As one of the invited attendees at the Volta Conference, it was this work that von Kármán presented to the audience. He was extending the use of the old source–sink superposition method used for flows over airships to the case of supersonic sources and sinks for axisymmetric bodies. While the industry and the NACA were sneaking up on Mach 1, von Kármán was concentrating on what happens above Mach 1.

The general aeronautics community was suddenly awakened to the realities of the unknown flight regime in November 1941, when Lockheed test pilot Ralph Virden could not pull the new, high-performance P-38 out of a high-speed dive and crashed. Virden was the first human fatality due to adverse compressibility effects, and the P-38, shown in Fig. 8, was the first airplane to suffer from these effects. The P-38 exceeded its critical Mach number in an operational dive and penetrated well into the regime of the compressibility burble at its terminal dive speed, as shown by the bar chart in Fig. 9 (Ref. 13). The problem encountered by Virden, and many other P-38 pilots at that time, was that, beyond a certain speed in a dive, the elevator controls suddenly felt as if they were locked. To make things worse, the tail suddenly produced more lift, pulling the P-38 into an even steeper dive. This was called the "tuck-under" problem. (See Chapter 7 of Ref. 14 for more details on the tuck-under problem.) It is important to note that the NACA soon solved this problem, using its expertise in compressibility effects. Although Lockheed consulted various aerodynamicists, including von Kármán at Cal Tech, it turned out that NACA researchers at Langley Memorial Laboratory and Ames Aeronautical Laboratory, with their accumulated

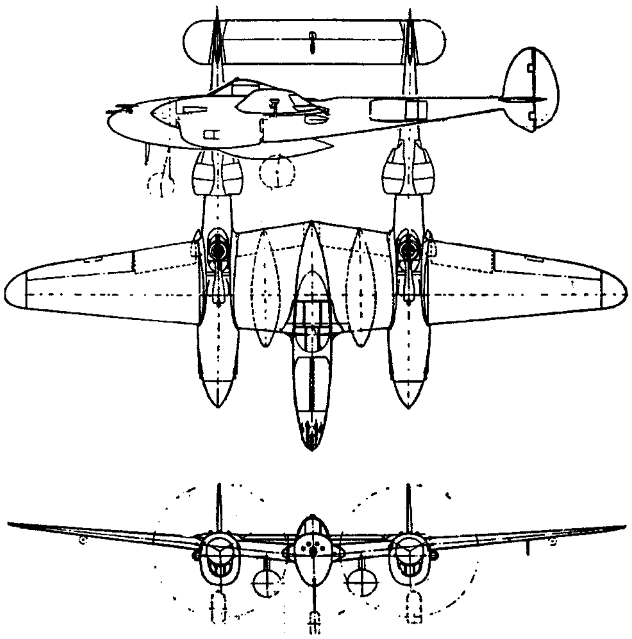

Fig. 8 Lockheed P-38.

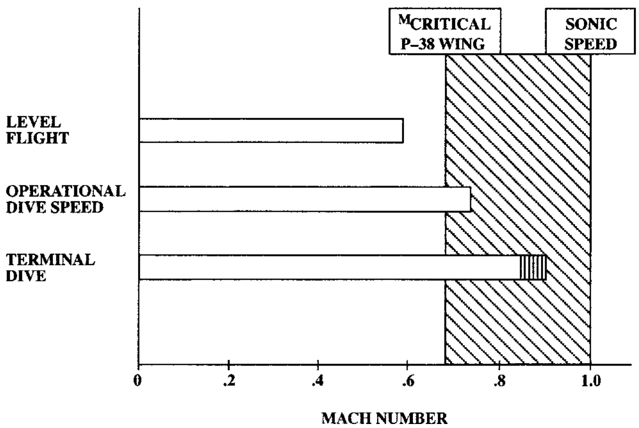

Fig. 9 Bar chart showing the magnitude of how much the P-38 penetrated the compressibility regime.[13]

experience in compressibility effects, were the only ones to properly diagnose the problem. The wing of the P-38 lost lift when it encountered the compressibility burble. As a result, the downwash angle of the flow behind the wing was reduced. This in turn increased the effective angle of attack of the flow encountered by the horizontal tail, increasing the lift on the tail, and pitching the P-38 to a progressively steepening dive totally beyond the control of the pilot. NACA's solution was to place a special flap under the wing, to be employed only when these compressibility effects were encountered. The flap was not a conventional dive flap intended to reduce the speed. Rather, the idea was to use the flap to maintain lift in the face of the compressibility burble, hence eliminating the change in the downwash angle and therefore allowing the horizontal tail to function properly. This is a graphic example of how, in the early days of high-speed flight, NACA compressibility research was found to be vital as real airplanes began to sneak up on Mach 1.

After the Volta Conference, von Kármán returned to the United States with an increased sense of urgency about building supersonic wind tunnels. His efforts to convince the government fell on deaf ears. Finally, in the heat of World War II, Cal Tech received a contract in 1942 to build a supersonic tunnel at the U.S. Army's Aberdeen Proving Ground in Maryland. With a rectangular test section of 15 by 20 in., it became, in von Kármán's words, "the first large superspeed tunnel of its kind in the United States."

In Ref. 7 von Kármán recalls the P-38 tuck-under problem, and how he was consulted by Lockheed engineers with questions about its nature. He diagnosed it as a compressibility problem. He makes no comment about ideas for possible solutions and says nothing about the NACA's role in the final fix.

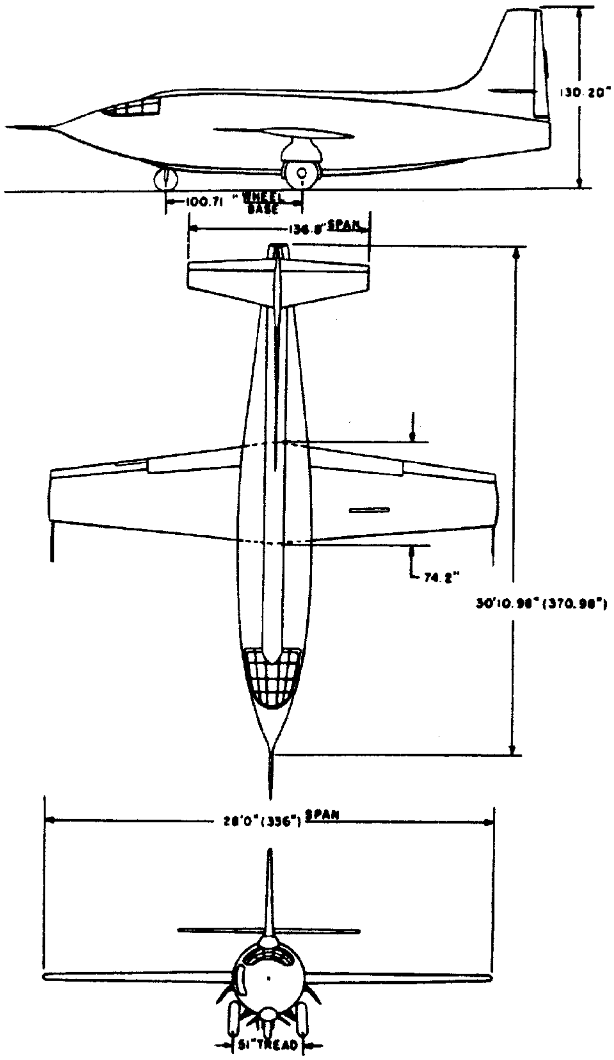

Fig. 10 Bell X-1.

Toward the end of World War II, the invention of the jet engine was making high-speed flight near Mach 1 a reality. It was inevitable that airplanes would eventually fly faster than the speed of sound. This became a reality on 14 October 1947, when the Bell X-1 with Chuck Yeager at the controls flew at Mach 1.06, the first airplane to break the sound barrier in level flight (Fig. 10). Designed with the help of the accumulated knowledge discussed earlier, the aeronautical engineering community had finally sneaked up to, and exceeded, flight at Mach 1.

During World War II, von Kármán became ensconced as the U.S. Army Air Force's chief technical advisor. A long-time friend of Gen. Hap Arnold, von Kármán shared the absolute trust of the general of the U.S. Air Force. During the war, von Kármán established at Cal Tech the first substantive graduate courses on compressible flow and high-speed aerodynamics. But as time progressed, he spent less time on the campus and more time traveling as the nation's leading consultant in aeronautics. In 1945 he was the chief architect of a U.S. Air Force study entitled Toward New Horizons; *this document set the future technological course for the U.S. Air Force for the next two decades. (For an interesting and detailed discussion of von Kármán's interaction with the U.S. Air Force, see Ref. 15.)*

Transonic and Supersonic Flight

Along with the jet engine, it was the development of swept wings that made transonic and supersonic flight practical. The idea of using swept wings for high-speed airplanes was first advanced by the German aerodynamicist Adolf Busemann at the Volta Conference

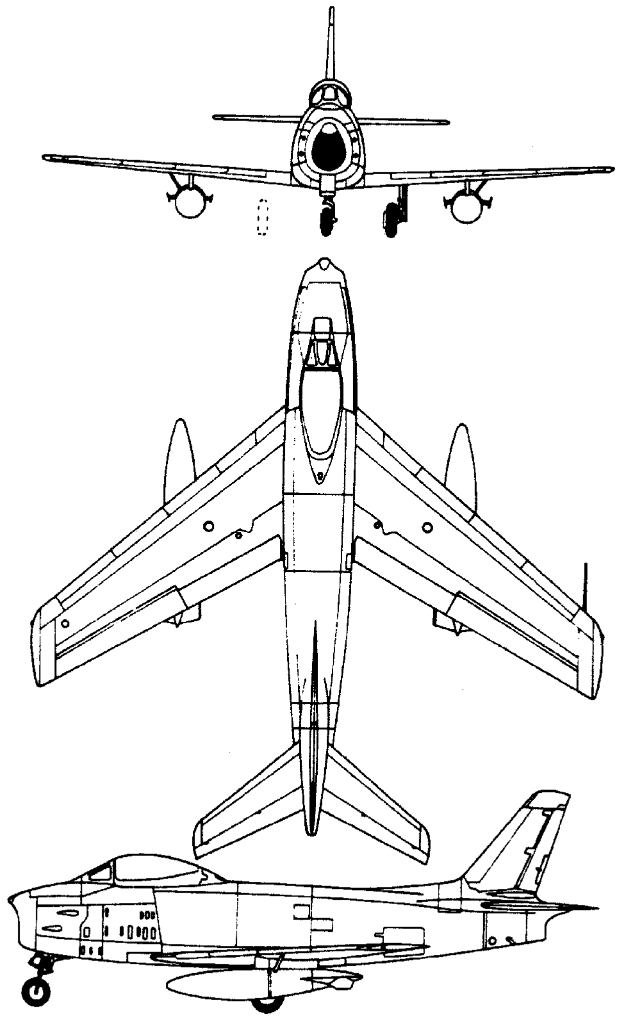

Fig. 11 North American F-86.

in 1935; he was thinking of their application to supersonic flight. Little attention to this concept was paid by the American attendees, including von Kármán, who essentially forgot about it until much later. However, during the war, Germany carried out extensive wind-tunnel research on swept wings for both transonic and supersonic applications. The swept wing was independently conceived in the United States by R. T. Jones in 1945. The work by Jones, along with the concurrent discovery of the massive amount of swept-wing data in Germany after V-E Day, resulted in the aggressive decision by North American to design a swept-wing fighter, the F-86 (Fig. 11), and by Boeing to build a swept-wing bomber, the B-47. Both of these airplanes were in existence by 1947, the same year that the Bell X-1 broke the sound barrier. Unfortunately, we do not have the space remaining in this paper to tell the complete story of the development of the swept-wing concept, with all its excitement and intrigue. See Ref. 1 for the details.

On April 18, 1947, von Kármán walked into the auditorium of the U.S. Chamber of Commerce in Washington, D.C., and delivered the prestigious Tenth Wright Brothers Lecture at the Institute of the Aeronautical Sciences. Entitled "Supersonic Aerodynamics—Principles and Applications," (Ref. 16), this paper was an encompassing survey of supersonic flow, both theory and experiment. In 1947, it represented a high-water mark in the development of the basic ideas in supersonic aerodynamics. In retrospective, what has been accomplished since then can be viewed as just filling in the details. In the comments from the audience after von Kármán's presentation, we can get a feeling for the situation. For example, Capt. Walter S. Diehl, the most respected aeronautical engineer in the Navy's Bureau of Aeronautics declared: "It will come to many as a pleasant surprise to find that so much is already known regarding flow conditions at supersonic speeds. All of those who work with supersonic aerodynamics owe a debt of gratitude to Dr. von Kármán for his lecture." W. Bailey Oswald, Chief Aerodynamicist for the Douglas Aircraft Company and the man responsible for the aerodynamics of the famous DC-3, stated after the lecture "Today we have more basic knowledge of the aerodynamics of supersonic flight than that available in subsonic flight to the pioneers in aviation."

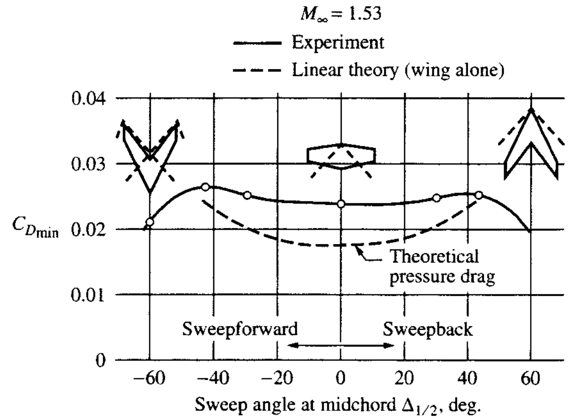

Fig. 12 Effect of wing sweep on supersonic drag. Data by Vincenti (Ref. 17).

In 1947, NACA's first large supersonic wind tunnel was in operation at the Ames Aeronautical Laboratory, with a 1 by 3 ft test section and a Mach number range from 1.4 to 2.2. This tunnel is worth special notice, because in it Walter G. Vincenti, a young NACA aeronautical engineer, carried out the first definitive study of wing planform shapes for supersonic flight (Ref. 17). This study identified two extremes for planform shape to reduce wave drag at supersonic speeds. One is to use a low aspect ratio straight wing, the design feature chosen later for the Lockheed F-104 Mach 2 fighter. The other is a swept wing, with the leading edge swept inside the Mach cone. The effect of wing sweep angle on wave drag is shown by Vincenti's data given in Fig. 12; the freestream Mach number was 1.53, and the definite reduction in drag when the wing is either swept back or swept forward by more than 49 deg (inside the Mach cone) is clearly evident. Vincenti's work, originally carried out in 1946–1947, was initially classified and was not published until 1949 (Ref. 17).

Hypersonic Flight

Faster and higher, for all practical purposes, this has been the driving potential behind the development of aviation since the Wrights' first successful flight in 1903. This credo was never more true than during the 15 years following Chuck Yeager's first supersonic flight in the Bell X-1. Once the sound barrier was broken, it was left far behind in the dust. The next goal became manned *hypersonic* flight, Mach 5 and beyond. This goal was achieved on 23 June 1961, when U.S. Air Force Maj. Robert White flew the X-15 at Mach 5.3 and in so doing accomplished the first "mile-per-second" flight in an airplane.

Hypersonics is the last frontier in high-speed flight. The extension of this frontier is still going on as I write these words. Unfortunately, we are out of space in this paper, and I regret that I can not continue with the story of the development of hypersonics, a subject near and dear to my heart. Let me refer you to Ref. 18 for a brief history and general technical development of hypersonic flow.

Epilog

In the postwar years, von Kármán went on to form AGARD, the Advisory Group for Aeronautical Research and Development, as part of NATO. Also, in 1958 he helped to establish an international training center for experimental aerodynamics in Belgium, which is now the highly respected von Kármán Institute for Fluid Dynamics.

On 6 May 1963 von Kármán died in Aachen of heart failure, five days before his 82nd birthday. His lifetime had witnessed the whole spectrum of flight, from the Wright Flyer to the hypersonic X-15. It is appropriate to end this paper with two "von-Kármánisms," taken from his autobiography[7]:

"Science is not something whose truths we can absolutely believe. The moment we cannot explain some phenomenon with the laws we have obtained up to now, we have to change these laws and find some new ones that fit."

"One finds that in the history of science almost every problem has been worked on by somebody else. This should not discourage anyone from pursuing his own path."

References

[1]Anderson, J. D., Jr., *A History of Aerodynamics and Its Impact on Flying Machines*, Cambridge Univ. Press, New York, 1997 (hardback) and 1998 (paperback).

[2]Anderson, J. D., Jr., "Research in Supersonic Flight and the Breaking of the Sound Barrier," *From Engineering Science to Big Science*, edited by P. E. Mack, NASA History Series, NASA SP-4219, 1998, Chap. 3, pp. 59–90.

[3]Newton, I., *Philosophiae Naturalis Principia Mathematica*, Book II, Proposition 50, London, 1687; revised translation by F. Cajori, Univ. of California Press, Berkeley, CA, 1947.

[4]de Laplace, P. S., "Sur la Vitesse du son dans l'aire et dan l'eau," *Annales de Chimie et de Physique*, 1816.

[5]Anderson, J. D., Jr., *Modern Compressible Flow: With Historical Perspective*, 2nd ed., McGraw–Hill, New York, 1990.

[6]Stodola, A. B., *Steam Turbines*, translated by L. C. Loewenstein, Van Nostrand, New York, 1905; originally published as *Die Dampfturbinen*, Velag von Julius Springer, Berlin, 1904.

[7]von Kármán, T., and Edson, L., *The Wind and Beyond*, Little, Brown and Co., Boston, 1967.[†]

[8]Caldwell, F. W., and Fales, F. M., "Wind Tunnel Studies in Aerodynamics Phenomena at High Speed," NACA TR 83, 1920.

[9]Briggs, L. J., and Dryden, H. L., "Pressure Distributions Over Airfoils at High Speeds," NACA TR 255, 1926.

[10]Stack, J., "The NACA High-Speed Tunnel and Tests of Six Propeller Sections," NACA TR 463, 1933.

[11]Anderson, J. D., Jr., *Aircraft Performance and Design*, McGraw–Hill, Boston, 1999.

[12]von Kármán, T., and Moore, N. B., "Resistance of Slender Bodies Moving with Supersonic Velocities, with Special Reference to Projectiles," *ASME Transactions*, Vol. 34, 1932, pp. 303–310.

[13]Foss, R. L., "From Propellers to Jets in Fighter Aircraft Design," *Diamond Jubilee of Powered Flight: The Evolution of Aircraft Design*, edited by J. Pinson, AIAA, New York, 1978, pp. 51–54.

[14]Anderson, J. D., Jr., *Introduction to Flight*, 4th ed., McGraw–Hill, Boston, 2000.

[15]Daso, D., *Architects of American Air Supremacy: General Hap Arnold and Dr. Theodore von Kármán*, Air Univ. Press, Maxwell AFB, AL, 1997.

[16]von Kármán, T., "Supersonic Aerodynamics—Principles and Applications," *Journal of the Aeronautical Sciences*, Vol. 14, No. 7, 1947, pp. 373–409.

[17]Vincenti, W. G., "Comparison Between Theory and Experiment for Wings at Supersonic Speeds," *Second International Aeronautical Conference*, edited by B. H. Harck, Inst. of the Aeronautical Sciences, New York, 1949, pp. 534–555; also NACA TR 1033, 1951.

[18]Anderson, J. D., Jr., *Hypersonic and High Temperature Gas Dynamics*, McGraw–Hill, New York, 1989; reprinted by AIAA, Reston, VA, 2000.

G. M. Faeth
Editor-in-Chief

[†]This is von Kármán's autobiography, published posthumously.