engine of 1490 horsepower; by comparison, one of the highest performance fighters in use at the end of World War I, the 1807-pound SPAD XIII C.1 (chapter 2), had a drag area of 8.33 square feet (a circular disc 3.26 feet in diameter) and was powered with a 200-horsepower engine. The corresponding values of the ratio of power to drag area are 392.11 and 24.01, respectively. Also contributing significantly to the large increases in maximum speed were the development of the supercharger and controllable-pitch propeller, both of which permitted efficient high-power flight in the low-density, high-altitude environment. No increases in the maximum speed of operational propeller-driven aircraft have been achieved since the end of World War II because of the inherent limitations imposed by the effects of compressibility on the efficiency of conventional propellers.

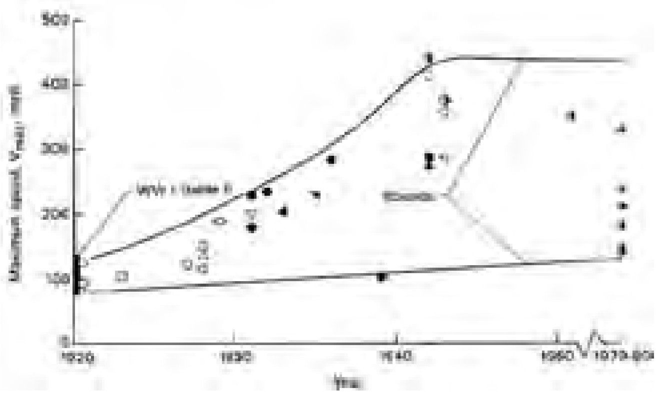


Figure 7.2 - Trends in maximum speed of propeller-driven aircraft.

The lower bound in figure 7.2 shows an increase in maximum speed from about 80 miles per hour to about 130 miles per hour. This bound indicates a continued desire for low-performance aircraft throughout the years. The general aviation aircraft of today are seen to encompass a range of maximum speed from about 130 miles per hour to almost 350 miles per hour, which indicates the wide range of technical sophistication in contemporary propeller-driven aircraft.

Although not shown in the data presented in figure 7.2, the performance of representative, specially built, propeller-driven racing aircraft through the years may be of some interest and is indicated as follows:

1. 1913, absolute speed record of 126.64 miles per hour established by French Deperdussin landplane

2. 1920, absolute speed record of 194.49 miles per hour established by French Nieuport 29V landplane

3. 1923, absolute speed record of 267.16 miles per hour established by American Curtiss R2C-1 landplane

4. 1927, absolute speed record of 297.83 miles per hour established by Italian Marcchi M-52 seaplane

5. 1931, absolute speed record of 406.94 miles per hour established by British Supermarine S-6B seaplane

6. 1934, absolute speed record of 440.60 miles per hour established by Italian Marcchi-Castoldi MC-72 seaplane (This record for propeller-driven seaplanes still stands and is unlikely to be surpassed in the near future.)

7. 1938, absolute speed record of 469.22 miles per hour established by German Messerschmitt 209VI landplane

8. 1969, absolute speed record of 483.04 miles per hour established by highly modified American Grumman F8F landplane

The world speed records cited above are officially recognized by the Federation Aeronautique Internationale and were established under sea-level flight conditions.

STALLING SPEED, WING LOADING, AND MAXIMUM LIFT COEFFICIENT

The stalling speed, wing loading, and maximum lift coefficient are shown as a function of years for various aircraft in figures 7.3, 7.4, and 7.5. The short, unpaved fields that served as airports in the early 1920's, together with the relatively poor flying characteristics of aircraft of that period, dictated the necessity for low values of the stalling speed. Values of the stalling speed of 40 to 50 miles per hour were not unusual, although precise data are not shown in figure 7.3 for the year 1920. High-lift devices were essentially unknown at that time; hence, the wing loadings needed to give the low values of the stalling speed were correspondingly low, as shown in figure 7.4. Values of the wing loading from 5 to 10 pounds per square foot were typical, and the 14-pound wing loading of the DH-4 was considered high in 1920. For a given atmospheric density, the wing loading is, of course, related to the square of the stalling speed by the value of the wing maximum

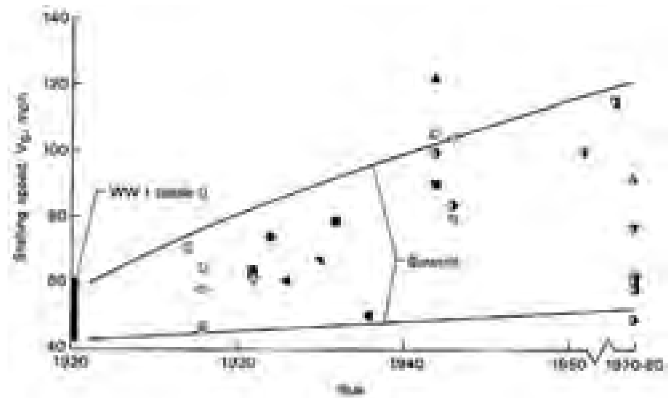


Figure 7.3 - Trends in stalling speed of propeller-driven aircraft.

lift coefficient. Values of the maximum lift coefficient slightly in excess of a value of 1 were typical of unflapped aircraft with thin airfoil sections in 1920, as shown in figure 7.5. The demands for increased high-speed performance resulted in increases in wing loading and, hence, increases in the stalling speed. By the time of World War II, the stalling speeds of high-performance military aircraft were in the range of 80 to 100 miles per hour; wing loadings were in the range of 40 to 60 pounds per square foot. The development and the associated use of powerful high-lift devices, such as described in chapter 5, resulted in aircraft maximum lift coefficients of the order of 2.0 to 2.5 for high-performance aircraft in the World War II period. These high-lift devices, and consequent high maximum lift coefficient, prevented the stalling speed from increasing to an even greater extent than that shown in figure 7.3. Since World War II, the stalling speed of high-performance aircraft has continued to increase and is seen in figure 7.3 to be 115 miles per hour for the contemporary Lockheed C-130 cargo transport. The wing loading for this aircraft is about 90 pounds per square foot, as shown in figure 7.4, and the maximum lift coefficient is about 2.75. The highest maximum lift coefficient of any of the aircraft for which data are shown in figure 7.5 is about 3.0 and was obtained by the Lockheed Model 1049G Constellation. The corresponding wing loading for this aircraft is about 80 pounds per square foot. The high maximum lift coefficient of the Constellation gave a relatively slow stalling speed of about 100 miles per hour.

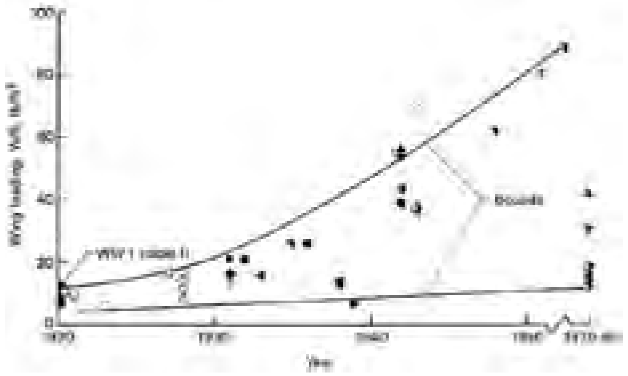


Figure 7.4 - Trends in wing loading of propeller-driven aircraft.

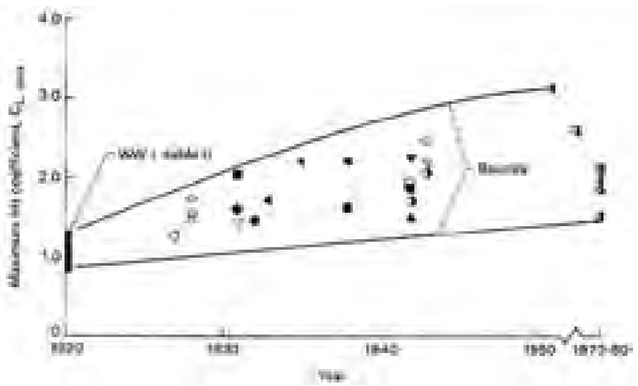


Figure 7.5 Trends in maximum lift coefficient of propeller-driven aircraft.

The lower bounds in figures 7.3, 7.4, and 7.5 show modest increases in stalling speed, wing loading, and maximum lift coefficient for aircraft of relatively low performance. The data for current general aviation aircraft show a wide spread in level of technology, insofar as maximum lift coefficients are concerned, and a wide range of values of stalling speed and wing loading. Values of maximum lift coefficient for these aircraft vary from about 1.3 to about 2.2. The higher values of maximum lift coefficient achieved by current high-technology general aviation aircraft are about the same as those of military aircraft in World War II. The wing loading and stalling speeds of the high-performance general aviation aircraft of today are also seen to be in the same order as those of World War II military aircraft.

POWER LOADING

The power loading data shown in figure 7.6 appear to have nearly constant values for the upper and lower bounds. Within these bounds, the transport and bomber-type aircraft have power loadings that vary from about 12 pounds per horsepower in 1928 to 8 to 10 pounds per horsepower by the 1950's. Low-performance aircraft have a higher upper bound value of the power loading of about 16 pounds per horsepower although the venerable Piper Cub J-3 had a power loading value of about 19 pounds per horsepower. The lower bound of the power loading is formed by fighter aircraft, which tend to have power loadings in the range from 5 to 6 pounds per horsepower. These low values of power loadings have, through the years, been dictated by the rate of climb and maneuvering performance characteristics required in fighter-type aircraft. Present-day general aviation aircraft have power loadings that vary from nearly 16 pounds per horsepower for the very low-performance type of pleasure or training aircraft to about 8 pounds per horsepower for the high-performance Beech King Air 200 (at low altitude).

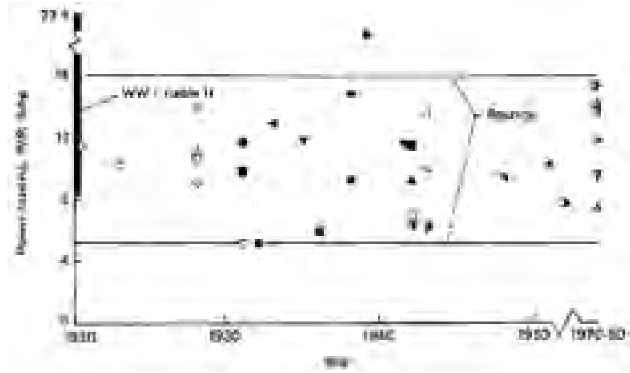


Figure 7.6 Trends in power loading of propeller-driven aircraft.

ZERO-LIFT DRAG COEFFICIENT AND SKIN FRICTION PARAMETER

The value of the zero-lift drag coefficient $C_{D,0}$ is often used as an indicator of the aerodynamic cleanness or refinement of an aircraft. Values Of $C_{D,O}$ calculated according to the methods of appendix C are shown as a function of years in figure 7.7. The lower bound of $C_{D,0}$ drops sharply from a value of about 0.040 in 1920 to a value of about 0.021 in the early 1930's. A smaller reduction in the lower bound values

Of $C_{D,0}$ took place in the years between the early 1930's and the years of World War II. The general aviation aircraft of today show a spread in the values Of $C_{D},_{O}$ from near the upper bound to near the lower bound. The lower bound curve shows the dramatic reduction in $C_{D,0}$ that accompanied the basic change in airplane configuration from a strut-and-wire-braced biplane with a fixed landing gear to the highly streamlined, internally braced monoplane with retractable landing gear. As indicated in chapter 4, this transformation had largely taken place for high-performance operational aircraft by the early 1930's. Detailed aerodynamic refinements such as described in chapter 5 were responsible for further improvements in aerodynamic efficiency as indicated by the lower bound curve. The zero-lift drag coefficient, although useful as a measure of comparative aerodynamic refinement, has a basic limitation because the coefficient is based on wing area, and, for a given wing area, many different fuselage and tail sizes may be employed. Thus, differences in zero-lift drag coefficients may be interpreted as a difference in aerodynamic refinement when the difference may result from a significant difference in the ratio of wetted area to wing area.

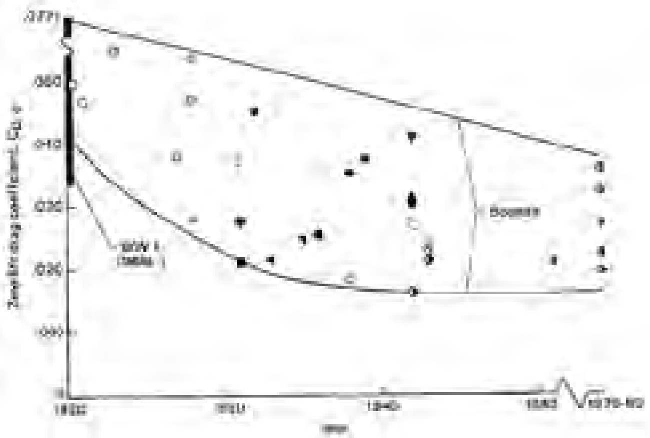


Figure 7. 7 - Trends in zero-lift drag coefficient of propeller-driven aircraft.

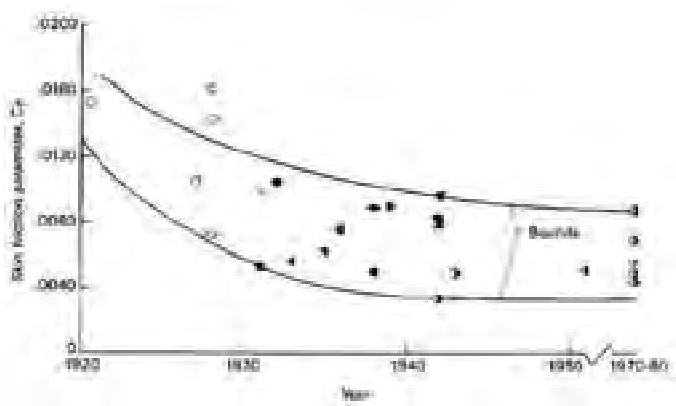


Figure 7.8 - Trends in skin friction Parameter C_F, {ptr: line over C} of propeller-driven aircraft. [ref. 90].

In order to remove the effect of variations in the ratio of wetted area to wing area, a zero-lift drag coefficient based on total wetted area rather than wing area was estimated in reference 90 for most of the aircraft for which drag data are given in figure 7.7. The reference area for

this coefficient, termed the skin friction parameter C_F {ptr: line over C} consisted of the total surface area of the fuselage, wings, and tail surfaces. The parameter C_F {ptr: line over C} was obtained from multiplication of $C_{D},_{O}$ {ptr: line over C} by the ratio of wing area to total wetted area. Values of C_F, {ptr: line over C} taken from reference 90 are shown as a function of years in figure 7.8. The upper and lower bounds of the data show the same trends as do those for the zero-lift drag coefficient shown in figure 7.7. The lower bounds of the skin friction parameter indicate that essentially no progress has been made in reducing C_F {ptr: line over C} since World War II, and little progress has been made since the early 1930's. The data for the current general aviation aircraft fall generally between the upper and lower bounds but do not reach as low a value as that of the lower bound curve. This suggests that these aircraft can be refined to a value at least as low as that achieved during World War II. There is little likelihood, however, that values of C_F {ptr: line over C} significantly lower than the lower bound shown in figure 7.8 can be achieved unless some breakthrough is made that permits the achievement of a significant extent of laminar flow on the aircraft. Other than reductions in the value of the skin friction parameter, future reductions in the airplane zero-lift drag coefficient $C_{D,O}$ {ptr: line over C} can perhaps be achieved through configuration design aimed at reducing the ratio of wetted area to wing area. The pure flying wing represents the ultimate improvement by this means.

MAXIMUM LIFT-DRAG RATIO

The maximum lift-drag ratio of the various aircraft was calculated according to the methods described in appendix C and is shown as a function of years in figure 7.9. The value of the maximum lift-drag ratio $(L/D)_{max.}$ is a measure of the aerodynamic cruising efficiency of the aircraft. The upper bound of $(L/D)_{max}$ varies from values of about 9 in 1920 to a value of 16.8 for the World War II Boeing B-29 and 16.0 for the Lockheed 1049G in 1952. The $(L/D)_{max}$ upper-bound curve shows a sharp rise between 1920 and the early 1930's, which corresponds to the reduction in zero-lift drag coefficient shown in figure 7.7 and to the emergence of the monoplane with its higher aspect ratio as compared with the biplane. Little change in maximum L/D has taken place since the end of World War II. Any further increases in maximum lift-drag ratio will require reductions in the value of the zero-lift drag coefficient and/or increases in wing aspect ratio that may be possible through the use of improved structural materials.

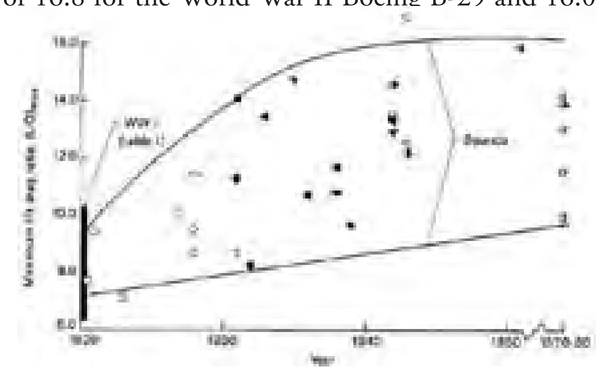


Figure 7.9 - Trends in maximum lift-drag ratio of propeller-driven aircraft.

Chapter Four

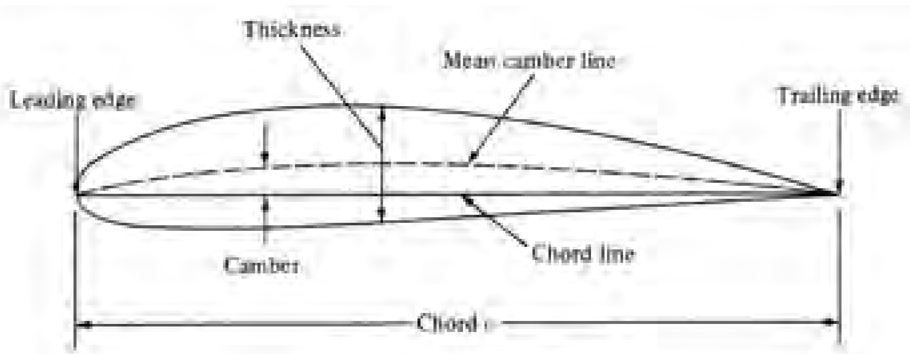
On the Wing

Destination Document:

Historical retrospective from aeronautical engineer Ed Rees of North American Aviation, Inc., in "A Tribute to Dutch Kindelberger: The Mustang—A Great War Horse," The Airpower Historian [9] (Oct. 1962): 201.

The design touchstone of the Mustang was the laminar flow wing, a high-lift, low-drag airfoil developed by the National Advisory Committee for Aeronautics (NACA) and considered by most engineers as being too revolutionary for use in a mass-produced airplane. The chiefs of the aerodynamics sections believed in it so thoroughly that they promised in case of failure to produce a conventional wing within 30 days. Since wing design is the toughest of all components and usually determines the schedule for the rest of the design job, the entire project hung tenuously on the then-unproven laminar flow concept.

"The Bird is on the Wing" is a well-known line from Edward Fitzgerald's 1859 translation of *The Rubaiyat of Omar Khayyam*, written in the late 11th century. The medieval Persian poet refers metaphorically to the fleeting "Bird of Time," which "has but a little way to fly," and certainly not to anything practical about the actual technology of flying—not even to flying carpets. Still, from an engineering perspective, nothing could be truer about the mechanics of flight. The essence of an



Basic to airfoil geometry are the coordinates of the upper and lower surface, as well as such parameters as maximum thickness, maximum camber, position of maximum thickness, position of maximum camber, and nose radius. From the beginning of airfoil research and development, aeronautical engineers and aircraft designers generated airfoil sections simply by adjusting these parameters. Over the years, these adjustments became more and more analytical and systematic. Courtesy of John D. Anderson, Jr.

airplane is unquestionably its wing; it is what the "bird" is all about. Designed to lift the machine up into the air and sustain its flight, it is the structure that performs the most basic, required functions; it also embodies the most aesthetic and ethereal aspect of the airplane's overall form and function.

Designing a highly effective wing for a particular aircraft requirement has proven over the decades to be one of the most challenging tasks facing aerodynamicists. More theoretical work and experimental energy has gone into exploring the complexities of wing design than into the delineation of any other aerodynamic component, and none has brought greater dividends. Similarly, nowhere in aeronautical technology has "engineering as artistry" been more evident than in the creative process of designing wing shapes. Higher mathematics and the most advanced wind tunnels have systematically explored the mysterious interactions between wing shapes and airflows, but aesthetic considerations have played a vital role in wing design even into the modern electronic age of the high-speed computer.

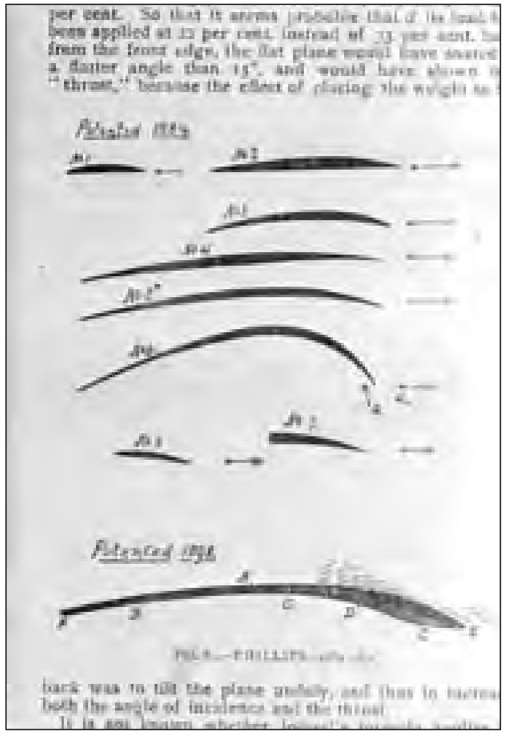
As the last line of the Destination Document for this chapter suggests, whether it is for a fabulously successful airplane like the P-51 Mustang of World War II fame or for some miserable failure of a machine (and there have been more than a few in aerospace history), the wing has proven to be not only the toughest of all aerodynamic components to design but also the one on which the ultimate fate of most aerodynamic configurations has depended. It should be obvious why, in a documentary study of aerodynamic development, the history of the evolution of the wing should be singled out. So much about the progress of aeronautics from before the Wright brothers to the present has depended fundamentally upon determining ever more effective airfoil shapes for various wing applications.

No era of aeronautical history witnessed more rapid improvement in airfoil design than the period from the mid-1920s into the early years of World War II. In a little over a decade's time, as the propeller-driven airplane reached its mature (and some might argue, ultimate) form, the wings of the world's airplanes evolved from intuitively derived, cut-and-try, and aerodynamically primitive shapes into advanced streamlined, highly reliable, and sometimes counterintuitive structures that were systematically engineered, a great number of them in the NACA laboratory. Demonstrating how that critical evolution took place, and how the NACA's research program contributed to it from the 1920s into World War II, is the main purpose of this chapter's documentary collection. More specifically, the drama of the chapter is provided by the NACA's quest for the so-called laminar flow airfoil, the aerodynamicist's dream of the ultimate low-drag wing that would enable a streamlined aircraft to fly more aerodynamically "pure" than ever before.

As the reader will see in the collection of documents to come, the path to the achievement of laminar-flow wings by the NACA, to the limited extent they *were* achieved, was anything but simple or straight. Like the search of medieval alchemists to turn base metal into gold, or anyone else looking for the pot of gold at the end of a rainbow, the quest of NACA aerodynamicists for a wing that would possess

the many advantages of laminar flow was full of adventure, promise, and expectation of final achievement. In the end, however, it fell short of its lofty goal, a critical disappointment, made worse for those most directly involved by the exaggerated claims and hype that the NACA and other American aviation publicists had made for the endeavor along the way.

To place the NACA's laminar flow airfoil development in full historical context, one must go back to the history of wing section research and aerodynamic development more generally, starting right after the Wright brothers.[1]



The first serious work on the development of airfoil sections began in the 1880s. Although earlier experimenters had shown that flat plates produced lift when set at an angle of incidence, some suspected that shapes with curvature more closely resembling bird wings would produce more lift. British experimenter Horatio F. Phillips (1845-1912) patented a series of more highly cambered airfoils after testing them in a wind tunnel he had built. He continued to patent curved airfoils into the 1890s. National Air and Space Museum, Smithsonian Institution (SI A-32247-D)

Even with the Wright brothers' experience with airfoils in mind, the earliest airplane designers possessed such scanty knowledge of aerodynamics that they could do little more than guess at how any sort of lifting surface they drew up would actually perform in flight. Common sense and observation of the long graceful wings of many large birds in flight suggested that efficient wings needed to be long and slender so as to use as much air as possible to support the carrying weight. Moreover, the proven successes of the wing shapes employed by Lilienthal, Langley, and especially the Wrights indicated that a certain amount of wing curvature (or camber) gave much more satisfactory results than did flat surfaces. Thus, airplane designers of the early 20th century followed the lead of the inventors of the airplane and went with the long, thin wing. This shape complicated the actual construction of the airplane, of course, because a long, slender wing arrangement could only be accomplished structurally at the time by employing a deep truss. Typically,

[1] Significant parts of the introductory essay to follow derive from James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958*, NASA SP-4305 (Washington, 1987), by permission of the author.

Octave Chanute understood the importance of wing shape for flight. In 1893 he wrote that "it seems very desirable that further scientific experiments be made on concavo-convex surfaces of varying shapes, for it is not impossible that the difference between success and failure of a proposed flying machine will depend upon the sustaining effect between a plane surface and one properly curved to get a maximum of 'lift'." National Air and Space Museum, Smithsonian Institution (SI 84-10696)

this type of construction meant a biplane arrangement involving an aerodynamically messy array of supporting wires and struts bracing two sets of wings. Only a very minor degree of streamlining was achieved, which was done not by delineating improved airfoil shapes but simply by enclosing the framework of a wing completely rather than by just covering it with a single stretched-tight cloth surface on one side, as had been the case with the pioneering gliders and airplanes.

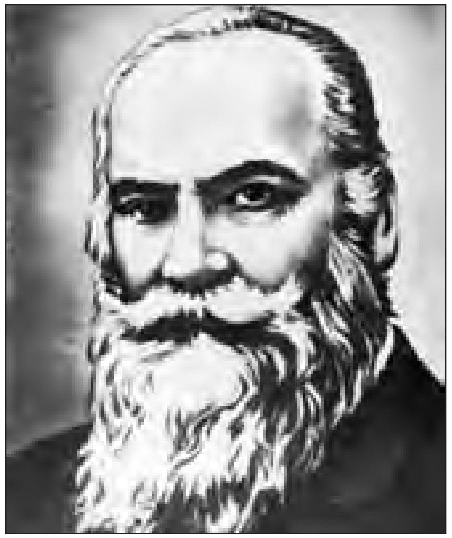
Some basic theory that would later prove extremely helpful to the understanding of lifting surfaces developed early in the century, but few airplane builders or others interested in the practical engineering of airplanes knew of it—or knew enough higher mathematics to take advantage of this information. In an article first published in Germany in 1912, but not available in the United States until after World War I, Professor Ludwig Prandtl at the University of Göttingen proposed what came to be known as the "lifting-line theory." (Prandtl was influenced in this hypothesis by the earlier work of England's Frederick W. Lanchester, who in key respects initiated the first great age of theoretical aerodynamics in the 1890s with his concepts—rejected by fellow scientists at the time—of how lift was generated in relation to a circulatory flow about an airfoil and how trailing vortices at the tips of wings caused drag, what later became known as "induced drag.") Without delving into the complexities of the mathematics involved, what the lifting-line theory did was quantify the study of a wing (or any other type of airfoil, whether it was a propeller blade, tail fin, or a rudder) by permitting its "characteristics" to be segregated into two elements that could be considered separately: those intrinsically associated with the shape of the wing (cross-) section and those associated with

Designing "by eye" and without any attempt at systematization, Louis Blériot was able to increase curvature over the forward part of the wing section of his historic number 11 airplane. The added wing camber in that location helped the airplane to make its historic crossing over the English Channel in 1909. National Air and Space Museum, Smithsonian Institution (SI 78-14792)

the wing planform (the outline of the wing when viewed from above) or twist (any varying angles of attack along its span or length). With greater knowledge of wing section characteristics in mind, the aerodynamicist could then calculate roughly the angle of zero lift, the lift curve slope, the span loading, the drag for high speed and cruise conditions, and the maximum lift coefficient and stalling characteristics. Lifting-line theory did not work for every performance parameter of a wing, and generalized solutions of the equations were far too complex for complete answers. Nonetheless, aerodynamicists following Lanchester's and Prandtl's lead were able to provide some useful approximations and began to pursue studies of their own that eventually promoted a greatly enriched mathematical understanding of how wings worked and how their shapes might be improved.

Wing sections of different outlines, thicknesses, and curvatures began to proliferate in the 1910s, and virtually all of them were designed "essentially by eye and without any attempt at systematization."[2] In this manner, Frenchman Louis Blériot was able to increase the curvature over the forward part of his wing section successfully, which helped his airplane to make its historic crossing of the English Channel in 1909. Similarly, between 1912 and 1915, British engineers at the fledgling Royal Aircraft Factory managed to design a series of practical airfoils, some of them made thicker and with a rounder leading edge and sharper trailing edge, resulting in slightly improved aerodynamic performance. In truth, though, the Royal Aircraft Factory engineers evolved their shapes principally with structural considerations in mind rather than any novel aerodynamic insight. Designers in the United States followed the British lead, either copying the dimensions of a superior R.A.F section exactly (notably R.A.F, 6 or 15) or modifying one only slightly, as in the case

[2] Clark B. Millikan, *Aerodynamics of the Airplane* (New York: John Wiley & Sons, 1941), p. 66.

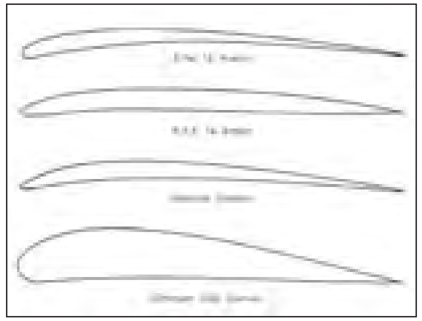


An equation derived independently by Martin E. Kutta and Nikolai Joukowsky (Zhukovsky) between 1902 and 1906 allowed the lift of an airfoil to be calculated for the first time with mathematical precision. In notes published in Russian and French journals in 1906, Joukowski (1847-1921) calculated the lift per unit span of an airfoil by using the following relationship, $L = \rho V \Gamma$, where L is lift and is Γ is the circulation of air around an airfoil. In Joukowski's derivation, the latter was a quantity equal to the line integral along a closed curve of the velocity resolved along that curve. The most important historical point to remember about this equation is that it represented a revolutionary development in theoretical aerodynamics, one that enabled the precise calculation of an airfoil's lift. National Air and Space Museum, Smithsonian Institution (SI 83-7699)

of the United States Army's most effective wing shape of the World War I era, the U.S.A. 27.

Still, bias for the thin wing persisted. Empirical test methods reinforced it. Because the small, atmospheric wind tunnels of the early years were incapable of testing at anything but low Reynolds numbers, their data showed that thin, highly cambered (or arched) wing sections had the most favorable properties. At low Reynolds numbers, airflow over thick sections "separated" early and resulted in unsatisfactory performance. Furthermore, especially in America, there was always the memory that the Wrights had achieved their historic flight in 1903 with a long, slender airfoil. Convinced that the longest span with the thinnest sections generated the greatest lift, some German propeller designers even went so far as to make their blades from mere fabric stretched by centrifugal force. Nearly all World War I aircraft, with the important exceptions of some advanced German aircraft designed by Junkers and Fokker, employed extremely thin wings requiring for external strength and rigidity a messy conglomeration of wires, struts, and cables. Junkers and Fokker tried thicker wing sections in a few of their aircraft, in part because the leading German aerodynamical laboratory at Göttinger was recommending them in confidential wartime reports.

It is hardly surprising that the world's first systematically engineered wing sections developed at Prandtl's Göttingen laboratory, the institution where advanced aerodynamic theory and premiere wind tunnel technology met really for the first time anywhere—doing so early in World War I, just in time for use by the German air force. Göttingen based its wing sections, interestingly, on a family of shapes derived mathematically by the age's foremost Russian aerodynamicist, Nikolai E. Joukowski (1847–1921), who operated a wind tunnel laboratory in Moscow. In 1910, Joukowski showed how a circle could be transformed into airfoils by a mathematical trick known as "conformal transformation." The trick allowed a bright aerodynamicist to compute the surface pressure (or pressure distribution) on an



These four airfoils—one French, one British, and two German—were typical of the types of airfoil shapes employed in wings of World War I airplanes. Laurence K. Loftin, Jr, *Quest for Performance*, Fig. 2.9, p. 24. http://www.hq.nasa.gov/office/pao/History/SP-468/ch2-2.htm

airfoil with some accuracy, from which some rather accurate lift values could be determined. In practice at Göttingen, the transformation method enabled the design of a series of "reasonable-looking airfoils" that were to be tested in wind tunnels and in flight, with researchers noting differences in performance brought on by the slightest variation of a wing parameter.[3] Iterating the Joukowski family of airfoils into effective, streamlined wing shapes proved extremely slow and laborious because of the sophisticated mathematics it involved, but the rigorous thinking and methods of Prandtl and

The most advanced feature of the Fokker D-VII airplane of World War I was its internally braced cantilever wings involving very thick airfoil sections. Many of the fine characteristics of this biplane, one of the most renowned of Germany's fighters, were due to its wing thickness, which was unusual for its day. Fokker built the D-VII wing around a Göttingen 418 airfoil. Laurence K. Loftin, Jr, *Quest for Performance*, p. 34. http://www.hq.nasa.gov/office/pao/History/SP-468/ch2-2.htm

his cohorts at Göttingen created some useful wing shapes. Generally of a thicker shape and featuring large-radius leading edges and very thin trailing edges, the very best Göttingen airfoils, notably Göttingen 387 and 398, proved very effective in flight. They were to be used on airplanes for many years to come, not only in Europe but in the U.S. as well. The famous Clark Y airfoil, designed by Colonel Virginius E.

[3] Anderson, *A History of Aerodynamics*, p. 289.

Airfoil research took many different forms. At NACA's Langley Memorial Aeronautical Laboratory in 1921, the performance of a model wing was tested by being suspended beneath a Curtiss JN-4 "Jenny" aircraft, which employed a Royal Air Force 15-airfoil section. NASA Image #L-00130 (LaRC)

Clark of the U.S. Army in 1922 and employed on a number of noteworthy American aircraft of the 1920s, including the Ryan monoplane that flew Lindbergh across the Atlantic in 1927, was in fact a design offshoot of the Göttingen family.

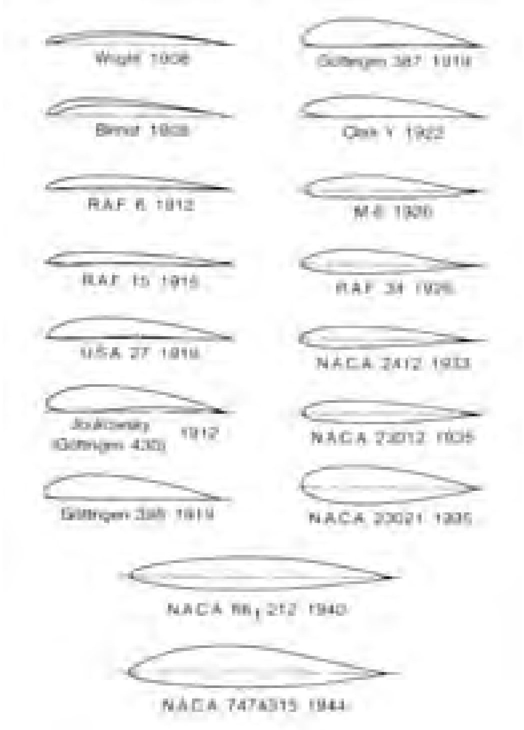
In the United States, one of the first things that the National Advisory Committee for Aeronautics did when it came to life in 1915 was focus American attention on wings. In its first *Annual Report* to Congress, the NACA called for "the evaluation of more efficient wings of practical form, embodying suitable dimensions for an economical structure, with moderate travel of the center of pressure and still affording a large angle of attack combined with efficient action." The Committee could not carry out this work itself, because Langley Memorial Aeronautical Laboratory was at that time still no more than a dream. The best the NACA could do toward improving wing design was to support wind tunnel tests at the Massachusetts Institute of Technology (MIT), which were under the auspices of the airplane engineering department of the Bureau of Aircraft Production. It was this experimental program that resulted, in 1918, in the introduction of the U.S.A. family, the largest single group of related airfoils developed in America up to that time.

This chapter's first document is the public announcement of the initial six airfoils in the U.S.A. series. Entitled "Aerofoils and Aerofoil Structural Combinations," by Lt. Col. Edgar S. Gorrell and Maj. H.S. Martin of the U.S. Army Signals Corps, the NACA published this report as *Technical Report (TR) 18* in 1918. Also in 1918, sponsored wind tunnel experiments at MIT looked specifically into the suitability of utilizing thick U.S.A. wing sections in the design of internally braced monoplanes. Unfortunately, there was still no effective theory or sufficiently capable wind tunnels to help design them. But at least a long and dedicated American search for truly effective airfoils for different advanced airplane requirements had begun.

At the end of the war, the NACA supplemented its support of the MIT wind tunnel program with a laborious effort by its small technical staff in Washington to bring together the results of airfoil investigations at all the European laboratories but still not including Göttingen or any other lab in Germany. In June 1919, the Committee opened an intelligence office in Paris to collect, exchange, translate, and abstract reports as well as miscellaneous technical and scientific information related to aeronautics. One of the early fruits of this labor was the NACA *TR 93*, published in 1920. Too technical in nature to include in our collection, *TR 93* provided a comprehensive and handy digest of standardized test information about all the different airfoils employed by the Allied powers. The report offered graphic illustrations of the detailed shapes and performance characteristics of more than 200 airfoils, as well as four index charts that classified the wings according to aerodynamic and structural properties. The intention was to make it easier for an American designer to pick out a wing section suited to the particular flying machine on which he was working. In retrospect, it is plain that many of the plots were totally unreasonable—no doubt because the NACA personnel who interpreted the collected data, like those who made the original tests, did not really understand how and why certain shapes influenced section characteristics as they did. Despite the flaws, however, the effort that went into the preparation of this report and others like it mobilized the NACA staff to manage a solid program of airfoil experiments once research facilities were ready at Langley laboratory.

Workmen in the patternmakers' shop at NACA Langley manufacture a wing skeleton for a Thomas-Morse MB-3 airplane for pressure distribution studies in flight, June 1922. The MB-3's wing employed a Royal Air Force 15 airfoil. NASA Image #L-00184 (LaRC)

When NACA Langley began routine operation in June 1920, the empirical approach was still the most sensible way to better wings. Wing section theory as developed before World War I by Joukowski, Prandtl, and others (including Martin W. Kutta, who, along with Joukowski, was responsible for inventing the circulation theory of lift, a "revolutionary development in theoretical aerodynamics"[4]), permitted the rough determination of lift-curve slopes and pitching moments, but little else. It was possible to transform from the pressure distribution around a circle, which was known theoretically, to the flow distribution measured around an airfoil, and thus create an approximate airfoil shape, but the mathematics required for the transformation was too abstruse for the average engineer, perhaps especially in America. Further, there was no way to measure the practical value of the mathematical formulations other than via systematic wind tunnel testing. Prandtl had refined the Kutta-Joukowski method, but his refinement still allowed only for the rough calculation of wing section characteristics.



The historical evolution of airfoil sections, 1908-1944. The last two shapes are NACA low-drag sections designed to have laminar flow over 60 to 70 percent of chord on both the upper and lower surface. NASA Image #L-1990-04334 (LaRC)

Some of the most popular airfoils of the 1920s would thus still be produced by highly intuitive methods: cut-and-try procedures based neither on theory nor on systematic experimentation. For the wing section of his successful seaplane, Grover Loening took the top curvature of the RAF 15 wing section and, for the underside, drew a streamlined curve with a reverse in the center, which enclosed the spars. The net result of this artistic rendition was so good that Loening, who did not want other people to copy his product, decided not to submit it for tests anywhere. Col. Virginius Clark, U.S.A., designed one of the 1920s' most popular airfoils for wings, the Clark Y, simply by deploying the thickness distribution of a Göttingen airfoil above a flat undersurface; he chose the feature only because it was highly desirable as a reference surface for applying the protractor in the manufacture and maintenance of propellers.[5]

[4] Anderson, p. 250.

[5] See Grover Loening, *Our Wings Grow Faster* (New York, 1935).

Aviation magazine published a brief but illuminating interview with Virginius Clark in its 17 October 1927 issue. Although it appears in our documentary collection slightly ahead of its time (that is, out of chronological order), we have placed it early in the chapter as a representation of the intuitive stage of airfoil design that predominated in the U.S. into the late 1920s.

Clark certainly enjoyed great success with his airfoils, but the days of such trust in personal intuition were numbered. The cut-and-try method, although successful in the hands of a few talented practitioners like Clark and Loening, had too spotty a success record to continue forever. More and more aeronautical engineers from the 1920s on realized that a wide range of effective airfoils would be created only by using some more systematic analytical method involving tests in a significant and reliable wind tunnel.

The scene of the most important airfoil research conducted anywhere in the world shifted in the early 1920s from Göttingen to NACA Langley. This change happened when Prandtl's brilliant young protégé Dr. Max Munk emigrated to the U.S., bringing not only his idea for a variable-density tunnel with him (see chapter 2) and his extraordinary theoretical abilities but also his experience in developing Göttingen airfoils.

Munk's variable-density tunnel (VDT), which began operation at Langley in October 1922, made possible a huge advance in the experimental method by which to understand airfoils. Airfoil expert Ira H. Abbott, an aeronautical engineer who went to work at Langley immediately after graduating from MIT in 1929 (and who remained with the government research agency until his retirement from NASA in the early 1970s), described the VDT's significance for airfoil development in a 1980 historical retrospective on the evolution of aircraft wing design:

> All previous wind tunnel research on airfoils had been severely handicapped by the small scale of the tests, measured by Reynolds number. Experience had shown that the results of tests of small models could not be applied directly to full-scale flight conditions, and neither theory nor experience provided any means for correcting the results. Small-scale models were, however, essential to research, both because the small wind tunnels then existing would not accommodate large models, and because big models for the large wind tunnels later to be built were too expensive and cumbersome for extensive research.

As Abbott emphasized, the VDT "avoided this problem" by obtaining full-scale results from tests of small models (usually 5 by 30 inches), at 20 atmospheres pressure.[6]

[6] Ira H. Abbott, "Airfoils: Significance and Early Development," in *The Evolution of Aircraft Wing Design* (American Institute of Aeronautics and Astronautics/Dayton-Cincinnati Section, 1980), p. 22. Abbott presented this paper at an AIAA meeting held at the Air Force Museum in Dayton, Ohio, in March 1980.

With Munk supervising the work from his NACA office in Washington, Langley began its first systematic investigation of a series of wing sections in the VDT early in 1923. Although the research was to be essentially empirical, the idea behind the design of the airfoils derived from a highly intuitive theory conceived by Munk as an outgrowth of his Göttingen experience and his further thinking about the design application of Joukowski's mathematical trick of conformal mapping. In his "General Theory of Thin Wing Sections," published by the NACA in 1922, Munk expressed a more helpful engineering approach to the theoretical prediction of airfoil lift and moments when the airflow in which it operated was considered, for calculation purposes, nonviscous.[7]

The actual airflows in which wings fly, of course, do experience viscosity (an internal fluid friction) that definitely affects aerodynamic performance; for theoretical purposes, however, given the tremendous complexities of dealing with viscous flows and skin friction, aerodynamicists conceived of a perfect fluid, one that has no viscosity. "In such a perfect, nonviscous fluid," as professor of aeronautical engineering Alexander Klemin of New York University's Daniel Guggenheim School of Aeronautics wrote in a textbook published in 1930, "all bodies are perfectly streamlined and experience no resistance to motion." The value of the conception of a perfect fluid for Munk and other aerodynamicists of the time was that "the flow in such a fluid is easily calculated for simple bodies, and at least approximates the flow in an imperfect fluid such as air or water."[8] Results from such theory were not perfect themselves; for one thing, there were scale effects associated with viscosity that "lent continuing uncertainty to the applicability to full-scale airplanes of model results from wind tunnel tests."[9] Still, approximate nonviscous theory such as Munk's thin-airfoil theory did offer significant help where otherwise none could have been achieved.

Convinced that contemporary aerodynamicists would fail to produce significantly improved airfoils if they continued to let the wing section be dictated by the mathematical method, Munk decided to "start with a wing section, any technically valuable wing section, and fit the mathematics to the section." Even though the method required some simplifying assumptions and did not permit the calculation of maximum-lift coefficients, Munk's idea was still a major breakthrough, if not a watershed in the history of airfoil design.[10] By replacing the airfoil section with an infinitely thin curved line, it permitted the calculation of certain airfoil characteristics (e.g., lift-curve slope, pitching moments, and chord-wise distribution) directly in terms of easily identified parameters of the shape. A complete reproduction of Munk's *TR 142* of 1922 appears in this chapter's collection of documents.

[7] Anderson, p. 290.

[8] Alexander Klemin, *Simplified Aerodynamics* (Chicago: Goodheart-Willcox Co., Inc., 1930), p.200.

[9] Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore and London: The Johns Hopkins University Press, 1990), p. 35.

[10] For expert technical discussion of the importance of Munk's thin-airfoil theory in the history of aerodynamics, see Theodore Von Karman, *Aerodynamics: Selected Topics in the Light of the Historical Development* (Ithaca, New York, 1954), pp. 9-10, and Ira H. Abbott and Albert E. Von Doenhoff, *Wing Section Theory* (New York, 1959).

TR 142 implied, specifically, that characteristics such as the angle of zero lift and moment coefficient were determined primarily by the shape of the "mean" or "camber line" of the airfoil, the line halfway between the upper and lower surfaces. But in the report, Munk also extended his method to suggest what would happen if the camber, thickness, and thickness distribution of a wing section were varied independently, according to a method of systematic parameter variation. Munk's analysis suggested that a design having a slight upward camber near the trailing edge would result in a stable center of pressure travel. So, starting with a mean line pulled out analytically from one of the better Göttingen airfoils, the VDT research team wrapped a thickness form about the upper and lower surfaces of an airfoil. Then, by pulling the mean line (or camber) out, going to a symmetrical section, and changing all the ordinates to correspond to the correct proportion of thickness, it prescribed a family of 27 related airfoils. The NACA announced this airfoil family to the world in *TR 221*, published in 1925, also found in our documentary collection; NACA named the airfoils "M sections" in Munk's honor.

Ironically, Munk was forced to leave the NACA for good in early 1927, a result of a bitter dispute over his autocratic style of supervision that had led to the mass resignation of all the aerodynamic section heads. Fortunately, his approach to airfoil development stayed happily and securely in place. In fact, it climaxed in the 1930s in work at NACA Langley that would be directed by one of the other most brilliant and controversial characters in American aerodynamics (and certainly NACA) history, Eastman N. Jacobs. A 1924 graduate in mechanical engineering from the University of California at Berkeley, Jacobs reported to work at Langley in 1925 and remained there until his own, even more mysterious, departure (and complete disappearance from the aeronautical scene) in 1944. Put in charge of the VDT soon after Munk's resignation as chief of aerodynamics at Langley, Jacobs built upon the excellent work that Munk had started and took it to a significantly higher level of technological achievement. Under Jacobs's direction, the NACA developed and standardized a complete system of mathematically constructed airfoils, based on the results of actual wind tunnel testing and flight research. These airfoil families proved instantly and hugely successful not just in the U.S. but around the world. Instead of taking the time and bearing the great expense and time of conducting their own airfoils, most aircraft manufacturers relied entirely on the published characteristics of the NACA-derived wing sections. From NACA reports and their voluminous catalogs of shapes and pertinent data, the industry picked airfoils that became the wings for some of the best aircraft of their era, including the Douglas DC-3 transport and the B-17 Flying Fortress, as well as a number of postwar general aviation aircraft.

Some interesting insight into Jacobs's early plans for what would become the famous NACA 4-digit series of airfoils can be gleaned from a sequence of correspondence reproduced in this chapter from the year 1929. In essence, this chain of

Eastman N. Jacobs (1902-1987), head of the Variable Density Wind Tunnel (VDT) section at NACA Langley, played a critical role in the delineation of airfoil shapes in interwar America. The VDT research team at Langley in 1929. Eastman Jacobs is sitting (far left) at the control panel. NASA Image #L-3310 (LaRC)

Eastman Jacobs was adventurous in many ways besides aeronautical research. In the late 1920s, he bought a Pitcairn Mail Wing-type airplane, a small open-cockpit biplane with a 110-hp engine. In 1933, he flew back across Hampton Roads from nearby Norfolk, Virginia, without realizing he was in the eye of a hurricane. NASA Image #A76-1405 (Ames)

correspondence suggests something that has never been placed into the historical record—that a basic idea leading to the 4-digit series came from outside NACA, from a young and then little-known engineer, Ralph H. Upson, then working for the Aeromarine Klemm Corporation in Keyport, New Jersey. (Upson later became chief engineer for Henry John Heinz, grandson of the founder of the Heinz pickle and catsup company in Pittsburgh, when Heinz sought to build cargo- and troop-carrying gliders for air service in World War II. After the war, he worked at Boeing and taught aeronautical engineering at the University of Minnesota.) In no NACA history or history of aerodynamics has Upson ever been credited with any sort of role in the genesis of the 4-digit airfoils. As the documentation shows, however, he urged the NACA as early as 1928 to focus its airfoil research on the effects of varying section thickness and mean camber line, the fundamental concept behind the 4-digit series.

Whether Jacobs and his colleagues at Langley would have focused on the effects of thickness and mean camber line as the fundamental properties for further investigation without Upson's input is uncertain. What is definite is that the Jacobs team quickly determined in 1929 that their research should concentrate on the effects of varying those parameters and to move on to the selection of an initial thickness distribution and shape of camber from which to iterate a family of test airfoils. Ira Abbott, who joined Jacobs's VDT team in June 1929, many years later recalled only the technical details of how this happened. Robert Pinkerton, another VDT section member, found that the thickness distributions of efficient airfoils such as the Göttingen 398 and the Clark Y were nearly the same when the camber was removed and they were reduced to the same thickness. Jacobs accordingly selected a mathematically defined thickness distribution, which corresponded closely to that for such airfoils. The mean lines to be used were selected as those defined by two parabolic arcs tangent at the position of maximum mean line ordinate. These cambers appeared suitable for positions of the maximum ordinate varying between 20 and 70 percent of the chord.[11] Having selected these key variables, Jacobs and his fellow engineers were ready to start the research—almost ready, that was, given that their wind tunnel had gone haywire.

As soon as planning began for the test program that was to become the NACA 4-digit series, the precious piece of experimental equipment in which the tests were to take place, the VDT, started misbehaving badly. Redesigned and rebuilt with a closed-throat section, variable-speed drive system, and new balance following a catastrophic fire and explosion caused by a broken light bulb, which scorched its insides in August 1927, the new VDT simply did not work right. Its airstream, which needed to be steady, constant, and uniform to be of much help, was atrocious, and all attempts to smooth out the turbulence failed. There was no alternative but to rebuild the tunnel once again, a remedy that "horrified and exasperated" NACA

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[11] Abbott, "Airfoils," p. 22

officials, as there was little if any chance of an additional appropriation in the wake of the start of the Great Depression.[12] Because no special funds from Washington were available, the engineers at Langley had no alternative but to scavenge parts and materials, scrape up what little money they could from the lab's existing budget, and rebuild the machine themselves. It took about a year, but by late 1930, the tunnel was running again—although its turbulence problems were never totally solved. As early as 1932, Jacobs was telling his superiors that the rehabilitated VDT would never be a fully acceptable facility. What was needed, he said, was a new low-turbulence tunnel.

The next few documents in the chapter feature the outstanding results of the aerodynamic research that nevertheless ensued from the existing VDT: the NACA 4-digit series of airfoils. The first is a reproduction of *TR 460*, "The Characteristics

In the course of developing its second family of airfoils in the late 1920s and early 1930s, NACA devised a numerical code—patterned after that used to identify the composition of steel alloys—by which to describe the physical shapes. Until that time, researchers in the United States and abroad all designated airfoils simply by numbering them in the sequence in which they had been tested (M-1, M-2, M-3, and so on). In the new system, however, numbers would indicate the airfoil's critical geometrical properties. This digital code did not signify much to the man on the street, but to aeronautical engineers, it suggested everything important about an airfoil. What the integers meant in the case of NACA's 4-, 5-, and 6-digit series of airfoils is expressed below:

4	4	12
Maximum Camber	Position of Maximum camber in 1/10 of chord	Maximum thickness in percentage of chord

A popular airfoil from the NACA 4-digit series: N.A.C.A. 4412.

2	30	12
Approximate maximum camber in % of chord	Position of maximum camber in 2/100 of chord	Maximum thickness in % of chord

After the 4-digit sections came the 5-digit sections. These sections had the same thickness distribution but used a camber line with more curvature near the nose. One of the most effective in the 5-digit series was N.A.C.A. 23012, the major geometric characteristics of which were built into its numerical code.

6	3	2	2	12
Six-series	Location of minimum center of pressure in 1/10 of chord	Half width of low drag bucket in 1/10 of lift coefficient	Ideal lift coefficient in tenths	Maximum thickness in % of chord

The NACA's 6-series airfoils departed from the more simply designed 5-digit family in that they were generated from a more or less prescribed pressure distribution and were meant to achieve laminar flow. Below is an expression of the digital code built into the N.A.C.A. 63,2212 airfoil. After the six-series sections, airfoil design became much more specialized for particular applications.

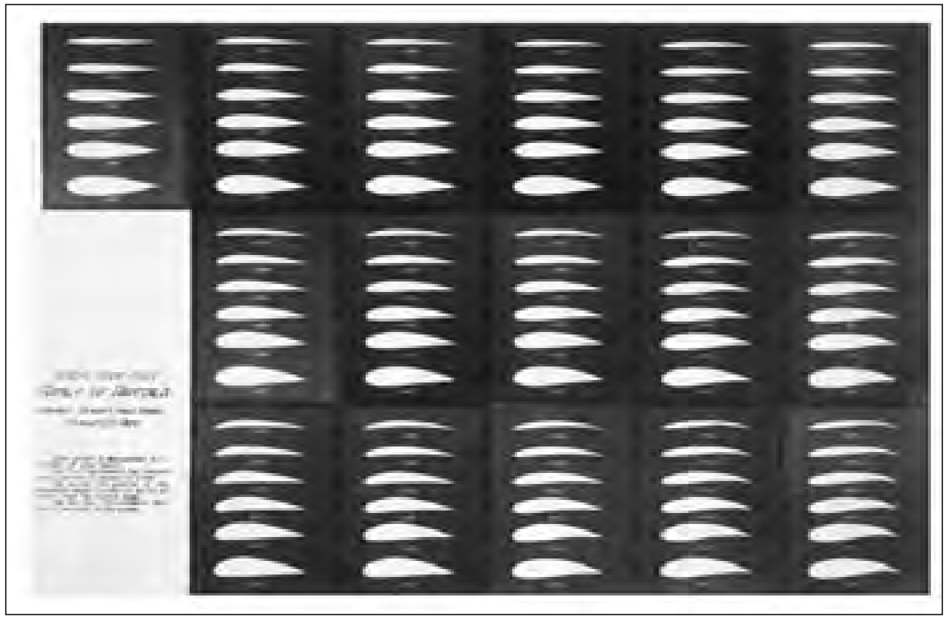
[12] Abbott, "Airfoils," p. 22.

of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel," by Eastman N. Jacobs, Kenneth E. Ward, and Robert M. Pinkerton. Immediately upon publication by the NACA in 1933, the report became a classic, an airplane designer's bible.

The NACA 4-digit series introduced by *TR 460* were instantly successful not only because of the systematic presentation of data and ingeniously simply numerical code for identifying an airfoil's geometrical properties; several of the airfoils were also highly efficient wing shapes. As the reader will read in the final section of the report, test results indicated, most significantly, that "the maximum lift increases with increased camber, the increase being more rapid as the camber moves forward or back of approximately the mid-chord position."

The chapter's next five documents appear in a string and bear testimony to the nearly universal acclaim given to the 4-digit series.

The NACA did not stop at four digits. Under Jacobs's direction, the Langley engineers expanded their research in the mid-1930s to look at the effects of still other variations of wing section characteristics, particularly at what happened when the position of maximum curvature was moved forward and backward. Moving maximum curvature to the rear of the section proved ineffective due to large pitching moments, but some airfoils with their camber quite far forward performed in very promising ways. In 1935, the NACA published *TR 537*, "Tests in the Variable-Density Wind Tunnel of Related Airfoils Having the Maximum Camber Unusually



By the end of the summer of 1929, tests in NACA Langley's VDT had produced the family of airfoils N.A.C.A. 0006 through N.A.C.A. 6721, shown here in cross section. Data on all of these airfoils were presented in NACA 1933 *Technical Report No. 460*, "The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel," by Eastman N. Jacobs, Kenneth E. Ward, and Robert M. Pinkerton. NASA Image #L-05344 (LaRC)

In 1937, NACA's Eastman Jacobs received the Sylvanus Albert Reed Award for his contributions to the aerodynamic improvement of airfoils. NASA Image #L-43999 (LaRC)

Far Forward," by Jacobs and Pinkerton. This report asserted that some of new sections, notably N.A.C.A. 23012, were "markedly superior to well-known and commonly used sections and should replace them in applications requiring a slightly cambered section of moderate thickness, having a small pitching-moment coefficient." Some aircraft designers worried about airfoils with maximum camber so far forward; their experience in full-flight suggested that airfoils of this type might be inclined to a sharp break in lift at the stall. But further NACA research alleviated this doubt, and by the late 1930s, the better sections in this new airfoil series had become extremely popular and widely used, notably a handful of sections in the 23000 series.

On 8 April 1937, shortly after seeing an updated report on the forward-camber airfoils (*TR 610)*, Charles H. Chatfield, head of the research division of United Aircraft Corporation in East Hartford, Connecticut, wrote to the NACA's George Lewis with a positive response to the new 5-digit series. Declaring that "these new airfoils are good structurally as well as aerodynamically," Chatfield went on to recommend another publication focusing just on the better of the airfoils, "so that a designer may have in one publication all the airfoils that he would be likely to consider seriously for any particular airplane." Chatfield's letter and Lewis's response to it are included in the chapter's documents.

In December 1937, the Institute of the Aeronautical Sciences selected Eastman Jacobs as the recipient of its prestigious Sylvanus Albert Reed Award for his contribution to the aerodynamic improvement of airfoils. Included in this chapter's documentary collection is George Lewis's nomination letter to the Institute of Aeronautical Sciences, along with a memorandum from Langley engineer R.C. Platt, who supplied Lewis with up-to-date information about the military and commercial aircraft employing NACA wing sections.

Ironically, not everything had actually been so rosy all the while with NACA airfoil research. Scale effects and unusually high turbulence in the VDT airstream had continued to plague its data throughout the mid-1930s, and no matter what Jacobs and his colleagues did to alleviate them, the problems would not go away. The first really shocking demonstration of how bad the VDT data were turning out to be came as early as 1932 when Langley's new Full-Scale Tunnel (see chapter 2) first got around to making some wing tests. As Ira Abbott of the VDT section recalled, "These tests showed that the VDT results indicated a rate of increase of drag with thickness ratio much greater than the Full-Scale Tunnel. This discrepancy was important because it directly affected the choice of wing thickness for the inner sections of monoplane wings."[13] As more and more tests in the full-scale tunnel (FST) showed good agreement with results obtained in flight, some of the prouder and less circumspect proponents of the FST began to say that results from the VDT bore little relation to what really happened in flight and that correct airfoil data could only be obtained from tests on full-scale wings in the FST. VDT defenders, although fully aware by this time of their facility's inherent defects, answered the charges of their peers by asserting that their machine was still the NACA's best cheap means of obtaining a wide range of comparative data on a multitude of related airfoils. FST test specifications called for aircraft and aircraft models that were simply too cumbersome and expensive, they argued, to permit the kind of systematic, scale-model programs accomplished in the VDT.

Other criticism came from outside of the NACA, as can be seen in Langley's response on 8 February 1933 to an article by Theodore von Kármán, entitled "A Few Present Problems in Aerodynamics," in which the renowned Caltech aerodynamicist questioned the validity of VDT airfoil data. Although the memorandum enclosed was signed by Henry J.E. Reid, Langley's engineer in charge, the substance of the memo repeated Jacobs's very strong, and negative, reaction to von Kármán's criticisms.

Jacobs answered the more general challenge to the value of VDT tests by introducing the concept of "effective Reynolds number." This was essentially a stopgap method of predicting the aerodynamic effect that could have been obtained if the VDT had zero turbulence. Jacobs mentioned the concept several times in *TR 610* but actually defined it first in *TR 530*, "Characteristics of the N.A.C.A. 23012 Airfoil from Tests in the Full-Scale and Variable-Density Tunnel," published in 1935. "In a wind tunnel having turbulence," Jacobs wrote, "the flow that is observed at a given Reynolds number…corresponds to the flow that would be observed in a turbulence-free stream at a higher value of the Reynolds number. The observed coefficients and scale effects likewise correspond more nearly to a higher value of the Reynolds number in free air than to the actual test Reynolds number in the free stream." Jacobs then suggested that the name *effective Reynolds number* should be used to refer to "this higher value of the Reynolds number at which corresponding flows would be observed in free air." All applications of wind tunnel and comparisons of data, whether between the VDT and FST or any other two tunnels, should be made at the adjusted value of the Reynolds number.

[13] Abbott, "Airfoils," p. 23.

Although "probably better than nothing," Jacobs's concept rested, in the words of his own colleagues, "on an inadequate theoretical foundation and on slender correlations" of VDT results with results from other tunnels.[14] Jacobs figured the effective Reynolds number by multiplying the test Reynolds number by the tunnel's "turbulence factor," another NACA invention. For the VDT, the turbulence factor was 2.6, the highest of all Langley tunnels. Despite its limitations, all NACA wind tunnel sections started using the concept of effective Reynolds number, in particular to show the effects of Reynolds number on maximum lift. Some way to compensate for tunnel turbulence was better than no way at all.

The factor of scale and the corrupting effects of turbulence on aerodynamic measurement stimulated thinking in the aeronautical community worldwide in the 1930s, but certainly no group gave it more thought than Jacobs and his cohorts at Langley, given that it was their pioneering research taking the heat. Close scrutiny of their work sparked the ingenuity of the VDT team in important ways. For example, they began to look more carefully at basic flow phenomena that might be the source of the consistent errors in their results. In particular, they examined the "boundary layer," the thin stratum of air very close to the surface of a moving airfoil in which the impact pressure (i.e., the reaction of the atmosphere to the moving airfoil) was reduced because of the air's viscosity. In this layer, which was separated from the contour of the airfoil by only a few thousands of an inch, the air particles changed from a smooth "laminar flow" near the leading edge to a more turbulent flow toward the rear of the airfoil. To visualize the nature of the airflow around airfoils and other objects, the Langley group constructed a small low-turbulence smoke tunnel next to the other equipment in the VDT building.. Photographs of the smoke flowing around test models facilitated study of the boundary layer's conditions as they changed from low-friction laminar flow to high-friction turbulent flow. The NACA engineers accelerated their pursuit of a means to remove air from the boundary layer through slots or holes in the wing surface. This effort dated back to 1926 and was intended to decrease drag and increase lift by postponing "transition" from laminar to turbulent flow. Work in the smoke tunnel eventually led them to the conclusion that two of the critical factors causing transition, and thus high skin-friction drag, were surface roughness (the rivet heads, corrugations, and surface discontinuities then common in manufactured airplane wings) and pressure distribution on the wing surface.

It was not just airfoil experts working with Jacobs in the VDT who promoted boundary-layer research. On 18 April 1932, a young engineer in Langley's small Physical Research Division, Hugh B. Freeman, sent a memo to the engineer-in-charge in which he declared that the field of boundary-layer control offered "greater possibilities for the improvement of aircraft performance and safety than any other."

[14] Abbott, "Airfoils," p. 23.

Freeman's three-page memo, included in this chapter's documents, concluded with an outline of the advantages of conducting the boundary-layer tests at full scale in the Propeller Research Tunnel rather than on scale models in the VDT. Although Freeman's tests faced some insurmountable problems and led to no breakthroughs, they represented a major new line of aerodynamic inquiry that the NACA would pursue vigorously in the years to come, not originally so much through laminar flow control (later termed *LFC*) by blowing or suction applied to the entire wing, as Freeman suggested, but by designing for natural laminar flow from wing section shape alone. The latter became Eastman Jacobs's greatest ambition, and for roughly the next 10 years, he pursued it with crusading zeal, like a knight in search of the Holy Grail.

His quest for laminar-flow airfoils began with a campaign to build a new and larger variable-density tunnel with a significantly smoother airstream, for it would be impossible to design them without one. As noted earlier, Jacobs had started to call for a new low-turbulence tunnel as early as 1932, but he did not get the ball rolling until an April 1935 memo to Langley's engineer in charge (a document not included in our collection) in which he reported the results of a staff conference on ways to increase the speed of airplanes. A low-turbulence pressure tunnel, he urged, would greatly enhance the two related lines of research that the VDT team had long been pursuing: development of new airfoils and better understanding of the basic aerodynamic relationship between airstream turbulence, boundary-layer flow, and wing performance. Although Jacobs believed that the existing VDT could still provide useful design data, he warned that the "airstream necessary for the continued investigation of the fundamental characteristics of large scale airflows cannot be obtained in the existing tunnel." Turbulence in the old tunnel did not completely invalidate results for airfoils like those of the 4- and 5-digit classes, but accurate experiments with airfoils and other bodies that might enjoy low-friction laminar flow could not be expected in the existing facility.[15]

Within two weeks after receiving a copy of Jacobs's proposal for comment, two of Langley's most influential division chiefs sent memos to their superiors elaborating their reasons why the NACA should reject Jacobs's idea. Smith J. DeFrance, head of the Full-Scale Tunnel, questioned whether the knowledge to be gained from the new equipment would warrant the expenditure of money.[16] But it was Dr. Theodore Theodorsen, the brilliant head of the small Physical Research Division, who expressed the most vociferous, historically significant, but ultimately incorrect objections to the facility Jacobs had in mind: "I think the variable-density tunnels

[15] Eastman Jacobs to Engineer-in-Charge, "New Variable-Density Tunnel," 26 Apr. 1935, Langley Correspondence Files, Code A206-1, in NASA Record Group 255, National Archives, Mid-Atlantic Region, Philadelphia, Pa.

[16] Smith J. DeFrance to Chief, Aerodynamics Division, "Mr. Jacobs' memorandum on Proposed New Variable-Density Tunnel," 4 May 1935, A206-1, RG 255, National Archives, Philadelphia.

have outlived themselves. I do not think that the variable-density tunnel has led to any fundamental discoveries. They contain a very large amount of turbulence in the airstream, a condition that cannot be avoided." "What is a new variable-density tunnel to be used for?" Theodorsen asked. "Several years will be required to investigate the tunnel, and then what?" There was "no more need for airfoil testing," the physicist boldly declared, except possibly in connection with some questions about flow conditions in the boundary layer better answered by theoreticians.[17]

Dr. Theodore Theodorsen, a Norwegian immigrant who came to work for the NACA in 1929, contributed at least as much to aerodynamics as did Eastman Jacobs. His long list of accomplishments included an improved thin-airfoil theory, a theory of arbitrary wing sections, a basic theory of flutter, and numerous improvements made to the form of engine cowlings and propellers. NASA Image #L-47543-B (LaRC)

While Jacobs and his VDT staff had been developing the 4- and 5-digit airfoils using a systematic experimental approach, Theodorsen had been tackling various airfoil problems from the theoretical angle. Although perhaps his greatest contribution during this period was his theory of oscillating airfoils with hinged flaps, related closely to the problem of flutter, Theodorsen also provided some very arresting insights into the relationship between pressure distribution and boundary-layer flow, and hence, on wing section characteristics.

In NACA *TR 41,* published in 1931, Theodorsen described a "Theory of Wing Sections of Arbitrary Shape," which made it possible, as long as the airflow did not separate from the airfoil, to predict the pressure distribution of an airfoil. Starting with an arbitrary airfoil, one changed the closed two-dimensional shape through a conformal transformation almost into a circle; then, by using a rapidly converging series, one transformed the bumpy circle into a true circle about which the flow was known. Although no one at the time thought it was reasonable to apply this theory for the purpose of a practical design, the knowledge of the pressure distribution made possible by this clever double transformation later suggested the answer to the riddle of how to shape a laminar-flow airfoil.

The introductory section of *TR 411* is reproduced in this chapter's documents. In it, Theodorsen suggested that Langley's airfoil research had reached an experimental impasse. It could only move ahead with the help of some new theory, which he hoped he had provided in his report.

[17] Dr. Theodore Theodorsen to Engineer-in-Charge, "Comments on Mr. Jacobs' Memorandum Regarding New Variable-Density Wind Tunnel," 4 May 1935, A206-1, RG 255, National Archives, Philadelphia.

It is difficult to pinpoint just when Eastman Jacobs first considered controlling the boundary layer through body shape—or, more accurately, through control of the pressures acting along the body surface. The idea seems to have been germinating in Jacobs's mind at least as early as 1929. In a memorandum on airfoil scale effects dated 13 November 1929 (included in our collection), Jacobs discussed the importance of the relationship between transition and airfoil drag and mentioned the dependence of the transition point on airfoil shape. At the time, he expected that "the possible large drag reductions through prolonging of laminar boundary layers" (i.e., through prolonging transition to turbulent flow) would become apparent "as the result of the systematic tests of airfoil shapes." By 1935, however, he definitely knew this process of discovery could not happen without new turbulence-free testing equipment.

The equipment was not immediately forthcoming. The NACA turned down Jacobs's request on two grounds. First, other important projects, including the construction of an expensive new tunnel for high-speed propeller research (eventually built at Langley as the 19-Foot Pressure Tunnel but which was not really used much for propeller research) were awaiting funding. Second, Congress would not understand the desirability of low turbulence in wind tunnels. It would take two more years of persuasion on Jacobs's part before the low-turbulence tunnel would be authorized, and, as will be seen, even then the NACA only got its way by calling the tunnel something else.

In late 1935, Jacobs returned to Langley after representing the NACA in Rome at the Fifth Volta Congress on High-Speed Aeronautics. Now more than ever, he was convinced that Langley had to have a low-turbulence pressure tunnel. During his trip, he had visited most of the larger aeronautical research laboratories on the continent, whenever possible examining new experimental facilities and discussing current work. He found the European nations to be in keen competition, spending "large sums of money building up their research establishments." While concluding that America's "present leading position" in aeronautical research and development was "not seriously menaced at this time," Jacobs warned that "we certainly cannot keep it long if we rest on our laurels" and fail to modernize our test equipment. At the end of his trip report (which is not included in our documents), the Langley engineer returned to an old theme: "It is again urged that modern variable-density tunnel equipment be built in this country capable of testing at full dynamic scale for modern aircraft."[18]

Jacobs also brought back some new insight into the nature of the boundary layer. While in England, he had spent a weekend at the home of Sir Geoffrey I.

[18] Jacobs to Engineer-in-Charge, "Trip to Europe," 11 Nov. 1935, E32-12, RG 255, National Archives, Philadelphia.

Taylor, professor of physics at Cambridge University, who had presented a paper on high-speed flow at the Volta Congress. In long private conversations, Taylor described for Jacobs the substance of his recent work in the statistical theory of turbulence. This theory seemed to indicate "the transition from laminar to turbulent flow was due to local separation caused by the pressure field."[19] By implication, this result said that transition could possibly be delayed or perhaps avoided by preventing laminar separation (i.e., by using a falling pressure gradient). As it turned out, this would, in fact, become the mechanism eventually used by Jacobs in his design of laminar-flow airfoils.

Jacobs also had the chance at Cambridge to talk at length with Professor B. Melville Jones (1887-1975), England's leading aerodynamicist (later knighted). Jacobs had followed Jones's work for years very closely. Jones's 1929 article on "The Streamline Airplane" (reproduced in chapter 3) had, in fact, stimulated Jacobs's early interest in laminar-flow airfoils by showing how perfect streamlining would eliminate pressure drag caused by flow separation. If Jones's ideal streamlined airplane could be realized, and if the best aircraft of the 1930s were coming closer and closer to it, the only fundamental airfoil problem left for the aerodynamicist to solve would be reducing skin-friction drag. And every expert in the field knew from Prandtl's early boundary-layer research that skin-friction drag was significantly less in laminar flow than in turbulent flow.

During Jacobs's visit, Jones reported that recent British flight work showed considerable laminar flow over the forward regions of very smooth wings where there were favorable pressure gradients. This finding encouraged Jacobs greatly, because he knew it pointed to the possibility that drag levels achieved by well-designed advanced aircraft could soon, in fact, be down to the value of skin friction. The only remaining opportunity for reducing drag would lie in encouraging laminar flow.

Melville Jones later presented his thoughts on the subject in the First Wright Brothers' Lecture, which he presented before the Institute of the Aeronautical Sciences at Columbia University in New York City, on 17 December 1937, on the occasion of the 34th anniversary of the Wrights' first flight. The *Journal of the Aeronautical Sciences* published Jones's talk in its January 1938 issue, a complete copy of which is reproduced in this chapter.

How Jacobs's own thinking evolved after his 1935 trip to Europe, to the point of going hard after laminar-flow airfoils, is not totally clear. The most explicit document in which Jacobs personally dealt with this process was written on 27 December 1938 and was entitled "Notes on the History of the Development of the Laminar-Flow Airfoils and on the Range of Shapes Included." This is one of the essential documents to examine in this chapter, but unfortunately, it provides only a skeleton narrative of when, where, and how Jacobs got his ideas about laminar-flow airfoils.

[19] Jacobs to Engineer-in-Charge, "Trip to Europe," 11 Nov. 1935, E32-12, RG 255, National Archives, Philadelphia.

One thing is certain: Jacobs returned to the U.S. in late 1935 convinced that airfoils could be designed to maintain laminar flow "simply by shaping them to have large running lengths of decreasing pressure along the surface."[20] At a laboratory conference on boundary-layer control in July 1936, he argued that "direct control through shape should be placed first on our program" and again urged his colleagues to support his idea for the construction of suitable turbulence-free testing equipment.[21] In the fall, he wrote an article on "Laminar and Turbulent Boundary Layer as Affecting Practical Aerodynamics." As readers will see when they examine it in our documentary collection, his article was, in essence, another plea for the new tunnel.

Achieving laminar flow through proper shaping for favorable pressure distribution was "a nice idea" but far more difficult to implement than Jacobs and his colleagues imagined. As Anderson has explained, "recent advances in airfoil theory had been oriented toward calculating the pressure distribution for a given airfoil shape," but what Jacobs needed to do was "turn that theory inside out and design an airfoil for a given pressure distribution."[22] Such theoretical manipulation was not Jacobs's forte.

Still, in a brilliant piece of creative engineering science, Jacobs managed to do it. With his commitment to the design of laminar-flow airfoils now overshadowing all of his other work, Jacobs disappeared from Langley Field for a few days to unravel the mysteries of Theodorsen's 1931 airfoil theory and to explore ways of reversing its procedure, which had been designed to predict the pressure distribution from a given shape. He called over to his house a friend, Robert T. Jones, a highly intuitive NACA researcher who had taken a few classes at Catholic University taught by Max Munk. Together, Jacobs and Jones decided that Theodorsen's method could not be used in the way desired without adding to the theory. Jones proposed an extension of the theory derived from Munk's thin-airfoil work that seemed to be a way of calculating a shape that would give a desired sequence of pressures, but this idea also proved too inaccurate.[23]

When Jacobs returned to the laboratory from his short working vacation, he challenged his staff to apply Theodorsen's theory in design. H. Julian "Harvey" Allen, one of the brightest members of the VDT staff, came up with one means of inverting the theory based on a linearization that started from a thin Joukowski airfoil. Applicable only to thin sections, Allen's way proved too inaccurate near the

[20] Anderson, *A History of Aerodynamics*, p. 349.

[21] Jacobs to Chief, Aerodynamics Division, 20 July 1936, AV400-1, RG 255, National Archives, Philadelphia.

[22] Anderson, *A History of Aerodynamics*, p. 349.

[23] Robert T. Jones, "Recollections from an Earlier Period in American Aeronautics," *Annual Review of Fluid Mechanics* 9 (1977): 10-11.

leading edge for prediction of local pressure gradients.[24]

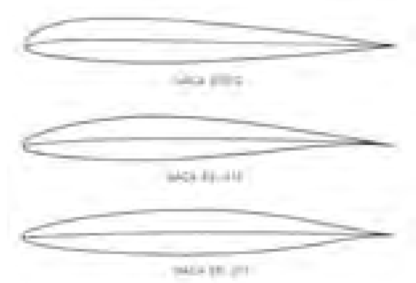
No one in the VDT section had any special training in advanced mathematics of the sort required, which prompted a few of the men to approach Theodorsen's Physical Research Division for assistance. According to Ira Abbott, another key member of Jacobs's staff: "We were told that even the statement of the problem was mathematical nonsense with the implication that it was only our ignorance that encourages us."[25] Theodorsen himself went to the trouble of showing that the shapes likely to result from an inversion of his theoretical method would be "unreal," things that looked like figure eights and surfaces that crossed over one another. Encouraged now by hearing this negative peer response, Jacobs stubbornly persisted in directing an all-out effort to devise a satisfactory inversion of the Theodorsen method.

The breakthrough came in the spring of 1938. The inversion, which Jacobs later said he modeled after Isaac Newton's clever method of approximating a square root, consisted essentially of changing a function in small increments in the conformal transformation of Theodorsen's theory. By taking an ordinary wing section like N.A.C.A. 0012 and "running it backwards," that was, designing its nose features according to the shape principles of the tail and its tail features according to the nose, Jacobs's team was able to arrive at an approximate shape that had falling pressures over most of the surface. It is impossible to document whether this single spectacular inversion ever took place; the inversion procedure may in fact have been a gradual refinement. Jacobs's role is not in dispute, however; he was the inspiration and driving force behind the entire laminar-flow program.

Something else essential to the development of laminar-flow airfoils also happened in 1938: a prototype of the low-turbulence tunnel that Jacobs had been seeking desperately for several years was finally built. Strangely, it was called "an icing tunnel." George Lewis continued to feel that NACA could not justify the expense of a new tunnel at Langley solely for the development of low turbulence. Congressmen simply would not understand the urgency. Lewis could, however, sell it on the basis of aircraft icing experiments. Many aircraft crashes traced to icing problems were attracting public attention in 1937, and the airlines were clamoring for useful information on the subject. Even if it meant stretching the truth more than a little bit, here was a way for the NACA to kill two birds with one stone. A perfunctory series of icing experiments was conducted during the summer of 1938, but immediately thereafter, the $103,000 pilot facility was converted into a low-turbulence tunnel for low-drag airfoil studies. It would be used in this way for three years, until the fall of 1941 and the eve of Pearl Harbor, when a new, more sophisticated, and even less turbulent machine, the Two-Dimensional Low-Turbulence Pressure Tunnel (cost, $611,000) was ready for operation.

[24] See H. Julian Allen, "A Simplified Method for the calculation of Airfoil Pressure Distribution," NACA *Technical Note 708*, 1939.

[25] Abbott, "Airfoils," pp. 23-24.



N.A.C.A. 23012 (top) was a conventional airfoil designed during the early 1930s. The other two airfoils, from the 6-digit series, were designed to maintain laminar flow over specified percentages of the chord. Comparing the top with the bottom two airfoils, one sees how the NACA designed "laminar-flow" sections by pushing the point of maximum thickness farther aft along the chord. The aft location was primarily due to the need to achieve a particular type of airfoil-surface pressure distribution that would enhance laminar flow. Laurence K. Loftin, Jr, *Quest for Performance*, Fig. 5.1, p. 105. http://www.hq.nasa.gov/office/pao/History/SP-468/ch5-2.htm

A June 1938 memorandum from Jacobs on the optimistic results of the preliminary round of tests with his first tentative laminar-flow model in the "ice tunnel" is included in this chapter's documentary collection. From it, he and his colleagues quickly designed a completely new family of airfoils for systematic testing: the NACA 6-series. By December of that year, he had grown so confident in the ultimate success of his work, that he composed his previously mentioned "Notes on the History of Development of the Laminar-Flow Airfoils."

In the summer of 1939, on the eve of Nazi Germany's invasion of Poland and the start of World War II, the NACA distributed two advance confidential reports prepared by Jacobs and his associates covering their new laminar-flow airfoils and their advantages over conventional airfoils.[26] The reports immediately caused a major buzz in the aircraft industry and military air services. By 1941, comments about the NACA having developed "a secret airfoil" were even popping into college aerodynamic textbooks, such as Newton H. Anderson's *Aircraft Layout and Detail Design*, a chapter of which is included in our documents.

The NACA tried to keep a lid on the laminar-flow developments but could not stop itself from at least previewing what its leaders were coming to regard as a truly major breakthrough. On the first page of its *Annual Report* for 1939, the NACA hinted: "Discovery during the past year of a new principle in airplane-wing design may prove of great importance. The transition from laminar to turbulent flow over a wing was so delayed as to reduce the profile drag, or basic air resistance, by approximately two-thirds." Though admitting that it was still too early to appraise this achievement, the NACA nonetheless suggested that its continued wing research should in the near future "increase the range and greatly improve the economy of both military and commercial aircraft."

With this long and very detailed technical story covering the conceptual genesis of the laminar-flow airfoils at Langley in mind, the reader is now ready to peruse a string of documents showing how the American aircraft industry, in association

[26] These reports were "Preliminary Report on Laminar-Flow Airfoils and New Methods Adopted for Airfoil and Boundary-Layer Investigations," June 1939, by Jacobs, and "Preliminary Investigation of Certain Laminar-Flow Airfoils for Application at High Speeds and Reynolds Numbers," August 1939, by Jacobs, Ira H. Abbott, and A.E. von Doenhoff.

In the spring of 1941, NACA Langley installed an experimental low-drag test panel on the wing of a Douglas B-18 airplane. The panel was fitted with suction slots and pressure tubes for a free flight investigation of the transition from laminar to turbulent flow in the boundary layer. Liquid manometers installed in the fuselage measured the pressure at each tube. NASA Image #L-25332 (LaRC)

with the NACA and the military air services, applied the new wings to World War II aircraft.

One of the major emphases of the documentary record is the experience of the North American P-51 Mustang, one of history's most remarkable airplanes and the first aircraft to employ a NACA laminar-flow airfoil. More than any other case study, the Mustang's performance in the war demonstrates how the NACA's laminar-flow airfoils proved to be a success, despite also being a failure. The record of this magnificent fighter plane confirmed expectations of appreciable improvements in speed and range as a result of the low-drag design, but practical experience with this and other aircraft using advanced NACA sections in the 1940s also showed that the airfoil did not perform as spectacularly in flight as in the laboratory. Manufacturing tolerances were off far enough, and maintenance of wing surfaces in the field were careless enough, that some significant points of aerodynamic similarity between the operational airfoil and the accurate, highly polished, and smooth test model were lost. Because the percentage drag effect of even minor wing surface roughness (e.g., dirt, dead bugs, and the dusty footprints of airplane crewmen) increased as airfoils became more efficient, laminar flow could be maintained in actual flight operation only in a very small region near the leading edge of the wing.

NACA Airfoil Sections Employed by the North American P-51 Mustang*

Aircraft	Wing root airfoil	Wing tip airfoil
NA-101 XP-51B Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-102 Mustang III	NAA/NACA 45-100	NAA/NACA 45-100
NA-102 P-51B Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-103 P-51C Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-104 P-51B Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-105 Mustang V	NACA 66-(1.8)15.5	NACA 66-(1.8)12
NA-105 Mustang VI	NACA 66-(1.8)15.5	NACA 66-(1.8)12
NA-105 XP-51F	NACA 66-(1.8)15.5	NACA 66-(1.8)12
NA-105 XP-51G	NACA 66-(1.8)15.5	NACA 66-(1.8)12
NA-105 XP-51J	NACA 66-(1.8)15.5	NACA 66-(1.8)12
NA-106 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-106 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-107 P-51C Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-109 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-109 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-110 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-110 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-111 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-111 P-51C Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-111 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-111 P-51K Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-112 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-112 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-117 P-51H Mustang	NACA 66-(1.8)15.5	NACA 66-(1.8)12
NA-122 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-122 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-124 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-124 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-126 P-51H Mustang	NACA 66-(1.8)15.5	NACA 66-(1.8)12
NA-127 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-127 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-138 Mustang IV	NAA/NACA 45-100	NAA/NACA 45-100
NA-138 P-51D Mustang	NAA/NACA 45-100	NAA/NACA 45-100
NA-139 P-51H Mustang	NACA 66-(1.8)15.5	NACA 66-(1.8)12

*Adapted from David Leidner, "The Incomplete Guide to Airfoil Usage," Analytical Methods, Inc., Redmond, WA 98052.

Still, the Mustang's airfoil section turned into an excellent wing. Ironically, this development was due to its high-speed performance rather than its low-drag. In "one of those rare instances in the history of technology in which a system becomes a success because it unexpectedly excels at something for which it was not originally designed," a decade of dedicated airfoil research by the NACA resulted, not in what Eastman Jacobs and his colleagues were after, but in something else, almost as good.[27] Not only were the NACA's 6-series laminar-flow airfoils used with great success on the Mustang, they were also to be employed on just about every other high-speed airplane that came after it, up to the time that sophisticated computer-aided design took over and started customizing advanced airfoil shapes in the 1980s.

The delineation of the so-called laminar-flow airfoils was thus a great contribution by the NACA, even if not exactly in the way, or to the degree, advertised. The last document in this chapter is an excerpt from Theodore von Kármán's 1945 publication for the Army Air Forces command, *Where We Stand.* There can be no question after reading this except that von Kármán, too, was a fan of the laminar-flow airfoil—just as were the German military pilots who confronted it over the battlefields of Europe and the German aeronautical engineers who wondered over its design features. But more than any other group, the people that valued the P-51's performance the most were the Allied bomber pilots who flew dangerous missions deep into the German heartland when no previous fighter could fly far enough to escort them all the way to their targets and back. Thanks in part to its highly efficient aerodynamic design, the P-51 could fly all the way to Berlin and back, saving innumerable lives of Allied crewmen. General Henry H. "Hap" Arnold, commanding general of the U.S. Army Air Forces in Europe at the time, called it "one of the great miracles of the war," the appearance of the long-range fighter escort "at just the right moment in the very nick of time to keep our bomber offensive going without a break."

This chapter's account of the laminar-flow story ends in 1945, but the quest for true laminar-flow wings most certainly did not end there. Aerodynamicists around the world have never really given up their quest for the pot of gold at the end of the rainbow, primarily because "the attainment of practical laminar flow may well represent the final breakthrough to which pure aerodynamics can lead us."[28] Immediately after the war, the British built a laminar flow flight-test aircraft, the Armstrong Whitworth A.W. 52, a swept-wing, twin jet flying wing. Unfortunately, the aerodynamic performance of this bold prototype also proved much worse in actual flight than what wind tunnel tests predicted—primarily in this case because the introduction of the swept wing "added confounded elements to the laminar flow equation." As "today's Eastman Jacobs" at Langley, Fayette S. Collier (head of

[27] Anderson, *A History of Aerodynamics*, p. 352.

[28] Stephan Wilkinson, "Go With the Flow," in *Air&Space Smithsonian* 10 (June/July 1995): 33.

NASA's Laminar Flow Control Project Office at Langley Research Center), pointed out in the mid-1990s, "Aerodynamicists had to go through a whole new learning process when swept wings came in, because now they were dealing with cross-flow disturbances as well as chordwise disturbances."[29]

Other laminar-flow projects followed, most of them involving efforts not just for shaping wing sections but for actively controlling the flow over the wing via sucking and blowing, ideas going back to the late 1920s. Following the failure with the A.W. 52, in 1955, the British initiated an active LFC project using three de Havilland Vampire jet fighters. Porous surfaces were given to the planes' wings through which the turbulent air in the boundary layer was sucked away. Aerodynamically, the tests showed promise, but structurally, the holes and additional elements required by the experimental system caused the airplanes some serious problems. Later, NASA tried something similar with a Lockheed F-94 interceptor, with roughly the same mixed results. In 1966, Northrop and the U.S. Air Force put together what has been called "the biggest laminar flow project ever attempted." Two Douglas WB-66 jets, previously used for weather reconnaissance, were converted into X21As by equipping their wings with a convoluted array of laminar-flow control apparatus: "thousands of razor-thin slits that were in turn perforated with over 815,000 minuscule holes, each of which sucked away turbulent air into a vast internal network of nearly 68,000 ducts, all leading to a pair of high-pressure pumps under the wings."[30] The X21A program proved that such a complex system was technically feasible but prohibitively expensive and a maintenance nightmare. The energy crisis of the 1970s rejuvenated NASA's laminar flow efforts, with different LFC test programs eventually being designed for the F-111 swing-wing at transonic speeds, the Grumman F-14, the Lockheed Jetstar, and a specially outfitted NASA Boeing 757, almost all of them somehow involving the potential aerodynamic benefits of active systems using pinholes in the wings, ducts, and pumps. Today, there are aerodynamicists at NASA and elsewhere who are still as enthralled with the idea of a laminar-flow wing as Eastman Jacobs and his associates were 60 years earlier. Whether the "miraculous" benefits of the technology will ever truly be realized is also still an open question.

[29] Quoted in Wilkinson, p. 35.

[30] Wilkinson, p. 36.

One of the reasons why many experts feel the North American P-51 Mustang represents the highest level of technical achievement ever accomplished in a propeller-driven fighter aircraft is its highly effective low-drag wing. The XP-51 was the first aircraft to incorporate an NACA laminar-flow airfoil. This is the second XP-51, which arrived at Langley in March 1943. NASA Image #L-34304 (LaRC)

The NACA put the Mustang through systematic drag reduction tests in Langley's Full Scale Tunnel. NASA Image #L-34590 (LaRC)

In the early 1950s the British conducted a wide-ranging program of laminar-flow control (LFC) research using three De Havilland Vampire jet fighters. The DeHavilland Vampire was Great Britain's second jet fighter of World War II, first flown in 1943. Powered by Rolls Royce engines, it could fly at 540 miles per hour, about 100 mph faster than the Spitfire. National Air and Space Museum, Smithsonian Institution (SI 2001-1109)

On the wing of the Vampire, researchers experimented with various porous surfaces in hopes of achieving prolonged laminar flow. The British tried a rolled metallic cloth on the wing surface, a technique that did not work, as roughness picked up in the mesh caused a premature transition to turbulent flow. They later used a perforated sheet metal. Eventually, they succeeded in providing a very smooth surfaces back to 25 percent of the chord. National Air and Space Museum (NASM 1A35429), Smithsonian Institution

In the early 1960s, NASA flew the Lockheed F-94 interceptor in a program designed to investigate the possibility of active laminar-flow control, but as with all other efforts in this area up to this time it achieved mixed results. Developed from the single-seat F-80 Shooting Star, America's first operational jet fighter, the two-seat F-94 Starfire served as the U.S.'s first operational jet all-weather interceptor. The first U.S. jet equipped with an afterburner, it could reach speeds as high as 630 miles per hour, cruising at 520 mph. National Air and Space Museum (NASM 1B13663), Smithsonian Institution

The F-94, which NASA flew in the early 1960s as part of a program of active laminar-flow-control experiments, employed a NACA 65-213 low-drag airfoil section. National Air and Space Museum, Smithsonian Institution (SI 82-14064)

Co-sponsored by the U.S. Air Force, the Northrop Corporation, and NASA, the biggest laminar flow project ever attempted began in 1963 and involved flight tests with the X-21, an experimental aircraft derived from the Douglas WB-66. Although the program encountered a number of serious difficulties, by the mid-1960s flights were attaining a significant degree of laminar flow over the X-21's wings. Some of the researchers involved believe that this program was terminated prematurely and could have produced even more helpful data. National Air and Space Museum (NASM 1B29178), Smithsonian Institution

The energy crisis of the early 1970s rejuvenated NASA's efforts to investigate new methods for laminar flow control. Its major research effort into the early 1980s involved a flight program with the General Dynamic F-111, a variable-sweep wing fighter developed in the 1960s under Secretary of Defense Robert S. McNamara as a plane that could be used by both the air force and the navy. One of the goals of the F-111 laminar flow program was to quantify the adverse effects of cross-flow instability due to wing sweep. The flight tests were carried out at Dryden Flight Research Center in 1980. Researchers installed airfoil "gloves" on the F-111, which was re-designated as the F-111/TACT (Transonic Aircraft Technology) airplane, and they tested it through a range of sweep angles. Results were again mixed, but provided the basis for a follow-on program involving another variable-sweep aircraft, the F-14. National Air and Space Museum (NASM 00049124), Smithsonian Institution

A navy fighter with very high performance and great operational versatility (and modified NACA 64A209.65 airfoil), the Grumman F-14 with its variable-sweep wing participated in laminar-flow flight experiments at NASA's Dryden Flight Research Center from 1984 to 1987. Results proved inconclusive, but the F-14 transition data did lead to an improved understanding of a number of complex aerodynamics effects related to wing cross-sectional shape, wing sweep, and the potential of boundary-layer suction (even though suction was not used on the F-14). National Aeronautics and Space Administration (NASA) via National Air and Space Museum (NASM 9A00420), Smithsonian Institution

The Documents

Document 4-1

Edgar S. Gorrell and H.S. Martin, "Aerofoils and Aerofoil Structural Combinations," NACA *Technical Report* 18 (Washington, 1918).

It will be obvious to the reader even from this brief early NACA report on airfoils that American engineers late in World War I were still oblivious to the significant theoretical work on which the Germans were basing their achievement of superior wing shapes, and were relying totally on empirical findings for further improvements. Gorrell and Martin make references to experimental programs at the National Physical Laboratory in England and at Eiffel's laboratory in France but no where in the article do they refer to the wartime work of Ludwig Prandtl and others at the University of Göttingen, which they will not know anything about until after Armistice Day.

Document 4-1, Edgar S. Gorrell and H.S. Martin, Aerofoils and Aerofoil Structural Combinations, NACA **Technical Report** ***18 (Washington, 1918).***

REPORT NO. 18.
AEROFOILS AND AEROFOIL STRUCTURAL COMBINATIONS.
By Edgar S. Gorrell and H.S. Martin.
INTRODUCTION.
FORMULAE NOTATION.
(Pounds, square feet, miles per hour units.)

A = Area of aerofoil in square feet. The brass model aerofoils were 18 by 3 inches.

C.P. = Center of pressure; i.e . the point of intersection of the resultant vector of forces with the plane of the aerofoil's chord.

D = Drag of the aerofoil as given by $D\text{-}K_xAV^2=D_1\text{-}D_0\text{-}D_s$.

Density = Density of standard air; i.e . 0.07608 lbs./cu. ft.

D_0 = Drag of the aerofoil when $V=0$.

D_1 = Drag of the aerofoil at the correct V for the test.

D_s = Drag of the spindle used as a spindle correction.

i = Angle of incidence; i.e . angle of wing chord to the wind.

K_x = Drag coefficient used in the standard formula $D=K_xAV^2$.
K_y = Drag coefficient used in the standard formula $L=K_yAV^2$.
L = Lift of the aerofoil as given by $L=K_yAV^2=L_1=L_0$.
L/D = Ratio of lift to drag.
L_0 = Lift of the aerofoil when $V=0$.
L_1 = Lift of the aerofoil at the correct V for the test.
M = Moment of resultant vector$=(M_1-M_0)/3.65$ for M.I.T. balance.
M_0 = Moment of resultant vector when $V=0$.
M_1 = Moment of resultant vector at the correct V or the test.
V = Velocity of the wind; i.e., 30 miles per hour for these tests.

Mathematical theory has not, as yet, been applied to the discontinuous motion past a, cambered surface using the term cambered as generally understood in aeronautics. For this reason, we are able to design aerofoils only by consideration of those forms which have been successful, by applying general rules learned by experience and by then testing the aerofoils in a reliable wind tunnel. A great many aerofoils have from time to time been tested and from them we know general rules which must be observed concerning camber and the variations of camber on the upper and lower surfaces, if we are to expect to attain even fair results. Results better than the ordinary are only attained when these general rules are observed, and patience and good fortune are combined. There are equations of curves which are very much like some aerofoils but they are not deduced from mathematical knowledge of the flow past an aerofoil but rather from the knowledge of the shape of these curves, and a good idea of the shape of a satisfactory aerofoil. It seems possible that eventually we shall know mathematically the best form for speed and climb, but the practical application of this knowledge may be more difficult than the present method of designing.

OBJECT OF THE TEST.

Although a great many aerofoils have been tested, many are useless from a practical point of view. It seems safe to assert that in this country nearly every aerofoil used is either one of the best five or six tested by M. Eiffel near Paris or by the National Physical Laboratory at Teddington, England, or based upon them, with some slight modifications. As will be seen from the results of these tests apparently slight modifications may make considerable differences.

We are thus limited to a few aerofoils, and some of these lack certain desirable characteristics as to the depth of wing spars combined with aerodynamical efficiency. It would seem of advantage to have the following results of the tests made upon the six structurally excellent and heretofore aerodynamically unknown aerofoils designed by the Aviation Section Signal Corps, United States Army. This constitutes the largest single group of aerofoils, excepting those of the N.P.L. and M. Eiffel, which has been tested and published.

DESIGN OF THE AEROFOILS

U.S.A.1 is a modification of the Clark aerofoil to receive a deeper rear spar. It was designed to be a good high-speed wing, with good L/D, having at the same time sufficient rear spar depth.

Depth of front spar = 0.0584 chord.
Depth of rear spar = 0.0497 chord.

U.S.A. 2 is a combination of the good characteristics of both R.A.F. 3 and R.A.F. 6. It is an aerofoil designed for use in a biplane combination as follows: The depth of the front spar measured along a line making an angle of 10° 45’ (angle of stagger) with the vertical is 0.875 that of R.A.F. 6. The depth of the rear spar is 0.88 that of the front spar of U.S.A. 2. The center of the front spar is 0.12 of the cord, and the center of the rear spar is 0.70 of the chord, from the leading edge. The curve of the upper surface is R.A.F. 3 and that of the lower surface is R.A.F. 3 lowered and modified to take the deeper spars.

U.S.A. 3 has the same structural features of U.S.A. 2. The nose is moved *forward* 3/8 inch and the ordinates are measured and calculated as a ratio of a 30-3/8-inch chord. These ordinates are then transposed to a 30-inch chord. The rear 0.8 of U.S.A. 3 is identical with the rear 0.8 of U.S.A. 2 and the changes necessitated occur in the leading 0.2 of the aerofoil.

U.S.A. 4 was designed as indicated for U.S.A. 3 except that the nose was moved 3/8 inch backward instead of forward as in U.S.A. 3.

U.S.A. 5 is not based upon any particular wing section but upon a general consideration of the factors necessary to result in an aerodynamically and structurally efficient aerofoil.

U.S.A. 6 is designed from the basic principles of a certain foreign aerofoil that has rendered particularly good results in the European conflict.

DISCUSSION OF THE RESULTS.

The results in no way contradict any of the known general principles regarding the effects of changing variations in the camber of aerofoils. There are rules for determining the relative value of different wing sections. The lift-drift ratio, which is a measure of the efficiency of an aerofoil, gives information as to the value of the wing. The qualities desired in a good aerofoil are high speed, or low resistance, great climbing ability, and excellent weight carrying capacity. Any one of these characteristics may be secured, but only at the expense of the other two to a certain extent. In a pursuit machine, where compromises are made to secure both high speed and excellent climbing ability, weight carrying is sacrificed. In a bombing machine weight carrying ability is desired to the partial sacrifice of speed and climb. In a training machine all three characteristics are desired, but in moderation. A machine designed for high speed alone has only a limited practical application.

It is generally conceded that there is no "best" aerofoil, for all have different characteristics and perform different functions. The selection of a desirable section depends on the performance required of the airplane desired.

All of the U.S.A. aerofoils have the fundamental quality of being structurally sound, permitting the use of sufficiently deep wing spars.

As suggested in Mr. Alexander Klemin's "Course in Aeronautics," the U.S.A. aerofoils are considered under the following headings:

(a) The maximum value of L/D, the angle at which it occurs, and the corresponding Ky. – The reason for this comparison is that an airplane in normal horizontal flight will generally be navigated at the angle giving the best L/D ratio, which is therefore important from an efficiency point of view. The value of the lift coefficient at the best L/D ratio is important because the greater the lift at this ratio the smaller the area of the wing surface required for the load. With a heavy machine a big lift coefficient is desirable. With a pursuit or racing machine a good L/D at small angles is desirable, so that with a sufficiently powerful motor a great speed may be obtained.

(b) The maximum Ky, the angle at which it occurs, and the corresponding L/D ratio. – The maximum Ky is a very important characteristic. The greater the maximum Ky, the slower is the speed at which a machine may fly and land. If large values of Ky are accompanied by good L/D ratios, then the machine will be efficient in climbing, though the best angle of climb is by no means at that of the maximum Ky. If the maximum Ky occurs at a high angle, then there are possibilities of good speed range.

(c) The shape of the burble point. – If the lift past the burble falls off very rapidly, the airplane can be quickly stalled. On the other hand, a wing with a flat lift curve at the burble point will avoid quick stalling. In all the U.S.A. aerofoils the shape of the curves at the burble points is sufficiently flat to be satisfactory.

(d) The L/D ratio at small angles of incidence and small values of Ky determine whether or not the aerofoil is really suitable for high speeds. We conform to Mr. Klemin's comparison value of Ky = 0.00086.

(e) Movement of center of pressure at low angles. – The importance of this fact is readily apparent from consideration of stability. In all the U.S.A. aerofoils the movement of the center of pressure is not prohibitive or unsatisfactory.

(f) Structural considerations are satisfactory in such aerofoils.

(g) Subheads (a), (b), and (d) are tabulated herewith for convenience of reference.

U.S.A. 1, its maximum L/D of 17.8, the highest of any U.S.A. aerofoils, occurs at 3.0°, at which point its center of pressure motion is fairly rapid but not so rapid as to make the aerofoil undesirable. This aerofoil would be undesirable as the wings of a very heavy machine, but it is very desirable as the wings of a fast pursuit machine. Its maximum Ky is sufficiently large to warrant a reasonable landing speed. Its L/D at small values of Ky is excellent and usually better than any of the other U.S.A. aerofoils. Because of its slow-landing speed and its great high speed and its burble point occurring at 15°, U.S.A. 1 would make the most satisfactory pursuit machine wing of all U.S.A. aerofoils with the greatest speed range of any U.S.A. aerofoils. Structurally it is excellent.

U.S.A. 4, with its large Ky of 0.00364, would be suitable and very desirable for heavy machines and for machines in which the designer is attempting to obtain a very slow landing speed. It is unsuitable for high speeds because of its low L/D values at small values of Ky. Structurally it is excellent.

U.S.A. 6 has a maximum L/D of 17.4, being second in this particular only to U.S.A. 1, of which the maximum L/D is 17.8. On both U. S.A. 6 and U.S.A. 1 the maximum L/D occurs at 3°. In each the maximum Ky is only fair. The maximum Ky of U.S.A. 1 is better than that of U.S.A. 6, so pursuit machines using U.S.A. 1 could be designed to have a slower landing speed than those using U.S.A. 6. It would appear, judging from the tabulation U.S.A. aerofoils just given, that U.S.A. 6 has better L/D values than has U.S.A. 1 for small values of Ky. However, when we examine this characteristic for many points, it is found that U.S.A. 1 has usually better L/D values for small values of Ky than has U.S.A. 6. Thus it seems that U.S.A. 1 is better than U.S.A. 6 for a pursuit machine. However, U.S.A. 6 could be used on a high-speed machine that is only a trifle slower than the machines using U.S.A. 1, but the machine using U.S.A. 6 would land much faster than the one using U.S.A. 1. At 3°, the angle of maximum L/D for both U.S.A. 1 and U.S.A. 6, the center of pressure movement of U.S.A. 6 is better than that of U.S.A. 1. U.S.A. 6 is undesirable for use on a heavy airplane. Structurally it is satisfactory.

U.S.A. 2 is next best to U.S.A. 4 for heavy machines or machines designed for slow speeds. It is unsatisfactory for a pursuit airplane. Structurally it is satisfactory.

U.S.A. 3 and U.S.A. 5 are above the average of aerofoils.

An off-hand estimate of the U.S.A. aerofoils would arrange them in order of merit as follows, but actual calculation might change this order.

U.S.A aerofoils arranged in order of preference	For carrying heavy loads or for slow landing speeds	For pursuit airplanes
Best	U.S.A. 4	U.S.A. 1
Second best	U.S.A. 2	U.S.A. 6
Third best	U.S.A. 5	U.S.A. 5
Fourth best	U.S.A. 3	U.S.A. 3
Fifth best	U.S.A. 1	U.S.A. 2
Sixth best (worst)	U.S.A. 6	U.S.A. 4

The general rules we have do not permit us to choose between two aerofoils of nearly the same characteristics, so a designer should actually go through the necessary computations, using each of the several possible aerofoils in order to ascertain which aerofoil is the best for the purposes of his design. As a matter of interest rough calculations are here given for a pursuit machine, and designers can follow the general method used herein for any type of airplane they may happen to be designing.

Among the U.S.A. aerofoils it seems apparent that U.S.A. 1 or U.S.A. 6 is best for a pursuit machine. For reasonable comparisons, the weight, horsepower available, and the parasite resistance should be the same for both machines. The weight will be assumed as 1,200 pounds, the parasite resistance as being represented by 0.025 V2 in pounds per square foot per mile per hour units, and the propeller efficiency as given by the following table, though such a propeller might be difficult to obtain in practice:

V in *mpt*	50	60	70	80	90	100	110	120
Efficiency	50	55	60	65	70	75	70	60

The horsepower available curve and the parasite resistance curve can then be plotted, the brake horsepower of the motor being assumed as 150. We may either assume a constant wing area and ascertain which wing section gives the best performance or we may prescribe certain performances and see which aerofoil section will come closer to or better the performances. This will result in variations in wing area and minor changes in weight which can be neglected. A low speed will be taken as 55 miles per hour. This will determine the area. The high speed and climb are to be the best obtainable under the assumed conditions.

Using the equation W = Ky AV2 we have 1200 = Ky A(2/55). The highest Ky of U.S.A. 1 is .00318 and of U.S.A. 6 is .00298, giving as areas required if U.S.A. 1 is used 124.5 square feet; if U.S.A. 6 is used 133.5 square feet.

$$1200 = (Ky)\ (124.5)\ (V^2) \text{ or}$$
$$Ky = 1200/(124.5)\ (V^2)$$

Thus we see that actual calculations demonstrate that U.S.A. 1 is better than U.S.A. 6 for a pursuit machine, considering speed above, for it has a greater high speed.

The best climb of U.S.A. 1 is 1,450 feet per minute at 70 miles per hour and for U.S.A. 6 it is 1,480 feet per minute at 60 miles per hour. Although U.S.A. 6 can climb 30 feet per minute faster than U.S.A. 1, yet the speed of U.S.A. 6 at which best climb occurs is 10 miles per hour less than the speed for tile best climb of U. S. A 1. We believe that the climbing ability of U.S.A. 1 is better for a pursuit machine than is that of U.S.A. 6. Hence U.S.A. 1 excels U.S.A. 6 in both speed and climb characteristics.

The above process should be pursued whenever there is any doubt between the relative desirability of two or more wing sections for specific purposes.

It would seem that Dr. Hunsaker is a trifle low in his estimate wherein he states that an increase in camber above 0.08 for the upper surface is disadvantageous since

four good U.S.A. aerofoils are cambered as follows:

U.S.A. 2 has a camber of 0.088 per cent of the chord.
U.S.A. 3 has a camber of 0.0868 per cent of the chord.
U.S.A. 4 has a camber of 0.089 per cent of the. chord.
U.S.A. 5 has a camber of 0.085 per cent of the chord.

It is generally conceded that the angle of no lift has no connection with the characteristics of an aerofoil. As a matter of interest the angle of no lift occurs in the U.S.A. aerofoil as follows:

Aerofoil	Angle of lift
U.S.A. 1	-2.5
U.S.A 2	-3.25
U.S.A 3	-2.9
U.S.A 4	-3.6
U.S.A 5	-3.05
U.S.A 6	-2.9

Aerofoils arranged in order of maximum negative angle of no lift	Aerofoils arranged in order of preference in order of preference as weight carriers or slow-speed qualities
U.S.A. 4	U.S.A. 4
U.S.A. 2	U.S.A. 2
U.S.A. 5	U.S.A. 5
U.S.A. 3 and U.S.A. 6	U.S.A. 3
U.S.A. 1	U.S.A. 6

From the above table it appears that perhaps at some future date it might be desirable to investigate whether or not the aerofoil with the greatest negative angle of no lift is also the best aerofoil for heavy aeroplanes or aero lanes designed for slow speeds.

Since the lowest value of Ky in the U.S.A. aerofoils occurs in U.S.A. 6, a designer designing for high speed only with no thought of other considerations, could probably obtain a higher speed with U.S.A. 6 than with any of the other U.S.A. aerofoils.

In order to check the values that we have obtained in the tests of the U.S.A. aerofoils, [a] R.A.F. 6 section made of wood was tested and found to conform to former tests which are known to be satisfactory.

An examination of all the published curves of the R.A.F. sections tested at the M.I.T. tunnel show the maximum L/D obtained varied between a little less than 16 to a trifle above 17. Our maximum L/D is equal to 16.78. On page 41 of "Reports on Wind Tunnel Experiments in Aerodynamics," Dr. Hunsaker says "It appears that undetected differences in workmanship and finish between two models may cause a change in coefficients of not more than 3 per cent." Let us assume for all R.A.F. sections tested at the M.I.T. tunnel L and D are correct within 3 per cent.

Possible error in L/D – (L+.03L)/(D-.03D) = L(1.03)/D(.97) = L/D (1.06)
or if the error be at the other extreme

Possible error in L/D = (L-.03L)/(D+.03D) = .97L/1.03D = L/D (0.94)

It is thus seen that all published results of the M.I.T. on tests of R.A.F. 6 are correct within the limits of workmanship and finish and that our test gives a result about the mean of all such tests.

It is suggested that it might be well if the United States Government owned standard brass aerofoils of the R.A.F. and Eiffel types constructed with absolute accuracy and which could be available for use on wind tunnels like the one at the M.I.T. for ecking the accuracy of the tunnel whenever desirable. The Government has standard weights and measurements. Why not apply this same idea to aeronautics?

In British Reports, 1912-13, No. 72, figure 14, the National Advisory Committee for aeronautics in England has suggested a method of corrections for LV. U.S.A. aerofoils were tested at an LV of 11 while R.A.F. 3, 4, 5, and 6 were tested at an LV of 6.3. Making the proper LV correction for the English tests of the R.A.F. 6, we find the N.P.L. results and our results for tests on the R.A.F. 6 give the same maximum L/D thus checking the accuracy of our series.

		Maximum $\frac{L}{D}$.			Maximum K_y.			K_y—[illegible]	
Wing.	LV—chord of wing in feet X relative wind in feet-seconds.	Angle in degrees.	K_y.	$\frac{L}{D}$	Angle in degrees.	K_y.	$\frac{L}{D}$	Angle in degrees.	$\frac{L}{D}$
U. S. A. 1	11	2.0	0.00153	17.8	13.0	0.00313	6.4	0.02	12.8
U. S. A. 2	11	4.0	.00185	14.2	15.3	.00327	6.3	.0	9.8
U. S. A. 3	11	4.0	.001706	16.4	15.4	.00342	6.5	.2	15.4
U. S. A. 4	11	4.0	.00177	15.10	14.0	.00304	8.1	.05	9.1
U. S. A. 5	11	2.0	.001565	16.81	14.0	.00296	5.21	.15	11.6
U. S. A. 6	11	2.0	.001455	17.4	14.0	.0028	7.27	.1	12.3

Document 4-2

Colonel Virginius E. Clark, "Design Your Own Airfoils," *Aviation* (Oct. 1927): 944-46.

When asked to disclose the secret of designing efficient airfoils, Clark responded in this published interview in 1927, "I would gladly tell you the secret if I knew of any. The airfoil sections just seem to lay themselves out and, when good luck attends, fair results are attained." Perhaps nowhere in history is there a more explicit expression of the role of cut-and-try empiricism and personal intuition in technological design than Clark's statement. By the time this interview was published, however, the intuitive stage of airfoil design was on its last leg. A much more advanced way of shaping airfoils had emerged, epitomized by the scientific engineering methods being developed at NACA Langley laboratory in Virginia.

Document 4-2, Colonel Virginius E. Clark, "Design Your Own Airfoils,"* Aviation *(Oct. 1927): 944-46.

Design Your Own Airfoils
An Interview With
COL. V. E. CLARK

Most of the successful airplanes in the United States use airfoils designed by Colonel Clark. Among the most commonly used of his airfoils are the U.S.A. 27 and the Clark V and Clark Y series. These have been used on Colonel Lindbergh's Ryan monoplane and many others of the more successful commercial strut-braced monoplanes; the Vought "Corsair", the Navy PN-10, and the Wright "Apache", all holding world's records; the Glenn Martin Navy T3M, the National Air Transport Mail and Express Planes, the Douglas "Round-the-World" cruisers, the Curtiss Pursuit and the Curtiss Observation, the Consolidated Army and Navy training planes, the Consolidated "Courier", the Douglas Mail Planes and the Douglas Observation and Transport planes, and on many other successful Military, Naval and commercial planes. The characteristics of the Clark Y as obtained by high pressure tests at the National Advisory Committee wind tunnel at Langley Field are shown in Fig. 1.

We asked Colonel Clark one day: "How do you go about designing these airfoils of yours? What is the secret?"

He laughed and said: "I would gladly tell you the secret if I knew of any. The airfoil sections just seem to lay themselves out and, when good luck attends, fair results are attained.

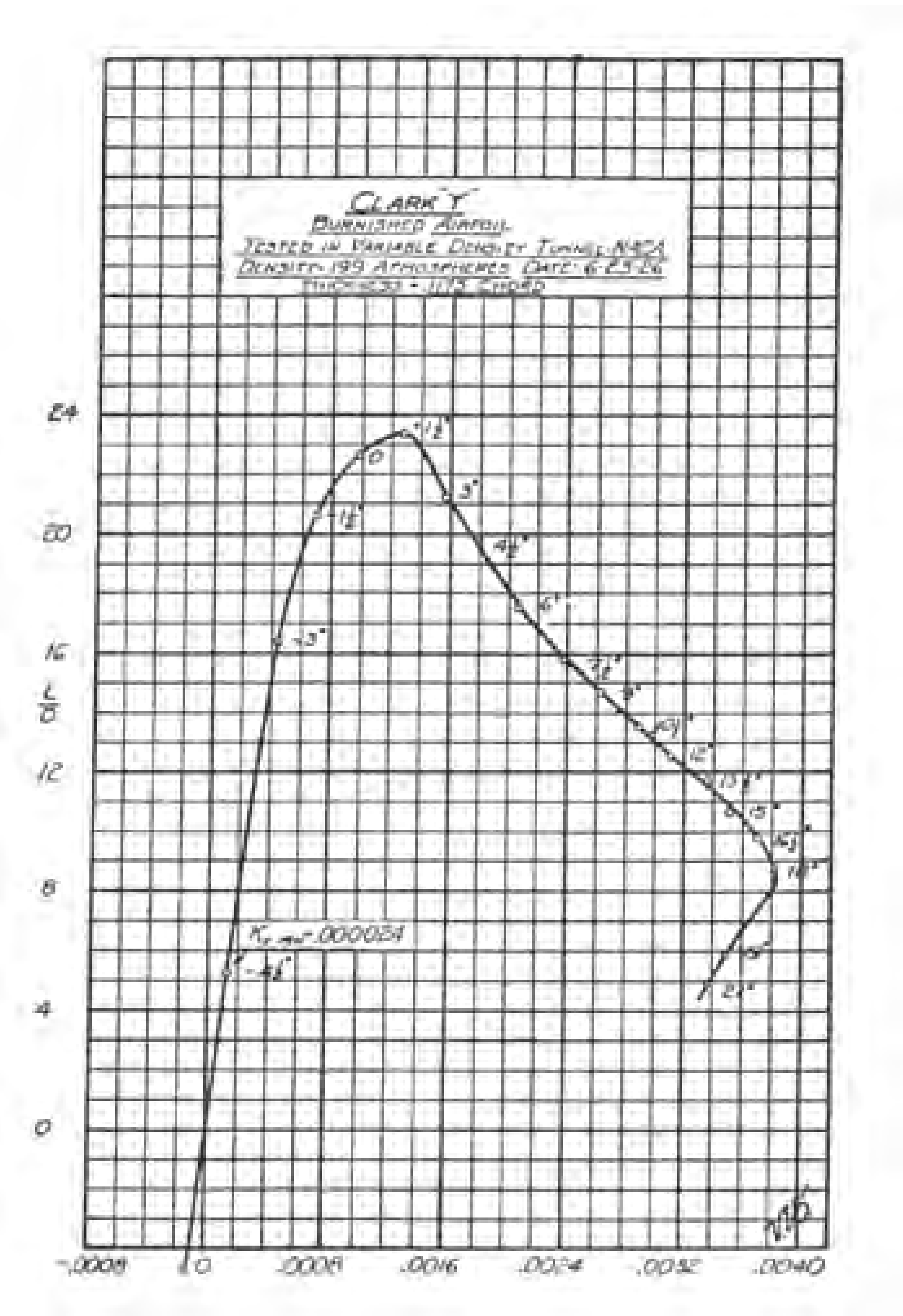


Figure 1

"My airfoils have been selected for various airplanes because comparative tests made in wind tunnels at a low value of the Reynolds number have indicated that they are fairly good. But, you know, the tests made by our National Advisory Committee for Aeronautics in their variable pressure tunnel at Langley Field prove, if we are to accept them, that even for the purposes of comparison, tests made at a low value of the Reynolds number are useless and misleading in many ways. Airfoil A may appear far superior to Airfoil B for a particular purpose when tested with a pressure of one atmosphere, whereas, when tested at twenty atmospheres, Airfoil B appears to be much better than Airfoil A for the same purpose. And no one has traced sufficient consistency in scale variations to justify a reliable system of rules for the prediction of full scale characteristics, having given the test results at low scale.

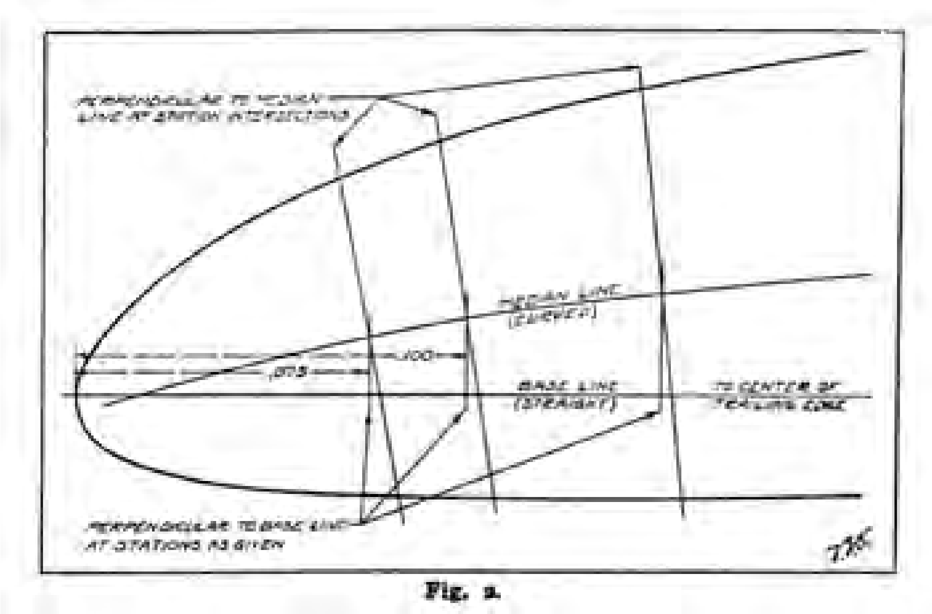
IMPOSSIBLE TO TEST EVERY AIRFOIL

"Therefore it is fair to assume that there are many airfoils which would be more popular than mine if they had been tested with twenty atmospheres' pressure.

"Unfortunately, the Advisory Committee, having taught us to be skeptical of low scale tunnel test results, cannot help us to reassure ourselves as to the merits of airfoils not tested at high value of the Reynolds number. Obviously, it would be impractical, and perhaps a grave misdirection of government funds, for the Langley Field laboratory to undertake to test every airfoil presented to it.

"Hence, if low scale tests are not indicative of comparative merit, and since high scale tests are unattainable, and as the mathematics have not yet been developed for the precise prediction of practical airfoil performance without supporting experimentation, it may be that we must, for a while forget about wind tunnels, for this particular purpose, and, as each new design problem arises, design an airfoil as we think it should be to best meet the requirements of the particular case;—build our wings accordingly, and hope for the best in full flight results.

"With this in mind, an 'adjustable' airfoil section, upon which you have the data has been laid down. By manipulation of the basic section,—changing the thickness or curvature of the median line, or both, according to the methods outlined,—an indefinite number of sections may be obtained, which are affinal. Airfoils tapered in plan, or in thickness ratio, or both, may also be constructed and their characteristics predicted. The thickness may be changed to meet structural demands (wing beam, depth, etc.) and the curvature of median line varied to obtain Maximum Lift Coefficient or Minimum Drag Coefficient to meet the 'performance' requirements of a particular design problem. These latter two important characteristics,—important not only of themselves,—but also because they usually constitute an index of merit for all-around applicability—have been 'predicted'. It takes a deal of temerity to venture such 'predictions', but, after all, for the reasons stated, these predictions of full scale characteristics probably will neither be confirmed nor contradicted. If they are no more inaccurate for the purpose of full flight performance calculations than low scale tunnel tests, as judged by the National Advisory Committee tests, the adjustable airfoil series may be useful.



“The layout method is shown in Fig. 2. A straight ‘base’ line is first drawn with the desired chord length. Perpendiculars to this line are erected at the stations indicated in Table I and the curved median line plotted and drawn. Then straight lines are drawn, in each case perpendicular to the median line at its point of intersection with the ‘base’ ordinate line, and the contour of the section plotted from Table II and drawn.

“If a higher maximum lift coefficient than that for the basic section is desired, at the sacrifice of drag and center-of-pressure travel, the ordinates from Table I are multiplied by a *constant* factor greater than unity, to give the desired characteristics ‘predicted’ in the chart, Fig. 3. Conversely, if low drag or center-of-pressure travel is more important than high lift for the particular case, the constant factor may be less than unity.

“If deeper spars than may be contained within the basic section are required for strength and rigidity, at the sacrifice of drag, the ordinates from Table II are multiplied by a *constant* factor greater than unity, a ‘fatter’ section drawn around the median line selected, and its characteristics predicted from Fig. 4.

“The combinations of camber and thickness are infinite.”

TABLE I

Ordinates of Median Line. For Maximum Displacement .0400 Chord Length

[A] Distance from Leading Edge expressed in Terms of Chord Length
[B] Ordinates of Median Line in Terms of Chord Length

[A]	.025	.05	.075	.10	.15	.20	.30
[B]	.00224	.00911	.01491	.01951	.02671	.03183	.03760

[A]	.40	.50	.60	.70	.80	.90	
[B]	.03995	.03872	.03471	.02877	.02086	.01114	

Ordinates at Leading and Trailing Edges are 0

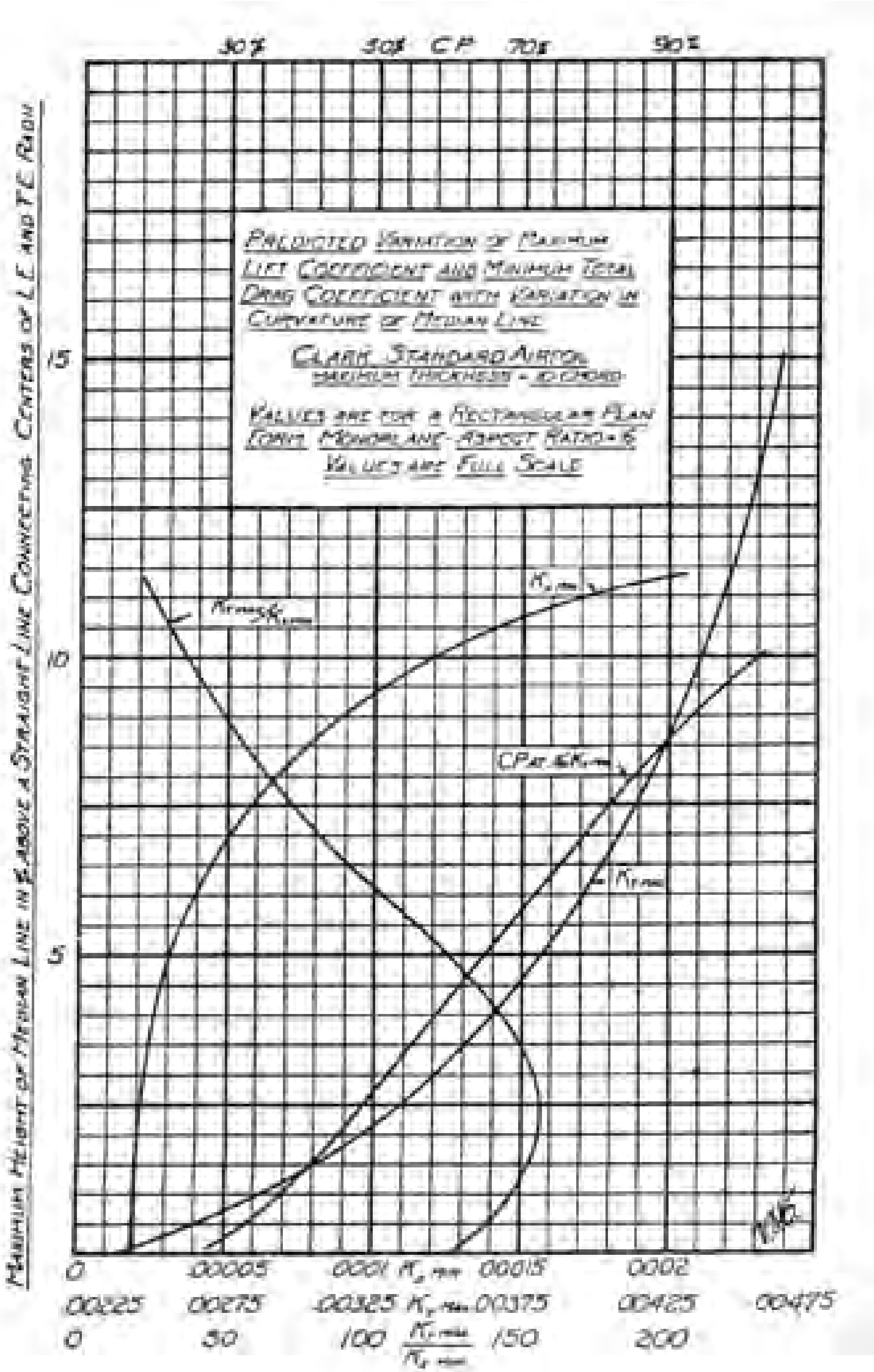
TABLE II

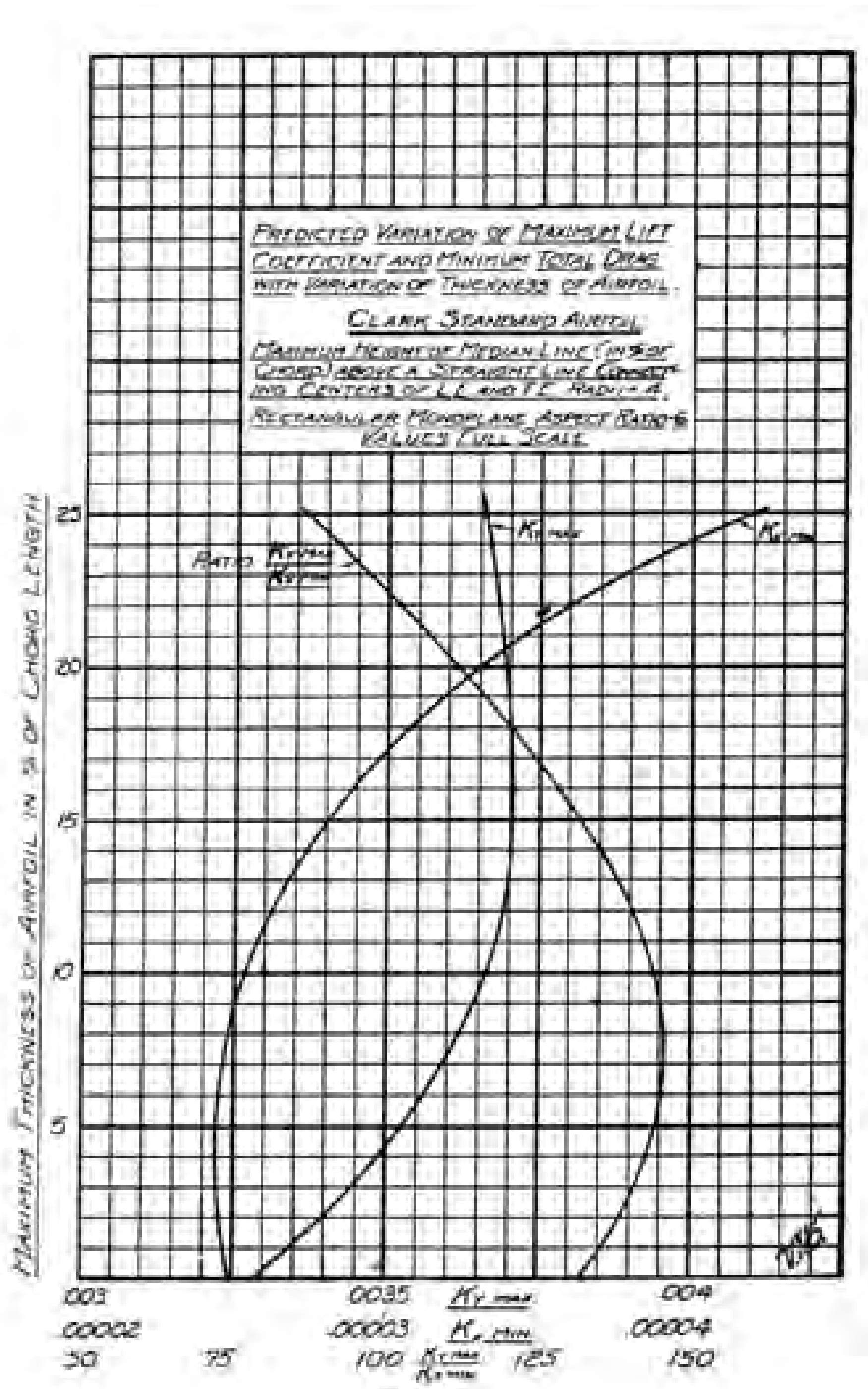
Half-thickness Ordinates. For Maximum Thickness .10 Chord Length

[C] Distance from L.E. in terms of Chord
[D] Half-thickness in terms of Chord

[C]	.025	.05	.075	.10	.15	.20	.30
[D]	.02191	.03016	.03582	.03996	.04539	.04856	.04985

[C]	.40	.50	.60	.70	.80	.90	1.00
[D]	.04722	.04236	.03593	.02836	.01988	.01077	.00119


30% 50% C.P. 70% 90%
PREDICTED VARIATION OF MAXIMUM LIFT COEFFICIENT AND MINIMUM TOTAL DRAG COEFFICIENT WITH VARIATION IN CURVATURE OF MEDIAN LINE
CLARK STANDARD AIRFOIL
VALUES ARE FOR A RECTANGULAR PLAN FORM MONOPLANE - ASPECT RATIO = 6
VALUES ARE FULL SCALE
CP AT .6 K
MAXIMUM HEIGHT OF MEDIAN LINE IN % ABOVE A STRAIGHT LINE CONNECTING CENTERS OF L.E. AND T.E. RADII
15
10
5
0 .00005 .0001 .00015 .0002
.00225 .00275 .00325 .00375 .00425 .00475
0 50 100 150 200
Fig. 3


PREDICTED VARIATION OF MAXIMUM LIFT COEFFICIENT AND MINIMUM TOTAL DRAG WITH VARIATION OF THICKNESS OF AIRFOIL.
CLARK STANDARD AIRFOIL
RECTANGULAR MONOPLANE ASPECT RATIO 6
VALUES FULL SCALE
RATIO
MAXIMUM THICKNESS OF AIRFOIL IN % OF CHORD LENGTH
25
20
15
10
5
.003 .0035 .004
.00002 .00003 .00004
50 75 100 125 150
Fig. 4

Document 4-3

Max M. Munk, "General Theory of Thin Wing Sections," NACA *Technical Report* 142 (Washington, 1922).

Munk's thin-airfoil theory was a turning point in the history of aerodynamics and therefore must be included in this chapter in spite of its highly arcane mathematical character. Mark Levinson, a retired professor of mechanical engineering at the University of Maine, has claimed in an unpublished history of early airfoil development ("Airfoil Profiles: Eyeballing, Design, and Selection, 1880-1922," March 1985, pp. 28-9) that TR 142 ushered in "the modern history of airfoil profiles." "All previous work, whether theoretical, experimental, or merely cut-and-try, may be considered as belonging to the pioneer period of that history." Munk's thin-airfoil history is to airfoil design what "the Euler-Bernouilli beam theory is to any of the modern, sophisticated theories of elastic rods or what lumped-parameter electric-circuit theory is to the full equations of electromagnetic field theory"—it is a theory of the "first order." Such theories prove "quite adequate for the purposes of engineering design: the good engineer understands the limitations of such approximate theories and knows when not to use them."

Walter G. Vincenti, a former NACA aerodynamicist at Ames Aeronautical Laboratory in California and professor emeritus of aerospace engineering at Stanford University, has written in *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (p. 36) that "Munk theory's provided a new and illuminating way to think about airfoils and caused a basic shift in airfoil design." Before Munk, airfoil designers used "experience and judgment" to draw an airfoil shape, hoping that the lift and drag would be favorable; after Munk, they could "synthesize profiles with approximately predictable lifting characteristics."

A reader untrained in aerodynamics will no doubt have a difficult time understanding the paper, in part because of Munk's own challenging composition style. Still, we encourage at least a brief examination of the paper, both to ascertain the highly mathematical nature of most aerodynamic theory, Munk's and others, and to gain some general insight into the contents of one of the most historic papers in the history of aerodynamics.

Document 4-3, Max M. Munk, "General Theory of Thin Wing Sections,"* *NACA* Technical Report *142 (Washington, 1922).

REPORT No. 142.

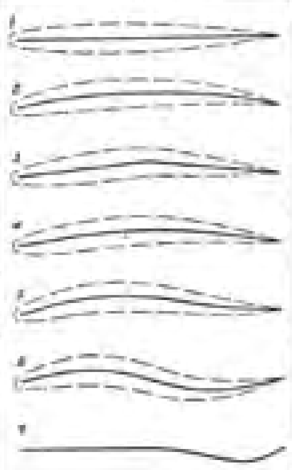
GENERAL THEORY OF THIN WING SECTIONS.

By Max M. Munk.

TABLE 1.

Per cent of chord	2.5	5	10	15	20	25	30	35	40	45	50
Factor	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Per cent of chord		[illegible]	60	[illegible]	70	75	80	85	90	95	97.5
Factor		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE 2.



Shape.	Equation of shape.	m	C_{m_0}
	$\eta = 0$	0	0
	[illegible]	[illegible]	0
	[illegible]	[illegible]	0
	[illegible]	[illegible]	0
	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]

RÉSUMÉ.

The following paper contains a new, simple method of calculating the air forces to which thin wings are subjected at small angles of attack, if their curvature is not too great. Two simple integrals are the result. They contain only the coordinates of the wing section. The first integral gives the angle of attack at which the lift of the wing is zero, the second integral gives the moment experienced by the wing when its angle is zero. The two constants thus obtained are sufficient to determine the lift and moment for any other angle of attack. This refers primarily to a two-dimensional flow in a nonviscous fluid. However, in combination with the theory of the aerodynamical induction, and with our empirical knowledge of the drag due to friction, the results are valuable for actual wings also. A particular result obtained is the calculation of the elevator effect. The following is an outline of the subject as treated in this report:

I. Introduction.
II. Calculation of the elevator effect.
III. General formula for any section.
IV. Examples of the zero angle.
V. Thin sections with upper and lower boundaries.
VI. The moment coefficient.
VII. Examples of the moment coefficient.
VIII. Table of the sections investigated.

I. INTRODUCTION.

By changing the angle between the stabilizer and the elevator the wing section formed by the combination of stabilizer and elevator is altered, and this alteration gives rise to new aerodynamical forces. It is useful to discuss this phenomenon from the theoretical point of view, however imperfect the result may be as a consequence of neglecting the viscosity of the air. A theoretical investigation at least gives the limit of what to expect. It enables the investigator to survey and keep in mind a great number of isolated experiences, whether the agreement between theory and experience be more or less close. It induces him to reflect on the phenomenon and thus becomes a source of progress by guiding him to new observations and experiments. It has often occurred even that some relation was thought to be confirmed by experience till the progress of theory made their relationship improbable. And only then the experiments confirmed the improved relation, contrary to what they were supposed to do before. A very conspicuous example of this is the discovery of differences in the atomic weight of certain elements. But is it really necessary to plead for the usefulness of theoretical work? This is nothing but systematical thinking and is not useless as sometimes supposed, but the difficulty of theoretical investigation makes many people dislike it.

In this first section I wish to give a short summary of the theory which I am going later to apply and expand. This theory deals with the relation between the shape of a wing section and the air forces applied to it by a nonviscous fluid. Only the two-dimensional problem is considered. The theory between forms the completion of the theory of the induced drag, in which latter the three-dimensional arrangement of the wings and the lift produced by them alone is considered, without paying attention to the details of producing the lift. The value of the induced drag and the effective angle of attack of every part of the wings result from the calculation. The theory of the wing section, however, gives no drag at all, for the drag additional to the induced drag is due to viscosity. Nor does the theory of the wing section give the true value of the maximum lift. It can be stated, therefore, that the theory of the wing section in its present state gives no indication whatsoever of the practical value of the wing investigated. Still there remain three important pieces of information which can be derived from the theory, all more been or less agreeing with the real phenomenon. These are the relation between the angle of attack and the lift, in particular the angle of attack for lift, the travel of the center of pressure, and the distribution of pressure. It has to be kept in mind that the angle of attack thus calculated for a particular lift coefficient is not yet the true angle of attack of a finite wing. The induced angle of attack has to be added.

We are indebted for the theory of the wing section to Kutta . He showed how the method of the two-dimensional potential can be used to calculate the flow around between sections and hence to deduce the resulting air forces. He confined himself to the straight line and simple circular segments. His idea is to pick out among the multitude of possible potential flows that particular one around the wing section, which at great distance degenerates into parallel flow and which leaves the wing section at the rear edge. His results are simple and important. The direction of the air flow in the case of zero lift of a circular segment of small curvature is parallel to the line dividing into equal parts the angle between the chord and the tangent at the rear end. The lift is proportional to the sine of the angle of attack. The slope of the curve of the lift coefficient plotted against the angle of attack is almost independent of the shape and it is 2π (the angle being measured in arc and the lift coefficient being formed by dividing of the lift per unit of the area by the dynamical pressure). That is, for small lift:

$$L = 2\pi\, S\, \alpha_1\, V^2\, (\rho / 2)$$

Joukowsky extended the theory, and investigated sections which at their rear end almost coincide with a circular segment, having there a common tangent for the upper and lower side. The entire form is generated from the circle, a circular segment forming as it were the skeleton of a Joukowsky section. Considering the connecting line between the rear edge and a pole near the center of curvature of the leading edge as the theoretical chord, the rule for the direction of the zero lift remains as before. The slope of the lift curve is hardly changed; the lift is proportional to the sine of the angles as before.

Karman replaced the circular segment in the Joukowsky section by one formed by two circular segments. This is already mentioned in the second paper of Kutta. These sections have two different tangents at the rear end, and the line which divides the rear angle into two equal parts determines the direction of the zero lift together with the theoretical chord as before. The law for the lift is the same again as for the circular segments of Kutta. Mises discusses in a general way how to obtain even more general sections and proves some general theorems concerning them. The most important is the theorem that the slope of the lift curve plotted as before is never smaller than 2π, and is always exactly 2π if the section is thin and the curvature small. So far it can be stated that only sections are investigated, the medial line of which is a circular segment. If the section is only moderately thick and if the curvature is moderate, too, the lift agrees with that of the segment according to the law found by Kutta.

Document 4-4

Max M. Munk and Elton W. Miller, "Model Tests with a Systematic Series of 27 Wing Sections at Full Reynolds Number," NACA *Technical Report* 221 (Washington, 1925).

This report by Dr. Max Munk announced the first airfoil family in NACA history. Coauthored by Langley engineer Elton W. Miller, it declared that wind-tunnel tests in the VDT showed "remarkable agreement" with Munk's thin-airfoil theory and resulted in the design of several sections (especially the M-6 and M-12) with excellent characteristics. Their most distinctive feature was an S-shaped mean camber line giving a reflexed (or folded back) trailing edge and a stationary center of pressure. The NACA, delighted that its VDT was establishing itself as the primary source worldwide for aerodynamic design data at high Reynolds number, even took the unusual step of naming the members of this experimental series the "M sections" after Munk, the same person who would be forced to resign from the organization two years later.

Though some were adopted for use, the "M section" airfoils never became tremendously popular with airplane builders, perhaps in part because of Munk's stormy departure from the NACA only a short time after their publication. More significantly, the research had not really been directed well enough to the production of airfoils suited to the needs of the time. Munk's method produced some effective shapes but not the optimum airfoils for the wings required by the higher performance, thicker-winged internally braced airplanes coming along in the late 1920s.

Document 4-4, Max M. Munk and Elton W. Miller, "Model Tests with a Systematic Series of 27 Wing Sections at Full Reynolds Number," NACA* Technical Report *221 (Washington, 1925).

REPORT No. 221

MODEL TESTS WITH A SYSTEMATIC SERIES OF 27 WING SECTIONS AT FULL REYNOLDS NUMBER

By, MAX M. MUNK and ELTON W. MILLER

SUMMARY

A systematic series of 27 wing sections, characterized by a small travel of the center of pressure, has been investigated at 20 atmospheres pressure in the variable density wind tunnel of the National Advisory Committee for Aeronautics.

The results are consistent with each other, and indicate that for such "stable" sections a small effective camber, a small effective S-shape and a thickness of 8 to 12 per cent lead to good aerodynamic properties

PURPOSE OF THE INVESTIGATION

This report contains the results of the investigation of the first systematic series of wing sections, 27 all together, made in the variable density wind tunnel of the National Advisory Committee for Aeronautics at about 20 atmospheres pressure. It was desired to obtain information about those aerodynamical properties of the wing sections which can not be computed. Those are the drag at several angles of attack, and the two values of the lift coefficient when (a) the lift coefficient has its maximum and (b) when the air forces change irregularly, commonly known as the "burble point." Without additional work, there was also obtained a check on the aerodynamic properties open to computation, namely, the lift and the moment.

PROGRAM OF THE INVESTIGATION

In this first systematic series the measurements were confined to one tank pressure, about 20 atmospheres. This gives approximately a full size, Reynolds number, for the model scale is about one-tenth, the velocity about one-half of the actual velocity.

The investigation was confined to such wing sections as have a very small travel of the center of pressure. The rate of the travel of the center of pressure is certainly an aerodynamic property of great practical importance, affecting the usefulness of the section for design purposes; it is not wise to compare the performance of several wing sections without taking the different rates of travel of the center of pressure, if any, into account. Within the useful range of the angle of attack, the wing sections described in this report have their center of pressure at about 25 per cent of the chord. Their rate of travel of the center of pressure is accordingly small, and the comparison of their performance is all that remains to be done. Wing sections with a larger rate of travel of the center of pressure may be taken up in a later research.

ARRANGEMENT OF THE TESTS

The 27 models were made of duralumin and were rectangular and not warped. The span is 30 inches; the aspect ratio is 6. The 27 wing sections form a systematic series. The series begins with three symmetrical sections of different thicknesses, Ml, M2, and M3. The curves are affine—i.e., the three sets of ordinates can be obtained from each other by multiplying each ordinate by a constant. Three more sections are then obtained by adding to each of the sets of ordinates M1, M2, M3

TABLE I

Section No. M1. Span 30 in. (76.2 cm). Area [illegible]. Average temperature [illegible] C. Average Reynolds No. [illegible]

Model No. [illegible]. Chord 5 in. (12.7 cm). Aspect ratio 6. Average pressure 20 atmos.

Angle of attack degrees	Dynamic pressure q kg/m²	Lift coefficient C_L	Drag coefficient C_D	Moment coefficient C_M
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE III

Section No. M3. Span 30 in. (76.2 cm). Area [illegible]. Average temperature [illegible] C. Average Reynolds No. [illegible]

Model No. [illegible]. Chord 5 in. (12.7 cm). Aspect ratio 6. Average pressure 20 [illegible] atmos.

Angle of attack degrees	Dynamic pressure q kg/m²	Lift coefficient C_L	Drag coefficient C_D	Moment coefficient C_M
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE II

Section No. M2. Span 30 in. (76.2 cm). Area [illegible]. Average temperature [illegible] C. Average Reynolds No. [illegible]

Model No. [illegible]. Chord 5 in. (12.7 cm). Aspect ratio 6. Average pressure [illegible] atmos.

Angle of attack degrees	Dynamic pressure q kg/m²	Lift coefficient C_L	Drag coefficient C_D	Moment coefficient C_M
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE IV

Section No. M4. Span 30 in. (76.2 cm). Area [illegible]. Average temperature [illegible] C. Average Reynolds No. [illegible]

Model No. [illegible]. Chord 5 in. (12.7 cm). Aspect ratio 6. Average pressure [illegible] atmos.

Angle of attack degrees	Dynamic pressure q kg/m²	Lift coefficient C_L	Drag coefficient C_D	Moment coefficient C_M
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

the set of ordinates of a certain camber line, say "a," so chosen that theoretically its center of pressure does not travel. The series is further increased by substituting double the ordinates, 2a for a; then another camber line "b," with the same stability characteristics, and then combinations of the two camber lines. The camber lines "a" and "b" will be most easily recognized in wing sections M4 and MI0. This process of obtaining the shapes of the wing sections leads to their classification in Table XXVIII. The ordinates of the sections are given in Table XXIX in per cent of the chord. Each figure contains a drawing of the section.

Each airfoil was exposed to the air stream of the variable density wind tunnel of the National Advisory Committee for Aeronautics. It was fastened by thin wires to the balance of this tunnel. Moreover, a skid rigidly fastened to the airfoil was hinged to a vertical bar, forming a part of the balance. This bar extends across the air stream in rear of the model; it is shielded from the air stream and can be moved up and down. When moved thus, the angle of attack of the airfoil is changed. After the airfoil was put in, the tank was closed and the air pressure increased up to about 20 atmospheres. The air forces of the airfoil were then determined over a range of several angles of attack. The drag of the wires and of other attachments were determined in a separate test under the same conditions of flow. The measured drag has been corrected for this drag of the fastening parts in the usual way.

RESULT OF THE TESTS

The results of the tests are given in Tables I to XXVII and are illustrated in the 27 figures. The angle of attack always refers to a line fixed with respect to the section as shown in each diagram. In the tables the air forces are represented by the lift coefficients, the drag coefficients, and the moment coefficients. The lift and drag coefficients are obtained by dividing the lift or drag by the wing and by the dynamic pressure V^2 ($\rho/2$) where V denotes the velocity of the air stream and ρ the mass density of the air. The diagrams are so-called polar curves. The lift coefficient is plotted vertically up, and against it to the right, the drag coefficient, and to the left the moment coefficient. This latter refers to the moment of the air forces with respect to a point of the chord, one quarter chord from the leading edge. This point is chosen because it gives the least variation of the moment coefficient. The moment is divided by the wing area, by the dynamic pressure, and by the length of the chord. The Reynolds number is computed with the chord as the characteristic length.

The parabola of the induced drag coefficient for the aspect ratio 6 has been inserted in each diagram. No correction has been made for the influence of the tunnel walls, which may be perceptible, as the wing span is half the tunnel throat diameter. This question is not yet sufficiently cleared up.

In Table XXX, a survey of the series and of the results obtained is given. The first column gives the number of the wing section. The next three columns contain the minimum drag coefficient, the lift coefficient at the "burble point," and the maximum lift coefficient, if any. The last column gives the average moment coefficient, which is always small for the wing sections considered in this investigation.

DISCUSSION OF THE RESULTS

The main results of this test lie in the presentation of new information about the properties of the wing sections given in the tables and in the diagrams.

It seems that a small travel of the center of pressure is generally combined with a smaller maximum lift coefficient. Good sections are in the neighborhood of M6.

The test charts show that at full size Reynolds number, the minimum drag is much smaller than we are accustomed to obtain in the ordinary atmospheric wind tunnel. The maximum lift is not necessarily larger at a larger Reynolds number.

MODEL TESTS

One remark concerning the results seems pertinent. As shown by mathematical reasoning in Technical Report No. 191 of the National Advisory Committee for Aeronautics, the moment curves in the diagrams should theoretically be straight vertical lines. Most of them have approximately this shape, but not all of them. The small discrepancies can often be explained by taking the second approximation of the computations into account. For instance, with actual sections of a finite thickness, the theoretical leading edge is situated halfway between the actual one and the center of curvature of the leading edge, giving a shorter effective chord than the

actual one. A very thick section, besides, is slightly more stable than a thin section of the same mean curve. Quite irregular moment curves can only be explained by sudden changes of the character of the flow just as at the burble point.

CONCLUSION

Looking at the results obtained in the variable density tunnel (including Technical Report No. 217) from a broader point of view, it is now established that the results obtained at the full size Reynolds number do not agree with the results at a diminished Reynolds number. Furthermore, tests now under way show that the variable density tunnel operated at one atmosphere gives results with a given wing section similar to the results obtained in other wind tunnels.

We conclude from these facts that the results obtained at full size Reynolds number will give better information to the designer than tests run at largely reduced Reynolds number. The information from the new tunnel will become more and more useful in the same degree as more results are obtained from it, so that results of new tests can be compared with results of similar older tests made under the same conditions.

Document 4-5(a-f)

(a) Ralph H. Upson to the NACA, "Attention: Mr. Victory," 19 November 1928, in Research Authorization (RA) file 270, Historical Archives, NASA Langley Research Center, Hampton, Va.

(b) Eastman N. Jacobs to Elton W. Miller, "Suggestions from Mr. R. H. Upson," undated (ca. 1 February 1929), RA file 270.

(c) Ralph H. Upson to Dr. G.W. Lewis, 19 March 1929, RA file 270.

(d) Eastman N. Jacobs to Elton W. Miller, 4 April 1929, RA file 270.

(e) G.W. Lewis to Langley Memorial Aeronautical Laboratory, "Airfoil tests suggested by Mr. R. H. Upson," 22 April 1929, RA file 270.

(f) Eastman N. Jacobs to Chief of the Aerodynamics Division (Elton W. Miller), "Airfoil testing program in Variable Density Tunnel," 17 May 1929, RA file 270.

This string of six short documents provides insight into the genesis of the NACA's famous four-digit airfoil series and suggests that an engineer outside of the NACA, Ralph H. Upson of the Aeromarine Klemm Corporation in New Jersey, played an important role in stimulating the research.

The story told by the documents begins on 19 November 1928 when Klemm sent a letter to the NACA (a) asking them to conduct a test that would provide additional information on the effect of median curvature of profile drag, and on the drag of squared ends of rectangular airfoils. Asked to respond to Upson's request, Langley engineer Eastman N. Jacobs, head of Langley's Variable-Density Tunnel section, sent an undated handwritten memo (b) to his boss, Elton W. Miller, chief of the aerodynamics division. In it, Jacobs explained how Upson's concerns could be addressed by further tests in the VDT. After receiving a response to his inquiry (a document not included) from Dr. George W. Lewis, the NACA's director of research in Washington, Upson again wrote the NACA (c), on 19 March 1929, this time directly to Lewis, with some additional questions, along with the assertion that "Of the many things that affect the so-called profile drag, thickness is surely the most important and fundamental." In particular Upson expressed serious concern that the wind-tunnel tests being proposed by the NACA engineers at Langley would fail to clarify the effect of thickness on the profile drag of an airfoil specifically; the tests, he felt, would mix up the three variables of thickness, median curvature, and type of curvature, and only leave him and others confused as to what wing section variable was actually causing a particular effect.

Again, Jacobs was brought into it, and his response (d) indicated agreement with Upson's criticism of the wind tunnel program as planned: it would be "better from both the theoretical and practical design standpoints" to treat the thickness variation and mean camber line shape as the fundamental properties of an airfoil, rather than variations in the shape of the upper and lower surfaces, the traditional emphasis.

On 22 April 1929, George Lewis approved (e) adding the testing recommended by Upson and endorsed by Jacobs to an existing NACA research authorization (no. 217), three months later to be superseded by a brand new RA (no. 290), calling for an "Investigation of Thickness and Mean Camber Line Shape on Airfoil Characteristics." In the meantime, on 17 May 1929, Jacobs, in a two-page memo to Elton Miller (f), laid out the desired airfoil testing program in the VDT and the engineering rationale for it. The last paragraph of this memo stated that the number of airfoils covered by the program might be as high as 80, the largest number of related airfoil shapes ever to be considered for a single test program up to that time.

As we will see later, Jacobs would be wrong, but only by two: the actual number would turn out to be 78.

Document 4-5(a), R.H. Upson to the NACA, "Attention: Mr. Victory," 19 November 1928, in Research Authorization (RA) file 270, Historical Archives, NASA Langley Research Center, Hampton, Va.

Aeromarine Klemm Corporation

Factory
New York Office
Keyport, N.J.
Paramount Building

Keyport, New Jersey
November 19, 1928.

National Advisory Committee for Aeronautics
3841 Navy Building
17th & B Streets, N.W.
Washington, D. C.

Attention: Mr. Victory.

Dear Sirs:

I have been making a little study on wing proportions which gives indications of very unusual value for practical design purposes. To prove the correctness of my premises, however, I am in very great need of some further information that so far I have been unable to get, viz.,

1. The effect of median curvature on profile drag.
2. The drag of square ends of rectangular airfoils.

R. & M. Report #946 gives evidence that the minimum profile drag is practically independent of median curvature, providing the latter is smooth and continuous. The experiments are confined to relatively thin sections at relatively low Reynolds numbers, however. Do you know of any experiments that have been made on thick sections at high Reynolds numbers?

I wrote once before on the subject of end drag, and also consulted Lieut. Diehl on the subject but apparently at that time there was little information available and none apparently on thick sections at high Reynolds numbers. The latter information, Item 2, is much more important than item 1. If you haven't as yet any accurate information available, don't you think that it would be worth while running a few simple experiments in the variable density tunnel to get at least two or three points on the curve? If you don't appreciate the importance of it, I think I can readily convince you of it the next time I am in Washington.

Yours very truly,
R. H. Upson

Document 4-5(b), Eastman N. Jacobs to Elton W. Miller, "Suggestions from Mr. R. H. Upson," undated (ca. 1 February 1929), RA file 270.

Memo to: Mr. Miller
Subject: Suggestions from Mr. R. H. Upson.
Reference: NACA Letter Jan. 23, 1929.

1. The two questions which Mr. Upson asked are both ones which should be answered by conducting tests in the variable density wind tunnel. The second question in regard to the drag of square ends of airfoils is, I think, the most important and also the easiest to investigate. It is likely that the scale effect on the drag of airfoil tips will be found to be large.

2. The first question, in regard to the effect of median curvature on profile drag, is a part of the more general problem of predicting airfoil characteristics. This question is considered and the existing data from tests in the variable density tunnel analyzed in the unpublished report on the above subject by G. J. Higgins. The tests to be carried out under R.A. 217 will be of value in answering such questions. Under this R.A. the upper camber is to be maintained constant and the lower varied from convex to concave thus changing the mean camber. It seems certain from disconnected tests made heretofore in the variable density tunnel, that there is a tendency for the profile drag to increase with mean camber for airfoils of a given thickness.

Eastman N. Jacobs
Assistant Aeronautical Engineer

Document 4-5(c), R.H. Upson to Dr. G.W. Lewis, 19 March 1929, RA file 270.

AEROMARINE KLEMM CORPORATION
Keyport, N.J.

March 19, 1929

Dr. G. W. Lewis
Director of Aeronautical Research
National Advisory Committee for Aeronautics
3841 Navy Building
Washington, D. C.

Dear Dr. Lewis:

In reference to your March 15th letter on profile drag, I hope you won't mind this further comment and inquiry on a subject to which I have given considerable thought, especially as my previous letter may not have been quite clear.

Of the many things that affect the so-called profile drag, thickness is surely the most important and fundamental, on account of its direct bearing on structural weight, stiffness and aspect ratio. For airfoils otherwise similar in type of curve, the thickness equation could probably be evaluated with fair accuracy from tests already made, if we knew the effect of median curvature, and the end drag for thick sections. But if several series of tests can be made it would seem better yet to make thickness the sole variable in any one series, minimizing the end drag by simply rounding the tips in front elevation. The end drag could also be checked by a test at small aspect ratio (say, half span).

In the tests you propose it is hard to see how you can avoid mixing up the three variables of thickness, median curvature and type or family of curve, all in one series. Of course, I appreciate that you have other objects in mind than the testing of profile drag. But for maximum utility in this respect I would strongly urge that the various tests be made susceptible of classification into groups and cross-groups, each of which involves the fewest and simplest possible variables, and that sections be included with a thickness ratio up to at least 25%.

The M series of airfoils (Report #221) are a good illustration of what I mean. The system in principle could hardly be improved upon; but unfortunately the range of thickness is insufficient for the range of modern design, and the cambers are confined to the relatively complex (though useful) reflex type.

I am trying to get off my chest here everything that might savor of criticism before the coming conference; not that you appear to mind, however, for you have always been wonderfully receptive to new ideas; also, if I am wrong I stand to be corrected.

With much appreciation for your interest.

Most sincerely,
R. H. Upson

Document 4-5(d), Eastman N. Jacobs to Elton W. Miller, 4 April 1929, RA file 270.

April 4, 1929

MEMORANDUM For Mr. Miller,

1. I am inclined to agree with Mr. Upson that the program as planned is not as good as the one which he has suggested. In our proposed program we vary the shape of the upper and lower surfaces of the airfoils, as these were once considered the fundamental properties of an airfoil. More recently there is a tendency to abandon this conception in favor of treating the thickness variation and mean camber line shape as the fundamental properties. This view is better from both the theoretical and practical design standpoints, because the shape of the mean camber line determines the angle of zero lift and pitching moment characteristics, and the thickness determines, almost independently, the drag, structure, desirable aspect ratio, structural weight, etc.

2. As previously stated, I agree with Mr. Upson about the importance of investigating the effect of tip shape and also its variation with thickness. It is reasonable to suppose that rounding the airfoil tips in front elevation will reduce the drag caused by the eddies produced by the sharp angles at the ends of the wing. This increment of profile drag should probably not be charged against the thick airfoils.

Eastman N. Jacobs,
Assistant Aeronautical Engineer

Document 4-5(e), G.W. Lewis to Langley Memorial Aeronautical Laboratory, "Airfoil tests suggested by Mr. R.H. Upson," 22 April 1929, RA file 270.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
3841 NAVY BUILDING, 17TH AND B STREETS NW.
WASHINGTON, D. C.

April 22, 1929.

To:	Langley Memorial Aeronautical Laboratory.
Subject:	Airfoil tests suggested by Mr. R. H. Upson.
Reference:	(a) L.M.A.L. letter EWM.B, April 4.
	(b) Research Authorization No. 217.

1. Reference (a) suggested that it would be desirable that some airfoil tests be conducted under research Authorization No. 217 on the basis of varying mean cambers instead of variations in the upper and lower surfaces, the tests to be carried out in the variable-density wind tunnel.

2. It is suggested that you forward to this office your suggestions as to revision of the wording of "Brief Description of Method" of Research Authorization No. 217 to embody the modifications in the program which you suggest in reference (a).

G. W. Lewis,
Director of Aeronautical Research

Document 4-5(f), Eastman N. Jacobs to Chief of the Aerodynamics Division (Elton W. Miller), "Airfoil testing program in Variable Density Tunnel," 17 May 1929, RA file 270.

May 17, 1929.

MEMORANDUM For Chief of Aerodynamics Division.
Subject: Airfoil testing program in Variable-Density Tunnel.
Reference: (a) NACA Let. Apr. 22, 1929.
(b) Research Authorization No. 217.

1. In accordance with the request of reference (a), a revised program of airfoil tests under Research Authorization No. 217 has been considered. An examination of several airfoils which have good aerodynamic characteristics indicates that, when they are reduced to the same maximum thickness, the variation of thickness along the chord is very nearly the same. For the Göttingen 398, Clark Y, C-62, and the R.A.F. 31 the deviation of the thickness variation from the mean is less than ±2 percent. It will, therefore, be necessary to study only various combinations of maximum thickness, maximum mean camber, and mean camber line shape.

2. My suggestions as to a suitable program are embodied in the following rewording of "Brief Description of Method" of Research Authorization No. 217. If it should be considered to change research Authorization No. 217, it is suggested that a program similar to this should be carried out under a new research authorization. However, it is believed that the research here outlined is so extensive that the one outlined under Research Authorization No. 217 is unnecessary, especially in view of the similar research, already completed, on the Navy propeller sections.

3. A family of airfoils is to be developed, all having the same relative variation in thickness along the chord, but having five values of the maximum thickness: 6, 9, 12, 15, 18, and 21 per cent of the chord. The thickness variation is to be chosen so that it will be similar to that of the best airfoils which have been developed in the past. The airfoils are to be formed by thickening four types of mean camber lines as follows: a straight line, three circular arcs, six curves having their maximum ordinate at four-tenths of the chord behind the leading edge and three curves having their maximum ordinate at three-tenths of the chord behind the leading edge. These airfoils are to be constructed of metal and tested in the Variable Density Tunnel at 1 and 20 atmospheres. The results are to be analyzed with a view to establishing the relation of the thickness and mean camber line to the aerodynamic characteristics of an airfoil.

4. The program, as outlined above, requires the testing of about eighty airfoils. A job order to cover further study of the development of such a family has been requested. This study may indicate that it will be unnecessary to investigate all of the eighty airfoils.

Eastman N. Jacobs,
Assistant Aeronautical Engineer

Document 4-6

Eastman N. Jacobs, Kenneth E. Ward, and Robert M. Pinkerton, "The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-density Wind Tunnel," NACA *Technical Report* 460 (Washington, 1933).

Besides providing data on a highly efficient series of new wing sections, *Technical Report 460* formally introduced the NACA's ingenious new way of numerically coding its airfoils. Devised by Eastman Jacobs with help from his closest associates, and patterned after a similar system used to identify the composition of steel alloys, the code literally enumerated an airfoil shape. Like all other aerodynamical laboratories, Langley until then had designated airfoils simply by numbering them in the sequence in which they had been tested (as in Munk's M-1, M-2, M-3, and so forth). In the new system, four numbers indicated the airfoil section's critical geometrical properties—thus the name the "four-digit" series. The first integer represented the maximum mean camber in percent of the chord; the second integer represented the position of the maximum mean camber in tenths of the chord from the leading edge; and the last two integers represented the maximum thickness in percent of the chord. Thus, airfoil "N.A.C.A. 2415" was a wing section having 2 percent camber at 0.4 of the chord from the leading edge, with thickness 15 percent of the chord. Zeroes were used for the first two integers when the section was symmetrical, as was the case of N.A.C.A. 0015.

In this simple graphic way, the NACA's numerical designation of wing profiles provided a wonderful shorthand statement of the values of the three critical airfoil parameters: the height and chordwise location of the uppermost point of the camber line and the magnitude of the maximum thickness. From the time TR 460 appeared in print, one could say, for instance, "N.A.C.A. 2415," and a complete airfoil shape would appear in any aerodynamicist's mind's eye. Reminding as much as instructing, the NACA's airfoil report complemented the coded information with graphic illustrations of two independent sets of curves. These curves communicated knowledge basic to an engineer's understanding of the relationships among an airfoil's variables. Pictorial representation of airfoil data – the outline of the physical shape reinforced by performance curves and the digital code – gave aeronautical engineers ready access to the wide range of parametric data necessary to their work. The NACA's digest gave them "a whole range of wings from which to choose, the way one might select home furnishings or automobile accessories from a catalog" (Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915-1958*, NASA SP-4103 (Washington, 1985) 2: 539-40).

Document 4-6, Eastman N. Jacobs, Kenneth E. Ward, and Robert M. Pinkerton, "The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-density Wind Tunnel,"
NACA **Technical Report** *460 (Washington, 1933).*

REPORT No. 460
THE CHARACTERISTICS OF 78 RELATED AIRFOIL SECTIONS FROM TESTS IN THE VARIABLE-DENSITY WIND TUNNEL

By EASTMAN N. JACOBS, KENNETH E. WARD, and ROBERT M. PINKERTON

SUMMARY

An investigation of a large group of related airfoils was made in the N.A.C.A. variable-density wind tunnel at a large value of the Reynolds number. The tests were made to provide data that may be directly employed for a rational choice of the most suitable airfoil section for a given application. The variation of the aerodynamic characteristics with variations in thickness and mean-line form were therefore systematically studied.

The related airfoil profiles for this investigation were developed by combining certain profile thickness forms, obtained by varying the maximum thickness of a basic distribution, with certain mean lines, obtained by varying the length and the position of the maximum mean-line ordinate. A number of values of these shape variables were used to derive a family of airfoils. For the purposes of this investigation the construction and tests were limited to 68 airfoils of this family. In addition to these, several supplementary airfoils have been included in order to study the effects of certain other changes in the form of the mean line and in the thickness distribution.

The results are presented in the standard graphic form representing the airfoil characteristics for infinite aspect ratio and for aspect ratio 6. A table is also given by means of which the important characteristics of all the airfoils may be conveniently compared. The variation of the aerodynamic characteristics with changes in shape is shown by additional curves and tables. A comparison is made, where possible, with thin-airfoil theory, a summary of which is presented in an appendix.

INTRODUCTION

The forms of the airfoil sections that are in common use today are, directly or indirectly, the result of investigations made at Göttingen of a large number of airfoils. Previously, airfoils such as the R.A.F. 15 and the U.S.A. 27, developed from airfoil profiles investigated in England, were widely used. All these investigations,

however, were made at low values of the Reynolds Number; therefore, the airfoils developed may not be the optimum ones for full-scale application. More recently a number of airfoils have been tested in the variable-density wind tunnel at values of the Reynolds Number approaching those of flight but, with the exception of the M-series and a series of propeller sections, the airfoils have not been systematically derived in such a way that the results could be satisfactorily correlated.

The design of an efficient airplane entails the careful balancing of many conflicting requirements. This statement is particularly true of the choice of the wing. Without a knowledge of the variations of the aerodynamic characteristics of the airfoil sections with the variations of shape that effect the weight of the structure, the designer cannot reach a satisfactory balance between the many conflicting requirements.

The purpose of the investigation reported herein was to obtain the characteristics at a large value of the Reynolds Number of a wide variety of related airfoils. The benefits of such a systematic investigation are evident. The results will greatly facilitate the choice of the most satisfactory airfoil for a given application and should eliminate much routine airfoil testing. Finally, because the results may be correlated to indicate the trends of the aerodynamic characteristics with changes of shape, they may point the way to the design of new shapes having better characteristics.

Airfoil profiles may be considered as made up of certain profile-thickness forms disposed about certain mean lines. The major shape variables then become two, the thickness form and the mean-line form. The thickness form is of particular importance from a structural standpoint. On the other hand, the form of the mean line determines almost independently some of the most important aerodynamic properties of the airfoil section, e.g., the angle of zero lift and the pitching-moment characteristics.

The related airfoil profiles for this investigation were derived by changing systematically these shape variables. The symmetrical profiles were defined in terms of a basic thickness variation, symmetrical airfoils of varying thickness being obtained by the application of factors to the basic ordinates. The cambered profiles were then developed by combining these thickness forms with various mean lines. The mean lines were obtained by varying the camber and by varying the shape of the mean line to alter the position of the maximum mean-line ordinate. *The maximum ordinate of the mean line is referred to throughout this report as the camber of the airfoil and the position of the maximum ordinate of the mean line as the position of the camber. An airfoil, produced as described above, is designated by a number of four digits: the first indicates the camber in percent of the chord; the second, the position of the camber in tenths of the chord from the leading edge; and the last two, the maximum thickness in percent of the chord.* Thus the N.A.C.A. 2315 airfoil has a maximum camber of 2 percent of the chord at a position 0.3 of the chord from the leading edge, and a maximum thickness of 15 percent of the chord; the N.A.C.A. 0012 airfoil is a symmetrical airfoil having a maximum thickness of 12 percent of the chord.

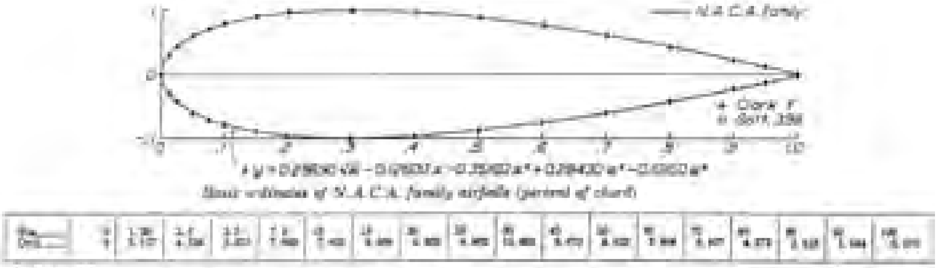


FIGURE 1.—Thickness variation.

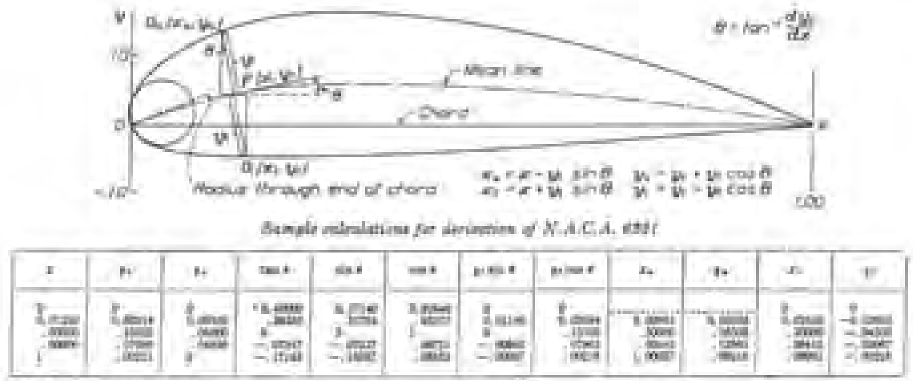


FIGURE 2.—Method of calculating ordinates of N.A.C.A. cambered airfoils.

In addition to the systematic series of airfoils, several supplementary airfoils have been included in order to study the effects of a few changes in the form of the mean line and in the thickness distribution.

Preliminary results which have been published include those for 12 symmetrical N.A.C.A. airfoils, the 00 series and other sections having different nose shapes; and those for 42 cambered airfoils, the 43 and 63 series, the 45 and 65 series, the 44 and 64 series, and the 24 series.

The tests were made in the variable-density wind tunnel of the National Advisory Committee for Aeronautics during the period from April 1931 to February 1932.

DESCRIPTION OF AIRFOILS

Well-known airfoils of a certain class including the Göttingen 398 and the Clark Y, which have proved to be efficient, are nearly alike when their camber is removed (mean line straightened) and they are reduced to the same maximum thickness. A thickness variation similar to that of these airfoils was therefore chosen for the development of the N.A.C.A. airfoils. An equation defining the shape was used as a method of producing fair profiles.

When the mean lines of certain airfoils in common use were reduced to the same maximum ordinate and compared it was found that their shapes were quite different. It was observed, however, that the range of shapes could be well covered by assuming some simple shape and varying the maximum ordinate and its position along the chord. The mean line was, therefore, arbitrarily defined by two parabolic equations of the form

$$y_c = b_0 + b_1 x + b_2 x^2$$

where the leading end of the mean line is at the origin and the trailing end is on the x axis at $x = 1$.

A family of related airfoils was derived. Seven values of the maximum thickness, 0.06, 0.09, 0.12, 0.15, 0.18, 0.21, and 0.25; four values of the camber, 0.00, 0.02, 0.04, and 0.06; and six values of the position of the camber, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 were used to derive the related sections of this family. The profiles of the airfoils derived are shown collectively in figure 3.

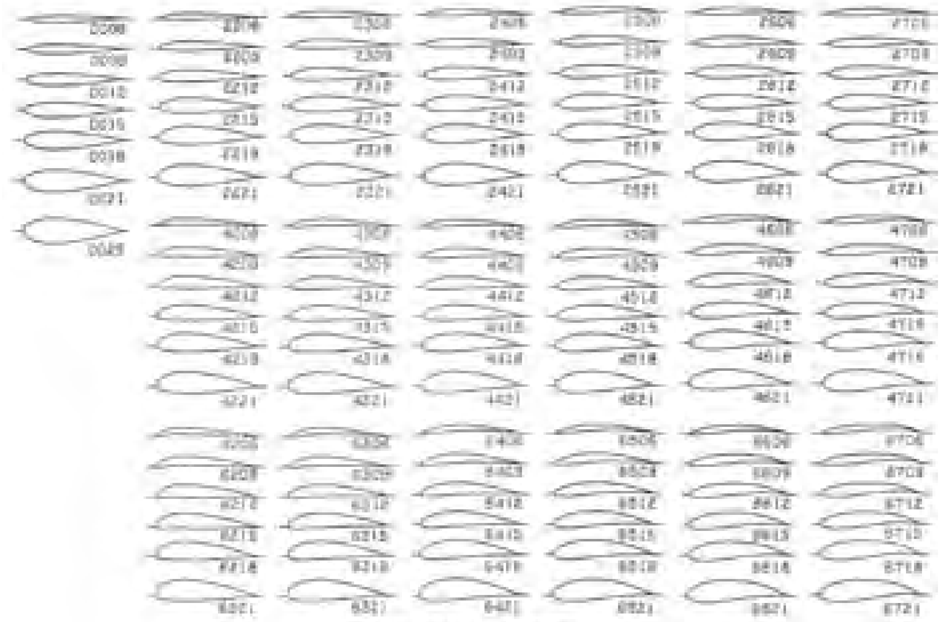


FIGURE 3.—N.A.C.A. airfoil profiles.

For the purposes of this investigation the construction and tests were limited to 68 of the airfoils. Tables of ordinates at the standard stations are given in the figures presenting the aerodynamic characteristics. These ordinates were obtained graphically from the computed ordinates for all but the symmetrical sections. Two sets of trailing-edge ordinates are given. Those enclosed by parentheses, which are given to facilitate construction, represent ordinates to which the surfaces are faired. In the construction of the models the trailing edges were rounded off.

Three groups of supplementary airfoils were also constructed and tested. The derivation of these airfoils will be considered later with the discussion.

APPARATUS AND METHODS

A description of the variable-density wind tunnel and the method of testing is given in reference 8. [N.A.C.A. TR 416, not included herein. See chapter 2 for a description of the variable-density tunnel.] The models, which are made of duralumin, have a chord of 5 inches and a span of 30 inches. They were constructed from the computed ordinates by the method described in reference 8.

Routine measurements of lift, drag, and pitching moment about a point on the chord one quarter of the chord behind its forward end were made at a Reynolds Number of approximately 3,000,000 (tank pressure, approximately 20 atmospheres). Groups of airfoils were first tested to study the variations with thickness, each group containing airfoils of different thicknesses but having the same mean line. Finally, all airfoils having a thickness of 12 percent of the chord were tested to study the variations with changes in the mean line.

RESULTS

The results are presented in the standard graphic form (figs. 4 to 8) as coefficients corrected after the method of reference 8 to give airfoil characteristics for infinite aspect ratio and aspect ratio 6. Where more than one test has been used for the analysis, the infinite aspect ratio characteristics from the earlier test have been indicated by additional points on the figure. Table I gives the important characteristics of all the airfoils.

CONCLUSIONS

The variation of the aerodynamic characteristics of the related airfoils with the geometric characteristics investigated may be summarized as follows:

Variation with thickness ratio:

1. The slope of the lift curve in the normal working range decreases with increased thickness, varying from 95 to 81 percent, approximately, of the theoretical slope for thin airfoils (2π per radian).

2. The angle of zero lift moves toward zero with increased thickness (above 9 to 12 percent of the chord thickness ratios).

3. The highest values of the maximum lift are obtained with sections of normal thickness ratios (9 to 15 percent).

4. The greatest instability of the air flow at maximum lift is encountered with the moderately thick, low-cambered sections.

5. The magnitude of the moment at zero lift decreases with increased thickness, varying from 97 to 64 percent, approximately (for normally shaped airfoils), of the values obtained by thin-airfoil theory.

6. The axis of constant moment usually passes slightly forward of the quarter-chord point, the displacement increasing with increased thickness.

7. The minimum profile drag varies with thickness approximately in accordance with the expression

$$C_{D_0 min} = k + 0.0056 + 0.01t + 0.1t^2$$

where the value of k depends upon the camber and t is the ratio of the maximum thickness to the chord.

8. The optimum lift coefficient (the lift coefficient corresponding to the minimum profile-drag coefficient) approaches zero as the thickness is increased.

9. The ratio of the maximum lift to the minimum profile drag is highest for airfoils of medium thickness ratios (9 to 12 percent).

Variation with camber:

1. The slope of the lift curve in the normal working range is little affected by the camber; a slight decrease in the slope is indicated as the position of the camber moves back.

2. The angle of zero lift is between 100 and 75 percent, approximately, of the value given by thin-airfoil theory, the smaller departures being for airfoils with the normal camber positions.

3. The maximum lift increases with increased camber, the increase being more rapid as the camber moves forward or back from a point near the 0.3*c* position.

4. Greater stability of the air flow at maximum lift is obtained with increased camber if the camber is in the normal positions (0.3*c* to 0.5*c*).

5. The moment at zero lift is nearly proportional to the camber. For any given thickness, the difference between the experimental value of the constant of proportionality and the value predicted by thin-airfoil theory is not appreciably affected by the position of the camber except for the sections having the maximum camber well back, where the difference becomes slightly greater.

6. The axis of constant moment moves forward as the camber moves back.

7. The minimum profile drag increases with increased camber, and also with a rearward movement of the camber.

8. The optimum lift coefficient increases with the camber and for the highly cambered sections a definite increase accompanies a forward movement of the camber.

9. The ratio of the maximum lift to the minimum profile drag tends to decrease with increased camber (above 2 percent of the chord) and with a rearward movement of the camber (for the highly cambered sections).

Document 4-7(a-e)

(a) C.W. Howard, Major, Air Corps, and Chief, Engineering Section, Materiel Division, Office of the Chief of the Division, Wright Field, Dayton, Oh., 13 Jan. 1933, in RA file 290, LHA, Hampton, Va.

(b) Montgomery Knight, Director, Daniel Guggenheim School of Aeronautics, Georgia School of Technology, Atlanta, Ga., to George W. Lewis, NACA, Navy Building, Washington, D.C., 19 Jan. 1932, in Research Authorization (RA) file 290, LHA, Hampton, Va.

(c) Edward P. Warner, Editor, *Aviation*, New York, N.Y., to George W. Lewis, NACA, 20 Jan. 1933, in RA file 290, LHA, Hampton, Va.

(d) G.W. Lewis to Dr. Joseph Ames, Johns Hopkins University, Baltimore, Md., 10 June 1933, in RA file 290, LHA, Hampton, Va.

(e) "Possible Saving by Use of N.A.C.A. 2415 Airfoil," undated (ca. summer 1932), in RA file 290, LHA, Hampton, Va.

This string of five short letters from 1933 presents some of the extremely favorable immediate reaction to the NACA's release of the four-digit airfoil data. On 13 January 1933, Major C.W. Howard, chief of the engineering section of the Army Air Corps at Wright Field, wrote a letter to Lewis (a), after receiving a preliminary version of what will become TR 460, applauding its "great value to the designer." The same week, Professor Montgomery Knight, director of the Daniel Guggenheim School of Aeronautics at what was then called the Georgia School of Technology in Atlanta (Georgia Tech), wrote favorably to the NACA's George Lewis after reading advanced copies of two papers by Eastman Jacobs, one of them a preliminary version of what would become TR 460. In his letter (b) Knight, a former NACA Langley engineer, expressed with confidence that "the tests on this extensive series should bring in a new era into the choice of airfoils for different purposes." The next day Lewis received a letter from Edward P. Warner (c) in which the distinguished editor of *Aviation* magazine called the airfoil report "a perfectly marvelous job." By mid-year, Lewis had received so many congratulatory letters about the new airfoils, including several from the aircraft industry, that in sending out copies of the final report, he boasted (d) to Dr. Joseph Ames, NACA Chairman and physics professor at Johns Hopkins University, that "Mr. Jacobs' report is the most extensive and valuable report of this character that has so far been published."

Finally, in preparation for congressional hearings on the NACA's 1934 budget estimates, the NACA staff prepared a statement (e) enclosed in this chapter's documentary collection entitled, "POSSIBLE SAVING BY USE OF N.A.C.A. 2415 AIRFOIL." This brief item estimated that, by changing from the Göttingen 387 airfoil currently employed to the N.A.C.A. 2415, a single "typical" airplane such as the Fairchild FC-2W2 could, over the course of a million hours flying time, save as much as $630,000 per year.

The NACA bureaucrats who fought the political and budgetary battles in Washington certainly were not beyond gamesmanship and hype in calculating the value of NACA research contributions, but no one can dispute the unparalleled achievement of the airfoil work and how much it helped the American aircraft industry in its design of wings. In his 1941 textbook on the *Aerodynamics of the Airplane* (New York: John Wiley & Sons, Inc.), Dr. Clark B. Millikan, Caltech professor of aeronautics, past president of the Institute of the Aeronautical Sciences, son of distinguished scientist Robert Millikan, and an individual with not terribly strong connections to the NACA, asserted (p. 67) that, "Since about 1935 systematic families of airfoils developed by the N.A.C.A. have been almost universally used in this country," not to mention significant use of them abroad. Whether or not any particular airfoil application saved so much money for a single airplane, in retrospect it seems more than clear that the value of the NACA airfoil families to aerodynamic efficiency, all told, had to be worth countless tens of millions.

Document 4-7(a), C.W. Howard, Major, Air Corps, and Chief, Engineering Section, Materiel Division, Office of the Chief of the Division, Wright Field, Dayton, Oh., 13 Jan. 1933, in RA file 290, LHA, Hampton, Va.

WAR DEPARTMENT
AIR CORPS
Materiel Division
Office of the Chief of Division
Wright Field, Dayton, Ohio

January 13, 1933

Dr. G. W. Lewis
National Advisory Committee for Aeronautics
3841 Navy Building, 17th and B Sts., N.W.
Washington, D.C.

Dear Dr. Lewis:

The preliminary copy of your report "The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel," by E. N. Jacobs, K. E. Ward, and R. M. Pinkerton, was studied with interest and the following comments are made.

This report is considered a very comprehensive systematic study of airfoil sections of rectangular planform. It is believed that an addition of similar discussions of effects, due to tapering in the plan view of the wing and due to interferences caused by locations of engine nacelles, fuselage, and the slipstream, which already have been published, would be of great value to the designer in search of the best wing combination for any particular case.

Very truly yours,

C. W. Howard, (Signed) A. J. Lyon
Major, Air Corps,
Chief, Engineering Section

Document 4-7(b), Montgomery Knight, Director, Daniel Guggenheim School of Aeronautics, Georgia School of Technology, Atlanta, Georgia, to George W. Lewis, NACA, Navy Building, Washington, D.C., 19 January 1932, in Research Authorization (RA) file 290, LHA, Hampton, Va.

GEORGIA SCHOOL OF TECHNOLOGY
Atlanta, Georgia
Daniel Guggenheim School of Aeronautics

January 19, 1932 (Note: This has to be 1933.)

Mr. George W. Lewis,
National Advisory Committee for Aeronautics,
Navy Building,
Washington, D.C.

Dear Mr. Lewis:

Thank you very much indeed for your kindness in sending the advanced copies of the two papers by Jacobs. I think he is to be complimented on his success in flattening the normal force curve for the Göttingen 398 by the simple expedient of sharpening the leading edge. It would be very interesting to see the results of autorotation tests or flight spinning tests with such a modified profile, particularly, to find out over how much of the span this modification would be necessary. I have an idea that improved efficiency could be obtained by having the sharpened leading edge extend inward from the tips, approximately to the inboard edge of the aileron. However, this is an obvious conclusion and I am sure it has occurred to you already. I shall look forward with interest to the results of further tests on this development.

The new N.A.C.A. 24-12 airfoil is a very good looking one and the characteristics are no less satisfactory. I am sure that the tests on this extensive series should bring about a new era into the choice of airfoils for different purposes. I, myself, intend to use this series almost exclusively in our work.

With kindest regards, I am

Yours sincerely,

MONTGOMERY KNIGHT
Director

Document 4-7(c), Edward P. Warner, Editor,* Aviation*, New York, N.Y., to George W. Lewis, NACA, 20 January 1933, in RA file 290, LHA, Hampton, Va.

AVIATION
330 West 42nd Street
New York, N.Y.

January 20, 1933

Dr. George W. Lewis,
National Advisory Committee for Aeronautics,
Navy Building,
Washington, D.C.

Dear George:

I have the report on The Characteristics of 76 Related Airfoil Sections, and my first observation has to be that it is a perfectly marvelous job. I have been waiting for it with eager anticipation for a long time, and the results fully justify my eagerness and expectancy. Please give my very warm congratulations to the authors.

With your leave I am going to do what I have so often done without anybody's leave, and keep this report in my file. I am quite unwilling to lose the opportunity of referring to the results of the research until such time as the Government Printing Office shall have put out the finished version.

While I haven't perhaps gone through the text of the report with the minute care that I have given to a few of them, a rather hasty examination leaves me thinking that it has been handled just about right. The curves in my copy were unfortunately rather badly printed, and are extremely difficult to study, but my only criticism at the moment would be that there has not been quite enough relative attention to the sort of presentation which the engineer without laboratory experience and without a profound knowledge of wing theory can use directly. I wouldn't want to sacrifice any of the curves that bear on the relationship between the laboratory results and the fundamental theory (such, for example, as Fig. 84), but I would like to suggest that there ought to be some more plotting of the characteristics that the engineer uses directly against the geometrical characteristics of the sections (such plotting as is done, for instance, in Figs. 85, 95 and 96). Aside from that I have nothing to suggest, but I do urgently hope the report can be brought out in the near future. I hope, also, that you can let me know at least a month ahead of time when it is to be published, and let me use either the present copy or a proof of the report in working up an article on airfoil characteristics in light of your studies. I should like to boil the whole thing down to a couple of pages, but obviously in order that such a presentation may be of interest it must come out practically simultaneously with the report itself, so that engineers will have a chance to look over the summary in the magazine before the report has come into our hands, been glanced at, and put aside.

Very sincerely,
E. P. W.
Edward P. Warner,
Editor

Document 4-7(d), G.W. Lewis to Dr. Joseph Ames, Johns Hopkins University, Baltimore, Md., 10 June 1933, in RA file 290, LHA.

June 10, 1933

Dear Doctor Ames:

I am forwarding herewith another report which I think the Aeronautical Research Committee will appreciate having. This is a report prepared by Mr. Jacobs on a group of seventy-eight related airfoils.

I noted in one of the British Reports that they are planning a very extensive investigation of airfoil characteristics in their new compressed-air wind tunnel. In connection with this proposed investigation the attached report will be of special interest. I personally feel that Mr. Jacobs' report is the most extensive and valuable report of this character that has so far been published. Certainly airfoils of the 2490 and 2200 series are now being used by manufacturers, especially the 2412 and 2212.

Sincerely yours,

G. W. Lewis
Director of Aeronautical Research

Dr. Joseph S. Ames,
Johns Hopkins University,
Baltimore, Maryland

Document 4-7(e), "Possible Saving by Use of N.A.C.A. 2415 Airfoil," undated (ca. summer 1932), in RA file 290, LHA.

POSSIBLE SAVING BY USE OF N.A.C.A. 2415 AIRFOIL.

Considering as typical the Fairchild FC-2W2, a drag or air resistance reduction may be accomplished by changing to a more efficient airfoil section. Applying the results of the N.A.C.A. airfoil tests, the N.A.C.A. 2415 section is found to be a more suitable section of the same thickness for this airplane than the present Göttingen 387 section. The direct reduction in drag due to the change in section is represented by the drag coefficient 0.0006. At the cruising speed of 100 m.p.h. this coefficient represents a drag saving of

0.0006 x 336 x 25.58

or approximately 5 pounds.

In addition to this drag reduction, the lower pitching moment of the N.A.C.A. 2415 allows a weight saving in the structure and smaller tail surfaces. From Technical Note 340, the reduced drag resulting from the use of smaller tail surfaces is estimated at 4 pounds. It is estimated that another reduction in drag of 3 pounds (20 pounds weight) would result indirectly from the weight saving, making the total reduction in drag of 12 pounds. This figure is considered a fair average for all airplanes.

The N.A.C.A. 2415 has a lower drag coefficient and a lower pitching moment than airfoils used on present day aircraft. Its substitution would result in a saving of approximately 12 pounds drag at 100 m.p.h. for most all airplanes flying during the past fiscal year.

$.035	=	cost of drag per lb. per hour				
428,930	=	hours flown by commercial airplanes				
247,745	=	"	"	"	Navy	"
371,254	=	"	"	"	Army	"
1,047,929	=	"	"	"	all	"

12 x .035 x 1,047,929 = $440,000.

Since cruising speed is higher than 100 m.p.h. in most cases and in the neighborhood of 120 m.p.h. we have

12 x (120^2 / 100^2) = 17.28 lbs. or

17.28 x .035 x 1,047,929 = $630,000.

Document 4-8(a-b)

(a) Charles H. Chatfield, Research Division, United Aircraft Corporation, East Hartford, Connecticut, to Dr. G.W. Lewis, NACA, 8 April 1937, in Research Authorization (RA) file 290, Historical Archives, NASA Langley Research Center, Hampton, Va.

(b) G.W. Lewis to Charles H. Chatfield, United Aircraft Corporation, 1 May 1937, RA file 290, Historical Archives, NASA Langley Research Center, Hampton, Va.

This pair of letters between the director of NACA research and head of United Aircraft's research division, provoked by the appearance of the NACA's new forward-camber airfoils, is highlighted by a brief but interesting exchange about the best way to make such a large volume of research data about different airfoils more useful and convenient to the airplane designer. Chatfield wanted the NACA to spotlight for industry only the more promising wing sections; Lewis believed that the requirements for wing sections varied so much that it would be impossible for the NACA to pre-select the airfoils that the industry would find useful.

Chatfield made specific reference to "N.A.C.A. 23012," certainly one of the best of the new forward-camber airfoils. Obviously, this was a five-digit airfoil. In this code, the first number still indicated the maximum camber in percent of the chord and the last two numbers still indicated the maximum thickness in percent of the chord; however, the middle two numbers indicated the position of maximum camber in percent of the chord rather than the previous single number in the four-digit series indicating maximum camber in tenths of the chord. Furthermore, the five-digit (and subsequent six-digit) series also indicated modifications like changes of the leading-edge radius or the position of maximum thickness by adding a suffix consisting of a dash and two more digits, as with N.A.C.A. 23012-64, one of the most outstanding sections in the popular 230-series, the family announced in 1935.

Eastman Jacobs explained this extended numbering system and summarized the advantages of the best new forward-camber airfoils in TR 610 of 1937, "Tests of Related Forward-Camber Airfoils in the Variable-Density Wind Tunnel," co-authored by Robert M. Pinkerton and Harry Greenburg.

Document 4-8(a), Charles H. Chatfield, Research Division, United Aircraft Corporation, East Hartford, Connecticut, to Dr. G.W. Lewis, NACA, 8 April 1937, in Research Authorization (RA) file 290, LHA, Hampton, Va.

UNITED AIRCRAFT CORPORATION
East Hartford, Connecticut
Research Division

April 8, 1937

Dr. G. W. Lewis
National Advisory Committee for Aeronautics
Navy Building
Washington, D.C.

Dear Dr. Lewis:

Thanks very much for the report "Tests of Related-Forward-Camber Airfoils in the Variable-Density Wind Tunnel" that you sent me with your letter of March 11th. It was interesting to see that the 23012 airfoil was not a freak case, but rather the best of a good strain. As a former stress analyst, I agree with the view expressed on page 11 of the report that these new airfoils are good structurally as well as aerodynamically. In the old days the sharp taper aft of the maximum ordinate was always troublesome.

Now that your extensive studies of airfoils have produced so many good ones, I think the time is approaching when a designer might lose sight of some of them. I, therefore, venture the suggestion that you issue a report giving the characteristics of the better of the airfoils in the various groups, so that a designer may have in one publication all the airfoils that he would be likely to consider seriously for any particular airplane. From the research point of view, it is certainly desirable to have available the characteristics of all the airfoils tested, but I doubt that the airfoils which were only steps in the development are of great interest to the practicing designer.

Yours very truly,
[Signed Chat]
Charles H. Chatfield

Document 4-8(b), G.W. Lewis to Charles H. Chatfield, United Aircraft Corporation, 1 May 1937, RA file 290, LHA.

May 1, 1937

Mr. Charles H. Chatfield,
United Aircraft Corporation,
East Hartford, Connecticut

Dear Chat:

I appreciate very much your letter of April 8 commenting on the report on forward-camber airfoils.

With reference to your suggestion about the desirability of presenting in one report data on the better airfoils in the various groups, the chief difficulty is the question of the method of selecting the airfoils to be presented. The determination of a basis for such a selection appears so difficult as to make the preparation of such a report of doubtful practical ability.

Of course the report on the forward-camber airfoils and the Committee's Technical Report No. 460 present in rather compact and easily usable form complete data on the airfoils used in the Committee's investigation.

There is now in preparation a report presenting the characteristics of a large number of miscellaneous airfoils and it is believed that these three reports will make available for ready use information on all the desirable airfoil sections investigated in the variable-density wind tunnel.

Sincerely yours,

G.W. Lewis
Director of Aeronautical Research

Document 4-9(a-b)

(a) G.W. Lewis, NACA, To The Members of the Board of Award, Sylvanus Albert Reed Award for 1937, 3 September 1937, in Research Authorization (RA) file 290, LHA, Hampton, Va.

(b) R.C. Platt, Memorandum for Dr. Lewis, "Airfoil sections employed for wings of modern airplanes," 2 September 1937, RA file 290, LHA.

Winning the Institute for Aeronautical Science's prestigious Sylvanus Albert Reed Award for 1937 represented not only the zenith of Eastman Jacobs' professional career but perhaps also the absolute highpoint of the NACA's reputation in aerodynamics—at least up to the point it won a trio of Collier Trophies for major aerodynamic breakthroughs (the X-1 breaking the sound barrier, the slotted-throat transonic wind tunnel, and the area rule) in the late 1940s and early 1950s.

Nominating a deserving NACA researcher for a prestigious national and international award was something that Lewis and other NACA officials started paying more attention to starting in the mid-1930s. The publicity surrounding the winning of scientific and engineering awards enhanced the NACA's reputation at just the time that the NACA was campaigning for significant funds for new construction. In particular, there was a growing concern over developments in Europe. In November 1935 the NACA's intelligence officer in Paris, John Jay Ide, reported that French had just completed a full-scale wind tunnel at Chalais-Meudon; the Italians had built an entire city, Guidonia, outside Rome, devoted to high-speed aeronautical research; and the Germans were in the midst of what appeared to be a major revitalization of their aeronautical resources. As a result of Nazi support, there would soon be five major regional stations for aeronautical research and development in Germany and a central establishment, the Deutsche Versuchsanstalt fur Luftfahrt (DVL) at Aldershof near Berlin. This news disturbed George Lewis so much that in the late summer of 1936 he crossed the Atlantic in the German airship *Hindenburg* in order to see for himself what the Europeans were doing. He visited England and France, but his real mission was to tour major aeronautical installations in Germany and Russia. In Germany he visited the Air Ministry in Berlin, the DVL, the Heinkel aircraft factory at Oranienbaum, and the University of Göttingen; in Russia, he concentrated on the operations of Moscow's Central Aerodynamic Institute.

Lewis came away alarmed over the warlike aspect of the expanded research programs in both Germany and Russia. The DVL at Aldershof looked to him "like a construction camp" being readied for experiments "with every conceivable device."

He estimated that between 1600 and 2000 well trained employees were working there, compared with only 350 at Langley. Although he still considered Langley "the single best and biggest aeronautical research complex in the world," he warned the government about the dangers of complacency (Lewis, "Report on Trip to Germany and Russia, September-October 1936," Langley Correspondence Files, Code E32-12, RG 255, National Archives, Philadelphia).

Lewis's were not the only warnings in those troubled times, but his were among those that paid off, preparing the way for the great expansion of NACA facilities undertaken in the years 1938 to 1941. By the time of the Japanese attack at Pearl Harbor, construction was nearing completion on two new separate NACA laboratories: Ames Aeronautical Laboratory near Palo Alto, California, and the Aircraft Engine Research Laboratory in Cleveland, Ohio (later renamed in honor of Lewis). Without these new laboratories, the NACA would never have been able to accomplish the tremendously increased workload brought on by the war.

Awards like Jacobs' were hardly enough to convince Congress that NACA merited more funding, but they certainly did not hurt. This is not to suggest that George Lewis nominated Jacobs or any other outstanding researcher for an award only so that the larger organization would get something out of it. Lewis truly enjoyed and admired "his boys" at Langley and wanted them to receive all the praise and reward they deserved—especially Jacobs, who he especially liked for his outstanding productivity and unselfish devotion to his work.

Interestingly, Jacobs' bold vision of what was possible technologically, a more and more freewheeling style, and a rather libertine personal lifestyle, would later try the patience of George Lewis to the breaking point. Lewis in the late 1930s not only had to order Jacobs to dismantle a primitive (and completely unauthorized) thermonuclear fusion reactor that Jacobs and an associate (Arthur Kantrowitz) had constructed in the VDT building, and later to keep a lid on his passion for a hybrid type of jet engine that he helped to design in the early 1940s, he eventually had to quietly encourage his resignation from the NACA. Along with his increasingly irresponsible and rebellious ways at the laboratory, Jacobs' personal life suffered from a series of scandals during the war that alienated many of his co-workers and finally convinced Lewis that NACA might be better off without him.

Seven years after winning the Sylvanus Albert Reed Award, the NACA's golden boy retired from government service to do independent consulting work back in his home state of California. He produced no technical work of any great worth after his departure from the NACA, and within the world of aeronautics turned into a shadowy figure of legend and mystery. Some stories had him running a hot dog stand at the beach in Malibu. Whatever actually happened to Jacobs is known only to his closest friends and family. But his demise was tragic, for at age 42 his outstanding career essentially ended.

Document 4-9(a), G.W. Lewis, NACA,
To The Members of the Board of Award, Sylvanus Albert Reed Award for 1937.

September 3, 1937

To The Members of the Board of Award,
Sylvanus Albert Reed Award for 1937:

I respectfully submit for consideration for the Sylvanus Albert Reed Award for 1937, the name of Eastman Nixon Jacobs.

Mr. Jacobs has been responsible for a number of years for the operation of the variable-density wind tunnel of the National Advisory Committee for Aeronautics, and was responsible also for the initiation of research on the special problems of airfoil sections for use in the design of airplanes. As a result of this research, he has developed what are acknowledged to be the most efficient airfoil sections now in existence.

The importance of Mr. Jacobs contribution is evidenced by the fact that the most generally successful and widely used airplanes are those which employ airfoils of the later N.A.C.A. series, which have been developed under his direction. Among these airplanes the highly successful Douglas, Lockheed, and Sikorsky transports; the Northrop and Consolidated military airplanes; and the Beechcraft, Fairchild, and Cessna airplanes of the lighter commercial type.

In the military field the airplanes which are now being produced in large quantities, such as the Douglas bomber, which uses the N.A.C.A. 2200 series, and the Boeing bomber, employ airfoils of N.A.C.A. series.

Mr. Jacobs' contribution in the development of more efficient airfoils is one of the outstanding factors that has made possible the superior performance of large present-day airplanes, both military and commercial.

Mr. Jacobs is unselfishly devoted to his work, and has not only contributed his own personal time and energies to his research activities, but has also given freely of his time in discussing the problems of airfoil design and in acquainting the engineers of the industry with the results of his investigations.

I am attaching hereto a list of present-day airplanes which use airfoils of N.A.C.A. series.

Respectfully,
G. W. Lewis

September 3, 1937

USE OF AIRFOILS OF N.A.C.A. SERIES
IN MODERN MILITARY AND COMMERCIAL AIRPLANES.

N.A.C.A. 22 series airfoils

- Army
  - Stearman PT-13
  - Consolidated P-30
  - " PB-2A
  - Curtiss 75
  - North American 22
  - " BT-9
  - " BT-10
  - Douglas B-18
- Navy
  - Curtiss SBC-3
  - " SOC-1
  - " BF2C-1
  - Douglas XP3D-2
  - " R2D-1
  - Great Lakes BG-1
  - " XB2G-1
  - Stearman JRS-1
- Commercial
  - Douglas DC-2
  - " DC-3
  - Sikorsky S-43
  - Arrow F
  - Fairchild F-45

N.A.C.A. 23 series airfoils

- No military
- Commercial
  - Monocoach
  - Curtiss A19-R

N.A.C.A. 24 series airfoils

- Army
  - Northrop 2J
  - " A-17
- Navy
  - Curtiss R4C-1
  - Northrop BT-1

- Commercial
  - Spartan 7-W
  - Cessna C-34
  - Luscomb Phantom
  - Fleetwings F-401

N.A.C.A. 230 series airfoils

- No Army
- Navy
  - Vought SB2U-1
- Commercial
  - Beechcraft, all models (2 basic types)
  - Martin 156
  - Taylorcraft
  - Barkley Grow TSP-1
  - Grumman G-21
  - Waterman Arrowbile
  - Lockheed 12

N.A.C.A. 00 series airfoils

- Army
  - Boeing 199
- No Navy
- Commercial
  - Boeing flying boat

Document 4-9(b), R.C. Platt, Memorandum for Dr. Lewis, "Airfoil sections employed for wings of modern airplanes," 2 September 1937, RA file 290, LHA, Hampton Va.

Washington D.C.

September 2, 1937

Memorandum for Dr. Lewis.
Subject: Airfoil sections employed for wings of modern airplanes.

1. Attached herewith is a list of the airfoil sections employed on modern army, navy, and commercial airplanes prepared by Mr. Helms and myself.

2. Of the 101 types listed, 66 employ N.A.C.A. airfoils, the other 35 do not.

3. It is interesting to note that of the whole list of the most generally successful and widely used airplanes are those which employ the later N.A.C.A. series airfoils. Among these are the highly successful Douglas, Lockheed, and Sikorsky transports; the Northrup and Consolidated military airplanes, and to the Beechcraft, Fairchild and Cessna of the lighter commercial types. Of particular note is the Cessna, which in competition with most representative of modern private-owner airplanes was adjudged the most efficient of the group. In the military field large orders have been placed for the new Douglas bomber employing the N.A.C.A. 22 series airfoil, succeeding the Martin B-10, which used Göttingen 398 airfoil. It is interesting to note that Martin in his more recent commercial types is adopting the latest improved N.A.C.A. airfoil, to-wit: the 230 series. Boeing likewise in their very large commercial airplanes, as well as in the highly successful 199 bomber, are using one of the more efficient N.A.C.A. airfoils - the 00 series.

Respectfully submitted,
R. C. Platt

Document 4-10

H.J.E. Reid, Engineer-in-Charge, Langley Field, to NACA, "Paper entitled 'A Few Present Problems in Aerodynamics,' by Dr. von Kármán," 8 February 1933, in RA file 290, LHA, Hampton, Va.

By 1933 Dr. Theodore von Kármán was already well on his way to becoming the dean of American aerodynamics. One of Ludwig Prandtl's most gifted protégés at Göttingen, von Kármán came to the United States in 1930 after being vigorously recruited by Dr. Robert Millikan to direct the new Guggenheim Aeronautical Laboratory at the California Institute of Technology (GALCIT) in Pasadena. Located on the West Coast in the years before the NACA had any presence there, von Kármán's ties to the NACA were never terribly strong. Although he certainly followed the results of NACA research and attended occasional aircraft engineering conferences at Langley, von Kármán never served on the NACA Main Committee or for that matter on any of its technical committees, not even its Committee on Aerodynamics.

In his paper "A Few Present Problems in Aerodynamics," not included in this chapter's documents, von Kármán pointed out a discrepancy between maximum lift data published by the NACA and results with the same airfoil in the GALCIT wind tunnel. In Langley's response to it, as expressed mostly by Eastman Jacobs, one detects something a bit more than a mere technical disagreement between two research groups. One also senses a feeling of rivalry between Langley and Caltech.

Certainly, by the late 1930s, a quiet rivalry existed. Caltech's own research program under von Kármán's supervision had been enriching the field of aerodynamics in some respects even more so than were Langley's. Caltech graduates held distinguished positions in colleges and universities across the country, but hardly any of them worked for the NACA. Perhaps most importantly, with the aircraft industry growing by leaps and bounds on the West Coast, the NACA recognized that it needed a stronger presence there, or the manufacturers and the military services would rely more on Caltech for advice and assistance than they already were. With this in mind, in 1939, the NACA chose Moffett Field in Sunnyvale, California, as the site for one of its two new research centers (what became the Ames Aeronautical Laboratory). At the same time, the NACA opposed federal spending for new wind tunnels at Caltech. NACA leadership, as southern California Congressman Carl Hinshaw complained in 1941, preferred to "retain a concentration of research facilities entirely within the NACA. They do not seem to be inclined to favor allowing these facilities to be spread out among the several qualified educational institutions. I do not just know whether it is the old question of professional jealousy or the old question of expanding bureaucracy or some other queer incomprehensible angle" (Congressional Record, 77/1, Vo. 87, Pt. 1, 1941, p. 416).

Dr. von Kármán felt much the same way about the NACA as did his congressman: that the NACA selfishly wanted the entire field to itself. He saw inherent dangers in an NACA monopoly, and, being an ambitious man and program builder, he wanted a much bigger piece of the pie for himself and Caltech. During the war von Kármán criticized the NACA for not getting more into rockets and jet propulsion, revolutionary technologies his own small Jet Propulsion Laboratory were pioneering. At the end of World War II, von Kármán strongly encouraged the Army Air Forces to establish bureaucratic structures and its own independent advisory groups and laboratories to conduct scientific research in the service of American military air supremacy. In essence, von Kármán advised the air forces (and the independent U.S. Air Force when it came to life in 1947) not to trust the NACA for the intensive research and development necessary to generate the ongoing technical advances required to keep the nation ahead of its enemies in terms of air power, but to build its own independent R&D establishment. By the early 1950s, he described the NACA as conservative and overly cautious and was literally in charge of a little aerodynamic research empire of his own.

Document 4-10, H.J.E. Reid, Engineer-in-Charge, Langley Field, to NACA, "Paper entitled 'A Few Present Problems in Aerodynamics,' by Dr. von Kármán," 8 February 1933, in RA file 290, LHA, Hampton, Va.

Langley Field Virginia,

February 8, 1933.

From LMAL
To NACA
Subject: Paper entitled "A Few Present Problems in Aerodynamics," by Dr. von Kármán.
Reference: NACA Let. Jan. 30, 1933, CW/NW

1. Dr. von Kármán's paper has been read by various members of the laboratory staff, as requested in letter of reference, and is desired to keep the paper a few days longer. It is therefore not being returned at this time.

2. With reference to the third paragraph of your letter, concerning the discrepancy of maximum lift of various airfoils as tested in the wind tunnel of California Institute of Technology and in our variable-density tunnel, the laboratory is not yet in a position to comment finally. The effects of turbulence and scale on airfoil characteristics have been under consideration for a long while at the laboratory, and it is appreciated that we should make every effort to bring into agreement the measurements from our various wind tunnels. To this end equipment is in preparation for making sphere drag tests in all the tunnels and we are accumulating information on the characteristics of the Clark Y airfoil in all the tunnels.

3. Mr. Jacobs offers the following comment with reference to Dr. von Kármán's comparison between the maximum lift of the 2412 airfoil as measured in the California Institute of Technology tunnel and in the variable-density tunnel:

The paper is too broad and general to justify much comment in detail. The parts dealing with the comparison of airfoil test results from the California Institute of Technology tunnel and from the variable-density tunnel should be considered.

To begin with, the paper contributes nothing new about the effects of turbulence on airfoil test results, except to present new test data for a tunnel that is relatively free from turbulence. The effects of turbulence were considered and conclusions, at least as accurate as von Kármán's, were reached by Stack in T.N. No. 364.

The sketches given by von Kármán to indicate the effects of turbulence on the breakdown of the flow over an airfoil are certainly misleading and inaccurate. He is mistaken about the position of the separation point "S" in the figure being independent of the value of the Reynolds number. We also question the statement to the effect that the separation that limits the lift can be avoided only when the transition point from laminar to turbulent flow in the boundary layer is ahead of the point "S." This separation may be only local, the flow at the boundary changing to turbulent soon after separation and closing in again, so that the effect on the lift may not be important.

"In regard to the presented test results, the Reynolds number range is rather limited and a poor method of plotting has been chosen. Plots against a logarithmic Reynolds number scale are considered preferable. His results for the 2412 airfoil are replotted in this form, together with our results for the Clark Y airfoil from 364 and from the full-scale tunnel for comparison. The results from the full-scale tunnel must be considered tentative, but all the results tend to indicate that the shape of von Kármán's curve "A" corresponding to the least turbulence is affected by something other than scale and turbulence. The air speeds in the California Institute of Technology tunnel may be so high that the maximum lift coefficients are influenced by compressibility."

H.J.E. Reid,
Engineer-in-Charge

Document 4-11

Eastman N. Jacobs, Memorandum to Engineer-in-Charge, "Scale effect on airfoils, conference," 11 April 1934," in RA file 88, Historical Archives, NASA Langley.

The concept of "effective Reynolds number" seems to have stemmed at least in part from an in-house conference on airfoil scale effects and turbulence held at Langley on 11 April 1934. Besides Eastman Jacobs, who authored the memo, others attending this meeting were Elton W. Miller, chief of the aerodynamics division; Fred E. Weick, assistant chief of aerodynamics; Carl Wenzinger, an engineer in the 7 X 10-Foot Atmospheric Wind Tunnel section who specialized in aerodynamic effects with reference to stability and control problems and to the lifting powers of wings; and Smith J. DeFrance, head of the Full-Scale Tunnel. (The exact identity of "Mr. Leisy," whose letter to the NACA is referenced early in Jacobs' memorandum, is unknown.)

"Scale effects' were a notorious difficulty with wind-tunnel testing, but they were especially plaguing to data coming from the Variable-Density Tunnel where 1/20th scale models were used, and in a very turbulent and low-speed airstream. Results from VDT tests simply could not be extrapolated reliably to the performance of the actual airplane. This meant that "practical engineers" really did not know how to use VDT data for their flight applications. Rightfully so, the NACA considered this to be a major problem and something that needed to be corrected.

Jacobs' concept of "effective Reynolds number," which he invented not long after this conference, became the NACA's stop-gap way of correcting for scale effects. Although not an altogether satisfactory solution, it remains even up to today a standard way of correcting for the problem. A *Dictionary of Technical Terms for Aerospace Use*, published by NASA in 1965 (NASA SP-7), lists the term and defines it as "A fictitious Reynolds number applied to the flow of air about a body in a wind tunnel, equal to the free-air Reynolds number at which the effect obtained is the same as the effect obtained in the wind tunnel" (p. 93).

Document 4-11, Eastman N. Jacobs, Memorandum to Engineer-in-Charge, "Scale effect on airfoils, conference," 11 April 1934," in RA file 88, LHA, Hampton, Va.

L. M. A. L.

Langley Field Va.,
April 11, 1934

MEMORANDUM For Engineer-in-Charge.

Subject: Scale effect on airfoils, conference.

1. A conference attended by the following members of the laboratory staff was held to discuss scale effect: Miller, Weick, Wenzinger, DeFrance, and Jacobs. A letter from Mr. Leisy together with Mr. Jacobs' reply was first considered as typical of the viewpoint of the practical engineers who wish to know how to use the variable-density tunnel data for their flight applications. Their problem is to predict the characteristics of the airfoil section at any value of the Reynolds number within the flight range, say 1,000,000 to 30,000,000. This problem was discussed in relation to the full-scale tunnel tests of the Clark Y airfoil, and the desirability of preparing a publication at this time discussing the solution of the problem, was considered. The relation of the proposed sphere tests to the general problem was also discussed.

2. The discussion brought out the fact that there are two rather distinct problems toward the solution of which our research should be definitely directed. These are:

(a) The problem of correcting full-scale tunnel test results to flight.

(b) The problem of correcting the variable-density tunnel results to flight at any Reynolds number within the flight range.

As regards the aerodynamic characteristics of airfoils, the second problem must be considered the more important, but its solution is to a large extent dependent on the solution of the first because we cannot test full-scale airfoils directly in flight. For our basic flight characteristics for comparison, we must depend largely on predictions from our airfoil tests in the full-scale tunnel.

3. Considering first, therefore, the problem of correcting the full-scale tunnel results to flight, either we must say that the corrections are so small that the results apply directly with sufficient accuracy, or we must evaluate turbulence corrections. For the time being, the first course is probably the best, the justification for it resting on the reasonably close agreement that has been obtained between flight and tunnel tests of the same airplanes. It might be advisable also to make sphere drag tests in the tunnel and in flight. The consensus of opinion was that sphere test data would be of some immediate value if they showed small differences between the tunnel and flight characteristics for the spheres.

4. Sooner or later, however, methods of correcting the full-scale tunnel data to zero turbulence will be desired. Probably the methods we devise for correcting the variable-density tunnel data for turbulence will be applied to the full-scale tunnel data to extrapolate to zero turbulence as determined by the characteristics of complete airplanes and spheres as measured in flight. In this connection it might possibly be advisable at some later time to investigate the characteristics of some airfoils, airplanes, and possibly spheres in the full-scale tunnel with increased turbulence so that in certain cases for the extrapolation to zero turbulence the shapes of the turbulence-effect curves may be more accurately established.

5. In regard to the main problem, that of correcting the variable-density tunnel results to flight at any value of the Reynolds number within the flight range, the data we now have, except for a few airfoils, are all at one value of the Reynolds number. Therefore, even if we could correct our data for turbulence, we would still not be in a position to predict flight characteristics at any desired Reynolds number.

6. The tests most urgently needed at present, therefore, are those for which authority was requested in our letter of August 16, 1932. The results are required to give the desired scale-effect data for a group of related airfoils. We are starting these tests in the variable-density tunnel on authority of N.A.C.A. letter of August 17, 1932 to investigate the scale effect for the following N.A.C.A. airfoils:

Thickness series	Thickness series with camber	
0009	2409	
0012	2412	6412 Camber series
0015	2415	
0018		6712

7. The recommended plan is, then, after analyzing this scale-effect data, to select some of the above airfoils for testing in the full-scale tunnel in order to determine their characteristics corresponding to the reduced turbulence of the full-scale tunnel. This information should form the basis for correcting all the results to zero turbulence and to any Reynolds number within the flight range.

8. It was decided in the meantime to continue the investigation in the 7 by 10 foot tunnel of the sphere-pressure system of measuring turbulence and to make preparations for measurements in flight. This system, if it proves satisfactory, will be used as a measure of the turbulence in the full-scale tunnel. The possibility of checking the sphere-pressure system in the N.A.C.A. tank both in the air and in the water was also discussed.

9. As regards the publication of the report covering the full-scale tunnel tests of the Clark Y, the consensus of opinion was that it might be published now substantially as it is, but that it should be very carefully edited to assure that it will give the reader the correct picture of the scale-effect and turbulence problem and the relation of that work to the Committee's general work on the problem.

10. The point we must keep in mind in formulating our programs is that it lends weight to our conclusions if we can show a relation between the effect of turbulence on a sphere and on airplanes and airfoils, but that the effect on airplanes and airfoils can be evaluated independently of spheres and other turbulence-measuring devices.

Eastman N. Jacobs
Associate Aeronautical Engineer.

Document 4-12

G.W. Lewis, Director of Aeronautical Research, NACA, to Mr. J.L. Naylor, Secretary, Aeronautical Research Committee, National Physical Laboratory, Teddington, Middlesex, England, 13 April 1937, in RA file 290, LHA, Hampton, Va.

Bothersome questions about the reliability of the NACA's airfoil data persisted late into the 1930s and had to be answered responsibly. One document in our collection that clearly indicates the NACA's need to respond to potentially embarrassing findings involves a letter from George Lewis, director of research for the NACA, to J.L. Naylor, secretary of the Aeronautical Research Committee for Britain's National Physical Laboratory, dated 13 April 1937. (This was just shortly before Lewis nominated Eastman Jacobs for the IAS award.)

Lewis was responding to preliminary confidential data showing that tests in the NPL's own compressed-air tunnel gave quite different drag numbers for the N.A.C.A. 23012 airfoil. Although admitting the discrepancies appeared "at first a little disturbing," Lewis tried to make light of them. First, he stated that "From past experience we have learned not to expect too much from comparisons of wind tunnel results." Then, he argued that the use of effective Reynolds number "now brings some of the results into fair agreement and that the agreement of the drag results tends to improve as we approach the higher Reynolds numbers in which we are particularly interested." Finally, he emphasized that, irrespective of the bothersome discrepancies, the British results, in general, confirmed the NACA's most important conclusion—that the N.A.C.A. 23012 was superior to most commonly used airfoils.

Document 4-12, G.W. Lewis, Director of Aeronautical Research, NACA, to Mr. J.L. Naylor, Secretary, Aeronautical Research Committee, National Physical Laboratory, Teddington, Middlesex, England, 13 April 1937, in RA file 290, LHA, Hampton, Va.

April 13, 1937

Mr. J. L. Naylor, Secretary,
Aeronautical Research Committee,
National Physical Laboratory,
Teddington, Middlesex.

Dear Mr. Naylor:

The Committee appreciates very much the opportunity to examine the preliminary confidential data from your compressed-air tunnel on the N.A.C.A. 23012 airfoil, which you kindly sent with your letter on February 15, 1937. This information was particularly interesting to the members of our staff at Langley Field. I note that you do not at present plan to publish this report, and agree that the difference in drag shown in the results from our variable-density wind tunnel appears at first a little disturbing. I note however, that you conclude in general that your results substantiate the claims made for the airfoil.

From past experience we have learned not to expect too much from comparisons of wind-tunnel results. Dryden's analyses of previous data in particular have shown that differences in wind-tunnel turbulence may produce marked discrepancies in the results from different wind tunnels. The fact that the use of the "effective Reynolds number" now brings some of the results into fair agreement and that the agreement of the drag results tends to improve as we approach the higher Reynolds numbers in which we are particularly interested seems to us to be encouraging. That some discrepancies still remain indicates we do not yet fully understand the subject and that further work remains to be done.

At his request, I am transmitting the following comments by Mr. Jacobs of our laboratory staff:

"The failure of the results from this compressed air tunnel, variable-density tunnel and full-scale tunnel to show better agreement is in some respects disappointing. I think, however, that the difference is found are in the main to be attributed to differences in wind-tunnel turbulence, or, if you like, to our failure to completely correct it for these effects. In general, the results from the compressed air toddled appear about as we had expected from our comparisons of the results from the variable-density tunnel with those from the much less turbulent full-scale tunnel. Such differences were in fact predicted some time ago when we drafted our report on scale effect and before we had seen the results from the compressed-air tunnel on the N.A.C.A. 0012 airfoil. It now appears that the "turbulence factor" of the

compressed-air-tunnel is somewhere between 1.2 and 1.6, although our impression was that early sphere tests in the compressed-air tunnel showed a higher value than this.

"It is suggested that a sphere test of that type made here by Mr. Platt (Technical Report No. 558) would be of considerable value in the interpretation of the results from the compressed-air tunnel. This test is easily made but it is necessary that the sphere be smooth and steady, and that it be mounted from the rear. We would like to know whether any changes have been made in the compressed-air tunnel that might have changed the tunnel turbulence since the early sphere and airfoil tests were made."

"A few matters of secondary importance should also be mentioned. It is unfortunate that the complete scale-effect data for the N.A.C.A. 23012 airfoil as they will appear in our scale-effective report were not available in England when your report was prepared. The complete data extend to lower values of the Reynolds number and point the way to a better fairing of the experimental drag results. For example, the cross fairing indicates that our results at the next-to-the-highest Reynolds number (15 atmospheres) were somewhat high, owing to a slight roughness accumulated on the nose of the model during this and the lower pressure runs. The same result does not appear at the highest Reynolds numbers because the models, to avoid slight roughness effects that were known to be most critical at the highest Reynolds number, were carefully refinished and repolished before the final 20-atmosphere tests were made. It appears that the results from the compressed-air tunnel may be subject to similar roughness effects at the highest Reynolds numbers. The compressed-air-tunnel data shown in figures 2 and 4 indicate effects something like those found in the compressed-air tunnel with roughness on the N.A.C.A. 0012 (R. & M. No. 1708). Furthermore, the maximum lift coefficient for the N.A.C.A. 23012 is surprisingly low as compared with that of the chromium-plated N.A.C.A. 0012. We would suggest that the N.A.C.A. 23012 be highly polished and check-tested at the highest Reynolds number."

In regard to the scale-effect report referred to in the preceding comments by Mr. Jacobs, I am forwarding here with an advance confidential copy, as it contains our latest data from the variable-density tunnel on both the N.A.C.A. 0012 and the N.A.C.A. 23012 airfoils, together with rather complete discussions of various corrections now employed. We are now engaged, as the result of the various suggestions, in incorporating a few minor changes in the report. We hope that you will find this report as interesting and helpful as we have found your preliminary reports.

Sincerely, yours,

G. W. Lewis
Director of Aeronautical Research

Document 4-13

Hugh B. Freeman to Chief of the Aerodynamics Division [Elton W. Miller], "Boundary-layer research," 18 April 1932, in RA file 201, LHA, Hampton, VA.

An excellent popular account of "boundary layer" research from the year 1995 explains that there is really "no such thing as absolutely pure laminar flow, for there is always a very thin and relatively stagnant 'boundary layer' of air between the skin of an airplane and the free-stream air surrounding it." No matter how smooth the skin of an airplane wing may be, it has "microscopic irregularities that tickle the air going past it at high speed" forcing the closest molecules to stumble and lose speed. These molecules "impart their confusion" to some other molecules in the next outward layer, and they in turn cause similar chaos in the next. "Imagine a roaring river at flood stage; within an inch of its banks, the water barely moves, though it burbles and twists. Those banks are the equivalent of an airplane's wings experiencing non-laminar flow" (Stephan Wilkinson, "Go With the Flow," *Air & Space Smithsonian* 10 [June/July 1995]:33).

Aerodynamicists measure the thickness of the boundary layer from the surface to the point where the speed of the molecules is 99 percent of the stream velocity. In practical terms, this means that the boundary layer is never more than about an inch thick. But, as Hugh B. Freeman and other aerodynamic thinkers realized by the early 1930s, that one inch played all sorts of tricks on the aerodynamic efficiency of an airplane (or airship, for that matter). In particular, turbulence in the boundary layer created drag, the main retarding force acting upon a body in flight. The greater the turbulence, the greater the drag—and the greater the drag, the less efficient is the airplane. It will fly slower and not as far, or it will require more fuel, which added cost.

These basic facts of physics made boundary-layer research critical to the future of aerodynamic improvement. As Hugh B. Freeman declared in his memo to the engineer-in-charge in 1932, no field of research offered "greater possibilities for the improvement of aircraft performance and safety" than boundary-layer control.

In his memo Freeman proposed a program of investigation by the NACA aiming at laminar-flow control (LFC) rather than natural laminar flow. Natural laminar flow was based on the idea that laminar flows could be maintained farther back over the chord of a wing simply by designing the airfoil shape correctly. Freeman's idea, on the other hand, was to prolong laminar flow mechanically by using slots in the wing and a blower system to suck away some of the turbulent molecules on the wing's surface.

The idea was certainly not original to Freeman or to the NACA. In the mid-1920s Dr. Richard Katzmayr, another Prandtl student, who was serving as director of the Vienna Aerodynamical Institute in Austria, had come up with the idea of increasing lift by blowing compressed air over a wing surface. Curiosity about this promising line of new research led the NACA on 21 January 1929 to approve Research Authorization (RA) 201, "Investigation of Various Methods of Improving Wing Characteristics by Control of the Boundary Layer." Under this aurthorization, as Freeman's memo points out, Langley engineer Millard J. Bamber conducted wind-tunnel work in 1929 and 1930 on airfoil boundary layer control using "backward opening" slots. At roughly the same time, NACA Langley chief test pilot Thomas Carroll made test flights with a special wing incorporating an arrangement of sucking slots.

Freeman's own involvement in boundary-layer work began, interestingly enough, not with airplanes but with airships. Assigned to airship research upon reporting to work at Langley in 1931, Freeman somehow picked up quickly on the enormous potential of boundary-layer control for reducing airship drag. Looking back into what the NACA and others had been doing to better understand the boundary layer, he came across Katzmayr's promising results and the tentative preliminary experiments of Bamber and Carroll. Considering some careful iteration of Carroll's full-scale tests as the best way to go about gaining insights into boundary-layer control, young Freeman formally presented his proposal to engineer-in-charge Henry J. E. Reid. After consulting with key staff members who liked Freeman's plan, Reid approved the work for the Propeller Research Tunnel, where full-scale investigations on wings were possible.

In an extended analysis of RA 201 that appears in Vol. 2 of *Model Research: The National Advisory Committee for Aeronautics*, 1917-1958 (NASA SP-4103, 1985), historian Alex Roland underscored the historic significance of Freeman's April 1932 memo. "This was truly a new departure in the history of R.A. 201," Roland emphasized. "Previous efforts had sought for ways to delay separation and increase the velocity gradient within the boundary layer. Freeman would concentrate on delaying the transition from laminar to turbulent flow." The idea was "by no means original with him, but his work on airships and his reading of earlier NACA efforts convinced him that this was a promising line of research and one with which the NACA should be deeply involved." Subsequent developments proved him right. Following his lead, NACA researchers, notably Eastman Jacobs, "would make their greatest contribution to boundary-layer control, the laminar-flow airfoil" (*Model Research*, II: 538).

Document 4-13, Hugh B. Freeman to Chief of the Aerodynamics Division [Elton W. Miller], "Boundary-layer research," 18 April 1932, in RA file 201, LHA, Hampton, Va.

April 18, 1932

MEMORANDUM For Chief Aerodynamics Division
Subject: Boundary-layer research.

1. The purpose of this memorandum is to call attention to the lack of large-scale experimental data relative to the boundary-layer problem and to suggest a program of research which will provide information along these lines.

2. The field of boundary-layer control, in this writer's opinion, offers greater possibilities for the improvement of aircraft performance and safety than any other. This is because the control of the boundary layer influences every important aerodynamic characteristic of an aircraft. The three most important advantages offered by the control of the boundary layer are: (1) increase in lift, (2) an increase in the angle-of-attack range below the burble, and (3) a decrease in minimum drag. The first two advantages have been shown repeatedly by tests on small models, principally those of Oscar Schrenk in Germany, who obtained a maximum lift coefficient of $C_L = 5.0$ and an L/D ratio of 50 by the method of removing the boundary layer on the upper surface of an airfoil by suction. The possibility of realizing the third advantage is shown by Figure 1 (Original figures not included herein.) in which is plotted the drag of the ZRS-4 airship computed for laminar and turbulent boundary layers. From these curves it is seen that if a method of controlling the boundary layer could be devised which would force the flow to remain laminar instead of changing to turbulent, the drag (of even a well streamlined body) could be reduced to about 10 percent of its present low value. The same thing holds true for the drag of the wings and fuselage or an airplane, since the Reynolds number in this case is greater than those shown, and hence a greater portion of the boundary layer is turbulent. It is not expected that a reduction as great as that cited above will be obtained in practice, of course, but even a 10 or 20 percent reduction in the drag of an airship or of an airplane would certainly be worthwhile.

3. The only serious experimental work which has been undertaken at this laboratory on boundary-layer control is that of Mr. Bamber. His tests, while they showed substantial improvement in the lift coefficient, were never carried to a logical conclusion. As he pointed out in his report, if multiple slots had been tested and also suction slots (i.e., slots opening normal to the surface) even more favorable results would have been obtained. Small-scale tests are at a disadvantage, however, even under the best of conditions, because of the fact that the boundary layer on small models is so extremely thin that it is not possible to construct slots in the surface which are not out of all proportion to this thickness and which will not distort the flow.

4. The full-scale tests reported by Carroll, at this laboratory (file No. 1115.6/1), transmitted with L.M.A.L. letter September 15, 1927, unpublished, on boundary-layer control by the method of pressure slots was a step in the right direction. In these tests, however, only two slots (backward opening) were used; the position of these slots, in the light of more recent experiments, was not very good; only one wing pressure was used; this pressure was not measured, and only one wing of the biplane was fitted with the slots. In spite of these limitations, however, the results showed a 6 percent gain in the rate of climb and a considerable increase in the maximum angle of attack at which the plane could fly. If the slots had been changed to simple suction slots normal to the surface and the air had been sucked into the wing instead of being blown out, the results would no doubt have been much more favorable.

5. There are several advantages to be gained by conducting the tests at full scale. these are enumerated as follows:

(1) The elimination of scale effect which is especially great in the flow through slots.

(2) The boundary layer is much thicker than on small models and hence the slot structure may be built in proportion, offering a minimum of disturbance to the flow.

(3) The blower system and the apparatus for measuring the boundary layer may be installed inside the wing, greatly simplifying the method of testing and the accuracy of the measurements.

(4) The power expended in driving the blower and the efficiency of the blower and slot system may be determined by direct measurements.

Hugh B. Freeman,
Assistant Physicist.

Document 4-14

Theodore Theodorsen, Senior Physicist, to Engineer-in-Charge, "Boundary layer removal," 4 Feb. 1932, in RA 88, LHA, Hampton, Va.

Dr. Theodore Theodorsen was definitely someone to listen to, not just at Langley but in the American aeronautics community generally. The man possessed one of the country's most brilliant scientific minds and in the long run contributed at least as much to modern aerodynamics as Eastman Jacobs did, if not more.

Following an engineering degree from his homeland's Norwegian Institute of Technology at Trondheim in 1922, Theodorsen came to the United States and earned a Ph.D. in physics from Johns Hopkins University. Encouraged by Dr. Joseph Ames, Johns Hopkins' president and chairman of the Executive Committee of the NACA, Theodorsen came to Langley in 1929 as an associate physicist. Within a short time, the talented young man was made head of the Physical Research Division, Langley's smallest division. Because his administrative duties were light, he was able to concentrate on his own work.

The list of his accomplishments just during the 1930s is prodigious: he improved thin-airfoil theory by introducing the best angle of streamlining; devised an elegant theory of arbitrary wing sections; developed the basic theory of aircraft flutter; made improvements to NACA engine cowlings and ducted propellers; expanded propeller theory and developed scaling laws for propeller vibrations; performed the first NACA in-house aircraft noise research; worked on fire prevention in aircraft and on means of icing removal and prevention; made early measurements of skin friction at transonic and supersonic speeds, and much more. In fact, although historians to this date have not generally recognized it, a strong case can be made that Theodorsen was the most thoughtful and productive researcher at the NACA during his 18-year tenure there. He resigned from the NACA in 1947 in order to help administer a new aeronautical institute being organized in Brazil. He later served as chief scientist for the U.S. Air Force and chief of research for Republic Aviation Corporation. (See *A Modern View and Appreciation of the Works of Theodore Theodorsen, Physicist and Engineer*, ed. Earl H. Dowell (Washington: American Institute of Aeronautics and Astronautics, 1992.)

Theodorsen's idea of "feathers" for boundary layer control may not make sense upon first reading, but essentially what he was suggesting was the idea of a "slotted flap." The significance of the flap, a hinged airfoil in the form of a long narrow strip attached to the rear of a wing, was discussed in Chapter 3 in relation to the design revolution of the 1930s. Essentially, a flap provided higher lift than a wing without flaps could manage. The NACA did not invent the flap; the flap evolved continuously from the idea of "ailerons" invented by French airplane designer and pilot Henry Farman for improved lateral control of his 1908 airplane. The technology grew from there. Late in World War I, German pilot G.V. Lachman tried out the first "slotted wing," with its long spanwise slot located near the leading edge of the wing. Soon after the war, Britain's Handley Page was running wind-tunnel tests indicating that slotted wings improved lift by as much as a whopping 60 percent. In the 1920s, numerous wing flap modifications followed, including ones invented by Orville Wright and Harlan D. Fowler, an engineer working for the U.S. Army who subsequently designed effective flaps for the Glenn L. Martin Company. By the time Theodorsen conceived his notion of "feathers," airplane designers worldwide had embraced the idea of flaps. There was no more practical way for them to deal with increasing speeds and wing loadings of the modern airplane.

The NACA was involved in flap research in a major way. It conducted pioneering experiments on various types, including split flaps, slotted flaps, and later on spoilers, double- and triple-slotted flaps, slats, and many other types of wing appendages in various combinations on both the front and back of the wing, designed for high-lift. In a sense, what Theodorsen was calling for in 1932 with his idea of "feathers" was an experimental slotted-flap system. It was a rather odd expression of a good idea that would pay off when such high-lift systems were effectively incorporated, particularly on large airplanes where the aerodynamic advantages were the greatest.

Theodorsen's memo also demonstrates a few interesting points about the personality of one of the NACA's leading aerodynamicists. Being primarily a theoretician did not stop him from suggesting even the most direct analogy from nature (like the one he made here based on bird feathers), nor did it inhibit him from proposing and carrying out the simplest experiment. (The suggestion he made in this memo was approved by the engineer-in-charge; Theodorsen put together some simple tests in the VDT on a wing section with two or three "feathery" modifications.) The first line of his memo also suggests how a problem could absolutely monopolize his attention. One of his closest associates in the Physical Research Division, Isadore Edward Garrick, remembered Theodorsen's rapt method of working. Having decided that something like boundary layer control was worth his thinking about, "he would work on it during relatively short periods of intense concentrated activity, almost incommunicado, followed by periods of apparent desultory inactivity." And once he became convinced that he had a good idea, he expressed it, without fear of ridicule and hoping that others would take it seriously and talk to him about it in an open, friendly, and constructive way. Equally, he allowed his subordinates to develop their own talents and resources without fear of embarrassment or ridicule. Not that he was not a stern critic, for he most definitely was. But Theodorsen was always helpful when asked, even if a junior associate came to him with a raw or semi-finished product. (Isadore Edward Garrick, "Sharing His Insights and Innovations," in *Modern View and Appreciation of Theodore Theodorsen*, p. 21).

Document 4-14, Theodore Theodorsen, Senior Physicist, to Engineer-in-Charge, "Boundary layer removal," 4 Feb. 1932, in RA 88, LHA, Hampton, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
LANGLEY MEMORIAL AERONAUTICAL LABORATORY
LANGLEY FIELD, HAMPTON, VA.

February 4, 1932

MEMORANDUM For Engineer-in-Charge
Subject: Boundary layer removal

1. I have given the question of boundary layer removal an examination as regards its theoretical possibilities. The result is so interesting that I shall submit the essential conclusion for your immediate consideration.

2. To increase lift and high angle control it is necessary to equip the trailing and end edges of the wing with "feathers"; that is, flexible marrow plates with a rather rigid central core or stem. It is significant that the birds, in spite of the handicap of low Reynolds numbers, have resorted to this trick. The operating principle of the "feathers" is to suck off the boundary layer. The kinetic energy of the lower side air stream is utilized to pump the dead air from the upper side along the stem of each "feather" when bent down. The most efficient size of the "feathers" can be approximately predicted. The best shape may, however, differ to some extent because of the larger Reynolds numbers. It is possible to attach the "feathers" directly to the wing or to the ailerons. Incidentally, all guiding surfaces, for instance the rudder, should apparently be equipped with "feathers."

Theodore Theodorsen
Senior Physicist

Document 4-15

Theodore Theodorsen, Introduction, "Theory of Wing Sections of Arbitrary Shape," NACA *Technical Report* 411 (Washington, 1931).

Dr. Theodore Theodorsen was practical enough to realize that the "imperfect status" of wing theory required designers to make their airfoils "independent of theoretical restrictions." But more than anyone else at Langley he saw the need for the NACA's research staff to fertilize its experimental routine with a stronger dose of theory. In his opinion, to discover more advanced airfoils the NACA did not need a new wind tunnel as Eastman Jacobs was suggesting but rather better mathematical and physical understanding of the effects of the basic aerodynamic phenomena on wing performance. The implication of his argument was that the experimentalists at Langley had become too interested in and dependent upon equipment for their own good.

Jacobs disagreed totally with the idea that theoreticians could answer the remaining questions about airfoils better than could experimentalists; he also rejected the argument that it was unnecessary and impossible for the NACA or anyone else to build a pressure tunnel having low airstream turbulence, which was one of Theodorsen's points. But Jacobs, in principle, did not oppose Theodorsen's notion of theory's critical role in successful research. Nor did he disagree that many Langley researchers were weak mathematically, as that was common for engineers trained in American colleges and universities. An adventurous man with an expansive outlook on what was possible, Jacobs kept up with and understood the most current theory—though he did not devote much of his own time to its study—and valued its role in creating the fundamental but directly useful technological information expected of the NACA. Jacobs' problem with Theodorsen was more a battle over "turf." At Langley both men controlled fiefdoms, and because both men were so valuable, NACA officials had permitted the feudal arrangement to flourish. Usually the two men worked on completely separate activities, but occasionally they had to work together—and then they inevitably clashed.

The introduction to TR 411 is one of the most remarkable openings to any NACA or NASA technical report ever published. Few formal publications of the agency have ever expressed such thoughtful statements on research philosophy and almost none have involved criticisms of colleagues, no matter how indirect.

Document 4-15, Theodore Theodorsen, Introduction, "Theory of Wing Sections of Arbitrary Shape," NACA* Technical Report *411 (Washington, 1931).

REPORT NO. 411
THEORY OF WING SECTIONS OF ARBITRARY SHAPE
By THEODORE THEODORSEN

SUMMARY

This paper presents a solution of the problem of the theoretical flow of a frictionless incompressible fluid past airfoils of arbitrary forms. The velocity of the 2 dimensional flow is explicitly expressed for any point at the surface, and for any orientation, by an exact expression containing a number of parameters which are functions of the form only and which may be evaluated by convenient graphical methods. The method is particularly simple and convenient for bodies of streamline forms. The results have been applied to typical airfoils and compared with experimental data.

INTRODUCTION

The theory of airfoils is of vital importance in aeronautics. It is true that the limit of perfection as regards efficiency has almost been reached. This attainment is a result of persistent and extensive testing by a large number of institutions rather than of the fact that the important design factors are known. Without the knowledge of the theory of the airflow around airfoils it is well-nigh impossible to judge or interpret the results of experimental work intelligently or to make other than random improvements at the expense of much useless testing.

A science can develop on a purely experimental basis only for a certain time. Theory is a process of systematic arrangement and simplification of known facts. As long as the facts are few and obvious no theory is necessary, but when they become many and less simple theory is needed. Although the experimenting itself may require little effort, it is, however, often exceedingly difficult to analyze the results of even simple experiments. There exists, therefore, always a tendency to produce more test results than can be digested by theory or applied by industry. A large number of investigations are carried on with little regard for the theory and much testing of airfoils is done with insufficient knowledge of the ultimate possibilities. This state of affairs is due largely to the very common belief that the theory of the actual airfoil necessarily would be approximate, clumsy, and awkward, and therefore useless for nearly all purposes.

The various types of airfoils exhibit quite different properties, and it is one of the objects of aerodynamical science to detect and define in precise manner the factors contributing to the perfection of the airfoil. Above all, we must work toward the end of obtaining a thorough understanding of the ideal case, which is the ultimate limit of performance. We may then attempt to specify and define the nature of the deviations from the ideal case.

No method has been available for the determination of the potential flow around an arbitrary thick wing section. The exclusive object of the following report is to present a method by which the flow velocity at any point along the surface of a thick airfoil may be determined with any desired accuracy. The velocity of the potential flow around the thick airfoil has been expressed by an exact formula, no approximation having been made in the analysis. The evaluation for specific cases, however, requires a graphical determination of some auxiliary parameters. Since the airfoil is perfectly arbitrary, it is, of course, obvious that graphical methods are to some extent unavoidable.

Curiously enough, the theory of actual airfoils as presented in this report has been brought into a much simpler form than has hitherto been the case with the theory of thin airfoils. In the theory of thin airfoils certain approximations have restricted its application to small cambers only. This undesirable feature has been avoided, and the results obtained in this report have a complete applicability to airfoils of any camber and thickness.

The author has pointed out in an earlier report that another difficulty exists in the theory of thin airfoils. It consists in the fact that in potential flow the velocity at the leading edge is infinite at all angles except one. This particular angle at which the theory actually applies has been defined as the ideal angle of attack. In the present work we shall not go any further into this theory, since it is included in the following theory as a special case of rather limited practical importance.

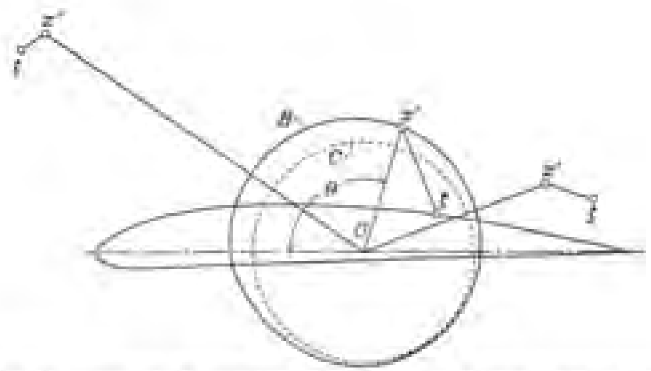


FIGURE 1.—Showing the transformation from a nearcircular curve B into an airfoil

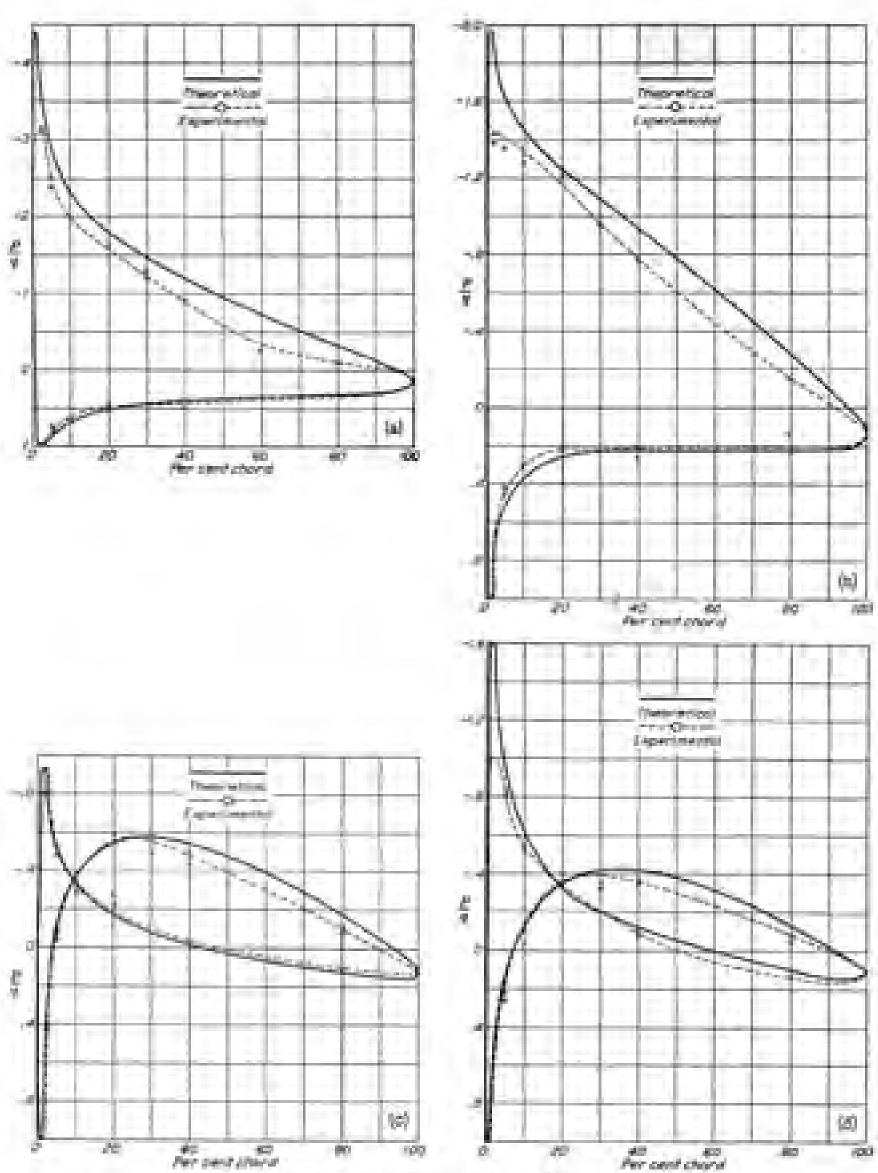


FIGURE 2.—[illegible] Clark Y; $\frac{P}{q}$ against per cent chord
(a) [illegible] (b) [illegible] (c) [illegible] (d) [illegible]

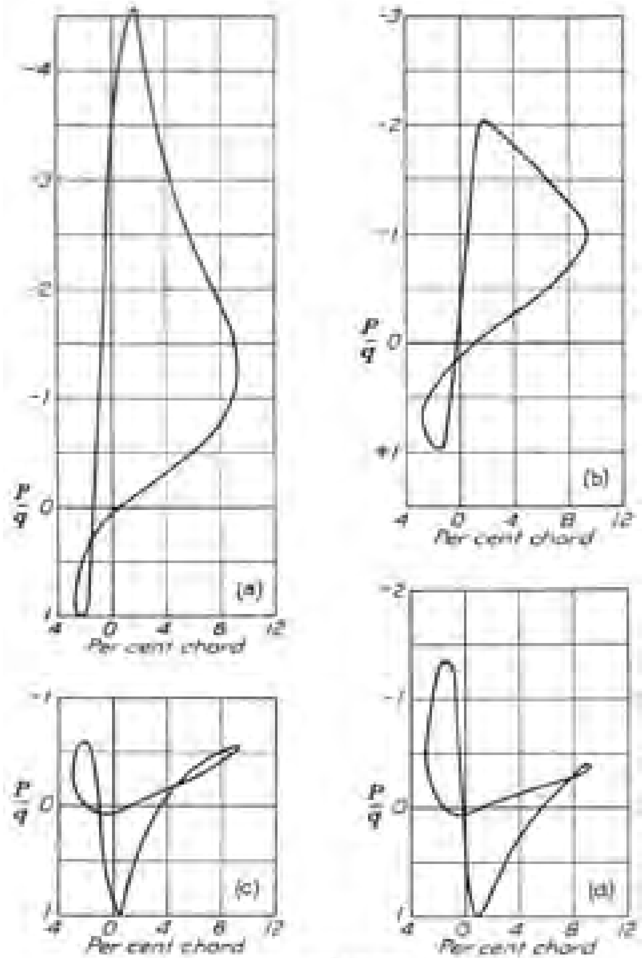


FIGURE 3.—Theoretical pressure distribution along x-axis of Clark Y
(a) α=9° 23′, (b) α=2° 13′, (c) α=−1° 16′, (d) α=−3° 15′

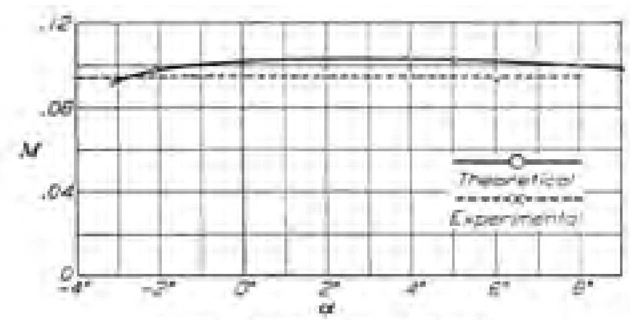


FIGURE 4.—Moment against angle of attack

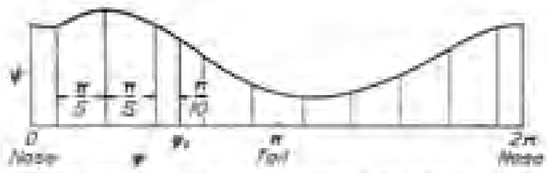


FIGURE 5.—The ψ against φ curve, illustrating method of evaluation of ε.

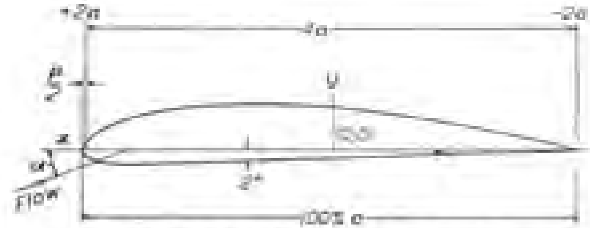


FIGURE 6.—Clark Y airfoil—showing system of coordinates

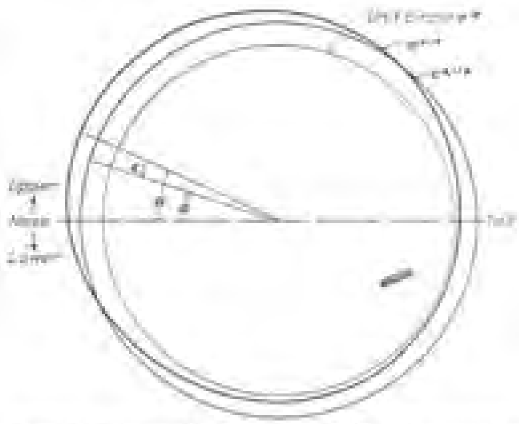


FIGURE 7.—The unit circle, the circle, and the corresponding curve

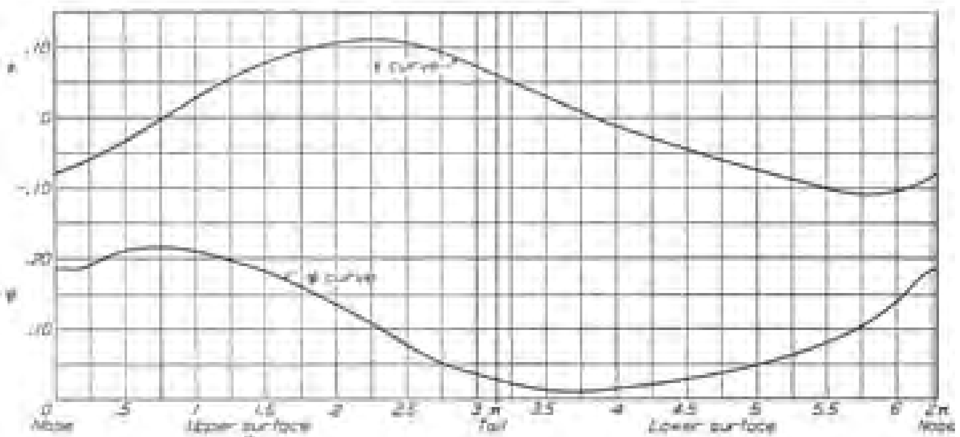


FIGURE 8.—(a) The ψ against φ curve for the Clark Y. (b) The ε against φ curve for the Clark Y.

TABLE I

CLARK Y

UPPER SURFACE

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LOWER SURFACE

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE II

CLARK Y

[illegible]

	Upper surface						Lower surface					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table II gives the numerical values for Figure 2a in detail as an example. See also Table I.

TABLE III

Figure	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE IV

Figure	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

Document 4-16
Eastman Jacobs, Memorandum to Engineer-in-Charge, "Program for study of scale effect on airfoils," 13 November 1929, in RA file 88, LHA, Hampton, Va.

Eastman Jacobs himself would later spotlight this memo as evidence of his early awareness of the possibilities "for controlling boundary layer directly through body shape or through control of the usual pressures acting along the body surface." (See Document 4-18.) It is interesting that Jacobs cited a conversation with George Lewis, the NACA's director for research, as the stimulus for his study of scale effects, which suggests that Lewis himself was no lightweight when it came to addressing fundamental aerodynamic problems.

At the time, it is clear from this memo, Jacobs expected the VDT to provide the experimental data needed to arrive at the specific airfoil shapes that delayed transition and sustained laminar flow. It would not be long, however, before he became convinced that the turbulence in the existing Variable-Density Tunnel could never be resolved. Without a new low-turbulence pressure tunnel, no practical investigation of this type of boundary layer control for improved airfoils would be possible.

Document 4-16, Eastman Jacobs, Memorandum to Engineer-in-Charge, "Program for study of scale effect on airfoils," 13 November 1929, in RA file 88, LHA, Hampton, Va.

November 13, 1929.

MEMORANDUM For Engineer-in-Charge

Subject: Program for study of scale effect on airfoils.

1. A recent conversation with Mr. Lewis caused me to devote some more intensive thought and study to the mechanism and causes of scale effect on airfoils. Any one who has given the subject much attention realizes that the effect of the dynamic scale originates in the very thing and boundary layer along the surface of a body, for it is only in this layer that the viscous forces are of sufficient magnitude to have any immediate effect on the flow. This does not mean that only the flow in the boundary layer is altered by the scale, because changes in the boundary layer may, and do in some cases, radically alter the general flow, e.g., the Prandtl experiment of boundary layer control in a diffuser. What it does mean is that when the ratio of mass to viscous forces in a flow is changed by changing the density of the air in the tunnel, the immediate effects must be sought in the boundary layer where this ratio is sufficiently large to be of importance.

2. The character of the following in the boundary layer is important in determining the aerodynamic characteristics of airfoils for two reasons; first, because it influences directly the skin friction on the surface which in turn determines a considerable part of the profile drag of good airfoils, and second, because it controls the position of separation points of the fall and consequently the character of the entire flow under certain conditions. The character of the flow in the boundary layer may be described as either laminar or eddying (following Dryden's nomenclature). The direction of flow in either case may become reversed, thus producing a separation point, but the reversal is resisted to a greater extent by the eddying boundary layer. In general, the boundary layer over an airfoil is partially eddying and partially laminar, the amount of each type depending on the Reynolds number as well as on other conditions. Both the drag and the conditions under which reversed flow takes place depend on the Reynolds number of the boundary layer as well as on the character of the boundary layer, whether eddying or laminar, but according to different laws for the eddying end for the laminar boundary players.

3. The point of transition from laminar to eddying flow in the boundary layer is therefore of particular importance. It depends, of course, on the shade and attitude of the airfoil, but of greater interest from the standpoint of scale effect is it gets a variation with Reynolds number. Dryden and Kuethe have considered the relation of the transition point on airship forms to the Reynolds number and to the initial turbulence of the airstream. It is probable that any investigation of a similar nature, applied to airfoils in the Variable Density Wind Tunnel over a wide range of the Reynolds number, would throw light on the causes and mechanism of scale effect. The character of the airfoil surface might be expected to have a marked effect on the position of the transition point so that the effects of different surfaces should be studied as well as the effects of changes in initial turbulence and Reynolds number.

Part of the work in connection with the investigation could be done under Research Authorization Number 177, "Determination of Effect of Polish of the Surface on Airfoil Models," and the part dealing with the effect of turbulence could be done under Research Authorization No. 203, "Study of Characteristics of Very Thick Airfoil Sections," or it could be done under Research Authorization No. 88, "An Investigation in the Variable Density Wind Tunnel of Scale Effect on Airfoils." The results of the investigation would determine the advisability of preparing a special research authorization providing for an investigation of the mechanism of the scale effect on airfoils, and would indicate more clearly how such an investigation should proceed.

Eastman N. Jacobs
Associate Aeronautical Engineer

Document 4-17

B. Melvill Jones, "Flight Experiments on the Boundary Layer," *Journal of the Aeronautical Sciences* 5 (January 1938): 81-101. First Wright Brother's [sic] Lecture, Presented before the Institute of the Aeronautical Sciences at Columbia University, New York, 17 December 1937.

John Anderson has called B. Melvill Jones's First Wright Brother's Lecture of December 1937 "a fitting closure to one phase in the development of applied aerodynamics in the era of the advanced propeller-driven airplane" (*A History of Aerodynamics*, p. 354). This was the phase when the "call to action" for aeronautical engineers was to "Streamline" – to design aerodynamic bodies with the lowest possible form drag. Jones himself had ushered in the new age in 1929, when he delivered his famous address "The Streamline Airplane" to the Royal Aeronautical Society (see Chapter 3). An incredible amount of worthwhile streamlining for airplanes was done in the next eight years, including the NACA low-drag cowling, retractable landing gear, stressed-skin aluminum structures, flush riveting, more efficient airfoils, and much more. In 1937, Jones was telling his audience that the next hurdle was to reduce friction drag, the most significant major source of drag that remained—and the one that would be the hardest to do anything about.

Over 300 members of the Institute of the Aeronautical Sciences heard Jones's talk, including Orville Wright. Four days later, on 21 December 1937, he repeated it at an IAS meeting at Caltech. Both talks stimulated a major—and a very positive—reaction. A Douglas aircraft engineer who attended the West Coast talk by the name of Francis Clauser recognized what Anderson has called "the historical full-circle significance" (*A History of Aerodynamics*, pp. 354-5) of Jones's address: "It was a pleasure to hear from the man who provided the stimulation some years ago which has led to the practical elimination of unnecessary form drag in modern airplanes and it is reassuring that this same man is now engaged in research which may conceivably reduce the remaining skin friction to some fraction of its present value." The full account of Clauser's remarks can be read at the end of Jones's paper, in the commentary section.

Notably, the IAS also chose the NACA's George Lewis and Eastman Jacobs to be two of the select individuals commenting on Jones's historic paper. It is interesting that Lewis, from his special perspective as a research director, commented on "the many different problems of experimental technique," which required "the utmost ingenuity to solve." Jacobs, on the other hand, dealt squarely with the promise of laminar-flow airfoils implied by Jones's boundary-layer work. From his standpoint, "the outstanding result" of Jones's tests was that "he has definitely shown what we have suspected for a long time: that extensive laminar layers must be recognized as possibly existing on actual airplanes in flight." The outstanding question still needing an answer, in his mind, was "How much further can we go in maintaining these desirable low-drag laminar layers?"

Jacobs left his seat at Melvill Jones's talk determined to answer the question.

Document 4-17, B. Melvill Jones, "Flight Experiments on the Boundary Layer,"* Journal of the Aeronautical Sciences *5, January 1938.

JOURNAL OF THE AERONAUTICAL SCIENCES

JANUARY, 1938

FLIGHT EXPERIMENTS ON THE BOUNDARY LAYER

B. Melville Jones, Cambridge University, England

First Wright brothers' Lecture
Presented before the Institute of the Aeronautical Sciences at Columbia University, New York
December 17, 1937

FOREWORD

This lecture is to be the first of a series to be delivered annually in honor of those famous pioneers the Wright brothers. I am told that the lecture itself should be severely technical and should not deal in compliments, but it is right for me to record, before beginning, the deep admiration which I have always had for Wilbur and Orville Wright, ever since the time when they were the half mythical heroes of my school days. I am acutely aware of the honor which you have done me in asking me to inaugurate a series of lectures in their honor. I shall not discuss the work of the Wrights, which is familiar to all, and it would be an impertinence to attempt elaborate praise of men whose names will remain household words when I and the majority of those present have been long forgotten.

INTRODUCTION

The authorities of the Institute of the Aeronautical Sciences have decided, so I am instructed, that the Wright brothers' Lecture should deal with subjects upon which the lecturer is engaged at the time, rather than with a general survey of some wide branch of aeronautical knowledge. This decision has the advantage that the lecturer is actively interested in the subject about which he talks, but it leaves to chance the question whether he is in a position to end his lecture with simple and clear cut conclusions. I mention this because the problem upon which we are working at Cambridge, and about which I shall speak, is not yet solved and my lecture must, perforce, be confined to a discussion of aims and methods and of results so far obtained; it does not contain that simple statement of conclusions which is the ultimate aim of all good research. After this explanation you will not, I hope, be disappointed when the lecture ends on a note of interrogation.

The material from which the lecture has been constructed is drawn mainly from experiments made in flight at Cambridge, but in order to make it as complete as possible, results from Government Research Establishments with which we work in close cooperation are quoted. For permission to do this I have to thank the British Air Ministry and the various persons directly concerned. I have also to thank the British Aeronautical Research Committee for permission to use information which has been submitted to them but which, at the time of writing, has not been published.

The title of the lecture is Flight Experiments on the Boundary Layer and it deals more specifically with the transition of the layer from the laminar to the turbulent form. Everyone interested in modern aeronautics is of course well aware of the general field of knowledge surrounding this subject; that the resistance to motion, of modern aircraft arises mainly from the friction of air acting upon exposed surfaces; that this skin-friction, as it is called, is applied in a comparatively thin layer of air immediately overlying the exposed surfaces; that these "boundary layers" in the air take one of two forms, a smooth or "laminar" form near the front of the exposed surface, and a turbulent form towards the rear; finally that the friction of the laminar layer is much less than that of the turbulent layer, so that the mean friction coefficient of the whole exposed surface—the figure used by the designer in laying out his performance chart—depends upon the precise location on the surface of the line at which transition occurs.

The order of magnitude of the changes which occur in the drag of a smooth wing, when the point of transition from the laminar to turbulent flow moves forward or backward along the wing profile, is illustrated in Fig. 1. Here, ordinates represent the conventional profile-drag coefficient and abscissae relate to the mean distance—measured parallel to the wing chord—between the leading edge of the wing and the points where turbulence begins on the upper and lower surfaces, respectively. The drag coefficients were obtained in flight by the now well known method in which small pitot and static-pressure tubes are made to traverse the wing wake; the transition points were located by methods shortly to be described. The use of the mean transition point as a basis for plotting is open to objection because the velocity distributions on the two surfaces are not in general the same, but some sacrifice of precision is justified in order to bring the various results together on a simple diagram suitable for a preliminary survey of the situation. The precise positions of the points where turbulence was found to begin on each surface in various circumstances will be considered later.

The individual points in Fig. 1 relate to wings of various thickness, with lift coefficients between 0.3 and 0.4; the crosses relate to experiments made at Cambridge, and the other points to experiments made by the Royal Aircraft Establishment, Farnborough. To obtain the two points for the wing of thickness ratio 0.10 the point of transition on the upper surface was fixed at x/c = 0.24 and 0.07, respectively (see legend of Fig. 1 for definitions), whilst that on the under surface remained unaltered at about x/c = 0.16; the points on the upper surface were fixed by attaching wires of about 0.01 in. diameter transversely on the surface. To obtain the two more forward points for the wing of thickness ratio 0.30, the points of transition on both the upper and under surfaces were fixed by sticking thin paper sheets to the surfaces with their front edges in appropriate positions for which x/c was the same for both surfaces. For all the other points in Fig. 1., transition occurred spontaneously on surfaces which had been carefully smoothed and polished. The point corresponding to spontaneous transition for the wing of thickness ratio 0.10 has not been plotted because it lies very close to the more rearward of the two points for which transition was controlled.

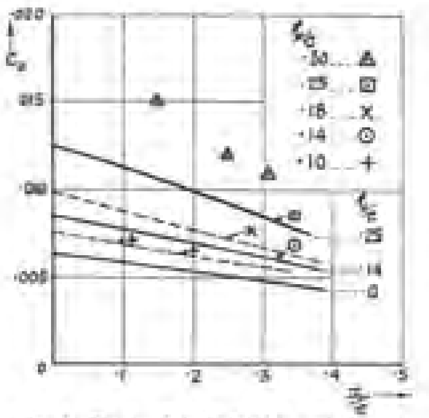


Fig. 1. Drag coefficient related to point of transition. Ordinates represent conventional profile drag coefficients. Abscissae show the mean values of the distances s from the leading edge of the points of transition from laminar to turbulent flow on the upper and under surfaces of various wings. The distance s is measured parallel to the wing chord which is of length c. The maximum wing thickness is represented by t. The drag coefficients shown by the curves are computed as described in the text. The figure relates to a wing Reynolds Number of seven millions and slight adjustments of the order 2 percent to 3 percent have in some cases been made to the observed drag values, to allow for the fact that they were obtained when the Reynolds Number had values ranging from five to eight millions.

The continuous curves in Fig. 1 are from computations made with certain simplifying assumptions. That for which t/c is zero relates to an ideally smooth thin flat plate and is built up from the Blasius solution for the laminar layer and the Prandtl-Karman logarithmic curve for the friction of the turbulent layer, the change from laminar to turbulent flow being assumed to occur suddenly and without change of momentum loss. The two continuous curves for which t/c is 0.14 and 0.25, respectively, are from calculations made at Farnborough by H. B. Squire and A. D. Young. In these the skin friction of the laminar layer was calculated step-by-step along the wing profile, using Polhausen's approximate method of representing the velocity cross-sections by fourth power polynomials; the friction of the turbulent part of the layer was computed by a similar process on the assumption that the velocity cross-section of the layer retains a constant form. Here also transition was assumed to occur suddenly without change of momentum loss. The drag coefficients shown by these curves are greater than the resultants of the skin friction forces, because they contain some "form drag" which can be shown to be an inevitable consequence of skin friction acting upon a wing of finite thickness. The intermediate broken curves have been obtained by interpolation from the computed continuous curves and have been added merely to aid comparison with the experimental points for wings of corresponding thickness ratio.

Though the basis on which Fig. 1 is constructed is not such as to allow fine points of difference to be examined, the figure suffices to illustrate clearly the three main conclusions of practical importance which can be drawn from the experiments to be discussed. These are: (1) That when the transition points are known the profile drags of smooth fair-shaped wings of moderate thickness can be computed with sufficient accuracy for most practical purposes from the known values of skin friction on a smooth flat plate. (2) That at moderate values of the wing Reynolds number—five to ten million—transition can be postponed to distances greater than 0.3 chords from the leading edge, with a consequent reduction of drag of the order 30 to 35 percent of the drag with the layer wholly turbulent. (3) That very small roughnesses or imperfections of surface are sufficient to move transition points forward and so increase drag.

In relation to the third conclusion it may be mentioned that, in one instance at Cambridge, when the wing Reynolds number was about ten millions, a piece of tinfoil 0.002 in. thick, stuck down on the wing surface, appreciably influenced the position of transition. Again, at Farnborough, the drag of a smooth wing—measured by the pitot-traverse method—was appreciably increased when the aeroplane had flown through a cloud and this is considered to have been the result of a forward movement of the transition point, caused by mist drops deposited on the wing surface. Very small—barely perceptible—waves on the wing surface have also been shown materially to affect the point of transition and therefore the drag.

These considerations show the practical importance of knowing where upon the wings and other exposed surfaces of an aeroplane the boundary layer passes from the laminar to the turbulent flow, and they explain why the factors which influence the onset of turbulence are occupying the attention of many aeronautical research laboratories besides that at Cambridge.

METHODS OF EXPERIMENT

It is of course well known that the transition of the boundary layer from the laminar to the turbulent form is a gradual process, so that strictly one should speak of a transition region rather than of a transition point. The experiments of H. L. Dryden and others have shown also that the transition region itself does not remain stationary, but is subject to rapid to-and-fro movements, so that in strict accuracy one cannot speak of a transition point without first defining it in relation to the mean position of a fluctuating transition region. In the experiments to be described, however, the effects of rapid fluctuations are automatically meaned by the slow response of the apparatus, and its indication of transition is sufficiently sharp to define a point on the wing surface which for practical purposes can conveniently be called the transition point.

The hot wire anemometer which has been widely used for the study of transition in the laboratory is not a convenient instrument for use in flight, and an alternative method involving very small pitot tubes has therefore been developed. This method depends on the changes which occur during transition in the mean velocity cross-section of the boundary layer. Typical velocity cross-sections just before and just after transition are shown in the left-hand diagram of Fig. 2, whilst the right-hand diagram of that figure shows, in sketch form, the changes which would occur in the pressure registered by a very small pitot tube moved through the transition region along lines lying parallel to the wing surface, such as AA, BB, etc. in the left-hand diagram. It can be seen from this figure that a small pitot tube moved in the direction of flow at a constant distance from the wing surface, along a line such as AA which just before transition lies just outside the laminar layer, will register, as indicated by line A of the right-hand diagram, a small fall of pressure as it passes into the thicker turbulent layer. Pitot tubes moved in a similar manner along lines, such as BB or CC, situated closer to the wing surface will, on the other hand, register a rise of pressure as they pass through the transition region. The distance along the wing surface within which these changes of mean pressure occur varies of course with circumstances, but in the experiments to be described it was generally of the order four inches.

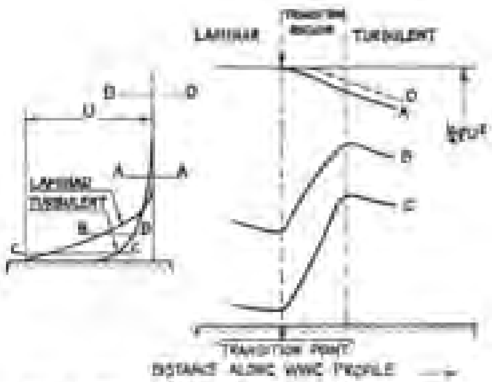


Fig. 2. Diagrams for explaining the methods used for locating the region of transition to turbulent flow. The left-hand diagram shows typical distributions of mean velocity in the boundary layer just before and just after the onset of turbulence. The right-hand diagram shows the variation of pressure in a pitot tube moved through the transition region along lines parallel to the wing surface at various distances from it.

The phenomena described above can obviously be used to detect transition. In wind tunnel experiments it is generally more convenient to use pitot tubes close to the wing surface, in which pressure rises as the pitot passes into the turbulent part of the layer, for this method gives, when the external stream is smooth, a very precise indication of the first onset of turbulence and, since the exploring pitot can be placed in actual contact with the solid surface, it is not necessary to make any but a rough estimate of the thickness of the laminar layer before beginning the experiment.

In flight experiments, on the other hand, it is generally more convenient to use a pitot tube which lies altogether outside the laminar layer and in which pressure falls as it moves into the turbulent layer. There are two reasons for this: one is that, in straight flight at altitudes where the air is steady, total-pressure is very accurately

the same at all parts of the potential stream, so that an exploring pitot, coupled through a manometer to another pitot conveniently situated anywhere in the potential stream, enables minute defects in total-pressure to be easily detected: the other is that the bore of the outside pitot tube can be made much larger than that of the inside pitot. The latter is a great advantage in flight experiments because a small pitot-tube implies a large lag in the response of the manometer to pressure changes and a possibility of error due to change of pressure and temperature consequent upon an accidental or deliberate change of height. This latter consideration is not so important in laboratory experiments where the capacity of the connecting tubes can be kept small and the external pressure and temperature can be maintained more nearly constant.

At first sight it might be supposed that the method of the outside pitot suffers from the severe disadvantage that the thickness of the laminar layer must be accurately known before the experiment begins, but a rough consideration of the quantities involved is sufficient to show that this is not so, unless very great accuracy in location of the transition point is required. The slope relative to the wing surface, of the effective outside boundary of the layer in the transition region is of the order 1/25, so that a displacement of the outside pitot away from the wing surface by as much as 0.1 in. will shift the point where total-pressure loss is first detected by no more than 2.5 in. The effective thickness of the laminar layer just before transition upon a smooth wing at ordinary flight speeds is seldom much greater than 0.05 in. so that no great percentage accuracy in the estimation of its thickness is necessary in order to adjust the distance of the outside pitot from the wing surface so that it always lies outside the laminar layer, without being so far away from it as to make

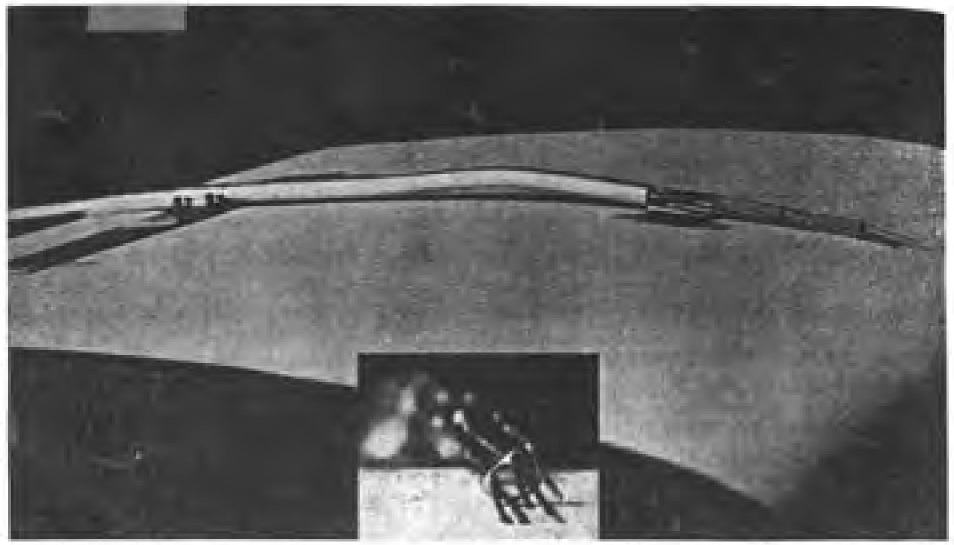


Fig. 3. Photographs of the five-tube head used for exploring the transition region in flight. The four tubes with orifices in the form of horizontal slits register total pressure at various distances from the wing surface, their outside dimensions at the front end are 0.012 in. deep and 0.004 in. wide. The tube with round closed end registers static-pressure.

the position of the transition point uncertain by more than 1 or 2 inches. For example, the pressure variations in a pitot moved along DD in Fig. 2 would be roughly as indicated by the broken curve D in the right-hand diagram, and the corresponding shift in the supposed position of the transition point would be no more than some 2 in. It is apparent from this consideration why much larger pitot tubes can be used by the outside method than by the inside method.

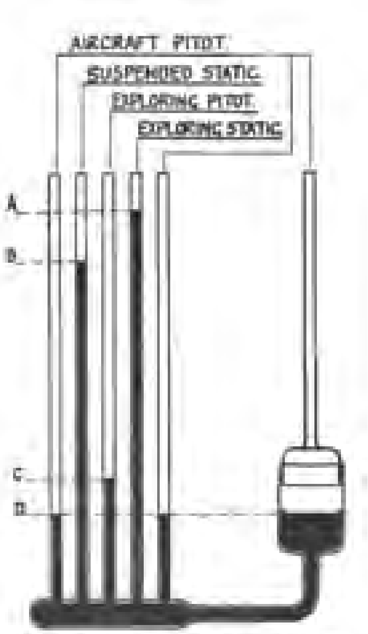


Fig. 4. Diagram illustrating manometer connections. [illegible]

The most recent form taken by the pressure heads used in flight experiments at Cambridge is shown in Fig. 3. Here five tubes are used, each of 0.042 in. external diameter. One of these is a static-pressure tube by means of which the pressure distribution along the wing profile can be recorded. The other four are pitot tubes with flattened orifices of external depth (perpendicular to the wing surface) of 0.012 in. and width 0.064 in. One of these tubes, known as the surface pitot, is in actual contact with the wing surface, whilst the other three are situated at various distances from the wing surface, such that two lie within the laminar layer and the third lies outside it. A convenient method of using this group of tubes is to fix them in some chosen position on the wing and record the pressures in them when the aeroplane is flown at various steady speeds. The change of incidence and of Reynolds number consequent upon change of flight speed cause the transition region to move along the wing profile and, if the position occupied by the tubes lies within the travel of the region, the conditions under which it passes them can be determined.

The manometer used in these experiments was of the multiple "U" tube type illustrated diagrammatically in Fig. 4. The tubes contain alcohol and records were made of the shadow of the meniscus thrown upon a sensitized paper close behind the tubes. This manometer enabled pressure differences to be measured to within about 1 percent of the impact pressure at the lower flight speeds and of course with greater accuracy at greater speeds.

A typical record from this instrument is shown plotted on a lift coefficient base in Fig. 5. In this instance the transition point moved backwards on the wing with increase of lift coefficient, so that the right-hand size of the figure relates to a laminar boundary layer and the transition point coincided with the orifices of the tubes

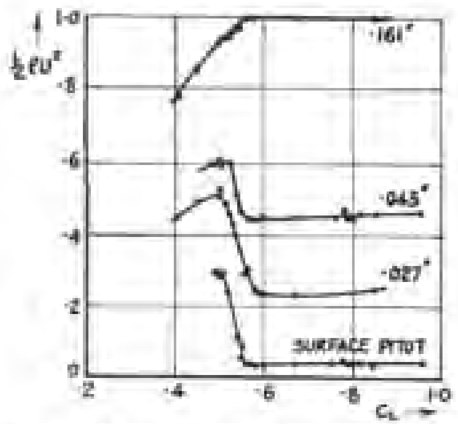


Fig. 5. Typical observations of total pressure in the transition region. These observations are from the four slit-ended pitot tubes illustrated in Fig. 3, which were situated on the under surface of the wing of thickness ratio 0.18 at 0.27 chords from the leading edge. The numbers written on each curve show the distance of the middle of the slit shaped orifices from the wing surface. Ordinates represent the total pressure registered by the tubes and abscissae the lift coefficient of the whole aeroplane. As lift coefficient increased the transition point moved backwards on the wing past the orifices of the tubes.

at lift coefficient 0.55. Judging from the rate of movement of the transition point with change of lift coefficient, estimated from this and similar experiments with the tubes fixed in different positions on the wing, the transition region illustrated in this figure occupied about 4 inches of the wing profile.

The rather complicated arrangement of five tubes described above was devised to enable the form of the laminar layer just before transition and the character of the transition region itself to be investigated; but when no more is required than to determine approximately the point where turbulence begins, much simpler arrangements can be used. In the earliest flight experiments on this subject at Cambridge a single pitot tube only was used, with circular end about 0.05 in. external diameter. This was stuck on to the wing surface with adhesive tape and the front bent up slightly so that the orifice lay just outside the estimated thickness of the laminar layer. In this simple way it is easy to find the position of the transition point on a wing within about a couple of inches, but unless the position of the tube can be altered in flight or the position of the transition region is roughly known beforehand, two or three flights may be necessary.

A refinement is to provide a second pitot tube and manometer and to place this second tube about twice as far from the wing surface as the first. This enables the slope of the outer boundary of the layer to be roughly determined and, since in the transition region this slope is some ten to twenty times as great as that of the laminar layer just before transition, all doubt as to whether transition has really occurred can be removed. After a little experience this refinement becomes unnecessary because, in the transition region, the characteristic shape of the curve of total pressure against distance along the wing is easily distinguished from the shape which results when the pitot merely enters gradually into the thickening laminar layer.

By such simple devices transition points could, if desired, be quickly and easily determined in testing organizations such as those of manufacturing firms, where the object is rather to ascertain what happens to specific aeroplanes than—as in research organizations—to investigate the general character of new phenomena.

The majority of the experimental results which will shortly be discussed were obtained with apparatus of complication intermediate between the five-tube arrangement illustrated in Fig. 3 and the single fixed pitot tube mentioned above.

At Cambridge, for example, the greater part of the work has been done with a three-tube instrument, of which one tube was in the form of a static-pressure tube whilst the other two were circular-ended pitot tubes both situated outside the laminar layer. These three tubes were rigidly connected together so that their working ends formed a small triangle and the whole was mounted on the wing in such a way that the tubes could be pushed by a small electric motor forwards and backwards along the wing profile, the object of the movement being to allow a larger number of observations to be made in a single flight. At Farnborough a somewhat similar arrangement of four tubes—one static-pressure and three pitot—has been extensively employed.

RESULTS OF EXPERIMENTS

The experimental observations which are now to be considered were obtained in flight upon portions of wings of which the surfaces were carefully smoothed and polished. The coverings in some cases were considerably thicker than is usual in present practice, the object being to eliminate as far as possible the slight waviness which is often observed on wing surfaces and is the cause of local variations in the pressure gradients along the profile. Even so, the makers did not always succeed in eliminating every trace of surface waves, the effect of which on the observations were exceedingly interesting. The observations have all been made along profiles which lay between the body and inner ends of the ailerons, sufficiently far from either it is thought to avoid interference from those parts or from the airscrew slipstream.

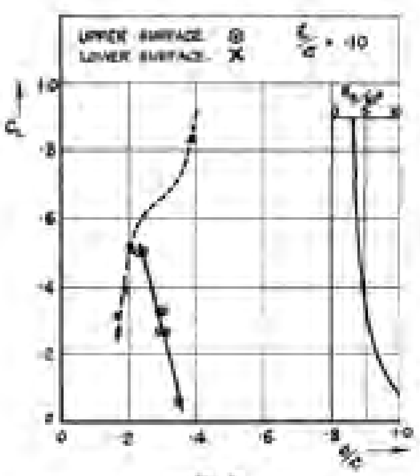
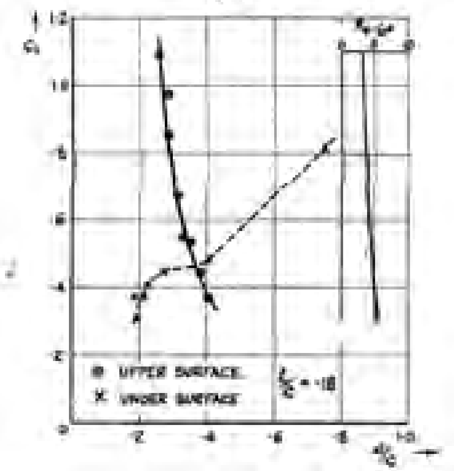


Fig. 6



The available information relating to the point of onset of turbulence on wings in flight is displayed in Figs. 6, 7, and 8, in which ordinates represent the lift coefficient of the aeroplane as a whole, and abscissae the distance of the transition point—measured round the wing profile—from the front stagnation point.

Fig. 6 shows the results of the first British experiments of this kind, which were made at Cambridge early in the present year upon the lower wing of a military biplane known as the Hart, the chord of which was 5 ft. in length. The approximate value of the wing Reynolds number appropriate to each lift coefficient is shown at the right-hand side of the figure. All the observations but one were made in level flight, with indicated flight speeds ranging from 60 to 120 m.p.h., at heights—round about 10,000 ft.—where the air was sufficiently calm to allow accurate observation. The exception is the point at lift coefficient 0.06; this point was obtained from observations made in long steep dives at an indicated air-speed of 240 m.p.h. The figure is built up from observations made in many different flights extending over several months.

On the upper surface of the wing the position of the transition point at each lift coefficient seemed to be very definitely established, but on the under surface, at lift coefficients round about 0.65, consistent results were more difficult to obtain, the position of the transition point being apparently very sensitive to air speed. A similar sensitivity at a different lift coefficient had been observed in some preliminary experiments made by very simple methods upon the same wing while it still had a standard fabric covering. Fig. 6 shows that at low lift coefficients the transition point on the under surface was much further forward than on the upper surface, but that as the lift coefficient increased the point on the under surface moved backwards whilst that on the upper surface moved forward.

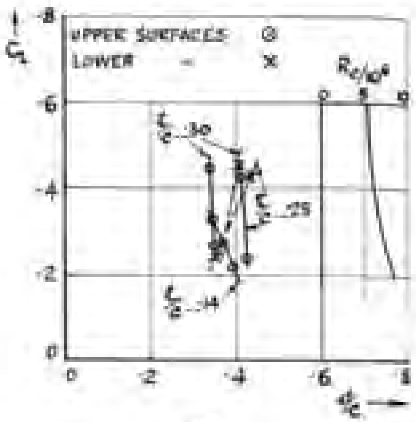


Fig. 8

Figs. 6, 7, 8.—Observations of the points of transition in the boundary layer of smooth wings in flight. Ordinates represent the lift coefficient for the whole aeroplane, abscissae the ratio to the wing chord c of distance—measured round the wing profile—between the front stagnation point and the point where turbulence first begins. The thickness ratio t/c of the wing profile is shown in each figure. The approximate Reynolds Number R, of the wing at each value of the lift coefficient is shown by a curve on the right-hand side of the figure. Figs. 6 and 7 are from experiments at Cambridge and Fig. 8 from experiments at Farnborough.

Fig. 7 shows similar results obtained at Cambridge for a thicker wing of a small monoplane. In the place where the experiments were made the chord of this wing was 6.2 ft. in length; the maximum level speed of this aeroplane was, however, lower than that of the Hart, so that the Reynolds number realized in level flight was about the same. These experiments, like those on the Hart, involved many flights on different days. The two points shown by squares in the group relating to the upper surface of the wing came, in fact, from check experiments made six months after the experiments which gave the other points in the figure had been completed. As with the Hart, the upper surface points were relatively easy to obtain, whilst on the under surface there was a range of lift coefficients in this instance round about 0.45, within which the position of the point of transition moved rapidly with change of lift coefficient, and seemed sensitive to surrounding conditions. As with the Hart wing also, transition occurred relatively far forward on the under surface at small lift coefficients, and the point moved backwards on the under surface and forwards on the upper surface as lift coefficient increased.

An interesting feature of this and the previous figure is the accuracy with which the observation points fall upon definite curves, despite the fact that they were obtained from experiments on many different days; to the observers it seemed almost as though they were locating points actually fixed upon the wings. This surprising consistency suggests strongly that, in these experiments at least, the cause of transition is to be sought in the system of flow set up by the aeroplane itself and not in disturbances pre-existing in the atmosphere through which it flies; for it is unlikely that the nature and amount of atmospheric turbulence would remain exactly the same from day to day and from place to place. This deduction from flight experiment, if correct, is important, because wind tunnel experiments, upon which we have hitherto had to rely have shown transition to be strongly influenced by turbulence of the tunnel stream. Some years ago G. I. Taylor suggested that the rate of energy dissipation per unit volume of the atmosphere is too small for small scale turbulence of the kind which is known to influence boundary layer transition in wind tunnel experiments to be maintained, and it now seems probable, though not yet certain, that the atmosphere must from the present point of view be regarded as free from turbulence.

Fig. 8 shows the results of similar experiments at the Royal Aircraft Establishment, Farnborough, upon the wings of a small monoplane which was designed so that it could be reconstructed with wings of various thicknesses. The thickness/chord ratios of the wings examined were 0.14, 0.25, and 0.30, respectively. The two thinner wings were of conventional design tapering slightly from root to tip, but the profile of thickness ratio 0.30 was obtained by fitting a bulge on the 0.25 wing, which extended for about the half of one chord on each side of the measurement section. Previous wind tunnel experiments had shown that the boundary layer on a bulge of this kind is not seriously influenced by rapid changes of wing thickness on the sides of the bulge, but this matter is still under investigation. The main interest of these experiments lies in the fact that although the Reynolds number reached in level flight was appreciably higher than that in the Cambridge experiments the transition points were even further back on the wing and the marked forward movement, observed in the Cambridge experiments at low lift coefficients, did not occur, though there was still a slight tendency for the point to move forward on the under surface and backward on the upper surface as lift increased. It is not yet known whether the absence in the Farnborough experiments of this marked forward movement on the under surface was due to a better technique in laying on the wing covering or to a difference in the designed form of the wing profile; there is, as will be seen, some evidence of slight imperfections in the shape of the under surfaces of the Cambridge wings, although the surfaces were always well smoothed and highly polished. It is worth noting that Stuper in his experiments on the boundary layer of a wing in flight found transition points on the under surfaces in forward positions similar to those observed at Cambridge.

This, then, is the experimental evidence so far available in England upon the position of the point where turbulence begins in the boundary layer of smooth wings in flight. It shows conclusively that it is possible to retain a laminar layer over at least one-third of the whole wing surface, even when the Reynolds number is as high as eight millions. Experiments are now being made at Farnborough to carry observations of this kind up to larger Reynolds numbers, but conclusive results are not to hand at the time of writing. Drag experiments which have been already made at high Reynolds numbers by the pitot-traverse method suggest, however, that though the points of transition may move forward somewhat at the higher numbers, they certainly do not move right forward to the leading edge and the laminar form of the boundary layer can still be retained over a considerable proportion of the wing surface.

It remains to consider in rather more detail the circumstances in which transition occurred in the experiments which have been described, in order to see whether any light can be thrown upon the factors which influence it, but before this can be done it is necessary to give brief attention to some of the well known conclusions which can be drawn from a consideration of the dimensions of the quantities involved.

THEORETICAL CONSIDERATION

If the boundary layer is thin enough for Prandtl's well known approximation to the equations of motion to be applied, then it is easily shown that the shape of the velocity cross-section of the laminar layer at any given position on a wing of given shape at given incidence, is independent of the size of the wing, the speed of flight and the density and viscosity of the air. If δ be a linear dimension defining the thickness of the layer, then it can also be shown that

$$R_\delta^2 \propto R_c$$

where R_δ stands for $\delta\, U/v$ and R_c for $c\, U_0/v$ in which U_0 is the velocity relative to the wing of the undisturbed air at a great distance, U is the velocity of the air just outside the boundary layer, c is the wing chord, and v the kinematic viscosity of the air.

In analyzing experimental observations it is convenient to choose for the linear quantity δ the value known as the "displacement thickness" and to represent it by the symbol δ_* which is defined as follows:

$$\delta_* = 1/U \int_0^\infty (U - u)dy$$

where u stands for velocity within the layer at a point distant y from the wing surface.

For a flat plate in a flow field of uniform pressure, any of the well known mathematical solutions of Prandtl's approximate equations for motion within the laminar boundary layer give a relation which is very closely represented by

$$1/3\ R^2_{\delta^*} = R_z$$

where R_z stands for *xu/v*, in which *x* is distance from the leading edge.

The expression $(1/3)R^2_{\delta^*}$ therefore provides a convenient dimensionless quantity, or number, by which to define the thickness of the laminar layer at any position on a wing, for it has the properties that it varies directly with the wing Reynolds number (R_c) and is, for the flat plate, equal to the familiar *x* Reynolds number, by reference to which the already considerable amount of experimental data on transition is generally recorded. For brevity, this expression will be described as the *thickness number* and will be represented by the symbol N, so that

$$N = 1/3\ R^2_{\delta^*}$$

In considering the factors which may influence transition, the natural relation of the investigator is to examine first whether they can be defined in relation to the local conditions within and immediately surrounding the layer near the transition point. The extreme thinness of the layer in comparison with the size of the wing suggests that this may be so, and if it is so, and if it is unnecessary to take into account time fluctuations of the quantities involved suggests that transition should depend upon three parameters, N, λ, and C, of which N has already been defined, λ stands for $(\delta^2/v)(p'/\rho U)$, where p is the pressure gradient just outside the layer in the direction of flow and C stands for the ratio of δ_* to the radius of curvature of the wing surface in a plane parallel to the direction of flow.

It does not follow from these considerations that transition must depend solely, or even primarily, upon the three dimensionless parameters N, λ, and C; in fact the weight of evidence is, as will be seen, against this. The dimensionless analysis does no more than show that if, as seems at first sight probable, the phenomenon under consideration depends only on the variables from which the parameters are constructed, then it must be possible to express the conditions under which it occurs as functions of the parameters.

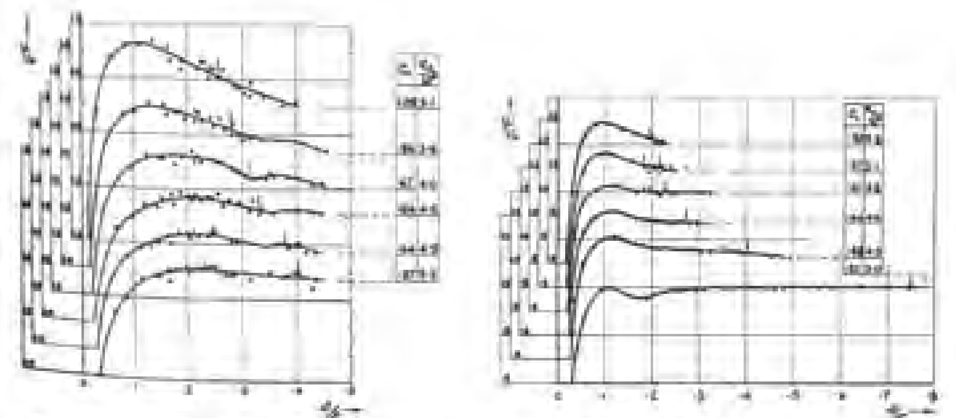
It is not impossible, of course, that the conditions which govern the onset of turbulence may include other factors, such for example as something which has occurred during the passage of the air from the front stagnation point to the point of transition, or even conceivably something which would happen in the laminar layer if it continued beyond the point where transition occurs in steady flight. It is conceivable that transition may occur first in some part of the boundary layer much

further back on the wing and that the turbulence then runs forward under the influence of the pressure gradients set up locally in the potential flow by the rapid increase of boundary layer thickness which accompanies transition. Again, it must be remembered that the quantities which have so far been measured in flight are time-means only, of quantities which may have been fluctuating and it is therefore possible that the primary cause of transition may ultimately be associated with fluctuations which have not been recorded in the flight experiments.

CONSIDERATION OF THE FACTORS WHICH MAY CONTROL TRANSITION

In order to examine whether the factors which control the transition from laminar to turbulent flow in the boundary layer can be simply expressed in terms of the three dimensionless parameters, N, λ, C, of the previous section, the values of these parameters have been estimated by step-by-step computation, starting from the front stagnation point and working backwards along the wing profiles to the observed transition points. In these computations the velocity U in the potential flow just outside the boundary layer and the pressure gradient p' along the profile were obtained from curves based on pressures actually registered in flight by the small static-pressure tubes previously described. Graphs, based on a typical series of such observations of pressure, are reproduced in Figs. 9 and 10 to show the order of accuracy attained in the experiment. The quantity actually plotted in these figures is not the pressure itself, but the velocity U just outside the boundary layer which can, of course, be deduced from the pressure by using the Bernoulli Theorem.

The computations of the values of the parameters were made by Polhausen's method in which velocity cross-sections of the boundary layer are represented as polynomials of the fourth order. This method is approximate only, and doubt has been expressed as to its accuracy when applied in circumstances where the param-



Figs. 9 and 10. Specimen curves from observations of pressure distribution measured in flight. Ordinates show ratios of the speed U relative to the wing of the air just outside the boundary layer to the speed U_0 of the air at a great distance from the wing, the values being obtained by means of the Bernoulli Theorem from measurements of pressure made with a small travelling static-pressure tube similar to that illustrated in Fig. 3. Abscissae represent the ratio to the wing chord c of distance s, measured round the wing profile, from the stagnation point to the observation point. The curves are fair curves drawn through the observation points and the short vertical marks upon them show where turbulence was observed to begin.

eter λ is negative. Some experimental check was therefore required to determine whether the method gives sufficiently accurate information in the circumstances in which it has been applied. For this purpose a very careful set of observations were made in flight with the five-tube arrangement illustrated in Fig. 3. These tubes were fastened at a fixed position on the surface of the wing of thickness ratio 0.18 and the pressures registered by them were recorded when flying steadily with various values of the lift coefficient. The velocity cross-sections of the boundary layer at the orifices of the tubes were then computed from pressure distributions obtained in previous experiments.

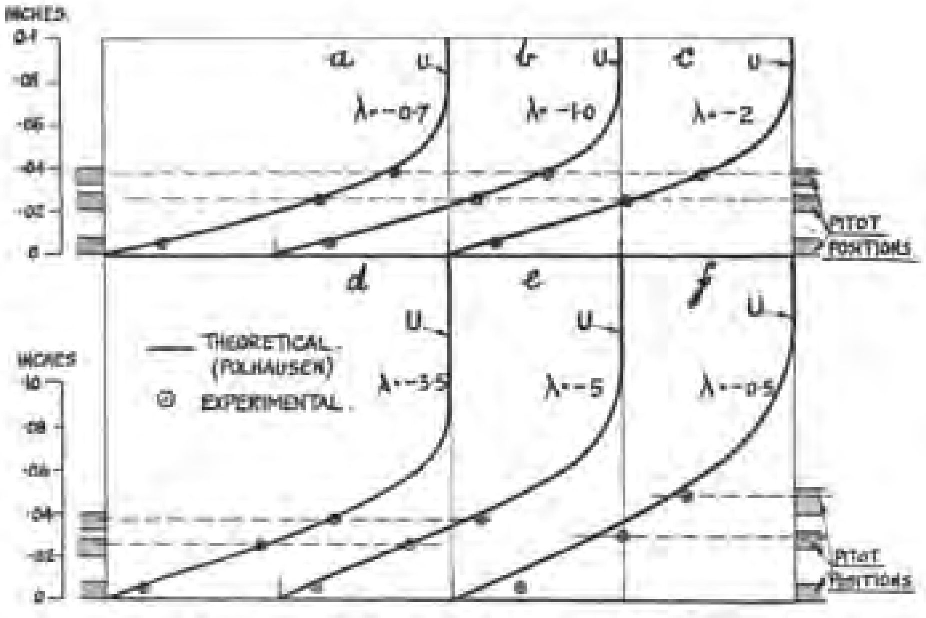


Fig. 11. Comparison between computed and observed velocity cross-sections of the laminar boundary layer. Ordinates represent distance from the wing surface and abscissae air velocity expressed as a fraction of the velocity outside the layer. The curves are computed by Polhausen's method and the points are from flight experiments with pitot tubes whose positions and depths are shown at the sides of the figure. The effective centres of the two outer pitots are taken as on the broken lines which are displaced from the geometrical centres by distances equal to [illegible] times the external depth of the flattened ends of the tubes, in accordance with the conclusions in footnote 11. The effective centres of the tubes in contact with the wing surface are estimated from information in footnote 12.

A comparison between computed and observed values is shown in Fig. 11 (a) to (f), in which (a) to (e) relate to a position on the upper surface of the wing, 20 in. behind the stagnation point, measured along the surface, whilst (f) relates to a position on the under surface 26.5 in. behind the stagnation point. The remarkably close agreement shown in Figs. (a) to (e) may be to some extent accidental, for it is not considered that the distances of the pitot tubes from the wing surface were known with certainty to an accuracy greater than about 0.004 in., but the experiment shows that, in this instance, Polhausen's method gave δ_* values which agreed with the observed values within, say, 10 percent, even when the negative values of λ were as great numerically as five.

It is of some interest to consider the variation of the computed values of the parameters N, λ, and C at different positions along the wing profile, between the forward stagnation point and the point of transition and a few typical curves illustrating these distributions are therefore reproduced in Fig. 12. In this figure the parameter N is defined, not by its actual value, which varies with the wing's Reynolds number R_c, but by the ratio N/R_c, which, for any given position on a wing of given shape at given lift coefficient, is a constant independent of R_c. For a flat in a uniform pressure field, N is, as has been seen, equal to R, where s is the distance from the leading edge, hence the variation of N/R_c with s/c for a flat plate is represented in Fig. 12 by a straight line inclined at 45°.

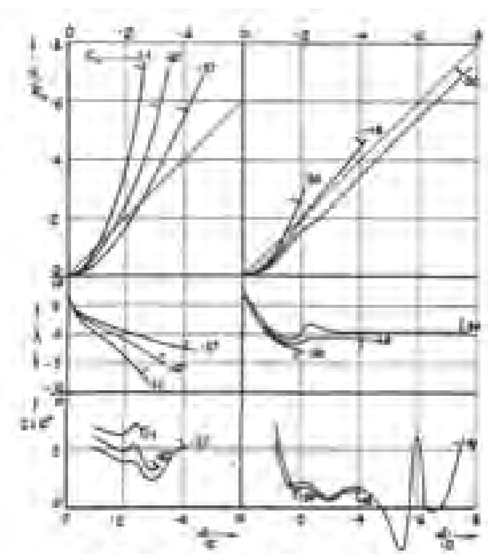


Fig. 12. Examples of the distribution of certain dimensionless quantities which define local conditions in the laminar boundary layer. The thickness/chord ratio of the wing to which these curves relate was 0.18. Lift coefficients are written against the curves, and the observed points of transition are shown by short cross lines on each curve. Abscissae represent ratios to the wing chord c of distance s, measured along the wing profile from the front stagnation point. Of the other symbols, N defines the layer thickness, λ the pressure gradient within the layer, and C the curvature of the wing profile; they are more precisely defined in the text. Negative values of λ correspond to rising pressure gradients and separation of flow from the wing surface is generally assumed to occur when λ = −12.

The radius of curvature of the wing surface which is involved in the parameter C was obtained by an instrument of which two points, 6 in. apart, were pressed lightly on the surface, whilst a third, midway between them, actuated a micrometer dial. The measured radii were, therefore, mean values over 6 in. of the profile.

The curves in Fig. 12 are of some general interest, because they are fairly well typical of any wing of moderate thickness and conventional profile. Such curves can, of course, be obtained for any wing profile by computation alone, without experimental determination of the pressure distribution, since the latter can be obtained in the usual way from potential flow theory, but in the present instance it was thought preferable to employ the measured pressure distributions so as to include the effects of accidental variations of the actual wing profile from the designed profile.

The point where turbulence was observed to begin in the experiments from which the pressure distributions were obtained is marked on each curve and, where the curve is carried slightly beyond this point, the implication is that the laminar layer would have taken the computed form if turbulence had not, in fact, intervened. A difficulty of interpretation arises here on account of the characteristic kink which always occurs in the pressure distribution curves near the point of transi-

TABLE I

Data Relating to the Laminar Boundary Layer of Certain Wings, from Computations Based on Measured Pressure Distributions

			C_L	$R_s/10^6$	s/c	λ	$N/10^3$	$C \times 10^4$
CAMBRIDGE	t/c = .10	Upper Surface	.06	10.8	.35	−1.0	3.7	1
			.27	5.8	.32	−2.1	2.0	2
			.27	5.5	.30	−2.2	2.4	2
			.33	5.2	.30	−2.2	2.1	2
			.33	4.9	.30	−2.1	1.9	2
			.50	4.0	.23	−3.7	1.5	2
			.50	4.2	.25	−4.1	1.6	2
		Under	.27	5.3	.17	+0.1	0.8	1
			.32	4.8	.17	−0.4	0.8	1
			.38	4.4	.19	0.0	0.7	1
			.51	3.9	.21	+0.4	0.6	2
			.58		.40			
	t/c = .18	Upper	.37	5.3	.40	−2.2	3.0	5
			.44	4.9	.38	−2.5	2.8	5
			.54	4.5	.33	−3.5	2.4	4
			.67	4.0	.31	−4.6	2.3	4
			.85	3.6	.28	−5.2	2.2	5
			1.09	3.1	.26	−7.2	2.2	7
		Under	.30	5.6	.19	−4.4	1.0	1
			.37	5.8	.18	−3.1	1.1	1
			.37	5.1	.22	−4.2	1.5	1
			.41	4.8	.23	−2.1	1.2	1
			.44	4.6	.27	−0.8	1.3	1
			.48	4.3	.40	−1.0	1.9	1
			.82		.73	0.0	2.3	5
FARNBOROUGH	.14	Up.	.33	6.8	.35	−2.8	2.8	3
			.22	8.2	.40	−3.7	3.7	3
	.25	Up.	.43	5.7	.41	−6.9	4.3	5
			.24	7.7	.42	−5.3	4.5	4
		Un.	.43	5.7	.43	−4.9	3.4	4
			.24	7.7	.35	−3.1	3.3	3
	.30	Up.	.45	5.6	.34	−4.0	3.2	4
			.27	7.4	.35	−3.9	4.1	4
		Un.	.45	5.6	.40	−1.3	2.9	4
			.27	7.4	.37	−2.0	3.9	4

tion (see Figs. 9 and 10). In the present instance all quoted values of λ have been obtained from fair curves drawn through the points without regard to the kink, the reason for this procedure being that the kink is regarded as a consequence of transition itself, and the ultimate object of the research is to find how far it is possible to predict the point of transition from estimated information concerning the laminar layer in the absence of transition.

The N/R_c curves at the top of Fig. 12 show that near the front of a fairly thick wing the displacement thickness of the laminar layer at any given distance from the stagnation point is much less than it would be in corresponding circumstances at the same distance from the leading edge of a flat plate. They show, however, that as distance from the stagnation point increases the thickness of the layer begins to increase more rapidly than on a flat plate, until somewhere not far from the point on minimum pressure (λ = 0) the local Reynolds number of the layer thickness catches up the flat plate values and eventually rises considerably above them. Only in one curve, that relating to the under surface at very large lift coefficients, does the displacement thickness remain always below the corresponding flat plate values.

The λ curves, half way down Fig. 12, all start at the front stagnation point of the wing from Polhausen's figure, –7.05, and fall rapidly as distance from the stagnation point increases. They pass, of course, through zero at the point of minimum pressure, and on the upper surfaces the negative values thenceforward increase numerically up to the point where turbulence begins. The values for the under surface at first fall off more rapidly than those of the upper surface and, after passing through zero, rapidly rise, sometimes crossing the zero line again before they eventually settle down to a value not far different from zero. It seems probable that the more violent bends in these under surface λ curves are to be attributed to some imperfection in the shape of the surface itself, and it is not improbable that they are in some way associated with the relatively early onset of turbulence observed on the under surface of this wing. Similar double bends associated with forward positions of the transition point were also noticeable in the corresponding curves—not here reproduced—for the under surface of the wing of 10 percent thickness/chord ratio.

The curves at the bottom of Fig. 12 show approximately the variations of the parameter C. The violent fluctuations of the curve for the under surface between lift coefficients 0.5 and 0.8 are due to an imperfection of the wing surface in the form of a barely perceptible wave. It is of some interest to observe that this violent fluctuation of the C curve did not immediately cause transition to the turbulent regime.

The computed values of the three parameters N, λ, and C, relating to the laminar boundary layer at points where transition to the turbulent form had been observe in flight, are collected together in Table 1, and the values of N given in this Table are plotted against the appropriate values of λ in Fig. 13. It appears from the Table and figure that the λ values at transition all lie, speaking broadly, between 0 and –7, but that within this range there appears to be no simple relation between the two parameters.

The situation is not appreciably clarified when the values of the curvature parameter C are taken into consideration, for although Table 1 shows that the very low values of N and λ observed on the under surfaces of the Cambridge wings are associated with low C values, the very high values of N and λ found at Farnborough are associated with lower C than those of many of the Cambridge upper surface observations. Though the observations recorded in Table 1 do not preclude the hypothesis that surface curvature may have some influence on transition, they certainly show that in these experiments it did not exert the predominating influence.

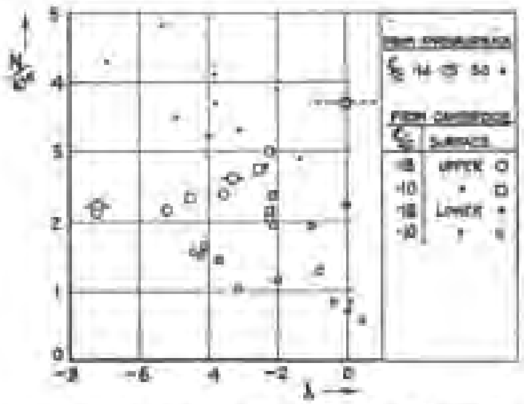


Fig. 13. Values of *N* and λ at transition for a number of different wings in flight. The parameters *N* and λ are defined in the text and further information relating to the circumstance in which each point was obtained is given in Table 1. The wide scatter of the points from different wings shows that these two parameters alone are insufficient to define the conditions which lead to transition in these experiments. The broken horizontal line through one of the small squares shows that in this instance the value of λ was not known with certainty within the limits shown by the line.

One feature which stands out clearly in Fig. 13 is that the two series of points representing observations on the upper surfaces of the wings examined at Cambridge fall very closely upon definite curves, though the curve is not the same for both wings. This consistency of the points for each wing taken alone is, of course, a direct consequence of the close functional relations between the lift coefficient and the position of the transition point which are revealed in Figs. 6 and 7; for, at any given point on a profile, both N and λ (as computed) are functions of lift coefficient. Bearing in mind the fact that the experiments in which these points were observed were made on many different days, sometimes with intervals of months intervening, it seems difficult to escape the conclusion already mentioned that the onset of turbulence was occurring under the influence of some dominating parameter whose origin is to be sought in the system of flow set up by the wings themselves. The wide scattering in Fig. 13 of the points for different wings shows, however, equally clearly that in these particular experiments the conditions leading to transition cannot be expressed simply in terms of the three parameters, N, λ, and C.

What the parameter which was controlling transition may be is still uncertain, but there are at the time of writing some indications from various sources as to its probable nature. It will be recalled that the apparatus used for observing the conditions of flow near the point of transition was of a kind which records time-means only of values which may in fact have been fluctuating. If therefore, keeping in mind the thinness of the laminar layer, we still retain the hypothesis that the onset of turbulence is determined by local conditions, we are almost forced to the conclusion

that the unknown parameter is to be sought in some form of fluctuation superimposed upon the mean flow.

H. L. Dryden using a hot wire anemometer within the laminar layer of a flat plate in a wind tunnel, has found just such fluctuations of surprisingly slow period and has published a figure which suggests strongly that in his experiments these fluctuations were in fact the primary cause of the ultimate break-down of the laminar flow. L. Schiller experimenting in similar circumstances has found similar fluctuations and had also shown that the point of transition can be controlled within a very wide range by slight alterations of the incidence of the flat plate, which caused relatively large displacements of the stagnation point on the rounded leading edge.

Working in collaboration with G. I. Taylor, we have recently constructed at Cambridge a small wind tunnel in which the working stream is remarkably free from turbulence, the root-mean-square of the longitudinal fluctuations of velocity being of the order of 0.1 percent of the mean speed, whilst that of the lateral fluctuations is about 0.2 percent of the mean speed. In this tunnel, using a flat glass plate 3/8 in. thick with rounded leading edge, we have observed the same phenomena as were observed by Dryden and Schiller; that is to say, hot wire examination has shown that relatively long period fluctuations of velocity occur in the laminar layer without being apparent in the potential flow outside the layer, and that the point of transition can be powerfully and very definitely controlled by slight alterations of incidence.

Consideration of results such as these from our own and other laboratories suggests that the final transition of the boundary layer to the fully turbulent condition may be the direct consequence of transient separation of the flow from the solid surface, brought about by these relatively slow fluctuations, but no experiment of which we are aware has, as yet, revealed with any certainty the origin of the fluctuations themselves. Whether for example their origin is to be found in minute fluctuations of the external stream, which become greatly magnified within the layer, or whether it is to be sought in some property inherent in the boundary layer itself, is a question which has yet to be determined, though the similarity of the fluctuations observed in the smooth flow of our new tunnel to those observed by Dryden in a stream of greater turbulence, lends some support to the latter view.

In the unusually smooth stream of our new tunnel we find, as was to be expected, that transition can be postponed until the value of N is considerably greater than the values usually obtained in tunnels of greater turbulence. Our new tunnel is not long enough to realize values of N much above three million, but this value has been reached without transition to the turbulent regime and it seems probable that in longer equally smooth tunnels it will be exceeded, even when the value of λ at transition is zero or slightly negative.

By modifying the shape of the tunnel walls one can produce, within limits, any desired sequence of pressure gradients along the surface of the plate, and we find, by this means, that the value of N associated with any given value of λ at transition can be greatly altered by changing the gradients through which the air has passed on its way to the transition point. Thus, the introduction of a sharp falling pressure-gradient, followed by a rising gradient, causes transition to be postponed to larger N values than when the rise of pressure is continuous from near the leading edge, and in this way we have succeeded in realizing N values greater than two million, even when the negative value of λ was as great as seven. These observations support the conclusion previously drawn from the flight experiments, that the conditions which lead to transition cannot be expressed solely in terms of the mean values of quantities in the immediate neighborhood of the transition point itself.

The introduction of artificially generated turbulence into the smooth air stream is found to have the well known consequence of causing transition to occur earlier than in the smooth stream and to cause the mean transition point—as located by slow-reading pitot tubes—to become much less clearly defined; no doubt because the amplitude of the to-and-fro movement of the transition region is greatly increased. This explains the remarkable precision and definition of the majority of experiments for the location of the point of transition in flight, in comparison with the results of previous experiments in wind tunnels. We find also that phenomena, such as the delicate dependence of the point of transition on the incidence of a flat plate, become much less apparent and definite when the turbulence of the tunnel stream is increased. It is now, in fact, becoming apparent that the more interesting features of the phenomenon of transition have in the past been masked by wind tunnel turbulence, and that the extension of the experiments to free flight coupled with the greater smoothness of flow in modern wind tunnels is opening up new fields for investigation.

It is yet too early to hazard an opinion as to what will be the final outcome of experiments of the kind we have been discussing. Whether or not the stream of information which comes in almost daily from aeronautic laboratories in many countries will ultimately reveal the possibility of controlling transition so as still further to reduce drag, or whether it will merely enable the point of transition to be predicted without enabling it to be controlled is a question which awaits an answer. For my part I am not able even to guess what the answer will be, but knowing that the problem is being intensively studied in the United States, I have, with the consent of my colleagues in England, told you exactly what we are doing and where we are as yet uncertain, in the hope that the discussion to follow will bring to light complementary evidence which, combined with our own, will enable a clearer picture to be formed of a phenomenon in which theorists and engineers alike are intensely interested.

DISCUSSION

Professor Jones' paper was presented at the Pupin Physics Laboratories of Columbia University on the afternoon of December 17, as a lecture which gave the principal results of the research work up to the time Professor Jones left Cambridge University two weeks before.

There were about 300 members and guests of the Institute present including Orville Wright.

Dr. Nicholas Murray Butler, President of Columbia University, welcomed the guest speaker, Mr. Wright, and members of the Institute. He spoke of his early interest in aviation and of the interest of Columbia University in the growth of the Institute, as all of its Annual Technical Meetings had been held in the Pupin Physics Laboratories. He expressed the hope that the Institute would continue to find the facilities of Columbia University helpful in its work. He praised the work of the Wright brothers and spoke of the great aeronautical development which their work inaugurated.

INTRODUCTION

Dr. Clark B. Millikan
California Institute of Technology

As you all know we are today privileged to be present at what will, I am sure, be remembered as an historic occasion: the first Wright brothers' Lecture. I shall not spend any time discussing the significance of the occasion since this will be done tonight. However, before introducing the speaker, I do wish to express our great appreciation to Columbia University, to Dr. Butler, and to Professor Pegram for their kindness in making this meeting place available and in welcoming us so warmly. Columbia saw the birth of the Institute, and all of our technical sessions have been held at it. It is, therefore, most happy for us that now the inaugural Wright brothers' Lecture is held under its auspices. Thank you again Dr. Butler and Professor Pegram.

I have been fortunate in knowing today's speaker for over seven years. Unfortunately the chances for personal contact have been few, but I have been able to follow his work fairly closely.

All of his contributions seem to me to have been marked by certain definite characteristics: (1) an interest in scientific problems which are closely related to the actual flight of aircraft; (2) a penetrating analysis of the problems attacked so that the simple fundamentals appear out of a maze of apparent complications; and (3) extreme ingenuity in developing simple experimental methods for studying the problems.

All of these characteristics appear strikingly in the work which the speaker has chosen for his subject today.

B. C. Boulton
The Glenn L. Martin Company

In this significant paper Professor Jones does not tell us how to control the boundary layer and hence vastly increase airplane performance, but like a true scientist he records basic phenomena and does much to lay a sound foundation on which others can build. Most of us shy off when the subject of boundary layer is mentioned and feel that it is too abstruse for the engineer; that it must be left to the scientist and mathematician. The present paper, however, does much to remove this barrier and gives us all a concrete realization and at least partial understanding of the subject. I will leave to my able colleagues in this discussion the more difficult task of commenting on the theory involved and will limit myself to emphasizing some aspects of special significance to the engineer.

In Fig. 1 it is of importance to note that the slope of the curves of decreasing drag with aft movement of the transition point is greatest for thick airfoils. With larger wings of higher aspect ratio the thickness ratios used are higher. In such cases the gain to be derived by using all means of maintaining laminar flow is great; also the corresponding loss. It may be remarked that except for thickness ratios of .30 and .10, the slopes of the curves are determined mathematically rather than experimentally. Another point that is rather amazing is that the forward transition point in the case of $t/c = .3$ was produced by the use of a thin sheet of paper. In another case a sheet of foil .002 in. thick affected the transition point. The sacrifice involved in a lap joint becomes painfully evident. This brings home to us the truth of the N.A.C.A. tests on the effect of roughness shown at the last annual conference. The fact which Professor Jones brings out that slight waves in an otherwise smooth surface also materially affect the transition point especially interests me. In the interests of weight saving we may use thin gauge material on a leading edge and feel, if the rivets are flushed, that all is right. If the material, because of its thinness, is wavy, all is not right, and on a long range aircraft the additional drag, so caused, may involve far more weight in fuel expenditure than that due to differences in gage. This is of significance structurally, and indicates we must count on the wing leading edge for structural strength since it must be reasonably heavy to secure low drag.

I believe it has been the general impression that as a wing becomes larger, little roughnesses due to skin laps and rivets become less important. Professor Jones points out the tendency with increasing Reynolds number for the transition point to move forward, though also holding out the possibility that with care the drag of wings on very large airplanes can be greatly reduced by keeping part of the flow laminar instead of entirely turbulent as would usually be assumed.

Of particular interest is the statement, verified by the constancy of the flight test results, that small scale turbulence does not exist in the atmosphere, and so for exploration of the boundary layer, flight experiments are more reliable than wind-tunnel tests. Turbulence in the latter case tends to mask the phenomena being investigated. As Professor Jones suggests it may be possible for an airplane manufacturer, using a single pitot tube just outside the laminar boundary layer, to make valuable investigations on the effect of different wing finishes and types of rivets as part of normal flight testing.

I would like to ask Professor Jones whether work has been done or is planned shortly, on exploring the boundary layer on hulls or fuselages. Since such elements constitute such a large proportion of the airplane drag, such work might prove to be of great value.

In recent flight tests at our plant we obtained a great reduction in drag through the use of cowl flaps on a radial engine to throttle to a minimum the cooling air at high speed. Part of the gain was due to increased pumping efficiency but we would like to enquire whether Professor Jones believes that the high speed air from the narrow gill slot could have acted as a sort of boundary layer control, thus further reducing the drag.

Dr. Hugh L. Dryden
National Bureau of Standards

The Institute is greatly indebted to Professor Jones for his very clear presentation of the practical importance to the airplane designer of an understanding of the nature of the flow in boundary layers and in particular of the factors controlling the transition from laminar to eddying flow. He and his colleagues honor us by making available in the Wright brothers' Lecture information of fundamental importance not hitherto published. Research workers in this country do have some additional information to add to that of Professor Jones, but must join him in admitting that the problem has not been solved and it is not known whether it will ultimately be possible to control transition to reduce drag. The more data obtained, the more complicated appear the phenomena.

In the experiments described by Professor Jones, a number of factors operating together influence the position of the point of transition and make analysis exceedingly difficult. Thus the increase of Reynolds number with decreasing lift coefficient tends to move the point of transition upstream, whereas the effect of the change in pressure distribution accompanying the decreasing lift coefficient may tend to move the point of transition downstream. It may therefore be possible to find some airplanes for which the point of transition is nearly stationary as the angle of attack is changed. The available theories are not adequate to describe the influence of the several factors and more experimental work is needed with conditions controlled to give but one variable factor at a time. Reynolds numbers and turbulence conditions corresponding to those in flight can however be obtained only in flight or in a full-scale wind tunnel of low turbulence.

The National Advisory Committee for Aeronautics has sponsored and financed a coordinated program of research on this problem at various university laboratories, at the National Bureau of Standards and in its own laboratories. The California Institute of Technology is studying the influence of curvature and roughness on transition and a progress report has been made available in Technical Note 613 of the National Advisory Committee for Aeronautics. The Massachusetts Institute of Technology is studying the influence of pressure gradient and the National Bureau of Standards the influence of wind-tunnel turbulence. The Langley Field Memorial laboratory is investigating the phenomena at large Reynolds numbers in the full-scale wind tunnel and in flight. By permission of Dr. G. W. Lewis, I am able to discuss the problem in the light of our work at the National Bureau of Standards, making use of some data not yet published by the Committee.

The use of a small number of total head tubes for determining transition is in general satisfactory and makes possible a fairly rapid accumulation of data. There is, however, a certain danger of missing an important phenomenon, namely, that of laminar or quasi-laminar separation, followed by a return of the flow to the surface, a phenomenon to which Professor Jones himself directed attention in his paper on Stalling in the Journal of the Royal Aeronautical Society, Vol. 38, p. 753, 1934. We have observed this phenomenon in recent experiments on the boundary layer near an elliptic cylinder.

The results of a detailed survey of the laminar boundary layer near this cylinder, in which laminar separation occurred, have been published. Comparison with theoretical calculations by Pohlhausen's method did not lend confidence in that method for computing separation, separation occurring for $\lambda = -5.4$ instead of Pohlhausen's value of -12. The theoretical speed distributions agreed fairly well with the observed distribution for values of the parameter λ between $+7$ and -5. Professor Jones' data in Fig. 11 are in agreement with this result. The limitations of Pohlhausen's method should, however, be clearly understood. The method developed by von Karman and Millikan is much better although requiring more tedious computations. (See Millikan, Clark B, A Theoretical Calculation of the Laminar Boundary Layer Around on Elliptical Cylinder, and Its Comparison With Experiment, Journal of the Aeronautical Sciences, Vol. 3, No. 3, January, 1936.)

Our recent measurements at the National Bureau of Standards were on the same elliptic cylinder at a higher speed (70 ft. per sec.) where transition occurred before separation. A contour map of the speed distribution as obtained by hot-wire measurements is shown in Fig. 1. Between 10.2 and 10.8 inches from the nose a region of reversed flow can be demonstrated by the use of smoke, lampblack, and oil on the surface, or any similar method. Since the hot wire is essentially a non-directional instrument, the reversal is not shown in the hot-wire measurements. From 10.8 inches to the second separation at 12 inches, the flow near the surface is in the direction of the main stream. The diagram is based on traverses at stations along the cylinder spaced 1 inch apart. By a method described later it can be demonstrated that a minimum in the local skin-friction coefficient occurs at 6.1 inches from the nose, although the phenomenon is not evident in the figure. We may therefore picture transition beginning at 6.1 inches, sufficient turbulence being produced to carry the layer some distance against the rising pressure but insufficient to prevent separation altogether in the region of rapidly rising pressure. The separation at 10.2

produces additional turbulence; the layer returns to the surface at 10.8 inches and separates again at 12 inches. Such a phenomenon might be missed by short-cut methods, but the apparatus of Professor Jones should detect it if the surface tube is included. If only the outer tube is used, the phenomena of separation and transition cannot readily be distinguished.

It may be noted that if transition is produced as a result of laminar separation, the point of separation is independent of Reynolds number only if the pressure distribution is independent of Reynolds number. We have observed that a laminar layer may separate, exist as a free laminar layer for some distance, and then become eddying. In such cases as the transition point in the free layer moves forward, the pressure distribution around the body is modified and the location of the point of laminar separation varies with Reynolds number.

We have used a hot-wire version of the surface tube, which has some advantages, and which we believe could be used in flight. The wire 0.00063 in. in diameter was mounted on a thin steel band 6 in. wide and 0.002 in. in thickness encircling the cylinder and capable of being moved around the contour of the cylinder so that the wire traversed the boundary layer at a small fixed distance from the surface (about 0.008 in.). While the actual measurement of speed is not easy with this arrangement, a simple electrical circuit permits the rapid location of the point where the speed is a minimum which corresponds to minimum skin friction on the surface or to the minimum total head shown by Professor Jones' surface tube. The device has been quite satisfactory in the laboratory and can probably be used in flight.

With this apparatus we have made rapid surveys of the effects of wind-tunnel turbulence which will be described in a forthcoming paper by G. B. Schubauer. A sufficient increase in the turbulence eliminates the first separation and region of reversed flow and the results on the location of transition check fairly well G. I. Taylor's formula for the relative influence of intensity and scale of turbulence.

Another interesting result is that when the turbulence is lowered beyond a certain point, further reduction does not move the point of transition farther from the nose, suggesting that the transition is then controlled by the pressure distribution system rather than by the turbulence of the external flow. A similar effect of Reynolds number is found at a suitable value of the turbulence, the transition point not moving aft of 6.1 inches as the Reynolds number is reduced.

Oscillograph records of fluctuations fail to show the sudden and intermittent transition observed on the flat plate. The intensity and frequency increase continuously with distance from the nose. There is a rather high maximum intensity at the transition much like that observed at the California Institute of Technology on the curved plate. Thus when pressure gradients and curvature are present the transition appears to be of a different character. There seems to be little doubt that the intensity and rate of fluctuations in the boundary layer are dependent on the sign and magnitude of pressure gradient and on the curvature as well as on the turbulence of the air stream.

As further results of the research sponsored by the National Advisory Committee for Aeronautics and of that conducted by Professor Jones and his colleagues become available, it is hoped that the picture may become clearer.

Dr. W. F. Durand
Stanford University

Referring first to the broad domain in which the work reported by Professor Jones finds its place, and to the wholly admirable character of the paper, both as to its content and as to the character of the treatment, I should like to emphasize what seems to me the profound importance of the activity which has characterized our study of the laws of fluid mechanics, in the broad sense, during the past ten or fifteen years.

I am not referring alone to the importance of this work in connection with its aeronautic applications, but rather to the broad significance which these laws play throughout the entire domain of nature. Matter, broadly speaking, is either fluid (liquid or gaseous) or solid, and throughout the entire domain of natural phenomena, the activities with which we are concerned and which touch our lives most closely involve, in an impressive degree the movement of a fluid, constrained or directed by a solid boundary; or more broadly, the relative movements of solids and fluids.

Thus the circulation of the blood in our veins and arteries; the movement of sap in trees; the flow of rivers and streams; the movement of the winds; the movement of water-borne and of air-borne craft—from such major class examples down to the most trivial actions as, for example, the agitation of a spoon in one's cup of coffee, in order to distribute more evenly the sugar in solution. These and thousands of other examples could be named, of activities or of natural functions, which touch our lives more or less closely and which all involve the phenomena attendant on the relative movement of solids and fluids; and thus mark the significance of the laws of what we call fluid mechanics.

And because of this, I hail with deep satisfaction the concentration of effort which these recent years have witnessed in the study of these phenomena, and in the better understanding of these laws which it has brought. And may not those who are especially concerned with the study of these laws in connection with the problems of air transport, take some measure of satisfaction in the thought that this study, on their part, will serve not only these immediate purposes, but also as a real contribution to a far wider domain of human activity; and that the refinement of laws which seems to be gradually developing out of such work as that described in Professor Jones' paper will find applications in domains of human interest far removed from those which have served as their immediate occasion. And may it not be said, that those who are thus serving the immediate interests of aeronautics, constitute, in effect, a service unit to all phases of human activity where a better understanding of the laws of fluid mechanics may enter as a significant factor.

Now with regard to Professor Jones' paper itself, I have been especially interested in his analysis of the conditions affecting the location of the transition point from laminar to turbulent flow, as expressible in terms of three non-dimensional parameters, and in the conclusion that three such parameters cannot include all the influential factors. In this connection the observations of Dr. Dryden regarding fluctuations in a laminar layer, and the suggestion of Professor Jones regarding the possible movement of the transition forward from the point of its initial formation, seem to me of special significance.

It seems quite clear that, as Professor Jones says, further observational work lies ahead—that until some adequate relation can be established between all further outlying essential phenomena and the basic conditions of the observations, we can hardly hope to be able to specify such additional parameter or parameters as may be required to give a complete account of the situation.

In the way of basic conditions affecting the observations, I have wondered regarding one characteristic of the air which, so far as I am aware, has not been usually taken into account as influential in connection with the study of these phenomena; and that is, the degree of ionization of the air. We have the physical characteristics of temperature, pressure, density, humidity, and viscosity; but may not, conceivably, the degree of ionization of the air be influential in connection with these obscure boundary phenomena? We know that it is influential in connection with other physical phenomena, as for example, the formation of rain droplets. Where we are approaching the ultimate in our study of this phenomena of the boundary layer, may it not be necessary to take some account of the electrical condition of the air as well as of its physical characteristics?

In closing, let me express my highest admiration for this paper and for the skill and resourcefulness with which the experiments were carried out. The researches here described belong to that supremely important type in which the locale is carried from the laboratory to the air, and to the condition of actual flight. And I am satisfied that, with this open door which has been provided by Professor Jones and his colleagues, these particular problems of the boundary layer will be carried through to some reasonably satisfactory and final conclusions.

Dr. J. C. Hunsaker
Massachusetts Institute of Technology

We are indebted to Professor Jones for a masterly survey of the state of knowledge regarding the breakdown of laminar flow, and in the true spirit of science he has given us the details of his own brilliant research results with an intimation of the direction in which they are leading him. Others who are working on the same problem are grateful for this disclosure and should respond in kind.

Professor Jones gives us evidence that the conditions for transition from laminar to turbulent flow cannot be expressed solely in terms of those parameters used in his experiments. However, I can add evidence that certain parameters are without doubt important.

At M.I.T., as a result of wind-tunnel research on flow separation and transition, we have good evidence that the transition point moves forward on a wing with increasing wind speed. Here the wing is held at a constant attitude and the only variable is the speed. Hence Reynolds number must be a controlling parameter.

We also confirm the fact that the thickness coefficient N of Professor Jones' notation must be important. Dr. Peters using a similar coefficient based on the momentum thickness found that transition took place always at about the same value of this coefficient for a flat plate and a wing and, furthermore, both on the upper and lower surfaces of the latter. This thickness coefficient appears to have a critical value.

In our work on hydraulic cavitation we have observed a periodic phenomenon associated with the flow through the throat of a Venturi nozzle, which suggests an analogy to periodic separation of air flow.

If we assume, as suggested by Professor Jones, that the laminar layer tends to separate and that transient separation actually takes place at breakdown into turbulence, we are led to believe that the instantaneous pressure gradient inside the boundary layer will differ from the mean value in the flow outside and should perhaps cause separation. Such separation will certainly break the flow down into turbulence. In general, turbulence is observed to be caused by separation or discontinuity.

A transient separation will cause a corresponding fluctuation in the local pressure gradient in the boundary layer, which in turn could cause a periodic fluctuation in the transition point as has been observed. The phenomenon of transient separation could then repeat itself in the manner observed for hydraulic cavitation.

When conditions are right the flow of water next to the walls of the throat separates to form vapor and turbulence. The vapor collapses, causes a sudden change in pressure in the throat with a return to continuous flow and a repetition of the cycle. The frequency of the repetition is a function of speed for given setting of the apparatus.

I do not wish to strain the analogy, but it seems to indicate that boundary flow phenomena are extremely sensitive to fluctuating pressures.

As to the scatter of the points on Professor Jones' final figure, I should like to point out that the pressure gradient in the laminar layer must be extremely sensitive to surface condition and must be extremely variable along any practical surface. Minute surface variations can very plausibly furnish a trigger action for transient separation, and may explain the scattering of results of tests made with different surfaces and attitudes. I, therefore, suggest that we do not worry about Fig. 13, nor try to draw general conclusions from it in view of the several sources of disturbance yet to be investigated.

It is most valuable to have the evidence of Professor Jones and his Cambridge colleagues spread before us in such clear form. American workers in this field will be greatly stimulated in continuing the attack on this fundamental problem of applied aerodynamics.

Dr. George W. Lewis
National Advisory Committee for Aeronautics

Before discussing the lecture proper I would like to express the sincere pleasure of the National Advisory Committee for Aeronautics on the selection of Professor Jones, a member of the British Aeronautical Research Committee, to present the first Wright brothers' Lecture before the Institute of the Aeronautical Sciences. I am sure that these lectures, carried on from year to year like those of the Royal Aeronautical Society, will be of great value in the advancement of aeronautical science, both in England and in this country. The National Advisory Committee has benefited often by the friendly and cooperative attitude of British research workers, so that I especially welcome this opportunity to share in entertaining a distinguished member of that group. We in this country who are primarily concerned with the scientific aspects of aeronautics look with great respect at the research staff of Cambridge University including, as it does, men of such eminence as Professor Jones and Professor Taylor.

Dr. Dryden has described to you the recent results obtained in our researches on transition in this country, so I wish to comment more on the engineering significance of Professor Jones' very interesting studies. Ever since the early days of flying, both manufacturers and research workers have been very much concerned with the problem of reducing drag, and it seems likely that this problem will continue to be important for some time in the future. It is of interest to note, however, that we are now entering into quite a new phase of the problem, and Professor Jones in his paper this afternoon has lived up to his reputation of being in the forefront of progress. We all remember his suggestion some years ago that the criterion of the aerodynamic cleanness of an airplane should be the closeness to which its drag approached the drag of a flat plate of the same wetted area. Up to the present time our efforts have largely been directed toward making the ratio as low as 1. Now, however, we appear to be entering a phase of investigation to bring this ratio below 1, actually to reduce the drag below what has sometimes been considered an irreducible minimum. To the designer of ten and fifteen years ago the increments of drag coefficient of which Professor Jones has spoken would have seemed insignificant, but on modern aircraft they represent a very appreciable and important part of the total. This is a real indication of recent aerodynamic progress.

To me one of the most remarkable features of Professor Jones' work is the apparent simplicity and directness with which he has obtained data applying to the case of particular interest, flight. I do not doubt that in the course of the investigation there arose many difficult problems of experimental technique which it required the utmost ingenuity to solve. It is noteworthy that Professor Jones has obtained data on very complicated phenomena with what appears to be very simple, understandable, and easily operable equipment.

I want to congratulate Professor Jones for presenting for the first time some definite figures on the dimension and location of the boundary layer. This will enable the designer to form some kind of mental picture of the factors that he must consider in attempting to secure minimum skin friction.

I. I. Sikorsky
Sikorsky Aircraft Division, United Aircraft Corporation

The lecture of Professor Jones was extremely interesting from a scientific standpoint. It is very probable that the ideas expressed will be very important in the near future, even from the standpoint of practical aeronautical engineering.

Ten or fifteen years ago the analysis of parasite resistance of an aircraft usually would have included some dozen items, such as struts, wires, wheels and their supports, separate power plant nacelles, and various other items. The profile drag of the wing in this case represented a minor item and the progress of design could best be achieved by simply reducing the number of protruding parts and improving the mutual interference of what was left. This work of cleaning up an airplane is nearly completed at the present time and in a well designed, modern airplane, particularly in a large, long-distance ship of the immediate future, we will usually find only three items of parasite resistance remaining, namely, the wing, the body, and the tail surface. This being the case, the resistance of the wing, even excluding the induced drag, becomes a major item that may approach one half of the total, while the skin friction of the whole airplane may eventually reach 75 percent of the total resistance. This being the case, it is important to study the methods which would permit controlling and, if possible, reducing this major item of resistance.

An important secondary problem in connection with this question appears to be a theoretical or experimental study of the question as to whether the skin friction of an ideal surface can be further reduced by artificial methods. By this we mean whether the remaining resistance is a basic figure similar to the induced drag figure which, we believe, cannot be reduced for the aircraft of given weight or span.

In line with this, it might be interesting to extend the study to birds flying. Some competent investigators believe that birds sometimes develop extremely high efficiency and L/D ratios that are far in excess of those obtained in aircraft. This factor is attributed to particular characteristics of wing feathers which permit the air to slip through, creating the effect of a boundary layer control. While I do not believe that birds really possess outstanding efficiency, yet further study may be of great interest. It is indeed extremely difficult because the tests that were made on wings of dead birds may not be identical to the conditions of a living bird.

Finally, we know at least two methods that would permit controlling the boundary layer and moving backward the point or region of transition from the laminar to the turbulent flow. These methods are the use of pressure or suction slots or the use of a sort of endless belt or built in rotors which would permit the surface of the wing to move backward at a velocity equal to that of the air stream. The latter method would probably eliminate entirely all separation. It appears important that aeronautical science should find out whether the weight and power expended on the

operation of these or other artificial boundary layer control devices would be such as to leave room for improvement in performance of the aircraft.

In conclusion, I believe that we all owe sincere thanks to Professor Jones for discussing this very important question in such a remarkably clear and interesting way.

Eastman N. Jacobs
National Advisory Committee for Aeronautics

Owing to the lack of time I must forego the expressions I would like to offer of my admiration of Professor Jones' work, and pass on immediately to the subject of transition now under discussion.

From my standpoint the outstanding result of Professor Jones' lecture is that he has definitely shown what we have suspected for a long time: that extensive laminar layers must be recognized as possibly existing on actual airplanes in flight within the Reynolds number range commonly encountered. As wind-tunnel operators, many of us have hoped that we could escape this conclusion. When large possible movements of the transition point are encountered, corresponding uncertainties about our drag predictions are introduced. The outlook for us is gloomy. We remember Baker's experiments also made in England in which he found in towing airship models in water that the drag was practically indeterminate until the transition point was fixed by means of a small chord attached around the forward surface of the model. In fact, Reynolds' classic experiments exhibited this same uncertainty. One rather definite result was obtained, i.e., the lower critical Reynolds number at which turbulence started in the tube tended to be suppressed. The uncertainty appeared when it was attempted to determine the highest Reynolds number at which laminar flow was possible; the more care exercised in controlling experimental conditions, the higher were the Reynolds number values obtained.

The turbulence present in the variable-density tunnel has accomplished much the same result as Baker's cord and Reynolds' initial turbulence but the results must now be regarded as pessimistic as compared with the lower drags that Professor Jones has obtained in flight under carefully controlled conditions. In fairness to the variable-density tunnel, however, it should be emphasized that the results may still be employed as conservative. If you ask us to predict how much lower drag you may hope for in flight, however, it appears that we wind-tunnel operators are on the spot.

In order to predict actual airfoil drag coefficients, it is clear that something must be known about the position of the transition point. On this subject Professor Jones has provided some important data and a significant analysis, but the work impresses me mainly as providing the necessary material for a first class mystery.

The subject is evidently a complicated one and Dr. Dryden in his discussion has pointed out further complications encountered during his investigation of the flow in the boundary layer about an elliptic cylinder. A simple partial solution of the mystery should nevertheless be sought.

It is possible that the desired simplification may be reached through further complication? Dryden's investigations have shown, for example, that Pohlhausen's λ, which is described by the speaker as a non-dimensional measure of the local pressure gradient, is not an adequate parameter to describe the condition of the laminar boundary layer at least in regions of adverse pressure gradient where separation may be imminent. Von Karman and Millikan, however, have worked out a more complicated method of analysis which von Doenhoff, of our staff, showed would give satisfactory results when applied to Dryden's measurements on the elliptic cylinder. Moreover, G. I. Taylor's suggestions about the nature of transition together with certain experiments under carefully controlled conditions of vanishingly small turbulence, including some made at our laboratory to study transition on a plate in the presence of an adverse pressure gradient, have indicated that, within limits, transition may be very closely associated with laminar separation.

Such consideration suggests a limiting extent of the laminar boundary layer and consequently a limiting position of the transition point. Perhaps the approach to the problem may thus be simplified by first considering the extent of this range in which the transition point may be expected to lie near the point of laminar separation. On the one hand this position is an important one because more extensive laminar layers would not even be desirable. We have seen in the smoke tunnel at low Reynolds numbers the unfortunate result of a much more extensive laminar layer. The laminar layer separates, leaving a wide turbulent wake and a high form drag if transition does not occur shortly after laminar separation. On the other hand, less extensive laminar layers are also undesirable, owing to the drag increase. Consequently, this limiting position also represents the optimum one. Furthermore, one mystery of the subject paper would tend to be cleared up if this position were actually reached in the experiments under discussion; that is, why the point of transition frequently appeared to be so definitely fixed on the wing.

Time did not permit much quantitative consideration of Professor Jones' data but von Doenhoff kindly made the necessary calculation for the top velocity distribution curve of Fig. 9. To me it is significant that the calculated laminar separation point came out within approximately 2 percent of the chord from Professor Jones' tick indicating his measured transition point. The significance is that with sufficient care, smooth surfaces, and in flight in turbulent-free air, the range defining at least a close approach to the optimum transition position appears to extend to surprisingly high Reynolds numbers, that is, the values of several million reached in Professor Jones' flight experiments. The question I have previously asked still remains: How much further can we go in maintaining these desirable low-drag laminar layers?

T. P. Wright
Curtiss-Wright Corporation

In this lecture I was struck, as I have been when reading the previous lectures Professor Jones has given, with the scientific approach which he makes to his research investigations, striving constantly for the building up of facts and exhibiting the necessary caution in their interpretation.

We all remember, I am certain, the fundamental importance of Professor Jones' 1929 lecture wherein he developed the conception of the streamline airplane, outlining the wastefulness of design as it then existed, inasmuch as sixty-six percent of the engine power was wasted in overcoming drag due to turbulence in the wake of forms of non-streamline sections used throughout. He pointed out the possibilities as well as the advantages of designing to truly streamline shape and I know that personally, I was tremendously impressed by the lessons he taught in that lecture as no doubt, were many others.

In 1936 Professor Jones showed that much of his original idea, had been attained and that subsequently we must exert our energies toward producing a smoother surface which would reduce skin friction itself, thereby setting up a new ideal for which to strive. In that lecture he alluded to the possibility of moving the transition point so as to increase the proportion of laminar flow in the boundary layer at the expense of the drag producing turbulent flow.

In the present lecture, I am impressed with the scientific methods used by Professor Jones in obtaining and interpreting facts which he hopes will shed useful light on the factors governing the location of the transition point. (The following shows the parallel reasoning of scientists working on similar problems. Last Spring, Eastman N. Jacobs of our own N.A.C.A. gave a paper on the subject of laminar and turbulent boundary layer in which at one point he said: "The situation with regard to the airfoil drag is particularly serious because we have no equipment capable of studying the subject experimentally in the higher full-scale range of Reynolds Number in which we are at present most interested. Recourse therefore must be had to theory." The mechanical means (using the Pitot Transverse Method) which Professor Jones has so well described to us today has apparently filled this need.

Professor Jones has shown us clearly many facts pertaining to the effect on location of the transition point of smooth wings, of parameters which are determined by the Reynolds number of the boundary layer, the pressure gradient, and the radius of curvature. Although he arrives at the conclusion that it is some parameter whose origin is to be sought in the system of flow of the wings themselves, I think he rather regretfully concludes that the particular parameters investigated did not, of themselves, permit satisfactory determination of the transition point location. His allusion to the possibility that fluctuations superimposed on the main flow in the boundary layer may represent a basis for a parameter which will be of great importance in the transition point question should be noted and is a fact also alluded to by Dryden and Jacobs. There may possibly be some analogy between instability of these fluctuations which, through causes yet to be determined, seem to transform a laminar flow to a highly turbulent flow, with the instability of wings or control surfaces which at certain speeds may be subject to small vibrations without increase in disturbance but which at slightly higher speeds lose control, so to speak, and go into a phase of extreme flutter.

I trust I will be pardoned for again quoting from Jacobs' paper of last Spring wherein he says: "the present knowledge of wind tunnels makes it appear feasible to construct suitable equipment giving an airstream of effectively zero turbulence and capable of reaching the very large Reynolds Number for which engineers will very soon require reliable data." Here also, it appears that Professor Jones has in great part succeeded. The tunnel on non-turbulent flow described in his lecture represents a tool which should be extremely interesting and useful in continuing the general studies on the phenomena of transition point and the results of which studies, coupled with additional full-scale tests may, we hope, form the basis for another lecture by Professor Jones a year hence.

Quantitatively, it appears rather early to predict the order of performance improvement that may evolve from this research. Four or five percent speed improvement appears likely in a relatively short time, with some attendant increase due to the super-smoothness required to effect rearward transition point movement. Jacobs, I recall, was very optimistic.

With the streamline airplane closely approximated in our present air transports and with the growing appreciation of the importance of smoothness of surface in reducing skin-friction drag, it appears that the next ideal for which we should continue striving is the airplane surrounded in larger part by laminar flow, a goal toward the attainment of which Professor Jones has contributed so much. We have closely approximated the airplane of streamline form—now, (as Professor Jones has pointed the way by advancing our knowledge of it, and although it seems improbable and may prove impossible) let us strive for the airplane of laminar flow.

The repetition of the First Wright brothers' Lecture by Professor B. Melville Jones at the Athenaeum of the California Institute of Technology in Pasadena on Tuesday evening, December 21, was the occasion of the most outstanding meeting of the Institute of the Aeronautical Sciences ever held on the Pacific Coast.

Professor and Mrs. Jones were honored on the evening of December 20 by a reception held at the home of Dr. Theodore von Karman, and on the evening of the lecture, they were guests of honor at a dinner in the Athenaeum attended by over one hundred members and guests of the Institute. In addition to Professor and Mrs. Jones at the speakers' table there were: Robert A. Millikan, Theodore von Karman, E. P. Lesley, H. Bateman, Clark B. Millikan, Elliott G. Reid, Hall L. Hibbard, Arthur E. Raymond, A. L. Klein, Carleton E. Stryker and Norton B. Moore.

After the dinner and before the lecture, a short business meeting of the Los Angeles Branch was held. This Branch has applied for its charter on Founders' Day, and the meeting was its first since the charter had been granted. The Standard Form of By-Laws was adopted, and the following officers were elected for 1938: Chairman, Hall L. Hibbard; Vice-Chairman, Clarence L. Johnson; Recorder, Richard M. Mock; and Treasurer, E. E. Sechler. Another meeting of the Branch will be held on Friday, February 11.

At the lecture, a wire from Major Gardner was read: "Greetings from the Institute on occasion of holding first Wright Brothers' lecture on West Coast and organization of our most active Branch. Our sincere appreciation to Professor Jones for his willingness to give his important paper before our Southern California members."

Clark B. Millikan introduced Professor Jones, whose splendid lecture was enjoyed by well over two hundred listeners, and which was followed by a lively discussion entered into by Theodore von Karman, F. H. Clauser, H. Bateman, A. E. Lombard, and others.

Francis H. Clauser
Douglas Aircraft Company

It was a pleasure to hear from the man who provided the stimulus some years ago which has lead to the practical elimination of unnecessary form drag in modern airplanes and it is reassuring that this same man is now engaged in research which may conceivably reduce the remaining skin friction to some fraction of its present value.

One interesting point of the talk was the extremely small roughness necessary to precipitate transition. I wonder if Professor Jones has any data on either this effect or on the effect of roughness on the skin friction of the turbulent layer which might be compared with the permissible roughness given by current theory.

The speaker's remarks suggested the possibility of shaping the lower wing profile such that $dp/dx = 0$ at cruising velocities and thus preserving the laminar layer to great lengths over the surface. I wonder if he had attempted anything along these lines.

It would be of interest to know Professor Jones' ideas on the possibilities of drag reduction by boundary layer removal at the points of transition, thus having only laminar layers on the wing profile.

Lastly, what are Professor Jones' fondest hopes regarding large drag reductions by preserving the laminar layer throughout the entire length of the boundary layer? Here Professor Jones may cast scientific caution to the winds and speculate as in his fondest dreams.

LETTER TO THE EDITOR

December 17, 1937

Dear Sir:

In the April, 1937 issue of the Journal, R. S. Hatcher published an article on "Rational Shear Analysis of Box Girders." In the November, 1937 issue, George N. Mangurian published, in the form of a "Letter to the Editor" a set of formulae which is both more general and much simpler. For the benefit of younger students, who might become confused, it seems very desirable to say a few words on the physical meaning behind Mangurian's formulae.

Inspection identifies Managurian's basic formula for e as established by the oldest approximate method in existence, the so-called Centroid of Inertia method. This method was established in the days of wooden two-spar wings and gives very good approximations for true two-spar structures. For box-beams, however, it holds only if there action resembles that of two-spar wings. The indiscriminate application of the method to box-beams may lead to disastrous consequences, as shown in the following example.

Fig. 1 represents a fairly common type of construction, the nose and the tail furnishing no structural strength. Now it has been sometimes practice to pierce the rear shear web with large round holes to give access to the interior of the wing. This reduces the effective thickness t_2 practically to zero. Substituting $t_2 = 0$ in Hatcher's formula gives the elastic center location as H, while Mangurian's formula gives M. Reference to any good text book on strength of materials will show that Hatcher's location is the correct one.

Assuming a load applied at 50 percent of the wing chord (old L.A.A. case), Mangurian's formula gives only bending, no torsion, while Hatcher's formula gives correctly a very heavy torque added to the bending. This error is the more serious because the box considered is weak in torsion.

The distribution of stresses in a box beam is a statically indeterminate problem. For more than half a century it has been a recognized principle of engineering mechanics that such problems can be solved only by taking into account the elastic properties of the structure. It is not always possible to do this very completely, but any rule such as Mangurian's which violates a very important condition should be ear-marked very clearly as a sort of rule-of-thumb, very useful in the hands of a man who knows when not to use it, but a dangerous tool to put in the hand of a neophyte.

Paul Kuhn
National Advisory Committee for Aeronautics.

Document 4-18

Eastman N. Jacobs, Senior Aeronautical Engineer, to Engineer-In-Charge, "Notes on the history of the development of the laminar-flow airfoils and on the range of shapes included," 27 December 1938, in RA file 290, LHA, Hampton, Va.

Unfortunately, engineers often do not make good historians, at least when they are documenting the intellectual processes involved in their own current work. This short memo from Eastman Jacobs on the history of the development of the laminar-flow airfoils is not nearly as illuminating as one might hope it to be. Although Jacobs in this memo did a fair job of tracing his basic line of thinking back to earlier NACA reports, research authorizations, and even to some of his own memos, he did not provide a very introspective account of the history of his ideas (and others) leading to his concept of laminar-flow airfoils.

It is not known why Jacobs wrote this memo, or for whom. Such "Notes on the history" of any NACA development were extremely rare. They were usually provoked by a request from the NACA's Washington office for information that could be used for publicity purposes. It seems unlikely that this was the case with Jacobs' memo, though, as it was not written in the style usually seen when publicity was the goal.

Document 4-18, Eastman N. Jacobs, Senior Aeronautical Engineer, to Engineer-In-Charge, "Notes on the history of the development of the laminar-flow airfoils and on the range of shapes included," 27 December 1938, copy in LHA, Hampton, VA.

Langley Field
December 27, 1938

MEMORANDUM For Engineer-in-Charge.

Subject: Notes on the history of the development of the laminar-flow airfoils and on the range of shape included.

1. We have been familiar with the possible large drag reductions through prolonging of laminar boundary layers, particularly since the international airship model tests (1922-1923) were made in various wind tunnels for wind-tunnel standardization purposes. (See N.A.C.A. Technical Note No. 264, 1927.) It is difficult to state, however, just when I first considered plans for controlling the boundary

layer directly through the body shape or through control of the usual pressures acting along the body surfaces. Certainly the possibilities were clearly in mind in connection with our airfoil work before 1930 as shown by my memorandum of November 13, 1929; Research Authorization No. 88 on airfoil scale effect, which discussed the importance of transition on airfoil drag, and mentioned the dependence of the transition point on the airfoil shape. It was then expected that the gains would become apparent as the result of our systematic tests of various airfoil shapes. It is now known that little was found owing to the turbulence present in the variable-density tunnel and to the tunnel-wall and end effects present in the 24-inch high-speed tunnel. The long delay of almost 10 years may be largely attributed to these disturbing effects which tended to make the gains appear small or impractical. The ensuing work which finally disclosed and permitted the removal of the difficulties was, however, carried on continuously in the meantime.

2. Another line of attack is shown by a memorandum by Freeman dated April 18, 1932, which pointed out the possibility of drag reductions through boundary-layer control to delay transition on airships. (R.A. No. 201) In a laboratory conference on boundary-layer control (July 20, 1936) I compared the two methods and urged the necessity for new turbulence-free testing equipment as the primary necessity and emphasized that the direct control through shape appeared to be the most likely method and the one that should be placed first on our program before investigating the usual forms of boundary-layer control. The situation as it then existed is brought out in my S. A. E. paper: Laminar and Turbulent Boundary Layer as Affecting Practical Aerodynamics, March 12, 1937, which was a plea for suitable turbulence-free testing equipment. I remember deliberately withholding a disclosure of the details concerning the possible gains which I had definitely in mind at the time of the preparation of this paper, although I had disclosed earlier the possibilities of the new form of boundary-layer control in relation to airfoils as one of the most likely avenues of approach in my talk at the Manufacturers Conference on fundamental airfoil research and transition studies in May 1936. I wished to avoid building up too much hope for future advances without experimental verification, which seemed to require new testing facilities.

3. When the construction of the required new equipment was well under way, Pinkerton was asked, in

[illegible] AIRFOIL

Upper Surface		Lower Surface	
Station	Ordinate	Station	Ordinate
Percent	Percent	Percent	Percent
0	0	0	0
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
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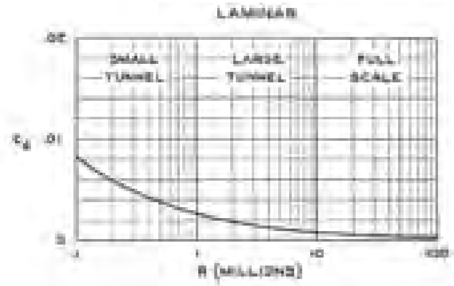
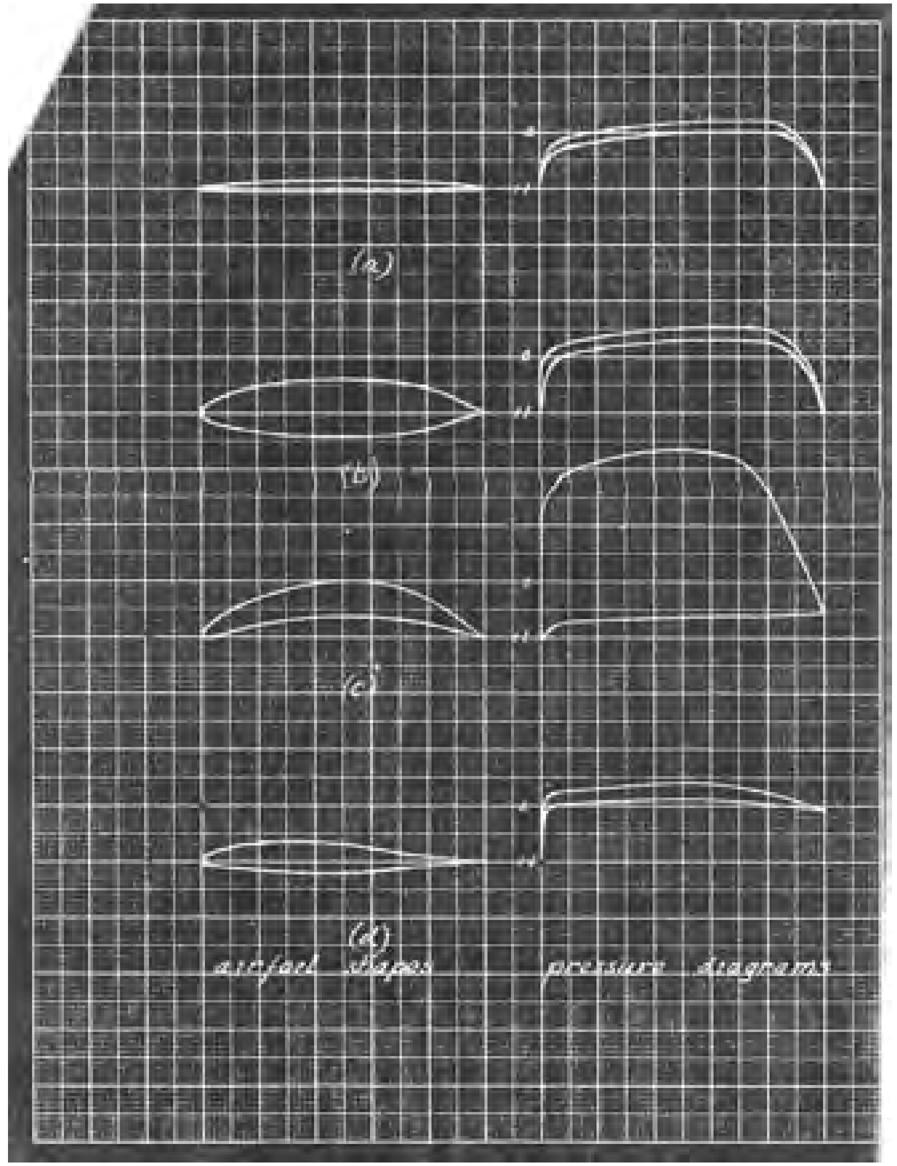


Fig. 1a (above) – Representation of Laminary Boundary Layer on the Upper Surface of an Airfoil
Fig. 1b (right) – Variation of Laminar Skin-Friction Drag Coefficient with Reynolds Number



December 1937, to seek airfoil shapes of the type required. A first approximation to a suitable shape was soon found, the pressure distribution verified theoretically, and a model constructed for tests. The large gains possible were first definitely established experimentally when this model was tested on June 23, 1938, in comparison with a conventional airfoil. The new airfoil showed a drag of the order of one-half that of the conventional airfoil. These tests were conducted as soon as possible after the new equipment had been put into operation and the test work and development have been pursued continuously and diligently ever since that time except for a forced short interruption for some icing investigations.

4. In order to indicate further the scope of the "laminar-flow" airfoils, the enclosed sketch has been prepared to suggest the range of shapes included. The form (a) is that which tests have shown to have the lowest drag of any investigation. This shape is designated N.A.C.A. 381-204 and a table of its ordinates is attached. Form (b) shows how the section thickness may be increased when required from other considerations. Form (c) shows how the desired laminar flow characteristics may be retained even at high lift coefficient. The purpose is accomplished by the use of a suitable, greatly exaggerated mean-line curvature. Form (d) is arrived at through somewhat different considerations. The forward part of the airfoil is derived to give the laminar-flow form but the rear portion is designed to give an easy and small pressure recovery as shown by the pressure-distribution diagram at the right of the figure. This character of airfoil is designed for the combined use of slot suction methods of boundary-layer control on the rear portion with the hope by this means of maintaining laminar flow over the entire body surface. Work is now going forward on this project but no test results are yet available.

Eastman N. Jacobs,
Senior Aeronautical Engineer.

Document 4-19

Eastman N. Jacobs, "Laminar and Turbulent Boundary Layers as Affecting Practical Aerodynamics," *Journal of the Society of Automotive Engineers* 40 (March 1937): 468-72.

Eastman Jacobs presented this paper at the National Aeronautic Meeting of the Society of Automotive Engineers in Washington, DC, on 12 March 1937. Supplementing his talk with slides and motion pictures, Jacobs described the general nature of boundary-layer phenomena and emphasized the lack of knowledge concerning the transition from laminar to turbulent flow.

This paper was especially significant to the aeronautics community of the late 1930s in showing "not what is known, but rather to emphasize that which is not known." Interestingly, one person in the audience who came to his feet afterwards to comment on Jacobs' paper was Dr. Max Munk, Jacobs' controversial predecessor as the head of airfoil research at NACA Langley and the father of the VDT. Munk's reaction to it, and to the whole idea of pursuing a laminar-flow airfoil, was very positive. "Expressing some concern as to whether Mr. Jacobs was optimistic or pessimistic in regard to the promise of future aerodynamic gains, Munk assured the session of his own optimism in this respect. He urged a continuation of this research as holding forth worthwhile promise." In reply, Jacobs reassured Munk of his own optimism and pointed out "the importance of reproducing flight conditions for the proper solution of the problem. He then went on to make a pitch for a new NACA low-turbulence tunnel. "This method necessitates equipment," he said, "whereby full-scale Reynolds numbers and low turbulence can be obtained" ("Two Aerodynamic Problems Debated," *Journal of the Society of Automotive Engineers 40* (April 1937): 26.

Document 4-19, Eastman N. Jacobs, "Laminar and Turbulent Boundary Layers as Affecting Practical Aerodynamics," **Journal of the Society of Automotive Engineers** *40, March 1937.*

LAMINAR AND TURBULENT BOUNDARY LAYERS AS AFFECTING PRACTICAL AERODYNAMICS

BY EASTMAN N. JACOBS

The main part of this paper deals with one of the unsolved problems that impedes further progress in the aerodynamics of airfoil sections in relation to further research. In studying laminar and turbulent flow, special consideration is given to determining where the transition from one to the other takes place along the airfoil surface.

With no equipment capable of studying the subject experimentally in the higher full-scale range of Reynolds numbers, the problem has been attacked theoretically by two methods: According to the first method, the laminar boundary layer is supposed to become unstable.

With the second method of attack the mechanism of transition is supposed to be something like separation. This comparison has the advantage that the separation phenomenon is comparatively well understood and can be dealt with quantitively by means of existing theory. Separation and its relation to the transition phenomenon are therefore considered, and the actual behavior of the flow during its change from laminar to turbulent is illustrated.

The final conclusion reached, however, is that we do not know but should find out whether theoretical gains indicated are possible. Such investigation will require suitable equipment capable of reaching these very large Reynolds numbers.

Recent progress in the most important field of practical aerodynamics, the flow about wing section, is due to an appreciation of the character of the flow as affected by variations of the section shape, the scale or Reynolds number of the flow, and the turbulence of the air stream. This progress has resulted in the development of improved wing sections, greater accuracy in the derivation of airfoil *section* characteristics from the usual airfoil tests, improved methods of predicting the section characteristics to be expected in flight at other Reynolds numbers and other conditions of turbulence than those under which the characteristics were measured and, finally, improved methods of predicting complete wing characteristics from the basic section characteristics.

This paper, however, deals with one important unsolved problem that stands in the way of further progress. Our lack of knowledge about the boundary layer constitutes the main difficulty. Two types of boundary layer are encountered which,

owing to their entirely different character and behavior, markedly influence the final practical aerodynamic characteristics of airfoil sections. These two types of boundary layer are known as laminar and turbulent. Figs. 1(a) and 2(a) show the two types as they might be imagined to occur on the upper surface of an airfoil section in flight (inasmuch as the complete laminar boundary layer could not actually exist but would separate from the airfoil surface). The very low resistance to separation as compared with the turbulent boundary layer is, in fact, one important characteristic

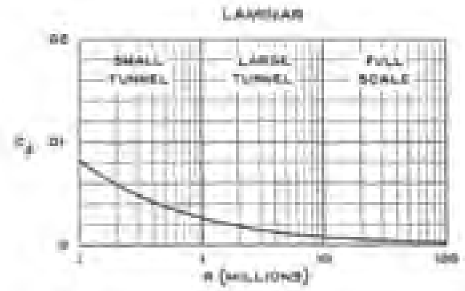


Fig. 1a (above) – Representation of Laminary Boundary Layer on the Upper Surface of an Airfoil
Fig. 1b (right) – Variation of Laminar Skin-Friction Drag Coefficient with Reynolds Number

of the laminar layer. Both types of boundary layer are shown as they would develop on a flat plate where separation would not be involved. The other important respect in which the two boundary layers show a marked difference is indicated by the numbers in Figs. 1(a) and 2(a) comparing the drag coefficients and by the skin-friction-drag variation with Reynolds number shown in Figs. 1(b) and 2(b).

A very large scale or Reynolds-number range is encountered in practical aerodynamics. Most of the figures presented herein such as Fig. 1(b) show a thousand-fold range of the Reynolds number, that is, from 100,000 to 100,000,000. The three main divisions shown on the plots, each representing a ten-fold range, have been indicated in Fig. 1(b) as small tunnel (100,000 to 1,000,000); large tunnel (1,000,000 to 10,000,000, which also covers the lower full-scale range including the landing conditions for existing transport airplanes); and full scale (10,000,000 to 100,000,000, which corresponds to the large future airplane or flying boat having a wing chord of 40 ft. and flying at 260 m.p.h.). The important result shown in Fig 2(b) then is the greatly reduced drag, corresponding to both types of boundary layer as these higher full-scale values of the Reynolds number are approached, and the

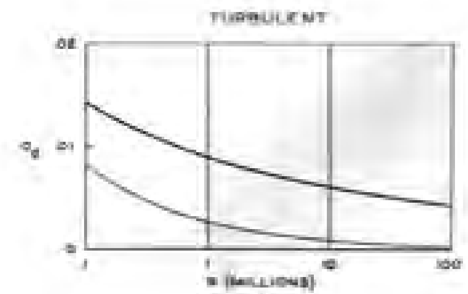


Fig. 2a (above) – Representation of Turbulent Boundary Layer on the Upper Surface of an Airfoil
Fig. 2b (right) – Variation of Turbulent Skin-Friction Drag Coefficient with Reynolds Number

increasing difference between the two, the laminar drag becoming almost insignificant in the higher full-scale range. In this range it obviously makes a great deal of difference in the drag whether the boundary layer is laminar or turbulent.

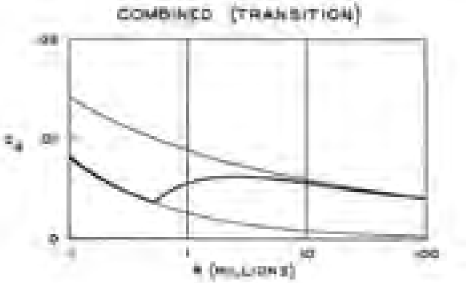


Fig. 3a (above) – An example of the Combined Laminar and Turbulent Boundary Layers on the Upper Surface of an Airfoil Showing the Transition Point

Fig. 3b (right) – An Actual (Combined Laminar and Turbulent) Variation of Skin-Friction Drag Coefficient on a Flat Plate

In general, both types are observed; the laminar appears over the forward part of the airfoil and changes to the turbulent somewhere along the airfoil surface at the so-called transition point (Fig. 3(a)). Owing to the difference in the character of the laminar and turbulent boundary layer, it is clearly essential to consider where the transition from one to the other takes place.

The classic studies by Osborne Reynolds of the flow in pipes showed that transition occurs at a certain value of the ratio we now know as the Reynolds number, dependent on the steadiness of the flow entering the pipe. When the transition occurs in the boundary-layer flow along a flat plate at a given Reynolds number (based on either the boundary-layer thickness or the distance of the transition point from the leading edge of the plate), the actual variation of the skin-friction drag with scale is presumably something like that shown in Fig. 3(b). Likewise, as Reynolds found in his pipe experiments, the transition occurs earlier or at a lower Reynolds number, if the air stream flowing over the plate is unsteady or turbulent. The effect of this early transition on the skin-friction drag coefficient, cd, of the plate is shown in Fig. 4.

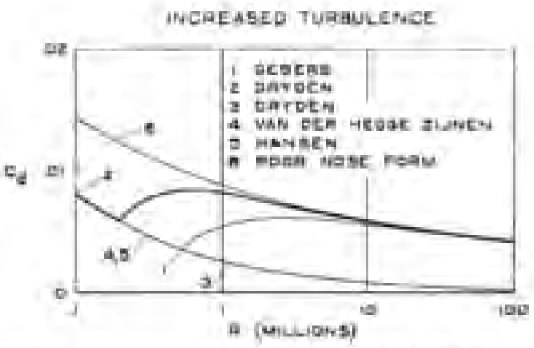


Fig. 4 – Skin Friction Variation with Reynolds Number on Flat Plate with Increased Turbulence – The Numbers Indicate Approximately Where Transition Was Encountered by Different Experimenters Under Various Conditions

Experimental results in general confirm this view of the subject but, as shown by Dryden, who has obtained transition points ranging between those indicated by the numbers 2 and 3 in Fig. 4, pressure variations along the plate also have a very important effect. Roughness of the plate or a poor nose form may also introduce

turbulence and thus hasten transition, even to the extent indicated by curve 6 in Fig. 4, which corresponds to transition at the leading edge and shows no effect of a laminar boundary layer. Finally, when airfoils are considered, the study of the occurrence of transition is complicated further by the presence of large variations of pressure along the surface and, possibly, by the curvature of the streamlines. Nevertheless, thin airfoils, which are associated with small pressure variations and curvatures, may at least by compared with flat plates as in Fig. 5. The resemblance to the corresponding curve for the flat plate with increased turbulence (Fig. 4) is striking.

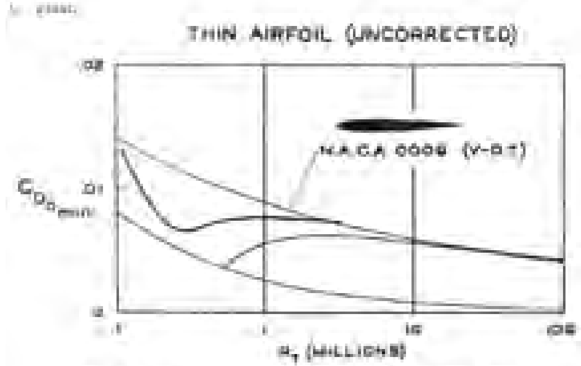


Fig. 5 – Comparison of Airfoil and Flat-Plate Drag

The effects of the increased turbulence in the variable-density tunnel may be taken into account on the basis of an effective Reynolds number approximately 2.6 times the test Reynolds number at which scale the corresponding transition conditions might be expected to occur in a turbulence-free stream. The turbulence factor, 2.6 for the variable-density tunnel, was determined as shown in Figs. 6 and 7 by a comparison of airfoil maximum-lift measurements in the tunnel and in free air. (The free-air results are actually inferred from tests in the N.A.C.A. full-scale tunnel). An interpretation of the drag on the basis of the effective Reynolds number with an allowance for the reduced skin friction at the higher Reynolds number results in a curve (Fig. 8) that is much like the well-known Gebers curve, representing the drag of a flat plate towed in water; moreover, thick airfoils (Fig. 9) have higher drag coefficients but appear to show similar

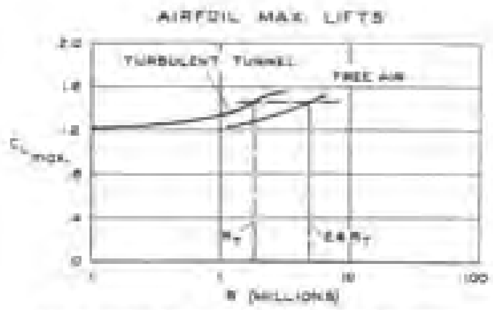


Fig. 6 – Airfoil Maximum Lift as Affected by Tunnel Turbulence

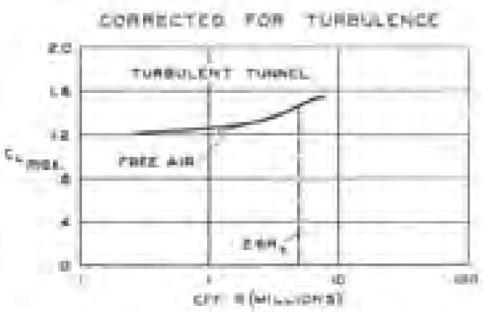


Fig. 7 – Same Measurements as Fig. 6 but Represented as a Function of Effective Reynolds Number

variations with the Reynolds number. On this basis airfoil results from the variable-density tunnel may be extrapolated into the higher full-scale range as indicated by the dotted line in Fig. 9.

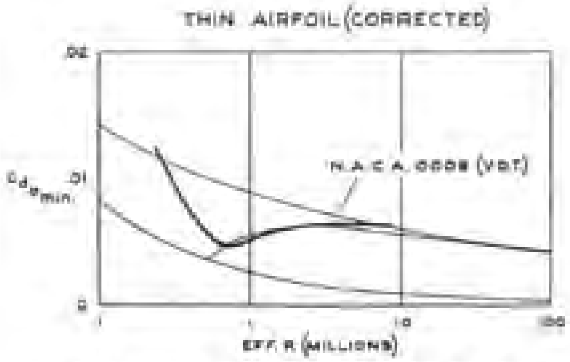


Fig. 8 - Comparison of Flat-Plate and Airfoil Drag Corrected to the Effective Reynolds Number

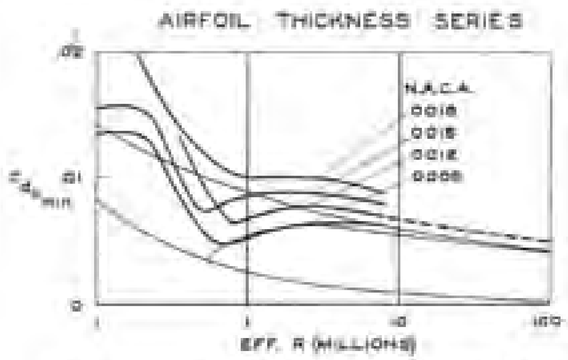


Fig. 9 - Variation of Drag with Reynolds Number for Symmetrical Airfoils of Varying Thickness

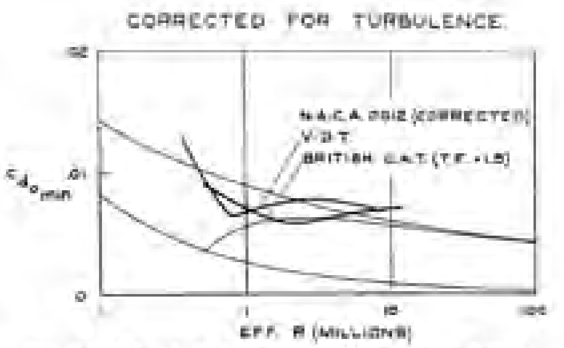


Fig. 10 - N.A.C.A. 0012 Airfoil Minimum Drag As Found from Different Tunnels

Up to this point the results, as corrected for turbulence, seem to be consistent and reasonable, but there remains the question: Do they apply accurately to flight conditions? The difficulty is that the turbulence factor and the effective Reynolds number are determined, in either sphere-drag or airfoil maximum-lift measurements, by the effects of turbulence on transition in a strong adverse pressure gradient in the neighborhood of the separation point, whereas Dryden's results have indicated that small changes of turbulence may produce large changes in the critical Reynolds number for flat plates. *In other words, the drag of a sphere or the maximum lift of an airfoil does not appear to be sensitive to small changes of turbulence as compared with the drag of a flat plate or an airfoil.* Consequently the usual turbulence correction when applied to the drag of an airfoil is likely to be too small. This expectation is supported by the comparison in Fig 10 of drag results for the N.A.C.A. 0012 airfoil from different tunnels. The rise in drag with increasing Reynolds number, probably associated with a forward movement of the transition point, is seen to occur too early in the more turbulent variable-density tunnel even after the turbulence effect has been

allowed for in the usual way by representing both sets of results at their effective Reynolds numbers. Furthermore, the rise is less abrupt in the less turbulent British compressed air tunnel so that it might be supposed that, in a turbulence-free stream or in free air, the rise would be still more gradual and would occur even later than indicated by the British compressed-air-tunnel results.

It thus appears that the interpretation of airfoil results on the basis of the effective Reynolds number, although it has proved in many instances to be a very useful engineering approximation, represents in reality an oversimplification. Unfortunately this conclusion leaves us without a reliable means of predicting airfoil-drag results, particularly in the higher full-scale flight range. In fairness to the results from the variable-density tunnel, however, it should be noted that drag values are often considered extremely uncertain, in fact sometimes almost indeterminate, in the range where a considerable movement of the transition point may occur. In practice slight roughness, vibration, or induced unsteadiness of the air flow near the airplane wing may bring about transition near the airfoil nose; thus this uncertainty concerning the drag may actually not appear in practice. On this basis the turbulence present in the variable-density tunnel accomplishes the same purpose. The results may thus be considered the most reliable available for *conservative* extrapolations into the higher full-scale range for aerodynamically smooth airfoils.

This consideration brings us, however, to the main subject of the paper. We know very little about why, how, or where transition occurs or, therefore, about the relative extent of the laminar and turbulent boundary layers. Finally, it follows that we have practically no certain knowledge about the two most important airfoil characteristics, C_{lmax} and C_{do}, because they are both directly affected by the occurrence of transition.

The situation with regard to the airfoil drag is particularly serious, because we have no equipment capable of studying the subject experimentally in the higher full-scale range of Reynolds number in which we are at present most interested. Recourse, therefore, must be had to theory.

The theoretical problem has been attacked by means of two methods. According to the first, the laminar boundary layer is supposed to become unstable. Small disturbances that were damped out by the viscous forces at low values of the Reynolds number lose, at high Reynolds numbers, the damping necessary to prevent their growth into turbulence. Many prominent mathematical physicists have attacked this phase of the problem without obtaining very satisfactory results.

According to the second method of attack, the mechanism of the transition is supposed to be something like that of separation. This comparison has the advantage that the separation phenomenon is comparatively well understood and can be dealt quantitatively with by means of existing theory. The separation referred to may occur only locally, but any return flow tends to cause an accumulation of dead air over which the main flow must run. When a local dead-air region or bump is overrun by the main flow, reduced pressures are created which tend to draw in additional dead air, thus augmenting the disturbance. The turbulence may be considered as the final result of the building up of the bump until its top is carried or curled over by the main overrunning flow and thus moves downstream to form a distinct eddy.

The details of the transition have been observed and photographed at moderate Reynolds numbers on a flat plate in the N.A.C.A. smoke tunnel. When the transition is not brought about prematurely by slight surface roughness which also may cause transition by first promoting separation, the normal transition was observed to be closely associated with laminar separation. In general, when the turbulence and roughness were both practically zero, the transition was never observed to occur appreciably forward of the point at which laminar separation normally occurred. Furthermore B. M. Jones at Cambridge reports that he and his associates have found in flight laminar boundary layers on very smooth airplane wings sufficiently extensive to approach the laminar separation region. The fact that such extensive laminar boundary layers are not ordinarily observed at high Reynolds numbers in wind tunnels may be explained as the result of the airstream turbulence. The turbulence tends to produce localized pressure gradients along the airfoil surface that combine with the general pressure gradient to produce local separation and hence, by this theory, also to produce transition at points farther forward than the usual separation point. In fact, this second method recently has gained much prestige owing to the fact that G. I. Taylor employed equivalent concepts to make quantitative predications about the results of sphere-drag tests in turbulent wind tunnels.

These concepts may now be extended to account, in a general way, for the difference between the two drag curves in Fig. 10. In the variable-density tunnel, where the pressure gradients associated with the turbulence are relatively large in relation to those along the airfoil surface, they may combine to produce an adverse gradient of sufficient intensity to start local separation, even in the generally favorable gradient field near the airfoil nose. A relatively early and rapid forward movement of the transition point, as indicated by the rising drag curve, is then obtained. In the British compressed-air tunnel, however, where the pressure gradients associated with the turbulence are relatively less, the transition point is more reluctant to pass forward into the generally favorable pressure field; hence the later and less rapid increase of the drag coefficient.

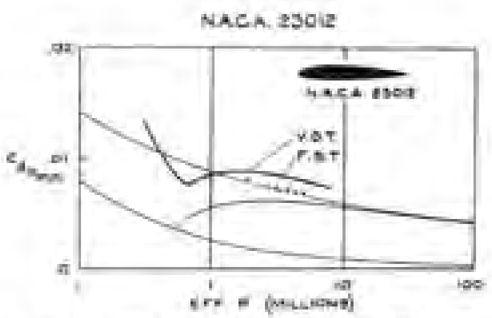


Fig. 11 – N.A.C.A. 23012 Airfoil Minimum Drag As Found from Different Tunnels

The few points shown in Fig. 11 for the N.A.C.A. 23012 airfoil and obtained from tests in the still less turbulent N.A.C.A. full-scale tunnel show, with increasing Reynolds number, little if any rise in drag that may be attributed to a forward movement of the transition point. On the other hand, the failure

of the drag points to fall much above the turbulent skin-friction curve indicated the presence of a rather extensive laminar layer. Otherwise the increased velocities over the airfoil, as compared with the flat plate, and the pressure drag would cause the airfoil drag to be considerably higher. This result may be associated with the theory that the forward movement of the transition point is caused by local pressure gradients associated with the tunnel turbulence, so that its movement is very slow when the turbulence is small; at least this theory seems tenable for smooth airfoils in the lower full-scale range. Now consider an extension of the same theory.

If the turbulence is zero, as it sometimes is in free air, the theory, carried to its logical conclusion, seems to indicate that the transition point will not move forward toward the leading edge of the airfoil as it does in the wind tunnel. If this supposition is true and other disturbances, such as turbulence originating near the nose or due to surface roughness, do not alter the situation, such a conclusion has considerable practical significance. A practical result is indicated in Fig. 12 by the dotted line showing how extrapolations should be made on this basis. The rise in drag associated with the forward movement of the transition point is assumed not to occur in free air at zero turbulence, the transition point remaining near the laminar separation point. It is then noted that the drag reached a surprisingly low figure at a Reynolds number of 100,000,000.

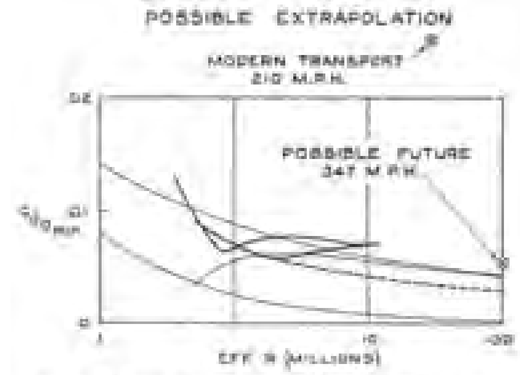


Fig. 12 – Possible Extrapolation of Tunnel Test Data into the Higher Full-Scale Range of the Reynolds Number

The importance of this possible result is further brought out by the comparison shown in Fig. 12 between two airplanes. The upper point (C_D = 0.0246) represents a conventional modern transport airplane having a speed of 210 m.p.h. The lower point represents a large hypothetical airplane having the same power and wing loading but designed to have very smooth surfaces, pusher propellers, and the other requirements necessary in order to take full advantage of the possible laminar flows over its forward surfaces. The combined wing, fuselage, interference, and tail-surface drag is based on actual tests of complete models in the variable-density tunnel but the extrapolation to 100,000,000 is based on the assumption that laminar boundary layers on the forward portions of the surfaces may be realized. The comparison is shown primarily to indicate that there is no necessity for pessimism concerning possible future aerodynamic improvement. Incidentally, even further drag reductions may be possible. For example, most of the fuselage and part of the tail-surface drag might have been eliminated by using the flying wing; furthermore, the possibilities of boundary-layer control have not even been considered. Nevertheless, the possible drag reductions considered allow a speed increase from 210 to 347 m.p.h.

The final conclusion, however, is that we do not know whether or not such gains are possible, but it is evident that the possible gains are large enough to justify immediate and careful investigation. Unfortunately, the necessary investigations require equipment that is not available. The present knowledge of wind tunnels makes it appear feasible to construct suitable equipment giving an air stream of effectively zero turbulence and capable of reaching the very large Reynolds numbers for which engineers will very soon require reliable data.

THE THROTTLE-STOP IN LIGHT FLEET UNITS

There is one item of which I have not spoken heretofore but which, to my mind, has been of such importance that I want to take the time to make special mention of it. I am referring to that little gadget known as the throttle-stop and I take a personal pride in the fact that our organization had a part in its development. The average fleet owner does not need the performance and top speed which is being built into the light automobiles of today. Economy of operation is far more desirable for our purposes, and you know that economy and performance do not travel together. We experimented with stopping our throttle at a point where it was only about one-third open, at which point the cars had a top speed of from 55 to 60 m.p.h. This we considered a sufficient rate for business purposes. The car was a little slower in acceleration and had to go into gear on climbing some hills, but it did have economy of operation. There was some growling from the drivers, as they are only human and, even as you and I, would like to have the best, be it in performance, speed, or appearance, but that growling disappeared when drivers were educated to the necessity for economy.

We formerly made our own throttle-stops and did our own work on the engines, but today we can all buy economy models with throttle-stops built into the car by the manufacturer.

The first paper, Flexible Exhaust-Valve Seats, by S. D. Heron, Ethyl Gasoline Corp., and A. L. Beall, Wright Aeronautical Corp., was read by Mr. Heron. He stated that, although some cylinder designs are attractive due to compactness and ease of securing large valve area, they are known to be subject to exhaust-valve-seat distortion. The investigation reported in the paper was carried out to determine whether the difficulties resulting from distortion can be overcome by flexibility in the valve head or valve seat, he announced.

In discussion following, A. T. Colwell, Thompson Products, Inc., stated that shallow and wide valve seat inserts gave poor results, whereas narrow and deep inserts gave good results. It also was stated that seats faced with Stellite gave good performance owing to their non-corrosiveness.

Flexible valve seats, according to Arthur Nutt, Wright Aeronautical Corp., may give four-valve cylinder heads a new lease on life. Two valves, he added, were used in this country mainly on account of seat distortion accompanying the four-valve type. The two-valve type of heads give from 400 to 500 hr. of satisfactory service provided no lead is used, he specified.

A. G. Elliot, Rolls-Royce, Ltd., criticized the flexible seats on the basis of: (1) increased heat-absorption area in the combustion-chamber; (2) restriction of the valve diameter; (3) increased heat flow up the valve stem which would cause carbon formation on the valve stem and springs.

In his conclusion, Mr. Heron remarked that there was nothing to be gained by using flexible valve-seat inserts in cases where distortion did not occur. Furthermore, when using flexible valve seats it is necessary to obtain all the internal valve cooling possible, he cautioned.

Other discussers were: C. D. Waldron, National Advisory Committee for Aeronautics; Harold Caminez, and A. L. Beall, the co-author.

In introducing his paper on The Determination of Ratings for Transport Aircraft Engines, R. F. Gagg, Wright Aeronautical Corp., stated that the objective in choosing an engine rating is to establish the limiting values in the operating procedure which permit a maximum of utility in power output and economy of fuel consistent with requirements for safety and durability.

In his paper Mr. Gagg pointed out the importance of design calculations, of single-cylinder laboratory tests, and of dynamometer calibrations of the engine performance.

Furthermore, he stated, after the engine ratings are determined on the basis of stress values, it becomes necessary to recheck the fuel consumption and detonation performance of the engine with the fuel tentatively selected for use.

Among those who discussed Mr. Gagg's paper were: F. C. Mock, Bendix Products Corp., Harold Caminez, and Charles Froesch, Eastern Airlines, North American Aviation, Inc., who submitted a written discussion which was read by A. L. Beall.

The need for controlled oil circulation governed by the viscosity rather than by the oil temperature was pointed out by Weldon Worth, U.S. Army Air Corps, in his paper "Lubrication and Cooling Problems of Aircraft Engines." Control of the oil temperature by means of the oil flow was more satisfactory than by the use of shutters on the radiator, he reported.

Mr. Worth described the oil-dilution system used for facilitating the starting of cold engines and which is now undergoing tests by the Air Corps. In this system he explained how provision is made for thinning the lubricating oil by the addition of gasoline prior to stopping the engine.

Among those who discussed this paper were: W. H. Robotham, Rolls-Royce, Ltd., R. M. Hazen, Allison Engineering Co., S. D. Heron, R. F. Gagg, Kenneth Campbell, Wright Aeronautical Corp., L. P. Saunders, Harrison Radiator Corp., A. G. Elliot, and Arthur Nutt. In reply to their questions, Mr. Worth stated that the hazard created by gas in the crankcase was not serious, as the mixture normally found in the crankcase was over-rich for combustion. There apparently was no undue wear caused by lead in the oil or caused by using a small quantity of oil very severely for a short time rather than a large quantity less severely for a longer period, he added. In normal operation, he concluded, about 2 qt. of gasoline are used for oil dilution, and the progress in diluting the oil can be observed on the oil pressure gauge.

TWO AERODYNAMIC PROBLEMS DEBATED

Pointing out that the purpose of his paper was to show not what is known, but rather to emphasize that which is not known, a resume of the researches leading to the realization of the importance of the boundary-layer phenomena, especially the transition from laminar to turbulent flow, was presented by E. N. Jacobs, National Advisory Committee for Aeronautics, in the first paper at the Practical Aerodynamic Problems Session, Laminar and Turbulent Boundary Layers as Affecting Practical Aerodynamics. Supplementing his talk with slides and motion pictures of the boundary layer over airfoils and flat plates, he indicated the general nature of the phenomenon and emphasized the lack of knowledge concerning the transition from laminar to turbulent flow. Peter Altman, University of Detroit, presided.

Expressing some concern as to whether Mr. Jacobs was optimistic or pessimistic in regard to promise of future aerodynamic gains, Dr. Max M. Munk assured the session of his own optimism in this respect. He urged a continuation of this research as holding forth worthwhile promise. T. P. Wright, Curtiss-Wright Corp., presented some rough figures on the possible gains to be expected and expressed an optimistic outlook. C. H. Chatfield, United Aircraft Corp., asked about the importance of roughness over the aft portion of airfoil.

In reply, Mr. Jacobs reassured Dr. Munk of his optimism and pointed out the importance of reproducing flight conditions for the proper solution of the problem. This method necessitates equipment whereby full-scale Reynolds numbers and low turbulence can be obtained, he indicated. Mr. Altman raised the question of double-peak lift curves and the influence of the type of lift-curve peak in design.

H. D. Fowler, Glenn L. Martin Cp., discussed the merits of the flap bearing his name and urged its use as a solution of the difficulties in present-day design in the session's second paper: The Practical Application of Fowler Flaps. He urged also that it not be discarded because of mechanical difficulties and emphasized the need of allowing for the flap in the basic design rather than the arbitrary application of a flap to an already established design. He discussed at some length the merits of this particular flap in the performance of its several functions.

F. E. Weick, Engineering and Research Corp., opened the discussion by raising a question as to the exclusive merit of the particular flap under discussion, indicating he did agree that in many functions it was superior to other types of flaps. T. P. Wright, reading from written discussion, emphasized the author's warning that a design should not be discarded because of mechanical difficulties.

Document 4-20

Eastman N. Jacobs, Senior Aeronautical Engineer, "Investigation of low-drag airfoil sections having extensive laminar boundary layers," undated (but typed 27 June 1938), in RA file 290, LHA, Hampton, Va.

In this memorandum to the engineer-in-charge, Eastman Jacobs presented the "significant findings" resulting from the first round of airfoil tests in what the NACA had rather mischievously called its "icing tunnel." In short, Jacobs reported that his preliminary experiments "have more than justified our hopes for low-drag airfoils."

The test program that followed led to the design of what would come to be known as the NACA "laminar flow airfoils." There were, in fact, several different families of these airfoils developed in the next eight to ten years.

Given the number and variety of NACA airfoil families created by the end of World War II, it is not easy for anyone but the true airfoil specialist to keep them straight. To summarize, the NACA program began with the "M series" developed by Max Munk in the mid-1920s. Next came the four-digit series developed by Jacobs and his colleagues. Then, in the mid-1930s, the NACA designed a five-digit series, but continued to work on modifications leading to better airfoils in the four-digit series. One of the best five-digit airfoils was "N.A.C.A. 23012," the most famous member of the celebrated "230" family, first announced in 1935. By 1939, "230" wings were the most widely used wing sections in the world, primarily because of their superiority in lifting.

With the emergence of interest in laminar flow came several new airfoil families, designated Series 1, 2, 3, 4, 5, and 6; all of them appeared by the end of World War II. Series 1 represented "the first attempt to develop sections having desired types of pressure distributions" and were "the first family of NACA low-drag high-critical-speed wing sections" (Ira H. Abbott and Albert E. Von Doenhoff, *Theory of Wing Sections* [New York: McGraw Hill, 1949], p. 118). Series 1 airfoils were designated not by one digit, as one might think, but by a five-digit number with a dash between the second and third numbers as in "N.A.C.A. 16-212." (The first integer represented the series designation; and the second integer represented the distance in tenths of the chord from the leading edge to the position of minimum pressure for the symmetrical section at zero lift. The first integer following the dash indicated the amount of camber expressed in terms of the design lift coefficient in tenths; and the last two numbers together indicated the thickness in percent of the chord.)

It was a wing of the Series 4 family that North American Aviation, Inc., selected in 1940 for its high-performance fighter plane, the P-51 Mustang. The Series 5 forms, which had a blunter nose than any previous NACA airfoils, proved impracticable for wings. But the Series 6, with its yet more favorable distribution of pressure over the chord, soon became the standard low-drag wing. By the end of 1944, Series 6 wings (which were designated by a six-digit number but also with a statement showing the type of mean line used, as in "N.A.C.A. 65,3-218, a= 0.5) were in use not only on the last version of the Mustang (the P51H) but also on the Bell P-63 Kingcobra, Douglas A-26 Invader, and jet-propelled Lockheed P-80 Shooting Star and Bell P-59 Airacomet. In comparison with conventional wing sections, the Series 6 airfoils looked quite different in that their maximum thickness was much farther back from the leading edge. Late in the war, NACA Series 7 wing sections also came to life and were characterized by a greater extent of possible laminar flow on the lower than on the upper surface.

Document 4-20, Eastman N. Jacobs, Senior Aeronautical Engineer, "Investigation of low-drag airfoil sections having extensive laminar boundary layers"

Langley Field, Va.
Undated.

MEMORANDUM For Engineer-in-Charge.

Subject: Investigation of low-drag airfoil sections having extensive laminar boundary layers.

1. Preliminary experiments in the ice tunnel have more than justified our hopes for low-drag airfoils through design to produce extensive laminar layers. We can now conclude definitely that the most likely form of boundary-layer control to reduce drag is through the use of the flow conditions and pressures ordinarily attainable over the section through changes of the section shape to provide the desired control to maintain laminar flow.

2. The significant findings are:

a. That a low-turbulence tunnel is required for this advanced type of airfoil testing. This conclusion is justified by the fact that the variable-density tunnel tests failed to show an unusually low drag for the same airfoil that showed a startlingly low drag in the ice tunnel.

b. That low drags, under conditions approximating those of flight, are readily attainable. Wake measurements in the ice tunnel for the first trial airfoil indicate as compared with the N.A.C.A. 0012, measured in the same

tunnel in exactly the same way, a reduction in drag of something like 30 percent.

c. That boundary-layer measurements on the upper surface of the same airfoil indicate laminar flow at a position 75 percent of the chord behind the leading edge on the 5-foot airfoil at a speed of 147 miles per hour.

3. These results are of such marked significance that we must at once give careful consideration to the course of future work. We now have an airfoil that may be expected to give unprecedentedly { low drags when applied to light airplanes or gliders at one certain lift coefficient (C_L = 0.2 approximately). Our investigation must now proceed immediately to include obvious extensions and improvements. These extensions will include derivation of modified airfoils having:

Longer laminar layers.
More or less favorable pressure gradients.
More or less thickness.
Higher lift coefficients for minimum drag.

In addition means, including flaps and boundary-layer control by suction, should be investigated for improving the relatively low maximum lift coefficients of these airfoils and one or more of the best sections should be investigated to higher speeds and Reynolds numbers in the 8-foot high-speed tunnel and to still higher Reynolds numbers in the pressure tunnel when it is available.

4. Authority to proceed with this work (building the models and tests in the ice tunnel) is requested and a job order request is attached to cover calculations required immediately to develop the series of the 12 or 15 sections required.

Eastman N. Jacobs
Senior Aeronautical Engineer.

(Typed 6/27/38)

Document 4-21

Eastman N. Jacobs, Senior Aeronautical Engineer, to Chief of the Aerodynamics Division, "Patent on airfoil developments," 9 December 1938, in RA file 290, LHA, Hampton, Va.

In this rather surprising memorandum, Jacobs suggested that the NACA initiate a patent application for the low-drag airfoils. Unfortunately, no other documents have been found in the NACA records to illuminate what happened to the idea. One of the most surprising aspects of the idea is that Jacobs began his memo by saying that Dr. George Lewis, the NACA's director of research, suggested the idea for a patent application.

The NACA was normally not in the business of patenting its research results. However, George Lewis's thinking might have been different on this issue as it related to laminar-flow airfoils, or such a patent application would apparently never be made. Perhaps this was for national security reasons. No doubt it was due in part to the fact that NACA research was paid for by the American taxpayer and needed to be available as freely and widely as possible in order to advance the cause of American aeronautics.

The whole issue of patents for Federal employees is very problematic, from both the legal and historical perspectives. No NACA or NASA history has dealt with the matter explicitly, and records related to the NACA policy are particularly hard to find. Some light on the issues raised by Jacobs' memo might be shed by reference to other Federal agency policy on patents by employees. In a long and detailed footnote to his *Measures for Progress: A History of the National Bureau of Standards* (Washington: U.S. Department of Commerce, 1966), Rexmond C. Cochrane clarified the policy for the NBS: "Traditionally, the Government retained rights to the use of inventions of Federal employees but otherwise left title to them with their inventors."

But not all government agencies followed this policy—for example, the NBS. For 20 years under the direction of Dr. Samuel Stratton, head of the NBS, "it was understood that any innovations or invention of a Bureau staff member was to be patented in the name of the Government for the use of the public." In 1921/22 this was challenged by NBS researchers Percival D. Lowell and Francis W. Dunmore, who claimed that one of their inventions was only remotely related to the Army Air Corps project on which they were working, and that they were deserving of a patent application of their own. It took ten years for the US District Court (in Delaware) to hand down a judgment that went for Lowell and Dunmore against the government. The ruling was appealed and eventually the matter made it to the U.S. Supreme Court. In 1933, the Supreme Court ruled, with only one judge dissenting, that "in the absence of a specific contractual agreement, all commercial rights to patents belonged to the inventor, whether or not the work was performed on Government time" (Cochrane, *Measures for Progress*, p. 348n).

But this does not mean that, even after 1933, all Federal agencies abided by the ruling in favor of the private rights of their inventors. As Cochrane explained, the policy put into effect by Stratton at the NBS "continued in force until modified in 1940, when [NBS] patents were procured by the Justice Department and assigned to the Secretary of Commerce for licensing under terms he prescribed" (Cochrane, *Measures for Progress*, p. 349n). Ten years later, the Federal policy of permitting employees to retain title to their own inventions (the policy that the NBS, for one, had not been followed) came to an end. Executive Order 10096, issued by President Harry S. Truman on 23 January 1950, declared that "all rights to any invention developed by a Government employee in the course of his assigned work belonged to the Government." (Cochrane, appendix C, p. 547.) This was later amended by Executive Order 10930. In October 1988 Congress issued a rule (53 FR 39734) establishing a "Uniform Patent Policy for Domestic Rights in Inventions Made by Government Employees [Docket No. 80627-8127]. This rule transferred the provisions of Executive Order 10096 (as amended by Executive Order 10930) from the Commission of Patents and Trademarks to the Under Secretary for Economic Affairs in the Department of Commerce. This final rule also established 37 CFR Part 501, which set forth this delegation of authority to the Under Secretary. In addition, it authorized each Government agency on its own to determine "whether the results of research, development, or other activity within the agency constitute an invention with the purview of Executive Order 10096, as amended by Executive Order 10930, and to determine initially the rights therein" in accordance with the provisions of the appropriate sections of Federal law.

From this short review, it should be clear that there was no uniform patent policy across the Federal government in the late 1930s. The only way, then, to know what the NACA's own policy amounted to at the time of Jacobs' memo of 1938, or at any other time, is to examine NACA policy and patent history, specifically.

One might suggest from some of the circumstantial evidence that the NACA probably handled patent matters similarly to NBS. Besides serving as the bureau director through the 1920s and 1930s, Stratton was also a prominent, and original, member of the NACA. He served as secretary of the Main Committee from 1917 to 1923 and chaired its Executive Committee during that same time. He remained on the Committee until October 1931. Given his early influence on the NACA, one might think that NACA patent policy would have been similar to that which Stratton directed at the NBS. However, that conclusion must remain hypothetical until historical research confirms it.

Unfortunately, Jacobs' memo does not help to clarify the picture. It called for a patent application, but it did not directly address the issue of who was making the application. The clear inference is that it should be the NACA itself, not Jacobs and his associates, applying for the patent. But why the NACA should apply for a patent for the new laminar-flow airfoils when it had not applied for patents for any of the earlier airfoil families, or for any other research results up to that point, is unclear.

Document 4-21, Eastman N. Jacobs, Senior Aeronautical Engineer, to Chief of the Aerodynamics Division, "Patent on airfoil developments," 9 December 1938.

Langley Field, Va.,
December 9, 1938.

MEMORANDUM For Chief Aerodynamics Division.

Subject: Patent on airfoil development.

1. As suggested by Dr. Lewis, it seems desirable to initiate a patent application covering our recent airfoil design advances. Suggest something as follows:

2. Previously, nearly all possible airfoil shapes have been tried. Various advantages have been claimed for various shapes, but the developments have in general led to airfoil section shapes of the so-called "streamline" form, that is, shapes having well faired contours, and <u>fine tail forms.</u> Such forms have been generally considered to represent the ultimate in low-drag wing-section shapes. Various forms of boundary-layer control have also been proposed for these "streamline" forms with the object of reducing the drag. We, however, know of no previous attempt to secure boundary-layer control through an intelligent development of new forms, not necessarily of the "streamline" type but intended primarily to control the boundary layer with the primary object of obtaining unusually low drag. By providing shapes to produce falling pressures downstream along the surface, the boundary layer is effectively controlled in such a way as to delay the transition. The invention consists of wing-section forms shaped primarily to control the boundary layer along a major part of the surface in such a way as to yield particularly desirable aerodynamic results.

3. Figure 1 represents the pressure distribution on a typical "streamline" form or nonlifting airfoil section. The minimum pressure occurs at A. From this point aft a pressure recovery begins, which might continue to 3 under favorable conditions without a breaking down of the associated boundary layer along the airfoil surface from the low-drag laminar form the higher-drag turbulent form, although the rising pressure tends to promote such a flow breakdown. At the point B, however, which represents the laminar-separation point, the flow <u>must</u> shortly thereafter either break down or lead to even more unfavorable separation effects. In any event, in the practical case an unnecessarily large portion of the surface is exposed to the drag-producing scouring effect of the turbulent boundary layer.

4. In figure 2 the form is altered in order to control the boundary layer. An altered distribution of thickness and relatively fine leading edge may be chosen to give a pressure distribution of the type shown having a gradual falling pressure over

the major part of the surface to the point A. In the practical case the transition to the turbulent flow again occurs between A and some point near B but only a relatively small proportion of the surface near the trailing edge is exposed to the scouring action of the turbulent flow.

5. In figure 3 the new form is further changed by curving the mean line in such a way that the airfoil may develop lift. A mean-line curve is chosen so that the lift is distributed in a way that does not affect the desirable character of the pressure distribution on either surface.

6. In figure 4 is indicated how the new airfoil form may be extended to provide a larger wing area or to permit better flow conditions at the trailing edge. A good compromise form, arrived at through tests, is shown in figure 5.

7. At large Reynolds numbers (large wings and high speeds) the boundary-layer control exerted by the falling pressures may become insufficient to delay the transition to the point A. This difficulty is overcome by removing a part of the boundary layer through slots in the surface or through a porous material forming all or part of the wing surface, and into the hollow wing interior where it is removed and discharged by means of a blower or other suitable device.

8. I claim:

(a) Wing-section shapes differing from the usual streamline forms which are altered from the conventional form with the object of controlling the boundary layer along a major part of surfaces in such a way as to yield particularly desirable aerodynamic results.

(b) Wing-section shapes designed to avoid rising pressures in the downstream direction over an extensive part of the airfoil surface with the object of reducing the drag.

(c) Wing-section shapes having the minimum pressure on both surfaces well aft.

(d) Wing section shapes having the laminar separation point on both surfaces well aft.

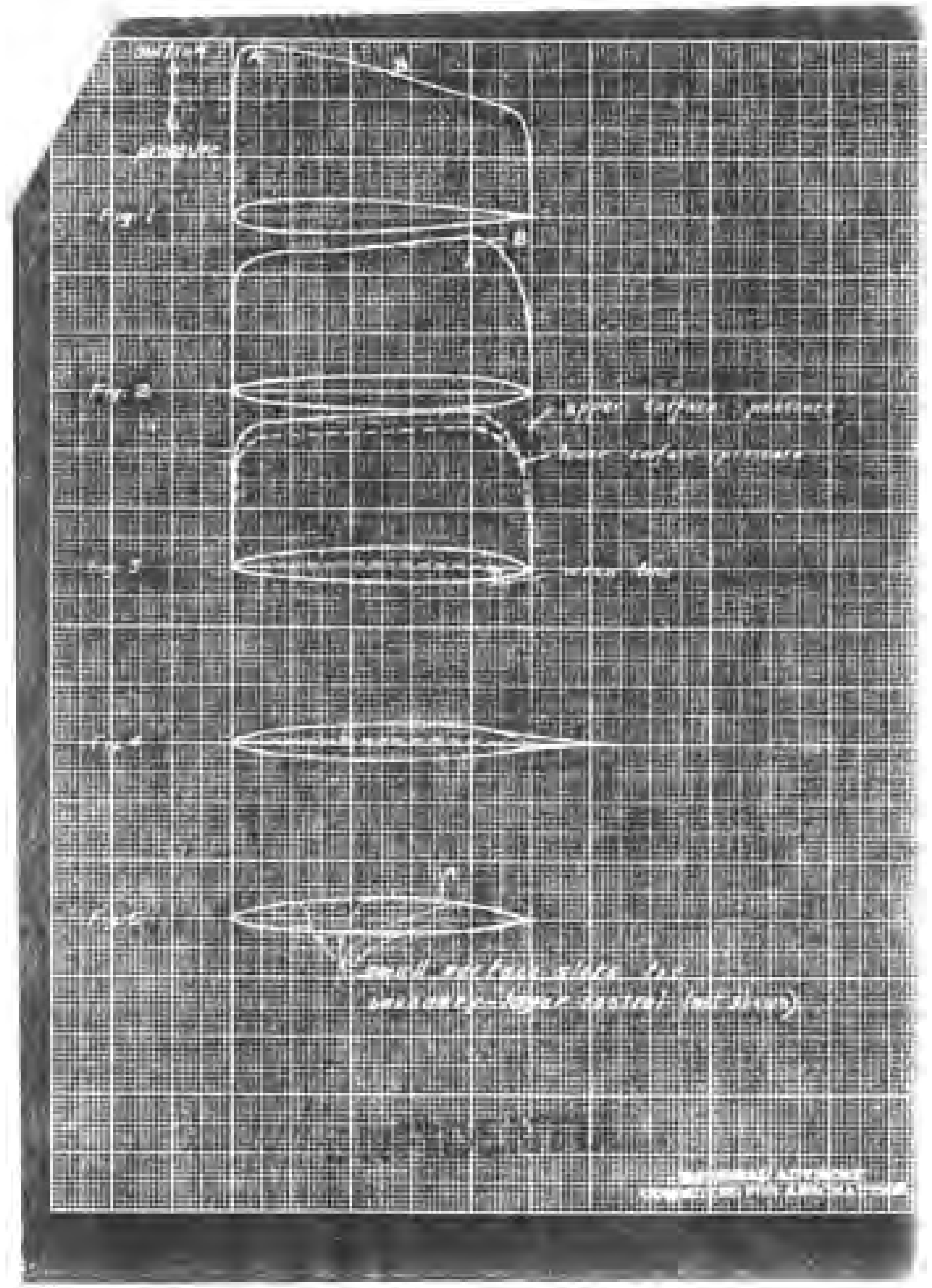
(e) The above-mentioned shapes further altered to permit carrying lift without a sacrifice of other desirable characteristics.

(f) The above-mentioned shapes further altered to give reflexed contours behind the minimum pressure point.

(g) The above-mentioned shapes further altered or supplemented by the addition of the usual forms of boundary-layer control.

(h) The above-mentioned shapes combined with boundary-layer removal through a porous material forming all or part of the wing surface.

Eastman N. Jacobs,
Senior Aeronautical Engineer.



Document 4-22

Newton H. Anderson, *Aircraft Layout and Detail Design* (New York and London: McGraw-Hill, 1941), pp. 83-89.

Newton H. Anderson was a Douglas Aircraft Company engineer who served as program director of the education department of the Institute of Aeronautical Sciences. Chapter 3 of his 1941 textbook was dedicated to "Airfoils," and nowhere in the engineering literature can one find a more instructive testimony to the value of NACA research in general and its systematic airfoil program in particular. Section 3.1 of his text supplies a good indicator of how influential the NACA airfoil work was to American industry. But it is Sections 3.5 and 3.6 that are especially remarkable, in that the whole method of airfoil design prepared by Anderson was based on NACA research.

Section 3.8 is based on a popular article, "From the Wind Tunnels of Langley," which appeared in the March 1941 issue of *Fortune* magazine. It provided an excellent and easily understood summary of the NACA's crucial role in airfoil development up to the start of World War II. Readers will want to look in particular for the paragraph that begins, "The N.A.C.A. has developed a secret airfoil," which could do no more than hint at the confidential laminar-flow development given how little public information has been released about it.

Document 4-22, Newton H. Anderson, **Aircraft Layout and Detail Design***, 1941.*

AIRCRAFT LAYOUT AND DETAIL DESIGN
By:
NEWTON H. ANDERSON, B.S.

3.8 The N.A.C.A. It has been shown in this chapter what an important part the National Advisory Committee for Aeronautics has played in the development of airfoils. However, the work of the N.A.C.A. is not limited to airfoils, but covers practically all branches of the aeronautical sciences. Whether the layout man realizes it or not, practically all of his design has been affected in some manner by the findings of this committee.

It was in 1915 that Congress established the N.A.C.A. with an appropriation of $5000 a year to "supervise and direct the scientific study of the problems of flight." As a measure of its growth and of the importance of its work, it should be noted that the appropriations for 1941 exceed $11,000,000.

The President appoints the committee of fifteen to serve without pay. Six are specially qualified civilians, two each from the Army, the Navy, and the Civil Aeronautics Administration, and one each from the Weather Bureau, the Smithsonian Institution, and the National Bureau of Standards. There are four major technical committees: (1) Aerodynamics, (2) Power Plants, (3) Aircraft Materials, (4) Aircraft Structures, whose titles define the scope of their work. The actual work is done by a staff of nearly a thousand employees.

The original laboratories are at Langley Field, Va., where practically all the research has been carried on in the past. However, a new engine research laboratory is being constructed at Cleveland, Ohio; at Sunnyvale, Calif., a new aerodynamic laboratory, the Ames Aeronautical laboratory, is being built at the old Navy dirigible base.

Fortune Magazine in its article on the N.A.C.A. stated that a perfect definition of the aircraft designer's goal is "the reduction of drag." This statement is no exaggeration for the aircraft designer must strive for better performance and more speed, and there are many things he may do to help attain that goal.

Since the reduction of drag is so important, the various types of drag and their meaning should be discussed. "Drag" is the term applied to those forces which resist the forward movement, or the lifting capacity, of an airplane. Probably everyone has tried holding his arm out of the window of a moving automobile and has experienced that invisible force of the air trying to push the arm back. As an airplane flies, the air is resisting its forward movement, juts as the air resisted the forward movement of the autoist's arm. The unfortunate thing about drag is that it increases as the square of the speed. An airplane flying at 200 m.p.h. will have four times as much drag as at 100 m.p.h. At 300 m.p.h. it will have nine times the drag of 100 m.p.h.

Some drag can be reduced, some cannot. Induced drag is the inevitable price paid for lift and cannot be reduced except very slightly. It is extremely difficult to define "induced drag" and to show clearly why it cannot appreciably be reduced. A simple analogy of an object moving through water may be drawn: the water is parted by the moving object and flows together in its wake, which sets up eddies. Energy, which can never be recovered, was imparted to the water to set it in motion. The airplane as it passes through the air moves this air; energy was expended to set it in motion. The imparting of this motion to the air manifests itself in the form of lost energy which is known as induced drag.

Parasite drag included the various kinds of drag that can be reduced. "Profile drag," one form of parasite drag, is a term applied to a wing to describe the effect of turbulence in the thin layer of air close to its surface and in its wake. Another form of parasite drag is interference drag which is due to eddies set up by the proximity of two structural members. Skin friction, another type of parasite drag, results when particles of air are forced along the exterior surface of the wing. When any liquid flows through a tube or pipe, the friction between the liquid and the walls of the tube resists the flow of the liquid. Since air is a liquid, there is a similar action between the air and the skin of the airplane.

The N.A.C.A. has led the world in the attack on parasite drag. Some of the more important contributions may be listed as: airfoils, engine cowling, location of

nacelles, location of the wing in relation to the fuselage, and a general cleanup of struts, landing gear, etc.

Until 1924, the Clark Y was considered a very good airfoil, but in that year the N.A.C.A. brought forth their "twenty-three-oh-twelve" (23012) which proved so superior to previous airfoils that approximately three-fourths of the world's airplanes today are using versions of this scientifically famous airfoil. Among other things, it is distinguished for its high ratio of lift to drag. This ratio (usually expressed as L/D or in conversation as "L over D") is similar to an efficiency factor; the higher the ratio, the greater the efficiency. In the 23012 airfoil, L/D goes up to 24, which is considered very good. This airfoil has an unfortunate tendency to stall suddenly, that is, it suddenly loses its lifting power. However, ways have been discovered to alleviate this tendency to stall, which will be discussed later.

Until about 1931, air-cooled engines had no cowling; the radial cylinders were fully exposed to the air stream. The N.A.C.A. developed a cowling that has been universally adopted and it is known as the N.A.C.A. cowling. It added approximately 20 m.p.h. to the first plane built with it, Frank Hawks's Lockheed. Although the engine is apparently closed in by the cowling, it directs the air stream so that cooling is more effective with the cowling than when the cylinders were fully exposed.

An exhaustive series of tests were performed in order to determine the most efficient location of the engine with respect to the wings for multi-engined airplanes. As a result of these tests started in 1929, the location of the engine nacelles in the leading edge of the wing is now standard, as in the Douglas transports. It has also been determined that a pusher propeller is more efficient than a tractor because it does not disturb the air flow over the wing. However, the pusher propeller has not received very wide use because of practical difficulties such as structural support, and equipment already in the wing as tanks, guns, landing gear, etc.

In the N.A.C.A.'s studies on the location of the wing with respect to the fuselage, it has been found that the mid-wing offers a minimum of interference drag, the high wing next, and the low wing a maximum. All three positions are used in today's airplanes; each position having certain advantages and other disadvantages. Although the mid-wing is most efficient from an aerodynamic standpoint, the spars passing through the fuselage may very effectively block any freedom of movement of crew or passengers in the fuselage itself. The high wing affords splendid vision for pilots and passengers; yet the problem of retracting the landing gear may become extremely complicated because of the large struts necessary. The low wing, although least desirable from an aerodynamics and visibility standpoint, has definite structural advantages. The spars through the fuselage are usually below the cabin floor level, and the shorter struts for the landing gear enable the wheel and mechanism to be neatly retracted into the wing. The logical answer then is the large fillets between the wing and fuselage which are so familiar on low-wing monoplanes today.

One has only to compare the latest designs with airplanes of a dozen years ago to appreciate the N.A.C.A.'s general cleanup of struts, wires, landing gear, landing lights, etc. The net result is that a present-day four-engined transport has but 40 percent of the drag of a single-engined monoplane of a dozen years ago.

There are but two ways to reduce parasite drag: smooth out the surfaces and change the contour. It is interesting to note that the N.A.C.A. found that a transport at 225 m.p.h. with lap joints and 3/32 in.-diameter brazier-head rivets required 182 hp. to pull them through the air. When flush joints with 1/16 in.-diameter brazier-head rivets were substituted, only 82 hp. was required. Even a coat of spray paint added 91 hp. more than the polished metal surface. Every layout man has had experience with flush joints and known the problems that arise at times to maintain a perfectly smooth exterior surface.

The designer can do little toward changing the contour, but the N.A.C.A. has done much, as will be shown. One common affliction of existing airfoils is turbulence in the boundary layer. This boundary layer is the thin sheet of air in contact with the surface and may vary in thickness from a few thousandths of an inch to 1½ in.

The air starts in at the leading edge with a smooth sliding flow called "laminar flow," and at the transition point, usually close to the leading edge, it breaks into turbulence. Everyone is familiar with the behavior of water flowing in a brook as it hits a projecting rock. The water flows around the rock and breaks into a series of eddies and becomes turbulent. Air behaves in the same way, although it is difficult to see and must be studied in smoke tunnels. This turbulence imposes profile drag which was mentioned earlier in this article.

The N.A.C.A. has developed a secret airfoil, commonly known as the "laminar wing," in which the transition point is almost at the trailing edge. Very little can be told about this wing except that its leading edge is rather thin and that the maximum camber (thickest portion) is father aft than usual. A glove-like structure having this new airfoil was built on a wing of a Douglas B-18, and the N.A.C.A. was able to check its flying characteristics. The one main objection to the laminar flow wing is that the surface must be as smooth as an automobile fender. A piece of scotch tape on the leading edge will make it break into turbulence, which explains the reason for such care being given to problems of flush joints on laminar flow wings. Laminar flow airfoils are being used in the propellers on many of today's aircraft, increasing the propeller's efficiency.

When parasite drag is fully under control, the only limitations on aircraft design will be those placed by nature: the height of the atmosphere (approximately 50 miles) and the speed of sound. At the speed of sound (approximately 1100 ft. per second or 750 m.p.h.), there occurs a peculiar form of drag known as "compressibility burble" which imposes a prohibitive drag, as far as efficient aircraft design is concerned. If it were not for compressibility burble, the range of gun-fired projectiles would be greatly increased; in this case, by increasing the powder charge, enough additional energy can be imparted to the projectile to overcome this drag. Obviously, such methods are impossible with aircraft, so that, unless some new means of propulsion is devised or unless means of controlling compressibility burble is discovered, the speed of an airplane will be limited by the speed of sound.

The N.A.C.A. has done much work on lift. The present-day flaps for landing which are standard on all airplanes result from N.A.C.A. tests and research. When the flaps are lowered at relatively slow speeds, they increase both the lift and drag, which not only slows the speed of the airplane, but also enables the airplane to remain aloft at a lower rate of speed. At times, in order to provide more flap area, the flaps are extended to the wing tips. This presents a problem of where to place the ailerons. One solution is to mount them on top of the wing on short vertical masts, in which case the aileron is known as a "spoiler." Other work of the N.A.C.A. relates to stall—that peculiar characteristic of a wing where, at certain attitudes of flight, the lift suddenly drops. This stalling characteristic of the N.A.C.A. 23012 and related airfoils was mentioned previously in this article. To alleviate this tendency to stall suddenly, the N.A.C.A. recommends giving the wing tips "wash out" which is no more than twisting the wing so that the incidence at the tip is less than that at the root. This explains why in the original design of a wing, the incidence so often decreases toward the tip. (See Fig. 3:3 where the incidence changed from 5 deg. at the root to 3 deg. at the tip.)

Although the model to be tested in a wind tunnel is usually mounted in the air stream on delicate measuring devices, the N.A.C.A. may use their free flight tunnel in which an exact model correctly balanced to agree with the actual airplane is actually flown. A tiny electric motor usually drives the propeller while the operator, by means of fine trailing wires, may operate the various control surfaces. Another operator controls the speed of the air stream so that the model will not smash itself against the walls of the tunnel.

The free spin tunnel may be used if the spinning characteristics are being investigated. Here the model, controls set for a spin, is tossed into a vertical tunnel having an uprushing blast of air. Then the operator moves the controls by means of the fine trailing wires and the recovery is studied. Before the N.A.C.A.'s spin tunnel, it was necessary for a pilot to take the airplane aloft, throw it in a spin and then hope for the best. If it did not come out of the spin, it was necessary for the manufacturer to build another airplane, making whatever changes were deemed advisable, and try it again. Now it is possible to make these changes in the model, thus saving much time and expense. The N.A.C.A. has found that the design of the tail is nearly everything in spin recovery. The vertical stabilizer and rudder should be large, with the horizontal stabilizer and elevator mounted rather high so as not to blanket the vertical surfaces while the plane is spinning.

Everyone who has ridden in an airplane is familiar with bumps" which are usually caused by uprising drafts of air. If the N.A.C.A. is investigating the behavior of an airplane in these vertical drafts, they use their gust tunnel. Here a model is catapulted into uprising currents of air, and its behavior is studied by means of cameras, etc. They have developed what is known as "V-G recorders," measuring instruments that record the severity of the bumps. They are carried on many planes in flight to measure actual flight conditions; very small ones are also carried by the models in the gust tunnel. There are many other tunnels and laboratories used by the N.A.C.A. in their research; however, it is impossible to discuss them all in this text. From the foregoing, the student can gain some idea of the magnitude and the complexity of the work. Much investigation has been done on materials, and many of them have been improved as a result of N.A.C.A. research and tests.

One of every service model of an Army or Navy airplane automatically goes to Langley Field for test, and invariably leaves 20 to 60 m.p.h. faster. The Bell Airacobra gained approximately 60 miles by changing air scoops, supercharger location, wheel wells, etc. When the manufacturers submit designs of a new model to the N.A.C.A., an opportunity is offered to eliminate some problems before they arise. The new Vought Navy fighter had the air ducts for the oil cooler changed, and the list could go on indefinitely.

Document 4-23(a-d)

(a) Eastman N. Jacobs to Engineer-In-Charge, "Conversation with Dr. Lewis regarding application of laminar-flow airfoils," 3 February 1939, RA file 290, LHA, Hampton, Va.

(b) H.J.E. Reid, Engineer-in-Charge, LMAL, to NACA, "Aerodynamically smooth finishes for airplanes—information for Vultee Aircraft, Inc.," 28 November 1940, in RA file 290.

(c) G.W. Lewis, Director of Aeronautical Research, to the Chairman of the NACA (Dr. Joseph Ames), "Investigation of laminar-flow low-drag wings," 27 November 1939, RA file 290.

(d) G.W. Lewis, Director of Aeronautical Research, to Langley Memorial Aeronautical Laboratory, "Investigation in flight of laminar-flow low-drag wings," 31 January 1940, RA file 290.

This quartet of documents involves NACA plans for flight-tests of laminar flow-wings in 1939 and 1940 and concern for the smoothness of wing finishes.

The first document concerns tests with a Douglas B-18 airplane, which would eventually be conducted at Langley in the spring of 1941. Langley installed an experimental low-drag test panel on the wing of the bomber and fitted the panel with suction slots and pressure tubes for a free-flight investigation of the transition from laminar to turbulent flow in the boundary layer. The pressure of each tube was measured by liquid manometers installed in the fuselage. Most significantly, an extraordinary amount of care had to be given to the finish of the laminar-flow test panel in order to make its surface as smooth and fair as possible. No less than 48 coats of paint and lacquer were applied to the laminar-flow test panel, and rubbed down with weather-dry paper after the twelfth and twentieth coats. (Normally, an airplane wing had only two coats of paint.) In addition, a proxlyn-glazing putty was also used to fill in surface depressions. Obviously, actual wings on operational aircraft were never going to be as smooth as the laminar-flow test panel, a fact that eventually compromised the aerodynamic performance of the NACA low-drag airfoils to a significant degree.

The second document in the string provides the NACA's response to a request from Vultee Aircraft, Inc., to know what finishes had been found to be the smoothest for wings.

The other two documents show that the NACA was interested in designing a small, laminar-flow "research airplane." If this had been done, it would have represented the first specially-built NACA research airplane in the organization's history, predating its involvement in the XS-1 transonic research airplane program by some five years.

The final document in the string reveals that the Committee on Aircraft Structures (chaired by Dr. Lyman J. Briggs of the National Bureau of Standards) approved of the idea on November 1939. The laminar-flow research airplane was never built, though scale-models of the concept were conducted in wind tunnels into early 1941. The airplane was a high-wing, pusher monoplane with exceptionally small tail surfaces. Pusher propellers were used to eliminate the undesirable effects of the slipstream on the flow over the wing. The tail surfaces were designed to give low static stability on the premise that a smoother riding airplane could be achieved inasmuch as gusts would produce straight sideways or vertical displacements rather than yawing or pitching moments.

Early in 1941, the NACA decided to push the development of its laminar-flow airplane as a large long-range bomber; however, it soon abandoned the project when the army became interested in the low-drag airfoil and it became evident that the P-51 would be flying long before the laminar-flow airplane could be put into the air.

Document 4-23(a), Eastman N. Jacobs to Engineer-In-Charge, "Conversation with Dr. Lewis regarding application of laminar-flow airfoils," February 1939.

Langley Field, Va.
February 3, 1939.

MEMORANDUM For Engineer-in-Charge.

Subject: Conversation with Dr. Lewis regarding application of laminar-flow airfoils.

1. In a conference January 30, 1939, attended by Dr. Lewis, Messrs. Reid, Miller, and Jacobs, the subject of our laminar flow investigations was discussed. First the fundamental work on transition was discussed and then further consideration was given to applications in flight of the new airfoils. It was first agreed that further fundamental flight investigations is essential to determine beyond question the limiting extent of the laminar boundary layer.

2. The application of the new airfoils to military airplanes was then considered. In reply to Dr. Lewis' questions concerning my recent memorandum requesting the loan of a B-18 from the Army, I indicated that the suggested procedure does not differ essentially from the plan he had suggested in an earlier conference when it was agreed that we should aim at the eventual application of the low-drag airfoil with boundary layer control to a P-39 airplane specially modified for the purpose. I pointed out that the suggested investigation with a glove on the B-18 as well as the high-speed-tunnel tests of the N.A.C.A. 472-212 will supply design data desired for the application to the P-39. He thought, however, and I agree also, that the 8 or 9 month period estimated for the B-18 tests indicated an excessive delay in the P-39 project. He was also reluctant to ask for the B-18 for such a long period. It was finally agreed, therefore, that the B-18 tests should be planned so that they can be completed much more quickly.

3. It is therefore recommended that design work on the B-18 be started immediately, and whole project expedited as much as possible.

Eastman N. Jacobs,
Senior Aeronautical Engineer.

Document 4-23(b), H.J.E. Reid, Engineer-in-Charge, LMAL, to NACA, "Aerodynamically smooth finishes for airplanes—information for Vultee Aircraft, Inc.," November 1940.

Langley Field, Va.
November 28, 1940.

From LMAL
To NACA

Subject: Aerodynamically smooth finishes for airplanes-in-formation for Vultee Aircraft, Inc.

Reference: NACA Let. Nov. 14, 1940, MMM AMJ ldl, enc.

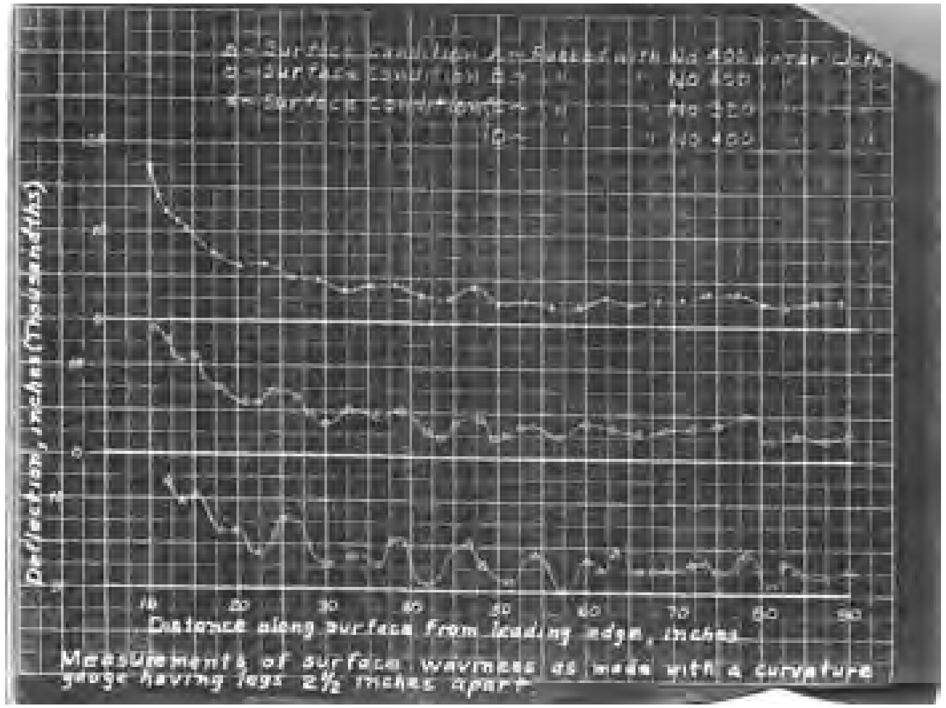
1. The Vultee Aircraft Company's letter dated November 7, 1940, which was forwarded by your office to the Laboratory and in which information is requested regarding finishes for airplanes both from the standpoint of obtaining smoothness and also means of determining the degree of smoothness obtained, has been brought to the attention of Messrs. E. N. Jacobs, Ernest Johnson, and members of the flight section.

2. Based on his experience with finishing models for laminar-flow studies, Mr. Jacobs refers to pages 8 and 9 of his Advance Confidential Report entitled "Preliminary Report on Laminar-Flow Airfoils and Methods Adopted for Airfoil and Boundary-Layer Investigations." Commenting further, Mr. Jacobs states that

> The work we have done since that time indicates that somewhat greater local roughness may be acceptable as aerodynamically smooth under some conditions. Our usual requirement, that no surface imperfection that can be felt should be accepted as aerodynamically smooth, thus seems, at least in some instances, to be somewhat too severe. On the other hand, bumps or depressions producing unfairness of a relatively long wave length appear to produce small adverse effects on transition, even though they are very difficult to detect without the use of a curvature gauge. We think at present that this type of surface defect or unfairness should in general be held sufficiently small so that it will produce no noticeable effects on the pressure distribution on the wing surface.

It is admitted that these requirements are rather indefinite, but there can be no assurance that very definite requirements may ever be reached, except in relation to specific situations. Although we have started a general investigation of these requirements of aerodynamic smoothness, it is considered better not to wait for any general results but to consult us about specific cases.

3. For the information of your office, it might be said that Mr. Jacobs makes the suggestion that since in two instances we have offered to investigate in the low-turbulence tunnel models to be supplied by manufacturers, and, further, since due to congestion in the Laboratory shops occasioned by the current which has handicapped somewhat our supply of models for this tunnel, pressure of work, if in agreement with the policy of your office, it might be deemed desirable to request them to supply a built-up test specimen for testing in this tunnel. It is believed that such a procedure would yield results which will mutually benefit the Laboratory as well as the manufacturer. If such a procedure is followed, a small portion of an actual wing or a built-up test specimen, having a spanwise length of 35 ¾ inches and any chord less than 90 inches, could be conveniently tested.



4. For the information of the Vultee company, the procedure followed in preparing for testing an experimental laminar-flow wing panel for flight tests on a B-18 airplane is given below by Mr. John A. Zalovcik, who is one of the engineers connected with this project. It will be noted in these comments that 48 coats of paint were applied to the wing surface, and it should be explained that at least 10 of these were necessary as a base for the wooden model used in order to waterproof it prior to the subsequent finishing process requiring the procedure of rubbing down with water cloth, and also that several coats were applied simultaneously during the various paint applications. It should suffice to say that with the condition represented by surface condition C and D, shown on the accompanying figure, good results

from the standpoint of drag will be obtained. The procedure mentioned above was as follows:

> The laminar-flow test panel mounted on the B-18 airplane was alternately sprayed with paint and sanded down with various grades of water cloth. The surfaces were first given about 12 coats of grey paint and then sanded with blocks using No. 280 water cloth. The panel was given 8 more coats of grey paint and sanded again. The surfaces were then given 14 coats of white lacquer (with white pigment) and sanded first with No. 320 water cloth and finally with No. 400. An index of surface waviness of the panel up to this point was obtained by making surface measurements with a curvature gage, having legs 2 ½ inches apart. The results of these measurements along the center line of the panel are given in the accompanying figure and are indicated as surface condition A. Amplitudes of the deflections of the curvature gage of about 0.005 inch magnitude were found over a number of sections of the panel surface. To improve this condition, the high places were rubbed down and the low places were filled in with grey paint, and then the entire surface was given 14 coats of grey and rubbed down with No. 320 water cloth. In this latter case the sanding was done with a bow 30 inches long with a strip of aluminum 6 inches wide and 1 1/16 inch thick stretched across ends and to which water cloth was cemented. The aluminum strip was weighted down with shot bags to give necessary pressure. Measurements were again made with the curvature gage and waves of 0.002 inch amplitude were found. (See surface condition B in the figure.) Sanding with the bow was continued until the condition C was obtained. The final surface condition was obtained by adding 8 coats of white lacquer and sanding with No. 400 water cloth. It will be noted that the final coating did not alter the surface waviness but only affected the texture. It may be added that the change in surface condition from that represented in the figure as condition A to that of condition D resulted in extending the run of the laminar-boundary layer about 10 percent of the chord.

5. It may be stated that the paint and lacquer described in the foregoing procedure is what is known as primer surfacer and any good grade of lacquer. In addition to these two finishers, a proxlyn-glazing putty is also used to fill in relatively large depressions in the surface during the process of finishing. It may be stated that the Laboratory has obtained the best results from these paints when thinners used with them are made by the same manufacturer. The putty has been obtained from the Acme White Lead Company, and the paint and lacquer from any of several companies, including Sherwin-Williams, Pittsburgh Plate Glass, and Egyptian Lacquer Company. The water cloth mentioned is commonly known as weather-dry paper.

H. J. E. Reid,
Engineer-in-Charge.

Document 4-23(c), G.W. Lewis, Director of Aeronautical Research, to the Chairman of the NACA (Dr. Joseph Ames), "Investigation of laminar-flow low-drag wings," November 1939.

November 27, 1939.

MEMORANDUM for the Chairman.

Subject: Investigation of laminar-flow low-drag wings.

1. During the past year the Committee has had under investigation in the two-dimensional low-turbulence wind tunnel certain laminar-flow airfoils. This investigation has been conducted under research authorization No. 290, "Investigation of Effect of Thickness and Mean Camber Line Shape on Airfoil Characteristics."

2. The investigation has proved successful. Certain wing forms have been developed having a profile drag of one-third that of the best wings now in use, but at relatively low Reynolds number. Since June, 1939, the investigation has been extended to forms having low drag at higher Reynolds number. Through the cooperation of the Army Air Corps a portion of a wing of the new design is being investigated on a Boeing B-18 bomber.

3. The project has reached a stage when it is necessary to make rather extensive flight tests with certain of the laminar-flow wings. The construction of a wing for laminar-flow presents certain structural problems, since it is necessary that there be no deformation of the wing under load and that the surface remain free of roughness and also free from wrinkles and other deformation.

4. The subject was discussed at the last meeting of the Committee on Aircraft Structures held on November 8. The matter was thoroughly considered and received the approval of that committee.

5.It is therefore recommended that the Committee proceed with the flight tests and that for this purpose a small airplane of approximately 2300 pounds be constructed with a wing incorporating the low-drag laminar-flow design. This airplane would be considered as research equipment for the investigation of laminar flow and not as a particular airplane development of the Committee.

G. W. Lewis,
Director of Aeronautical Research

Document 4-23(d), G.W. Lewis, Director of Aeronautical Research, to Langley Memorial Aeronautical Laboratory, "Investigation in flight of laminar-flow low-drag wings," January 1940.

Washington, D. C.
January 31, 1940.

From NACA
To LMAL

Subject: Investigation in flight of laminar-flow low-drag wings.

Reference: LMAL letter October 30, 1939, WHH. MHY. EWM.

1. At the meeting of the Committee on Aircraft Structures, held on November 8, 1939, there was discussion of the proposal that the Committee's laboratory construct a small airplane of approximately 2300 pounds, with a wing incorporating the low-drag laminar-flow airfoil, this airplane to be considered as research equipment for the investigation and not as a particular airplane development of the Committee. The discussion of this subject in the meeting of the Structures Committee occurred following the discussion of the proposal of the University of Maryland for an investigation of the strength of high-speed wing structures.

2. At the meeting of the Structures Committee the following resolution was adopted:

> "RESOLVED, That the Committee on Aircraft Structures recommends to the Executive Committee that approval be given to the Langley Memorial Aeronautical Laboratory to design and construct, or to have constructed, an experimental airplane incorporating laminar-type airfoil wing or wings to have places for two to four people and to fly at approximately 200 miles per hour with a useful flight range."

3. I have taken up with the Chairman of the Committee, Dr. Bush, the desirability of expediting this project, and the project has received his approval.

4. A new research authorization will be presented to the Executive Committee to cover the investigation in flight of a laminar-flow low-drag airfoil. The number 720 is tentatively assigned to this research authorization.

5. A separate letter will be written to the laboratory regarding the proposed research authorization to which the number 720 was previously assigned.

G. W. Lewis,
Director of Aeronautical Research

Document 4-24(a-e)

(a) Robert J. Woods, Chief Design Engineer, Bell Aircraft Corp., 2050 Elmwood Avenue, Buffalo NY, to NACA, "Attn: Dr. George W. Lewis," 25 March 1940, RA file 290, LHA, Hampton, Va.

(b) G.W. Lewis, Director of Aeronautical Research to Langley Memorial Aeronautical Laboratory, "Request for information on new airfoil sections—Bell Aircraft Corporation," 26 March 1940, RA file 290.

(c) H.J.E. Reid, Engineer-in-Charge, to NACA, "Request for information on new airfoil sections—Bell Aircraft Corporation," 27 March 1940, RA file 290.

(d) G.W. Lewis, Director of Aeronautical Research, to Robert J. Woods, Chief Design Engineer, Bell Aircraft Corporation, 29 March 1940, RA file 290.

(e) Eastman N. Jacobs to Engineer-in-Charge, "Visit of Mr. Robert J. Woods of Bell Aircraft to LMAL, February 5, 1941," CONFIDENTIAL, in RA file 290.

It did not take long for American industry to seek help from the NACA on the application of low-drag airfoils to the design of new aircraft. This string of five documents exemplifies how such an interaction in one case began. Robert J. Woods, Bell Aircraft's chief designer (and former NACA Langley researcher, 1928-29), contacted the NACA by letter on 25 March 1940, stating that "we have heard that your laboratory are [sic] conducting tests on laminar flow airfoils." Woods wanted up-to-date information that might help his company design the wing for its new airplane, the P-39 Airacobra, and he wanted the help as soon as possible.

From the back-and-forth within the NACA and from the response Woods received four days later from George Lewis, director of research for the NACA, it is clear that the NACA planned to proceed with caution in releasing data about the new airfoils. Lewis hoped that he could give Woods what he wanted in about a month.

The most interesting comment in the last document in this section is perhaps Eastman Jacobs's comment about the effect of dusty wings on the aerodynamic efficiency of the laminar-flow airfoils. (In actual performance during the war and afterwards, many aeronautical engineers in the U.S. would express disappointment in the NACA's low-drag airfoils because operational aircraft failed to achieve the very low drags measured in the wind tunnel because the surfaces of their wings could not be kept clean and smooth.) In this memo Jacobs noted that dusty wings "revert to low drag" as an airplane reaches high speed, "thus blowing the dust off the wing." To some extent, this proved to be the case, but the overall maintenance problems involving operational wings that had to be kept extremely smooth and fair meant that the problem would not be mitigated as much as Jacobs thought.

The identity of the "Colonel Green" mentioned in document 24-e should also be made clear. Carl Greene served in the late 1930s for the U.S. Army as chief of the engineering division of the Air Service Technical Command. In March 1939 he moved from Wright Field to Langley. His new job was to provide more regular liaison between the applied research and development activities of the Air Corps and the more basic research of the NACA. Besides funneling information to appropriate Air Corps offices, the occupants of "Greene House" across from the LMAL administration building enabled the army to keep up better with the detailed requirements of NACA Langley's research methods, facilities, programs, and personnel. To complete the conduit, the NACA later created its own liaison office at Wright Field.

Document 4-24(a), Robert J. Woods, Chief Design Engineer, Bell Aircraft Corp., 2050 Elmwood Avenue, Buffalo NY, to NACA, "Attn: Dr. George W. Lewis," March 1940.

BELL AIRCRAFT CORP.
2050 Elmwood Avenue
Buffalo, N. Y.

March 25, 1940

National Advisory Committee for Aeronautics
Navy Building
Washington, D. C.

Attention: Dr. George W. Lewis

Dear Dr. Lewis:

We have heard that your laboratory is conducting tests on laminar flow airfoils of the low drag at high speed angle of attack variety, at full scale Reynolds number values, both in the laboratory and in free flight tests.

We would like to ascertain at this time if any of this work has progressed to the point where you may send us data or information on your test results. Our present problem is for an airplane of 80 inch root chord, 50 inch tip chord. Symmetrical root airfoil section with a 15 percent thick maximum ordinate. Tip airfoil section N.A.C.A. 23009 with minor modifications to the under surface at the nose. The design velocity is approximately 475 m.p.h. at 20,000 ft. altitude, which corresponds to a Reynold's number value of approximately 18,000,000.

To be of use to us on our current design problem we must have any data you may be able to send us on or before April 3, 1940. We will greatly appreciate your comments on our problems and any help you may be able to give us.

With sincere best regards,

Very truly yours,

Robert J. Woods
Chief Design Engineer.

Document 4-24(b), G.W. Lewis, Director of Aeronautical Research to Langley Memorial Aeronautical Laboratory, "Request for information on new airfoil sections—Bell Aircraft Corporation," March 1940.

Washington, D.C.
March 26, 1940.

From NACA
To LMAL

Subject: Request for information on new airfoil sections—Bell Aircraft Corporation.

1. There is attached herewith a copy of a letter from R. J. Woods of the Bell Aircraft Corporation. You will note that they are interested in receiving information on new airfoil sections and that the information to be of use on their current design problem must be received on or before April 3, 1940.

2. I discussed with Mr. Jacobs on my last visit to Langley Field the current development of new airfoil sections, under his direction. I am of the opinion that the Committee should be careful in releasing new airfoil section data until thorough tests have been made and we are very sure of our grounds. Please advise me as soon as possible whether the information discussed with Mr. Jacobs can be released on or before April 3.

G. W. Lewis,
Director of Aeronautical Research.

Document 4-24(c), H.J.E. Reid, Engineer-in-Charge, to NACA, "Request for information on new airfoil sections—Bell Aircraft Corporation," March 1940.

Langley Field, Va.,
March 27, 1940.

From LMAL
To NACA

Subject: Request for information on new airfoil sections—Bell Aircraft Corporation.

Reference: NACA Let. Mar. 26, 1940, L:CMM, Enc.

1. Your letter of reference, together with Mr. Woods' letter of March 25 accompanying it, has been discussed with Mr. E. N. Jacobs, and he states that it will be quite impossible to prepare the airfoil information, which he discussed with Dr. Lewis on his last visit, for release in report form by April 3.

2. Mr. Jacobs states furthermore that it would not be possible, with the information contained in Mr. Woods' letter, to make any suggestion which would be helpful to him in choosing one of the newer airfoils, but he thinks if Mr. Woods cared to visit the Laboratory for a discussion that he might be able to suggest one of the newer sections on which information has been released.

H. J. E. Reid,
Engineer-in-Charge.

Document 4-24(d), G.W. Lewis, Director of Aeronautical Research, to Robert J. Woods, Chief Design Engineer, Bell Aircraft Corporation, March 1940.

March 29, 1940.

Mr. Robert J. Woods,
Chief Design Engineer,
Bell Aircraft Corporation,
2050 Elmwood Avenue,
Buffalo, New York.

Dear Mr. Woods:

I have your letter of March 25, and before replying referred your letter and your questions to the staff at Langley Field.

I have just received a reply. The letter has been discussed with Mr. E. N. Jacobs and others of the staff, and I regret very much that the Committee will not have for release any information on airfoil sections that can be used on or before April 3.

We are pushing the work with reference to new airfoil sections that can be used on high-speed aircraft as fast as we can. We, however, must be sure of the data. I hope that this information will be out within the next four weeks.

Sincerely yours,

G. W. Lewis
Director of Aeronautical Research.

Document 4-24(e), Eastman N. Jacobs to Engineer-in-Charge, "Visit of Mr. Robert J. Woods of Bell Aircraft to LMAL, February 1941.

Langley Field, Virginia
February 5, 1941

MEMORANDUM For Engineer-In-Charge.

Subject: Visit of Mr. Robert J. Woods of Bell Aircraft to LMAL, February 5, 1941.

1. After a general discussion of the Bell P-59 project with Bob Woods and several Army and NACA representatives, which will be reported separately, I had a discussion with Bob Woods in my office after lunch, concerning the selection of a laminar-flow airfoil for the P-39. The triad of such an airfoil on the P-39 is apparently Woods' own idea, although he discussed the matter with Colonel Greene before having the conference with me. We discussed what section thicknesses might be used, and although I said he might use an eighteen-percent thick section, he thought it would be safer to reduce it to sixteen, in view of the possibility that they might change to a higher-powered Continental motor within the next two years, so that the compressibility margin gained by the thinner airfoil could be more conservative. The recommendation was therefore approximately the same as for the P-59 project, for which he already has the required data. It was agreed, therefore, that he would use the NACA 66, 2-116 at the root and the NACA 66, 2-216 at the tip. He has the NACA 66, 2x-015 thickness ordinates, which may be scaled up to sixteen to produce the desired thickness distribution, and we gave him the necessary data on the a = .6 type mean line.

2. For studies of possible use as a tail surface section, we also gave him a copy of the attached thickness ordinates for the NACA 67, 1-015 airfoil.

3. For Mr. Bell's information it should be noted that dusty wings which show a high drag at low speeds have been observed to revert to low drag when the speed was increased, thus blowing the dust off the wing.

Eastman N. Jacobs
Principal Aeronautical Engineer

Document 4-25(a-g)

(a) Eastman N. Jacobs, Principal Aeronautical Engineer, Memorandum to Director of Aeronautical Research (George W. Lewis), "Application of new airfoil data to experimental military airplanes," 11 June 1940, NACA Langley Correspondence Files, Code 173-1, National Archives, Mid-Atlantic Region, Philadelphia, Pa.

(b) George W. Lewis, Director of Aeronautical Research, NACA, to Chief of the Bureau of Aeronautics, Navy Department, Washington, D.C., "Confidential memorandum report regarding the application of new airfoil-section data of the laminar-flow type for current and new airplane designs," 17 June 1940, RA file 290, LHA. (Also includes the attached confidential report, "Immediate Use of New Airfoil Sections of the Laminar-Flow Type," 14 June 1940.)

(c) W.H. Herrnstein, Aeronautical Engineer (LMAL), to Engineer-in-Charge, "Discussion between Dr. G. W. Lewis and members of Laboratory staff relative to airfoil selection problems," 15 July 1940, RA file 290.

(d) Edwin P. Hartman, Western Coordinating Officer of the NACA, Santa Monica, CA., to Coordinator of Research, "Visit to Ryan Aeronautical Company," 13 August 1940, in RA file 290.

(e) Eastman N. Jacobs, Principal Aeronautical Engineer, to Engineer-in-Charge, "Visit to the Buffalo Curtis plant at the request of Don Berlin, September 30, 1940," RA file 290.

(f) Arthur E. Raymond, Vice President of Engineering, Douglas Aircraft Company, Inc., Santa Monica, CA, to Dr. G. W. Lewis, Director of Aeronautical Research, NACA, 15 March 1941, RA file 290.

(g) Elton W. Miller, Chief of the Aerodynamics Division (LMAL) to Engineer-in-Charge, "Visit of Mr. L. C. Miller of the Brewster Company to the Laboratory on January 3, 1941," 4 January 1941, RA file 290.

The first six documents in this string testify to the extremely strong interest shown by many U.S. aircraft manufacturers in 1940 and 1941 for the NACA's low-drag airfoils. The first memo, from Eastman Jacobs on 11 June 1940, is fascinating for its commentary on the difficulties of NACA-army dealings and on how strongly the NACA engineers felt they needed to be in control of their own experimental programs. The name "Diehl" referred to in the first line of the memo was Walter S. Diehl, the U.S. Navy officer in charge of technical liaison with the NACA at the navy's Bureau of Aeronautics in Washington. A construction corps engineer who in his insistence on remaining a technical man refused throughout his career to pursue promotions via sea duty, Diehl was one of the NACA's strongest allies and most intimate associates from within the U.S. military. He was a regular visitor to Langley, and given that the NACA's Washington office was located in the Navy Building, Diehl interacted regularly with his friend and fellow engineer George Lewis.

The identity of "Mr. Deport" is not known. "Mr. J.A. Roche" was Jean Roche, who worked as a civilian aeronautical engineer for Col. Carl Greene in the Army's NACA liaison office at Langley Field.

The other documents in this section reflect not only the eagerness of industry to acquire detailed knowledge of the new laminar-flow airfoils but also the tenuous position the NACA was in concerning the release of information about them. On the one hand, the industry and the military services clamored for information, and the NACA engineers involved in the airfoil development, especially Jacobs, were convinced that it was going to be "easier than expected in practical applications to realize the low-drag properties of the new sections." NACA leadership, however, did not want the airfoils to promise too much; George Lewis in particular wanted to make sure that the NACA had enough solid information on the total performance of the new-type airfoils before turning them over to industry. The NACA prided itself on completely reliable research findings, and it did not want to mislead the country into moving down a technological path that might lead to mistakes and inferior fighting aircraft.

The final document, on the other hand, demonstrates that not everyone in the American aeronautics community was so excited about applying laminar-flow wings—at least not the Brewster Aeronautical Corporation. It also suggests that the U.S. Navy was "not supporting them as they might." This suggestion may shed light on the critical comment made by Jacobs about Walter Diehl in Document 25-a.

Document 4-25(a), Eastman N. Jacobs, Principal Aeronautical Engineer, Memorandum to Director of Aeronautical Research (George W. Lewis), "Application of new airfoil data to experimental military airplanes," June 1940.

Langley Field, Va.
June 11, 1940.

MEMORANDUM For Director of Aeronautical Research

Subject: Application of new airfoil data to experimental military airplanes.

1. Following up our discussion with Diehl in your office at which time you asked him to give further thought to possible applications, I asked him at the Laboratory if he had thought of anything yet. His reply was to the effect that he would rather have the Army apply the new wings first. Although I did not argue the point, his position must be considered technically unsound. No <u>one</u> application should be made first. On each experimental type, the best possible compromise should be reached in the choice of the particular wing section for that type in the light of our most recent technical data.

2. Following his comment, however, I contacted the Army Liaison Office here to find out how they feel about it. I discussed the matter with Mr. De Port at Mr. J. A. Roche's suggestion, because he happened to be here at the time, and also with Messrs. Roche and H. J. E. Reid. De Port seemed to get my point of view. In any event, it appears that the Army is willing to cooperate with us in the application of the new wings. We should appreciate that there is some chance of obtaining disappointing results unless the Army, the Committee, and the manufacturer are all behind the project. This requirement greatly complicates our procedure and makes it increasingly clear that we will eventually have to run an experimental airplane-construction shop under our direct control.

3. In the meantime, we must continue to work with the services and the manufacturers. The next step is to find out what experimental projects are possibilities. Roche considers the P-47 one of the best. I would like, therefore, to obtain authority to discuss the airfoil selection problem with Republic representatives.

4. Finally, I agreed with De Port that it would be desirable to give the Army a memorandum indicating the gains possible through the choice of better sections. I plan to prepare and transmit such a memorandum which might also be sent to manufacturers. In return, De Port agreed that he would try to keep us informed through their liaison office here of possible experimental types under consideration.

Eastman N. Jacobs,
Principal Aeronautical Engineer.

Document 4-25(b), George W. Lewis, Director of Aeronautical Research, NACA, to Chief of the Bureau of Aeronautics, Navy Department, Washington, D.C., "Confidential memorandum report regarding the application of new airfoil-section data of the laminar-flow type for current and new airplane designs," 17 June 1940.

June 17, 1940.

Lieutenant Colonel Carl F. Greene,
Air Corps, U.S.A.,
Liaison Officer at the N.A.C.A. Laboratory,
Langley Field,
Virginia.

Dear Colonel Greene:

There is attached hereto a copy of a confidential memorandum, prepared by Mr. Eastman N. Jacobs of our technical staff, on the consideration of airfoil sections of the laminar-flow type for current and new airplane designs. Letters have been written to the chief engineers of the following companies:

Bell Aircraft Corporation
Boeing Aircraft Company
Consolidated Aircraft Corporation
Curtiss-Wright Corporation
Douglass Aircraft Company, Inc.
Lockheed Aircraft Corporation
Glenn L. Martin Company
North American Aviation, Inc.
Republic Aviation Corporation
Vought-Sikorsky Aircraft

inviting them to send their engineers to Langley Field for conferences with members of our technical staff on the subject of the selection of airfoil sections. These conferences will be with individual companies, there being no group conferences.

If there are any other companies to which you wish invitations sent, please advise the Committee.

Sincerely yours,

G. W. Lewis
Director of Aeronautical Research.

Document 4-25(c), W.H. Herrnstein, Aeronautical Engineer (LMAL), to Engineer-in-Charge, "Discussion between Dr. G. W. Lewis and members of Laboratory staff relative to airfoil selection problems," July 1940.

Langley Field, Va.
July 15, 1940.

MEMORANDUM For Engineer-in-Charge.

Subject: Discussion between Dr. G. W. Lewis and members of Laboratory staff relative to airfoil selection problems.

1. On the afternoon of Monday, July 15, 1940, Dr. G. W. Lewis called a group to discuss, in the office of the Engineer-in-Charge, the future policy of the Committee regarding the type of airfoil information to be supplied, in view of the present national emergency. Those present were: Dr. Lewis, Messrs. E. N. Jacobs, J. Stack, C. J. Wensinger, I. H. Abbott, and R. G. Robinson.

2. Dr. Lewis called our attention to the fact that this country has set itself the task of building 25,000 fighting airplanes within the next two years, and that the Committee would have to help in this enterprise all they could, in spite of the fact that some of the airplanes to be built would not appear to members of the Laboratory staff as optimum arrangements. He also called attention to the fact that some manufacturers who had formerly been using the 230 series airfoil sections were attempting to develop new sections of their own, with the expectation that these new sections would be superior. One of his reasons in calling the group together was to see if they could not settle upon some course of action to supply the manufacturers with airfoil data that would show improvement over that for the old 230 series sections, but be a sort of compromise between them and the newer so-called laminar-flow types. In Dr. Lewis's opinion, the Committee does not have enough information on these newer type airfoil sections to turn them over to the industry with the expectation of the industry's making use of them. For instance, we know little about them, outside of the drag. Other information needed would be data regarding the maximum lift, pitching moments, and particularly stalling characteristics. This latter point was very strongly stressed.

3. Although Mr. Jacobs objected at first quite strongly to any sort of compromise, he agreed, and the rest of those present concurred, that it would be a very good idea to test some model airplanes in the 19-foot pressure tunnel, equipped with the new wing sections. In this way the best data at present procurable will be obtained for airplanes with the new wings as regards stalling characteristics and maximum lift. Further data will also be obtained concerning any possible peculiarities in the stability characteristics associated with the use of the new airfoils. Certain data on the airplane drag and the effects of additional changes, for which Dr.

Lewis agreed to give the aerodynamics group a reasonably wide latitude, will also be obtained. As regards the wing drag, Mr. Jacobs recommended deducting the value as measured by the wake method in the tunnel, and adding in suitable free air values for purposes of performance estimation. Dr. Lewis recommended that we test the following models in the order given:

XP-41, as modified by Dr. Theodorsen's division.
XP-46
XF4U-1

He further stated that he would get us some information on a couple of bomber models which he thinks we should test.

4. Dr. Lewis believes that the physical research division should be consulted freely on this program, especially so in regard to any possible changes on the after-body of the XP-46, in light of their experience with the XP-41.

5. Dr. Lewis also stressed the need for power plant reliability, and stated that the R-1830 engine, as used in the XP-41 airplane, is probably the most reliable power plant we have today for pursuit use.

W. H. Herrnstein,
Aeronautical Engineer

Document 4-25(d), Edwin P. Hartman, Western Coordinating Officer of the NACA, Santa Monica, CA., to Coordinator of Research, "Visit to Ryan Aeronautical Company," August 1940.

Santa Monica, Calif.
August 13, 1940.

MEMORANDUM For Coordinator of Research.

Subject: Visit to Ryan Aeronautical Company.

4. INQUIRIES AND REQUESTS: Airfoil Data—Mr. Boyd stated that he had heard something of the new high-speed airfoils being developed at the N.A.C.A. and was quite anxious to obtain information and design data on them. He said the Ryan Company was considering some rather high-speed designs, and information on the new airfoils would be extremely helpful even though the final development of the airfoils had not been reached by the N.A.C.A. I'm sure the Ryan Company will appreciate any information the Committee cares to send them on the new air-foils. They use the N.A.C.A. 24xx series on their trainer.

Edwin P. Hartman

Document 4-25(e), Eastman N. Jacobs, Principal Aeronautical Engineer, to Engineer-in-Charge, "Visit to the Buffalo Curtis plant at the request of Don Berlin, September 1940."

Langley Field, Virginia
October 3, 1940

MEMORANDUM For Engineer-in-Charge.

Subject: Visit to the Buffalo Curtiss plant at the request of Don Berlin, September 30, 1940.

1. Mr. Berlin met me for breakfast at the hotel and took me to the plant Monday morning. We discussed some general considerations of the application of the laminar-flow wing to the P4OD, some of the possible difficulties, and what wing area should be used. It was agreed that we should prefer to use the same wing area and plan form as the original airplane. Some general matters of performance requirements and production considerations were also discussed with the vice president, Mr. Wright. He read a telegram he had just received from Lord Beaverbrook offering the Curtiss Company warm congratulations for having met their delivery agreements on one of the first consignments of P40's.

2. Later I was given an opportunity of inspecting their production set-up, mainly on the P40. They have done some remarkable work on assembly line methods and their present large production seems to be moving smoothly. In spite of their greatly improved methods, however, I am more than ever convinced that research should be directed toward the elimination of much of the slow and costly riveting and spot welding.

3. The problems of the application of the low-drag wing were discussed with the project engineer and with Mr. Jenkins and Mr. Child. Mr. Fladder was also present but was interested more in a twin-motored bomber application. We have an inquiry concerning a wing for this project from the Liaison office, so I will review our discussion of it when I answer this inquiry.

4. In regard to the P4OD, I was shown their mock-up of the project and also the mock-up for the P46, which has changed considerably since the full-scale model was tested here. The P4OD is the more interesting airplane from the standpoint of immediate development. In fact, their production facilities have already been organized for it to such an extent that any change in the wing appears to be too late to work in on their first ships. It is therefore unfortunate that we did not get together earlier on a program.

5. The greatest difficulty in the application of the new wing was with space for landing gear retraction. A slightly larger wing area would have avoided the difficulty, but Mr. Berlin thought that the difficulties might be overcome. He also considered small blisters on the lower wing surface against which, I regret to admit, my protest was only weak.

6. The question of changing to a more conservative wing section near the fuselage, an N.A.C.A. 65 Series for example, in order to avoid danger of separation near the fuselage juncture, was also considered with them. Berlin, however, was not much afraid of this situation and considered it primarily a problem in filleting that could be worked out as an addition. He plans, nevertheless, to make some investigations at once of suitable fillets in their wind tunnel. We therefore agreed to go ahead with the original plan to carry the same section right in to the fuselage.

7. Another possibility considered was that of building an experimental wing using makeshift methods. I admire the bold stand Berlin takes on this possibility. Final plans should be made on the supposition that the wing will work out as expected without important changes. If successful, we are then much further advanced after the flight tests. I endorse such methods and strongly recommend that the governments support the project financially.

Eastman N. Jacobs
Principal Aeronautical Engineer

Document 4-25(f), Arthur E. Raymond, Vice President of Engineering, Douglas Aircraft Company, Inc., Santa Monica, CA, to Dr. G. W. Lewis, Director of Aeronautical Research, NACA, March 1941.

March 15, 1941

Dr. G. W. Lewis
Director of Aeronautical Research
National Advisory Committee on Aeronautics
Navy Building
Washington, D. C.

Dear Dr. Lewis:

Through the present preliminary design period of our new light bomber we have been particularly grateful for the assistance we have received from the N.A.C.A. with respect to various design recommendations, particularly for the invaluable aid rendered by your Mr. Eastman Jacobs in the selection of laminar flow airfoil sections.

You are familiar with the fact that we intend to construct a total of three laminar flow airfoil models for N.A.C.A. testing. These models are being made up according to the suggestions given by Mr. Jacobs. It would considerably accelerate our test program if we were to have the privilege of a short visit from Mr. Jacobs, at which time the following would be accomplished:

(a) A decision could be made concerning the satisfactory design of our laminar flow airfoil models with respect to suitability for testing in the new laminar flow tunnel. Such a procedure would obviate possible time delays due to design changes brought about by interchange of correspondence.

(b) A general discussion of the aerodynamic features of our new light bomber with Mr. Jacobs, during which his opinions could be obtained with respect to manufacturing tolerances which can be allowed, still maintaining laminar flow over the wing and high aerodynamic efficiency throughout the design.

In addition to our new light bomber design, we have several projects under way which incorporate laminar flow airfoils. As is usual in such newly developed features, many questions have arisen which are difficult to answer without a background of experience. Feeling that Mr. Jacobs has had this experience and can render us valuable aid on the two items described above, we respectfully request that he be permitted to spend a short time on the west coast in the immediate future if this will not interfere with your plans and schedule.

Very truly yours,

DOUGLAS AIRCRAFT COMPANY, INC.

A. E. Raymond
Vice President Engineering

Document 4-25(g), Elton W. Miller, Chief of the Aerodynamics Division (LMAL) to Engineer-in-Charge, "Visit of Mr. L. C. Miller of the Brewster Company to the Laboratory on January 3, 1941," 4 January 1941, RA file 290.

Langley Field, Va.
January 4, 1941.

MEMORANDUM For Engineer-in-Charge.

Subject: Visit of Mr. L. C. Miller of the Brewster Company to the Laboratory on January 3, 1941.

Regarding laminar-flow airfoils, Mr. Miller stated that he had been able to arouse very little interest on the part of his Company in applying the laminar-flow airfoils. He felt also that the Navy was not supporting them as they might. He wondered whether any further information had been obtained regarding the maximum lift characteristics of the laminar-flow airfoils. Mr. E. N. Jacobs informed him that tests in the 19-foot tunnel on one installation had shown the maximum-lift coefficient to be within about 0.1 of that obtained with a conventional wing. He suggested that if Mr. Miller had a particular application in view that he arrange for a model to be built for tests in the 19-foot tunnel where the lift characteristics will be reliably obtained. He suggested also that he might have a section of wing built for tests in the low-turbulence tunnel where the drag coefficient would be determined and where it would be possible to determine what degree of roughness may be tolerated without sacrificing the laminar-flow properties. An airfoil for this tunnel should have a span of 35-3/4 inches and a chord anywhere up to 100 inches.

Elton W. Miller
Chief Aerodynamics Division.

Document 4-26(a-d)

(a) George J. Mead, Director, Airplane and Engine Division, National Defense Council, Federal Reserve Building, to Aeronautical Board, Room 1907, Navy Building, 28 August 1940, NACA Langley Correspondence Files, Code E38-8, National Archives, Mid-Atlantic Region, Philadelphia, Pa.

(b) Ira C. Eaker, Lieutenant Colonel, Air Corps, For the Chief of the Air Corps, to Dr. George J. Mead, Director, Airplane and Engine Division, National Defense Council, Federal Reserve Building, September 1940, NACA Langley Correspondence File, Code A173-1, National Archives, Philadelphia, Pa.

(c) G.W. Lewis, Director of Aeronautical Research, NACA, to Edward J. Horkey, Aerodynamics Department, North American Aviation, Inc., Inglewood, CA, 1 November 1940, NACA Langley Correspondence Files, Code A173-1, National Archives, Mid-Atlantic Region, Philadelphia, Pa.

(d) Excerpts from North American Aviation, Inc., Manufacturing Division, Engineering Department, Inglewood CA, "Aerodynamic Load Calculations for Model NA-73 Airplane," North American Report NA-5041, 3 March 1941, RA file 290, LHA, Hampton, Va.

This string of documents sheds light on the genesis of the low-drag NACA airfoils that were to be used in the design of the North American P-51 Mustang, or what in the prototype phase was called Model NA-73. As North American engineer Ed Rees later recalled (see Destination Document, this chapter), this was the "design touchstone" of the Mustang: its novel high-lift, low-drag wing. Considered "too revolutionary" by many experts at the time, the North American designers grew totally devoted to it—and thus to the NACA research on which it was based. If the laminar-flow wing had proved a mistake, so, too, would have the Mustang. And the NACA's reputation for outstanding and reliable research might have been irreparably damaged. But the Mustang flew magnificently, in large part because of its wing. Many aircraft experts believe the P-51 represents the highest level of technical refinement ever achieved in a propeller-driven fighter aircraft. They do not get many arguments.

In *Frontiers of Flight: The Story of NACA Research* (New York: Alfred A. Knopf, 1948) author George W. Gray recalled how the airplane came to be. It had its origins, he wrote, in a series of conferences between North American Aviation, Inc., and a British airplane purchasing commission. "As the story goes, in April of 1940 [four months after Mead wrote his letter to the Aeronautics Board], the British gave the North American executives a list of the performance characteristics they wanted in an airplane, and specified that if the order was accepted the design must be completed and the prototype delivered for trial within 120 days."

Gray's story failed to give all the details. When the British commission arrived in the U.S., it meant to buy modified Curtiss P-40s and Bell P-39s. Because the assembly lines of the two companies could not produce all the airplanes Great Britain wanted, the commission also asked North American Aviation, Inc., to consider producing P-40s also. After thinking about it a while, NAA officials suggested to the British that it could offer a completely new and better airplane better suited to mass production, and that it could do it within the stipulated three-month deadline.

North American had by then received preliminary NACA reports on the low-drag airfoils, as had all the other companies building aircraft for the army and navy, and "its engineers were favorably impressed." Russell G. Robinson of NACA Headquarters, soon to be dispatched to Santa Monica, California, to organize the new NACA's West Coast Coordinating Office, helped North American to select the specific parameters for the laminar-flow airfoil shape for the experimental P-51 models, with significant input from Eastman Jacobs at Langley.

Although there was a great deal of concern within the company about selecting a brand new, untried type of airfoil, so much enthusiasm for the laminar-flow wings sprouted among its leaders that North American stuck its neck out and selected one of the NACA's Series 4 airfoils. "The margin of time available within the 120-day limit was so narrow that while the work of adapting the NACA low-drag wing was being rushed to completion by one group, other engineers were developing an alternative wing of conventional design in case the new idea failed to pan out successfully" (Gray, *Frontiers of Flight*, pp. 106-07). Even today, North American's decision to try the new wing seems a tremendous risk, in that the only data available was Jacobs' advance confidential report. The wing could have had poor stall or stability characteristics and any number of unknown problems. Fortunately, it did not.

The British approved North American's preliminary design in early May 1940 and by the end of the month ordered 320 of the aircraft. An XP-51 flew for the first time five months later, in October, and did so extremely well. It entered combat with the RAF in July 1942.

Of course, the wing only partly explained the Mustang's phenomenal success in the air. Later versions of the Mustang (there were several variants of which the P-51D was the most numerous and best known) had a remarkable Merlin engine, built by Rolls-Royce, capable of producing a then-amazing 1505 horsepower at an altitude of nearly 20,000 feet. (The Packard Motor Car Company built the engines under license in the United States.) Other vital statistics worth mentioning was the airplane's great range (1650 miles at a speed of 358 mph and altitude of 25,000 feet) and climbing ability (up to 20,000 feet in 7.3 minutes). It was also the only fighter plane of World War II to fly over three enemy capitals: Berlin, Rome, and Tokyo.

Most significantly from the aerodynamicist's point of view, the Mustang's coefficient of drag was a record low 0.0163, which meant that it was the "cleanest" airplane that had ever flown anywhere up to that time (and for quite a while thereafter). For those interested, Document 26-d provides the basic aerodynamic characteristics of the wing. The individuals involved in the design of the wing at North American were Edward J. Horkey, Irving L. Ashkenas, C. L. David, and H. J. Hoge. In cross-section their wing was slightly thicker than any of the "230" family airfoils, with maximum thickness farther back from the leading edge, nearer the center of the chord. Also, it had a cusped trailing edge.

Document 4-26(a), George J. Mead, Director, Airplane and Engine Division, National Defense Council, Federal Reserve Building, to Aeronautical Board, Room 1907, Navy Building, August 1940.

August 28, 1940

To: Aeronautical Board

Room 1907, Navy Building

From: George J. Mead

It has come to my attention that the North American Company are developing a fighter for the British, which is said to incorporate the new laminar-flow NACA wing. I should like to know, therefore, whether the Board has already approved an export license for this airplane. It does not seem desirable in the interests of national defense that this development be permitted to leave the country before our own aircraft are thus equipped.

Director,
Airplane and Engine Division

Document 4-26(b), Ira C. Eaker, Lieutenant Colonel, Air Corps, For the Chief of the Air Corps, to Dr. George J. Mead, Director, Airplane and Engine Division, National Defense Council, Federal Reserve Building, September 1940.

WAR DEPARTMENT
Office of the Chief of the Air Corps
WASHINGTON

September 5, 1940.

MEMORANDUM FOR: Dr. George J. Mead,
Director, Airplane and Engine Division,
National Defense Council, Federal Reserve Building.

Reference is had to your letter of August 28, 1940, addressed to the Aeronautical Board, requesting information regarding the new laminar-flow NACA wing.

Information has been received from the North American Aviation, Incorporated, that the wing sections being installed on the NA-73 type aircraft being manufactured for the British Government are based on NACA Report No. 411 (Wing Sections of Arbitrary Shapes) published in 1931 and Report No. 452 (General Potential Theory of Arbitrary Wing Sections) published in 1933. These reports are unrestricted publications. It is understood that this new Wing Section being developed by North American is equipped with slotted flaps and is not the Laminar-Flow NACA wing.

The NA-73, single seat pursuit type aircraft was officially released for export sale August 1, 1940, as a result of an Agreement signed by a representative of North American Aviation, Inc. and the War Department, and approved by the Assistant Secretary of War, May 8, 1940. This agreement specifies that the first NA-73 airplane built will be tested by the Air Corps and the fourth and tenth articles delivered to the Air Corps, which will furnish the Air Corps with complete information concerning any new Wing Sections and Flap Installations developed by the North American Company.

The Air Corps is conversant with this wing development and in accordance with the mutual agreement will receive full benefit of the engineering work being done without additional expense. It is believed that it will be to the best interest of the Air Corps to encourage the continuation of the research and development work being done by North American in connection with high speed wing sections for the NA-73 type airplane.

For the Chief of the Air Corps:

Ira C. Eaker
Lieut. Colonel, Air Corps,
Executive.

Document 4-26(c), G.W. Lewis, Director of Aeronautical Research, NACA, to Edward J. Horkey, Aerodynamics Department, North American Aviation, Inc., Inglewood, CA, 1 November 1940.

November 1, 1940.

Mr. E. J. Horkey,
Aerodynamics Department,
North American Aviation, Inc.,
Inglewood, California.

Dear Mr. Horkey:

In response to the inquiries contained in your letter of September 23, 1940, the following discussion has been prepared by our laboratory staff, and the replies are arranged in the same order as the questions in your letter:

I. WINGS

Mr. Jacobs has commented as follows:

A. NA-73X smoothness—In spite of the fact that your measurements show discontinuities at the rivets and joints of only 0.002 inch to 0.003 inch, it is believed that many of the irregularities shown are too large to permit the maintenance of laminar flow over them. Aside from the wrinkles, however, it is believed that most of these defects may be removed by means of points.

B. Machine guns—It will be very difficult to realize laminar flow over the part of the wing behind the machine gun blast tubes, and it is our experience that it cannot be done unless air is taken in the opening at the leading edge and unless the opening is located very near the front stagnation point. In this respect, the 50-caliber gun is located slightly too high and the outboard 30-caliber gun slightly too low. The other 30-caliber gun is much too low. To maintain laminar flow, the vertical height of the opening should be made as small as possible, say 3/4 inch. The length might be equal to the blast tube diameter, forming a spanwise slot faired out to a point at either end. The air flow discharge opening shown is considered satisfactory except that it should be restricted at the extreme back edge of the slot until the air leaving the slot at nearly flight speed will produce a flow of air into the intake openings at a speed of the order of one-third the flight speed.

C. New type section—Attached are ordinates for the NACA 65, 2-213.5 airfoil, which you might try for the tip. Its use will produce a slight discontinuity in the spanwise fairing lines where it joins the original wing at station 190.5. This defect is not considered serious, however, and the new section at the tip should produce a lower drag and a higher maximum lift. Of course, the section at station 190.5 cannot be altered, the new section fairing in from the 50-inch chord section at the tip to the old section. So little wing area is thus involved in the change that it is considered doubtful whether much change in the stalling characteristics will be observed.

D. Latest data on new wing sections—If you were designing a completely new wing, we would recommend the usage of the newer sections having larger leading edge radii and a somewhat more aft position of the minimum pressure. You could thus realize the possibility of obtaining lower drags, higher maximum lift coefficients, and somewhat increased critical speeds. If you contemplate building a new wing we will gladly recommend suitable sections.

E. Flaps—Slotted flaps have not been investigated on the newer types of laminar-flow airfoils, although some data have been obtained on split flaps. Because the behavior of the split flap on the new airfoils is about the same as its behavior on the old conventional airfoils, we expect the aileron type flap to behave similarly. Some tests of the aileron type flap in the high-speed range tend to confirm this belief.

Finally, we would greatly appreciate any information you can send us about the new airfoil as a result of your flight tests. We would be particularly interested in a comparison of the wind tunnel and flight stalling characteristics. It is understood that the first airplane will be delivered to the Army Air Corps. If it can be arranged with the Army, it seems desirable that the airplane should be brought to Langley Field so that we can make wing drag measurements on it in flight. Your cooperation on such a project would be appreciated.

II. POWER PLANT PROBLEMS.

Messrs. Silverstein and Biermann have prepared the following discussion:

A. WING DUCTS.

1. The duct leading edges on figures II-A-1-a and II-A-1-b appear satisfactory. If trouble is experienced on the model with early stalling it may be cured either by increasing the camber on the upper leading edge of the duct, or by lowering the duct-inlet opening. For the high-speed condition the symmetrical opening as shown in the photographs is slightly preferred.

2. Since sliding doors are liable to stick in operation due to wing deflections, dirt, etc., we have never worked much with them. We prefer regulation by means of a concealed flap such as shown in figure 6f of the advanced confidential report entitled "Full-Scale Wind Tunnel Investigation of Wing Cooling Duct" by F. R. Nickle and Arthur B. Freeman. A plain outward-opening flap may also be used; however, it is more costly in drag.

B. PROPELLER CUFFS.

Mr. Biermann has commented as follows:

1. Cuffs of a fineness ratio of 3.5 are about the same we have been testing and appear to be about as good as we can do at the present. Although the structural problem is not mine I doubt whether the cuffs will stay on if they are built according to the drawing. The centrifugal load must pass from the skin to the shank casting through four points as shown and I think the skin will tear out there. The problem is to distribute the load over a wide area of the skin.

We have calculated the angles recommended for the cuff settings based on our experience and tests of cuffs. Enclosed is a chart giving the angles computed.

III. FLIGHT TESTING.

A. AILERON CRITERIA

Mr. Gilruth has prepared the following discussion on this item:

1. Various pursuit types tested gave values of pb/2v ranging from 0.12 to 0.079, all of which were considered satisfactory by pilots.

2. With regard to the example given, it has been our experience that it is unwise to depend on aileron deflections greater than 20 degrees for additional control. With the BT-9, for example, aileron effectiveness tests show that the aileron did very little except produce additional yaw after 20 degrees up aileron was reached. Similar results have been observed on several other machines. In application of formula, therefore, it would seem advisable to use a max of 30 degrees rather than 42 degrees. In the actual airplane this would allow a considerable reduction of stick force (by permitting increased mechanical advantage) and still allow ample margin over the minimum satisfactory value since the pb/2v obtainable would be about 0.11.

3. A report describing the tests and analysis used in setting up this criterion should be available in a few weeks.

B. TRAILING BOMBS.

Mr. F. L. Thompson has commented as follows:

1. There are attached one copy each of drawing D-5391 and D-6375, showing the NACA suspended air-speed head and the total head meter that is used with it when the suspended head is used only for determining the static pressure. For a description of the method used by the Committee in making air-speed measurements, reference is made to NACA Technical Note 616.

2. Such calibrations as have been made to date for the suspended head have been confined to relatively low speeds and show the error to be less than one percent of the dynamic pressure. A calibration to cover the entire range of speeds over which this head might possibly be used is to be made at an early date but is not available at the present time. It is not anticipated, however, that there will be any appreciable variations in the calibration except possibly at very high speeds.

I trust that this information will be of assistance to you in solving your problems.

Very truly yours,

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

G. W. Lewis
Director of Aeronautical Research.

Document 4-26(d), Excerpts from North American Aviation, Inc., Manufacturing Division, Engineering Department, Inglewood CA, "Aerodynamic Load Calculations for Model NA-73 Airplane,"* North American Report NA-5041, *March 1941.

NORTH AMERICAN AVIATION INC.
MANUFACTURING DIVISION
INGLEWOOD, CALIF.

ENGINEERING DEPARTMENT

AERODYNAMIC LOAD CALCULATIONS
FOR
MODEL NA-73 AIRPLANE

DESCRIPTION

The N.A.A. Model NA-73 Airplane is a single-place, single engine, low wing monoplane.

The wing is of all-metal, stressed-skin, stringer construction and is fully cantilevered. It consists of two sections, tapered in both planform and thickness, joined at the centerline of the airplane. The airfoil sections which are used are of the laminar-flow type and were developed at N.A.A. as explained in the text. A two-degree structural twist is incorporated in the wing varying from one degree positive incidence at the root section to one degree negative at the tip. Self-sealing fuel tanks are mounted in the wing structure.

The all-metal fuselage is divided into two separable units for ease of repair. Both sections are of semi-monocoque construction covered with alclad. Two built-up cantilever beams form the engine mount.

Simple metal-covered flaps extend outward from the sides of the fuselage to the inboard end of the ailerons. All metal ailerons of the partially sealed type extend from the outboard end of the flaps to the tip sections.

The fixed tail surfaces are of all metal construction, while the movable surfaces have aluminum alloy frames with fabric coverings. The movable surfaces are statically and dynamically balanced.

The landing gear is of the full cantilever half-fork type and is retractable inboard into wells in the wings.

The engine used with this plane is a 12 cylinder, Prestone cooled, Allison V-1710 with a present military rating of 1000 H.P. at 2800 R.P.M. at sea level. The radiator is located aft of the pilot's cockpit and is provided with an air scoop having an adjustable inlet and outlet.

AERODYNAMIC CHARACTERISTICS AND DISCUSSION

The airplane characteristics used in this report are based partially on wind tunnel data and partially on theoretical calculations.

The airfoil section at the tip and at spanwise Station 50 were derived by performing a series of pressure distribution calculations until, at the design lift coefficient, the negative pressure reached a maximum at or near the 50% chord point with no adverse pressure gradient ahead of this point. The calculations were based on the method developed in Ref. (c). This method, based on potential-flow theory, was modified in accordance with Ref. (d) in order to minimize the discrepancies between the theoretical and measured results. The remaining wing sections were developed by linearly varying the ordinates between the two known sections.

The spanwise distribution of section characteristics will be based on theoretical calculations whenever possible and estimated from reference data when no means of theoretical treatment is known.

SPANWISE DISTRIBUTION OF AIRFOIL CHARACTERISTICS

The forces on an airplane wing may be considered as functions of the characteristics of the airfoil sections. Certain of these characteristics depend only on the section shape and may be computed mathematically. These include the horizontal and vertical locations of the aerodynamic center with reference to the airfoil chord, the pitching moment about the aerodynamic center and the angle of zero lift. Pages 16 to 67 contain the computations for the above characteristics at seven spanwise sections. The procedure used is that suggested and outlined in Ref. (c).

Since the remaining characteristics do not lend themselves to theoretical treatment, wind tunnel data must be utilized. From a perusal of available published data, including that of Refs. i, j, k and l, values of C_{lopt}, C_{domin} and C_{lmax} are assigned to the seven sections. These values are based mainly on variations in thickness and camber. Care is taken that the distribution of C_{lmax} results in the proper maximum lift coefficient for the wing.

The lift-curve slope is assumed to be constant along the span. Its value is obtained from the wind tunnel data, App. I, Page Z, corrected to infinite aspect ratio.

$$a_o = a / (1-18.24/n)\ a\ (1+ \tau)$$

where a_o = Lift-curve slope for infinite aspect ratio

a = Lift-curve slope for finite aspect ratio

= .0742 (App. I, Page z)

n = aspect ratio

$= 5.815$ (P.10)

τ = correction for shape of span-loading

curve = 0.18 (Ref. k Page 53)

$$a_o = \frac{.0742}{(1-18.24/5.815) \times .0742\ (1+.18)}$$

$= .1022$

The characteristics obtained by the above methods are tabulated in the left hand portion of Table XXV, Page 71 and plotted on Page 70. From these spanwise distribution curves, the remainder of Table XXV, Page 71 is completed.

AIRPLANE COEFFICIENTS

The full-scale airplane aerodynamic coefficients used in this report are based on the results of wind tunnel tests on a 1/4th scale model of the NA-73 Airplane. The tests were made at the Guggenheim Aeronautics Laboratory, California Institute of Technology, and at the University of Washington Aeronautical Laboratory.

The results of the tests performed at GALCIT are used in this report with the exception of the maximum negative lift coefficient taken from the UWAL tests. All of the test curves from which data were taken are reproduced in App. I.

The Reynolds number of the wind tunnel tests was approximately 1.8×10^6 while the full-scale Reynolds number at H.A.A. is about 16.7×10^6.

The airplane coefficients are listed in Table XXVII and plotted and extrapolated on page 83. The Reynolds number extrapolation for the positive maximum lift coefficient, Page 79, follows the trend of a similar extrapolation for the N.A.C.A. 23012 airfoil presented in Ref. k, Page 117. The negative maximum lift coefficient is extrapolated in a similar manner using a slightly smaller C_{lmax}.

The airplane drag curves are extrapolated to agree with the full-scale maximum lift coefficients of the wing. Due to a lack of reference data concerning the extrapolation with Reynolds number of the minimum wing drag of laminar-flow airfoil, no extrapolation is performed. The wings of the airplane are smooth and, therefore, it is considered that the increase in drag coefficient for surface roughness is approximately .0001. An increase in the drag coefficient of the fuselage of .0039 is assumed. This is due to the effect of the surface roughness, carburetor scoop, radiator scoop, exhaust stacks and wing-fuselage interference as determined from wind tunnel investigation.

In order to obtain the pitching moments over the entire flight range, the aerodynamic center of the wing alone and of the wing-fuselage combination is first calculated on pages 81 and 82. The constant pitching moment around each of these centers is also determined and used to compute the required pitching moments around the wind tunnel model C.G. position.

Lift, drag and moment coefficients over the entire flight range are listed in Table XXVIII, Page 84. The lift and drag coefficients are resolved into components perpendicular and parallel to the thrust line, and, with the moment coefficients, are transferred to the aerodynamic center of the wing alone. A correction factor, arising from a difference in the model M.A.C. and the M.A.C. calculated for the full-scale airplane, is used to slightly reduce the wind tunnel moment coefficient values prior to their transfer.

CALCULATION OF CRITICAL SPEED

In the investigation of the effects of compressibility phenomena on the characteristics of an airplane, it is important to know the free air velocity at which the velocity of the air over the wing reaches the local speed of sound. This velocity, referred to as the "critical speed," varies along the span and with the angle of attack of the wing.

The maximum critical speed will occur in the vicinity of zero wing lift, however, in this report, it is assumed that the maximum critical speed occurs at minimum airplane drag. In order to obtain an average value along the span, the critical speed calculations are based on the airfoil section at the M.A.C. of the wing, Station 97.67.

The air pressure, at that point on an airfoil over which the air velocity has reached the speed of sound, will have the highest negative value that exists over the airfoil surface. Therefore, the pressure distribution at the M.A.C. section, (Y/ b/2 = .4375) is calculated at minimum airplane drag.

From the curves, Page 83, it is seen that minimum airplane drag occurs at a wing C_L of .100. The calculation of the section lift coefficient c_{lo} follows:

$c_{la1} = 1.060$ (P .75) $F_1 = .006$

(Ref. f, Page 15)

$c_{lb} = .0125$ (P .76) $F_2 = .002$

$\Delta c_L = F_1 \times F_2 = .006 \times .002 = .0001$

$c_L" = .1000 - .0001 = .0999$

$c_{la}" = .0999 \times 1.060 = .1059$ (Ref. f, Page 18)

$c_{lo} = .1059 + .0125 = .1184$

$= C"_{2a} + C_{2a} + C_{2b}$

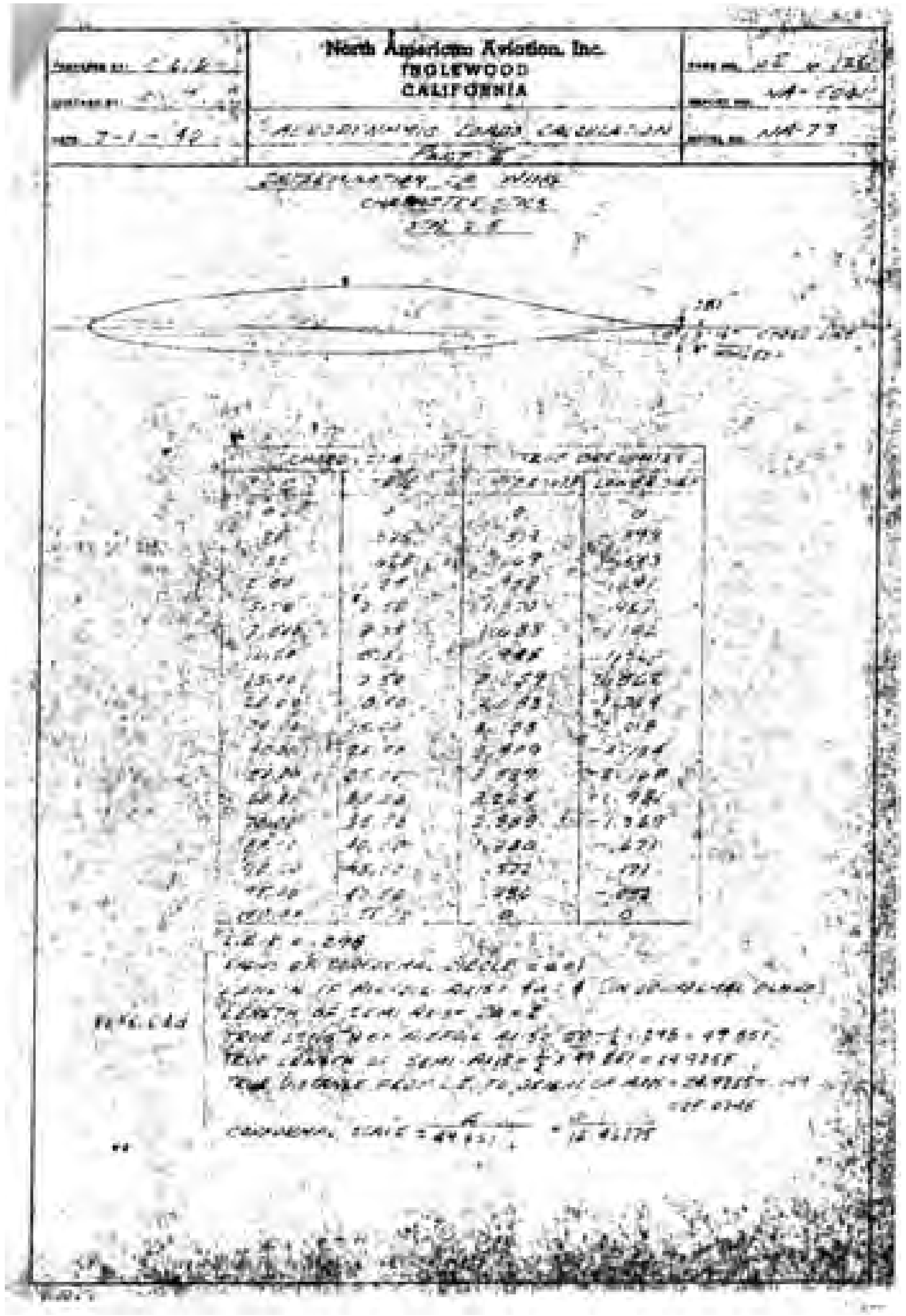
From Page 14, the slope of the lift curve at wind tunnel speed is .1022. For use in the pressure distributions for critical speed, this slope is modified by the slope correction factors (P. 90) to agree with the high angle of attack speed.

$$a_o = .1022 \text{ X } (1.060/1.006) = .1077$$

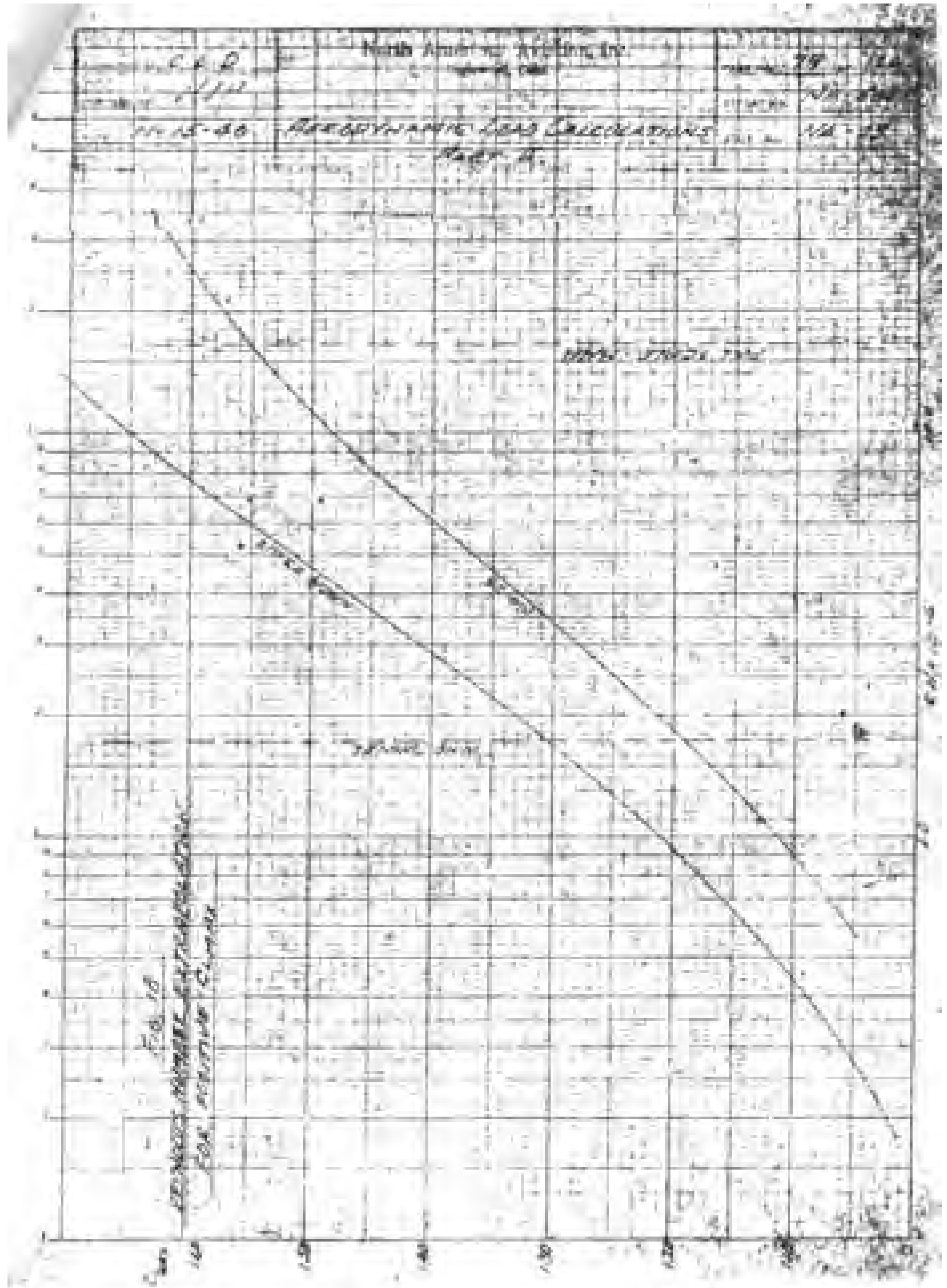
where F_m at 115.4 M.P.H. = 1.006
F_m at 260 M.P.H. = 1.060

From the computations on page 86, it is evident that variations in the value of the slope of the lift curve has little effect on the value of the maximum negative pressure coefficient.

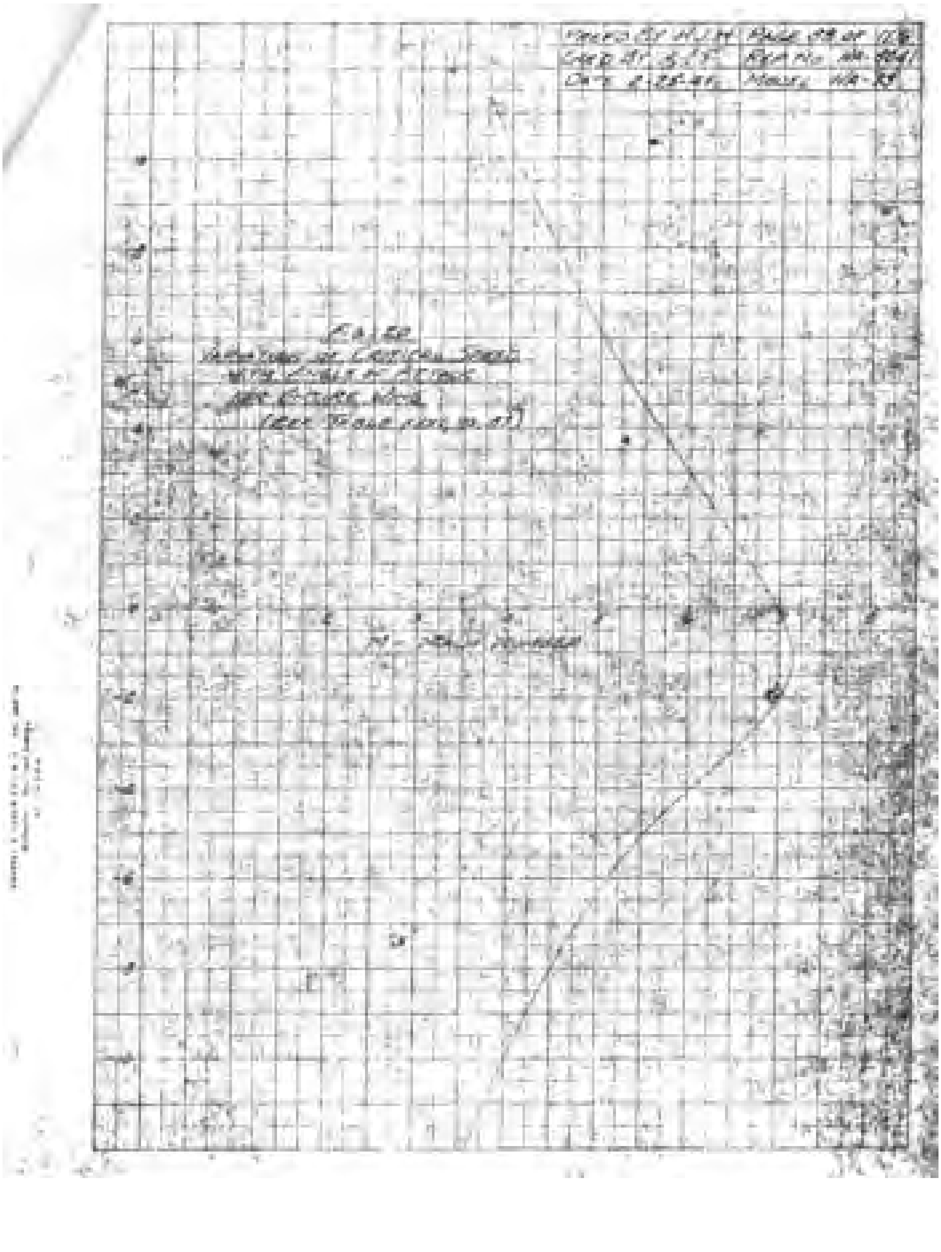
With the above basic data and the method detailed in Ref. d, the maximum negative pressure coefficient (P/q) is calculated on Page 86 to be -.5299. The corresponding Mach number, taken from Ref. b, Page 51, is .715. In a similar fashion, the critical Mach numbers over a range of angles of attack are determined in Table XXXI, Page 87 and plotted on Page 88.


North American Aviation, Inc.
INGLEWOOD
CALIFORNIA

AERODYNAMIC LOADS CALCULATION
PART II


North American Aviation, Inc.

AERODYNAMIC LOAD CALCULATIONS
PART II



Document 4-27(a-d)

(a) Edward Warner, Civil Aeronautics Board, Washington, D.C., to Eastman N. Jacobs, Principal Aeronautical Engineer, NACA Langley, 12 October 1940, RA file 290, LHA, Hampton, Va.

(b) Eastman N. Jacobs, Principal Aeronautical Engineer, NACA Langley, to Dr. Edward Warner, NACA, Navy Building, Washington, D.C., 24 October 1940, Langley Correspondence Files, Code E38-8, National Archives, Mid-Atlantic Region, Philadelphia, Pa.

(c) Eastman N. Jacobs, Principal Aeronautical Engineer, to Dr. Edward P. Warner, Chairman, Committee on Aerodynamics, NACA, Navy Building, Washington, D.C., 27 November 1940, RA file 290.

(d) G.W. Lewis to LMAL, "Report by Mr. Jacobs on present status of laminar-flow wing development, for next meeting of the Aerodynamics Committee, to be held the latter part of January," 14 December 1940, RA file 290.

Additional insight into the NACA's early treatment of its laminar-flow airfoil development can be gained from a review of the following four documents. They refer mainly to a possible laminar-flow wing application for the Curtiss P-40D. In Document 27-B, Eastman Jacobs declared what can only be termed one of the grossest exaggerations of the war, that the laminar-flow application on the P-40 was "the most important single technical project in the United States today."

George Lewis's memo dated 14 December 1940 is interesting for its concern over circulating among the NACA Aerodynamics Committee proprietary information about a possible laminar-flow application by Curtiss for the P-40.

Document 4-27(a), Edward Warner, Civil Aeronautics Board, Washington, D.C., to Eastman N. Jacobs, Principal Aeronautical Engineer, NACA Langley, October 1940.

CIVIL AERONAUTICS BOARD
WASHINGTON

OCTOBER 12, 1940.

Mr. Eastman N. Jacobs,
Principal Aeronautical Engineer,
National Advisory Committee for Aeronautics,
Langley Field,
Hampton, Virginia.

Dear Mr. Jacobs:

I was very much interested in your letter of October 4th about the supersonic tunnel and the possibilities of increasing the Mach Number at Langley Field. I take it from your longhand postscript that you have now had the desired talk with Dr. Dryden, and I am asking that he let us have his comments in such time and fashion as may be convenient for him.

I was also interested in what you said about the usefulness of committee discussions in connection with the development and application of the new airfoils. I hope that you will, at your convenience, let me have something more specific on that for possible distribution in advance of the next meeting of the committee. To make these meetings as useful as possible, we want to circulate a maximum of preliminary information in advance. To get the members fully informed in advance is the best possible preparation for a really useful discussion.

Sincerely,

Edward Warner

Document 4-27(b), Eastman N. Jacobs, Principal Aeronautical Engineer, NACA Langley, to Dr. Edward Warner, NACA, Navy Building, Washington, D.C., October 1940.

October 24, 1940

Dr. Edward Warner
National Advisory Committee For Aeronautics
Navy Building
Washington, D. C.

Dear Dr. Warner:

Your last letter of October 12, showing so much interest in the application of the new airfoils, and your interest in the usefulness of the committee in the matter of course pleased me very much. Perhaps I may be expected to be over-enthusiastic about the project, but I honestly think that the immediate application of our recent airfoil research in the form of a new wing for the Curtiss P-40D airplane is the most important single technical project in the entire United States today. This immediate application you will remember was suggested by Mr. T. P. Wright at the last meeting of your committee and I agreed that it was an excellent suggestion and that we should all work together on it.

The enclosed letter will indicate about what has happened since then. As far as I know, Curtiss are going ahead on the project with reasonable speed, although they had not yet gone far when I visited the Buffalo plant on September 30. I have wondered if it would be desirable to suggest that the Army representative on our committee check on all phases of the project and report to us from the Army's standpoint on the progress, at our next committee meeting. I can review the progress from the research standpoint.

I hoped to write you giving rather complete details, but so far have had trouble finding the necessary time. This brief note is being written before I leave on a short trip to discuss the supersonic tunnel blower with Allis-Chalmers in Milwaukee. On my return I will try to find time to prepare something that might be circulated to the committee members. In the meantime I would be glad to receive your suggestions.

Sincerely yours,

Eastman N. Jacobs
Principal Aeronautical Engineer

Document 4-27(c), Eastman N. Jacobs, Principal Aeronautical Engineer, to Dr. Edward P. Warner, Chairman, Committee on Aerodynamics, NACA, Navy Building, Washington, D.C., November 1940.

Langley Field, Virginia
November 27, 1940

Dr. Edward Warner
Chairman Committee on Aerodynamics
National Advisory Committee for Aeronautics
Navy Building
Washington, D. C.

Dear Dr. Warner:

In accordance with the suggestion in your letter of October 12, I have prepared the attached outline of the problems encountered in the use of the laminar-flow airfoils and the progress being made in solving these problems. I hope that you will find this draft of the subject suitable for circulation to the members of the Aerodynamics Committee, so that it can be brought up for discussion at the next meeting of the committee.

Very sincerely yours,

Eastman N. Jacobs
Principal Aeronautical Engineer

LOW-DRAG AIRFOILS

It has been established that airfoil drags may be greatly reduced through the use of wing sections of suitable shapes and with smooth and fair surfaces which permit the use of the low-drag properties of extensive laminar boundary layers. It has also been shown that the new laminar-flow sections may be designed to give results little different from conventional sections when used in a rough condition or outside their design range of low drag. There seems to be no reason, therefore, why they should not be employed at once on new types of military airplanes in place of the old conventional sections.

Actually, some applications on new military types are going forward through the cooperation of the services and certain manufacturers. In addition, the Committee has a project in the 19-foot pressure tunnel investigating a complete model of an air-cooled pursuit airplane with a laminar-flow wing, and a Navy fighter model with a wing of the new type substituted for the original wing. It would appear at first sight therefore, that the development and application of the new wings is progressing satisfactorily. On the other hand, many of the projects are in a preliminary form and much preliminary lay-out work and wind tunnel testing remain to be done before the actual wing design is even started. It may be years before flight test checks are obtained on some of these applications.

In the meantime, we need actual flight checks on the characteristics of the new wings, because the wind tunnel results are not complete and entirely reliable. Furthermore, the most important research remaining to be done concerning the laminar-flow wings has to do with their practical construction and maintenance under service conditions. These phases of the research and development will necessarily tend to become cooperative projects with the builders and operators and will finally pass almost entirely to them. If we had the necessary shop facilities, we might get on with this research more quickly by building and testing some practical wings here at the Committee's Laboratory, but for military types under existing conditions it seems advisable to pass at once to the cooperative phase of the research. At this point the Aerodynamics Committee seems to me to become an agency of vital importance. It should serve the important functions of guiding and coordinating the required activities of the N.A.C.A., the services, and the manufacturers. The committee has, in fact, started to function in this capacity.

You will remember that I mentioned at the last meeting on August 8 some of the developments in the laminar-flow airfoils and that Ted Wright suggested that thicker airfoils would be desirable on modern pursuit types in order to give internal space for more and larger armament. The discussion thus led to the conclusion that it would be desirable to investigate a wing of the new type as soon as possible for the Curtiss P-40-D airplane. Within the next few days a request came through Colonel Greene's Army Liaison Office here, from Curtiss, for some of the new and thicker airfoils for lay-out purposes on pursuit airplanes. We replied on August 13, giving them ordinates of the NACA 66, 2-018 airfoil, which we considered should be suitable for lay-out purposes and should give a drag coefficient of .0036 or less, below R = 20,000,000.

Following this, on August 21, Mr. Don Berlin visited the Army Liaison Office and I was called over to discuss possible new sections for the P-40-D airplane. After some discussion of the possibility of model tests in the 19-foot pressure tunnel, I suggested that we should all try to get together on some definite program. In discussing various possible programs, we finally agreed that tunnel tests would be unnecessary if, as the Army representatives (Colonel Greene and Mr. J. A. Roché) agreed, the maximum lift coefficient and stalling characteristics were not required to be known in advance. We all agreed, therefore, to cooperate toward the construction of a wing for flight tests as soon as possible. I suggested, however, that we might help by testing in the low-turbulence tunnel a wing sample to be built by Curtiss, to investigate the effects of construction imperfections, effects of camouflage paint, etc., although any such tests were not to hold up construction of the wing. Later, a suitable camber for the basic thickness form I had already sent to Curtiss was discussed. No final conclusion was reached, and it was agreed that we should look into the matter and make a definite recommendation later.

Fortunately, I had an opportunity of going over the question with Mr. T. P. Wright the next morning. After going over most of our more recent airfoil data, we agreed that a small amount of camber seemed desirable, and I made recommendations to the Curtiss Company accordingly on August 23.

In discussing with Mr. Wright the question of obtaining the desired surface conditions on the wings in practice, we used our surface curvatures gauge to check the surface conditions of a service P-40 against some commonly used wing surfaces, and found the P-40 wing, in some regions at least, to be of a different order of fairness. In fact, it appears that the construction methods now employed might not require drastic changes beyond the use of carefully applied butt joints between the wing cover plates. Furthermore, Mr. Wright informed me that additional improvements had already been made on the Curtiss-Wright transport, so that they were familiar with the problem of producing an improved wing surface.

Mr. Berlin wrote the Army Liaison Office on September 5 concerning some possible control surface difficulties, which I think we were able to clear up. In this letter he stated that they were proceeding with the design of a laminar-flow wing for the P-40-D airplane, in accordance with the information we had furnished them on August 21, stating "We expect to proceed with all possible effort in order to get a wing of this type on an airplane at the earliest possible date."

On September 30, I visited the Curtiss plant with the hope that I might aid in speeding up the project. I was much impressed by the P-40-D mock-up, and became more than ever convinced that this is the airplane on which to continue the investigations of the new type of wing. In fact, it seems to be the most interesting pursuit airplane available, from the standpoint of immediate development, although the production facilities have already been organized for it to such an extent that it may be too late to work in a wing change on their first production airplane. It is unfortunate, therefore, that we did not get together earlier on the program.

The greatest difficulty with the application of the new wing was the space for landing gear retraction. A slightly larger wing would have avoided the difficulty, but Mr. Berlin thought that it might be overcome.

The possibility of changing to a more conservative wing section near the fuselage, an NACA 65-series, for example, in order to avoid the danger of separation near the fuselage juncture, was also considered with them. Berlin, however, was not much afraid of this situation and considered the problem to be primarily one of filleting that could be worked out as an addition. We therefore agreed to go ahead with the original plan to carry the same section right into the fuselage.

The possibility was also discussed of building an experimental wing using makeshift methods. I concur in the stand Berlin takes on this possibility. "Final plans should be made on the supposition that the wing will work out as expected without important changes; if successful, we are then much further advanced after the flight tests." I certainly favor such methods and strongly recommend that the Government support the project financially. Since that time I have picked up a little information about the progress of the project from time to time, and had a few minutes to discuss it here with Mr. Berlin within the past two weeks, although most of the day of his visit was spent in going over the details of nearly all our airfoil results with Mr. Child, who is in charge of the Aerodynamics Department at Curtiss. As a result of these discussions, it appears that the project had not moved forward much in the preceding month since my visit to Curtiss, and it appears that they have considered the application of the wing as applying now to a new pursuit airplane development. Whether or not this pursuit may be considered satisfactory will depend on possible delays involved. If the new pursuit type is like the others, so that it will require an extended program of wind tunnel investigations, the application of the new wing to it does not meet our requirements for a flight application on which we can continue our investigations within a reasonable time. On the other hand, if it represents only a development of the P-40-D which can go forward at once, it may be considered satisfactory.

It thus appears that these questions may now be considered to advantage by the Aerodynamics Committee. For that reason, the preceding outline of this work has been prepared for circulation to the members. It is hoped that the Army representatives in particular and Mr. T. P. Wright may find time to investigate the questions brought up and the present status of the project, so that they may report on and discuss our progress at the next meeting of the Committee.

Document 4-27(d), G.W. Lewis to LMAL, "Report by Mr. Jacobs on present status of laminar-flow wing development, for next meeting of the Aerodynamics Committee, to be held the latter part of January," December 1940.

Washington, D. C.
December 14, 1940.

From NACA
To LMAL

Subject: Report by Mr. Jacobs on present status of laminar-flow wing development, for next meeting of the Aerodynamics Committee, to be held the latter part of January.

1. Doctor Warner has taken up with me the memorandum report prepared by Mr. Jacobs, on low-drag wings, and submitted to Doctor Warner with a letter dated November 27. Doctor Warner requested my advice as to whether it would be desirable to send a copy of this memorandum to all the members of the Aerodynamics Committee.

2. I told Doctor Warner that I did not think it desirable to do so, as the subject of Mr. Jacobs' memorandum had to do largely with the application of a modified laminar-flow wing to the P-40 airplane, and with relationships between the Committee, the Army Liaison Office, and the Curtiss Company.

3. I suggested that Mr. Jacobs prepare a more general review of the subject for confidential circulation to the members of the committee in advance of the meeting of the Aerodynamics Committee which is to be held immediately following the annual meeting of the Institute of the Aeronautical Sciences in New York. It is requested that Mr. Jacobs prepare a general review of the present status of low-drag airfoils.

G. W. Lewis,
Director of Aeronautical Research.

Document 4-28(a-h)

(a) Vannevar Bush, Chairman, NACA, to Brigadier General C. L. Lindemann, Air Attache, British Embassy, Washington, D.C., 21 December 1940, RA file 290, LHA, Hampton, Va.

(b) G.W. Lewis, Director of Aeronautical Research, NACA, to Sir Henry Tizard, Chairman, Aeronautical Research Committee, c/o Director of Intelligence, Air Ministry, London, W.C. 2, England, 2 January 1941, RA file 290.

(c) H.T. Tizard, Ministry of Aircraft Production, Millbank, to Dr. George Lewis, Director of Research, NACA, 12 February 1941, RA file 290.

(d) G.W. Lewis to Tizard (via British Embassy for Diplomatic Pouch), 25 March 1941, RA file 290.

(e) Edward Warner, American Embassy, 1 Grosvenor Square, London, to Dr. George W. Lewis, NACA 1500 New Hampshire Ave., Washington, D.C., 25 August 1942, Langley Correspondence Files, NASA Record Group 255, Code E38-8, National Archives, Mid-Atlantic Region, Philadelphia, PA. (Copy also in Milton Ames Collection, Box 4, Files 51-2, Historical Archives, NASA Langley Research Center, Hampton, Va.).

(f) Eastman N. Jacobs, Principal Aeronautical Engineer, NACA Langley, to Engineer-in-Charge, "Low-drag airfoils in England," 22 September 1942, Langley Correspondence Files, RG 255, Code E38-8, National Archives, Mid-Atlantic Region, Philadelphia, Pa. (Copy also in Ames Collection, Box 4, Files 51-2, LHA, Hampton, Va.)

(g) Ivan H. Driggs, Aviation Design Research Branch, Bureau of Aeronautics, Navy Department, Washington, D.C., to Experiments and Developments Branch, BuAer, "British Views upon Airfoils for High Speed Aircraft," 16 August 1943, in Langley Correspondence Files, RG 255, Code A173-1, National Archives, Mid-Atlantic Region, Philadelphia, Pa.

(h) Ira H. Abbott, Senior Aeronautical Engineer, to Engineer-in-Charge, "British views upon airfoils for high-speed aircraft," 13 September 1943, in Langley Correspondence Files, RG 255, Code A173-1, National Archives, Mid-Atlantic Region, Philadelphia, Pa.

The longest string of documents in our volume up to this point tell an illuminating story of the critical British reaction to the NACA laminar-flow airfoils and the equally critical response of the NACA's airfoil experts to it. In essence, the British were quite skeptical of the American data because it derived from aerodynamically clean test models that could not possibly perform as well in actual operation. They felt, as Edward P. Warner reported back from London in August 1942 (28-e), that "the establishment of laminar flow can have only a relatively small effect," and that the outstanding performance of the P-51 Mustang, with which they were greatly impressed, had "little to do with" the laminar-flow wing.

The NACA airfoil experts thought the British thinking about laminar-flow airfoils was generally wrong. No one in the United States was saying that the new wings could perform as predicted unless the aircraft operators, i.e., the Allied air forces, learned to maintain the highly polished and clean wing surfaces that were required. Part of the reason for the mistaken British opinion also involved differences in how aerodynamic data was gathered and the fact that the British lacked the same low-turbulence equipment for testing.

On the other hand, it is obvious Warner was seriously concerned that the NACA laminar-flow results might in fact be too promising, and that skeptical British reaction was in fact on the mark. In his P.S. to George Lewis, he wrote, "Needless to say, I hope that the optimism on this subject which prevails in the United States will prove to be fully justified."

In key respects, the British analysis of the limited prospects of the laminar-flow wing proved quite correct, as Warner feared. R.A.E. engineers realized as early as 1942 what NACA engineers would not be willing to concede until later in the war: that the greatest advantage of so-called laminar-flow airfoils was not really low drag, as had been billed, but their excellent high-speed characteristics, which reduced compressibility problems to a minimum.

Document 4-28(a), Vannevar Bush, Chairman, NACA, to Brigadier General C. L. Lindemann, Air Attache, British Embassy, Washington, D.C., December 1940.

December 21, 1940.

Brigadier General C. L. Lindemann,
Air Attache,
British Embassy
Washington, D. C.

Dear General Lindemann:

Doctor Lewis informs me that the British Air Ministry would like to obtain such information as we have released on the so-called "laminar-flow airfoils."

The first confidential report released by the Committee was entitled "Preliminary Report on Laminar-Flow Airfoils and New Methods Adopted for Airfoil and Boundary-Layer Investigations." This is a general theoretical discussion with some preliminary results obtained in the low-turbulence wind tunnel at Langley Field. Subsequent to that, two reports have been released, entitled "Preliminary Investigations of Certain Laminar-Flow Airfoils for Application at High Speeds and Reynolds Numbers," and "Wind-Tunnel Investigation of the Lift Characteristics of an NACA 27-212 Airfoil Equipped with Two Types of Flap." The Committee has not released any reports on laminar-flow airfoils which contain the necessary information required by the aircraft designer. This is because we do not have a low-turbulence wind tunnel of a size adequate to investigate laminar-flow airfoils at high Reynolds Numbers.

To correct this situation and to furnish the best information that we have to American aircraft designers, we have invited to Langley Field representatives of the aircraft companies to discuss particular designs with members of our technical staff.

The Committee would be very pleased to have you send to Langley Field a representative of the British Air Ministry to discuss particular designs with the members of our staff.

Sincerely yours,

V. Bush,
Chairman.

Document 4-28(b), G.W. Lewis, Director of Aeronautical Research, NACA, to Sir Henry Tizard, Chairman, Aeronautical Research Committee, c/o Director of Intelligence, Air Ministry, London, W.C. 2, England, January 1941.

January 2, 1941.

Sir Henry T. Tizard,
Chairman, Aeronautical Research Committee,
c/o Director of Intelligence, Air Ministry,
London, W.C. 2, ENGLAND.

Dear Sir Henry:

For your information, I am attaching hereto a copy of a letter to General Lindemann, transmitting such information as we have prepared on the so-called "laminar-flow airfoils."

You will recall that when you were here I stated that we were working on the laminar-flow type airfoil but were not in a position to make a definite recommendation as a result of actual use of the airfoil in flight.

The situation has not changed. As yet we have not been able to have constructed a wing using the laminar-flow airfoil. A project for constructing such a wing for the Curtiss P-40 airplane has been under way for a few months, but very little progress has been made.

The nearest approach to the use of the laminar-flow airfoil is the wing that is used on the North American XP-51, designated by the British as the "Mustang". In cooperation with the Committee, the engineers of the North American Aviation Company have used a modified laminar-flow wing. The airplane has been flown, but recently crashed as a result of engine failure near the ground which necessitated a forced landing in a rough field.

I have talked with the pilots, and they have advised me that the stalling characteristics and the control characteristics of the airplane are very satisfactory. We do not have any indication as to the drag characteristics of the wing or as to the performance of the airplane with all-out power, as the engine was never operated at more than sixty per cent of its rated power before the crash.

With kind regards and best wishes for the coming year,

Sincerely yours,

G. W. Lewis,
Director of Aeronautical Research

Document 4-28(c), H.T. Tizard, Ministry of Aircraft Production, Millbank, to Dr. George Lewis, Director of Research, NACA, February 1941.

12th February 1941.

Dear Dr. Lewis,

I was much interested to have your letter of January 2nd, but sorry to hear that your Curtiss P.40 aeroplane with the new wings had made very little progress so far. We hope you will keep us informed about the progress of these experiments as we attach a great deal of value to them.

It may interest you to know that we have had an airfoil .20c thick with maximum thickness at .50 of the chord in flight, and have achieved transition points on the upper and lower surfaces as far back as .6 of the chord; so we feel that we have already made the first step from the laboratory stage into the field of practical design.

I am hoping that Mr. Relf, whom you know, will be able to pay a visit to America this Spring, and before he goes Dr. Darwin, the present Director of the National Physical Laboratory, will be going to Washington as the Head of our Scientific Mission there. Darwin is a member of the Aeronautical Research Committee, although he would not pretend to be an expert on aerodynamics. I am sure, however, that he will be anxious to get into touch with you.

Yours very sincerely,

H. T. Tizard

Dr. G. W. Lewis,
Director of Aeronautical Research,
National Advisory Committee for Aeronautics,
Navy Building,
Washington, D. C.

Document 4-28(d), G.W. Lewis to Tizard (via British Embassy for Diplomatic Pouch), March 1941.

March 25, 1941.

Sir Henry T. Tizard,
Ministry of Aircraft Production,
Millbank, S. W. 1,
London,
ENGLAND.

Dear Sir Henry:

Thank you very much for your letter of February 12, 1941. I am indeed very pleased and interested to learn that you have constructed and flown a type of low-drag airfoil .20c thick with maximum thickness at the 50 percent point. The results that you have obtained in achieving transition points on the upper surface as far back as .6 of the chord are most encouraging.

Unfortunately, the necessity of expediting the production program of present types of aircraft has made it impossible for us to obtain flight tests of the low-drag wing. The nearest we have come to it is, of course, the wing used on the North American "Mustang." I have talked to the pilots who have flown this airplane and they advise me that it has good flying characteristics and good stalling characteristics, and the high-speed performance of this airplane exceeds by some eleven miles the expected performance. All of the increase cannot, of course, be attributed to the low-drag wing. A part of it, no doubt, results from the clean design.

The delay in applying a low-drag wing to the P-40 was caused by the fact that an entirely new landing gear would have to be designed to eliminate the projection at the leading edge of the wing on the present P-40. The P-60 airplane, which is a modified P-40 using the low-drag wing, is now under construction and has been approved as a production type, although we have no flight tests.

Mr. Relf's proposed visit to America would be most helpful, and I shall be delighted to see him. I am pleased to learn that Doctor Darwin will be in Washington in the near future.

Mr. Taylor, who is working under the direction of Professor Parkin on the icing problem, together with two assistants, has been in Washington and spent a day at Langley Field. We are having a meeting of our Special Subcommittee on Deicing Problems about the 15th of April. Mr. Taylor will be invited to attend this meeting.

You will recall that we fitted the Lockheed 12 airplane with a heating system from the exhaust of the engine. This modification was completed some time ago, but unfortunately we have not been able to find any severe icing conditions on the West Coast. There is a great deal of interest in the use of heat as a means of deicing

the wings and possibly the tail surfaces. The Douglas company is at present designing a heating system using the Stewart Warner gasoline burners plus the heat from the engine oil radiators, with the idea of using this method of deicing on the DC-6 and the XA-26.

Any further information on the results you obtain in the flight tests with the low-drag wing will be greatly appreciated.

Sincerely yours,

G. W. Lewis
Director of Aeronautical Research

Document 4-28(e) Edward Warner, American Embassy, 1 Grosvenor Square, London, to Dr. George W. Lewis, NACA 1500 New Hampshire Ave., Washington, D.C., August 1942.

American Embassy
1, Grosvenor Sq.,
25 August 1942.

Dr. George W. Lewis,
National Advisory Committee of Aeronautics,
1500 New Hampshire Ave.,
Washington, D. C.

Dear George:

I have now had the opportunity of talking about laminar-flow wings at some length with Farren, Perring, Douglas, Stevens, and Squire, at the R.A.E., and have also discussed with them various designers in the industry. I am sure you are well informed on the general point of view of British aerodynamicists, but possibly I can add something to the information which you have previously received.

The general belief at the R.A.E. is that the establishment of laminar flow can have only a relatively small effect, and they are not satisfied with the direct measurement of drag in the wind tunnel in the case of the laminar-flow airfoils. They prefer the computation of drag, based on a direct study of the type of flow prevailing over the various portions of the wing, as being both more revealing as to the functioning of the wing and more accurate for practical use. The feeling continues, much as it was a year ago, that true laminar flow will in any case be restricted to a comparatively limited portion of the wing, and that the wings had better be designed in recognition of that fact; and that there cannot in any event be any maintenance of laminar flow in the slip-stream. I suppose there would be general agreement on the latter point.

Another point that occasions great anxiety at the R.A.E. is the effect of interferences, such as those of body-wing intersections, on the laminar-flow performance. Another is the determination of the maximum lift coefficient. They are very doubtful of the adequacy, or indeed the validity, of existing wind-tunnel techniques for this purpose.

In the specific case of the P-51, the performance of which has made a great impression, there is official conviction here that the laminar-flow wing has little to do with the performance. It was first remarked, when I discussed that airplane; "Well, it really hadn't much of a laminar-flow section;" that was subsequently modified to a suggestion that the wing design was such that laminar flow could only exist near the tips; and finally that a skin joint running parallel to the span was sufficient to destroy any laminar flow beyond the first 25% of the chord. Mr. Squire, one of the younger men who seems to be specializing in this matter under the general direction of Douglas, had computed the effect of laminar flow on the P-51 performance as being 5 or 6 m.p.h. at most. The remainder of the good performance was attributed to a variety of other small points, including an exceptionally good surface finish and the position of the radiator.

One expression of the general position of the R.A.E. was that they felt relatively little interest in the laminar-flow section as such, but a great deal in compressibility; and that it fortunately happened that the airfoil form favorable to laminar flow was also one favorable to keeping compressibility to a minimum.

Designers here are not much excited about the idea. New airplanes are coming through without laminar-flow sections, and there is some disposition to feel that such sections will present their greatest benefit on some other fellow's airplane. One idea that I have encountered is that they are of substantial value only on machines for very long range, where most flights will be at very close to a fixed approximate angle of attack.

The Typhoon II is using a wing designed to have some laminar-flow characteristics, its maximum thickness being at 38% of the chord. The finish of the prototype is exceptional and makes even the P-51 (Mustang) seem crude by comparison. Several coats of pyroxylin lacquer are used, with a final high surface polish, and the construction is so smooth and the filling of cracks and depressions so well done that it looks like a plywood construction. Only the closest examination serves to show location of any of the rivets, or joints in the skin. I believe however that the wing, although freer from abrupt local discontinuity than the Mustang's, may not be quite so free from waviness. The exceptional smoothness of contour and the freedom from any ripples or distortions in the wing of the Mustang, helped by the thickness and the relatively generous support of the skin, are widely remarked. I think the Hawker people expect more gain in performance from the direct effect of a good surface finish, and from the fact that the wing thickness has been reduced by 20% as compared with that of the Typhon I, than from the change in airfoil section.

I was disturbed, some days after these conversations at the R.A.E., when I heard from Colonel Chidlaw, who accompanied General Echols here, that direct comparative tests of a laminar-flow wing and one of conventional section on the P-47 had shown very little benefit from the former. That would seem rather to confirm the British position. I hope nothing will interfere with Relf's trip to the United States, of the prospect of which you told me, as it ought to be most useful for Relf and Jacobs to get together and talk a lot of these matters out, and discuss the interpretation that is to be put on the data so far accumulated and on such as are yet to be secured.

Sincerely,

Ed Warner

P.S. I have tried in this letter to give a fair indication, by particular example, of the feeling that exists here with respect to laminar-flow wings. Needless to say, I hope that the optimism on this subject which prevails in the United States will prove to be fully justified. I think that in this particular case the British have rather resigned hope of large accomplishment before they have had full justification for doing so; but in saying that, I want to couple with it an expression of the greatest admiration for the general quality of the British research effort and the way in which it is being carried on in wartime. As was the case during my visit a year ago, I find the variety and the quality of the work being done at the R.A.E. and elsewhere most impressive.

Document 4-28(f) Eastman N. Jacobs, Principal Aeronautical Engineer, NACA Langley, to Engineer-in-Charge, "Low-drag airfoils in England," September 1942.

Langley Field, Virginia
September 22, 1942

MEMORANDUM For Engineer-in-Charge.

Subject: Low-drag airfoils in England.

Reference: Dr. E. P. Warner's let. To Dr. G. W. Lewis, Aug. 25, 1942.

1. It is unfortunate that the British are so pessimistic about realizing substantial gains through the use of extensive laminar flow on wings, and the situation is not improved by Colonel Chidlaw's premature comments on results obtained by the P-47. I had hoped that we could count on the British to show the Army how to maintain the desired wing surface conditions in service in case our military people fail in this important phase of the development. Sir Henry Tizard assured me that they would do so if we could give them airplanes showing substantial gains.

2. I will look forward to talking with Relf about our low-drag-airfoil work, but think nevertheless that I should go to England as soon as the situation here permits.

Eastman N. Jacobs
Principal Aeronautical Engineer

Document 4-28(g), Ivan H. Driggs, Aviation Design Research Branch, Bureau of Aeronautics, Navy Department, Washington, D.C., to Experiments and Developments Branch, BuAer, "British Views upon Airfoils for High Speed Aircraft," August 1943.

NAVY DEPARTMENT
Bureau of Aeronautics
Washington

16 August 1943

From: Aviation Design Research Branch.
To: Experiments and Developments Branch.

SUBJECT: British Views upon Airfoils for High Speed Aircraft.

1. During a recent trip to England an opportunity was afforded to discuss the subject problem with Captain Liptrot of the M.A.P., Dr. Goldstein and Mr. Relf of the N.P.L., Mr. Smelt of the R.A.E. and various engineers at Gloster Aircraft and de Havilland. With respect to compressibility all the people contacted were in complete accord but the Low Drag Airfoil as suggested by the N.A.C.A. meets with no uniform acceptance or approval.

2. All of the newer fighters and particularly those using jets are employing airfoils that have much lower thickness ratios than present American practice. The root sections are almost invariably 12 to 13% thick and the tip sections around 8 to 8 +%. An exception to this statement is the De Haviland "Ace" which uses a 15% airfoil at the wing root. The British are convinced that thickness ratio is the most important single variable affecting the critical Mach number of any airfoil; the shape, providing it is reasonably good, having less effect. The sections are being designed for as near a rectangular pressure distribution as possible at the design lift coefficient which is determined by the design speed of the airplane and the wing loading. Thus for any given C_L the least possible maximum negative pressure is obtained and consequently the highest critical Mach number. This principle is not the same as that used by the N.A.C.A. in the development of the L.D. sections, where the airfoil design is such that the negative pressure curve at first rises sharply and then at a less rapid rate to a point well back on the chord line, after which the pressure is recovered by a rapid decrease of negative pressure to the trailing edge. The sketches below illustrate the difference in principle between the two airfoil types.

3. Dr. Goldstein believes that the N.A.C.A. type airfoils have sacrificed something in critical Mach number in order to obtain more extensive laminar flow and a higher C_{Lmax} than he believes necessary. It is probable that the British type airfoil will have a slightly higher critical speed than the N.A.C.A. type at the same lift

coefficient due to a lower peak negative pressure. However, the positive slope to the pressure curve of the N.A.C.A. type helps to stabilize the otherwise unstable laminar boundary layer and therefore promote a lower profile drag at the design lift coefficient. It is probable that the British type airfoil will require much better surface conditions to obtain the same percentage of laminar boundary layer, but the British seem willing to accept this reduction to obtain higher critical speeds. Mr. Smelt was of the opinion that 35% laminar flow could be readily obtained in practice. Dr. Goldstein made the point that in the final analysis the operating and maintenance people will determine the amount of laminar flow that will be obtained on any wing, no matter what its shape or original condition when it left the manufacturer. He pointed out that accumulations of dried salt spray or hoar frost or the results of careless walking over the wing surface will probably upset the delicate balance in the unstable laminar boundary layer, resulting in performance that is inferior to that which would be obtained from an airfoil not so radically designed. Dr. Goldstein said that it might be that a change in airfoil section would be necessary along the span of a tractor airplane if it were desired to obtain the maximum possible L.D. effect, since an airfoil that would be most suitable outside the slipstream might be quite inferior when exposed to the turbulent air thrown back by the propeller.

4. Dr. Goldstein stated that he has developed means of calculating the airfoil shape required to produce any chosen pressure distribution curve. It was impossible to arrive at any understanding of his mathematical processes in one or two days so that no attempt was made to do so. Dr. Goldstein seemed most willing to cooperate but stated that it would take a trained mathematical physicist a number of months work at N.P.L. to become thoroughly familiar with all the processes. He offered to train any man that the Bureau of Aeronautics might desire to send to him to work in cooperation with his own staff for not less than 6 months. He also stated that he would further like to furnish the Bureau of Aeronautics with the ordinates of some of his airfoils for test in the new Carderrock tunnels if desired. He pointed out that as far as L.D. testing is concerned the tunnel turbulence must be very low. Not knowing just how far it was planned to reduce the turbulence in these tunnels no arrangements were made to obtain such ordinates for test while in England. Dr. Goldstein is of the opinion that the pressure distribution at high lift coefficients can be controlled to a reasonable extent so as to increase the critical Mach number of the wing during a high "g" turn at altitude. He believes this requirement to be of primary importance in maneuverability. A given airfoil may be greatly superior to another in giving a high C_{Lmax} when tested at low speed and would lead one to assume that greater maneuverability would result from its use. On the other hand the second airfoil might actually prove superior when executing a high speed turn at altitude since it might be designed to give a more favorable pressure distribution at the angle for C_{Lmax} and thereby be less affected by compressibility. Dr. Goldstein exhibited a drawing of the airfoil that he has designed for the new Spitfire (Griffon engine) on which he had tried out his theories. The section appeared perfectly normal with no concavity over the rear portion. The high speed tunnel tests had proven that a reduction in the drag of about 25% at a Mach number of .80 could be anticipated in comparison with the original Spitfire wing section. This airfoil is 12% thick.

5. Dr. Goldstein discussed items that he considered must be decided before the proper choice of an airfoil could be made for any airplane. These points are repeated below as given to the writer. It is to be noted that not all of the following list will apply to every airplane; for instance, a heavy low speed plane will not be concerned with compressibility.

1. The desired critical Mach number for wing and tail surfaces, taking interference into account.
2. The stowage room desired within the wing for guns, ammunition, fuel, landing gear and structure. This and point 1 largely determine the thickness ratios that can be used.
3. The lift coefficient at which the drag and the Mach number are to be the most favorable.
4. The wing geometry, taper ratio, aspect ratio, etc. This is required in order to control the position and extent of the stall.
5. The desired moment coefficient at zero lift coefficient in order to control the tail loads in a dive.
6. The desired C_{Lmax} and the flap type to be employed to obtain it.
7. The lateral control requirements as defined by the turning circle and time to bank.
8. The desirability of obtaining a small variation of the profile drag coefficient with C_L that is a high value of wing efficiency, e. This point is particularly important for the long range, slower airplanes.
9. The type of wing construction and the surface conditions the manufacture proposes. This point includes consideration of holes, cracks, doors and their fit slots and general surface fairness.
10. Whether the maintenance personnel are capable of keeping up the surface properly under operational conditions.
11. The tactical use of the airplane, whether fighter, intruder, bomber, etc.
12. The propeller location, whether pusher or tractor.

After Dr. Goldstein had enumerated the above items, it was very evident why he did not believe that airfoils should be "taken off the shelf" as he expressed it, but must be scientifically designed for each problem. This statement is probably true at this time but it would appear that as experience is obtained in the use of his methods families might be developed which would be suitable for various airplane types.

6. Although the point was not specifically discussed with Dr. Goldstein it appears to the writer that too much consideration is being given to airfoil section characteristics as measured in two dimensional flow and that not enough attention is being paid to what happens when the airfoil section is employed on a wing operating in a three dimensional flow. Extreme types of pressure distribution curves may be very unstable and degenerate into entirely different shapes under the action of strong lateral flows which may exist in actual practice. Present wind tunnel tests on N.A.C.A. type L.D. wings show such lateral flow at lift coefficients only moderately above the design C_L. It appears that there are many points that must be cleared up by thoughtful analysis and careful testing before all the airfoil theories can be accepted wholesale.

7. Dr. Goldstein was questioned in regard to two phenomena that had been observed in testing L.D. wings in the N.A.C.A. tunnels. The first was the extremely poor value of the wing efficiency, e, caused by an unusually rapid increase in C_D with C_L. He stated that their L.D. sections had been tested in two dimensional flow only, since they had no tunnels that gave sufficiently high R.N. at a turbulence factor low enough to make complete wing tests of any value. The second question concerned the discrepancy between the minimum drag of complete wings as determined on the wind tunnel balance and as found by the momentum survey method in the two dimensional tunnel and at the center of the span of a model wing. He stated that there should be complete agreement if all of the momentum changes were determined by the survey and integrated over the span. It was his belief that the survey should extend from tunnel wall to tunnel wall and should not be confined to one particular section of the flow aft the wing. In this connection, he pointed out that he did not agree with the N.A.C.A. with respect to the method used in determining the lift coefficient in the two dimensional tunnel. He stated that in order to determine the lift by measuring the pressure change on the tunnel walls, it was necessary to go to infinity in both directions and there might be considerable error in the extrapolation employed by the N.A.C.A. Dr. Goldstein prefers to measure the pressure distribution over the airfoil and integrate that. This latter method does appear to be the most direct and to serve another purpose as well, since pressure distribution curves are essential to the predication of critical Mach numbers from low speed tests.

8. Invariably the British feel that the P-51, Mustang is a remarkable airplane but there is no acknowledgment that its superior performance is due to a semi-low drag wing. Captain Liptrot of the M.A.P. stated that the drag of this airplane as delivered from the manufacturer is 50 lbs. at 100 ft./sec. while the Spitfire is about 61 lbs. at the same speed as received. He stated that when the latter airplane is faired up with tape over all cracks, etc., and the surface put into the same condition as that of the Mustang, the drag is reduced to the same figure of 50 lbs. It is his belief that the superior performance of the P-51 should be credited to the Manufacturing Division of North American for producing the airplane with no cracks or leaks, correct alignment of all doors, and cowlings, and in maintaining the proper surface conditions over the whole airplane in quantity production. It is his belief that a like treatment to any airplane which has a good basic aerodynamic form will produce like results. This appears to be the very realistic and eminently practical viewpoint of an experienced engineer.

Ivan H. Driggs

Document 4-28(h), Ira H. Abbott, Senior Aeronautical Engineer, to Engineer-in-Charge, "British views upon airfoils for high-speed aircraft," September 1943.

Langley Field, Virginia
September 13, 1943

MEMORANDUM For Engineer-in-Charge.

Subject: British views upon airfoils for high-speed aircraft.

Reference: NACA let. Aug. 27, 1943

1. The British views upon airfoils for high-speed aircraft as expressed in the memorandum by Mr. Ivan H. Driggs, enclosed with the reference letter (a), do not differ fundamentally in any serious way from our views. Several details of Mr. Driggs' memorandum, however, differ sharply from our views and deserve comment. It is particularly surprising that the views expressed differ in some details so greatly from the views expressed by Dr. Goldstein at the time of his last visit to this laboratory.

2. It is unfortunate that comparisons should be emphasized between British wings designed for extremely high-speed aircraft and NACA low-drag airfoils, which have been designed for aircraft operating at lower speeds. Our work on airfoils has been largely confined to such airfoils as are of immediate interest to the Army and Navy, and most such airfoils have been developed for application to airplanes with designed for high speeds not over about 450 miles per hour. Neither the Army nor the Navy has shown interest in airfoils for extremely high-speed airplanes. NACA low-drag airfoils developed for such airplanes would be very similar to the British airfoils although they might differ in detail.

3. It is our belief that the design principles of NACA low-drag airfoils are con-

sistent with high speed. It is true, of course, that if nothing else except freedom from compressibility at extreme speeds is desired, slightly higher critical speeds may be obtained by large sacrifices in other desirable qualities. We agree that thickness ratio is the most important single variable affecting the critical Mach number of any airfoil. Airfoils for extremely high speeds must, accordingly, be thin. The principle of designing for as nearly a rectangular load and pressure distribution as practical has been in use for a long time in the design of NACA low-drag airfoils. It should be pointed out that carrying this principle to an extreme, as apparently recommended in the memorandum by Mr. Driggs, results not only in inability to maintain extensive laminar flow and in a vanishingly small low-drag range, but also in a vanishingly small range of lift coefficients where high critical Mach numbers are obtainable. The low-drag range is also the range of high critical Mach numbers. The type of pressure distribution advocated by Mr. Driggs would peak near the leading edge at only small departures from the design lift coefficient, with serious loss in critical speed. We question the practicability of an airfoil design which would allow high critical speeds over such a small range of lift coefficients. Incidentally, the sketch showing the type of pressure distribution of NACA low-drag airfoils is not typical.

4. We have recently undertaken work to increase the critical Mach numbers of NACA low-drag airfoils beyond the point possible with rectangular load distributions. This work shows considerable promise, although it is not yet evident to what extent other desirable properties of the airfoils must be sacrificed to obtain appreciably higher critical Mach numbers for a given thickness of airfoil.

5. We agree that maintenance will determine the amount of laminar flow obtainable no matter what condition the wing was in when it left the manufacturer. With regard to the effects of roughness, the airfoil sections recommended by us will not have inferior performance to conventional sections when equally rough.

6. With regard to methods of deriving airfoils, it appears from what we know that Dr. Goldstein is rapidly approaching our methods. Exactly what method is now used by Dr. Goldstein is not known, but available information indicates he is following a line of development of processes very similar to ours.

7. We appreciate the importance of three-dimensional flow but feel that such effects have sometimes been exaggerated. We cannot escape the fact that good two-dimensional test equipment is in existence and has amply demonstrated its worth. Low-turbulence three-dimensional test equipment is not yet available. Pending the time such equipment is available, existing equipment should be used to its best advantage.

8. The determination of wing efficiency factors with low-drag airfoils has caused considerable trouble, principally because the fundamental concept is erroneous. Any airfoil with a low-drag range will show a more rapid rise of drag outside the low-drag range than will a conventional airfoil, even though the actual drag at any particular lift coefficient be no greater. It would be more nearly fair to say that the low-drag airfoil shows a sharper reduction in drag within the low-drag range. The picture has been further complicated by some tests of wings with poorly chosen sections and by tests made at too low values of the Reynolds number. Rapid scale effects on drag occur outside the low-drag range at all Reynolds numbers obtainable in any three-dimensional-flow tunnel.

9. We agree that drag values obtained by balances and wake surveys should check. Such wake surveys have been made on numerous occasions over the whole span, as suggested by Dr. Goldstein. It is my belief that the discrepancies shown by these measurements, when present, may be explained on the basis of inadequate corrections to the balance results.

10. Surprise is felt that Dr. Goldstein does not agree with us with respect to our methods of measuring lift in the two-dimensional tunnels. Dr. Goldstein went over this method with us and expressed satisfaction with it. Considerable error cannot be present in our method for the reasons stated because the so-called "extrapolation" amounts to only a few percent in most cases and is made as accurately as perfect fluid theory permits. In addition, several checks of the method against balance measurements and lifts obtained from integration of pressure distributions over the model have been made with excellent results. It should also be noted that pressure-distribution orifices in the model interfere with the flow over the model producing, in some cases, erroneous measurements.

11. It is agreed that excellent performance of any airplane will be obtained only by attention to detail in every particular. Any item of an airplane can ruin its performance, while no one item by itself can make a good airplane. It is considered highly improper to pervert this argument into one for accepting a mediocre treatment for one part of the airplane because of the effects of other details.

12. In view of this memorandum, it is thought that a visit by Mr. Driggs to the Laboratory to discuss airfoil problems would be mutually advantageous.

Ira H. Abbott
Senior Aeronautical Engineer

Document 4-29

Edwin P. Hartman, NACA West Coast Coordinating Office, to Chief of Research Coordination, NACA, "Information from the industry on the application of low-drag airfoils," CONFIDENTIAL, 29 July 1944, Langley Correspondence Files, RG 255, Code A173-1, National Archives, Mid-Atlantic Region, Philadelphia, PA.

By the summer of 1944, U.S. aircraft manufacturers had made enough different applications that it was hard for the NACA to keep up with them. In this memorandum Edwin P. Hartman of the NACA's Western Coordinating Office in Santa Monica, California, compiled a list of the airplanes designed on the West Coast to which NACA low-drag airfoils had been applied. The list turned out to be 27 airplanes long, with 13 of the airplanes currently flying.

But from the historical perspective this memorandum contributes much more than just a handy digest of World War II laminar-flow applications. The last part of Hartman's memo, starting with Paragraph 11, offers the most direct, introspective, and critical commentary on the U.S. aircraft's industry's judgment of the laminar-flow research than has ever been put into the historical record. To summarize, Hartman reports that airplane designers in industry by mid-1944, at Douglas Aircraft Company in particular (Hartman worked from a Santa Monica office and thus dealt with Douglas engineers on a regular basis), felt that the laminar-flow airfoils had "not performed as might have been expected from the NACA data." "It has been a costly experiment," Douglas engineers had told him, "not only for the companies but also for the nation." Reading Hartman's report, one is reminded of the British skepticism. expressed more than two years earlier.

Document 4-29, Edwin P. Hartman, NACA West Coast Coordinating Office, to Chief of Research Coordination, NACA, "Information from the industry on the application of low-drag airfoils," CONFIDENTIAL, July 1944.

Santa Monica, California
July 29, 1944

MEMORANDUM For Chief of Research Coordination

Subject: Information from the industry on the application of low-drag airfoils.

1. Following your suggestions, I have taken preliminary steps to obtain much

available, reliable data as the industry has regarding the application of low-drag airfoils. Inasmuch as almost all the low-drag airfoils used by the west coast aircraft companies have been tested in the Committee's wind tunnels, either as individual sections or as parts of complete models or airplanes, it is presumed that the committee has all necessary data concerning the designations and profiles of these sections. It is also assumed that the Committee is in a position to obtain drawings showing the actual wing construction of these airplanes from the Army and Navy. Indeed, it is gathered from your memorandum that the Committee wants only the small amount of reliable airfoil test data known to have been obtained in flight by the North American and the Douglas Santa Monica aircraft companies and any similar data obtained by other companies.

2. To the best of my knowledge, the following is a complete list of the airplanes designed on the west coast to which NACA low-drag airfoils or some modification thereof have been applied.

Airplane	Now Flying	Airplane	Now Flying
1. B-29	x	15. BTD-1	x
2. XPBB-1 (?)	x	16. XB-35	
3. XF8B-1		17. N9M	x
4. XP-58	(AAL w-t tests)	18. XP-54	x
5. XP-80	x	19. XA-41	x
6. XR60-1		20. XP-81	
7. XB-42	x	21. XB-36 (C-99)	
8. XB-43		22. XPB5Y-1 (?)	
9. XC-74		23. D-2	x
10. P-51A, B	x	24. HK-1	
11. XP-51F, G	x	25. XF-11	
12. P-51H		26. XFR-1	x
13. P-82		27. XBDR-1	
14. A-26	x		

3. For all of these airplanes that are now flying, there should be some information, either quantitative or qualitative, indicating the success of the airfoil application. I believe, however, that only in the cases of the P-51A and the KP-54 have any quantitative measurements of section drag been made. In the case of the XC-74, the

drag characteristics of the chosen section were obtained in flight by extensive tests of a glove mounted on an A-17 airplane. Tests of gloves representing sections for the XR60-1 and also, I believe, the XP-80 (one on each wing of a P-38 airplane) are soon to be started by Lockheed.

4. In the procurement of the available flight-test drag data on low-drag airfoils, requests have been made to:

(1) North American for data on the P-51A and P-51F airplanes. (Some data on C_{Lmax} for the P-51F (or G) will be available in about two weeks.) The North American data on the P-51A are already in the hands of the NACA, and IMAL has of course obtained extensive additional data on the airplane during recent flight tests.

(2) Consolidated Vultee for section momentum drag data on the XP-54.

(3) Douglas Santa Monica for data on tests of the XC-74 glove on an A-17 airplane. Dr. Klein, to whom I was referred for these data, said that, because of certain peculiarities in their organization, he was not sure that the data could be made available to the Committee. He will, however, take the matter up with Mr. Raymond.

5. The just-mentioned data requested of the aircraft companies are, I gather, all that the Committee wants me to obtain. I will, however, take steps to obtain any further qualitative or quantitative information concerning the other low-drag-airfoil applications that the Committee may suggest.

6. Examination of the rather vague suggestions made by Aerodynamics Committee members, which apparently led to the NACA's decision to prepare a summary report, indicated that further investigation into the matter would be desirable. Therefore, in order to obtain a clearer picture of the industry's wishes with regard to the content of the report, I discussed the matter with Mr. L. E. Root, of Douglas, who apparently was the Aerodynamics Committee member who originated the suggestion of writing the summary report. The general subject of low-drag airfoils and the summary report was subsequently discussed with Messrs. L. L. Waite and E. J. Horkey, of North American; Drs. W. B. Oswald and F. Clauser, of the Douglas Aircraft Company, Inc.; and Mr. Philip Colman, of the Lockheed Aircraft Corporation. The following paragraphs present the ideas and suggestions obtained from the discussions with these men.

7. MR. ROOT: Concerning his suggestion that the Committee write a summary report on low-drag airfoils, Mr. Root said he had actually had in mind the writing of either two or three reports: the first one, a collection of existing NACA wind-tunnel and flight-test data with a rationalized explanation of their use in future low-drag-airfoil applications; the second, a collection of qualitative and quantitative information from the industry concerning all the details of their experience in applying low-drag airfoils to their airplanes; and the third, a report showing how present available data could be used to obviate the troubles that the companies have encountered and providing the necessary additional material required for the successful application of the airfoils.

8. The data for the second report could, he said, be obtained by asking the aircraft designers such questions as:

a) What factors entered into the choice of the section used and what were the reasons for selecting a low-drag section?

(b) Did data from wind-tunnel tests confirm the basis for selection?

(c) What steps were taken to acquaint engineering and production groups in the plant with the problems of low-drag-airfoil application?

(d) Did flight-test data confirm the basis for the airfoil selection?

(e) Has the airfoil selected affected the aileron performance?

(f) Has the airfoil selected affected the stability and control of the airplane?

(g) Did any weight penalty result from the use of the section?

(h) Has the maximum lift coefficient obtained in flight been as much as expected at the time the airfoil was selected?

9. The Douglas aerodynamics group is under high pressure at the present time because of weaknesses displayed by the BTD-1 and the A-26 airplanes and is therefore inclined to be critical of factors (low-drag airfoils) which, they think, may have contributed to these weaknesses. I gathered that neither the BTD nor the A-26 developed the maximum lift coefficient that was expected when the airfoils were selected, and it is apparent from the performance of the airplanes that extensive laminar flow is obtained in neither case. I believe that Mr. Root also attributes certain stability difficulties of the BTD to the airfoil selection.

10. Mr. Root stated that, as long as Douglas El Segundo continues to build Navy airplanes, they will probably never again make use of low-drag airfoils, at least not until data are forthcoming from the NACA, or elsewhere, proving that a definite gain can be obtained with these airfoils and showing how a successful practical application can be made. Douglas's future use of conventional airfoils will be determined not only by the fact that the Navy believes low-drag sections to have no advantage over NACA 2400 series sections at high speeds and to have serious disadvantages at low speeds but also to the fact that the aerodynamics group has no evidence, of its own or from other companies, with which to prove to the Douglas engineering management that low-drag airfoils are superior or even equal to conventional airfoils.

11. Douglas engineers appreciate that the NACA cannot be expected to come out and build their wings for them and that the industry must be willing to take some chances in trying new things in order to improve the efficiency of its aircraft. They feel, however, that the industry has been willing to take these chances, as evidenced by the 20 or more low-drag-airfoil applications on west-coast airplanes, and that, on the whole, the airfoils so applied have not performed as might have been expected from the NACA data on those airfoils.

12. It has been a costly experiment, Douglas engineers think, not only for the companies but also for the nation. They feel that it is high time for a critical examination of all the applications to be made to find out why the failures have occurred and why, in none of the applications that Douglas engineers know of, has extensive laminar flow been obtained.

13. Mr. Root said that the industry had been encouraged directly by the NACA, as well as indirectly through recommendations made by the NACA to the services, to use low-drag airfoils. He feels, therefore, that the NACA has some responsibility in the success or failure of the application of low-drag airfoils to aircraft. He said he thought it would be to the interest of the NACA to do everything possible to ensure that its development of low-drag airfoils did not collapse because of unsuccessful applications which it might have helped prevent by taking a closer interest in the applications.

14. Douglas aerodynamics men had planned to measure the section drag of the A-26 and the SB2D-1 wings but were prevented from doing so by organizational difficulties. They feel that only the NACA is in a position to obtain wing-section drag data on airplanes on which low-drag-airfoil applications have been made. Measurements that the Committee could make on these airplanes would, Douglas engineers feel, be of tremendous assistance in future applications of low-drag airfoils.

15. Mr. Root pointed out that the success of a Navy airplane depended very greatly on its performance at low speeds. In this connection, he said he thought the designers of aircraft did not appreciate the dangers of obtaining low maximum lift coefficients through the use of low-drag airfoils. He also thought that the thicker wing-tip sections recommended for low-drag airfoils would have a distinctly deleterious effect upon lateral control, so important in Navy airplanes.

16. Douglas engineers believe that it would be highly desirable to make comparative tests on an airplane equipped, in the first instance, with a conventional, say NACA 2400 series, airfoil and, in the second instance, with a low-drag airfoil. If the airplane with the low-drag airfoil showed outstandingly improved performance, it would provide tremendous encouragement for designers to use low-drag sections in the future.

17. According to Douglas engineers, designers are now in a questioning, skeptical frame of mind. Many applications of low-drag airfoils have been made but there is no definite evidence that the performance of these airplanes is improved by the use of low-drag airfoils or is even as good as if conventional sections had been used. Considering the millions and millions of dollars that are going into these airplanes, Douglas engineers feel that it would be well worthwhile to make some experiments

comparing conventional and low-drag airfoils on different types of airplanes.

18. Mr. Root pointed out that the rush of the construction of a new military airplane was such that the company just did not have the time to make the necessary airfoil tests to properly select a low-drag airfoil for the airplane and thus was forced either to use a conventional section with known characteristics or to blindly select a low-drag airfoil from the far too meager supply of low-drag-airfoil data that are available.

19. Another handicap, Mr. Root said, was that in order to make a successful low-drag-airfoil application, it was necessary to reeducate engineering, tooling, and production groups throughout the whole plant in the problems associated with the application. Even after that was done, he said, in the rush of production and with the poor type of labor available, it was almost impossible to build airplanes with sufficiently smooth surfaces to obtain extensive laminar flow. It was his opinion, Mr. Root said, that the most rearward limit of laminar flow on a low-drag airfoil was the location of the first wing-skin joint, usually at the front spar.

20. NORTH AMERICAN COMMENTS: Messrs. Waite and Horkey agreed that a report collecting and rationalizing existing NACA wind-tunnel and flight-test data on low-drag airfoils would be helpful to designers, but they saw no use in the Committee's preparing a report of the type suggested by Mr. Root describing the experiences of other companies in the application of low-drag airfoils.

21. Although North American engineers are not too hopeful of obtaining extensive laminar flow on any of their low-drag-airfoil applications, they do feel that their low-drag-airfoil application in the case of the P-51B and P-51F has been successful. Their feelings in this matter are apparently based on the generally good performance of the P-51B and F airplanes, on the absence of serious compressibility difficulties, and on the good stalling characteristics and fairly low stalling speed of the airplane.

22. Mr. Waite said he would prefer to have the NACA go ahead and get fundamental data on the low-drag sections and leave the building of the wings to them. Mr. Horkey said he thought that all aircraft companies would like to have the NACA run tests on families of airfoils to fill in the vast gaps that exist at present in airfoil data. Despairing of getting such data from the NACA, aircraft companies were reported to be planning to obtain the data from tests in their own or other available wind tunnels. I gathered that North American engineers would also like to see comparison tests run on an airplane equipped alternately with a conventional wing and with a low-drag wing.

23. North American engineers said they would furnish the Committee with all the data they had from their tests of the wings on P-51 airplanes; however, it was their belief that the Committee already has all the reports they have prepared up to the present time. Mr. Horkey said, however, that they would supply the Committee with the results of some maximum-lift-coefficient determinations which they were making on the P-51F airplane and which should be available in a couple of weeks.

24. Concerning the optimum location for the wing-skin joint, Mr. Horkey stated that they had tried three different locations from the stagnation point aft and did not know which was best.

25. Mr. Waite stated that high-speed airplanes were being designed in this country having wing sections only 10 percent thick. He said he was afraid the companies would find themselves in trouble with airfoils of this thickness although there seemed to be no way of avoiding shock-wave formation with any thicker sections. Some other solution to the airfoil problem for high-speed airplanes is clearly needed, North American engineers believe. They also feel that the Committee should be developing airfoils for efficient-as-possible operation in the supercritical and supersonic realms of flight.

26. DOUGLAS SANTA MONICA COMMENTS: Dr. Oswald thought the summary report the Committee plans to write on low-drag airfoils would be of some help, but neither he nor Dr. Clauser thought that any report covering the experiences of the industry would be of much benefit or a feasible project for the NACA. Dr. Oswald believes, however, that the NACA should make a careful examination of all the airplanes with a low-drag-airfoil application to find out why none of them seem to be getting extensive laminar flow and to obtain some useful information that would be helpful to the industry in future applications and to the NACA in planning further research on low-drag airfoils. He feels that the NACA is in the best position to obtain and correlate flight-test data on airplanes with low-drag airfoils and that this should be an important part of the Committee's airfoil-development program.

27. Dr. Oswald pointed out that not nearly sufficient data exist to enable a designer to make a rational selection of a low-drag airfoil. The only alternative is for the company to run an extensive test program of its own for which there was little time available and which was difficult to sell to the company management. The real need of the industry, Dr. Oswald stated, is for some new airfoils that will have a much better chance than present ones of achieving the favorable characteristics which NACA test data credit to present low-drag airfoils.

28. Millions of dollars have been spent in low-drag-airfoil applications which apparently have been unsuccessful, Dr. Oswald said, and he thought it was time for something to be done about it. The hands of the Douglas aerodynamics groups are tied in this matter. They would like to examine their own low-drag-airfoil applications to find out what was wrong with them but, because of organizational difficulties, they are prevented from doing so. The help of the NACA is therefore needed and can best be supplied by careful examination and tests of existing applications and through further research to provide the necessary data for a successful practical application of these airfoils.

29. Dr. Clauser felt that new data were needed rather than a rehash of the existing data already available to the industry; he also thought that a collection of the opinions of the various companies with regard to the application of low-drag airfoils

would be of no great value to Douglas. Dr. Clauser emphasized the need for fundamental research on airfoils rather than just running tests on families of airfoils.

30. The suggestions that Drs. Oswald and Clauser made for needed data are included in the list at the end of this memorandum, which presents the suggestions for needed research obtained during my discussions with various men in the industry.

31. I inquired of Dr. Clauser concerning the availability of the data they obtained in the A-17 glove tests; he referred me to Dr. A. L. Klein, who was said to assist Mr. Raymond in matters of that kind.

32. LOCKHEED COMMENTS: My conversation on the low-drag-airfoil problem with Mr. Colman was very limited. Mr. Colman said he thought the survey report that the Committee was planning to write on low-drag airfoils would be helpful, but he also said he thought the opinions and experiences of other companies regarding the application of low-drag airfoils would neither be of much help to them nor make a suitable subject for an NACA report. He said that, although Lockheed had been slow in adopting low-drag airfoils, they had now been converted to the use of these airfoils and were very much pleased with the results of the application made on their pursuit airplane. He stated that, although they had no definite measurements indicating the extent of the laminar flow obtained on the wing of this airplane, they thought they were getting extensive laminar flow because, when tufts were added to the wing surface, a notable decrease in speed was observed. Mr. Colman made a suggestion for needed research work in the field of low-drag airfoils that has been put in the following list of suggestions received from various men in aircraft companies.

33. SUGGESTIONS FOR FURTHER RESEARCH ON LOW-DRAG AIRFOILS:

(1) The relative effects of waves and roughness at various points on the surface of the wings with different pressure gradients. In order to make the study fundamental, Dr. Clauser suggests that it be a study of the relation between waves and pressure gradients on the airfoil as affecting laminar flow and separation. Permissible waviness as a function of pressure gradient and boundary-layer thickness.

(2) Effect of different kinds of paint on laminar flow. Dr. Clauser suggests that this be defined as a study of micro-roughness on airfoils. Permissible roughness (size and shape) as a function of pressure gradient and boundary-layer thickness.

(3) More data at high Reynolds and Mach numbers. Lockheed particularly is interested in data at high Reynolds numbers. They feel that such data can best be obtained in flight.

(4) Data for complete families of low-drag airfoils.

(5) Effects of different locations of wing-skin joints in practical applications. Aluminum sheets are made only in certain widths, and these widths are sufficiently small that skin joints must be incorporated fairly close to the wing leading edge on both upper and lower surfaces.

(6) Data for choice of optimum nose radius for compressibility and C_{Lmax}.

(7) Determination of turbulent separation parameters.

(8) Effect of wing configuration on the successful application of low-drag sections.

(9) Fundamental study of airfoils to obtain a section that will provide high lift. This suggestion was made by Dr. Clauser, who stated that the Committee's work so far has been in the direction of low drag and feels that, with a similar type of approach, the Committee might be able to design an airfoil with a maximum lift coefficient, without the use of flaps, of as much as 2 or 3. A study of the factors that make for high lift, he feels, might result in the design of an airfoil that would be a far better compromise between high lift and low drag than the present low-drag airfoils.

(10) Design of optimum airfoils for use in propeller slipstream. Dr. Oswald pointed out that in many ships, as much as 60 percent of the wing is bathed in slipstream and that we do not know the best shape of airfoil to use in such locations.

(11) The effect of airfoil sections and thickness on aileron performance.

(12) Representative flap tests on all airfoils tested.

(13) Study of airfoils designed to get low drag at high lift coefficients, in other words, highly cambered sections. This is Lockheed's suggestion.

(14) Standardized wing-duct dimensions and exit design.

(15) Desirable internal structure and skin-joint designs.

(16) Further study of airfoils with reflexed camber line, suggested by Mr. Horkey, who asked the question, "Is a high C_{mo} serious at high Mach numbers?"

(17) Comparative tests of airplanes with conventional and low-drag wings showing how much can be gained through the use of low-drag wings to provide incentive for the use of low-drag wing sections.

(18) Development of permanent long-life finish for low-drag airfoils that will maintain laminar flow.

Edwin P. Hartman.

Document 4-30(a-b)

(a) Theodore von Kármán, "Laminar Flow Wings," in *Where We Stand* (written in 1945 and issued as an Army Air Forces Report in 1946); reprinted in *Prophecy Fulfilled: "Toward New Horizons" and Its Legacy* (Air Force History and Museums Program, 1994), ed. Michael H. Gorn, pp. 69-72.

(b) Von Kármán, "Aerodynamic Problems," in *Science, The Key to Air Supremacy* (originally published in 1945 as part of the multi-volume "*Toward New Horizons*," reprinted in *Prophecy Fulfilled*, pp. 108-09).

The delineation of the laminar-flow airfoils was a great contribution by the NACA, even if not exactly in the way, or to the degree, advertised. It was certainly not the NACA alone that promoted the value of the promising new technology. The last document in this chapter holds two excerpts from Theodore von Kármán, one from *Where We Stand* and another from *Science, The Key To Supremacy*, both written right at the end of the war. There can be no question after reading the excerpts that von Kármán, too, was a fan of the laminar-flow airfoil. So, too, were the German pilots who faced the P-51 in aerial combat and the German aeronautical engineers who marveled over what to them were the Mustang's mysterious design features.

But more than any other group, the people that surely valued the P-51's performance the most were the Allied bomber pilots who flew dangerous missions deep into the German heartland when no previous fighter plane could fly far enough to escort them all the way to their targets and back. Thanks in large part to its highly efficient aerodynamic design, the P-51 could fly all the way to Berlin and back, saving innumerable lives of Allied crewmen in the process. General Henry H. "Hap" Arnold, commanding general of the U.S. Army Air Forces in Europe at the time, called it "one of the great miracles of the war," the appearance of the long-range fighter escort "at just the right moment in the very nick of time to keep our bomber offensive going without a break."

Even von Kármán exaggerated the contributions of the laminar-flow wing to the P-51's overall performance abilities. But, as the second excerpt shows, in particular, as an aerodynamicist he was tremendously excited by the potential of the laminar-flow concept. The "initial successes of the laminar flow wing are so encouraging," he wrote in 1945, "that in future research we should strive to go the whole way." The P-51 was not the end of the aerodynamicist's quest for smooth air flow via boundary layer control, it was just a milestone along the way.

Document 4-30(a), Theodore von Kármán, "Laminar Flow Wings," in* Where We Stand *(written in 1945 and issued as an Army Air Forces Report in 1946).

LAMINAR FLOW WINGS

In this field we were far ahead of the Germans. In the following paragraphs, the German developed status will first be given, followed by our own.

GERMAN DEVELOPMENTS

According to the German dynamicist Schlichting, German work on laminar flow airfoils did not start until about the end of 1938. By 1940, Schlichting considered that the fundamentals were known. Drag coefficients as low as 0.0027 were reached at a Reynolds number of 5×10^6, but the German scientists were unable to retain the low drag at higher Reynolds numbers. They were handicapped by lack of suitable low-turbulence wind tunnels. On one occasion, Prandtl reported: "Suitable wind tunnels for the conduct of airfoil investigations at sufficiently high Reynolds number and at low turbulence are lacking in Germany. On the other hand, it is known that in the U.S.A. particular installations created for this purpose are working exceptionally vigorously in this field."

Tests were made on a Japanese laminar flow airfoil, on three airfoils derived from one member of an obsolete NACA Series 27215 (which was described in a captured French secret report), and on a few airfoils designed by Schlichting. The Germans also had some information on a Russian laminar flow airfoil obtained from a captured report.

The Germans never used laminar flow airfoils on aircraft. They were astonished and mystified by the performance of the Mustang and made many wind-tunnel and flight tests. They gave the following tabulation of wing profile drag coefficients (obtained by momentum method) for a number of airplanes at lift coefficient of 0.2:

He-177	0.0109
FW-190	0.0089
Ju-288	0.0102
Mustang	0.0072
Me-109B	0.0101

The German comment is: "The drag of this only foreign original airfoil tested up till now is far below the drag of all German wings tested in which it should be remembered that it was tested without any smoothing layer."

Another writer says: "A comparison of flight measurements shows quite unmistakably that the Mustang is far superior aerodynamically to all other airplanes and that it maintains this superiority in spite of its considerably greater wing area."

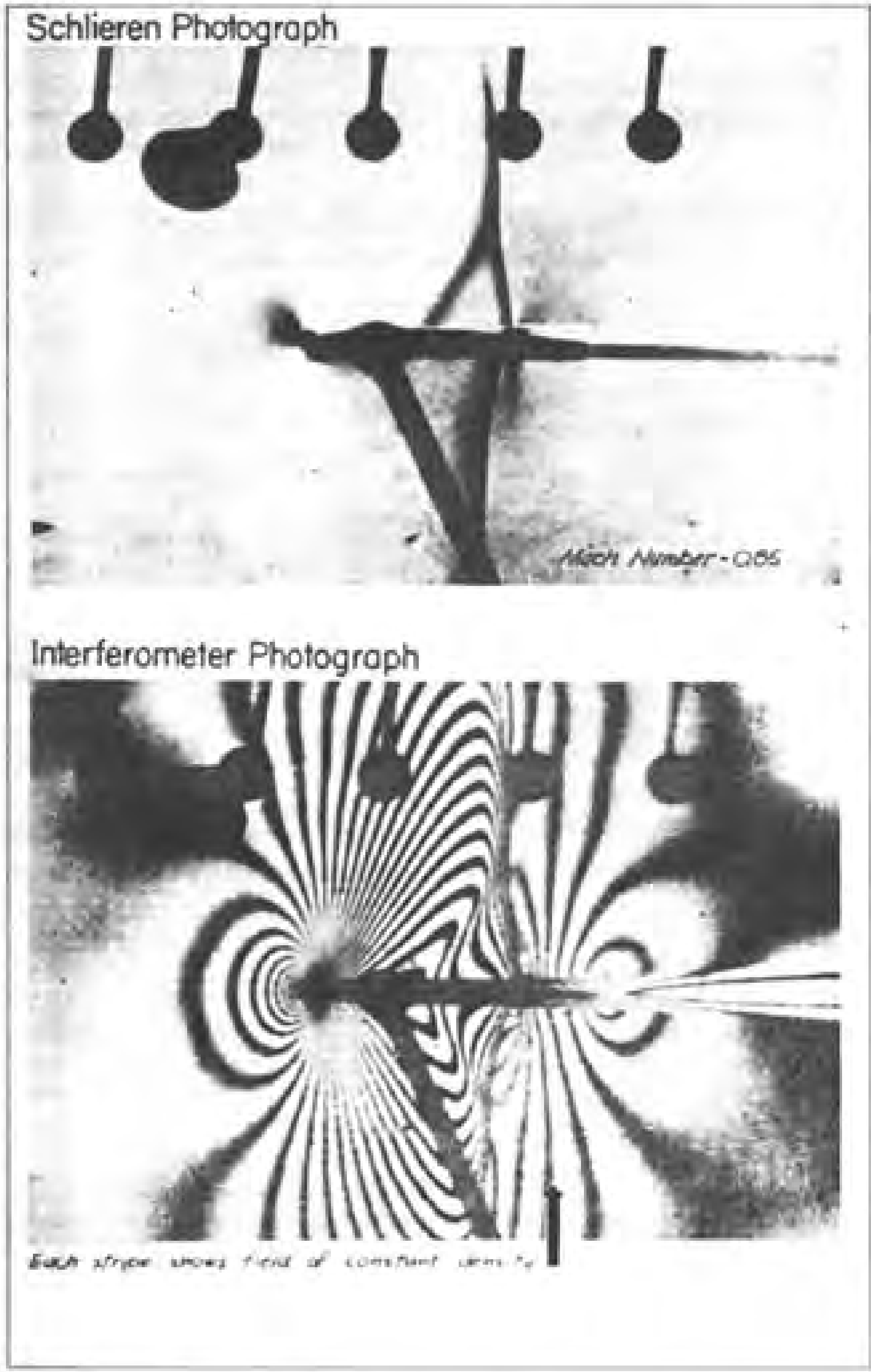


Figure 15–High-Speed Airflow Photographs

ALLIED DEVELOPMENTS

The NACA began investigations of laminar flow airfoils in a low-turbulence wind tunnel in the spring of 1938, and the encouraging nature of the results obtained (without details) were described in the Wilbur Wright Lecture of the Royal Aeronautical Society on 25 May 1939, and in the NACA Annual Report for 1939. In June 1939, an advance confidential report by Jacobs was released. A summary was published in March 1942 in confidential form. The most recent summary was released in March 1945, and this summary has been kept up to date by supplementary sheets.

As indicated in the summary of German developments, the Allies are far ahead in low-turbulence wind-tunnel equipment and in knowledge of laminar flow airfoils and their application to aircraft. Drag coefficients as low as 0.003 at a Reynolds number of 20 X 106 have been obtained.

A summary of the present state of knowledge is given in the NACA restricted report L5C05, "Summary of Airfoil Data," by Abbott, von Doenhoff, and Stivers, March 1945.

BOUNDARY LAYER CONTROL

In this field the Germans had an advanced start and had just about reached a practical state. A discussion of German and Allied developments follows.

German Developments. Considerable work was done on boundary layer control at AVA, Gottingen, starting in 1925. The first airplane with boundary layer control was built and flown in 1932.

From about 1942 on, work was intensified. Schwier obtained a maximum lift coefficient of 4.3. using pressure jet boundary layer control in wind tunnel tests. In July 1943, Stuper obtained a maximum lift coefficient 3.8 in full-scale flight tests with boundary layer control by suction. The maximum lift coefficient on his airplane without boundary layer control was 1.9. About the same time, a maximum lift coefficient of 3.4 with boundary layer control was reported in wind-tunnel tests of a four-motored airplane which was to be developed by Junkers. A unique suction and pressure-jet boundary layer control system was used. Air was sucked in over the inboard portion of the wing, just ahead of the flaps, and blown out over the outboard portion of the wing, just ahead of the ailerons. In November 1943, Wagner outlined work which was done at Arado, showing a maximum lift coefficient of 4.0 to be possible.

All German investigators noted that the internal wing ducting required and the power required to drive the boundary layer control equipment constituted serious obstacles to the successful, practical application of boundary layer control. However, it was felt that these obstacles could be successfully met. At the end of the war, an Arado transport airplane, having low landing and take-off speeds because of boundary layer control, was in service in the German Air Force.

UNITED STATES DEVELOPMENTS

An L-1 airplane was equipped with boundary layer control by suction. The maximum lift coefficient was 3.5 without boundary layer control and 3.6 with boundary layer control. The landing speed of the modified L-1 was considerably higher than that of the original airplane due to the weight of the boundary layer control equipment.

Boundary layer control has an important application in making low landing speeds possible on high-speed aircraft. It also appears that the potentialities of boundary layer control in the transonic speed range have never been systematically evaluated. We found that some interesting work was done by Ackeret at the Institute of Technology in Zurich, Switzerland. The Scientific Advisory Group recommends that an intensive research program on boundary layer control be undertaken by the Army Air Forces.

Document 4-30(b), von Kármán, "Aerodynamic Problems," in* Science, The Key to Air Supremacy *(originally published in 1945).

AERODYNAMIC PROBLEMS

2.20 Improvements in the lift-drag ratio proportionately increase the range of an airplane. Therefore, efforts should be concentrated to attain such improvements. In 1935, an eminent American aerodynamicist, who, ironically enough, later became instrumental in the development of the laminar wing, declared that in his opinion no more major progress can be expected in aerodynamic science. He referred to the fact that with the discovery of the wing theory, lift and drag became calculable quantities, and the performance of the airplane could be fairly exactly predicted. Also, the designer learned the rules of streamlining and methods of eliminating superfluous drag by "cleaning up" the airplane. By use of systematic and detailed wind-tunnel tests, this cleaning up process became almost perfect, so that further improvements can be expected only in exceptional cases. However, even in the fairly well explored subsonic speed range, new possibilities appeared with the discovery of the laminar wing section and the efforts to design an efficient flying wing.

2.21 The concept of the laminar wing is based on the fundamental fact that when the flow in the boundary layer of a surface moving in air is laminar, the surface friction is very much less than in the case when turbulent motion takes place in the same layer. The laminar wing sections which we are using in the present-day design, endeavor to keep the boundary layer laminar over a portion of the wing surface by means of an appropriate shape of the section. This method was applied in the design of quite a few of our modern airplanes, with considerable success. The proposal was first received with skepticism. Several objections were raised; that the expected effects of drag reduction could only be obtained if the wing surface is extremely smooth, and that the beneficial effect could only be attained for small values of the lift coefficient, thus restricting the benefit of the reduced friction to certain flight attitudes. Nevertheless, it appears that the initial successes of the laminar wing are so encouraging that in future research we should strive to go the whole way, i.e., to try to secure laminar flow in the boundary layer by positive measures along the entire wing and in a large range of angles of attack. It is known that theoretically this aim can be attained by the so-called boundary layer control. Results along this line are already available, for example, in the tests carried out by Professor J. Ackeret and his collaborators at the Technical University at Zurich. It is true that the process requires extremely smooth surfaces with relatively narrow slots extending spanwise along the wing. This might cause practical difficulties (for example, in the case of icing). However, looking into the future, extreme smoothness might be realized by materials now in the making, and it will certainly be worthwhile to put in a great amount of research work to eliminate other possible practical obstacles. There is even the possibility of eventual elimination of conventional movable control surfaces, by use of boundary layer control to effect changes in lift and moment.

2.22 The same principle can be applied also to reductions of the drag and airplane for example, bodies with circular cross sections. In the case of wings, it will be necessary to subdivide the wing into a number of compartments, with individually regulated boundary layer control. In the case of bodies, it might be sufficient to apply the control at a few critical cross sections.

2.23 The fundamental idea of the flying wing is the elimination of the parasite drag contributed by such parts of the airplane as do not produce lift. The tailless airplane is an even more controversial subject than the laminar wing. As does every unorthodox type, it introduces some new problems. The fact that the longitudinal control is placed in the wing involves control force characteristics which are different from those occurring in conventional airplanes. Much discussed problems are the proper method of securing directional stability, and the best arrangement for sweepback. As a matter of fact, the designs which have been produced up to now have not yet brought a final decision concerning the relative advantages and disadvantages of the flying wing and the tailless airplane. However, as the global character of aerial transportation, and especially aerial warfare, becomes more and more evident, it is apparent that our present airplanes are inadequate to meet the demand for range. Therefore, the two methods promising essential aerodynamic progress, namely boundary layer control and tailless design, should be explored with adequate facilities.

2.24 The large decrease in the value of the lift-drag ratio at the Mach number of about 0.8 is due to the rather sudden increase of the drag of the airplane. This increase is essentially due to the fact that the relative velocity of the air locally becomes larger than the velocity of sound. Simultaneously with the increase of the drag, difficulties are encountered, in most cases, in the stability and control of the airplane. Generally these phenomena are designated as compressibility effects; we prefer to use the designation "transonic problem." Obviously, in order to extend the speed limit of high-speed airplanes, a thorough investigation of the aerodynamic phenomena in the transonic range is needed. As a matter of fact, the aerodynamics of both the subsonic and supersonic ranges are better known than that of the transonic range, which extends approximately between the Mach numbers of 0.8 and 1.2. One reason is that the mathematical analysis is extremely difficult, since the flow around the airplane is partly subsonic and partly supersonic. Another great difficulty is caused by the unreliability of wind-tunnel tests in this range. Flight tests, dropping tests, and measurements on models carried by rockets are the main sources for experimental information.

2.25 Fighters and interceptors now in the making operate actually at the border of the transonic range. Hence, every method which is able to raise the limit of the rapid drag increase is of great importance. German scientists observed that increase of drag of the wing can be postponed to higher Mach numbers by sufficient sweepback. This method is generally used now in the design of fast fighters and interceptors. Designers are seeking means to reduce the excess weight and the difficulties in stability and control connected with the swept-back wing shape. However, this solution is not necessarily a final one. When our knowledge of aerodynamic phenomena in the transonic range has been more firmly established, we may find methods for eliminating the separation of the flow behind the shock wave, and the fundamental trouble, namely the occurrence of shock waves. In the subsonic range aerodynamic research brought rich returns. It can be expected that the same process will repeat itself and will lead to the solution of the transonic problem.

2.26 One of the main questions in the supersonic speed range is the feasibility of long-range flight. The supersonic airplane necessitates very high wing loading with small size of the wing. Hence, in most cases, the volume available in the wing for fuel or payload is very small, and a disproportion appears between the sizes of the wing and the fuselage. In other words, the resistance of the body in comparison with the resistance of the wing is much greater than in the case of the conventional subsonic airplane. It appears that the best solution is offered by a fuselage of large fineness ratio. A rather thorough investigation of the problem was made by the Scientific Advisory Group on this question. These investigations suggest that, assuming a given ratio between fuel and total weight and a certain space required in the fuselage, the range is essentially a function of the altitude at which the supersonic flight takes place. A preceding diagram shows an example of the variation of range with altitude. The ideal application of such a supersonic airplane is the pilotless bomber. Similar types of supersonic airplanes will serve as pilotless interceptors. The best speed range for the latter device may be between 1.2 and 1.5 times sound velocity.

2.27 The fact that in the case of the supersonic airplane, the body resistance contributes a relatively larger portion to the total drag than in the case of subsonic planes calls for study of an all-wing design. However, supersonic flight requires wings with small thickness-chord ratio. Hence, one can create sufficient space only by using a wing shape of very small aspect ratio. It is fortunate that, in the supersonic range, triangular-shaped wings give relatively high lift-drag ratios in comparison with other plan forms. Hence, for manned interceptors a series of all-wing airplanes should be tried, eventually with a small cockpit for a pilot. Such a series should extend from a tailless airplane similar to the Me-163 to pure triangular-shaped airplanes.

2.28 Besides the lift and drag properties, the questions of stability and control are the most important. The change of the flow regime introduces difficulties in the transonic range. But also in the pure supersonic range, very little is known about the efficiency of aerodynamic control surfaces and control forces. This field needs thorough exploration by all means available, starting with wind-tunnel tests and ending with flight tests. Possibly in addition to conventional means, displacements of weights or direct control of pressure distribution by modification of the flow, as in the case of boundary layer control, are necessary.

2.29 The difficulties of landing are much more serious for supersonic than for subsonic airplanes because of their high-wing loading. The wing loading decreases with altitude and supersonic airplanes designed for stratospheric flight may land without special devices. However, systematic investigations are necessary of high-lift devices suitable for use on the thin, sharp-nosed airfoils that are desirable for supersonic flight. This must include the problem of raising the maximum lift of triangular, low-aspect-ratio wings, and particularly of reducing the extremely large angles at which such wings now attain their maximum lift. In addition, devices such as rockets, which produce simultaneously deceleratory thrust and increase of lift for the short period of landing should be studied.

NASA History Series

Reference Works, NASA SP-4000:

Grimwood, James M. *Project Mercury: A Chronology*. NASA SP-4001, 1963.

Grimwood, James M., and C. Barton Hacker, with Peter J. Vorzimmer. *Project Gemini Technology and Operations: A Chronology*. NASA SP-4002, 1969.

Link, Mae Mills. *Space Medicine in Project Mercury*. NASA SP-4003, 1965.

Astronautics and Aeronautics, 1963: Chronology of Science, Technology, and Policy. NASA SP-4004, 1964.

Astronautics and Aeronautics, 1964: Chronology of Science, Technology, and Policy. NASA SP-4005, 1965.

Astronautics and Aeronautics, 1965: Chronology of Science, Technology, and Policy. NASA SP-4006, 1966.

Astronautics and Aeronautics, 1966: Chronology of Science, Technology, and Policy. NASA SP-4007, 1967.

Astronautics and Aeronautics, 1967: Chronology of Science, Technology, and Policy. NASA SP-4008, 1968.

Ertel, Ivan D., and Mary Louise Morse. *The Apollo Spacecraft: A Chronology, Volume I, Through November 7, 1962*. NASA SP-4009, 1969.

Morse, Mary Louise, and Jean Kernahan Bays. *The Apollo Spacecraft: A Chronology, Volume II, November 8, 1962–September 30, 1964*. NASA SP-4009, 1973.

Brooks, Courtney G., and Ivan D. Ertel. *The Apollo Spacecraft: A Chronology, Volume III, October 1, 1964–January 20, 1966*. NASA SP-4009, 1973.

Ertel, Ivan D., and Roland W. Newkirk, with Courtney G. Brooks. *The Apollo Spacecraft: A Chronology, Volume IV, January 21, 1966–July 13, 1974*. NASA SP-4009, 1978.

Astronautics and Aeronautics, 1968: Chronology of Science, Technology, and Policy. NASA SP-4010, 1969.

Newkirk, Roland W., and Ivan D. Ertel, with Courtney G. Brooks. *Skylab: A Chronology*. NASA SP-4011, 1977.

Van Nimmen, Jane, and Leonard C. Bruno, with Robert L. Rosholt. *NASA Historical Data Book, Volume I: NASA Resources, 1958–1968*. NASA SP-4012, 1976, rep. ed. 1988.

Ezell, Linda Neuman. *NASA Historical Data Book, Volume II: Programs and Projects, 1958–1968*. NASA SP-4012, 1988.

Ezell, Linda Neuman. *NASA Historical Data Book, Volume III: Programs and Projects, 1969–1978*. NASA SP-4012, 1988.

Gawdiak, Ihor Y., with Helen Fedor, compilers. *NASA Historical Data Book, Volume IV: NASA Resources, 1969–1978*. NASA SP-4012, 1994.

Rumerman, Judy A., compiler. *NASA Historical Data Book, 1979–1988: Volume V, NASA Launch Systems, Space Transportation, Human Spaceflight, and Space Science*. NASA SP-4012, 1999.

Rumerman, Judy A., compiler. *NASA Historical Data Book, Volume VI: NASA Space Applications, Aeronautics and Space Research and Technology, Tracking and Data Acquisition/Space Operations, Commercial Programs, and Resources, 1979–1988*. NASA SP-2000-4012, 2000.

Astronautics and Aeronautics, 1969: Chronology of Science, Technology, and Policy. NASA SP-4014, 1970.

Astronautics and Aeronautics, 1970: Chronology of Science, Technology, and Policy. NASA SP-4015, 1972.

Astronautics and Aeronautics, 1971: Chronology of Science, Technology, and Policy. NASA SP-4016, 1972.

Astronautics and Aeronautics, 1972: Chronology of Science, Technology, and Policy. NASA SP-4017, 1974.

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Astronautics and Aeronautics, 1976: Chronology of Science, Technology, and Policy. NASA SP-4021, 1984.

Astronautics and Aeronautics, 1977: Chronology of Science, Technology, and Policy. NASA SP-4022, 1986.

Astronautics and Aeronautics, 1978: Chronology of Science, Technology, and Policy. NASA SP-4023, 1986.

Astronautics and Aeronautics, 1979–1984: Chronology of Science, Technology, and Policy. NASA SP-4024, 1988.

Astronautics and Aeronautics, 1985: Chronology of Science, Technology, and Policy. NASA SP-4025, 1990.

Noordung, Hermann. *The Problem of Space Travel: The Rocket Motor. Edited by Ernst Stuhlinger and J. D. Hunley, with Jennifer Garland*. NASA SP-4026, 1995.

Astronautics and Aeronautics, 1986–1990: A Chronology. NASA SP-4027, 1997.

Astronautics and Aeronautics, 1990–1995: A Chronology. NASA SP-2000-4028, 2000.

Management Histories, NASA SP-4100:

Rosholt, Robert L. *An Administrative History of NASA, 1958–1963*. NASA SP-4101, 1966.

Levine, Arnold S. *Managing NASA in the Apollo Era*. NASA SP-4102, 1982.

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Fries, Sylvia D. *NASA Engineers and the Age of Apollo*. NASA SP-4104, 1992.

Glennan, T. Keith. *The Birth of NASA: The Diary of T. Keith Glennan. J. D. Hunley, editor*. NASA SP-4105, 1993.

Seamans, Robert C., Jr. *Aiming at Targets: The Autobiography of Robert C. Seamans, Jr*. NASA SP-4106, 1996.

Garber, Stephen J., editor. *Looking Backward, Looking Forward: Forty Years of U.S. Human Spaceflight Symposium*. NASA SP-2002-4107, 2002.

Mallick, Donald L. with Peter W. Merlin. *The Smell of Kerosene: A Test Pilot's Odyssey*. NASA SP-4108, 2003.

Iliff, Kenneth W. and Curtis L. Peebles. *From Runway to Orbit: Reflections of a*

NASA Engineer. NASA SP-2004-4109, 2004.

Chertok, Boris. *Rockets and People, Volume 1*. NASA SP-2005-4110, 2005.

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Dawson, Virginia P. and Mark D. Bowles. *Realizing the Dream of Flight: Biographical Essays in Honor of the Centennial of Flight, 1903-2003*. NASA SP-2005-4112, 2005.

Project Histories, NASA SP-4200:

Swenson, Loyd S., Jr., James M. Grimwood, and Charles C. Alexander. *This New Ocean: A History of Project Mercury*. NASA SP-4201, 1966; rep. ed. 1998.

Green, Constance McLaughlin, and Milton Lomask. *Vanguard: A History*. NASA SP-4202, 1970; rep. ed. Smithsonian Institution Press, 1971.

Hacker, Barton C., and James M. Grimwood. *On the Shoulders of Titans: A History of Project Gemini*. NASA SP-4203, 1977.

Benson, Charles D., and William Barnaby Faherty. *Moonport: A History of Apollo Launch Facilities and Operations*. NASA SP-4204, 1978.

Brooks, Courtney G., James M. Grimwood, and Loyd S. Swenson, Jr. *Chariots for Apollo: A History of Manned Lunar Spacecraft*. NASA SP-4205, 1979.

Bilstein, Roger E. *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles*. NASA SP-4206, 1980, rep. ed. 1997.

SP-4207 not published.

Compton, W. David, and Charles D. Benson. *Living and Working in Space: A History of Skylab*. NASA SP-4208, 1983.

Ezell, Edward Clinton, and Linda Neuman Ezell. *The Partnership: A History of the Apollo-Soyuz Test Project*. NASA SP-4209, 1978.

Hall, R. Cargill. *Lunar Impact: A History of Project Ranger*. NASA SP-4210, 1977.

Newell, Homer E. B*eyond the Atmosphere: Early Years of Space Science*. NASA SP-4211, 1980.

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Pitts, John A. *The Human Factor: Biomedicine in the Manned Space Program to 1980*. NASA SP-4213, 1985.

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Leary, William M. *"We Freeze to Please": A History of NASA's Icing Research Tunnel and the Quest for Flight Safety*. NASA SP-2002-4226, 2002.

Mudgway, Douglas J. *Uplink-Downlink: A History of the Deep Space Network 1957–1997*. NASA SP-2001-4227, 2001.

Dawson, Virginia P. and Mark D. Bowles. *Taming Liquid Hydrogen: The Centaur Upper Stage Rocket, 1958-2002*. NASA SP-2004-4230, 2004.

Meltzer, Michael. *Mission to Jupiter: A History of the Galileo Project*. NASA SP-2007-4231.

Center Histories, NASA SP-4300:

Rosenthal, Alfred. *Venture into Space: Early Years of Goddard Space Flight Center*. NASA SP-4301, 1985.

Hartman, Edwin P. *Adventures in Research: A History of Ames Research Center, 1940–1965*. NASA SP-4302, 1970.

Hallion, Richard P. *On the Frontier: Flight Research at Dryden, 1946–1981*. NASA SP-4303, 1984.

Muenger, Elizabeth A. *Searching the Horizon: A History of Ames Research Center, 1940–1976*. NASA SP-4304, 1985.

Hansen, James R. *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958*. NASA SP-4305, 1987.

Dawson, Virginia P. *Engines and Innovation: Lewis Laboratory and American Propulsion Technology*. NASA SP-4306, 1991.

Dethloff, Henry C. *"Suddenly Tomorrow Came . . .": A History of the Johnson Space Center.* NASA SP-4307, 1993.

Hansen, James R. *Spaceflight Revolution: NASA Langley Research Center from Sputnik to Apollo*. NASA SP-4308, 1995.

Wallace, Lane E. *Flights of Discovery: 50 Years at the NASA Dryden Flight Research Center*. NASA SP-4309, 1996.

Herring, Mack R. *Way Station to Space: A History of the John C. Stennis Space Center*. NASA SP-4310, 1997.

Wallace, Harold D., Jr. *Wallops Station and the Creation of the American Space Program*. NASA SP-4311, 1997.

Wallace, Lane E. *Dreams, Hopes, Realities: NASA's Goddard Space Flight Center, The First Forty Years*. NASA SP-4312, 1999.

Dunar, Andrew J., and Stephen P. Waring. *Power to Explore: A History of the Marshall Space Flight Center*. NASA SP-4313, 1999.

Bugos, Glenn E. *Atmosphere of Freedom: Sixty Years at the NASA Ames Research Center*. NASA SP-2000-4314, 2000.

Schultz, James. *Crafting Flight: Aircraft Pioneers and the Contributions of the Men and Women of NASA Langley Research Center*. NASA SP-2003-4316, 2003.

General Histories, NASA SP-4400:

Corliss, William R. *NASA Sounding Rockets, 1958–1968: A Historical Summary*. NASA SP-4401, 1971.

Wells, Helen T., Susan H. Whiteley, and Carrie Karegeannes. *Origins of NASA Names*. NASA SP-4402, 1976.

Anderson, Frank W., Jr. *Orders of Magnitude: A History of NACA and NASA, 1915–1980*. NASA SP-4403, 1981.

Sloop, John L. *Liquid Hydrogen as a Propulsion Fuel, 1945–1959*. NASA SP-4404, 1978.

Roland, Alex. *A Spacefaring People: Perspectives on Early Spaceflight*. NASA SP-4405, 1985.

Bilstein, Roger E. *Orders of Magnitude: A History of the NACA and NASA, 1915–1990*. NASA SP-4406, 1989.

Logsdon, John M., editor, with Linda J. Lear, Jannelle Warren-Findley, Ray A. Williamson, and Dwayne A. Day. *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume I, Organizing for Exploration*. NASA SP-4407, 1995.

Logsdon, John M., editor, with Dwayne A. Day and Roger D. Launius. *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume II, Relations with Other Organizations*. NASA SP-4407, 1996.

Logsdon, John M., editor, with Roger D. Launius, David H. Onkst, and Stephen J. Garber. *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume III, Using Space*. NASA SP-4407, 1998.

Logsdon, John M., general editor, with Ray A. Williamson, Roger D. Launius, Russell J. Acker, Stephen J. Garber, and Jonathan L. Friedman. *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume IV,* *Accessing Space*. NASA SP-4407, 1999.

Logsdon, John M., general editor, with Amy Paige Snyder, Roger D. Launius, Stephen J. Garber, and Regan Anne Newport. *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V, Exploring the Cosmos*. NASA SP-2001-4407, 2001.

Siddiqi, Asif A. *Challenge to Apollo: The Soviet Union and the Space Race, 1945–1974*. NASA SP-2000-4408, 2000.

Hansen, James R., editor. *The Wind and Beyond: Journey into the History of Aerodynamics in America, Volume 1, The Ascent of the Airplane*. NASA SP-2003-4409, 2003.

Monographs in Aerospace History, NASA SP-4500:

Launius, Roger D. and Aaron K. Gillette, compilers, *Toward a History of the Space Shuttle: An Annotated Bibliography.* Monograph in Aerospace History, No. 1, 1992.

Launius, Roger D., and J. D. Hunley, compilers, *An Annotated Bibliography of the Apollo Program.* Monograph in Aerospace History, No. 2, 1994.

Launius, Roger D. Apollo: A Retrospective Analysis. Monograph in Aerospace History, No. 3, 1994.

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No monograph 28.

Chambers, Joseph R. *Concept to Reality: Contributions of the NASA Langley Research Center to U.S. Civil Aircraft of the 1990s.* SP-2003-4529, 2003.

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Renstrom, Arthur G. *Wilbur and Orville Wright: A Chronology Commemorating the One-Hundredth Anniversary of the First Powered Flight on December 17, 1903*. NASA SP-2003-4532, 2002.

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Cover: *Fluid Dynamics*, Tina York. The study of fluid dynamics attempts to explain what happens to an object when it encounters the friction of atmospheric resistance (such as a plane encountering resistance as it speeds through the air). The artist has decided to depict the effect of air flow as a plane or other flying objects move through the air. NASA Image 95-HC-379.

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