The Wind and Beyond

A Documentary Journey into the History of Aerodynamics in America

Volume II

James R. Hansen, Editor

with Jeremy Kinney, D. Bryan Taylor, Molly Prickett, and J. Lawrence Lee

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The airplane ranks as one of history's most ingenious and phenomenal inventions. It has surely been one of the most world changing. How ideas about aerodynamics first came together and how the science and technology evolved to forge the airplane into the revolutionary machine that it became is the epic story told in this six-volume series, *The Wind and Beyond: A Documentary Journey through the History of Aerodynamics in America.*

Following up on Volume I's account of the invention of the airplane and the creation of the original aeronautical research establishment in the United States, Volume II explores the airplane design revolution of the 1920s and 1930s and the quest for improved airfoils. Subsequent volumes cover the aerodynamics of airships, flying boats, rotary-wing aircraft, breaking the sound barrier, and more.

In 2005, the Society for the History of Technology awarded its first annual Eugene S. Ferguson Prize for outstanding and original reference works to *The Wind and Beyond.* The citation read in part:

"*The Wind and Beyond* is remarkable in its breadth of vision. Its purview includes not just aerodynamical theories and research results, but also innovative airships and airship components as well as the institutions in which and through which aerodynamics developed… Each [chapter] essay is original in two ways. First, each is a first-rate piece of scholarship in its own right. Second, the very decision to include these narratives is significant: they comprise roughly 10 percent of the contents of the volume, but they make the other 90 percent both accessible and meaningful to the nonspecialist reader, simultaneously enhancing the value of and enlarging the potential audience for the whole volume….*The Wind and Beyond* will be a boon both to students and to established scholars in several ways. Like many similar collections, it provides one-stop access to documents that were previously scattered in many different places. Going beyond other similar collections, however, *The Wind and Beyond* makes the documents intellectually as well as physically accessible…The end result is an eminently readable reference work, one that is truly, as its title suggests, the beginning of a journey rather than the end."

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Volume II: Reinventing the Airplane

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Foreword

Airplane travel is surely one of the most significant technological achievements of the last century. The impact of the airplane goes far beyond the realm of the history of technology and touches upon virtually every aspect of society from economics to politics to engineering and science. While space exploration often claims more public glory than aeronautics research, many more individuals have been able to fly within the Earth's atmosphere than above it. Thus aeronautics and air travel have had an enormous practical impact on many more individuals.

The first two volumes in the *Wind and Beyond* series and the succeeding four now in preparation all cover the impact of aerodynamic development on the evolution of the airplane in America. As the six-volume series will ultimately demonstrate, just as the airplane is a defining technology of the twentieth century, aerodynamics has been the defining element of the airplane. The forthcoming volumes will proceed roughly in chronological order, covering such developments as the advent of commercial airliners, flying boats, rotary aircraft, supersonic flight, and hypersonic flight.

This series is designed as an aeronautics companion to the *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program* (NASA SP-4407) series of books. As with *Exploring the Unknown*, the documents collected during this research project were assembled from diverse public and private sources. A major repository of primary source materials relative to the history of the civil space program is the NASA Historical Reference Collection in the NASA History Division. Historical materials housed at NASA Field Centers, academic institutions, and Presidential libraries were other sources of documents considered for inclusion, as were papers in the archives of private individuals and corporations.

The format of this volume also is very similar to that of the *Exploring the Unknown* volumes. Each section in the present volume is introduced by an overview essay that is intended to introduce and complement the documents in the section and to place them in a chronological and substantive context. Each essay contains references to the documents in the section it introduces, and many also contain references to documents in other sections of the collection. These introductory essays are the responsibility of Dr. Hansen, the series author and chief editor, and the views and conclusions contained therein do not necessarily represent the opinions of either Auburn University or NASA.

The documents included in each section were chosen by Dr. Hansen's project team from a much longer list initially assembled by the research staff. The contents of this volume emphasize primary documents, including long-out-of-print essays and articles as well as material from the private recollections of important actors in shaping aerodynamic thinking in the United States and abroad. Some key legislation and policy statements are also included. As much as possible, the contents of these volumes comprise an integrated historical narrative, though Dr. Hansen's team encourages readers to supplement the account found herein with other sources that have already or will become available.

Please note that the chapters in this series are numbered sequentially. Thus the first chapter in this second volume is referred to as chapter three and so forth.

For the most part, the documents included in each section are arranged chronologically. Each document is assigned its own number in terms of the section in which it is placed. As a result, for example, the fifteenth document in the first chapter of this volume is designated "Document 3-15." Each document is accompanied by a headnote setting out its context and providing a background narrative. These headnotes also provide specific information and explanatory notes about people and events discussed. Many of the documents, as is the case with Document 3-15, involve document "strings," i.e., Document 3-15 (a-e). Such strings involve multiple documents—in this case, five of them (a through e) that have been grouped together because they relate to one another in a significant way. Together, they work to tell one documentary "story."

The editorial method that has been adopted seeks to preserve, as much as possible, the spelling, grammar, and language usage as they appear in the original documents. We have sometimes changed punctuation to enhance readability. We have used the designation [abridged] to note where sections of a document have not been included in this publication, and we have avoided including words and phrases that had been deleted in the original document unless they contribute to an understanding of what was going on in the mind of the writer in making the record. Marginal notations on the original documents are inserted into the text of the documents in brackets, each clearly marked as a marginal comment. Page numbers in the original document are noted in brackets internal to the document text. Copies of all documents in their original form are available for research by any interested person at the NASA History Division or Auburn University.

While the *Exploring the Unknown* series has been a good model in many ways, this volume indeed represents an expedition into uncharted waters. Dr. Hansen and his team have crafted a landmark work that will not only be an important reference work in the history of aeronautics, but interesting and informative reading as well. We hope you enjoy this useful book and the forthcoming volumes.

Dr. Steven J. Dick
NASA Chief Historian
Director, NASA History Division

Acknowledgments

This volume represents the collected efforts of many members of an outstanding team. At Auburn University, a number of individuals provided generous assistance to Dr. James R. Hansen's project team. Dr. Paul F. Parks, former University Provost, strongly encouraged and supported the project from its inception, as did Dr. Michael C. Moriarty, former Vice President for Research. To undertake his leadership of the project, Dr. Hansen gave up his job as Chair of the Department of History, something he would not have felt comfortable doing without being certain that the administration of his department would be in the capable hands of worthy successors—first, Dr. Larry Gerber, and then Dr. William F. Trimble. Both Gerber and Trimble gave hearty and vocal support to Auburn's NASA history project. A number of colleagues in aerospace history gave help to the project, including Distinguished University Professor Dr. W. David Lewis and Dr. Stephen L. McFarland. Dr. Roy V. Houchin, who earned a Ph.D. under Hansen, lent aid and comfort to the project team from his vantage point inside the U.S. Air Force. A number of Hansen's graduate students helped the project in various ways, notably Andrew Baird, and Kristen Starr, as did Dr. David Arnold, also of the USAF, and Dr. Amy E. Foster of the University of Central Florida, who earned their Ph.D.s in aerospace history during the time period when this project was being conducted.

A number of people in the NASA History Division deserve credit. Jane Odom, Colin Fries, and John Hargenrader helped track down documents from our Historical Reference Collection. Nadine Andreassen provided much valuable general assistance and helped with the distribution. Interns Rebecca Anderson, Giny Cheong, Jennifer Chu, and Caitlin Gallogly also helped out tremendously.

Also at NASA Headquarters, Tony Springer in the Aeronautics Research Mission Directorate served as an invaluable sounding board on technical aeronautics issues. Now at the National Air and Space Museum, former NASA Chief Historian Roger D. Launius is owed a special debt of gratitude for providing the initial impetus and guidance for this worthy project.

A talented group of professionals handled the production of this book. Heidi Pongratz at Maryland Composition oversaw the copyediting of this book. Tom Powers and Stanley Artis at NASA Headquarters acted as invaluable coordinating liaisons with the graphic design group at Stennis Space Center. At Stennis, Angela Lane handled the layout with skill and grace, Danny Nowlin did an expert job proofreading, and Sheilah Ware oversaw the production process. Headquarters printing specialist David Dixon expertly handled this last and crucial stage of production.

Introduction to Volume II

Reinventing the Airplane

The history of aeronautical technology concerns much more than just the nuts and bolts of airplanes and spacecraft, much more than just the history of propellers and wings, more than the history of landing gear and jet engines, more than the ornithology of P-51s and F-22s, or the genealogy of X-planes. The history of flight technology is just as much a story of people and ideas as are histories dealing with any other topic related to society and culture. Scholars who write about the history of aerospace technology have plenty to say about the research, design, building, maintaining, and utilizing of flight vehicles, but their studies are no less human, no less connected to social, political, or cultural forces because they deal with technical matters.

The history of aeronautical technology tells us a lot about our existence as a thinking, dreaming, planning, scheming, aspiring, and playful species. As aerospace industry analysts William D. Siuru and John D. Busick noted in relation to their study of the evolution of modern aircraft technology, humankind's journey through the ages has been eased and accelerated, but also *complicated* by our unique and irrepressible knack for technology and invention.[1] From the stone ax and clay pot to the electron microscope and Human Genome Project, our technological creations have been ingenious, phenomenal, and occasionally—for good and for ill—of world-shaking significance.

This is, by all means, true for the airplane, one of the most ingenious and phenomenal—if slow-to-come—inventions in history, and surely one of the most world-shaking. In how many ways has the flying machine changed society? As Antoine de Saint Exupéry wrote in 1939, it has "unveiled for us the true face of the Earth."[2] It has brought people together, changed our economy, added an unprecedented new dimension to warfare, affected everything from government, public administration, international relations, international policies, manufacturing, marketing, mining, cities, and real estate, to media, railroads, ocean shipping, agriculture, and forestry. It has affected population, the family, religion, health, recreation, education, crime, and even sex.[3]

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1 William D. Siuru, John D. Busick, *Future Flight: The Next Generation of Aircraft Technology*, 2nd ed. (Tab Books, 1994), p. 3.

2 Antoine de Saint Exupéry, *Wind, Sand, and Stars,* translated from French by Lewis Galatiere (New York, 1939), p. 97.

3 One of the most remarkable analyses of the overall impact of aviation on the world came right after World War II with William Fielding Ogburn's *The Social Effects of Aviation* (Boston, 1946).

It has not been all for the good. In the 90 years from the tragic death of Lt. Thomas Selfridge in Orville Wright's airplane at Fort Myers, Virginia, in 1908, to the use of commercial airliners by terrorists to attack New York and Washington, DC in September 2001, there has never been a time when aviation did not know terrible accidents. Aviation has also brought human conflict to new depths of destruction. Despite this fact, the flying machine has always inspired "great expectations"—perhaps too great, given that it is, after all, just one of our *many* machines. Orville Wright summed up our loftiest ambitions for aviation when he said that it had been his hope (and that of brother Wilbur) that they were giving the world "an invention which would make further wars practically impossible." Unfortunately, history proved them wrong, and it did not take long to do it. As much as we admire the "Bishop's Boys" for their dream of a benevolent instrument of global peace, we are equally astonished by how such extraordinarily clear and logical thinkers could have been so ordinarily naive about the forces in the world around them. Maybe someday their vision will be proved right, and the world will discover, as the Wrights did, that peace, like flight, requires not brute power, but control and balance.

Contrary to what many engineers, most technocrats, and the great majority of industrial entrepreneurs seem to believe; contrary to people who use the Internet to read the morning paper, or to golfers who cannot enjoy a round of golf without riding in an electric golf cart and swinging a $500 titanium-headed driver; contrary to what many people in modern consumer society seem to believe, *technology is not inherently good*. In the words of one of the founding fathers of the history of technology as a discipline, Melvin C. Kranzberg, "technology is neither good, nor bad, nor is it neutral." Kranzberg called this "The First Law of the History of Technology."[4]

By its very nature, no technology is absolutely "good"—and none is bad. But neither is technology ever *neutral*. Depending on how we design technology, and even more on how we *use* technology, it will affect us, and change us, in some way. Whether the effects and changes turn out to be good or bad, or both inseparably together, is not predestined in the inherent qualities of the technology itself but rather depends on the broader context and values within which we live our lives. The human consequences of the airplane have gone far beyond what the Wrights or anyone else imagined in 1903. If it had been invented at a different time, or if it had been introduced into a different context or under different circumstances, the invention of the airplane might have led to quite different results. In this case, as in others, "The river of history could have cut a different canyon."[5]

Kranzberg's first law reminds us to "compare short-term versus long-term results, the utopian hopes versus the spotted actuality, the what-might-have-been against what actually happened, and the trade-offs among various 'goods' and possible 'bads.'" All of these comparisons can be made "by seeing how technology interacts in different ways with different values and institutions, indeed, with the entire sociocultural milieu."[6]

But Kranzberg's first law is not the only "law" apropos to consideration of the history of flight technology. Another basic insight comes not from historians, but from those who work in the aerospace industry. There is a saying in that industry: "Requirements push and technology pulls." What this means, in a nutshell, is that the requirements of new missions, or even the need to improve upon current jobs, often drives engineers and scientists to work on the leading edge of technology. They are being "pushed" by ever more demanding requirements to find solutions to problems through the invention of new ideas. Technology then "pulls" by attracting those responsible for finding a way to meet the requirements for the newest concepts germinating in university, government, and commercial laboratories. For the push and pull to work together effectively, it takes forward-thinking planning smart enough to envision a way to use the new technology successfully in the design of a brand new aircraft.

This sequence of developments—(1) requirements [or needs], (2) technology, and (3) concepts—has been, and still is, basic to the technological progress of most modern aircraft—and perhaps *all* military aircraft. "Requirements push and technology pulls" may be just a more complicated way of the old saying, "Necessity is the mother of invention." There is considerable common sense, and historical validity, to this aphorism, but it is also true that it is not always the case—or always that illuminating of what actually is going on. Sometimes "necessity is *not* the mother of invention," but rather "*invention* is the mother of necessity." This was, in fact, Kranzberg's second law of the history of technology—and it makes us think about aerospace technology in some very important ways.

Once the Wrights invented the airplane, all sorts of things really needed to happen. Over the course of the next 30 years, as this volume shows, the airplane was in a sense *reinvented* as the Wrights' achievement was completely rethought and reworked by emerging groups of professionals dedicated to the airplane's improvement and greater practicality. What Kranzberg's second law illuminates is that "Every technical innovation seems to require additional technical advances in order to make it fully effective."[7]In the case of the airplane, the invention quickly necessitated all sorts of auxiliary technologies: advanced structures and materials, new wing shapes, streamlined aerodynamics, retractable landing gear, efficient low-drag engine cowlings, variable-pitch propellers, and much more. But perhaps even more importantly, it also necessitated new social forms and organizations (e.g., military

[4] Melvin C. Kranzberg's classic essay "Technology and History: 'Kranzberg's Laws'" (in *Technology and Culture* 27 [July 1986]: 544-560) offers penetrating and witty analysis of the interactions between technology and its social context.

[5] See George Will, "What Paths Would the Nation Have Taken Had Taylor Lived?" *Washington Post*, 20 June 1991. Will's article raises fascinating issues relevant to the historical "what-ifs" and "might-have-beens."

[6] "Kranzberg's Laws," 547-548.

[7] "Kranzberg's Laws," 548-549.

air services, airlines, airports, government bureaus, research laboratories, engineering curricula, and much more) in order to make the airplane more fully practicable. "While it might be said that each of these other developments occurred in a response to a specific need," Kranzberg claimed, "it was the original invention that mothered the necessity."

It is important to underscore one last, essential point before moving into this second volume of *The Wind and Beyond.* Just because the history of technology involves technology, it does not mean that technical factors always take precedence. In the real world, "soft" and "mushy" things such as politics and culture, for example, what bankers think can make them money or what activists say may harm the environment, often override good technical or engineering logic. *And they should.* Some might say that is why an American SST has never flown. That is why in the history of the American space program, all the thoughtful and well-intentioned talk about "the next logical step" has almost never led to it. After launching a man into space via Project Mercury, NASA said that the next logical step was to establish a permanent manned presence in low earth orbit, but instead the country landed men on the moon. After going to the moon via Project Apollo, the next logical step was to build an earth-orbiting space station along with a space shuttle to service it, but instead, the Nixon Administration decided that the country could not afford both and could manage temporarily with just the shuttle, although the space station had always been the shuttle's main reason for existing. After the shuttle, surely the next logical step was to build a space station, but once again, the country found reasons to postpone building one.

Clearly, logic does not determine the history of technology, and technologically "sweet" solutions do not always triumph over political and social forces. Historical logic, if we even want to use that phrase, is not the logic of engineers and scientists; it is the logic of Lewis Carroll's *Through the Looking Glass*. In that all-too-real fantasy land, Tweedledee explains logic to Alice: "Contrariwise, if it was so, it might be; and if it were so, it would be; but as it isn't, it ain't. That's logic." Tweedledee's logic is the only kind the American space program has ever known, or probably ever will.

So, when stumbling across a book about the history of aerospace technology, a reader should not be put off because he might think the book, and author's brain, is simply full of engineering tables and equations. There is a lot of "soft and mushy stuff" there also. It is what makes our species human, an essential part of what makes us brilliant, and a large part of what drives us nuts. It is what makes the history of technology one of the most complex and fascinating subjects one can possibly study.

There may be a bigger message here as well. In 1998, Microsoft's Bill Gates said about the Wright brothers' invention in a speech he gave at *Time Magazine*'s 75th anniversary celebration of the airplane that, "We have to understand that engineering breakthroughs are not just mechanical or scientific, they are liberating forces that can continually improve people's lives."

Let us hope that the flying machine, in the 21st century, does "free" us, in *more positive* ways, than it has been able to do in the century just passed. There is no guarantee that it will. But like our dear Wright brothers gazing into their future that is our present, let us proceed into this new millennium with optimism that our globe's political environment will improve so that our future generations can enjoy our technical advances and not be destroyed by them. It is something in which the Wrights would want us not only to apply our best problem-solving and inventive skills, but also in which to invest our limitless capacity to hope and to trust.

Biographies of Volume II Contributors

James R. Hansen, Professor of History and Director of the Honors College at Auburn University, has written about aerospace history for the past 26 years. His newest book, *First Man: The Life of Neil A. Armstrong* (Simon & Schuster, 2005), offers insight into the life and times of the first man on the Moon, but also sheds new light on many of the aerospace events and personalities that shaped America in the second half of the 20th century. His two-volume study of NASA Langley Research Center—*Engineer in Charge* (NASA SP-4305, 1987) and *Spaceflight Revolution* (NASA SP-4308, 1995) earned significant critical acclaim. His other books include *From the Ground Up* (Smithsonian, 1988), *Enchanted Rendezvous* (NASA Monographs in Aerospace History #4, 1995), and *The Bird Is On The Wing* (Texas A&M University Press, 2003).

Jeremy R. Kinney is a curator in the Aeronautics Division, National Air and Space Museum, Smithsonian Institution, and holds a Ph.D. in the history of technology from Auburn, with a specialization in aerospace history. Prior to joining NASM, he served as the American Historical Association NASA Fellow in Aerospace History.

D. Bryan Taylor is a doctoral candidate in the history of technology at Auburn. He holds an M.A. in history from Brigham Young University.

Molly F. Prickett holds a B.A. degree in English from Auburn University.

J. Lawrence Lee holds B.M.E., M.A., and Ph.D. degrees from Auburn. He is an engineer-historian at the Historic American Engineering Record, a branch of the U.S. National Parks Service, and is former chair of the History and Heritage Committee of the American Society of Mechanical Engineering.

Chapter Three

The Design Revolution

Destination Document:

The DC-3 freed the airlines from complete dependency on government mail pay. It was the first airplane that could make money just by handling passengers. With previous aircraft, if you multiplied the number of seats by the fares being charged, you couldn't break even—not even with a 100 percent full load. Economically, the DC-3 let us expand and develop new routes where there was no mail pay.

C. R. Smith, President of American Airlines, ca. 1938, quoted by Robert J. Serling,* Eagle: The Story of American Airlines *(New York: St. Martins, 1985), p. 110.

On a Streamline to the DC-3

In 1935, the National Aeronautics Association (NAA) awarded its prestigious Collier Trophy to the Douglas Aircraft Company for its new family of twin-engine transport planes. The trophy, awarded annually, recognized the greatest achievement in American aviation. In doing so, the NAA acknowledged not only a superlative aircraft but also a revolution in the design of airplanes. In the three decades since the achievement of flight by the Wright brothers, the flying machine had evolved from a fragile contraption of wood, wire, and cloth into a sleek and sturdy

The Douglas DC-3 became the most popular and reliable propeller-driven airliner in aviation history and its appearance in the mid-1930s marked the culmination of the design revolution in American aircraft. (SI Negative No. ACC 1997-0033) form of modern public transportation. The Douglas transport honored by the 1935 Collier Trophy featured all-metal construction, an enclosed streamlined shape with cantilever monoplane wings, cowled radial engines, controllable pitch propellers, high-lift flaps, and retractable landing gear. One of the great airplanes of all time, the Douglas DC-3, represented not only what was to become one of the truly classic designs in aviation history but also the culmination of a creative process involving an almost total "reinvention" of the airplane.

The reinvention of the airplane flowed from many technological streams that converged in the years following World War I. Aviation technology had progressed in significant ways in the fifteen years after Kitty Hawk, but strut-and-wire-braced open-cockpit biplanes with fixed landing gear still pretty much reflected the state of the art. Aircraft designers worked from a very limited understanding of aerodynamics, and their products were primarily the result of empirical, even "cut-and-try," engineering. A few potential breakthroughs appeared during the war, but frail wooden biplanes covered with fabric, braced by wires, powered by heavy water-cooled engines, and driven by hand-carved wooden propellers still ruled the airways in 1918. The principles of aeronautical engineering had yet to be fully discovered, and only a few programs at major schools such as Massachusetts Institute of Technology (MIT) and the University of Michigan existed to find these ideas and teach them to students. Aircraft design remained a largely intuitive practice requiring bold speculation and daring, in both a financial and technological sense.

In terms of engineering, a number of unknowns endangered aircraft performance. Even those few professional aeronautical engineers who did exist did not know for sure how to reduce engine drag without degrading cooling. They did not know with certainty how to shape wings to increase lift or diminish the effects of turbulence. They did not know how and when flaps, ailerons, and other control surfaces worked best. In addition, they did not even know if it was worthwhile to retract landing gears—according to certain pundits, the added weight and structural complexity of a retractable undercarriage was not worth the saving in air resistance. Aeronautical engineers suspected that substantial increases in aerodynamic efficiency might follow on the heels of correct answers to just a few of these technical concerns, but they did not know exactly how, or even whether to try, to get at them.

In significant ways, the process of "reinventing the airplane" that unfolded in the 1920s and 1930s grew naturally out of these questions and suspicions. Institutionally, the process took shape and gained momentum as a growing body of professionals began to attack the problems obstructing the immediate progress of aviation, particularly those vexing the fledgling military air services and aircraft manufacturing and operating industries. Major new institutions played critical roles. In the United States, the National Advisory Committee for Aeronautics (NACA) and the research agenda of its Langley Memorial Aeronautical Laboratory was formative in defining what needed to be accomplished. Following its establishment in 1915, the NACA conducted research into basic aerodynamic, structural, and propulsion

problems. Solutions to these problems in the interwar period led in fundamental ways to the design and operation of advanced aircraft like the Douglas DC-3, which were safer, faster, higher-flying, and generally more versatile and dependable than any aircraft ever flown. New research and development tools, especially the wind tunnel, played a key role in the process of reinventing the airplane, as engineers worked to create the most effective streamlined shape possible.

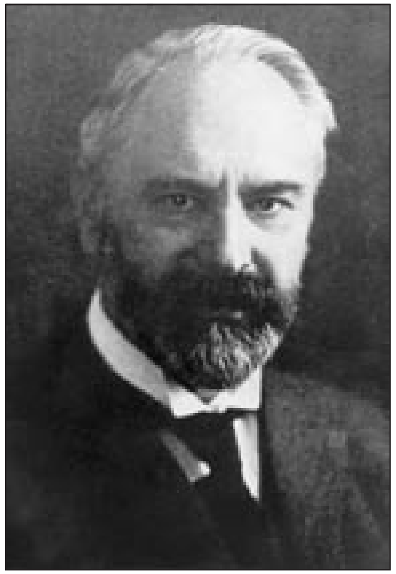
One of the central problems addressed by the airplane design revolution of the 1920s and 1930s was aerodynamic drag reduction. In his history of aerodynamics, John D. Anderson has asserted that, "The major thrust in the age of the advanced propeller-driven airplane can be summarized in a word: *streamlining*.[1] Aircraft designers of the interwar period understood streamlining, in Anderson's words, as "adopting a form that is so shaped and so free of protuberances that it produces no eddies in the airflow over it." In essence, streamlining meant drag reduction, and drag reduction enabled aircraft to fly farther and carry heavier loads. Reduced drag would also allow aircraft to fly faster without expending more energy and fuel resources, meaning that the same size airplane could perform the same work with less energy cost. All the way back to the days of Sir George Cayley, aeronautical experts had been aware of the presence of aerodynamic drag (i.e., the resistance to the forward movement of body in a fluid like air). But because the sources and even the actual composition of aerodynamic drag were not well understood, few quantitative or otherwise nonintuitive methods were available to pioneering designers to lessen the effects of drag on aircraft performance.

Frederick W. Lanchester's experimental and nonquantitative search for a "streamlined form" resulted in his 1907 pioneering book, *Aerodynamics.* (SI Negative No. 45374-C)

As with most revolutions, the aircraft design revolution of the 1920s and 1930s drew upon earlier ideas not materialized in tangible ways during their own day. Without question, the reinvention of the airplane depended on this sort of heritage. It drew inspiration as well as practical lessons from what pioneers in theoretical aerodynamics discovered back in the late 19th century.

In key respects, it was the work of English engineer and automobile maker Frederick W. Lanchester that inaugurated the first great age of aerodynamic theory. Curiously, Lanchester's work was largely experimental and nonquantitative, involving a program of experiments

[1] John D. Anderson, Jr., *A History of Aerodynamics and Its Impact on Flying Machines* (Cambridge University Press, 1997), p. 319.



German physics professor Ludwig Prandtl pioneered the academic study of drag and the use of streamlining to improve aerodynamic efficiency overall in the 1920s and 1930s. (SI Negative No. 74-10601)

initiated in the early 1890s, with cambered airfoils. The principle objective of Lanchester's work was to define an efficient low-drag shape with smooth contours that offered no resistance to the passage of airwaves along its surface; he called this shape a "streamline form." Lanchester realized that irregularity in an airfoil's shape caused disturbances in an airflow and resulted in a significant amount of drag. Unfortunately, Lanchester's work did not receive the attention it deserved at the time, in part because his theories lacked the type of truly quantitative methodology that could have practically aided early aircraft designers. Document 3-1 provides excerpts from Lanchester's 1907 book, *Aerodynamics*, featuring his concept of streamlining.

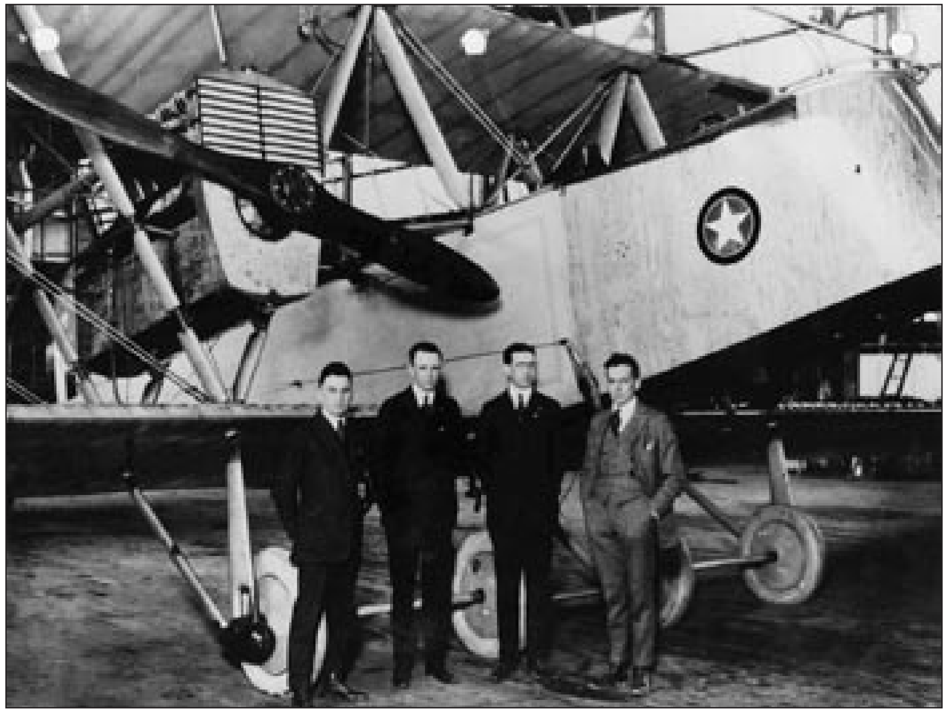
Another formative aerodynamic thinker for the subsequent revolution in airplane design of the 1920s and 1930s was the influential German physics professor Ludwig Prandtl, much of whose work supported Lanchester's ideas about streamlining. The best understanding of aerodynamic drag at the turn of the century was based on what little was known about the performance of hydrodynamic forms. Yet both Lanchester and Prandtl realized that air and water were far different media—for one example, air created more frictional resistance than water. Addressing this issue at the Third International Congress of Mathematicians at Heidelberg in 1904, Prandtl observed that an ideal airflow moved in smooth parallel layers. But in real-world circumstances, such as the flow of air over a wing surface, this so-called laminar flow became turbulent, resulting in significant drag. What Prandtl reported in 1904—to a largely disinterested audience of purer-minded mathematicians—was that an airflow changed in dramatic fashion from zero to constant velocity in a very thin "transition layer" right next to the surface of the airfoil. In this extremely narrow zone, later to become known as the "boundary layer," transition from laminar to turbulent flow affected aircraft performance profoundly.[2], Prandtl's boundary-layer hypothesis of 1904 (excerpted as Document 3-2) offered major new opportunities for aircraft designers and aeronautical engineers. What

[2] The first known reference to the term "boundary layer," according to the *Oxford English Dictionary*, came in 1921, when Dutch fluid mechanics specialist J. M. Burgers wrote in his country's *Proceedings of the Royal Academy of Science* (Proc. K. Acad. Wetensch [Amsterdam]) that "we can calculate the distribution of the vorticity in the boundary layer, when we suppose the velocity outside the boundary later to be known." The second recorded use of the term, according to the *OED*, came in an article appearing in *Flight* magazine on 20 November 1924: "The deductions from the boundary layer theory gave a rather poor approximation to the truth."

Grover Loening (left), seen here with Orville Wright (right) in 1913, was one of the earliest aeronautical engineers employed by the United States government and advocated the streamline form as the ideal shape for an airplane. (SI Negative No. 80-5407)

he taught about airflow in the boundary layer near the surface of an aerodynamic body provided the first rational basis for calculating what came to be known as "skin friction drag." His theory also promoted vastly improved understanding of the dynamics of flow separation around an aerodynamic body, which was a major source of " form drag." Prandtl's students also learned that the best way to lessen the effects of "parasitic drag" (i.e., the combination of skin friction drag and form drag) was to delineate smoother contours for wings and other aerodynamic forms. In sum, Prandtl's work, like Lanchester's, not only highlighted the problem of drag, it underscored the practical advantages of streamlining.

While the work of Lanchester and Prandtl provided an essential theoretical basis for understanding drag, the concept of streamlining saw little practical application in the vast majority of aircraft designs emerging from World War I. Angular shapes and drag-producing protuberances were still ubiquitous features. Nevertheless, the idea of improving aircraft performance through streamlining did catch the attention of some people in the aeronautical community during the war. One such individual was Alexander Klemin, a civilian research working for the U.S. Army Air Service, who explored the idea of streamlining in a 1918 textbook entitled *Aeronautical Engineering and Airplane Design*, one of the first works of its kind published in the United States (see Document 3-3). A graduate of the aeronautical engineering program at MIT, Klemin came to head the Aeronautical Research Department at the U.S. Army Air Service's engineering facility at McCook Field, in Dayton, Ohio.



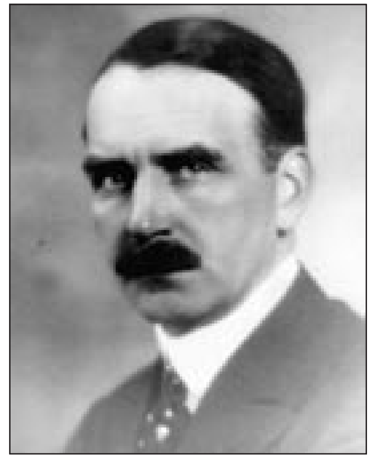
Aircraft such as the biplane, strut-and-wire braced Martin MB-1 Bomber represented the state of the art in aerodynamic design circa 1917. The designers of the aircraft, Laurence D. Bell (left), Glenn A. Martin (second from right), Donald W. Douglas (right), and James Kindleberger (not pictured), would use the advances of the design revolution to create vastly different aircraft. (Martin test pilot, Thomas E. Springer, is second from left.) (SI Negative No. 43067)

Equating "resistance" to "drag," he noted in his groundbreaking textbook that a streamline form was the ideal shape for an airplane. But major obstacles blocked the achievement of ideal streamlining, notably the realities of conventional design practice, which necessitated the incorporation of mammoth and strangely shaped engines, the bodies of pilots and passengers, plus messy structural items such as bracing wires and struts. Somehow, Klemin concluded, many of these obstacles would have to be overcome if an airplane 's aerodynamic effectiveness were ever to improve much.

After the war, more and more aviation advocates placed an emphasis on aircraft efficiency, culminating in 1922 when pioneering French aircraft manufacturer Louis Breguet issued a clarion call for the development of streamlined designs. In an address before the Royal Aeronautical Society in London entitled "Aerodynamic Efficiency and the Reduction of Aircraft Costs" (see Document 3-4), Breguet outlined the problem in both technical and economic terms, and he articulated various social incentives for the improvement of civilian aircraft in the postwar period. Breguet believed that an improvement in the lift-to-drag ratio, which he called the "fineness" of an aircraft design, would enhance an airplane's economic potential by

efficiently extending its range. To achieve an economic range through the improvement of the lift-to-drag ratio, Breguet called for the use of streamlining, specifically suggesting such measures as the use of retractable landing gear. He even defined a target "fineness" ratio for commercial aircraft—a ratio ultimately achieved just over a decade later in the design of the Douglas DC series.

Another factor that proved to play a critical role in spurring both the development and general acceptance of streamlined aircraft designs was performance at air races, which became enormously popular in Europe and America in the late 1920s and 1930s. At the international level, the greatest of these races, such as the Schneider Trophy competition, presented opportunities for benign competition between world powers; victories won and records set were perceived by all as signs of national technological prowess. Within a given country, races held similar significant meanings; for example, in the United States, the Army and Navy worked feverishly to come in first in the competitions, hoping through first-place finishes and world and national records to secure greater political support for the development of the air forces.



French aircraft builder Louis Breguet made one of the strongest cases for the social and economic benefits of aerodynamic streamlining in a 1922 speech delivered before the Royal Aeronautical Society entitled, "Aerodynamical Efficiency and the Reduction of Transport Costs." (SI Negative No. 77-542 or 78-13907)

The air races fostered experimentation and rapid technological development, much as automobile races did and still do. Both the Army and Navy used wind tunnels to refine their racers to get the utmost speed out of them. Many racing aircraft employed groundbreaking devices that would become part of the modern airplane; these included streamlined designs, cantilever wings, and retractable landing gear. In 1923, an American airplane, the U.S. Navy Curtiss CR3s, took first and second place in the Schneider Cup international seaplane race in Cowes, England, the winner at a top speed of 177.38 miles per hour (mph). The aircraft employed new technology, including flush wing radiators and a solid aluminum alloy propeller. This propeller incorporated aerodynamically advanced thin airfoil sections based on the designs of Dr. Sylvanus A. Reed. At the tips of the propeller blades, the airflow reached speeds approaching the speed of sound. But it was the sleek, streamlined fuselage of the aircraft that really captured everyone's eye. As contemporary observers noted, everything about the airplane spelled "speed" (see Document 3-5). Another Navy Curtiss racer, the R2C-1, won the 1923 Pulitzer Trophy Race in St. Louis, Missouri. In doing so, the slender little airplane set new world speed records of 243.8 mph for 100 km and 243.7 mph for 200 km over a closed circuit. No other aircraft flying at the time could boast cleaner aerodynamics. Curtiss designers got the airplane's zero-lift drag coefficient

The streamlined fuselage, flush wing radiators, and solid aluminum alloy Reed propeller of the navy Curtiss CR-3 racer highlighted the role of aerodynamics in high-speed aircraft design. Lt. David Rittenhouse (in cockpit) flew the CR-3 to victory in the 1923 Schneider Cup international seaplane race in Cowes, England. (SI Negative No. A-47217)

($C_{D,O}$)—considered by many experts as the best indicator of the aerodynamic cleanness or refinement of an aircraft.[3] In fact, it ranks among the lowest values in the entire history of aerodynamics for propeller-driven aircraft—lower than that enjoyed by four of the sleekest aircraft produced by the airplane design revolution of the 1930s: the Lockheed Vega (0.0278), Lockheed Orion (0.0210), Boeing 247D (0.0212), and Douglas DC-3 (0.0249). Only a few American prop-driven planes have ever achieved lower zero-lift drag coefficient. Noteworthy among these were the Beechcraft D17S four-place monoplane of 1939 (0.0182), North American P-51D fighter plane of 1944 (0.0163), and Beech Bonanza V-35 general aviation aircraft of 1970 (0.0192).

3 For a clear explanation of the significance of the zero-lift drag coefficient, see Laurence K. Loftin, Jr., *Quest for Performance: The Evolution of Modern Aircraft* (Washington, DC: NASA SP-468, 1985), pp. 4-5, 158-160. Loftin defined this coefficient *Cd, o* as "a nondimensional number that relates the zero-lift drag of the aircraft, in pounds, to its size and the speed and altitude at which it is flying. Generally speaking, the smaller the value of the number, the more aerodynamically clean the aircraft." As useful as it is as a measure of aerodynamic refinement, the significance of the zero-lift drag coefficient is limited in application because it is based on wing area and because, for a given wing area, several different sizes of fuselage and tail may be employed. Thus, as Loftin made clear, "differences in zero-lift drag coefficients may be interpreted as a difference in aerodynamic refinement" when, in fact, the difference may be the product of differences in the ratio of "wetted" area (i.e., the area of the entire body that comes in direct contact with the airflow) to wing area (Loftin, pp. 158-159).

The challenges and glories of air racing definitely inspired streamlining, but in the minds of many, the association of streamlined shapes with racing implied that the technology of highly sleek and efficient aerodynamics belonged only to the realm of high-speed applications. But this was hardly the case. Advanced aerodynamic refinement in the form of streamlining was already beginning to play a critical role in the design of a number of revolutionary civil and commercial aircraft as well, a technological development that would help stimulate the first great age of aviation as an effective mode of mass public transportation.

One of the first nonmilitary or racing aircraft to demonstrate streamline design was the boldly innovative Lockheed Vega of 1926, designed by engineering genius John K. Northrop. Self-taught, highly creative, and remarkably proficient in transferring a speculative design from his "mind's eye" to reality, "Jack" Northrop stood ready at the leading edge of the streamlining movement in the United States, albeit from a direction quite different from that of building racers or being immersed academically in aerodynamic theory. His "feel" for aerodynamic refinement was more "aesthetic," in that it involved a heightened sensitivity for what looked beautiful and was in "good taste." Not that Northrop did not base his designs in engineering practicality. The key to the Vega's aerodynamic efficiency rested in the techniques he used in its construction. Lightweight, strong, and remarkably streamlined, the Vega represented a dramatic departure from previous designs in that it was a single-engine, high-wing cantilever monoplane with a semimonocoque (*monocoque* meaning "one shell") plywood stressed skin fuselage. The cantilever wing featured internal bracing. A major new feature incorporated in later Vega airplanes was a circular cowling surrounding the 450-horsepower Pratt & Whitney Wasp air-cooled engine. This cowling concept derived from the NACA's systematic identification of efficient cowling forms, ones that not only reduced drag but also at the same time, improved cooling of the engine. The only major nonstreamline element of the Vega's profile was its fixed landing gear, but in later versions, even that had fairings called "pants" around its wheels, which also helped to reduce drag. As mentioned previously, the airplane benefited from a very low zero-lift drag coefficient, which helped it to reach a maximum speed of 190 mph. Airlines used the plane to fly passengers (six at a time), and a number of pilots, including Amelia Earhart and Ruth Nichols, broke records in it. In a Vega named *Winnie Mae*, Wiley Post flew solo around the world in the summer of 1933, need-

Jack Northrop's innovative construction techniques facilitated his design of highly efficient and aesthetic streamline aircraft designs such as the Lockheed Vega and the Northrop Alpha. (SI Negative No. 75-5442)

The Lockheed Vega of 1926 represented a dramatic departure from previous designs with its monocoque construction, NACA cowling, and teardrop wheel pants. Wiley Post flew the Lockheed Vega 5-B "Winnie Mae" solo around the world in only seven and one-half days during the summer of 1933. (SI Negative No. A-47516)

ing only seven and one-half days. In Document 3-6, Northrop recorded some of his views on streamlining and its relationship to construction technology as embodied in the Lockheed Vega.

The development of streamlined aircraft did not come all at once. Perhaps more than any other single element, it awaited widespread recognition of the advantages of streamlining by some of its most influential leaders, if not the aeronautical community as a whole (see Document 3-7). The initial focus of the efforts to reinvent the airplane hinged on the independent development of specific airplane parts, what aviation historian Richard K. Smith referred to as "shelf items.[4] These included components such as airfoils, engine cowlings and nacelles, flaps, propellers, fillets, and retractable landing gear. Government researchers, engineers in industry, and lone inventors played a part in developing these innovations—for the most part, separately and individually. Designers and manufacturers would then incorporate and synthesize the new technology into final aircraft design as needed. Despite their "shelf-item" status, these innovations were not truly "stand-alone" technologies that could simply be put on the airplane; they had to be integrated into a total design. One important function performed by the NACA was full-scale wind tunnel testing of the aerodynamic advantages inherent to all these various components as they were located on new airplanes, which provided data tables and computations so designers could use the information for a variety of future designs. Richard K. Smith further

[4] Richard K. Smith, "Better: The Quest for Excellence," in *Milestones of Aviation*, ed. John T. Greenwood (New York: MacMillan, 1989), p. 240, 243-4.

observed that the leading developer of many of these "shelf items" was the NACA itself. In his view, "no other institution in the world contributed more to the definition of the modern airplane".[5] The improved components, along with the fundamental understanding of the mechanism of drag that resulted from NACA research, became widely disseminated throughout the aeronautical engineering community and the aircraft industry during this crucial transition period.

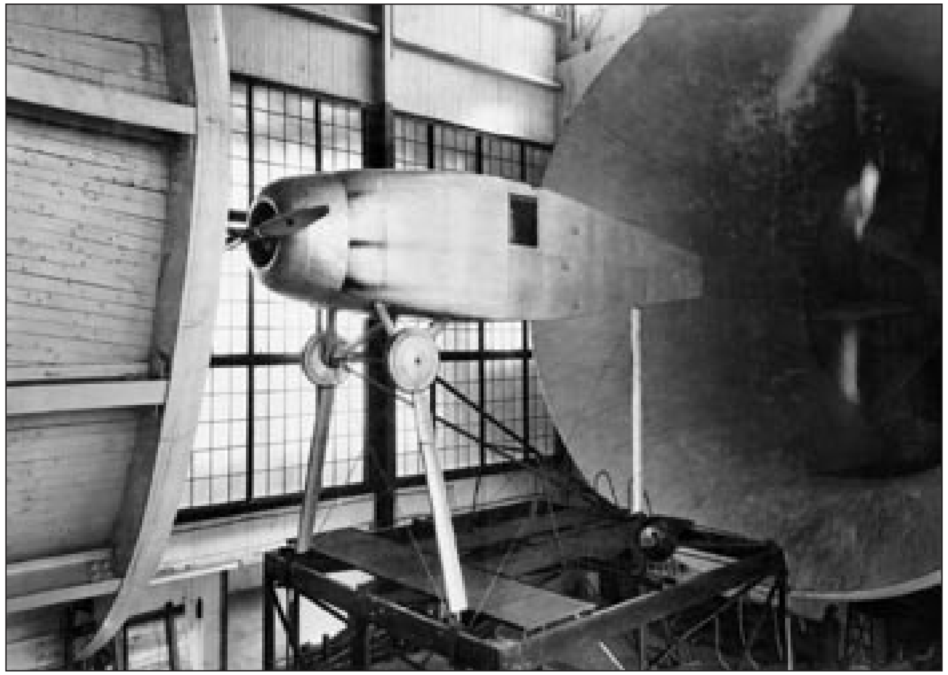
Without question, the NACA contributed greatly to virtually every aspect of airplane aerodynamics during the late 1920s and early 1930s. Some of the most important work was in the development of improved airfoils, a subject treated in detail in the next chapter. But the NACA team at Langley laboratory in Virginia also worked on many other areas of aircraft component improvement. For example, some of the first projects in the new Propeller Research Tunnel (PRT), which began operations in July 1927, concerned improvement of the aerodynamic qualities of engine installations, struts, and landing gear. The first important step in this work was to determine through systematic experimental parameter variation exactly how much drag a particular component produced.

The test program that initiated the NACA's move toward the widespread reduction of drag focused on engine cowlings. Aerodynamic tests on one of the Army's small Sperry Messenger airplanes in Langley's PRT in late 1927 revealed that the exposed cylinders of the air-cooled radial engine caused 17 percent of all drag plaguing the aircraft. The most obvious solution to this problem was simply to cover the engine with some sort of streamlined shroud or cowling. But such a covering, it was thought, would restrict airflow past the cylinders and cause the engine to overheat. With this in mind, cowlings were not used very often. But the drag problem grew into a more and more critical concern, so much so that at the NACA's first annual manufacturers' conference, held at Langley in May 1926, representatives of the aircraft industry and the U.S. Navy's Bureau of Aeronautics identified it as a national priority. The challenge for the NACA was to define a form of cowling that significantly improved aerodynamic efficiency without degrading cooling.[6]

Documents 3-8, 3-9, and 3-10 all relate to the NACA's cowling program, for which the NACA won its first Collier Trophy in 1929. The first of these documents is from the autobiography of Fred E. Weick, the Langley engineer who masterminded the development of the NACA's low-drag cowling. In it, he recalled in

[5] Smith, "Better," p. 240.

[6] For a complete analysis of the history of the NACA cowling program, see James R. Hansen, "Engineering Science and the Development of the NACA Low-Drag Engine Cowling," in *From Engineering Science to Big Science: The NACA and NASA Collier Trophy Research Project Winners,* ed., Pamela E. Mack (Washington DC: NASA SP-4219, 1998), pp. 1-27. This chapter is an updated and expanded version of Chapter 5 of Hansen's *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958* (Washington DC: NASA SP-4305, 1987), entitled "The Cowling Program: Experimental Impasse and Beyond," pp. 123-139.



The inclusion of NACA Cowling No. 10, seen here undergoing tests in the 20-foot tunnel in September 1928, into the design of the Martin B-10 bomber increased the airplane's maximum speed by 30 mph to 225 mph and reduced its landing speed significantly. (NASA Image No. 1974-L-02730)

The NACA won its first Collier Trophy in 1929 for its innovative work on low-drag cowlings. (NASA Image No. L-1990-04348)

The inclusion of the NACA low-drag cowling to the Texaco Lockheed Air Express allowed Frank Hawks to establish a new Los Angeles to New York nonstop record of 18 hours, 13 minutes in February 1929. (SI Negative No. A31250-G; Videodisc No. 2B-11966)

Hubert C. H. Townend of the British National Physical Laboratory developed a low-drag engine cowling in 1929. Known as the "Townend ring," the design reduced drag with little degradation of engine cooling and was widely adopted in Europe and America. (SI Negative No. 76-17366)

The alternative to the NACA cowling was the Townend ring, seen here mounted on a Boeing P-26 Peashooter perched in the Langley Full-Scale Tunnel for aerodynamic testing. (NASA Image No. L-09819)

The NACA worked to improve existing designs such as the Fokker Trimotor with the addition of experimental low-drag cowlings and streamline engine nacelles in 1929. (NASA Image No. L-03333)

extraordinary detail the careful experimental process by which the NACA arrived at its award-winning shape. The second involves a string of documents, the first of which relates to the stunning performance in February 1929 of a Lockheed Air Express, a derivative of the Lockheed Vega. Equipped with a NACA low-drag cowling that increased its speed from 157 to 177 mph, this aircraft, piloted by Frank Hawks, established a new Los Angeles to New York nonstop record (18 hours and 13 minutes). The third presents a trio of documents concerning the appearance of other new forms of engine cowlings that came to rival the NACA design.

During the process of developing better components for an aircraft, the work on one "shelf item" often led to study of different problems. This situation happened in regard to the NACA cowling, as research engineers found that the cowl did not benefit all aircraft equally: its effectiveness depended on the shape of the airplane behind it. While these complexities spurred on additional work related to cowlings, it also led to other lines of investigation. The original purpose of NACA's Langley Propeller Research Tunnel (PRT) was to develop improved propellers. But early tests in the PRT demonstrated that the machine could be used to study other problems, notably the overall effect of a propeller in combination with the placement of an engine and the placement of engine nacelles in relation to wings. These unintended lines of research led not only to data very significant to aircraft designers but to a few entirely new concepts. In studying the overall effect of the propeller in combination with the placement of the engine, for example, NACA researchers came to express their results in a new quantitative relationship they called "propulsive efficiency." This term reflected the overall propeller output in reference to its mounting on the aircraft. Propulsive efficiency calculations soon became a standard analytical tool in the design of propeller-driven airplanes and played a crucial role in the development of modern streamlined aircraft.

As Fred Weick recalled in our excerpt from his autobiography (Document 3-8), another one of these inadvertent research programs, one devoted to the proper placement of engine nacelles, originated in 1929 when the PRT team at Langley began testing cowling forms on a multiengine aircraft, the Fokker trimotor. When speed trials with the big transport proved extremely disappointing, Weick and his associates started to wonder how the position of the nacelles with respect to the wing might be affecting drag. This was a critical design revolution, especially for multiengine aircraft, as big commercial and military aircraft were bound to be. In the case of the Fokker (as well as the Ford) trimotor, the original design location of the wing engines was slightly below the wing's surface. As the air flowed back between the wing and nacelle, the expansion required was too great for the air to flow over the contour smoothly. The NACA Langley flight research division, in association with the PRT team, tried fairing in this space, but they achieved only a small improvement.

Eventually the NACA's systematic empirical approach yielded dividends. With the help of his assistants, Weick laid out a series of model tests in the PRT with NACA-cowled nacelles placed in 21 different positions with respect to the wing:

above it, below it, and within its leading edge. The resulting data on the nacelle's effect on the lift, drag, and "propulsive efficiency" of the big Fokker trimotor made it clear that the optimum location of the nacelle was directly in line with the wing and with the propeller fairly well ahead. Although their primary emphasis was on drag and improved cooling, the tests at Langley also confirmed that NACA cowling No. 10—the form that completely covered the engine but still managed to cool it by directing air to its hottest spots through ducts and baffles—could actually increase the lift of the airplane's wing in some cases, if the engine was situated in the optimum position.[7]

In transmitting this important information confidentially to the Army, Navy, and industry, the NACA helped build a several-months lead for American aircraft designers over rival European companies. After 1932, nearly all American transport and bombing airplanes—including the Martin B-10, Douglas DC-3, Boeing B-17, and many other famous aircraft of the era that followed—employed radial wing-mounted engines with the NACA-cowled nacelles located approximately in what Weick and his associates had identified as the optimum position. Without question, this combination led to an entire new generation of highly effective airplanes with which airlines for the first time could become financially self-supporting and no longer in need of government subsidies. Paradoxically, as Document 3-11 suggests, some leaders of the U.S. aircraft industry at the time did not fully credit NACA research for this essential contribution to what was quickly becoming a blossoming design revolution.

Another critical component in the reinvention of the airplane was the development of high-lift devices, primarily flaps. Essentially a section of the wing's trailing edge that could be hinged downward to increase the camber of the wing, a flap promised to boost lift and reduce the aircraft's stalling speed. It permitted a better angle of approach and lower speed on landing, important considerations not only for aircraft efficiency but also for safety. The earliest trailing edge flaps simply increased aircraft drag during landing and approach instead of boosting lift, but the desirable element was a structure that did both. In the 1930s, the introduction of high-lift devices such as flaps allowed engineers to design aircraft with higher wing loadings (i.e., the ratio of the gross weight of an airplane to the total planform area of its wing or wings). This was a new aerodynamic technology that proved crucial to the transition from biplanes to monoplanes.

[7] We considered including the following NACA technical reports from 1932 in this chapter collection of documents, but, due to length, determined, it would suffice simply to reference them in a footnote: Donald H. Wood, "Tests of Nacelle-Propeller Combinations in Various Positions with Reference to Wings. Part I. Thick Wing—NACA Cowled Nacelle—Tractor Propeller," NACA *Technical Report 415* (Washington, 1932); and Donald H. Wood, "Tests of Nacelle-Propeller Combinations in Various Positions with Reference to Wings. II.—Thick Wing—Various Radial-Engine Cowlings—Tractor Propeller," NACA *Technical Report 436* (Washington, 1932).

It is perhaps curious to those unfamiliar with the history of aircraft technology to learn that it took so long for wing flaps to become commonplace. The basic idea for them had been around since the aileron device invented by Frenchman Henry Farman in 1908 to get around the Wright brothers patent for wing warping. Farman invented what came to be known as the aileron. Various inventors had created aileron devices prior to Farman, but they had all been separate rotatable surfaces placed in front of (not behind) a wing or sometimes, in the cases of biplanes, even between them. What distinguished Farman's aileron was that the surface was integrated directly into the wing as aircraft designers still incorporate them today. The modern definition of an aileron says that it is "a moveable control surface or device, one of a pair or set located in or attached to the wings on both sides of an airplane, the primary usefulness of which is controlling the airplane laterally or in roll by creating unequal or opposing lifting forces on opposite sides of the airplane.[8] But this definition applies to the word *aileron* only after Farman's innovation of 1908.

A few ideas for flaps sprouted during World War I, but not actually that many, since flying speeds were still too low to make such devices useful. As John D. Anderson explains in his history of aerodynamics, "the low wing loadings made flaps essentially redundant and most pilots rarely bothered to use them.[9] After the war, engineers in various countries pursued new concepts for high-lift mechanisms. In a case of nearly simultaneous invention occurring just before 1920, Dr. Gustav V. Lachmann in Germany and Frederick Handley Page in England invented the "wing slot." Lachmann's original design called for simply a long, spanwise slot located near the leading edge. His idea was to create a pressure differential between the lower and upper surfaces of the wing. This differential would impel a high-energy jet of air through the slot. This jet flowed tangentially over the top surface of the wing, along the way energizing the transition layer (i.e., boundary layer); delayed flow separation to much higher angles of attack; prevented stall; and increased lift in wind tunnel tests by a whopping 60 percent. Frederick Handley Page, who pooled patent rights with Lachmann in 1921 (Lachmann actually went to work for Page's company in 1929), went one step further. He combined a slot and a flap to create the slotted flap, a design that exposed a slot between the flap and the wing when deflected. In combination with the thick new airfoil sections then being designed (see the next chapter), the Page slotted flap reliably produced even greater lift. Still, airplane designers mostly stayed away from flaps. In the United States, this neglect included a new type of "split flap" invented in 1920 by Orville Wright and associate J. M. H. Jacobs in a small laboratory provided by the Army at McCook Field in Dayton. In the 1920s, it was hard to find any aircraft with flaps except for those designed by Page and Lachmann.

[8] Frank Davis Adams, *Aeronautical Dictionary* (Washington DC: NASA, 1959), p. 7.

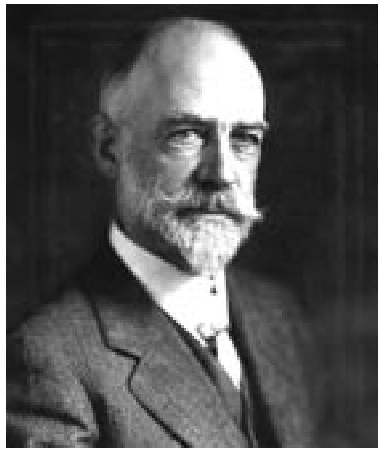
[9] Anderson, *A History of Aerodynamics and Its Impact on Flying Machines*, p. 365.

It was not until the early 1930s that the idea of flaps started to entice many airplane designers—the result of the rapidly increasing speed of aircraft and their higher and higher wing loadings. The string of items comprising Document 3-12 traces the development of one of the most attractive and ultimately successful of these American high-lift designs, known as the "Fowler flap." Invented in 1924, this was an extensible trailing-edge flap that increased both the camber and wing area. Fowler flaps came to be used on several new aircraft from the 1930s on, notably planes built by Glenn L. Martin (in 1933, Martin hired Fowler to design flaps for him), as well as the Lockheed 14 twin-engine airliner of 1937. The Boeing B-29 bomber of World War II employed Fowler wing flaps (although they did not help much to improve the high stalling speed of 105 mph for the big plane); so, too, did later versions of the Lockheed P-38 "Lightning," for greater maneuverability. The wings of the Boeing B-17 employed very powerful Fowler flaps, designed specifically to keep the landing speed within acceptable limits.[10] The Germans even gave their Messerschmitt ME 262 jet fighter Fowler high-lift flaps, along the trailing edge of the wing (and in combination with full-span "slats"—that is, long narrow vanes or auxiliary airfoils—in the leading edges). After the war, Boeing's B-52 bomber augmented its lift via Fowler single-slotted flaps located at the trailing edge of the wing. So Fowler's invention of 1924 had a long shelf life.

Although the Fowler flap was only one of many different flaps designed and used after 1930, it is enlightening in Document 3-12 to follow how this one brand of flap disseminated through the American aeronautics community during the early 1930s. Similar studies could be made with the split flap, which was actually the type first tried on American aircraft. The Northrop Gamma used split flaps, as did the Douglas DC-1, in 1932, and the DC-3, in 1935. Split flaps ruled the roost early on—some suggest it happened in deference to Orville Wright, one of its inventors. About the time designers started to convert to Fowler flaps and other sorts of slotted flaps, the double-slotted flap appeared—on Italy's 1937 M-32 bomber and the Douglas A-26 bomber of 1941. From the DC-6 on, Douglas put double-slotted flaps on the wings of all its airliners. The triple-slotted flap made its first appearance with the Boeing 727 jet airliner in the early 1960s.

Perhaps an even more critical area of aerodynamic refinement necessary for the airplane design revolution of the interwar period involved advancing the state of the art in propeller performance. Again, the NACA played a fundamental role, conducting and supporting propeller research on a consistent basis from its inception as an organization in 1915. The committee's first *Annual Report* acknowledged the need "for more efficient air propellers, able to retain their efficiency over a variety of flight conditions." In the ensuing years, one of its strongest and most regularly funded programs focused on the improvement of propellers.

[10] Laurence K. Loftin. Jr., *Quest for Performance*, pp. 124, 132, and 139.



William F. Durand's long career in aeronautics included his pioneering, with Everett P. Lesley, a standard table of aerodynamic design coefficients for propellers from 1917 to 1926. (NASM Videodisc No. 2B-57570)

What NACA researchers most contributed was systematic correlation between airfoil theory, model propeller tests, and full-flight testing to find the best method of designing aerodynamically efficient propellers. Differences between the three sources of information about propellers showed that a significant gap still existed between empirical and theoretical knowledge. The first method, involving what was called "blade element theory," assumed that a propeller blade was a series of isolated airfoil sections that represented an ordinary wing as they traveled in a helical path. Blade element theory enabled engineers to design propellers that were 70 to 80 percent efficient. The multitalented Fred Weick, who authored a textbook on propellers for McGraw-Hill in 1931, said that blade-element theory enabled no more than a "cut-and-try process" when it came to designing new airfoils.

The second method involved testing model propellers in wind tunnels. The idea was to acquire reliable data from scale models that, through the law of similitude, could be applied to similar geometric bodies of full size. By the 1920s, this type of testing already had a distinguished history. From 1917 to 1926, professors William F. Durand and Everett P. Lesley of Stanford University conducted a program of "Experimental Research on Air Propellers" that provided a standard table of propeller design coefficients, which any designer could utilize.[11] Unfortunately, to make the data applicable for design, one had to carry out mathematical conversions that did not always work out right. It was thus vital to correlate experimental results with theory and with full-scale testing if the resulting propeller shape was to perform as expected.

The final method, full-scale testing, represented the final, ultimate check for propeller efficiency and design. NACA researchers in the 1920s found that the efficiencies of full-scale propellers were often six to ten percent greater than the efficiency of corresponding model propellers. A NACA report of 1925 attested that researchers "can never rely absolutely" upon model data until they verify it through full-scale flight tests. Testing the real thing in the actual flight environment, however, was expensive, time-consuming, potentially dangerous, and often inaccurate if researchers used poorly maintained testing equipment or inadequate techniques.

[11] See Walter G. Vincenti, Chap. 6, "Data for Design: The Air Propeller Tests of W. F. Durand and E. P. Lesley, 1916-1926," *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore and London: Johns Hopkins University Press, 1990), pp. 136-169.

Increased awareness of, and exposure to, the inadequacies of theory, wind tunnel experiment, and flight testing convinced the NACA that some form of "hybridization" of the three methods was necessary. In 1925, the NACA authorized the construction of the 20-foot PRT at Langley. In the following years, Fred Weick, Donald H. Wood, and other Langley researchers conducted various test programs that contributed to the fundamental development of the propeller—especially regarding the use of metal propellers. Their investigations found that by using blades that were thinner toward the tips, they could increase propeller efficiency. Propeller designers had already been aware that thin blade sections were ideal for high-speed applications because they did not suffer from what soon came to be known as "compressibility burble," which amounted to a sharp increase in drag at high speeds. But until propellers were manufactured in metal, this benefit could not be realized. Wooden propellers and their thick sections, necessary for structural integrity, suffered severe drag limitations at high speeds. To turn faster, propellers needed to be thinner, which required the strength of metal.

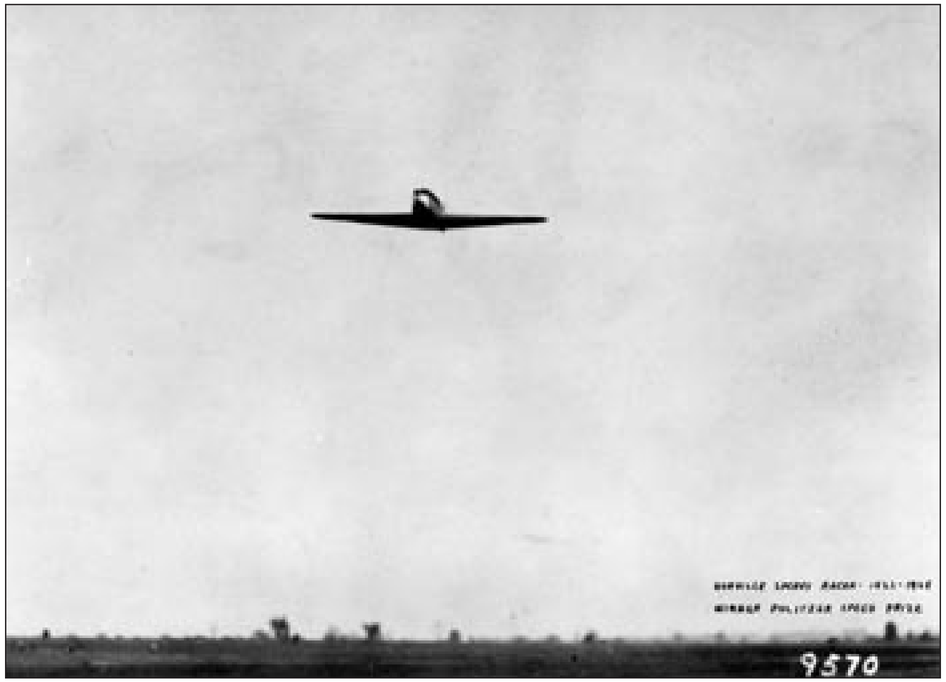
A significant breakthrough in propeller aerodynamics came in the form of the metal, multipiece, variable-pitch propeller—a technological development mostly associated with a research group, from the late 1910s into the late 1920s, under the leadership of Frank Caldwell in the Army's aircraft engineering division at McCook Field. During the first quarter of the century, aircraft propellers had all come with fixed pitch, meaning that the angle at which each propeller blade struck the air remained static. Caldwell's group at McCook recognized earlier that the ideal pitch of a propeller was not the same for different flight conditions. Low-pitch settings were more efficient for taking off and climbing, while high-pitch settings were better for cruising at altitude. With a fixed-pitch propeller, the setting of pitch involved an inherent compromise that somewhere sacrificed efficiency. The invention of the variable-pitch propeller bridged the gap between what could be considered the two major thrusts of the airplane design revolution of the interwar period: increased engine power and decreased drag.

Nothing illustrated the need for a variable-pitch propeller more than Charles A. Lindbergh's dramatic takeoff for Paris on 20 May 1927. Clearing telephone wires at the end of Long Island's Roosevelt Field by only 20 feet, Lindbergh's ground-adjustable propeller was set at a blade angle just below the optimum setting for cruise specifically to accommodate a better takeoff. Searching for every bit of economy for the 3,610-mile transatlantic flight, Lindbergh almost did not get off the ground. Document 3-13 features an April 1927 letter from Standard Steel Propeller Company to Ryan Airlines, a month before Lindbergh's takeoff, which dealt with the critical pitch setting for Lindbergh's historic *Spirit of St. Louis* Ryan-built airplane.

It was apparent to aeronautical engineers well before Lindbergh's takeoff that a method to adjust the pitch of the propellers automatically in flight was needed to improve aircraft performance. But experience proved it was not easy to design a mechanical system to accomplish this task reliably and as precisely as desired. Dr. H.

Lindbergh gambled that a ground-adjustable pitch propeller set just below the optimum setting for cruise would give him long-range efficiency while safely getting the Spirit of St. Louis off the ground at Roosevelt Field. The resultant dramatic takeoff for Paris on 20 May 1927 highlighted the need for variable-pitch propellers. (SI Negative No. A-4819A)

S. Hele-Shaw and T. E. Beacham patented a variable-pitch propeller mechanism in Great Britain in 1924, but it found little application, in part because the need for it was not as great as it was in America. The reason was topographical. Traversing North America by air meant surmounting obstacles like the Appalachian and Rocky Mountains. In 1929, McCook (later Wright) Field engineer Frank Caldwell, who had designed most of the detachable-blade metal propellers in use, resigned from the service to become chief engineer for Hamilton Standard Propeller Company. (He moved into this position just as United Aircraft bought out Standard Steel and joined the two companies, forming Hamilton Standard.) As head of Hamilton's production plant in Pittsburgh, Caldwell devoted himself to perfecting a controllable-pitch propeller, which he accomplished by 1933. Called "the gear shift of the air," Caldwell's device enabled pilots to adjust the pitch of their propeller blades automatically to match different flight conditions. This mechanism resulted in dramatic improvement in performance and won for Caldwell and Hamilton Standard the Collier Trophy in 1933 (see Document 3-14). Improvements in propellers con-



The Verville-Sperry R-3 racer, winner of the 1924 Pulitzer Race, was an important precursor for "modern" high-performance aircraft with its streamline design and retractable landing gear. (NASM Videodisc No. 1B-95330)

tinued, and by 1936, several new aircraft featured constant-speed propellers that could automatically adjust pitch. The NACA contributed key research data during this period relevant to the design and operation of controllable-pitch propellers.

Another essential shelf item developed during the design revolution of the inter-war period, one meant to eliminate a significant source of drag, was retractable landing gear. As Frenchman Louis Breguet had declared in his 1922 Royal Aeronautical Society lecture on "Aerodynamical Efficiency and the Reduction of Transport Costs," the undercarriage should be made to disappear (refer to Document 3-4), but it took a while longer before much happened to eliminate it. Some aviation historians have written that the first American aircraft to incorporate retractable landing gear was the Boeing Monomail of 1930, but this is incorrect.[12] In the 1923 Pulitzer Trophy Race at Mitchell Field, Long Island, the Army entered a low-wing monoplane, an advanced version of the Verville-Sperry R-3, which incorporated retractable landing gear. Mechanical problems forced the R-3 to drop out of the race, which was won by a sleek Curtiss Racer flown by Lt. Alford J. Williams at the then-terrific speed of 245.3 mph— almost 40 mph faster than the speed the race was won at only a year

[12] See, for example, John D. Anderson, Jr., "Faster and Higher: The Quest for Speed and Power, " in *Milestones of Aviation* (New York: Hugh Lauter Levin, 1989), pp. 105-106. The Dayton-Wright RB-1 of the 1920s was also equipped with a landing gear that was semiretractable.

The highly successful Lockheed Orion utilized retractable landing gear and an aerodynamically refined shape to generate unprecedented overall performance. Nevertheless, its wooden construction and lack of a high-lift flap system and a variable-pitch propeller kept it from being a truly revolutionary airplane. (SI Negative No. 1996-0012; Videodisc No. 1B-14112)

before. The following year, 1924, the Verville-Sperry won the Pulitzer race, but at a speed of 215 mph, 30 mph slower than that achieved by Al Williams in his Curtiss Racer. Clearly, retractable landing gear represented a major aerodynamic advance, but it was not the only factor defining the performance of an aircraft.

In terms of integrating a number of critical new design features, including retractable landing gear, the Boeing Monomail stands out. This airplane was unprecedented in incorporating an all-metal structure, a smooth stressed skin, a cantilevered wing, and a Townend ring cowling. Unfortunately, it also possessed an ineffective propeller that cancelled out most of the benefits of the lower drag. Because its speed range was so extensive, the Monomail needed a variable-pitch propeller—a design then not yet available. Its fixed-pitch propeller could not match the plane's high speed and takeoff requirements.

In 1931, the Monomail was followed by a much more successful airplane employing retractable landing gear, the Lockheed Orion, a low-wing version of the pioneering Vega. (Also in 1931, the U.S. Navy procured its first aircraft with retractable gear, the Grumman XFF-1 two-seat fighter.) In comparison to the fixed-wing Lockheed Vega that came out just before, the advantages of the Orion's retractable gear were obvious: a maximum speed of 226 mph compared to 190 mph and a zero-lift drag coefficient of 0.0210 compared to 0.0278. These figures meant that the Orion could outperform any contemporary military aircraft.

The use of retractable landing gear was delayed for so long primarily due to a general belief in the industry that such gear was too heavy for practical use. Compared to what appeared to be subtle aerodynamic benefits, the difficulties of designing a reliable undercarriage that could be mechanically retracted into the body of an aircraft were glaringly obvious. More than any other single factor, it was the spectacular improvements realized with the Orion, which proved that the advantages far superseded what actually amounted to small increases in weight, that put retractable landing gear front and center of the shelf of new important new aircraft compo-

Fred E. Weick's W-1 home-built experimental airplane with steerable, tricycle gear precipitated a major change in how engineers designed modern aircraft. (NASA Image No. L-11151)

nents. As new streamline designs started flying in the 1930s, the same fixed landing gear that previously had accounted for only a small percentage of the overall drag of an airplane, usually in biplane form, now accounted for a significant portion of a monoplane's drag. As Laurence K. Loftin noted in *Quest for Performance*, "The configuration and design details of the Lockheed Orion represented an extremely high level of aerodynamic efficiency, a level that has seldom been exceeded in the years since 1931." Yet, as Loftin also pointed out, the Orion "lacked several features that later became an integral part of the propeller-driven aircraft in its final definitive form."[13] Like the Monomail, it also did not have a variable-pitch propeller, which meant its engine was not efficient over an entire range of flight conditions. This limitation became clearer and clearer to aeronautical engineers in the early 1930s, stimulating the development of the controllable-pitch propeller, without which the full aerodynamic potential of a high performance, low-drag aircraft simply could not be reached. The Orion also had only a simple trailing-edge flap, one designed to increase drag for approach and landing but not to increase maximum-lift coefficient. It really needed a high-lift system that increased maximum lift and reduced stalling speed. As suggested earlier, an advanced form of flaps was necessary—something that became standard equipment on high-performance aircraft by the late 1930s.

Aerodynamically speaking, "retracting" technology was the key to landing gear (Document 3-15). But before leaving the subject of this particular "shelf component," it is important to note the critical importance of developing *steerable*, tricycle

[13] Loftin, *Quest for Performance*, pp. 89-90.

landing gear. This was another development for which the NACA deserves considerable credit, and again, largely through the pioneering work of Fred Weick.

As with many other aeronautical engineers in the 1920s and 1930s, Weick dreamed of building a low-cost and simple-to-fly airplane that was so inherently safe and inexpensive to operate and maintain that air travel in it could, for certain purposes, compete with automobiles as a mode of private and family transports. Weick pursued his dream in earnest in the early 1930s, when he and a small group of colleagues from NACA Langley designed the "W-1" in a private venture. This home-built experimental airplane had several unique features, including an elevator with upward travel that was limited to the point where the airplane could not be forced into a spin. Another innovative feature of the W-1 was its coordinated control system. Weick's idea here was to reduce the number of controls from three to two by connecting the ailerons and rudder, thus eliminating the possibility of crossing these two controls and thereby simplifying the process of learning to fly.

In order to make it easier both to taxi and land the plane, Weick and his associates also equipped the W-1 with what was then an unconventional undercarriage: they moved the two main wheels a short distance behind the plane's center of gravity, took away the tail wheel, and added a nose wheel that could be steered. Such an arrangement, Weick thought, stood a very good chance of eliminating "ground looping," a serious problem even into the 1930s. All landplanes in production were still being equipped with tail skids—or, when paved runways came into use, with tail wheels. These gears had their main fixed-axis wheels located ahead of the center of gravity, were naturally unstable directionally, and thus tended to ground loop. Automobiles, bicycles, and motorcycles were stable in this regard because their main fixed-axis wheels were in back of the center of gravity. The conventional tail-wheel-type gears also nosed over easily, because the main wheels were just a little ahead of the center of gravity. Some of the early pusher airplanes, popular around 1910, had a single wheel well ahead of the center of gravity and two wheels in back of the center of gravity, which took care of the nosing-over difficulty reasonably well. But all wheels were on fixed axes and could be steered very well on the ground. All of these realizations led Weick to conclude that the undercarriage of the W-1 needed to be quite different. Weick dubbed his new steerable undercarriage a "tricycle gear," and it was a name that stuck. (In March 1932, Weick received a U.S. patent for his W-1 design with steerable tricycle gear; he received another patent for a two-control airplane design incorporating a tricycle landing gear in March 1938; see Document 3-16). The gear performed extremely well for the W-1; the results were published in NACA reports. When first learning of Weick's gear, some people in the industry said that it was just a reversion to the three-wheeled gears that had been used on pusher airplanes before World War I, but this was not the case. Airplanes during that era had fixed nose wheels, and operations took place in open grass fields, with a great deal of manpower available for handling the airplane. This meant that people in those days had not cared whether gear was stable in taxiing or not. There is no

The one-and-only Douglas DC-4E represented many of the aerodynamic innovations that evolved during the 1920s and 1930s. It was the first large transport to use tricycle gear and its design process helped originate NACA research in the establishment of stability and control specifications prepared to insure good flying qualities. (SI Negative No. A0193510)

question that Weick's tricycle gear was a new line of thought and a worthwhile improvement. At the NACA conference in 1935, Orville Wright had made exactly these points to Weick, which encouraged him greatly.

It was also in 1935 that engineers with the Douglas company showed the first interest in applying the tricycle gear to large airplanes. Dr. Arthur Raymond, chief engineer at Douglas, sent F. R. Cohlbaum and W. Bailey Oswald to Langley to find out about the tricycle gear on the W-1 and to ask questions about what it might do for larger airplanes. After their visit, Douglas, in cooperation with the Army, tried the tricycle gear on one of its Dolphin airplanes, which originally possessed a tail-wheel-type gear. The Dolphin was an amphibian flying boat, and the Douglas engineers simply moved the wheels of the main gear back a bit and put a castering nose wheel under the front of the hull. These tests confirmed the gear's advantages. In October 1935 TransContinental and Western Air (as TWA was known before 1950) also asked for information about the possible use of tricycle gear on a transport airplane. The NACA responded by pointing out the various advantages of the gear, plus the fact that with a twin-engine transport, one could extend the forward part of the fuselage sufficiently to support the nose gear well forward and also provide a satisfactorily long wheelbase.

Soon thereafter, three or four airlines met with Douglas in the hope of getting a transport that was larger than even the new DC-3 that had just appeared. Edward P. Warner, a former NACA chief physicist, editor of *Aviation* magazine, and professor

of aeronautics at MIT, served as a consultant to this group, and he visited Langley Field several times to review the possibilities of applying the tricycle gear to such a large transport.[14] The result of this activity was the one-and-only Douglas DC-4E, the first large transport to use the tricycle gear. Even then, the Douglas engineers made provisions for returning to a tail-wheel-type gear in case they were not entirely happy with the tricycle gear. During World War II, a modified version of the DC-4 was used in military activities as the C-54, complete with tricycle landing gear. The tricycle gear was also used on other military aircraft, including the Douglas A-20, Lockheed P-38, Bell P-39 and P-63, Consolidated B-24, North American B-25,

NACA engineers found that with the later addition of wing fillets and a NACA cowling, the diminutive McDonnell Doodlebug experienced greatly reduced buffeting and aerodynamic interference. (SI Negative No. A43437-C)

Martin B-26, and Boeing B-29. It eventually became the standard gear for most all military, airline, and general aviation airplanes. Even the NASA Space Shuttle, arguably the world's most sophisticated aircraft, benefits from the same type of tricycle gear with steerable and castered nose wheel that Weick designed back in the 1930s.[15] Again, this development did not relate directly to improved aerodynamics, but it shows how various new design features synergized in the airplane design revolution of the interwar years.

Another part of this synergy came in the form of wing fillets, which were concave fairings used to smooth the interior angle of the wing-fuselage juncture. With-

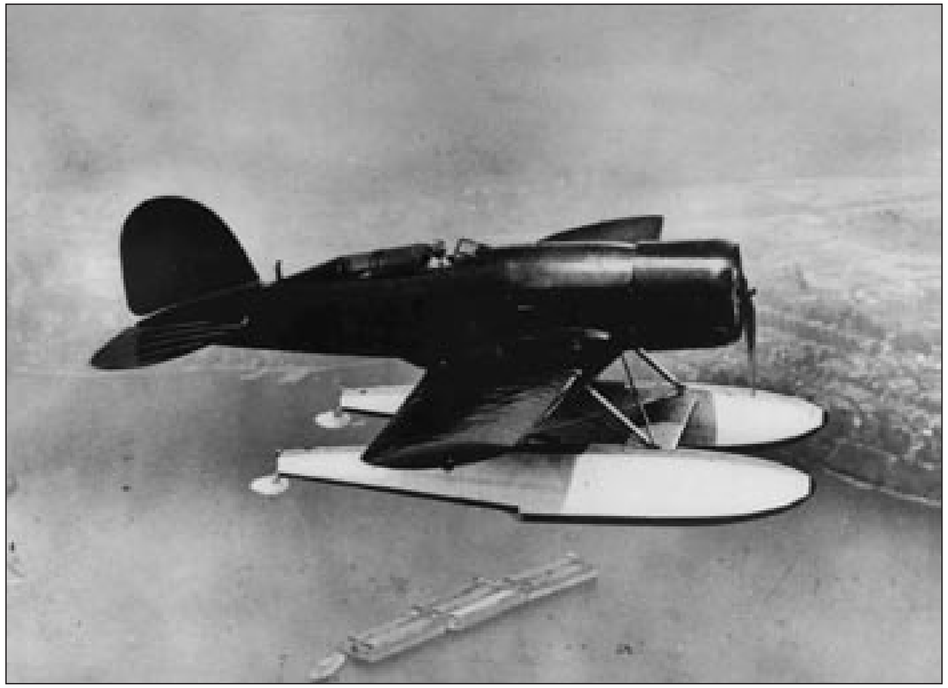
[14] For an account of Edward P. Warner's outstanding career in American aviation, see Roger E. Bilstein, "Edward Pearson Warner and the New Air Age," in *Aviation's Golden Age: Portraits from the 1920s and 1930s*, ed. William M. Leary (Iowa City IA: University of Iowa Press, 1989), pp. 113-126. In various ways, technically and politically, Warner made notable contributions to the "reinvention" of the airplane.

[15] For Weick's account of his development of the tricycle gear for the W-1 airplane, see Weick and Hansen, *From the Ground Up*, pp. 131-140.

out fillets, the intersection of wing and fuselage experienced airflow interference. A smooth "fairing" of the area where the wing joined the fuselage (i.e., fitting and shaping so as to make it smooth and streamlined) greatly improved the handling characteristics and efficiency of low-wing monoplanes. Developed at the Guggenheim Aeronautical Laboratory of the California Institute of Technology under the direction of Theodore von Kármán, the fillet soon became a standard feature of monoplane designs (see Document 3-17). Both the Boeing Monomail of 1930 and the Northrop Alpha of 1931 benefited from wing fillets, as would the culminating airplane of the design revolution, the Douglas DC-3. As for the Alpha, the advantages of wing fillets could not overcome its basic aerodynamic obstacles, notably a fixed landing gear and an open cockpit for the pilot. It is curious that so many new aircraft during this era combined anachronistic features with important new innovations. But such combinations of old and new are, in fact, typical of transitory times before all the features of a new technology come together and form a new design paradigm.

Equally typical of the transitory period is the appearance of a "mainstay design," one that maximized the existing state of the art but offered a sophisticated overall product that nonetheless augured important elements about the future. Such an aircraft was the ubiquitous Ford Trimotor, a 13- to 15-passenger transport that did the lion's share of work for America's budding airlines in the late 1920s and early 1930s. Although the Trimotor remained aerodynamically primitive in some respects, such as its fixed landing gear and uncowled engine nacelles, aerodynamic refinement, as Document 3-18 shows, had been one of the goals of Ford Motor Company's Aircraft Engineering Department when it started designing the Trimotor from 1925 to 1926. Henry Ford had built a mammoth reputation as a manufacturing and production genius in the automobile industry, and he wanted to do something similar

The Ford Trimotor 5-AT-B was a "mainstay design" for America's growing commercial airline industry, but its improperly placed engine nacelles below the wing, angular windscreen, exposed engines, ground-adjustable pitch propellers, fixed landing gear, and corrugated aluminum construction did not reflect the rapid advances in aerodynamic streamline design. (SI Negative No. 47937-J)



Aircraft such as the Lockheed Sirius "Tingmissartoq" flown by Charles and Anne Lindbergh represented the transitional nature of aerodynamic design with its advanced streamline shape combined with an open cockpit, ground-adjustable pitch propeller, and large floats. (SI Negative No. A-5172)

The Martin B-10 represented the revolution in combat airplane design, and in key respects, presaged the total package of a "reinvented" airplane. (SI Negative No. 78-1328)

The Boeing 247D integrated all the most desirable features emerging from the airplane design revolution, making it the first "modern airliner." (SI Negative No. 75-12118)

with airplanes. So resolved, he put the resources of his entire company behind the building of a Ford transport. He even bought out the Stout Engineering Company, which had recent experience with producing an innovative, cantilever-wing transport design. Stout's transport, which was also all metal, would soon become famous for running on the Stout-Ford airlines between Chicago, Detroit, and Cleveland. Ford would soon have William B. Stout himself at work, in his small engineering laboratory in Dearborn, Michigan, on the design of the Ford Trimotor.

Two other airplanes that represented a link between old and new were the previously mentioned Lockheed Vega, which appeared within one year of the Ford Trimotor, and the Lockheed Sirius of 1930. All three planes reflect the flux and indeterminacy of aerodynamic development of aircraft during the late 1920s, before all of the components of the airplane design revolution came together into a coherent whole. Synergy of all the necessary shelf items was not yet possible, because not all the shelf items had yet appeared, so to speak, "on the shelf." But all three designs indicate that their designers were, without question, paying attention to reducing aerodynamic drag through streamlining. Harold Hicks replaced George Pruden as the head of Ford's Aircraft Engineering Department (Henry Ford fired Pruden for a breach of company etiquette; he appeared in a newspaper photo as a representative of the Ford Company) and oversaw the development of the trimotors. Document 3-19 concerns the design of the Sirius airplane. Document 3-20 details yet another one of these transition types—one that stimulated a revolution in combat airplane

design and in key respects presaged the total package of a "reinvented" airplane—the Martin B-10 bomber.

But the aircraft that integrated all the most desirable features emerging from the airplane design revolution even more fully was the Boeing 247. Aviation historians consider this Boeing design, first flown in February 1933, to be the first "modern airliner." The definitive version of the airplane, the model 247D, had the following features: all-metal, stressed-skin construction; cantilever wings; retractable landing gear; an efficiently cowled, lightweight radial engine; controllable-pitch propellers; and single-speed geared supercharger. Model 247D was also the first transport aircraft to employ rubber de-icing boots and to have a significant amount of instrumentation for blind flying. Aerodynamically, the design was quite far advanced, with split-type landing flaps and a fairly high wing loading. Its 0.0212 $C_{D,O}$ was rather low, and its 13.5 maximum lift-drag ratio was quite high; both numbers compared favorably with the performance of virtually all previous aircraft. Operating for the airlines, the Boeing 247 carried up to ten passengers comfortably, at a cruising speed of 185 mph at 7,500 feet. In service mainly with United Airlines(along with Boeing, its maker, part of the United Aircraft and Transport Corporation), the airplane established a new standard for commercial air travel. In doing so, it provoked other aircraft manufacturers, as well as the airline operators, to seek the design of their own more refined aircraft.

Jack Frye's August 1932 letter to American aircraft manufacturers requesting a new all-metal airliner for TWA led to the creation of the Douglas DC-series aircraft. (SI Negative No. 75-5208)

One aviation executive who desperately sought a new airplane was Jack Frye, vice president for operations of Transcontinental and Western Airlines (TWA), a company that was precluded from buying the new Boeing 247 because of the corporate connection between Boeing and United Airlines. On 2 August 1932, Frye sent letters to Curtiss-Wright, Ford, Martin, Consolidated, and Douglas seeking proposals for a new all-metal trimotor design, one that he hoped could profitably replace TWA's aging fleet of Fokker trimotors. That letter, reproduced in its entirety as Document 3-21, reflected Frye's belief that trimotored aircraft were still the norm for airline operation. Interestingly, the TWA leader stipulated no other design details and only suggested a few of the desired performance characteristics. He left it up to the manufacturers to establish the formal design parameters.

Intrigued by the challenge of producing a design that might even turn out better than the Boeing 247, Donald W. Douglas and his design team in Santa Monica, California, began work on a 12-passenger twin-engine airliner incorporating all the latest advances in aircraft components and design. This included certain features that the Boeing 247 lacked, notably variable-pitch propellers and split flaps for higher wing loading. A Douglas delegation headed by a young Caltech graduate, Arthur E. Raymond, traveled to TWA's offices in New York City and won the contract for the new airplane. After ten months of development work, the first of the new Douglas DC series transports, the DC-1, took to the air in July 1933. The prototype all-metal DC-1 incorporated the most advanced innovations of the time. In addition to the newest shelf items, the Douglas design team utilized the latest in aeronautical design methods to fully integrate them into the overall design. This utilization included an unprecedented level of "research for design" conducted within a wind tunnel (see Document 3-22).

It was not just technological incentive that led to the DC-1's innovative design. Economic incentives further hastened technical innovation when Douglas engineers elongated the fuselage of the DC-1 prototype (see Document 3-23) to allow for two more passengers, bringing the capacity up to 14. The resultant DC-2 first flew on 11 May 1934 and became the first commercially available Douglas transport. Flying TWA's 18-hour "Sky Chief" transcontinental route from Newark to Los Angeles (with en route stops at Chicago, Kansas City, and Albuquerque) at speeds up to 175 mph, the DC-2 carried the same amount of passengers as the old trimotors at less cost and at faster speeds. The success of the DC-2 was not just national but international. It was also stunning. In 1934, a DC-2 flown by the Dutch airline

Dutch KLM's use of the DC-2 in the 1934 London-to-Melbourne MacRobertson Trophy Race announced to the world the growing ascendancy of American aeronautical technology. (SI Negative No. 523183)

KLM finished second in the 11,300-mile London-to-Melbourne MacRobertson Trophy Race—and amazingly did so with a full load of mail and three passengers. Quickly, KLM ordered a dozen DC-2s, followed by numerous orders from other European carriers. For the first time, an American airliner began to outcompete the Fokker transports, which had dominated European airline service for several years. Although a British plane had won the MacRobertson Race, the winner had been a special customized racer, the De Havilland D.H.88 Comet. British aviation leaders recognized that the real significance of the race lay in the American commercial airliner coming in second. The editor of London's *Saturday Review* declared soon after the race: "Britain has won the greatest air race in history, but she has yet to start on an even greater air race: a race in commercial and military supremacy." Sadly, no British airplane, not even the best machine in regular use with the Royal Air Force "at the present time is fast enough to have finished the race within a thousand miles of the American machines." (A Boeing 247 flown by Roscoe Turner and Clyde Pangborn finished third in the race, two and a half hours behind the DC-2.) "It is almost incredible, but it is true," the British newspaperman lamented.[16]

In the design of the Douglas DC-2, the two main approaches that American engineering had been following for the purpose of streamlining aircraft designs (i.e., commercial efficiency and greater speed) converged very successfully, and American aviation benefited greatly from it, on a worldwide scale. The DC-2 clearly outperformed all other airliners. For the first time, American industry was producing a transport so superior to all others available that even European carriers committed to their own national aviation industries had no choice but to start flying the American planes. The significance of the DC-2 does not end there. As historian Richard K. Smith noted, the appearance of the DC-2 also created, for the first time, "a distinct division of labor between the design of military and civil aircraft." Before 1933, bombers were typically just converted airliners with bomb shackles, armor, and guns added. But the new streamlined forms dictated more specialized designs. Streamlining called for bombs to be carried internally, and because bombs took less space than a load of passengers, from this point on "cross-section designs of bombers and airline equipment would move in opposite directions."[17] In this sense, the reinvention of the airplane brought on greater specialization. Streamlining was a general objective, but the special forms of streamlining required by aircraft with significantly different missions led to one of the clearest bifurcations in aircraft design history. This was a critical element of change that is often missed when discussing the airplane design revolution of the interwar years.

As mentioned earlier, the DC-2 design incorporated the latest refinements enjoyed by the Boeing 247, plus a higher wing loading and split-type flaps. The Douglas Company found itself in the enviable position of trying to fill an over-

[16] Quoted in Terry Gwynn-Jones, "Farther: The Quest for Distance," in *Milestones of Aviation*, p. 67.

[17] Richard K. Smith, "Better: The Quest for Excellence," in *Milestones of Aviation*, p. 253.

The highly successful DC series of aircraft, such as the Douglas Skysleeper Transport designed for American airlines, garnered Douglas Aircraft the 1935 Collier Trophy. (NASM File No. AD-761192-75)

whelming backlog of orders for the plane. Designing an even bigger and more effective transport became a growing possibility when Cyrus Rowlett "C.R." Smith of American Airlines, the third U.S. transcontinental service (with TWA and United) wanted an aircraft to replace the fleet of aging Curtiss Condor biplanes that American had been using on its nighttime Pullman-style sleeper service. American's chief engineer, William Littlewood, determined that by widening the fuselage of the DC-2 by 26 inches and adding 10 feet to its wingspan, it could accommodate 14 sleeping berths. The revised airplane, known as the Douglas Skysleeper Transport, made its maiden flight on 17 December 1935, in celebration of the 32nd anniversary of the Wrights' flight at Kitty Hawk. Fitted with Wright R-1820 engines and outfitted for 21 daytime passengers (without the sleepers), the airplane flew as the DC-3. On 1 July 1936, President Franklin D. Roosevelt, on behalf of the National Aeronautic Association, presented the Robert J. Collier Trophy to the Douglas Company for the greatest achievement in American aviation in 1935, the refinement of the DC series aircraft. In his remarks, President Roosevelt said, "This airplane by reason of its high speed, economy, and quiet passenger comfort has been generally adopted by transport lines throughout the United States. Its merit has been further recognized by its adoption abroad, and its influence on foreign design is already apparent."[18]

Soon, the DC-3 became the most popular and reliable propeller-driven airliner in aviation history. Its appearance marked the culmination of the design revolution in American aircraft and, as C. R. Smith, president of American Airlines, noted in

[18] Quoted in Douglas J. Ingells, *The Plane that Changed the World: A Biography of the DC-3* (Fallbrook, CA: Aero Publishers, Inc.), p. 166.

our Destination Document, it was the first airplane that enabled the airlines to make money by solely carrying passengers. Technologically, it represented a completed synergy of virtually all the major innovations that had taken place in aircraft design since 1920. Aerodynamically, the airplane was extremely far advanced, producing a very low $C_{D,O}$ of 0.0249; this was 17 percent less efficient than the Boeing 247, which had an extremely low value of 0.0212. But this difference was because the DC-3 had a much larger fuselage—to accommodate three-abreast seating—that resulted in a larger ratio of wetted area (for wings and wing-like surfaces, the wetted area is related to the exposed planform area) to wing area. The DC-3 enjoyed a very high L/D, a ratio of 14.7. This L/D was higher than anything that came before—and better than virtually all that came after, certainly with propellers. (Only the Boeing B-29 bomber of 1944 and the Lockheed L.1049G Super Constellation airliner of the early 1950s enjoyed higher L/Ds, of 16.8 and 16.0, respectively.) One very noteworthy aerodynamic feature of the DC-3 was its sweptback wing. This was not engineered for the same reasons that wings of transonic and supersonic aircraft would later be given sweepback; rather, it had to do with positioning the airplane's aerodynamic center properly in respect to its center of gravity. To some extent, this had been done also with the DC-2. But as the design of the DC-3 evolved, it became evident to Douglas's engineers that the center of gravity was located farther toward the rear (or aft) than they expected. They mounted the outer panels of the DC-3 wing with greater sweepback, moving the aerodynamic center to the correct position. This change helped the airplane achieve a cruising speed of 185 mph (at 10,000 feet) when carrying a full load of 21 passengers. In other words, the DC-3 benefited from an even more streamlined shape than its predecessors, while increasing capacity by 50 percent. Thanks not only to streamlining but also to the entire process of reinventing the airplane, for the first time, the American airline industry had a passenger aircraft that could make a profit without a government airmail subsidy.

C.R. Smith's need for new aircraft for American Airlines resulted in the DC-3, which Smith declared as the first airliner to enable the airlines to make money by solely carrying passengers. (SI Negative No. 8094; Videodisc No. 2B-75566)

Without a doubt, 1934, 1935, and 1936 were banner years for both American and global aviation. From the point of view of aviation only, it has been argued that it was the aircraft developments associated with this period that, as much as anything else technological contributed directly by American industry, helped begin to lift the U.S. economy out of the Great Depression; aircraft developments certainly played a part in the general recovery that ultimately depended on involvement in the Second World War. By the mid-1930s, the streamlined shape defined largely by the American aeronautics community became standard in all new aircraft designs, making advance performance through design refinement a reality and the U.S. aircraft industry the world leader (see Document 3-24). As seen in this chapter and its documents, a myriad of new flight technologies contributed to this airplane design revolution. Although major developments in propulsion, structures and materials, flight instrumentation, and stability and control technology played fundamental roles in the reinvention of the airplane, the role of aerodynamic refinement was primary in many ways. The introduction of superior propellers with controllable pitch, cantilever wings, wing fillets, flaps, efficient engine cowlings, proper nacelle placement, and retractable landing gear all pushed the airplane to extraordinary new levels of sophistication and performance. So, too, did the definition of advanced airfoils, perhaps the most important single component contributing to the airplane design revolution. This was such a crucial topic for aerodynamicists, that it will be explored separately as the entire focus of the next chapter.

It took more than just the integration of various airplane components to cement the airplane design revolution within professional aeronautical practice and prepare aeronautical engineers for the future. Even after the reinvented airplane had been made essentially complete in the form of the DC-3, significant problems still affected total airplane performance. As Document 3-25 shows, one of these problems was aerodynamic stall, the potentially dangerous, even fatal, flight condition when an aircraft started to fly at an angle of attack greater than the angle of maximum lift, resulting in a loss of lift and an increase in drag. Stall had always been a concern for engineers and pilots, but in the early years of aviation, stalling speeds had remained low, in the range of 40 to 50 mph. This was due to the relatively poor flying characteristics of aircraft of that period, the fact they did not benefit from high-lift devices, and related directly to the short, unpaved fields then serving as airports. A pilot simply could not come in for a landing at a very high speed and expect to land safely.

The design revolution of the interwar years changed the descent and landing situation dramatically. The flying characteristics of airplanes improved greatly. High-lift devices became sophisticated and commonplace; runways became paved and quite long. Aircraft could manage landings at much higher speeds; but in doing so, they ran new risks of stalling not experienced earlier. The stalling speed of the DC-3 rose to over 60 mph; the Boeing B-17 to over 80; the North American P-51 to about 100; the Martin B-26F's stalling speed rose to over 120 mph. By the start of World War II, the stalling speeds of virtually all advanced aircraft had risen into the range of 80 to 100 mph; without the help of high-lift devices, stalling speeds would, in fact, have become much higher, further increasing risk. Increased speeds generally equated to progress in aviation, but landing at higher and higher speeds, even with the aid of high-lift devices, raised new issues that aeronautical engineers had to resolve.

The NACA had conducted many studies related to stall before the mid-1930s, but the operating problems of a large new airliner as revolutionary as the DC-3 sparked a new wave of concern. In September 1937, United Airlines loaned NACA Langley one of its DC-3 Mainliners in order to conduct stall tests (see Document 3-25). Out of this specific program came a more general investigation into stalling. Through the 1940s, the NACA worked on various stall-warning indicators and continued to look generally into stall phenomena. In the early 1940s, as readers will learn in a later document in this chapter, the NACA also played the key role in spelling out "stalling characteristics" as part of a larger program of establishing uniform "flying qualities" requirements for American aircraft.

In flying United Airlines' DC-3 Mainliner in late 1937, NACA Langley investigated more than the stalling problem; it also looked into the equally if not more dangerous problem of aircraft icing. As historian Glenn Bugos has explained, icing was a critical systems-wide problem for aircraft, then and now:

> Ice caused aircraft to crash by adding weight and preventing the pilot from climbing above the icing clouds, so that the aircraft gradually lost altitude and slammed into the ground . . . [I]ce accreted along the wing and tail leading edges disturbing lift and adding drag. Ice clogged the interstices of rudders and ailerons, preventing control and inducing buffeting. It changed the aerodynamic profile of the propeller, causing it to vibrate and exert less thrust per horsepower. It coated windshields, so the pilot flew blind. Ice made antenna wires oscillate and snap, and generated static that rendered useless most radio communication and navigation. It distorted pitot shapes, so that pilots got erroneous airspeed readings. And it clogged carburetors, suffocating the engine.

Within minutes, pilots could lose all of their critical systems, not just the engine, wings, control surfaces, indicators, and radio, but also their own sight as well.[19]

Icing was a problem to which the NACA committed considerable time and energy. A rash of aircraft accidents traced to icing problems attracted public attention in the late 1930s; a number of commercial operators, not just United Airlines, clamored for useful information on the subject. The NACA launched a comprehensive study of the icing problem that would last for many years. Researchers looked for mechanical, chemical, and thermal ways of breaking up ice before it formed dangerously on an airplane's vital surfaces. Innovative new tests looking for answers to icing began in flight and in wind tunnels. Various de-icing systems were tried, including a thermal (heat-directed) system for which the NACA and its

[19] Glenn Bugos, "Lewis Rodert, Epistemological Liaison and Thermal De-Icing at Ames," in *From Engineering Science to Big Science: The NACA and NASA Collier Trophy Research Project Winners*, ed. Pamela E. Mack (Washington, DC: NASA SP-4219, 1998), p. 32).

engineer Lewis Rodert won the Collier Trophy for 1946. Document 3-26 surveys the NACA's pioneering work on aircraft icing from the late 1930s to 1948. It was a research specialization that NASA would pursue with vigor.

Another generic problem that the NACA investigated (to the advantage of the airplane design revolution of the 1930s) centered on gust loads and gust alleviation. One event sparking early interest in this problem was the destruction of the ZR-1 Navy airship *Shenandoah*, which crashed in a thunderstorm near Ava, Ohio, on 3 September 1925, killing 14 of 43 on board. Engineers in the PRT section at Langley reacted to this tragedy by mounting some rudimentary equipment on the top of their tunnel building trying to test the magnitude of gusts found in the free air. Later, NACA researchers collected pressure distribution measurements of air loads in wind tunnels and in flight, but there was still no strong impetus to apply them to the design of specific aircraft. Not until the early 1930s did a coordinated NACA program of gust research begin that was interested in applying such data to aircraft design. A few special NACA committees then formed to oversee loads research. Eventually, Langley created a separate structures research division and, in 1938, built a structures research laboratory.

As this commitment materialized, it grew clearer and clearer to everyone that the stresses brought on by gusts had to be a more essential factor in the design of aircraft, especially civil airliners. Understanding gust loads lay somewhere about midway between aerodynamics and meteorology, and without question threatened the safe and comfortable operation of aircraft, with special concern for passenger transports. As an aerodynamic problem, the NACA first conducted gust loads research "on the premise that a gust acted almost like an instantaneous change of attack of the airplane encountering it."[20] Engineers who came to specialize in the problem, notably Langley's Richard V. Rhode (a 1925 University of Wisconsin graduate who would win the Wright Brothers Medal of 1935 for his gust loads research) later refined this concept by taking into consideration the distance over which a gust extended and the time it took for the wing flow to adjust to the new angle of attack. Rhode's concept of a "sharp edge" gust became "the backbone for all gust research."[21] Document 3-27 provides a string of documents from the 1930s concerning the emerging importance of this major new field of research.

Although not covered by any documents in this chapter, the NACA's study of gust loads for the purpose of articulating design requirements carried over into several other critical areas, some of which concerned military more than civilian aircraft. One of these areas involved a systematic exploration, both theoretical and experimental, into the dangers of aerodynamic flutter. Another concerned the loads

[20] Hartley A. Soulé, "Synopsis of the History of the Langley Research Center, 1915-1939," HQA HHN-40, 1966, p. 39.

[21] Soulé, "Synopsis," p. 39.

and stresses on combat aircraft while dive-bombing. In the 1930s, NACA researchers worked out charts showing the relationships between dive angle, speed, and the angle required for recovery. Using these charts, the Navy established design requirements for its dive-bombers around 1935. The NACA later conducted other flight dive tests meant to ensure that elevator control force would not hinder the acceleration a pilot needed to recover his aircraft from a dive. Through this research program, the U.S. aeronautics community came to a much better understanding of the distribution of loads between the various parts of the airplane—wing, fuselage, and tail surfaces—and how these individual parts were "loaded" by the wide range of maneuvers, some of them extreme undertakings by a high-performance aircraft.

As already suggested in reference to defining "stalling characteristics," another major NACA contribution of this period was its specifying of uniform "flying quality" requirements for American aircraft (see Document 3-28). As already emphasized, the airplane design revolution of the interwar period involved more than the development of aircraft component technology and its various integrations and synergies. It also involved broader intellectual developments—notably the translation of ill-defined problems, issues understood and handled previously in a largely qualitative and subjective manner, into much more objective problems defined and resolved on a stronger quantitative basis. In this respect, the reinvention of the airplane hinged on an epistemological reorientation within American engineering, one that changed not only what aeronautical engineers knew but how they knew it.

In retirement, as part of a productive second career as a historian of technology, former NACA/NASA research engineer Walter G. Vincenti delved deeply into this epistemological transition. Several chapters in his prizewinning 1990 book, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History,* looked into the significance of this change, how and why it happened, as well as its impact on the wider world of aviation. In particular, his chapter, "Establishment of Design Requirements: Flying Quality Specifications for American Aircraft, 1915-1943," analyzed the complex intellectual and social process by which U.S. aeronautical engineers in the 1920s and 1930s came to establish more objective specifications for aircraft design.

Aeronautical engineers as late as the start of World War II really did not know how to phrase, let alone categorize, their observations about the performance of an airplane. Everyone associated with aircraft development and operation wanted good flying and handling characteristics. They wanted machines that precisely, rapidly, and predictably obeyed a pilot's inputs—without unwanted dips or drops and without the pilot having to manhandle controls. Pilots, however, had a hard time putting what they wanted into words. For example, a pilot reported his machine as "tail heavy" or commented on the "lightness" of his controls, but nowhere were any of these terms defined concretely. Pilots described what "flying qualities" were most acceptable to them impressionistically, in their own words, to their own apparent satisfaction, but without a clear, quantitative basis. Whatever was actually tangible in the relationship between the "feel" of an aircraft and its actual nuts-and-bolts performance remained vague and imprecise.

Vincenti's chapter revealed the 25-year process it took, from 1918 to 1943, before "flying qualities" became well enough defined to be specified. As with so many elements of the airplane design revolution, what unfolds in Vincenti's story is the history of an idea: "The notion that specifications could usefully be written for something as subjectively perceived as flying qualities had itself to be realized intellectually and verified in the real world. It was not at all an obvious or obviously useful idea at the outset."[22] By the early 1940s, however, specifications did become defined, as did the whole concept of "flying qualities." NACA test pilot Melvin N. Gough defined that concept early in World War II as "the stability and control characteristics that have an important bearing on the safety of flight and on the pilot's impressions of the ease and precision with which the aircraft may be flown and maneuvered."[23]

The string of documents in Document 3-28 all relate to the research program undertaken by the NACA from the mid-1930s onward to establish precise "flying qualities." In essence what the NACA did, primarily through flight research of full-scale aircraft, was measure how aircraft responded to specific control inputs and then correlate them with pilots' opinions of the aircraft's behavior. The NACA investigators then related what they found to the engineering parameters that had been employed in designing the aircraft. The result was a long menu of "requirements" essentially falling into three main categories. The first group, "requirements for longitudinal stability and control," subdivided into:

(1) elevator control and takeoff;
(2) elevator control in steady flight;
(3) longitudinal trimming device;
(4) elevator control in accelerated flight;
(5) uncontrolled longitudinal motion;
(6) limits of trim due to power and flaps; and
(7) elevator control and spinning.

The second category, "requirements for lateral stability and control," subdivided into:

(1) aileron control characteristics;
(2) yaw due to ailerons;
(3) rudder and aileron trim devices;
(4) limits of rolling moment due to sideslip;

[22] Walter G. Vincenti, "Establishment of Design Requirements: Flying Quality Specifications for American Aircraft, 1918-1943," in *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore and London: The Johns Hopkins University Press, 1990), p. 52.

[23] Quoted in Loftin, *Quest for Performance*, p. 117.

(5) rudder control characteristics;
(6) yawing moment due to sideslip;
(7) crosswind force characteristics;
(8) pitching moments due to sideslip; and
(9) uncontrolled lateral and directional motion.

The third category, "stalling characteristics," has been discussed earlier in this chapter in relation to the Douglas DC-3. In his book chapter on the "Establishment of Design Requirements," Vincenti looked at the NACA's articulation of all the sub-divisions, with a specific focus on elevator control in steady flight, uncontrolled longitudinal motion, and elevator control in accelerated flight, all part of the "requirements for longitudinal stability and control."[24]

As Document 3-28 indicates, the immediate catalyst for the NACA's flying-quality research came in 1935 and resulted from a set of specifications prepared for the Douglas DC-4E. Edward P. Warner, the accomplished aeronautical researcher and former editor of *Aviation* who was then working as a consultant for the Douglas Aircraft Company, asked the NACA to help him specify the stability and control characteristics to be built into the DC-4 transport. In December 1935, the NACA Aerodynamics Committee, which was chaired by Warner, approved what became Research Authorization (RA) 509, "Preliminary Study of Control Requirements for Large Transport Airplanes." The purpose of this investigation was to determine "what specific qualities pilots desired, so that they could be numerically specified in future design competitions." A team of NACA Langley researchers under Hartley A. Soulé started this work in 1936 using a Stinson cabin monoplane. Langley instrumented the airplane so that its response characteristics, following known control inputs from the test pilot, could be measured, related to design parameters, and correlated with the pilot's qualitative evaluation of the ease and precision with which he maneuvered the plane. Soulé's team continued this effort using all 12 different airplanes that could be obtained for this purpose until 1941, when it was ready to specify its first set of uniform requirements for the flying qualities of airplanes.

The U.S. Army and Navy enthusiastically welcomed the NACA's product and started to revise the preliminary specifications to meet their immediate requirements. In 1942, both services asked the NACA to continue validating and upgrading handling requirements specifically for military aircraft. This request made many more airplanes available to the NACA as well as a broader view than would have been possible with just a few select commercial aircraft. By the end of World War II, the NACA had measured the stability and flying qualities of 60 different aircraft, and military and civil aircraft handling requirements had been standardized. This effort foreshadowed the extensive work that would be undertaken in the field over the next five decades, leading to the present uniform rating system. Unquestionably,

[24] Vincenti, "Establishment of Design Requirements," pp. 93-98.

the appearance of more objectively defined flying qualities proved to be a culminating development in the airplane design revolution, one that led to a more concrete understanding of aircraft operation, a sounder approach to aircraft design, and a much improved sense of the pilot-machine interface.

Not all revolutionary episodes turn out so neat and tidy, but one can say that the airplane design revolution ended with a literal "dusting off" of what had become of the modern airplane, at least in its sleek military forms. Within the context of NACA research, this final stage took the form of "drag cleanup," a program of systematic aerodynamic refinement involving dozens of aircraft that were to see action in World War II.

One might think that with the appearance of the revolutionary DC-3 that the aerodynamics of propeller-driven aircraft had become so refined that no further improvements could be made. An ultrasleek internally braced monoplane with retractable landing gear like the DC-3 could be expected to enjoy something akin to "ideal" aerodynamics, but in actual service, that hardly proved to be the case. Ideally, in aerodynamic terms, the drag of such an airplane—more specifically, its $C_{D,O}$, defined earlier—should be extremely low, "only slightly in excess of that which would be calculated with the use of the total wetted area of the airplane and a skin friction corresponding to a turbulent boundary layer."[25] But, as facts murder theory, real-world circumstances tended to tarnish and undermine this ideal. In actual service, not even aircraft like the DC-3 ever achieved their ideal drag coefficient. Roughness or unevenness on an aircraft's surface, even smashed insects on a wing, disturbed smooth airflow and increased drag. So, too, did antenna or guns projecting outside the smooth basic contour of an airplane. Even air unintentionally leaking through an aircraft structure influenced aerodynamic performance in adverse ways. Sometimes, an aircraft in actual service experienced twice as much drag as its calculated ideal (based on wetted area and a turbulent skin friction factor). This was true, for example, of the Messerschmitt 109 fighter, the archenemy of the Spitfire and the Hurricane during the Battle of Britain in 1940.

What this underscored was the absolute need for "detailed design" work if actual drag were to come anywhere close to ideal values. Everything about an airplane and its parts required meticulous attention. In the early 1930s, experience in the NACA's 30-by-60-foot Full-Scale Tunnel (FST) at Langley indicated that even the most minute external protuberances could seriously undermine aerodynamic performance, but it took a desire to obtain every last ounce of benefit from the airplane design revolution, plus the threat of war, before the U.S. aeronautics community, specifically the U.S. military, sought systematic "drag cleanup" for their aircraft.

What first prompted the NACA's systematic drag cleanup program was a loud cry for help from the U.S. Navy, which in 1938 was unhappy with the 250-mph flight test performance of its new experimental fighter, the Brewster XF2A Buffalo. The Bureau of Aeronautics wanted the NACA to look for " kinks" or "bugs" in the plane's general design and to determine, in only one week's time, what drag reduction could be expected from changes that might readily be incorporated in the event that the XF2A was put into production. The NACA quickly agreed, and even before a formal research authorization was transmitted to Langley laboratory, the NACA flew an XF2A to Langley Field for tests in the FST. The FST team at Langley acted quickly to satisfy the Navy's urgent request, and within a few weeks had discovered ways to increase the Buffalo's speed by 31 mph to 281, more than a 10 percent improvement in performance.

[25] Loftin, *Quest for Performance*, p. 108.

Word got around, and soon not just the Navy but the Army as well was sending all of its new prototypes to Langley for drag cleanup. Between April 1938 and November 1940, Langley gave 18 different military prototypes thorough goings-over in the FST to see if the airplanes could be improved in any way. On this list was the Grumman XF4F-2 Wildcat (June 1938), Vought-Sikorsky SB2U-1 Vindicator (August 1938), Curtiss P-36A Mohawk (August 1938), Curtiss XP-40 Kittyhawk (August 1938), Grumman XF4F-3 Wildcat (September 1939), Republic XP-47 Thunderbolt (May 1940), Chance Vought XF4U-1 Corsair (September 1940), and Consolidated XB-32 Dominator (November 1940). Through its systematic drag reduction investigations in Langley's FST, the NACA did its best to help industry realize some dramatic increases of speed in its production aircraft. This effort can be seen clearly in the contents of both Document 3-29, which concerns drag cleanup of the XF2A, XP-40, and XP-41, and Document 3-30, involving drag cleanup of the Bell XP-39 Airacobra. Although the history of the XP-39 Army fighter plane's top speed was complicated by a series of changes related to its engine, armor, and guns (which significantly increased the machine's overall weight, and thus made speed increases difficult), careful analysis confirms that if the XP-39 had not gone through drag testing, the production Airacobra's top speed of just under 370 mph would have been quite a bit lower, in the range of 25 to 30 mph.[26]

A great deal more drag cleanup work was started when a second NACA laboratory—the Ames Aeronautical Laboratory—opened for business at Moffett Field in Sunnyvale, California, near San Francisco, from 1940 to 1941. With so much of the aircraft industry located on the West Coast, it was quicker and easier to test the new planes at Ames rather than at Langley. Thus, in addition to a new family of high-speed wind tunnels, at Ames, the NACA constructed a 7- by 10-foot wind tunnel and a 40- by 80-foot wind tunnel that also began to serve as workhorse facilities in the comprehensive drag cleanup program.

In terms of the history of aerodynamics, compared to bold new inventions or ingenious new theories, the significance of the NACA's drag cleanup work might seem pedestrian. But this sort of systematic experimental investigation should not

[26] See James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958* (Washington, DC: NASA SP-4305, 1987), pp. 198-202.

be underestimated—not as a valuable type of engineering science, and certainly not in the context of what happened in World War II. By pointing out ways for aircraft to gain a few extra miles per hour, the NACA effort might often have made the difference in performance between Allied victory and defeat in the air. In measurable aerodynamic terms, the difference seems miniscule. In the case of the Seversky XP-41, for example, cleanup reduced the airplane's drag coefficient from 0.0275 to 0.0226, a difference of 0.0049. But for those who understood the impact of such small numbers, this type of difference was whopping. Realizing seemingly tiny differences such as this figure provided the coup de grace for the airplane design revolution, leading into World War II.

Improved aircraft manufacturing techniques also played a critical role in aerodynamic refinement, particularly through the introduction of flush riveting, which eliminated the dome-shaped rivet heads that protruded untidily above an aircraft's surface (see Document 3-31). Industry even worked to smooth the camouflage paint it used on combat aircraft, trying to minimize the surface roughness of the paint; this step involved water-sanding the airplane's surface with fine sandpaper and rubbing it down with powdered pumice. So important to the aerodynamic performance of an airplane were even the most minor details of design and fabrication that many aircraft manufacturers assembled comprehensive manuals for their employees by which to ensure an aircraft as "clean" as possible. Document 3-32 provides excerpts from one such manual put together by the Boeing Aircraft Company in 1940. Of course, under actual combat conditions, it was nearly impossible to maintain the aircraft in pristine conditions, meaning that the aerodynamic numbers achieved in wind tunnel tests were hardly ever achieved in reality. Still, without the original "cleaning up," the airplanes would have turned out to be that much "dirtier" in actual practice. The starting point of the design in terms of aerodynamic cleanness did make a significant difference.

Thus, it was an almost totally reinvented airplane that fought World War II, and no country did more to generate that revolution and then realize its full potential than the United States, which put the new form of airplane to enormous use in defeating the Axis powers. Of course, another revolution was already brewing, one based on a bold new type of engine, the turbojet. For it, the NACA and the rest of the American aeronautics community did not provide the visionaries; they surfaced in Europe, in the rebellious intellects of British engineer Frank Whittle and German engineer Hans von Ohain. All the while, American aeronautics kept its focus on ever-greater refinement of propeller-driven aircraft, a concentration that may have cost it a chance to explore the concept of jet propulsion more fully—along perhaps with some other revolutionary ideas in aeronautical science and technology such as rockets and cruise missiles. Some critics blamed (and still do blame) the NACA for tunnel vision; others defend the organization by saying that there was no way for it, politically, to get so far out ahead of its clients—and those clients were not interested in pursuing such radical alternative technologies so early. One NACA engineer

has written that "it would have been quite impossible in the prewar period to have any major support from the military, industry, or from Congress for research and development aimed at such radical concepts as the turbojet, the rocket engine, or transonic or supersonic aircraft," and another engineer has commented that "it is certain that if the NACA had had the foresight to do research on the turbine engine in the decade before World War II, the agency would have met with such technical ridicule and criticism about wasting the taxpayers' money that it would either have had to drop it or have been eliminated."[27]

Luckily, the "failure" of NACA researchers and other American engineers to anticipate the jet engine's potential as quickly as a few men in Germany and Great Britain made little difference in the practical outcome of World War II. A handful of jet planes flew in the war, such as the German Messerschmitt Me 262 and the British Gloster Meteor, but they really did not fly effectively enough, in great enough number, or in well enough synchronization with operating squadrons of propeller-driven aircraft, to make a critical difference. Before jet airplanes could reach their potential, they needed to go through the same sort of exhaustive, systems-wide development that prop planes experienced in the two decades between the wars. Jets would eventually go through that years-long, systematic process, as we will see documented in a later volume of this overall study. But by the end of the war, that process had barely started.

Propeller-driven aircraft would continue to be built, and continue to develop, for various purposes well after the appearance of successful jets, even to the present. In 1985, Laurence K. Loftin, Jr., who had then recently retired from NASA after a long career in aeronautical research, called the period from 1945 to 1980 one of "Design Maturity" (see Document 3-31). In terms of basic configuration, propeller-driven airplanes would not change much after the war—although some of them would benefit from the addition of the turboprop, advanced superchargers, and cabin pressurization. In terms of aerodynamics, however, their level of refinement would never surpass the best aircraft of World War II. Attempts would certainly be made to apply new ideas in aerodynamics and other areas, and many excellent propeller-driven airplanes would be built, both as transport aircraft, such as the Vickers Viscount 810 of the late 1940s and Lockheed Super Constellation and Lockheed C-130 turboprop cargo transport of the 1950s, as well as some remarkable general aviation aircraft, such as the Piper Cherokee, Cessna Skyhawk, Beech Bonanza, Cessna 310, and the Beech Super King Air. Much more functional and safe "crop dusters" and other agricultural airplanes would fly, such as the Piper Pawnee. Enthusiasts of "homebuilts" and sailplanes (which, of course, are propellerless) would seek ways

[27] John V. Becker, *High-Speed Frontier: Case Studies of Four NACA Programs, 1920-1950* (Washington, DC: NASA SP-445, 1980), p. 31, and Ira H. Abbott. "A Review and Commentary of a Thesis by Arthur L. Levine, Entitled 'A Study of the Major Policy Decisions of the National Advisory Committee for Aeronautics,' Dated 1963," NASA HQ History Office Archive, HHN-35, Apr. 1964, p. 135.

of improving aerodynamic performance. But generally speaking, the aerodynamics just did not improve that much. What Loftin observed in terms of "design trends" for propeller-driven aircraft since 1945 was clearly a kind of "steady state" that he predicted would continue indefinitely into the future.

When the last volume of *The Wind and Beyond* is published in a few years, readers will want to compare Loftin's assessment with that of Dennis Bushnell, also a NASA Langley aerodynamicist. Unlike Loftin, Bushnell will argue in very strong terms in "The Shape of Things to Come – Views of the Future of Aerodynamics," that aerodynamics has not settled in as a mature or plateau technology and that it has been intellectually constraining to consider it so. Although Bushnell's historical assessment of what has happened specifically in the design of propeller-driven aircraft will not be much different from Loftin's, his explanations for why a steady state has prevailed in the second half of the twentieth century will be. In Bushnell's view, the last word about the form of all aircraft, including those prop-driven, has not yet been written. A new wave of knowledge inspired by a "renaissance of aerodynamics" may change everyone's opinion about what has happened in the past and what could still happen in the future.

The Documents

Document 3-1

Excerpts from Frederick W. Lanchester, *Aerodynamics*: *Constituting the First Volume of a Complete Work on Aerial Flight* (New York: D. Van Nostrand Company, 1908), pp. 10-45.

The following excerpts from Frederick W. Lanchester's 1907 book, *Aerodynamics,* feature his pioneering concept of the "streamline," one of the central themes of the airplane design revolution that was to unfold in the era between the two world wars. As Lanchester described it in his book, his goal was to define an ideal streamline form (by this, he meant an efficient low-drag shape having ultrasmooth contours offering no resistance to the passage of air along its surface). All of the excerpts below are from chapter one of Lanchester's book, entitled "Fluid Resistance and its Associated Phenomena." The author reproduces the continuously running section of the book most concerned with streamlining.

Lanchester's ideas on drag and streamlining directly refuted the widely held but incorrect theory developed earlier by American scientist Samuel P. Langley that skin friction was a negligible factor in aircraft performance. Lanchester was also one of the first to identify and discuss the airflow vortices present at the tips of a wing in flight–a phenomenon that later came to be known as the source for "induced drag." Lanchester gave only preliminary consideration to the notion of induced drag (which actually proved to be quite significant at low speeds), conjecturing that it was simply a necessary part of the cost of gaining lift. The Englishman's focus was, rather, on the ideal streamlined shape, one that would minimize other sources of drag besides induced drag.

Document 3-1, Excerpts from Frederick W. Lanchester, Aerodynamics: Constituting the First Volume of a Complete Work on Aerial Flight *New York: D. Van Nostrand Company, 1908.*

§ 9. On Streamline Form.–When a body of fish-shaped or ichthyoid form travels in the direction of its axis through a frictionless fluid there is no disturbance left in its wake. Now we have seen that in any case the fluid as a whole receives no momentum, so that it is perhaps scarcely legitimate to argue that there is no resistance because there is no communication of momentum, although this is a common statement.[1] It is clear, however, that if there is no residuary disturbance there is no necessary expenditure of energy, and this equally implies that the resistance is nil.

The fluid in the vicinity of a streamline body is of necessity in a state of motion and contains energy, but this energy is conserved, and accompanies the body in its travels, just as in the case of the energy of a wave. It adds to the kinetic energy of the body in motion just as would an addition to its mass.

According to the mathematical theory of Euler and Lagrange, all bodies are of streamline form. This conclusion, which would otherwise constitute a reduction ad absurdum, is usually explained on the ground that the fluid of theory is inviscid, whereas real fluids possess viscosity. It is questionable whether this explanation alone is adequate.

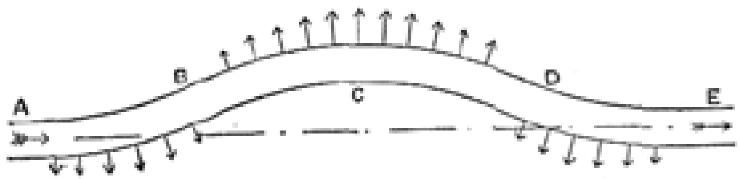


Fig. 2.

§ 10. Froude's Demonstration.–An explanation of the manner of the conservation of kinetic energy, in the case of a streamline body, has been given by the late Mr. A.V. Froude.

Referring to Fig. 2, A, B, C, D, E, represents a bent pipe, through which a fluid is supposed to flow, say in the direction of the lettering, the direction at A and at E being in the same straight line; it is assumed that the fluid is frictionless. Now so long as the bends in the pipe are sufficiently gradual, we know that they cause no sensible resistance to the motion of the fluid. We have excluded viscous resistance by hypothesis, and if the areas at the points A and E are equal there is no change in the kinetic energy. Moreover, the sectional area of the pipe between the points A and E may vary so long as the variations are gradual; change of pressure will accompany change of area on well-known hydrodynamic principles, but no net resistance is introduced; consequently the motion of the fluid through the pipe does not involve any energy expenditure whatever.

Let us now examine the forces exerted by the fluid on different portions of the pipe in its passage. The path of the particles of fluid in the length between the points A and B is such as denotes upward acceleration, and consequently the fluid here must be acted on by an upward force supplied by the walls of the pipe, and the reaction exerted by the fluid on the pipe is equal and opposite. A shorter way is to

[1] This somewhat academic objection would cease to apply if any means could be found to properly define the *idea* which undoubtedly is conveyed to the mind by the argument in question.

regard this reaction as the centrifugal component of the curvilinear path of the flow, and as such it may be indicated by arrows as in the figure.

By assuming the bends in the pipe to be equal and a uniform velocity throughout, it follows that these centrifugal components exactly balance one another, each to each, and the pipe has no unbalanced force tending to push it in one direction or the other. The argument may be found presented in this form in White's "Naval Architecture." The same net result follows, no matter what the exact form of the bends, or whether or not the velocity is uniform, provided the bends are smooth and the cross-section (and therefore the velocity) is the same at E as at A, for under these circumstances the pressure at A will be the same as at E, the applied forces thus being balanced, and there will be no momentum communicated by the fluid in its passage.

When a streamline body travels through a fluid the lines of flow may be regarded as passing round it as if conveyed by a number of pipes as in Fig. 2. It is convenient, and it in no way alters the problem, to look upon the body as stationary in an infinite stream of fluid (Fig. 3); we are then able to show clearly the lines of flow relatively to the surface of the body. Now let us take first the fluid stream that skirts the surface itself, and let us suppose this included between the walls of an imaginary pipe, then forces will be developed in a manner represented in Fig. 2, and these forces may be taken as acting on the surface of the body. It is not necessary to suppose that there is actual tension in the fluid, as might be imagined from Fig. 3, where the forces act outward from the body, this is obviated by the general hydrostatic pressure that obtains in the region; the forces as drawn are those supplied by the motion of the fluid, and can be looked upon as superposed on those due to the static pressure.

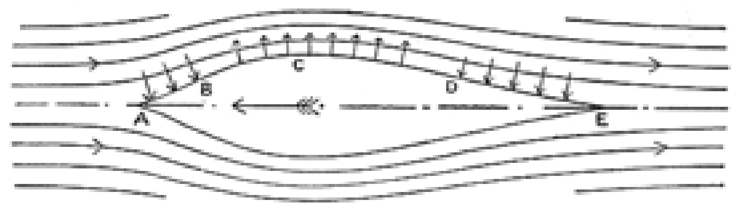


Fig. 3.

If, similarly, we deal with the next surrounding layer of fluid, we find that the pressure to which it gives rise acts to reinforce that of the layer underneath (i.e., nearer the body), and so on, just as in hydrostatics the pressure is continually increased by the addition of superincumbent layers of fluid, and thus we find that the body is subjected to increased pressure acting on its front and rear, and diminished pressure over its middle portion. Now it has been shown, in the case of the pipe, that the algebraic sum of all forces in the line of motion is zero, so that in the streamline body the sum of the forces produced by the pressure on its surfaces will be zero, that is to say, it will experience no resistance in its motion through the fluid.

It may be taken as corollary to the above, that in a viscous fluid the resistance of a body of streamline form will be represented approximately by the tangential resistance of its exposed area as determined for a flat plate of the same general proportions. This is the form of allowance suggested by Froude; a more elaborate and accurate method has been given by Rankine, in which allowance is made for the variation in the velocity of the fluid at different points on the surface of the body. Neither of these methods includes any allowance for viscous loss owing to the distortion of the fluid in the vicinity of the body.

§ 11. The Transference of Energy by the Body.–It is of interest to examine the question of the transference of energy through the streamline body itself from one part of the fluid to the other. For the purpose of reference the different portions of the body have been named as in Fig. 4, the head, the shoulder, the buttock, and the tail, the head and shoulder together being termed (as in naval architecture) the entrance, and the buttock and tail the run. The dividing line between the entrance and run is situated at the point of maximum section, and the dividing line between the head and shoulder on the one hand, and between the buttock and tail on the other, is the line on the surface of the body at which the pressure is that of the hydrostatic "head."

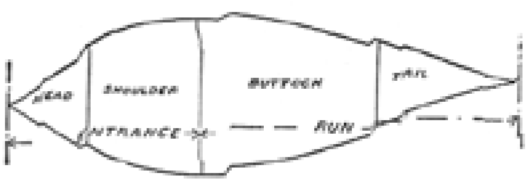


Fig. 4.

Now, as the body advances, the head, being subject to pressure in excess of that due to the hydrostatic "head," is therefore doing work on the fluid; that is to say, transmitting energy to the fluid; the shoulder also advancing towards the fluid is subject to pressure less than that due to hydrostatic head, and is consequently receiving energy from the fluid; the buttock, which is receding from the fluid, is also a region of minus pressure and so does work on the fluid; and lastly, the tail is receding under excess pressure and so receives energy. We thus see that there are two regions, the head and buttock, that give up energy continuously to the fluid, and two regions, the shoulder and tail, that continuously receive it back again. The condition of perfect streamline motion is that the enemy account shall balance.

§ 12. Need for Hydrostatic Pressure, Cavitation.–The motion impressed on the fluid by the pressure region of the head is compulsory, unless (as may happen in the case of a navigable balloon) deformation of the envelope can take place. The motion impressed by the shoulder, on the contrary, depends upon hydrostatic pressure, for otherwise there is no obligation on the part of the fluid to follow the surface of the body. Hydrostatic pressure is necessary to prevent the formation of a void. The pressure measured from the real zero must everywhere be positive, otherwise the fluid will become discontinuous and cease to follow the surface. This is a difficulty that has been actually experienced in connection with screw propellers, and termed cavitation.

§ 13. The Motion in the Fluid.–It has been shown that the head of a streamline form is surrounded by a region of increased pressure. Consequently the fluid as it approaches this region will have its velocity reduced, and the streamlines will widen out, as shown in Fig. 3 (see also Figs. 42, 44, 45, etc.). This behavior of the fluid illustrates a point of considerable importance, which is frequently overlooked. Whenever a body is moving in a fluid, its influence becomes sensible considerably in advance of the position it happens to occupy at any instant. The particles of fluid commence to adjust themselves to the impending change with just as much certainty as if the body acted directly on the distant particles through some independent agency, and when the body itself arrives on the scene the motion of the fluid is already conformable to its surfaces. There is no impact, as is the case with the Newtonian medium, and the pressure distribution is more often than not quite different from what might be predicted on the Newtonian basis.–This behavior of a fluid is due to its continuity.

It follows from elementary considerations that the fluid in the "amidships" region possesses a velocity greater than the general velocity of the fluid (the body, as before, being reckoned stationary). We know that at and about the region C, Fig. 3, the fluid has a less area through which to pass than at other points in the field of flow. It is in sum less than the normal area of the stream by the area of cross-section of the body at the point chosen. But the field of flow is made up of a vast number of tubes of flow, so that in general each tube of flow will be contracted to a greater or less extent, the area of section of the tubes being less at points where the area of the body section is greater. We know that a contraction in a tube of flow denotes an increase of velocity.

Thus on the whole the velocity of the fluid is augmented across any normal plane that intersects the body itself, but the increase of velocity is not in any sense uniform in its distribution. In fact, towards the extremities of the body, and in its immediate neighborhood, we have already seen that the motion of the fluid is actually slower than the general stream.

The motion of the fluid is examined from a quantitative point of view in a subsequent chapter (Chap. III.), where plottings are given of the hydrodynamic solution in certain cases.

§ 14. A Question of Relative Motion.–The motion of the fluid has so far been considered from the point of view of an observer fixed relatively to the body; it will be found instructive to examine the same motions from the standpoint of the fluid itself, that is to say, to treat the problem literally as a body moving through the fluid, instead of as a fluid in motion round a fixed body.

It is evident that the difference is merely one of relative motion. The problems are identical: we require to consider the motions as plotted on co-ordinates belonging to the fluid instead of co-ordinates fixed to the body itself. The relation of the streamlines (which we have so far discussed) to the paths of motion (which we now propose to examine) is analogous to that of the cycloid or trochoid to its generating circle.

§ 15. Displacement of the Fluid.–An unfamiliar effect of the passage of a body through a fluid is a permanent displacement of the fluid particles. This displacement may be readily demonstrated. If a mass of fluid be moved from any one part of an enclosure to any other part, the enclosure being supposed filled with fluid, there is a circulation of fluid from one side to the other during transit; and if we suppose it to be moved from one side to the other of an imaginary barrier surface, then an equal volume of fluid must cross the same barrier surface in the opposite direction. Now it is of no importance whether the thing we move be a volume of fluid or a solid body, so that when a streamline body passes from one side to the other of a surface composed of adjacent particles of fluid, that surface will undergo displacement in the reverse direction to that in which the body is moving, and the volume included between the positions occupied before and after transit will be equal to the volume of the body itself.

Moreover, since the actual transference of the fluid is clue to a circulation from the advancing to the receding side of the body, it will take place principally in the immediate vicinity of the body and less in regions more remote; it is, therefore, immaterial whether the fluid be contained within an enclosure or whether one or more of its confines be free surfaces, provided that continuity is maintained, and that the body is not in the vicinity of a free surface.

§ 16. Orbital Motion of the Fluid Particles.–Since the motion of the fluid results in a permanent displacement, the motion of a particle does not, strictly speaking, constitute an orbit. It is, however, convenient in cases such as the present to speak of the motion as orbital.

If we could follow the path of a particle along any streamline, and note its change of position relatively to an imaginary particle moving in the path and with the velocity of the undisturbed stream, we should have data for plotting the orbital motion corresponding to the particular streamline chosen. Thus we know that the amplitude of the orbit of any particle, measured at right angles to the direction of flight, is equal to that of the corresponding streamline.

We further know that, in general, the particles have a retrograde motion–that is, their final position is astern of their initial position–also that the maximum retrograde velocity is to be found in the region of maximum amplitude. Beyond this we know that the initial motion of any particle is in the same direction as of the body, and that this initial motion is greater for particles near the axis of flight than for those far away.

Let b, b, b, etc., Fig. 5, represent the final position of a series of particles originally situated in the plane a, a, a; then the orbits of these particles will originate on

the plane a, a, a, and terminate of the surface b, b, b, and the motion will be of the character shown.

The form of the surface b, b, b, will be different for different forms of body. It will evidently approach the plane a, a, a, asymptotically, and generally will tend to form a cusp pointing along the axis of flight. The development of this cusp is greatest in cases where the extreme entrance and run are of bluff form, as in the Rankine Oval, Fig. 42, where the point of the cusp is never reached, the surface approaching the axis of light asymptotically. In reckoning the displacement of the fluid (§ 15), the volume included in the cusped surface forward of the plane a, a, must be considered negative, since here the fluid is displaced in the same direction as the motion of the body.

§ 17. Orbital Motion and Displacement, Experimental Demonstration.–The displacement of the fluid and the form of the orbit can be roughly demonstrated by a simple smoke experiment. If a smoke cloud be viewed against a dark background during the passage of a body of streamline form in its vicinity, the retrograde movement of the air is clearly visible. So long as the surface of the body is not too close, the movement is clean and precise, and the general character of the orbit form can be clearly made out; it is found to be, so far as the eye can judge, in complete accord with the foregoing theory. The commencement and end of the orbit, where the motion should be in the same direction as the body, is most difficult to observe, though even this detail is visible if the orbit selected be sufficiently near to the axis of flight. The difficulty here is that the latter part of the orbit is generally lost in consequence of the "frictional wake,"[2] i.e., the current set up by viscous stress in the immediate neighborhood of the body in motion. In all actual fluids a wake current of this kind is set up, and the displacement surface b, b, b, Fig. 5, is obliterated in the neighborhood of its cusp by a region of turbulence.

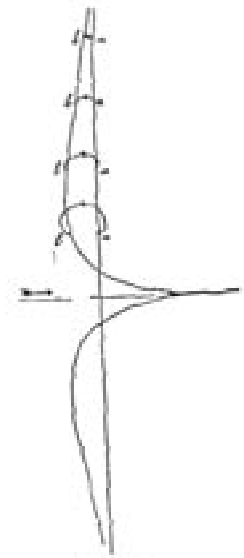


FIG. 5.

§ 18. Orbital Motion, Rankine's Investigation.–The form of the orbits of the fluid particles has been investigated theoretically for a certain class of body by Rankine (Phil. Trans., 1864).

Rankine closely studied the streamlines of a body of oval form, generated by a certain method from two foci (§ 77), and by calculation arrived at the equation to the orbit motion of the particles. The result gives a curve whose general appearance is given in Fig. 6 (actual plotting), in which the arrows represent the motion of the particle, the direction of motion of the body being from left to right.

[2] A term used in naval architecture.

Discussing the particular case in which the eccentricity of the oval vanishes, and the form merges into that of a circle, Rankine says,–"…The curvature of the orbit varies as the distance of the particle from a line parallel to the axis of X, and midway between that axis and the undisturbed position of the particle. This is the property of the looped or coiled elastic curve; therefore when the water-lines are cyclogenous the orbit of each particle of water forms one loop of an elastic curve." Further, he says–"The particle starts from a, is at first pushed forward, then deviates outwards and turns backwards, moving directly against the motion of the solid body as it passes the point of greatest breadth, as shown. The particle then turns inwards, and ends by following the body, coming to rest at b in advance of its original position."

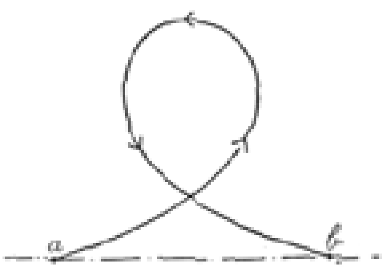


FIG. 6.

This orbit in some respects resembles that arrived at by the author, but differs in the one very important point that, whereas the author's method gives a retrograde displacement of the fluid as the net consequence of the passage of the body, Rankine's conclusion is exactly the contrary.

As the author's result is capable of experimental verification, it is evident that some subtle error must exist in Rankine's argument, the exact nature of which it is difficult to ascertain.

§ 19. Bodies of Imperfect Streamline Form.–In an actual fluid, bodies of other than streamline form experience resistance apart from that directly due to viscosity.

In the practical shaping of a streamline body it is found essential to avoid corners or sharp curves in the line of flow. Bodies in which duo precaution is not taken in this respect offer considerable resistance to motion, and the regions of abrupt curvature give rise to a discontinuity in the motion of the fluid. Thus Fig. 7 represents a double cone moving axially, and it will be noticed that the flow has not time to close in round the run, as it would do in a properly formed streamline body, but shoots past the sharp edge, as indicated in the figure. The region in the rear of the body, Z, is filled with fluid that does not partake of the general flow, and which is termed dead-water.

The resistance experienced by bodies of imperfect form is due to the work done on the fluid, which is not subsequently given back, as is the case with the streamline body. This resistance can be traced to two causes, namely, excess pressure on the surface in presentation and diminished pressure in the dead-water region. The former is of dynamic origin, the energy being expended in directly impressing motion on portions of the fluid; the latter is due to the entrainment or viscous drag experienced by the dead-water at the surface hounded by the live stream. It is generally believed that, in a fluid whose viscosity is negligible, the latter cause would be inoperative,

the whole resistance being then due to the excess pressure region in front of the body, the dead-water or wake being at approximately the hydrostatic pressure of the fluid.

The surface separating the live stream and the dead-water constitutes a discontinuity, since the velocity of the fluid, considered as a function of its position in space, is discontinuous. This case is not one of a physical discontinuity, such as discussed in § 12, for the region on either side of the surface is filled with the same kind of fluid; it is rather a kinetic discontinuity, that is to say a discontinuity of motion.

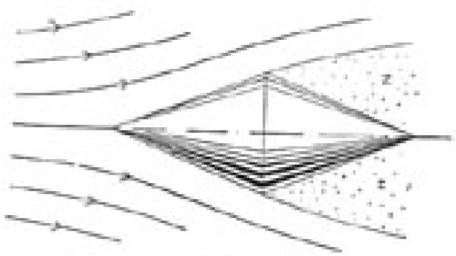


FIG. 7.

§ 20. The Doctrine of Kinetic Discontinuity.–The theory of kinetic discontinuity is of modern origin, having been introduced and developed by Kirchhoff, Helmholtz, and others, to account for the phenomenon of resistance in fluid motion. The analytical theory, based on the hypothesis of continuity, does not in general lead to results in harmony with experience. All bodies, according to the Eulerian theory, are of streamline form, provided that the hydrostatic pressure of the fluid is sufficient to prevent cavitation; we know that in practice this is not the case.

According to the teaching of Helmholtz and Kirchhoff, a kinetic discontinuity can be treated as if it were a physical discontinuity; that is to say, the contents of the dead-water region can be ignored; and this method of treatment is now generally recognized, although not universally so. The controversial aspect of the subject is discussed at length at the conclusion of Chap. III.

The principal objection to the theory of discontinuity is that in an inviscid fluid a surface of discontinuity involves rotation, and therefore, by a certain theorem of Lagrange, it is a condition that cannot be generated.[3] A further objection sometimes raised is that such a condition as that contemplated would be unstable, and that the surface of discontinuity, even if formed, would break up into a multitude of eddies. Whether this is the case or not in an inviscid fluid, it is certain that in a fluid possessed of viscosity a surface of discontinuity does commence to break up from the instant of its formation; but as this breaking up does not affect the problem in any important degree, the objection in the case of the inviscid fluid is probably also without weight.

In a real fluid a finite difference of velocity on opposite sides of any surface would betoken an infinite tangential force. Consequently the discontinuity becomes a stratum rather than a surface, and the stratum will either be a region in which a velocity gradient exists (§ 31), or it will become the seat of turbulent motion (§ 37), the latter in all probability.

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[3] Chap. III. §§ 65–71.

The conception of the discontinuity as a surface and the method involving this conception are in no way affected by these considerations. The term surface of discontinuity may be looked upon as an abstraction of that which is essential in a somewhat complex phenomenon.

§ 21. Experimental Demonstration of Kinetic Discontinuity.–The reality and importance of the discontinuous type of motion can be demonstrated conclusively by experiment.

In Fig. 8, a, b, c, is a hollow spherical globe in which d is a tube arranged to project in the manner shown. An ordinary lamp globe and chimney will be found to answer the purpose the former having one of its apertures closed by a paper disc. The whole is carefully filled with smoke and then moved through the air in a direction from right to left, the relative direction of the air being indicated by the arrow.

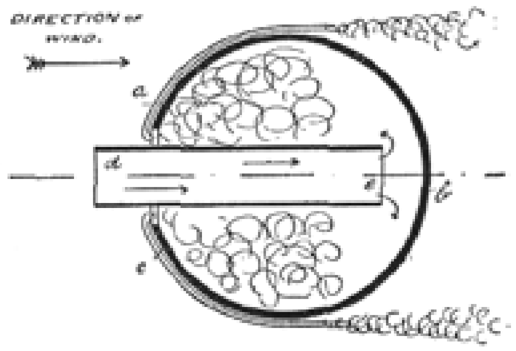
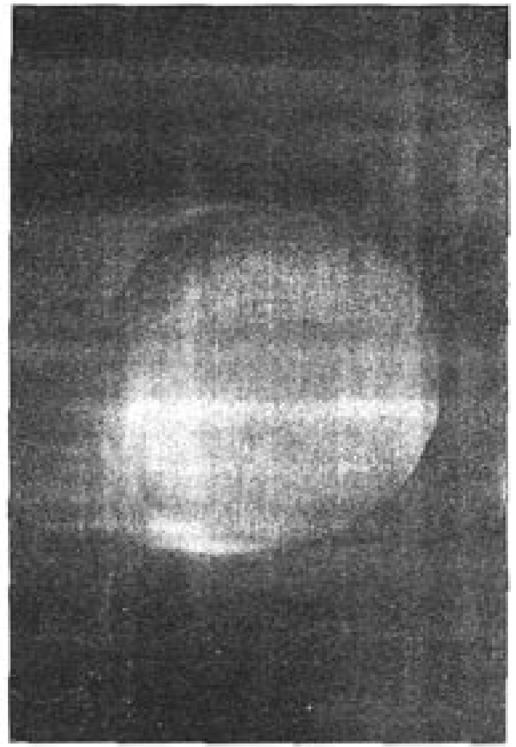


Fig. 8.

It will be found that the air will enter the tube and displace the smoke through the annular aperture. The issuing smoke follows the surface of the sphere in the most approved manner as far as the "equator," but then passes away at a tangent, the stratum discontinuity, the dead-water region, and the turbulent character of motion, being all clearly manifest. The discontinuity, as may have been anticipated, does not appear as a clean-cut surface; it is marked almost from the commencement, as indicated in the figure, by eddy motion; but when we remember that, according to the Fulerian theory, the lines of flow should carry the smoke along a symmetrical path to the opposite pole of the sphere, as in Fig. 45 (Chap. III.), the conclusion is plain.

The author has succeeded in photographing the flow round a cylinder in motion in a smoke-laden atmosphere (Fig. 9). In this example it may be noticed that the surface or stratum of discontinuity arises from a line some distance in front of the plane of maximum section; the difference in the behavior of a cylinder and sphere in this respect is clue to the fact that in the former case the lines of flow are cramped laterally, the motion being confined to two dimensions, whereas in the 1atter case, the motion being in three dimensions, the fluid can "get away" with greater facility. This difference is reflected in the lower coefficient of resistance found experimentally for the sphere than that ascertained for the cylinder. Thus in the experiments of Dines (§ 226) the pressure per square foot of maximum section on a 5/8-in. cylindrical rod was found to be more than double that on a 6-in. sphere, though doubtless the difference in size in the bodies compared may contribute something to the disparity.



The theory of discontinuity also receives support of the most convincing description from the experiments of Mutton, 1788, and Dines, 1889, by which it is shown that the pressure on a solid hemisphere, or a hemispherical cup (such as used on the Robinson anemometer), both in spherical presentation, does not differ from that on a complete sphere to an extent that experiment will disclose. This not only disposes of the streamline sphere of mathematical conception, but proves at the same time the approximate constancy of wake pressure under variation of rear body form. The same lesson is to be gleaned from experiments in the case of the hemisphere, cone, and circular plate (all in base presentation), whose resistance is found to be approximately equal (Fig. 17).

§ 22. Wake and Counterwake Currents.–Reference has already been made to the frictional wake current to which a streamline body gives rise owing to the viscous stress it exerts on the fluid in its neighborhood. With bodies of imperfect form there is, in addition to the frictional wake, a wake current constituted by the contents of the dead-water region, that is, the fluid contained within the surface of discontinuity.

The general motion of the wake current is in the same direction as the body itself, but, owing to the viscous drag exerted on it by the surrounding stream, this motion has superposed on it one of circulation, which probably results in the central portion of the wake traveling actually faster than the body[4] and the outer part slower, though Dines' experiments seem to point to the disturbance being of so complex a character that it is impossible to trace any clearly defined system.[5]

Now, since there can be no momentum communicated to the fluid in sum (§ 5), there must be surrounding the dead-water or wake current a counter-current in the opposite direction to that of the wake, that is, in the reverse direction to the

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4 Since writing this passage the author has observed this "overtaking" current photographed in Fig. 9. It may be faintly discerned in this Figure in the central region of the "dead-water."

5 "On Wind Pressure upon an Included Surface," Proc. Royal Soc., 1980.

motion of the body; and this counterwake current is being continuously generated, just as the wake current itself, and contains momentum equal and opposite to that of the wake. When in a fluid possessing viscosity the wake and counterwake currents intermingle by virtue of the viscous connection between them, and become involved in a general turbulence, the plus and minus momenta mutually cancel, and the final condition of the fluid at all points is one of zero momentum.

We may regard the counterwake current as a survival of the motion which, we have shown, must exist in the neighborhood of the maximum section of a streamline body (§ 13) opposite in direction to its motion through the fluid. The failure of the stream to close in behind the body means that this motion will persist.

The mingling of the wake and counterwake may be regarded as a phenomenon quite apart from the initial disturbance, and the turbulence or otherwise of the wake does not materially add to or detract from the pressure on the front face of the body, but concerns merely the ultimate disposal of the energy left behind in the fluid.

No distinction is necessary between the frictional wake and the dead-water wake so far as the production of a counterwake current is concerned. The total wake current is the sum of the two, and the total counterwake is equal and opposite to the total wake.

§ 23. Streamline Motion in the Light of the Theory of Discontinuity.–The theory of kinetic discontinuity presents the subject of streamline motion in a new light, and enables us to formulate a true definition of streamline form. Thus–

A streamline body is one that in its motion through a fluid does not give rise to a surface of discontinuity.

In the previous discussion, § 9 et seq., no attempt has been made to delineate streamline form, that is to say (according to the present definition), the form of body that in its motion through a fluid will not give rise to discontinuity. It has been assumed that such a body is a possibility, and from the physical requirements of the case the general character of the body form has been taken for granted.

Under our definition, if, as in the mathematical (Eulerian) theory, we assume continuity as hypothesis, then all bodies must be streamline, which is the well-known consequence. If, on the other hand, as in the Newtonian medium, we assume discontinuity, then it is evident by our definition that streamline form can have no existence, which, again, is what we know to be the case. It remains for us to demonstrate, on the assumption of the properties of an ordinary fluid, the conditions which govern the existence or otherwise of discontinuity, and so control the form of a streamline body.

In order that streamline motion should be possible such motion must be a stable state, so that, if we suppose that by some means a surface of discontinuity be initiated, the conditions must be such that the form of motion so produced is unstable.

Let us suppose that we have (Fig. 10) a streamline body made in two halves, and that the rear half, or run, be temporarily removed; then a surface of discontinuity will be developed, as indicated in the figure. Let now the detached portion be replaced. Then the question arises, What are the changed conditions that will interfere with the permanence of the discontinuous system of flow, as depicted in the figure?

If, in the first place, the fluid be taken as inviscid, and if, for the purpose of argument, we assume that the system of flow indicated in the figure is possible in an inviscid fluid, then it is evident that when the run is replaced we shall not have disturbed the conditions of flow, for our operations have been confined to the dead water region, where the fluid is at rest relatively to the body. Consequently the discontinuous system of flow will persist. That is to say, under the supposed conditions streamline motion is either unstable or is at best a condition of neutral equilibrium. Let us next introduce viscosity as a factor. The conditions are now altered, for the fluid in the dead-water region is no longer motionless, but is in active circulation, and the introduction of the rear half of the body obstructs the free path of the fluid, so that, as the outer layers of the dead-water are carried away by the viscous drag, the fluid in the interior has difficulty in finding its way back to take its place. This difficulty is greatest in the region from which the discontinuity springs, where the dead-water runs off to a "feather edge," and it is evident that some point of attenuation is reached at which the return flow becomes impossible, and the fluid will be "pumped out" or ejected from the region forward of this point. This brings the discontinuity further aft on the body, where the process can be supposed repeated, so that eventually the whole dead-water has been pumped away, and streamline motion supervenes. It is evident that the process will not occur in stages, as above suggested, but will be continuous.

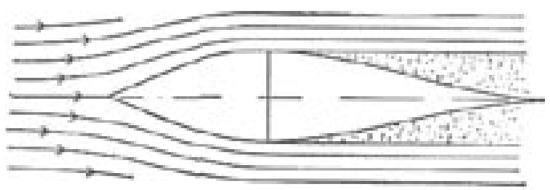


Fig. 10.

It might be supposed from the foregoing argument that the degree of curvature of the surface of the body would not be a matter of importance, as in any case the feather edge of the dead-water would be sufficiently fine to ensure the ejection of some small amount of the fluid, and this process by continuous repetition would eventually clear the wake of its contents. If the surface of the body were frictionless, doubtless this might be the case, but it is established that there is continuity between the surface of an immersed body and the surrounding fluid; that is to say, there is the same degree of viscous connection between the fluid and the surface as there is between one layer of the fluid and another. The consequence of this is that the dead-water never fines off entirely, but extends forward as a sort of sheath enveloping the whole surface of the body, and if the curvature at any point is too rapid, the ejection may not prove effective, and the discontinuity will persist. It is evident therefore that there will be some relation between the bluffness of form permissible and the viscosity of the fluid, and, other things being equal, the less the viscosity the finer will have to be the lines of the body. The theory evidently also points to the importance of smoothness of surface when the critical conditions are approached.

The subject is not yet exhausted. We know that the thickness of the stratum of fluid infected by skin friction increases with the distance from the "cut-water"; that is to say, the factor on which the curvature of the surface probably depends is relatively more important on the buttock than on the shoulder. Hence we may expect that the lines of entrance can with impunity be made less fine than the lines of the run.

Again, all forces due to the inertia of the fluid vary as the square of the velocity; those due to viscosity vary in the direct ratio of the velocity (§ 31). Therefore for different velocities the influence of viscosity predominates for low velocities, and that of inertia when the velocity is high. Consequently the form suited to high velocity will be that appropriate to low viscosity, and vice versa; that is to say, the higher the velocity the finer will be the lines required.

§ 24. Streamline Form in Practice.–The practical aspect of streamline form may be best studied from the bodies of fishes and birds, the lines of which have been gradually evolved by nature to meet the requirements of least resistance for motion through a fluid, water or air, as the case may be.

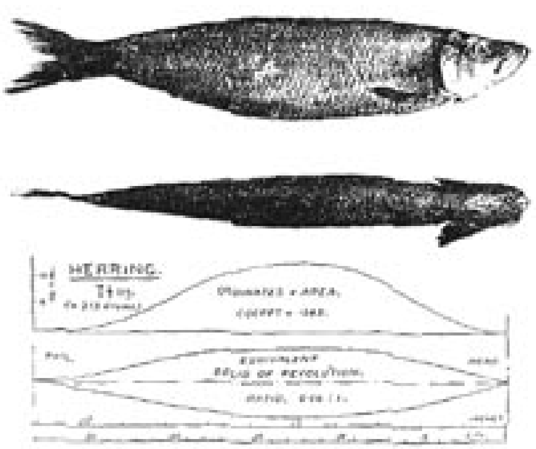


Fig. 11.

Since all animals have functions to perform other than mere locomotion, we find great diversity of detail, and we frequently meet with features whose existence is in no way connected with the present subject. We may readily recognize in these cases the exceptional development of certain organs or parts to meet the special requirements of a particular species, and by a sufficiently wide selection we can eliminate features that are not common, and so arrive at an appreciation of that which is essential. Thus the herring (Fig. 11), the trout (Fig. 12), or the salmon (Fig. 13) may be cited its typically fish shaped fish.

Beyond the lessons to be derived from these natural forms, there is very little practical information available. The lines of ships are governed by considerations foreign to the subject, the question of wave-malting, for example, being a matter of vital importance. The submarine has not yet reached its stage of development that would justify its form being taken as a fully evolved model; also, for obvious reasons,

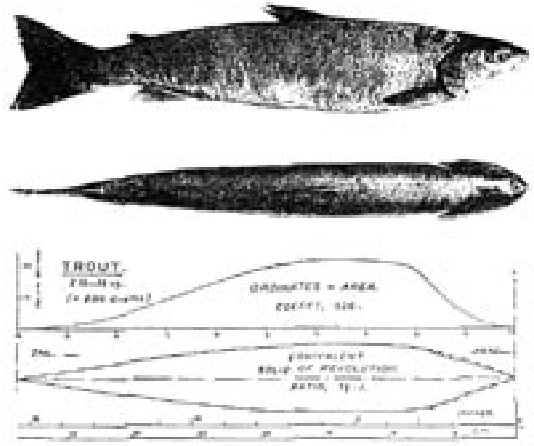


Fig. 12.

this type of vessel is one of which but little information has been published.

In Figs. 11 and 12 curves are given whose ordinates represent the area of cross-section at different points. This curve has been obtained by differentiating a displacement curve plotted from a series of immersion measurements. These measurements were made by a method of displacement, the fish, suspended tail downward, being lowered stage by stage into a vessel of water, measurements being made of the overflow.

The area curves have been further translated into the form of solids of revolution, which may be taken as the equivalent of the original form in each case. Some doubt exists as to the exact form in the region of the head, owing to the water entering the gills. The effect of this is very evident in the case of the trout (Fig. 12), where the form has been "made good" by a dotted line.

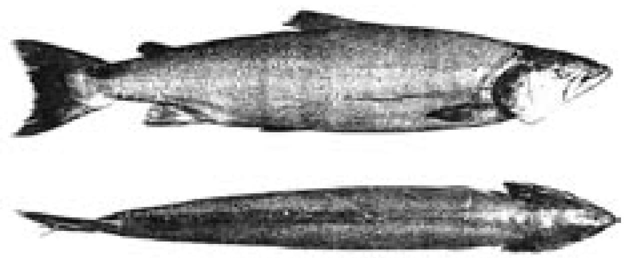


Fig. 13.

For the purpose of comparison outline elevations are given in Fig. 14 of three types of Whitehead torpedo. These are forms that have been developed by long experience, but the shape is largely dictated by special considerations. The bluff form of head, for example, in models A and C is adopted in order to bring the explosive charge into as close proximity as possible to the object attacked. It probably also gives a form that is more easily steered.

§ 25. Streamline Form.–Theory and Practice Compared.–Before a rigid comparison can be instituted between the theoretical results of § 23 and the actual forms found in nature considerable further information is required. We do not know with accuracy the speeds for which the different fish forms have been designed or are best adapted. We also lack knowledge on certain other important points. The present comparison must therefore be confined to generalities.

In the first place, we may take it that the conclusion as to the bluffer form being that suited to greater viscosity is fully borne out in practice, though the whole of the considerations bearing on this point are not here available. It is explained in Chap. II. that the viscosity divided by density (or kinetic viscosity) is the proper criterion in such a case as that under discussion, and on this basis air is far more viscous than water, so that we shall expect to find aerial forms bluffer in their lines than aqueous

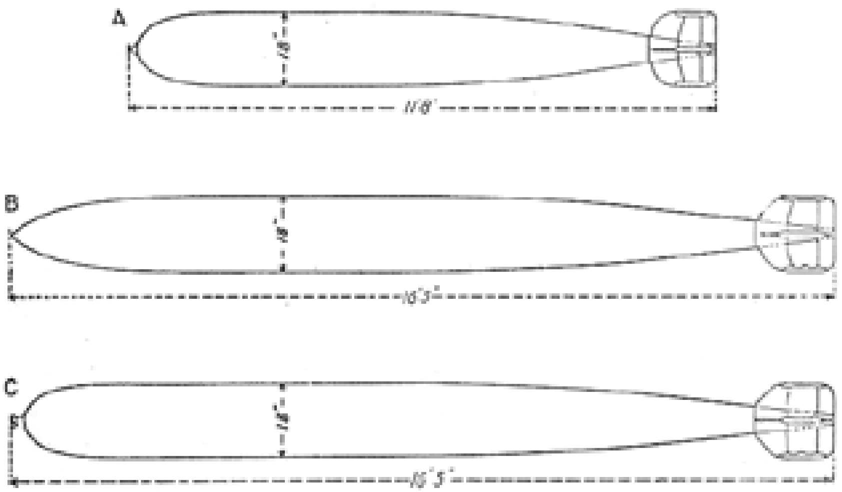


FIG. 14.

forms. Taking the solid of revolution as the basis of comparison, we have in the case of the herring and the trout the length approximately seven times the maximum diameter. The general ratio found amongst bird forms is about three or four to one, the samples chosen for measurement being as far apart as the albatross and the common sparrow. Consequently we find that the theoretical conclusion receives substantial confirmation.

The relation of fineness to speed is not so easy of demonstration, owing to the absence of accurate data. It would, however, seem to be sufficiently obvious as a matter of general experience that our conclusions hold good. It is almost certain that in general the fish with the finer lines are the faster swimmers. If this conclusion be accepted, the viscosity relation of the preceding paragraph is emphasized, for there is no doubt that the average speed of flight is greatly in excess of any ordinary velocity attained by fish.

§ 26. Mutilation of the Streamline Form.–There are certain types of body that may be regarded as mutilations of the streamline form, and the consequences of such mutilation may now be examined.

If, in the case of a body propelled at a constant velocity, the entire run be removed, as in § 23, the consequence is a surface of discontinuity emanating from the periphery of section. Under these circumstances, if we neglect the influence of viscosity and the consequent loss of wake pressure, the work done appears wholly in the counterwake current, on the production of which energy is being continu-

ously expended. This performance of work is otherwise represented by a resistance to motion, being the difference between the excess pressure on the head and the diminished pressure on the shoulder, according to the principle explained in § 11. If now we restore the buttock, so that the mutilation is confined to the simple loss of the tail (Fig. 15), the diminished pressure on the buttock acts as a drag upon the body, and more work must be expended in propulsion. This additional energy will appear in the fluid as a radial component in the motion of the stream which does not exist if the whole run is removed. It is probable that some of this energy is restored by an increase in the pressure of the dead water due to the converging stream, but we have no means of making a quantitative computation.

An illustration of this principle may be cited in the type of hull employed in a modern racing launch. The stern is cut off square and clean, and may constitute the maximum immersed section. There would seem in fact to be no logical compromise between a boat with an ordinary well-proportioned entrance and run, and one in which the latter is sacrificed entirely. In such a form, when traveling at high speed the water quits the transom entirely, and consequently sacrifice is made of the hydrostatic pressure on the immersed transom area. The point at which the front half of a boat thus takes less power for its propulsion than the whole is probably about that speed at which the skin friction on the run (the after-half), if present, exceeds the hydrostatic pressure on the maximum immersed section. This does not, however, determine the point at which it pays to make the sacrifice, owing to the fact that for the same capacity the truncated form has to be that of a larger model. The rating rule also exerts an arbitrary influence. When, as is usual, the length is penalized, an additional inducement is offered for the designer to adopt the truncated type. When the truncated type of hull is adopted it is advantageous to employ shallow draught, for the hydrostatic pressure for a given displacement is less. This form is also partly dictated by considerations relating to propulsion.

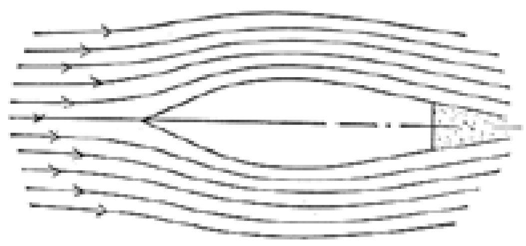


FIG. 15.

§ 27. Mutilation of the Streamline Form (continued).–In Fig. 16, A and B, the consequences of truncating the fore body, or entrance, of a streamline body are indicated diagrammatically. If, as in A, the mutilation be slight, the result may be merely a local disturbance of the lines of flow. A surface of discontinuity will probably arise, originating and terminating on the surface of the body in the manner shown. It is possible that if the streamline body be traveling at something approaching its critical velocity (at which even in its complete form it is on the point of giving rise to discontinuity), a minor mutilation such as here suggested might have more serious consequences.

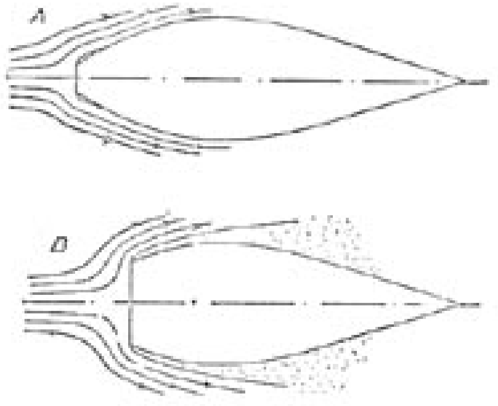


Fig. 16.

If the greater part of the entrance be removed, as shown at B, the surface of discontinuity generated quits the body for good, and the resistance becomes immediately as great as that of a normal plane of area and form equal to that of the section. This is in harmony with the experiments of Hutton and Dines, to which reference has already been made (Fig. 17), the three bodies shown being found to offer the same resistance within the limits of experimental error.

It is evident that the dictum of the late Mr. Froude, that it is "blunt tails rather than blunt noses that cause eddies" (and therefore involve a loss of power), is applicable only to bodies having already some approximation to streamline form. It is obviously useless to provide a nice sharp tail if previous attention has not been given to the shoulder and buttock lines. Mr. Froude probably meant that in a well-designed streamline form the tail should be finer in form than the head, a matter that up to his time had presumably been neglected.

The primary importance of easy shoulder lines has been long recognized as a fundamental feature in the design of projectiles. A full-sized section of a Metford 303 bullet, illustrating this point, is given in Fig. 18, and a streamline form of which it may be regarded as a "mutilation" is indicated by the dotted line.

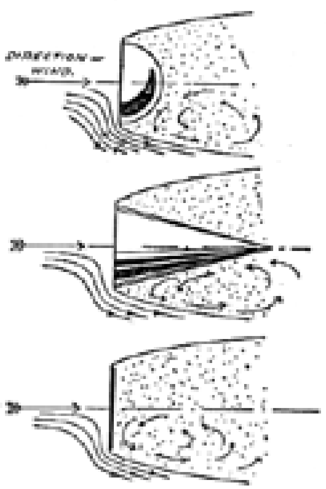


Fig. 17.

§ 28. Streamline Flow General.–Let us suppose an approximate streamline form to be built of bricks, and, in the first place, we will assume that the bricks are so small as to merely give rise to a superficial roughness. Then this roughness will add to the skin friction and will give rise to some local turbulence, but the general character of the flow system remains as before. We may go further and suppose the bricks so large as to form steps capable of giving rise to surfaces of discontinuity (Fig. 19). Then the resistance will be increased, and the layer of fluid next the body will be violently stirred up; but if we examine the fluid some distance away we shall still find it comparatively unaffected. If we now suppose the body to consist of a few large blocks, the depth of fluid affected by turbulence will be greater, but at a sufficient distance away we may still expect to find lines of flow of characteristic streamline form. We may therefore generalize and say, All bodies passing through a fluid are surrounded by a streamline system of a flow of a greater of less degree of perfection depending upon the conformability or otherwise of the surface of surfaces of the body.

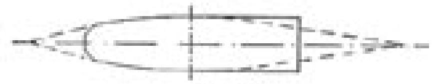


Fig. 18.

This proposition, if not sufficiently obvious from the considerations above given, may easily be demonstrated experimentally.

In the experiment described in § 17, the orbital motion of the particles of the fluid is demonstrated by the motion of an ichthyoid body in air irregularly charged with smoke. This orbital motion, with its consequent displacement, is quite characteristic, and if other shapes of the body be substituted for the streamline form, the motion can be observed much closer to the axis of flight than is the case for a sphere or other bluff form; also when the movement is complete nothing further happens. In the case of a sphere, the looked for movement duly takes place; but immediately after the whole of the fluid under observation is involved in a state of seething turbulence, where the wake and counterwake currents are mingling. If the point of observation is sufficiently remote, the orbital motion may be detected, even in the case of the normal plane, beyond the immediate reach of the wake turbulence.

§ 29. Displacement due to Fluid in Motion.–It has been shown (§ 15) that the fluid in the neighborhood of the path of flight of a streamline body undergoes displacement, and that the total displacement is equal to the volume of the body. It might be expected in the case of the normal plane, which possesses no volume, that the displacement would be nil, and such would doubtless be the case if the form of flow were that of the Eulerian theory.

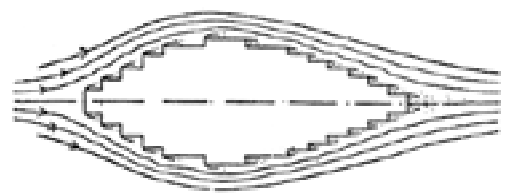


Fig. 19.

In actuality the normal plane, in common with bodies of bluff form, carries a quantity of fluid bodily in its wake, which from the present point of view becomes in effect part of the body, so that the displacement manifests itself just as if the plane were possessed of volume. This is characteristic of all bodies that give rise to discontinuous motion; the displacement is greater than the actual volume of the body. If there were no mingling of the wake and counterwake currents, the displacement would be infinite, for the counterwake current would persist indefinitely.

In the case of a streamline body, a certain amount of fluid is carried along with the body by viscosity, and this similarly increases the effective displacement volume.

It would appear from actual observation that, where the displacement is due to the attendant fluid, the outer streamlines have a motion closely resembling that produced by a streamline body, but that those nearer the axis of flight terminate in the turbulent wake; the commencement of the orbit is all that can be seen.

§ 30. Examples Illustrating Effects of Discontinuous Motion.–On the practical importance of the study of motion of the discontinuous type it is unnecessary to dwell. It is at present the only basis on which it is possible to account for the phenomenon of fluid resistance as experimentally known. Beyond this there are many examples and illustrations which are of especial interest, considered either as proofs of the theory itself or in relation to their actual consequence or utility.

A useful application of the principle is found in the screen employed on fast steamships to protect the navigating officer, and frequently the "watch," from the rush of air, without obstructing the field of vision. This is illustrated diagrammatically in Fig. 20, in which it will be seen that the live stream is carried clear over the sailor's head, the latter being protected by the surface of discontinuity. A similar device is frequently adopted in connection with the dashboard of a motor car.

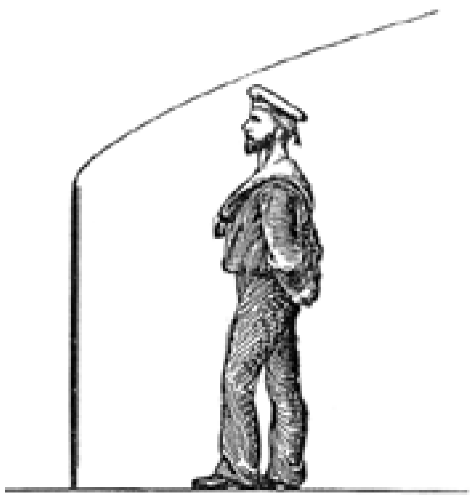


Fig. 20.

Evidence of the most striking kind of the existence of a surface of discontinuity is sometimes met with in the growth of trees in the immediate vicinity of the edge of a cliff (Fig. 21). It may be seen that the form of the surface is clearly delineated, the tree top being cut away as though it might have been sheared off by a stroke of a mighty scythe.

An interesting example of an indirect effect of discontinuity is to be found in the effect of "cut" or "side" on the flight of a ball. Let a ball (Fig. 22) moving in the direction of the arrow A have a spin in the direction of the arrow B. Now where the direction of motion of the surface of the ball is the same as the relative motion of the fluid, as at D, the surface will assist the stream in ejecting the dead water, so that the discontinuity will be delayed, and will only make its appearance at a point some distance further aft than usual. On the other hand, on the side that is opposing the stream the surface of the ball will pump air in, and so assist the discontinuity, which will make its appearance prematurely. The net result of this is that the counterwake will have a lateral component (downwards in the figure), and, on the principle of the continuous communication of momentum, there will be a reaction on the ball in the opposite direction, that is to say upwards. A ball may therefore be sustained against gravity or be made to "soar" by receiving a spin in the direction shown, or, if the spin be about a vertical axis, the path of the ball will be a curve (in plan), such that the aerodynamic reaction will be balanced by centrifugal force.

Fig. 21.

The actual means by which the reaction acting on the ball comes about may be understood from either of two points of view. We may (Fig. 22) regard this reaction as the centrifugal effect of the air passing over the ball preponderating greatly over that of the fluid passing underneath, or if we anticipate a knowledge of hydrodynamic theory (Chap. III.), we know that the greater proximity of the lines of flow in the former region is alone sufficient to indicate diminished pressure. The lines as drawn in the figure are not plottings–there is no way known of plotting a field of flow of this degree of complexity–but they may be taken as a very fair representation of what the plotting would be if it could be effected.

The reason that the streamlines have been shown rising to meet the ball in its progress will be better understood in the light of Chaps. III. and IV. This detail is related to more advanced considerations than can be entered into at present.

A further interesting example is found in the aerial tourbillion[6] (Fig. 23), in which the rotor K is a stick of segmental section mounted to revolve freely about the axis L. The plane face of the rotor is set truly at right angles to the axis of rotation. If this apparatus be held in a current of air with the plane face fronting the wind, as, for instance, by holding it outside the window of a railway carriage in motion, the rotor evinces no tendency to go round in the one direction or the other. If, however, a considerable initial spin be imparted in either direction, the wind will suddenly get a bite, so to speak, and the rotor will gather speed and spin at an enormous rate, as if it were furnished with sails like a well-designed windmill.

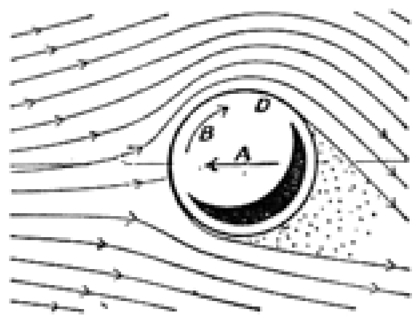


Fig. 22.

Referring to Fig. 24, we have at a the type of flow illustrated to which the blade of the rotor will give rise when its motion is normal to the air; b similarly indi-

[6] This interesting aerodynamic puzzle was first brought to the notice of the author by Mr. Henry Lea, consulting engineer, of Birmingham, who, it would appear, had it communicated to him by Mr. A. S. Dixon, who in turn had it show him when traveling in Italy by Mr. Patrick Alexander. The author has taken no steps to trace the matter further. The explanation here given is his own.

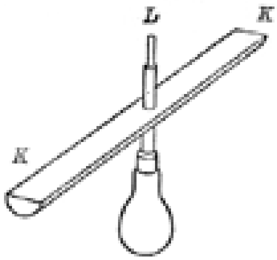


Fig. 23

cates the form of flow when the rotor is going round slowly, not fast enough for the air to take hold. In both these figures we have the flow independent of the "rear body form," and the rotor behaves just as if it were a flat plate. Now, let us suppose that the rotor be given a sufficient initial spin to bring about the state of things represented at c.

The surface of discontinuity that ordinarily springs from the leading edge has got so close to the rear body of the rotor as to have ejected the "dead-water" on that side, and the resulting form of flow will be something like that illustrated in Fig. 25. Here the pressure on the left-hand side (as shown) will be that of the "dead-water," which is, as we know, somewhat less than that of hydrostatic head, while that on the right hand side will, owing to the centrifugal component of the stream, be very

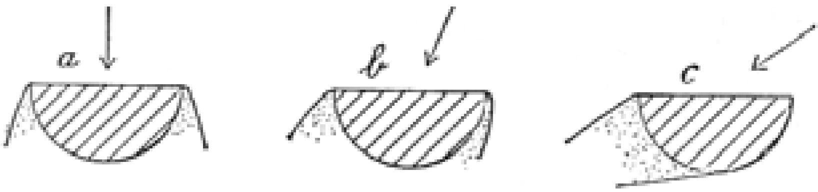


Fig. 24.

much lower; that is to say, the rotor will experience a force acting from left to right which is in the direction of the initial spin, so that the motion will be accelerated and will continue. The fact that the propelling force only comes into existence when the initial spin is sufficient to eject the dead water from the leading aide of the rotor blade fully explains the observed fact that a very considerable initial spin is necessary.

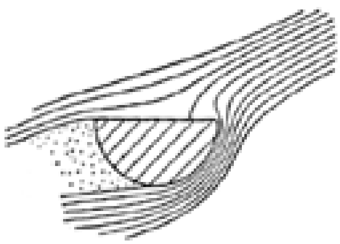


Fig. 25.

Document 3-2

Ludwig Prandtl, "Motion of Fluids with Very Little Viscosity," NACA Technical Memorandum No. 452 (Washington, DC, 1928), translation of "Über Flüssigkeitsbewegung bei sehr kleiner Reibung," in *Vier Abhandlungen zur Hydrodynamik und Aerodynamik,* ed. L. Prandtl and A. Betz (Göttingen: Selbstverlag der AVA, 1927, reissued 1944), pp. 1-8. The 1927 publication was a reprint of Prandtl's 1904 paper that had appeared in *Verhandlungen des III. Internationalen Mathematiker-Kongresses, Heidelberg, 1904,* ed. A. Krazer (Leipzig: Teubner, 1905), pp. 484-91.

This paper in which Germany's Dr. Ludwig Prandtl of the University of Göttingen introduced the concept of what came to be known as the "boundary layer" is, without question, one of the most classic expressions in the entire history of aerodynamics. Never before had anyone in fluid mechanics so embodied the ideal of binding theory and practice into a unified whole, one in which abstract theorems and experimental facts worked together for the purpose of fundamental applications.

In his 1982 book, *Bringing Aerodynamics to America,* historian Paul A. Hanle examined "The Achievement of Ludwig Prandtl" in detail. As Hanle explained, Prandtl's was an achievement crucial to "bringing aerodynamics to America" notably because two of his prize students, Max Munk and Theodore von Kármán, were to play critical roles after 1920 in the development of aeronautical research and development (R & D) capabilities in the United States. In Hanle's view, Prandtl's 1904 paper typified not only his own mode of research but also that of coming generations of scientists and engineers dedicated to aerodynamic R & D. Prandtl's arguments were "essentially physical," based on his "intuition reinforced by his confirming experiments." He gave roughly equal time to explaining his theory and to verifying it by reference to numerous drawings and photographs of flow taken from experiments in a water canal. The 1904 paper presented an approximate solution to the problem he posed, arrived at by numerical computation. Although highly technical, the piece could be easily surveyed. Even today, it deserves our attention for what it reveals about Prandtl's scientific turn of mind, an approach to solving problems that would influence American aerodynamics in many essential ways for years to come (*Bringing Aerodynamics to America* [Cambridge, MA, and London: The MIT Press, 1982], pp. 43-4.).

The central idea of Prandtl's paper rested in two sentences stated right near the beginning: "I have set myself the task of investigating systematically the motion of a fluid of which the internal resistance can be assumed very small. In fact, the resistance is supposed to be so small that it can be neglected wherever great velocity differences or cumulative effects of the resistance do not exist." As Hanle explained, what Prandtl called his "systematic investigation" in truth consisted of "treating no more than a few 'single questions' in broad outline" (Hanle, pp. 44-5). From this basis, it did not take him long to present the most important point of his paper: "By far, the most important question of this problem is the behavior of the fluid at the surfaces of the solid body." Sensing something physical about the airflow, Prandtl postulated the existence of a thin "transition layer" in which viscous effects were in fact extremely significant. Two insights in particular led him to hypothesize what came to be known as the boundary later; they were, in Hanle's words, that "the fluid must be immobile at the surface of the body" and that "the fluid must follow classical hydrodynamic streamlines only a short distance from the surface" (Hanle, p. 45).

In laying out a plan for solving problems involving the transition layer and presenting the necessary governing equations, Prandtl made the consequences of his hypothesis clear: "According to the above, the treatment of a certain process of flow therefore reduces to two parts in mutual interaction: one has on the one hand a free fluid, which can be treated as inviscid according to the vortex principles of Helmholtz; on the other hand, the transition layers at the fixed boundaries, whose motion is governed by the free fluid, but which for their part give the free motion its characteristic features by the emission of vortex layers."

Three other points should be made about this paper (all of them echoing Hanle) before sending the reader off to discover Prandtl's astuteness up close and personally. First, Prandtl gave absolutely no thought at this point in 1904 to the relevance of his hypothesis to the science of flight. He did not even become slightly interested in any theory of flight until 1906. So, "rather than his interest in flight leading Prandtl to the discovery of the boundary layer, cause and effect were likely reversed" (Hanle, p. 47).

Second, as suggested earlier, Prandlt's paper made little impression on the 80 or so people attending the Third International Congress of Mathematicians at Heidelberg. This helps to explain why it took as long as it did for his boundary-layer hypothesis to capture any widespread attention. Finally, it is remarkable, given its venerated place in the history of aerodynamics, that the 1904 paper was only eight pages long. Nevertheless, in those few pages, Prandtl laid the foundation for the modern theory of aerodynamic drag. In doing so, he provided in a sort of time capsule an important building block for the airplane design revolution of the 1920s and 1930s.

Document 3-2, Ludwig Prandtl, "Motion of Fluids with Very Little Viscosity,"
NACA Technical Memorandum No. 452 *Washington, DC, 1928.*

TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NO. 452

MOTION OF FLUIDS WITH VERY LITTLE VISCOSITY

By L. Prandtl

From "Vier Abhandlungen zur Hydrodynamik and Aerodynamik"

Gottingen, 1927

Washington
March, 1928

National Advisory Committee For Aeronautics Technical Memorandum No. 452 Motion Of Fluids With Very Little Viscosity.*

By L. Prandtl.

In classic hydrodynamics the motion of nonviscous fluids is chiefly discussed. For the motion of viscous fluids, we have the differential equation whose evaluation has been well confirmed by physical observations. As for solutions of this differential equation, we have, aside from unidimensional problems like those given by Lord Rayleigh (Proceedings of the London Mathematical Society, 11 page 57 = Papers I page 474 ff.), only the ones in which the inertia of the fluid is disregarded or plays no important role. The bidimensional and tridimensional problems, taking viscosity and inertia into account, still await solution. This is probably due to the troublesome properties of the differential equation. In the "Vector Symbolics" of Gibbs, ** this reads

$$\rho((\partial/v)/(\partial/t) + v_0\,\Delta v) + \Delta\,(V + p) = k\Delta^2 v$$

in which v is the velocity; ρ, the density; V, a function of the power; p, pressure; k, viscosity constant. There is also the continuity equation

$$\text{div } v = 0$$

for incompressible fluids, which alone will be here considered.

* "Ueber Flussigkeitsbewegung bei sehr kleiner Reibung." This paper was read before the Third International Congress of Mathematicians at Heidelberg in 1904. From "Vier Abhandlungen zur Hydrodynamik und Aerodynamik," pp. 1-8, Gottingen, 1927.

** aob scalar product, a x b vector product, Δ Hamilton differentiator

$$(\Delta = i\,(\partial/\partial x) + j\,(\partial/\partial y) + k\,(\partial/\partial z)).$$

From the differential equation, it is easy to infer that, for sufficiently slow and also slowly changing motions, the factor ρ, in contrast with the other time, can be as small as desired, so that the effect of the inertia can here be disregarded with sufficient approximation. Conversely, with sufficiently rapid motion, the quadratic

term v o Δ v (change of velocity due to change of location) is large enough to let the viscosity effect appear quite subordinate. The latter almost always happens in cases of fluid motion occurring in technology. It is therefore logical simply to use here the equation for non-viscous fluids. It is known, however, that the solutions of this equation generally agree very poorly with experience. I will recall only the Dirichlet sphere, which, according to the theory, should move without friction.

I have now set myself the task to investigate systematically the laws of motion of a fluid whose viscosity is assumed to be very small. The viscosity is supposed to be so small that it can be disregarded wherever there are no great velocity differences nor accumulative effects. This plan has proved to be very fruitful, in that, on the one hand, it produces mathematical formulas, which enable a solution of the problems and, on the other hand, the agreement with observations promises to be very satisfactory. To mention one instance now: when, for example, in the steady motion around a sphere, there is a transition from the motion with viscosity to the limit of nonviscosity, then something quite different from the Dirichlet motion is produced. The latter is then only an initial condition, which is soon disturbed by the effect of an ever-so-small viscosity.

I will not take up the individual problems. The force on the unit area, due to the viscosity, is

$$K = k\,\Delta^2\,v$$

If the vortex is represented by w = ½ rot v, then K = −2 k rot w, according to a well-known vector analytical transformation, taking into consideration that div v = 0. From this it follows directly that, for w = 0, also K = 0, that is, that however great the viscosity, a vortexless flow is possible. If, however, this is not obtained in certain cases, it is due to the fact that turbulent fluid from the boundary is injected into the vortexless flow.

With a periodic or cyclic motion, the effect of viscosity, even when it is very small, can accumulate with time. For permanence, therefore, the work of K, that is, the line integral ∫ K o d s along every streamline with cyclic motions, must be zero for a full cycle.

$$\int K \circ d s = (V_2 + p_2) - (V_1 + p_1).$$

A general formula for the distribution of the vortex can be derived from this with the aid of the Helmholtz vortex laws for bidimensional motions which have a flow function ψ (Cf. "Encyklopadie der mathematischen Wissenschaften," Vol. IV, 14, 7).

With steady flow we obtain *

$$-(dw/d\psi) = \frac{(V_2 + p_2) - (V_1 + p_1) / P}{2\,k \int v \circ d s}$$

With closed streamlines this becomes zero. Hence we obtain the simple result that, within a region of closed streamlines, the vortex assumes a constant value. For axially symmetrical motions with the flow in meridian planes, the vortex for closed streamlines is proportional to the radius w = cr. This gives a force K = 4 kc in the direction of the axis.

The most important aspect of the problem is the behavior of the fluid on the surface of the solid body. Sufficient account can be taken of the physical phenomena in the boundary layer between the fluid and the solid body by assuming that the fluid adheres to the surface and that, therefore, the velocity is either zero or equal to the velocity of the body. If, however, the viscosity is very slight and the path of the flow along the surface is not too long, then the velocity will have its normal value in immediate proximity to the surface. In the thin transition layer, the great velocity differences will then produce noticeable effects in spite of the small viscosity constants.

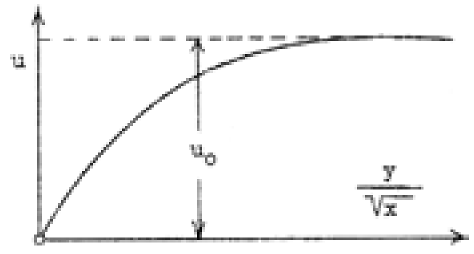


Fig.1.

This problem can be handled best by systematic omissions in the general differential equation. If k is taken as small in the second order, then the thickness of the transition layer will be small in the first order, like the normal components of the velocity. The lateral pressure differences can be disregarded, as likewise any curvature of the streamlines. The pressure distribution will be impressed on the transition layer by the free fluid.

For the problem which has thus far been discussed, we obtain in the steady condition (X-direction tangential, Y-direction normal, u and v the corresponding velocity components) the differential equation

$$\rho\ (u\ (\partial u/\partial x) + v\ (\partial u/\partial y) + dp/dx = k\ (\partial^2 u/\partial y^2)$$

and

$$\partial u/\partial x + \partial v/\partial y = 0.$$

* According to Helmholtz, the vortex of a particle is permanently proportional to its length in the direction of the vortex axis. Hence we have, with steady even flow on each streamline (ψ = const.), w constant, consequently w = fψ. Herewith

$$\int K\ o\ d\ s = 2k\int rot\ w\ o\ d\ s = 2k\ f'\ (\psi)\ \int rot\ \psi\ o\ ds = 2k\ f'\ (\psi)\ \int v\ o\ d\ s.$$

If, as usual, dp/dx is given throughout, as also the course of u for the initial cross section, then every numerical problem of this kind can be numerically solved, by obtaining the corresponding ∂u/∂x by squaring every u. Thus we can always make progress in the X-direction with the aid of one of the well-known approximation

methods (Cf. Kutta, "Zeitschrift fur Math. und Physik," Vol. 46, p. 435). One difficulty, however, consists in the various singularities developed on the solid surface. The simplest case of the conditions here considered is when the water flows along a flat thin plate. Here a reduction of the variables is possible and we can write u = f(y/√x). By the numerical solution of the resulting differential equation, we obtain for the drag the formula

$$R = 1.1 \ldots b\sqrt{(}\ k\ \rho\ l\ u_0^3$$

(b width, l length of plate, u_0 velocity of undisturbed water opposite plate). Figure 1 shows the course of u.

The most important practical result of these investigations is that, in certain cases, the flow separates from the surface at a point entirely determined by external conditions (Fig. 2). A fluid layer, which is set in rotation by the friction on the wall, is thus forced into the free fluid and, in accomplishing a complete transformation of the flow, plays the same role as the Helmholtz separation layers. A change in the viscosity constants k simply changes the thickness of the turbulent layer (proportional

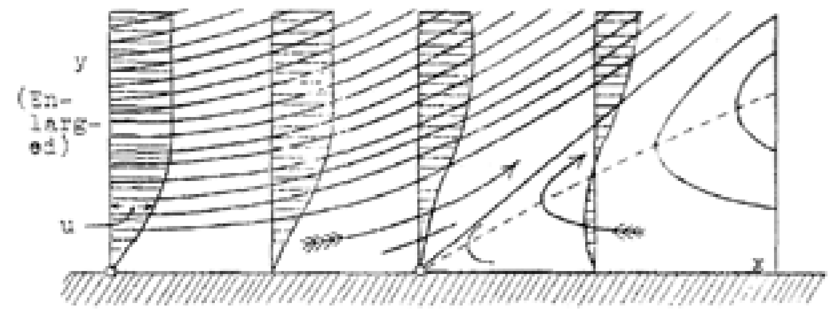


Fig.2

to the quantity √(kl/ρu)), everything else remaining unchanged. It is therefore possible to pass to the limit k = 0 and still retain the same flow figure.

As shown by closer consideration, the necessary condition for the separation of the flow is that there should be a pressure increase along the surface in the direction of the flow. The necessary magnitude of this pressure increase in definite cases can be determined only by the numerical evaluation of the problem which is yet to be undertaken. As a plausible reason for the separation of the flow, it may be stated that, with a pressure increase, the free fluid, its kinetic energy is partially converted into potential energy. The transition layers, however, have lost a large part of their kinetic energy and no longer possess enough energy to penetrate the region of higher pressure. They are therefore deflected laterally.

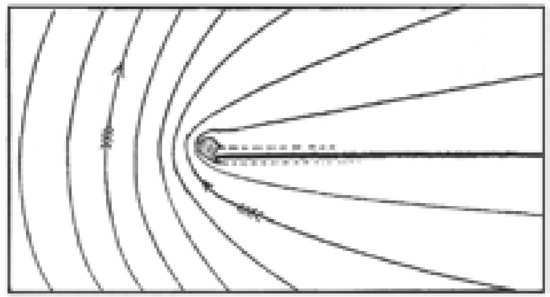


Fig.3

According to the preceding, the treatment of a given flow process is resolved into two components mutually related to one another. On the one hand, we have the free fluid, which can be treated as nonviscous according to the Helmholtz vortex laws, while, on the other hand, we have the transition layers on the solid boundaries, whose motion is determined by the free fluid, but which, in their turn, impart their characteristic impress to the free flow by the emission of turbulent layers.

I have attempted, in a few cases, to illustrate the process more clearly by diagrams of the streamlines, though no claim is made to quantitative accuracy. In so far as the flow is vortex-free, one can, in drawing, take advantage of the circumstance, that the streamlines form a quadratic system of curves with the lines of constant potential.

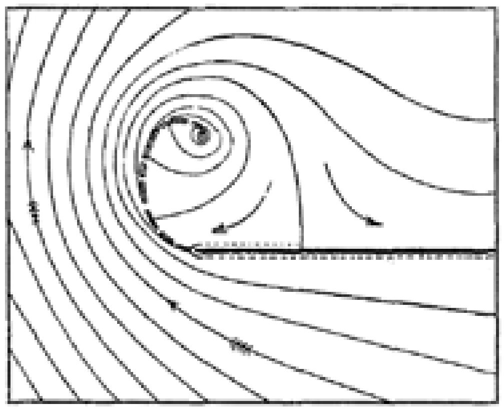


Fig.4

Figures 3-4 show, in two stages, the beginning of the flow around a wall projecting into the current. The vortex-free initial flow is rapidly transformed by a spiral separating layer. The vortex continually advances, leaving still water behind the finally stationary separating layer.

Figures 5-6 illustrate the analogous process with a cylinder. The fluid layers set in rotation by the friction are plainly indicated. Here also the separating layers extend into infinity. All these separating layers are labile. If a slight sinoidal disturbance is present, motions develop as shown in Figures 7-8. It is clearly seen how separate vortices are developed by the mutual interference of the flows. The vortex layer is rolled up inside these vortices, as shown in Figure 9. The lines of this figure are not streamlines, but such as were obtained by using a colored liquid.

I will now briefly describe experiments which I undertook for comparison with the theory. The experimental apparatus (Fig. 10) consists of a tank 1.5m (nearly 5 feet) long with an intermediate bottom. The water is set in motion by a paddle wheel and, after passing through the deflecting apparatus a and four sieves b, enters

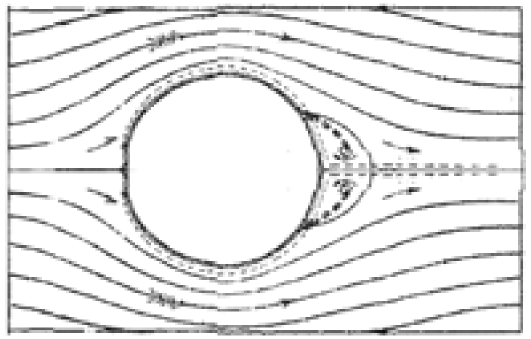


Fig.5

the upper channel comparatively free from vortices, the object to be tested being introduced at c. Fine scales of micaceous iron ore are suspended in the water. These scales indicate the nature of the flow, especially as regards the vortices, by the peculiarities of their reflection due to their orientation.

The accompanying photographs were obtained in this manner, the flow being from left to right. Nos. 1-4 show the flow past a wall projecting into the current. The separating or boundary layer, which passes off from the edge, is apparent. In No. 1 it is very small; in No. 2, concealed by strong disturbances; in No. 3, the vortex spreads over the whole picture; in No. 4, the permanent condition is shown. A disturbance is also evident above the wall. Since a higher pressure prevails in the corner, due to the obstruction of the water flow, even here the flow separates from the wall after awhile (Cf. Figs. 1-4). The various striae visible in the vortex-free portion of the flow (especially in Nos. 1-2) are due to the fact that, at the inception of the flow, the liquid was not entirely quiet. Nos. 5-6 show the flow around a curved obstacle or, from another viewpoint, through a continuously narrowing and then widening channel. No. 5 was taken shortly after the inception of the flow. One boundary layer has developed into a spiral, while the other has elongated and broken up into very regular vortices. On the convex side, near the right end, the beginning of the separation can be seen. No. 6 shows the permanent condition in which the flow begins to separate about at the narrowest cross section.

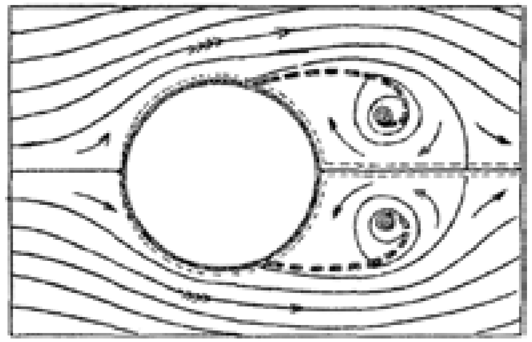


Fig.6

Nos. 7-10 show the flow around a cylindrical obstacle. No. 7 shows the beginning of the separation; Nos. 8-9, subsequent stages. Between the two vortices there is a line of water which belonged to the transition layer before the beginning of the separation. No. 10 shows the permanent condition. The wake of turbulent water behind the cylinder swings back and forth, whence the momentary unsymmetrical appearance. The cylinder has a slot along one of its generatrices. If this is placed

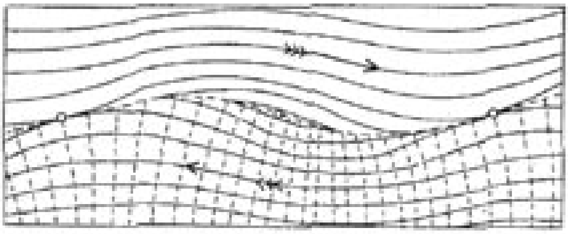


Fig.7

as shown in Nos. 11-12 and water is drawn out through a tube, the transition layer on one side can be intercepted. When this is missing, its effect, the separation, is eliminated. In No. 11, which corresponds, in point of time, to No. 9, there is seen only one vortex and the line. In No. 12 (permanent condition), the flow closely follows the surface of the cylinder till it reaches the slot, although only very little water enters the cylinder. A turbulent layer has developed instead on the flat wall of the tank (its first indication having appeared in No. 11). Since the velocity must diminish in the widening cross section and the pressure consequently increases ($\frac{1}{2} \rho v^2 + V + p$ = constant on every streamline), we have the conditions for the separation of the flow from the wall, so that even this striking phenomenon is explained by the theory presented.

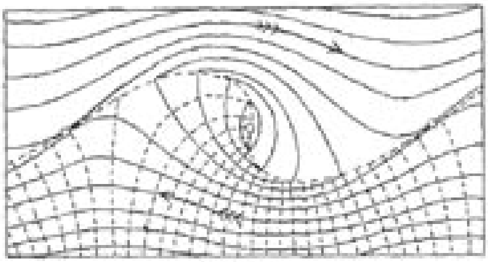


Fig.8

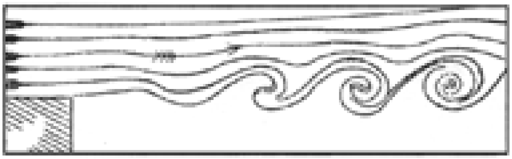


Fig.9

Translation by Dwight M. Miner, National Advisory Committee for Aeronautics.

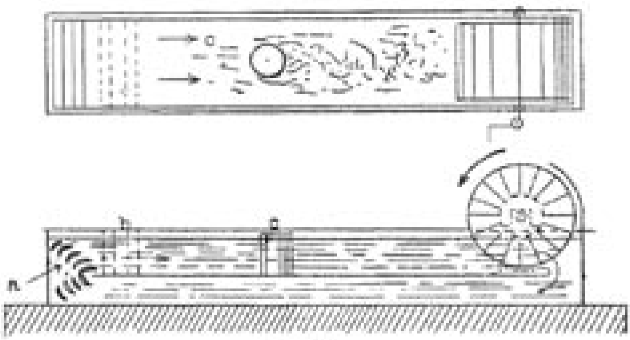


Fig.10

Document 3-3(a-b)

(a) Alexander Klemin, Chapter X: "Resistance of Various Airplane Parts," in *Aeronautical Engineering and Airplane Design* (New York: Gardner-Moffat, 1918), pp. 61-4.

(b) Grover C. Loening, *Military Aeroplanes: An Explanatory Consideration of their Characteristics, Performances, Construction, Maintenance, and Operation* (Boston: W.S. Best, 1918).

This pair of documents reproduces excerpts from two of the earliest aeronautical textbooks to appear in the United States, both in 1918. The author of the first text, Alexander Klemin, was a graduate of Massachusetts Institute of Technology's (MIT) aeronautical engineering program (he actually succeeded Jerome Hunsaker as the instructor in 1913) and the head of the U.S. Army Air Service's Aeronautical Research Department at McCook Field in Dayton, Ohio. The author of the second, Grover Loening (1888–1976), was an early aeronautical engineer and aviation manufacturer in the United States. He received an M.A. in aeronautics from Columbia in 1910, worked for Orville Wright, and served as chief aeronautical engineer of the Aviation Section of the Army Signal Corps at San Diego in 1914. Loening's book first appeared in 1915, but it was not fully recognized until three years later when he had the benefit of evaluating the rapid pace of technological development that took place during World War I. In 1917, he formed his own company, the Loening Aeronautical Engineering Corporation, and designed a strut-braced monoplane for the army and experimented with amphibious aircraft. Loening won the 1921 Collier for his Air Yacht, a five-seat monoplane boat, which evolved into the Loening Amphibian, said to be the first practical airplane of that type.

As might be expected, Klemin's text was the more theoretical of the two, indicative of his advanced education in aeronautics at MIT. Loening, on the other hand, wanted a book that would more practically benefit "aviators and students" and that featured the lessons and experiences of military aircraft design, manufacturing, and operation. In important ways, the two texts represent what in the history of American engineering education would come to be known as the "school culture" (Klemin) versus the "shop culture" (Loening). Shop culture, generally speaking, promoted a technical approach that could be applied directly to industrial work. In contrast, school culture placed more emphasis on basic studies in mathematics and science and on original research. To this day, some degree or another of tension between shop culture and school culture exists within most engineering communities and has shaped the personality of American engineering schools and professional organizations. Both approaches bear their type of fruit, although without question, the school culture approach has provided a much more solid basis for long-term fundamental development in aeronautics and most other highly technical fields.

One aspect that the two textbooks had in common was that they both reflected a state-of-the-art that had been largely driven by European developments in the years leading up to 1918. Much of the information provided in the texts was based on knowledge and experience gained during the war in Great Britain at its National Physical Laboratory in the 1910s, in France at Gustav Eiffel's laboratory, or gleaned from Germany's many aeronautical advances.

Document 3-3(a), Alexander Klemin, Chapter X: "Resistance of Various Airplane Parts".

Chapter X

RESISTANCE OF VARIOUS AIRPLANE PARTS

One of the most difficult problems in aeronautical design is the prediction of the total resistance of the machine. The wind tunnel test is a good check, but it is most important to assign resistance values to various parts and to tabulate them prior even to the construction of the model. In this chapter have been collected as far as possible all the data available for bodies, radiators, fittings, wheels, cables and wires and certain other miscellaneous objects.

AIRPLANE BODIES FROM THE AERODYNAMICAL POINT OF VIEW

If airplane bodies were designed from a purely aerodynamical point of view, they would follow dirigible practice and be of streamline form. There are, however, a number of structural requirements which have to be met, which preclude the employment of such forms. The body must enclose the power plant and the personnel, the length must be long enough to place the rudders well clear of the wash of the planes, the shape of the body must conform to structural requirements such as the use of four longitudinal girders, or a triangular form which has been found to be advantageous in steel construction.

No wind tunnel tests on bodies alone can determine exactly their resistance on an airplane, because the question is complicated by the position and form of the motor and the disposition of the tail surfaces. The propeller in a tractor machine also introduces three possible variations in drag coefficients: (1) when the propeller is pulling and there is a slip stream of velocity greater than the airplane velocity, (2) the resistance on a glide when the engine is shut down, but the propeller is revolving as an air motor, (3) when the propeller is not, revolving at all, the engine being held.

TRACTOR BODIES

In Table 1 is given a comparative table of resistance coefficients for area in normal presentation of a number of airplane bodies, and in Fig. 1 are shown sketches of the same bodies. Exact comparisons are impossible because some of the bodies are made for two men and others for one. Still quantitative conclusions can be drawn. The N. P. L. Model 5, more symmetrical than the B. E. 8, shows a distinct improvement over the latter which is somewhat discounted by the fact that the B. E. 8 carries two men unshielded. The B. F. 36, all almost perfect dirigible form, is markedly better than either of these two bodies.

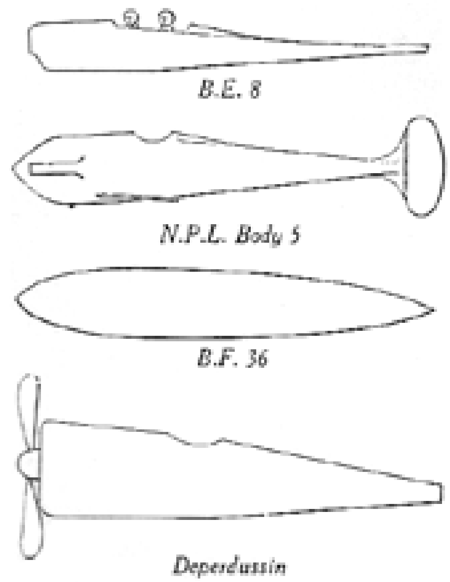


Fig. 1. Tractor Bodies.

The resistance of the body in an airplane is apparently a small quantity, but the figures given below do not represent the resistance of a body in full flight where it is increased by 40 percent, the propeller slip stream increasing the relative speed of the air by some 25 percent. Also, it must be remembered that with a best glide of 1 in 8, a 5-pound increase in resistance is practically equivalent to an added weight of 40 pounds. A blunt, square form of body such as is often seen in American practice may increase resistance even more, and better aerodynamical design of bodies seems a feature worth considering.

COMPARATIVE TABLE FOR TRACTOR BODIES
PUSHER BODIES

A pusher body such as the Farman 3, illustrated in Fig. 2, gives a not much larger resistance than the tractor bodies, but when the head resistance of the uncovered outriggers is taken into account, it will probably be found that, pusher arrangements offer considerably more resistance than tractor bodies.

RADIATOR RESISTANCE

The only values available for this are the results of some tests at the Massachusetts Institute of Technology. These were carried out on portions of a radiator of the honeycomb type having sixteen 1/4-inch cells to each square inch of the surface normal to the wind. The tests were repeated on two sizes of radiator section, one 0.25 square feet and the other 0.111 square feet, and at various speeds. No important variation in the resistance coefficient was apparent and the average coefficient

TABLE 1.

COMPARATIVE TABLE FOR TRACTOR BODIES.

Designation.	Coefficient of resistance, K where $R = KAV^2$ (A = area in normal presentation in square feet V = miles per hour; R = drag in lbs.)	Length / maximum depth.	Resistance for a body of 8 square feet normal presentation at a speed of 60 m. p. h.
British B. E. 3 (with 2 men)..	.000720	7.35	20.7
N. P. L. Model 5..............	.000420(approx.)	5.50	12.0
British B. F. 36 (dirigible form)	.000258	6.75	7.4
Deperdussin (enclosing rotary motor)	.001215	5.6	35.1

TABLE 2.

COMPARATIVE TABLE FOR PUSHER BODIES.

Designation.	Coefficient of resistance K where $R = KAV^2$ (A = maximum area in normal presentation in square feet; V = miles per hour; R = drag in lbs.)	Length.	Resistance for a body of 8 square feet normal presentation, at a speed of 60 m. p. h.
N. P. L. Model Body 3 (fairly symmetrical section)........	.000271	3	7.8
Farman 3 (body in form of a boat, two men unshielded)..	.000845	3.2	24.4

may be used for practical calculations. This has a value K_x = .000814 pounds per square foot of projected area per foot per second or .00173 pounds per square foot of projected area per mile per hour.

RESISTANCE OF FITTINGS

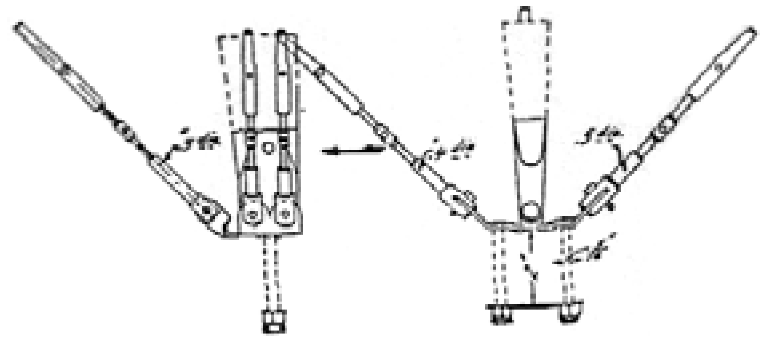
Fittings are so variable in design that it is impossible to give definite figures to meet every type of wing strut fitting. Tests were conducted at the Massachusetts Institute of Technology on the fittings of which dimension drawings are given in Fig. 3; the coefficients of resistance are $R = .00030\ V^2$ and $R = .00040\ V^2$ for the two types which at 60 miles an hour gives 1.07 and 1.44 respectively. Such figures will be at least approximately correct in design.

RESISTANCE OF AIRPLANE WHEELS

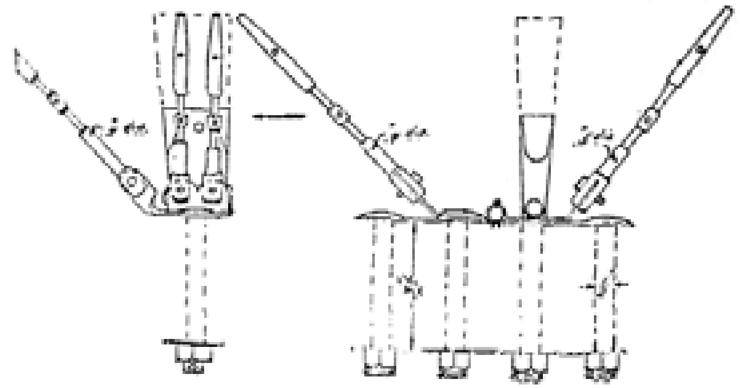
For a standard airplane wheel of about 26 X 4 inches in size, the drag found by the N. P. L. is about 1.7 pounds at 60 miles per hour. This again is sufficiently accurate for practical purposes. Eiffel has experimented with a number of wheels and has shown that no great variation need be expected front the above value. An important result from

FIG. 2. A PUSHER BODY.

the French experiments was the fact that an uncovered wheel had a resistance of 50 percent more than a covered wheel of similar dimensions. This justifies the standard practice of covering the wheel in.



Outer Panel. $R = .00030\ V^2$.



Inner Panel with Wing Hinge. $R = .00040\ V^2$.

FIG. 3. FITTINGS EMPLOYED IN TESTS FOR HEAD RESISTANCE AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY

CLARK STRUT FITTINGS. Resistance includes fitting, five turnbuckles and nuts but not dotted portions as indicated on drawings. Resistance in pounds; Velocity in miles per hour.

RESISTANCE OF WIRES AND METHODS OF PLOTTING

A certain complication is necessary in the methods of plotting the results for the resistance of cables and wires. As we have seen from the diagram of Fig. 19, in Chapter 3, of the Course, the resistance of a wire or any cylindrical body is partly due to turbulence, partly due to skin friction. It cannot therefore be represented by such a simple expression as

$$R = KLD\ V^2\ F\ (VD).$$

We do not know what function *F (VD)* is exactly, nor how it varies with size and scale except from experimental results, and comparisons of resistance varying as $LD\ V^2$ can only be made between two cables if *VD* is a constant. If *K* is taken as a function of *VD*, the *R* may be written $R = KLD\ V^2$ but then *K* must be plotted against *VD* in analyzing experimental results. This is the only rational and scientific method.

An empirical method, however, is sometimes employed with fair accuracy of plotting the resistance of a wire whose length is equal to its diameter against V^2D^2. This has the advantage that the graph approximates very closely to a straight line, the slope of which is equal to *K*, thus giving an easy means of determining a mean value of *K*.

RESISTANCE OF STATIONARY SMOOTH WIRES

The most accurate researches have been carried out at the N. P. L. and their results are, shown in Fig. 4 plotted against *VD*. In the expression $K = \frac{R}{LDV^2}$, *R* is in pounds, *L* in feet, *D* in feet, and *V* in miles per hour. But in the abscissae, values of *VD*, *V'* is in feet per second, and *D* is feet, so as to give the correct scale and speed relationships which must be in the same units.

The accuracy of the curve at its lowest portion is doubtful, since the flow is apparently just changing its nature at that point, and {AQ3} successive observations under the same conditions may give quite different results. On modern machines of fairly high speed, however, the valves of *VD* nearly always exceed 0.35 and consequently do not lie on this section of the curve.

Similar tests were made by Mr. Thurston and M. Eiffel, and the values obtained by the former are plotted in the same figure.Thurston's experiments, however, were very much earlier, and Eiffel's covered a less range and were performed with less sensitive apparatus, so it is advisable to use the N. P. L. results.

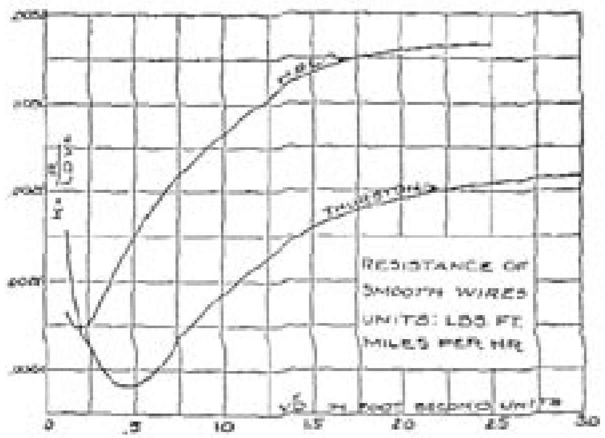


Fig. 4. Resistance of Smooth Wires Per Foot Run.

RESISTANCE OF VIBRATING WIRES

When the question of resistance first began to arouse interest, it was popularly supposed that a vibrating wire had much greater resistance than a stationary one. This, however, is not the case. Research on this point at the N.P.L. failed to disclose any difference whatever, although the balance would have shown deviations as small as 3 percent, even for the extremely small forces under consideration. Mr. Thurston, on the other hand, concluded that vibration at the rate of 15 per second increased the resistance by about 5 percent for small wires and by a somewhat smaller percentage for those of larger diameter. In any case, the effect is unimportant.

RESISTANCE OF STRANDED WIRES

The air resistance of stranded wires was also investigated at the N.P.L., and was found to be about 20 percent greater than that for a smooth wire of the same diameter. This is only approximate, as the coefficient depends on the number of strands, type of lay, etc. It is also impossible to plot the values of *K* against *VD* for wire rope, as the *VD* law holds good only for objects which possess strict geometrical similarity, a thing which stranded wires of different sizes never do.

RESISTANCE OF WIRES PLACED BEHIND ONE ANOTHER

The manner in which resistance is affected by the close juxtaposition of two wires, one behind the other, is a point of great interest. Here, too, it is at present necessary to rely on Mr. Thurston, although we hope to be able soon to present the results of some more extensive and accurate tests on this matter.

Fig. 5 gives, in terms of the resistance of a single bar, the resistance of two bars or wires separated by various distances. It will be seen that two wires placed one behind the other and spaced from 5 to 9 diameters apart, as is usual in double-wiring a biplane

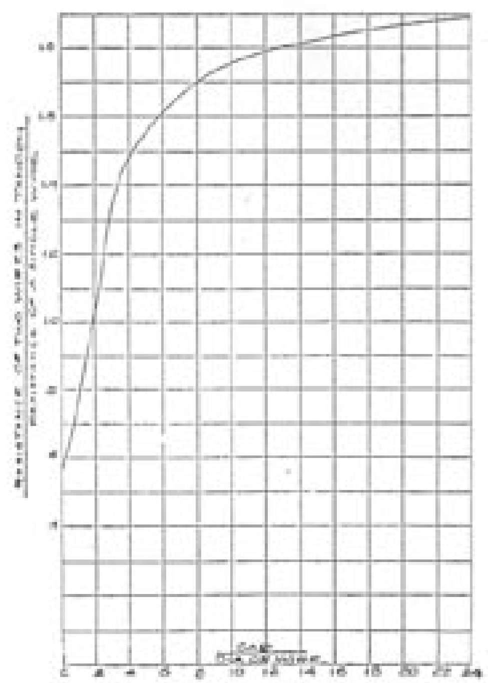


Fig. 5. Resistance of Wires in Tandem as a Ratio of the Resistance of a Single Wire.

cellule, have from 60 percent to 75 percent more resistance than a single wire. The force is, however, materially less than for the two wires placed side by side.

Eiffel has experimented on the resistance of inclined wires. As would be expected the resistance of a wire progressively decreases as its angle with the wind diminishes. Table 3 gives correcting values. This table has been omitted by the editor.

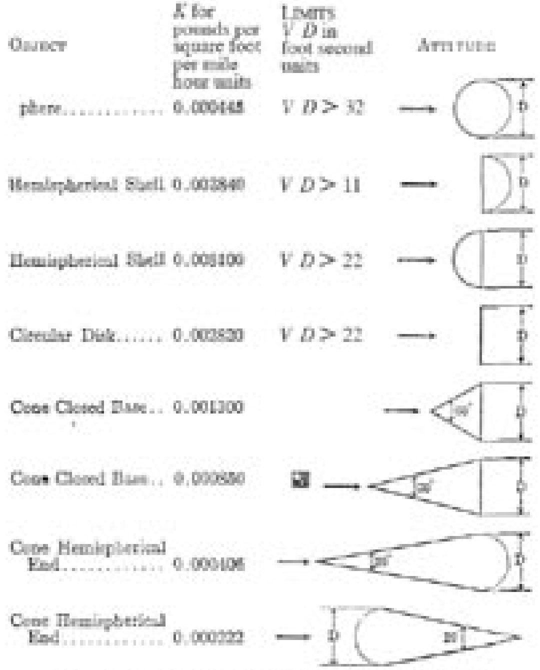


Fig. 6. Resistance of Miscellaneous Objects (After Eiffel)

SUGGESTIONS FOR STREAM-LINING WIRES

It has been suggested from time to time that wire resistance should be decreased by "stream-lining" or adding a triangular portion in back of the wire. From experiments by Ogilivie, however, it appears that a section made up of a semi-circle a triangle has a decidedly high resistance, and the gain from such a procedure wound be small.

Wires placed behind one another have also been covered in. The British Royal Aircraft Factory produces a very heavy R.A.F. wire in use on big machines which is stream-line in form. But the direction in which progress manifests itself at present is in the elimination of wires by certain modern trussing such as used in the recent Curtiss biplane.

RESISTANCE OF MISCELLANEOUS OBJECTS

This resistance of certain miscellaneous objects as deduced by Eiffel may sometimes be useful. The values for such objects within certain limits are illustrated in Fig. 6.

References for Part I, Chapter 10
AIRPLANE BODIES
British Report 1911-1912, page 52.
British Report 1912-1913, page 116.
"La Resistance de l'Air et l'Aviation," Eiffel, 1914, page 250.

AIRPLANE WHEELS
British Report 1912-1913, page 122.
"La Resistance de l'Air et l'Aviation," Eiffel, page 250.
WIRE AND CABLES
"Aerodynamic Resistance of Struts, Bars and Wires," by A. P. Thurston, *Aeronautical Journal*, April and July, 1912.
British Report 1910-1911.
"La Resistance de l'Air et l'Aviation," Eiffel, page 97.
"New Mechanical Engineers' Handbook," Section on Aeronautics, by J. C. Hunsaker.

Document 3-3(b), Grover C. Loening, Military Aeroplanes: An Explanatory Consideration of their Characteristics, Performances, Construction, Maintenance, and Operation *(Boston: W.S. Best, 1918).*

CHARACTERISTICS OF AIRFLOW.

Having defined air, the manner in which it flows may be considered. Air either flows smoothly past an object in **streamlines**—continuous filaments—or it breaks up into swirls and eddies, due to too abrupt a change in flow. The accompanying photographs of airflow illustrate this.

It is apparent that a spindle or fusiform shape, gently dividing the air at the front, and gradually permitting the filaments to close together at the rear, will give a smooth flow, which amounts to the same thing as a very low resistance. It is also evident that a flat surface creates very great disturbance, and consequently high resistance.

The curve of the streamlines, necessary to prevent disrupting them, may be computed for any speed, by applying fluid dynamics. But it must be kept in mind that a form of this kind gives its low resistance, only at one particular speed, since the path of flow is affected by the speed. It is unnecessary here to take up the determinations of these forms. If the streamlines flow smoothly past an object, and close up again without eddies, it follows that the only resistance experienced is frictional. There is hardly any shape, however, which does not create small eddy resistance.

Methods of measuring the resistance of the air that have been widely used, are the following:

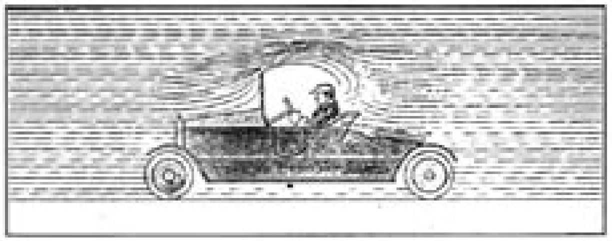
1. Dropping surfaces from a height and measuring time of drop and pressure, used by Newton, and Eiffel in his earliest experiments.

2. The whirling arm, used by Langley, and consisting of whirling the surface at the end of a large arm around a circle of large diameter and recording the resistance automatically.

3. The moving carriage, an automobile, trolley or car, as used in the experiments of the Duc de Guiche, Canovetti, and the Zossen Electric Railway tests.

4. By blowing or drawing air through a tunnel in which the object or a model of the object is placed. This method is the most modern and convenient, and permits of a uniformity of the air current, which cannot be obtained as easily in the open.

In wind tunnels the best practice is to draw the air in, through screens and channels that straighten it out, past the experimental chamber, and thence to the fan. Practically all the great Aerodynamic Laboratories use the wind tunnel method of experiment. The prominent ones are: the Eiffel laboratory in Paris, the National Physical Laboratory in England, and the tunnel at the Washington Navy Yard. The speed of the wind in the Eiffel laboratory can be brought up to almost 90 miles per hour (40 meters per second), and its size permits of testing many objects, such as struts, to full size and complete models of aeroplanes to one-tenth full size. Such a magnitude permits of exceedingly valuable determinations, and the work of the laboratories is daily being applied with entire success to full-sized aeroplanes, although the higher speeds of aeroplanes require considerable correction of wind tunnel results. This is particularly true in the measurement of pressures on wing sections at low angles.



THE AIR FLOW OVER A WINDSHIELD VISUALIZED

It must be borne in mind, therefore, that the air in a tunnel is confined and that all tunnel results are not perfectly adaptable to machines unless suitable corrections are applied.

Combining the results of all the laboratories, we may draw some general conclusions with regard to air resistance, as follows:

1. The resistance of an object in an airstream is proportional to the square of the velocity of the air.

In other words, if the velocity is doubled, it follows that the resistance will be increased four times, or if velocity is five times as great, the force on the same object would be twenty-five times as great. **This is merely an experimental fact.**

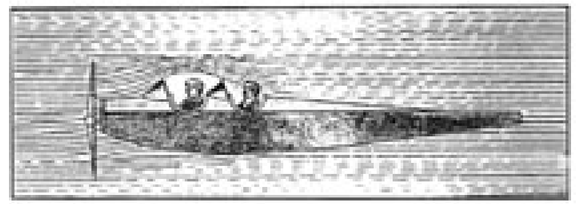
There are many ways of determining the manner in which the air flows past an object, such as noting the direction in which light silk threads are blown, or introducing smoke or particles into the air and photographing it. Ammonium Chloride is a very convenient smoke.

IMPORTANCE OF VISUALIZING THE AIR.

It is of great value in aeroplane work, to become accustomed to visualize the streamline flow of air, and ability to "see the air" often solves many problems of stability and reduction in resistance, without any recourse to mathematics or measurements. Besides this, there is offered in the study of airflow by photography, a field of investigation of great promise and absorbing interest.

It is a common experience that in a wind, at the front of a flat surface, there is a dead region of air, where no wind is felt. Photographs show this air cushion clearly.

In stability discussions, effect of following planes, interference and propeller stream action, priceless secrets would be revealed if the air could be followed in its every movement.



The air flow over the front wind shield throws the air into the rear man's face – a feature that could have been corrected, if the designer could have "seen the air."

DETERMINATION OF AIR RESISTANCE.

The nature of the action of air on objects has been considered, but we must know in addition with what force in pounds **P**, the air pushes on an object when it passes it at velocity **V**. We cannot refer to theory for this, satisfactorily, so we must obtain actual measurements of the air resistances on various objects.

2. Air Resistance Increases as the Object's Size Increases.

This experimental fact is also subject to modification, since, as the size of surface increases, the pressures are somewhat greater in proportion. But we can disregard this also without serious error.

3. The Air Density Influences the Air Resistance.

It has already been pointed out that heavy air (low altitude) has more resistance than light air (high altitude).

4. The Shape of an Object Controls its Air Resistance.

The beautiful streamline photographs have already discovered this for us, and show how easily and with what small resistance the air slides by a streamline shape.

Let us combine all this into a compact sentence called a formula, where **P** = the resistance in lbs., **S** = the area in sq. ft., **V** = the velocity through the air in miles per hour, **d** = the density of the air in lbs. per cubic foot, and finally describe the shape of the object in order to ascertain whether it is clumsy or streamline, by a numerical multiplier, which we will call **k**, and which we will define as a **"shape coefficient."**

In others words, $\mathbf{P = k.\ d.}\ S\ V^2$.

But to simplify matters, since all of these shape coefficients for various shapes have had to be measured, and mostly at sea level, we can call **d** also a numerical factor, and combine it with **k**, so that **kd=K**, which is a number, always applicable to that particular shape, and represents **the coefficient at sea level**, in which we can use, for any size body of that shape, at any speed, in order to obtain **the resistance at sea level**. For many different shapes, all we need, therefore, is for someone to measure and tell us what the values of **K** are for different shapes. Just as a grocer will tell you that a piece of cheese weighs half a pound because he measures it, so has M. Eiffel told the aviation world that **K** for a wire is .0026.

Therefore $\mathbf{P = KSV^2}$

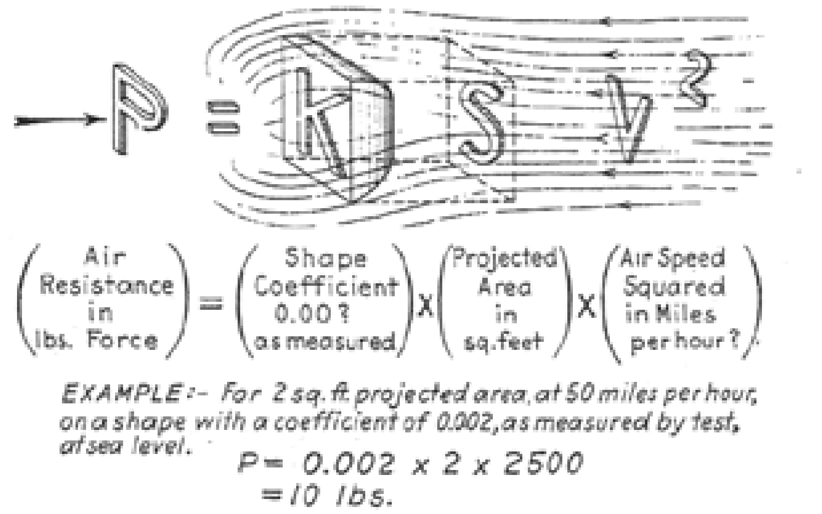
This formula applies to all air forces, whether they are resistances, as we are considering here, or lifting pressures as we will consider later—with this reservation, that the shape coefficient is either for resistance, or for lifting power, and one must always be careful to determine which it was meant to be measured for.

We may now proceed with the interesting study of what values of **K** have been found for various shapes, and not only will those be described by diagrams, but frequent numerical examples are given, of how to apply the data to determine values of air resistances. A study of this subject will give the student a most valuable insight into this branch of the science, and an appreciation of what shapes are "good" and "bad."

DEFINITIONS.

In Aerodynamical studies it has become customary in defining objects to use unfamiliar terms.

Aspect Ratio — is a term used to define the shape of a surface, and is the long span of the surface across the wind divided by the width.



Here is a picture of the fundamental and only necessary formula for practical aeroplane knowledge.

Fineness Ratio — is a term used to define the general shape of bodies, and is obtained by dividing the fore and aft length of the body by the greatest width across the wind.

Master Diameter — is the greatest width of a body across the wind.

Fairing — is used to denote the additional "tail" or filler used to make a poorly shaped body more streamline in form, thereby reducing its resistance.

Diametral plane —is the plane, passed through a body, facing the wind perpendicularly, and cutting through at the master-diameter.

Normal plane — is another expression for diametral plane, and merely refers to the maximum cross-sectional projection of the body. It also refers to a flat surface held normal (perpendicular) to the air current.

Equivalent Normal Plane — is the size of normal flat surface, that would give the same resistance as does the body referred to.

Flat Surfaces,
Normal to the Airstream.

SQUARE PLANES:

In square planes, normal to the air, the value of **K** is **.003** for surfaces up to two or three feet square, and **.0033** for very large surfaces like the sides of buildings.

It may be stated, therefore, for aeroplane usage, that **P**, the air resistance in lbs., of a square surface, **S** sq. ft., in area, at a velocity **V** miles per hour, is

$$P = .003\ S\ V^2$$

Thus, for a surface 2 feet square, at 70 miles an hour:

$$P = .003 \text{ X } 4 \text{ X } 4900$$
$$P = 58.8 \text{ pounds}$$

RECTANGLES:

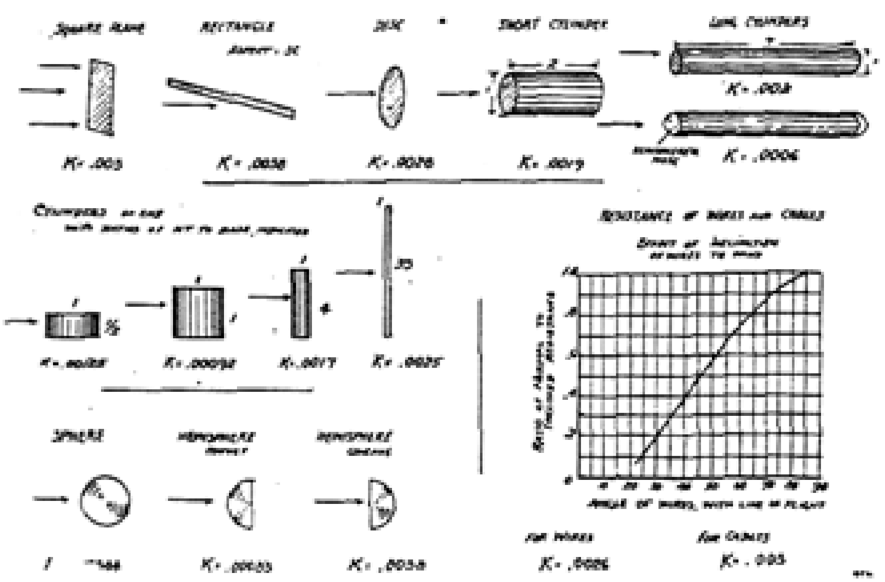
This aspect ratio of a square is one. Rectangles have aspect ratios above one, when presented normally to the air.

Up to an aspect of 5 or 6, **K** remains about **.003**.

An increase in the value of **K** is found for rectangles as the aspect ratio increases.

When the aspect ratio of the rectangles increases to 15, **K** becomes **.0035** and on further increasing the aspect ratio to 30, **K = .0038**.

A flat rectangle, perpendicular to the air current, with its dimension across the current, thirty times as large as its width, might be met with in rods, temporary struts, etc., and it is interesting to note how high the resistance would be.



The shape coefficients of various surfaces and bodies.

DISCS:

The shape of flat surfaces also affects their air resistance. Passing from a square plane to a round disc, reduces **K** to **.0028**, so that the air resistance of a disc 2 feet in diameter, at 60 miles per hour, is

$$P = KSV^2 = .0028 \text{ X } .7854 \text{ X } 4 \text{ X } 3600$$
$$P = 32 \text{ pounds}$$

In general rounded edges may be expected to reduce **K**, for flat surfaces.

Discs or flat rectangles, placed one in front of the other, interfere with each other and exhibit a most important phenomenon, shown on page 52.

CYLINDERS:

Passing from the disc to the cylinder, with the circular base facing the wind, the resistance is found to be less as the length of cylinder is increased, until the length becomes greater than 5 diameters, when the resistance is found to increase again. Some values of **K** are given on the chart on page 48.

Wires and cables are merely long cylinders. Extensive experiments have been conducted on them, and values of **K** found. For smooth wires **K** = **.0026**, whereas cables are found to have considerably higher resistance with **K** = **.003**.

Thus, a machine having 200 feet of 1/8 inch cable, giving a projected area of 200/96 = 2.08 sq. ft., will have an air resistance due to the cables at 80 miles an hour of

$$P = .003 \text{ X } 2.08 \text{ X } 6400$$
$$= 40 \text{ lbs.}$$

This high value immediately suggests the advisability of reduction of cable resistances. In double cables, it would prove beneficial to tape them together, so as to streamline each other. A graph is given showing the reduction in resistance due to inclining the wires i.e., staggered planes, on page 48.

SPHERES:

The resistance of the air on spheres presents a study of interest. The sphere is the simplest geometrical form, and, as a basic one, it should long ago have served as the unit form for air resistance. Lack of agreement in the experimental results of different laboratories was only cleared up when Eiffel discovered that an increase of speed of the air above 20 miles per hour caused a change of flow, due to the flattening out of vortices back of the sphere, which reduced the resistance considerably. And that above this speed, the nature of the air resistance remained constant. **K = .00044**, for a sphere, at speeds above 20 miles per hour, whereas at very low speeds **K** becomes **.001**. In having a smoother flow at the higher speeds, less lbs. of air are put in motion, which means that the resistance is less. This action of air, in tending to smoother flow with speed increase, is important to bear in mind.

STREAMLINE SHAPES:

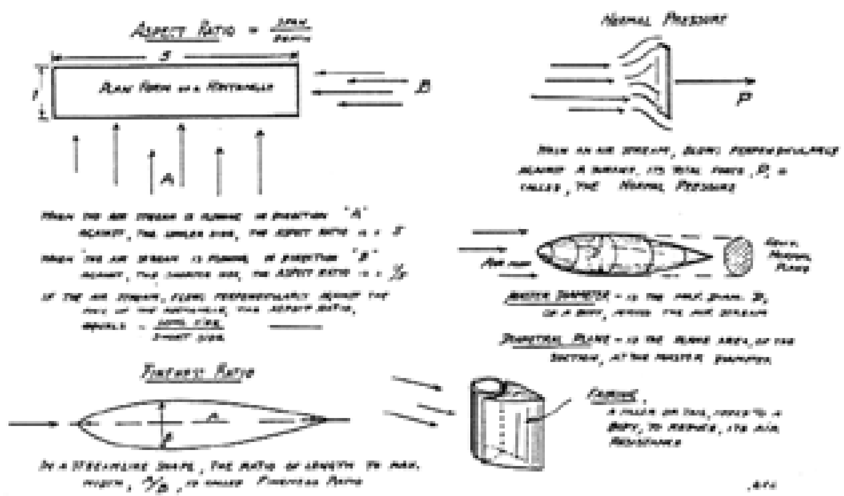
In this class may be included bodies of fusi-form or streamline form, shaped for least resistance. Their application to the design of tanks, fuselages, nacelles, hoods, etc., is of fundamental importance.

In a most interesting set of experiments, conducted by M. Eiffel, on streamline shapes, illustrated in the diagrams and chart on p. 52, the bodies consist of a nose, a cylindrical central portion, and a tail.

The results of the experiments show that:

1. The blunter the nose, the greater the resistance.
2. The shorter the central cylindrical portion is, for the same nose and tail, the lower the resistance.
3. The effect of shortening up the tail is not very great, although slightly increasing the resistance.

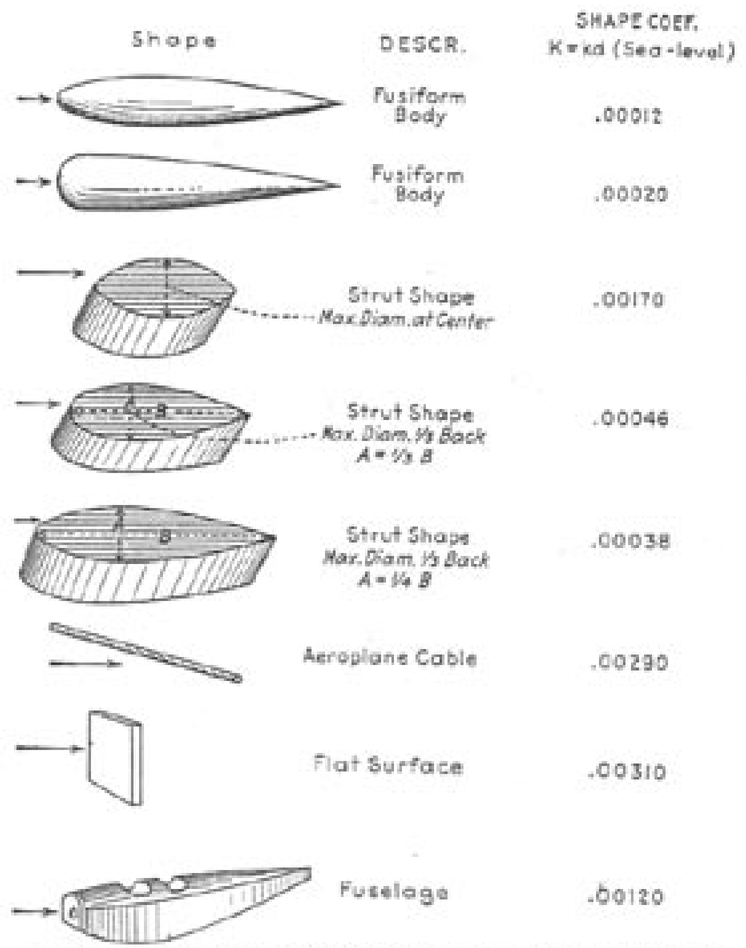
In each case, however, measurements made at speeds up to 90 miles an hour



showed that the resistance does not vary as V^2, the value of **K** becoming constantly less with speed increase. This is a very significant determination, and may be explained on the ground that, in bodies of this kind, the major part of the resistance at high speeds is frictional and therefore increases at much less than V^2. In addition the effect of velocity increase is to flatten out the flow and suppress eddies.

The values of K for these bodies are given.

The Goettingen Laboratory conducted extensive experiments on the best shapes



VALUES OF SHAPE COEFFICIENTS FOR SEVERAL SHAPES

for dirigible balloons which it is important to consider. The models tested measured 3.75 feet long and .62 feet in diameter, giving a fineness ratio of 6. The shapes in their order of least resistance and values of **K** for 25 m.p.h. are given. At higher speeds, still lower **Ks** would be expected.

The form No. 1, having the least resistance, is, perhaps, the best form that has ever been tested in a laboratory, and at high speeds would give a resistance about 1/25th of the normal pressure on its diametral plane. It is the form used in the Parseval non-rigid dirigibles.

It is interesting to note in studying low resistance bodies, how closely they resemble the shapes of fishes, and of birds, measurements of a fast swimming fish showing an almost exact resemblance to this Parseval shape.

As a general rule, the best streamline body is the one having a fineness ratio of 6 and with the master diameter about 40% back of the nose, both nose and tail being fairly well pointed.

STRUTS:

The application of fineness ratios, and shapes of least resistance, to improvement in the form of struts, has in many instances tremendously improved the performance of aeroplanes.

In addition to the form for least resistance, however, the weight of the struts and their strength are factors that must be considered in choosing the best shapes. We will confine ourselves here, however, to a study of the resistance of various shapes.

A group of strut sections are given and **K** for each one. It is to be noted that the effect of yawing is greatly to increase these resistances by presenting the strut sidewise to the air, and it will be necessary later to consider the amount of this increase.

Inclining the strut to the vertical, as in staggered planes, has the effect of increasing the length of section in the airstream, and, consequently, the resistance does not decrease for streamline shapes, while for blunter shapes, inclination reduces the resistance considerably.

In struts, as in bodies, an increase of velocity is accomplished by a reduction in the value of **K**, that is more noticeable the greater the fineness ratio, i.e., the longer the section of the strut. This is again due, probably, to the preponderance of friction in the total resistance.

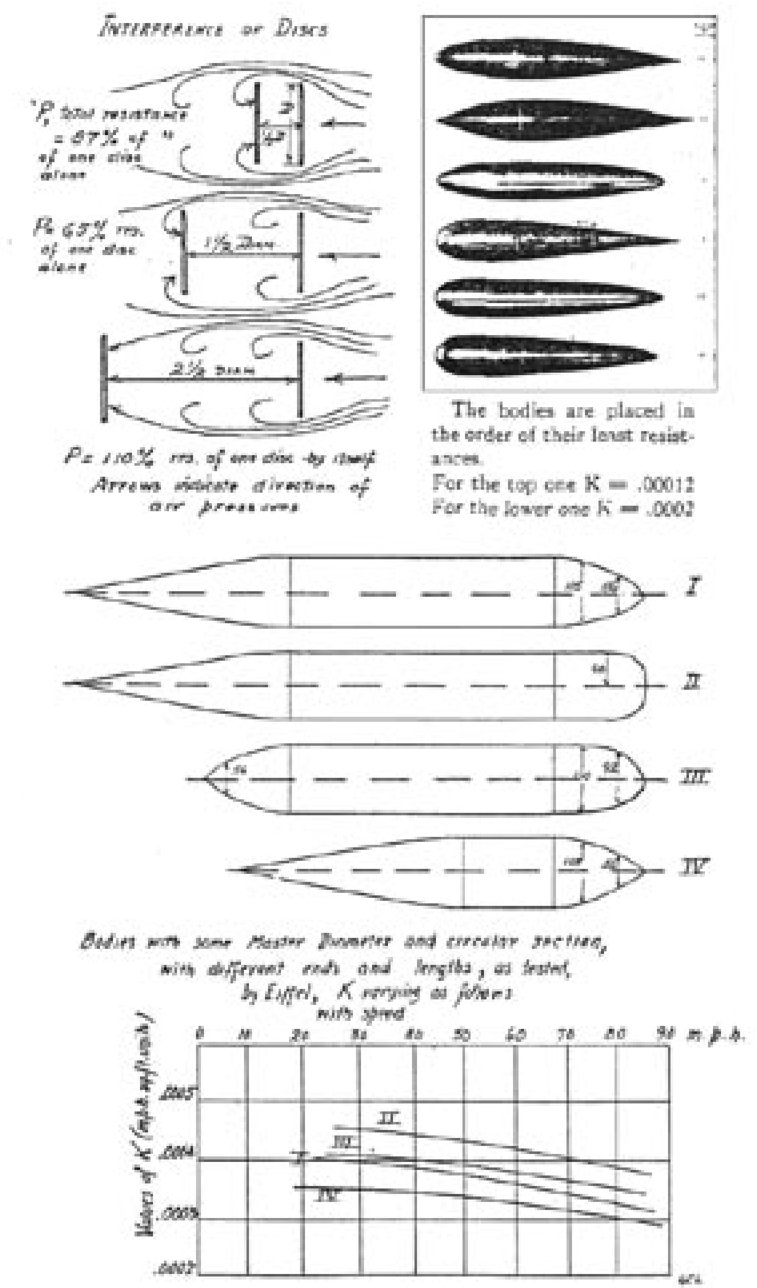
The results obtained in studies of strut resistance indicate the importance of having struts well made and of a uniform section. Just as in bodies, abrupt changes in contour must be avoided and attention paid to a smooth curve on either side of the central portion.

It is found, in general, that a fineness ratio of 5 to 1 is best for use, where a fin effect is desired, and where not,— the best fineness ratio is 3 to 1.

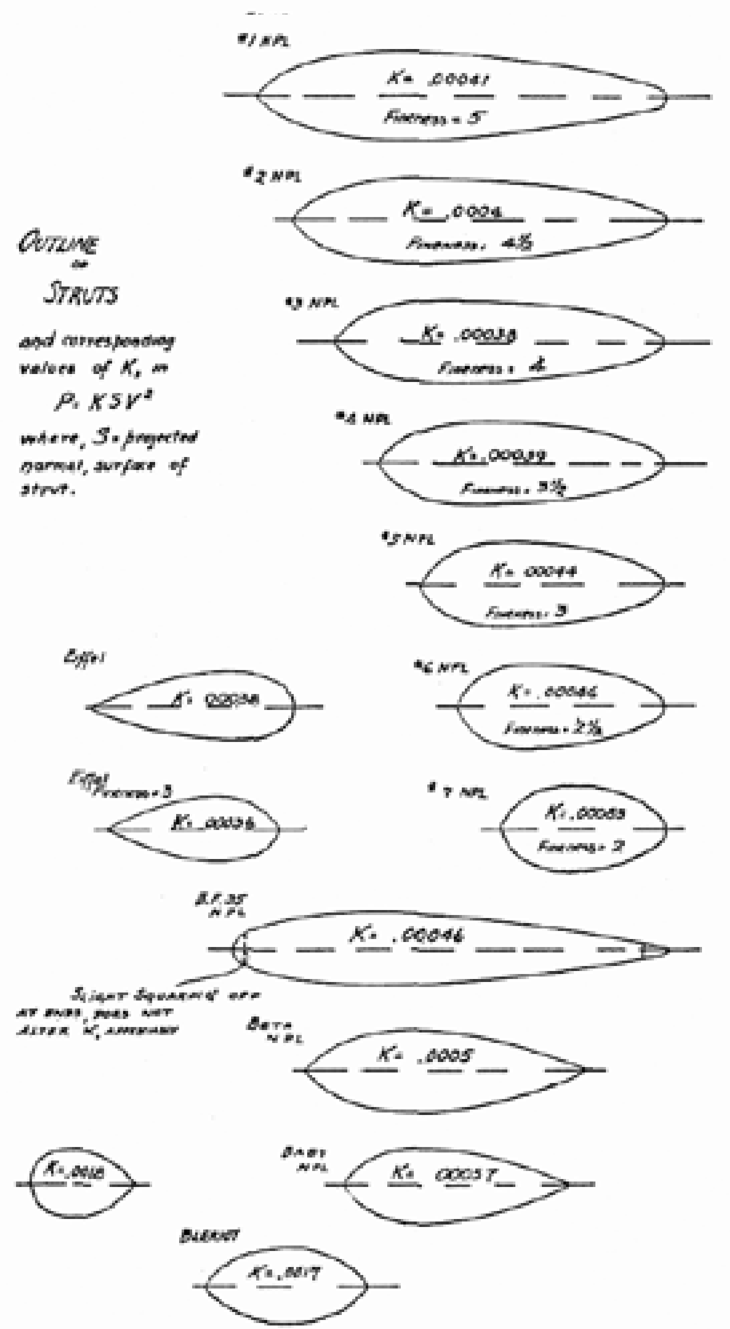
WHEELS:

The air resistance of chassis wheels is a considerable item in flight. Experiments have been conducted on various-sized wheels, and the results are as follows:

28 ½ inches diameter by 2 ½ inches tire, K = .0025
24 ½ inches diameter by 3 ½ inches tire, K = .00265
21 ½ inches diameter by 3 ½ inches tire, K = .0018
18 ½ inches diameter by 2 ½ inches tire, K = .0021



TOP LEFT — INTERFERENCE OF FOLLOWING DISCS — TOP RIGHT, THE BODIES TESTED AT GOETTINGEN — BELOW, BODIES TESTED BY EIFFEL.



THE RESISTANCE OF SEVERAL STRUTS OF DIFFERENT SHAPE

When the wheels are covered in, it is found in almost every case that the resistance is halved, so that for the 24 inch X 13 inch wheel, when covered in, K = .00133. An average **K** for wheels would be **.002**.

As an example, it is desired to determine the resistance of two 26 inch X 4 inch wheels at 80 m.p.h.

The projected surface = 1.4 sq. ft.
$\therefore$ P = .002 X 1.4 X 6400
= 18 lbs.

If the wheels were covered in at this high speed, about 9 lbs. would be saved in resistance; this would permit of carrying about 60 lbs. more load on an efficient machine, or would add 10 gallons more fuel.

SUMMARY:

The data given in this chapter enables the air resistance of various shaped bodies to be computed for any speed **V** and any size surface **S**, where **S** in the maximum cross-sectional projection of the body, perpendicular to the airstream. It is merely necessary to supply the numerical values of **K**, **S** (in sq. ft.), and **V** (in m.p.h.), in the formula.

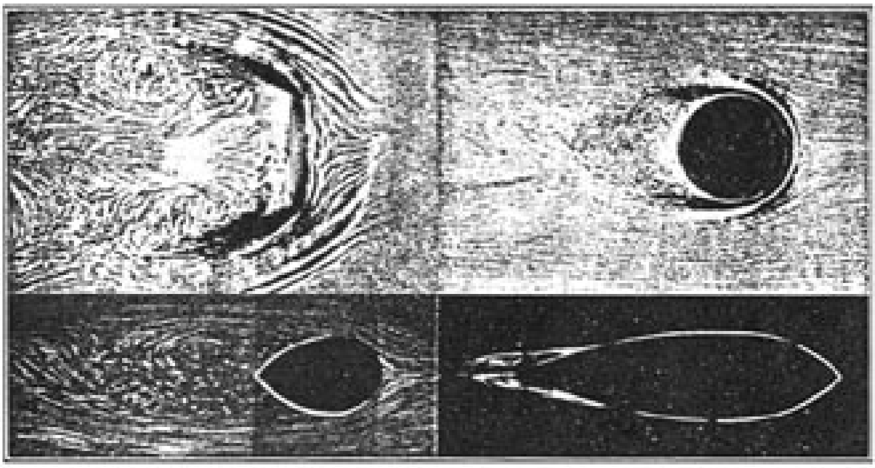
$$\mathbf{P = KSV^2}$$

Where **K = kd, d** being the density of the air, and the values here being correct only for sea level and therefore largely comparative.

It is well again to recall that the propeller of an aeroplane must give a pull or push great enough to overcome:

1. The resistance to motion of the struts, wires, body, wheels, fittings, skids, gas tanks, etc., called Structural Resistance.
2. The dynamic resistance of the wings and rudders, called the **Drift** and generated by the same pressure that gives the **Lift**.

In this chapter the first has been considered. And a study of the second may now be taken up.



THE FLOW OF AIR. UPPER LEFT, A FLAT SURFACE — UPPER RIGHT, A SPHERE — LOWER LEFT AND RIGHT, STRUTS OF DIFFERENT FINENESS RATIO.

Document 3-4

Louis Breguet, "Aerodynamical Efficiency and the Reduction of Air Transport Costs," *Aeronautical Journal* (August 1922): 307-320.

In a speech delivered before the Royal Aeronautical Society in 1922, French aircraft builder Louis Breguet made one of the strongest cases for the social and economic benefits of aerodynamic streamlining. The British *Aeronautical Journal* subsequently published his talk, which is included in its entirety below. The theme of his talk, as indicated in its title, was how improved aerodynamic efficiency could reduce the cost of air transport and thereby breathe life into civil and commercial aviation. To achieve this goal, engineers would need first and foremost to improve an airplane's "fineness ratio," by which he meant its lift-to-drag ratio. Improving this ratio would extend the range of aircraft and make their overall operation more efficient. The way to achieve this improvement was through the use of retractable landing gear and other forms of aerodynamic streamlining. Breguet even set a target for the fineness ratio of commercial aircraft, one that would be hit barely a decade later by the Douglas DC-series aircraft.

The aircraft that Breguet built after 1922 crept closer and closer to such levels of aerodynamic efficiency. The most remarkable of his designs, the Breguet XIX, which was refined from a 1921 military biplane, "enabled France's globe-trotting pilots to start an international craze for nonstop long-distance flying" (Terry Gwynn-Jones, "Farther," in *Milestones of Aviation* [Hugh Lauter Levin Associates, Inc., 1989], p. 46). Two of these flyers, Dieudonné Costes and his navigator Joseph Le Brix, in a Breguet XIX, made the first nonstop crossing of the south Atlantic in October 1927, five months after Lindbergh's historic flight thousands of miles to the north. A year earlier, in 1926, Breguet XIXs broke the nonstop flight record three different times; in the last, pilot Peltier D'Oisy flew a Breguet nearly 6,300 miles from Paris to Peking in just a little over two and one-half days.

Document 3-4, Louis Breguet, "Aerodynamical Efficiency and the Reduction of Air Transport Costs,"* Aeronautical Journal *(August 1922): 307-320.

PROCEEDINGS.

TWELFTH MEETING, 57TH SESSION.

A meeting of the Society was held in the rooms of the Royal Society of Arts, Adelphi, London, on Thursday, April 6th, 1922, the Chairman (Lieut.-Colonel M. O'Gorman) in the chair.

The CHAIRMAN said that the members were to hear M. Louis Breguet, whose name they were too well acquainted with to need any introduction from him. The members ought to know, however, that M. Breguet had been decorated in 1911 and subsequently promoted to the rank of officer of the Legion of Honour, in France, for the services he had rendered during the war, and moreover, that he was the President of what corresponded, in France, to the Society of British Aircraft Constructors, namely, the Chambre Syndicale des Industries Atsronautiques. (Applause.)

The CHAIRMAN then called upon M. Breguet to read his paper on "Aerodynamical Efficiency and the Reduction of Air Transport Costs."

AERODYNAMICAL EFFICIENCY AND THE REDUCTION OF AIR TRANSPORT COSTS.

The possibility for aeroplanes used in air transport services to be made to pay has, so far, been very often questioned, considering the present cost price per ton-mile flown.

I intend to demonstrate that one can, from now, predict an important reduction in air freight rates, not only through greater safety of flight mainly resulting from a longer life of aeroplanes and engines, but also through the betterment of several coefficients which characterise the aerodynamical qualities of aeroplanes.

The study of these coefficients can be made either by laboratory tests on models or by full-scale tests in flight which, if judiciously interpreted, should yield information sufficiently accurate for practical purposes.

May I remind you that the principles of aerodynamics lie in the following formulae:—

Rx = (Kx + o/S) SV2 ….. (I){

Wherein:—

Rz is the total drag of the whole aeroplane along the direction of motion.

Kz is a coefficient relating to R= and dependent upon the value of the angle of incidence in flight.

a- is the projected area, normally to the direction of motion, representing the passive resistances of the aeroplane.

S is the projected area of the wings on a plane parallel to the direction of motion.

V is the speed of the aeroplane along the trajectory.

R, = K,S V- (2).

wherein :—

R, is the lift of the aeroplane, normal to the direction of motion.

K, is a- coefficient relating to R, and dependent upon the value of the angle of incidence in flight.

R= = (K= + (T/S) SV2

Dividing equation No. (r) by equation No. (2), which gives the ratio of drag to lift, we have:

R./R, = (Ks + a-IS)IK9 = tan (3)

That expression tan 0 is usually tailed the "fineness" of the aeroplane, and every aeroplane is characterised by a certain minimum value of tan ¢ which can be represented by tan 0. The smaller tan 0m is the better will be the aerodynamical qualities of the aeroplane.

That fineness is used when calculating the longest distance which a given aeroplane can fly in a "no wind" atmosphere.

L = (622 pl m tan ¢m) log PI (P - p) (4)

wherein :—

L is the said longest distance in kilometres.

p is the efficiency of the propeller.

m is the "fuel and oil" consumption of the engine per horse-power and per hour in kilogs.

P is the total weight in kilogs. of the aeroplane and cargoes at the start. p is the weight in kilogs. of the "fuel and oil" consumed by the engine during the flight and which was included in P.

One at once realises the very great importance of the fineness tan ¢m which in that formula is the only term depending upon the aerodynamical qualities of the aeroplane.

For certain given values of L, p, -in and P, a reduction of tan ¢m causes a reduction in the "fuel and oil" consumption, and consequently increases the weight of paying freight which could be carried.

The conclusion is that one must bring to the minimum the value of tan ¢m. It can be obtained by choosing the best possible profile for the wings, the best designs for the body, empennage, etc. Moreover, the undercarriage should be made to disappear inside the body or the wings when the aeroplane is in flight, etc.

Another interesting coefficient appears when one calculates the power spent in horizontal flight is given by the formula :—

$$W = R_X V = (K + \sigma/S)\, SV^3$$

Where

W is the power in kilogrammetres
R_X is the drag in kilogs as calculated by formula (I)
S is the wing area in square metres
V is the speed in metres per second

On another side, the value of the lift, as given by formula (2), is equal to the total weight P of the aeroplane in horizontal flight. We thus have :

$$P = R_y = K_y SV^2$$

Eliminating the speed V between the two equations (5) and (6) we come to another formula giving the power W:

$$W = P\,\sqrt{(P/S)}\,(K_X + \sigma/S/(K_y)^{3/2}$$

We thus see that the necessary power is in direct proportion to the value of the term

$$(K_X + \sigma/S)/(K_y)^{3/2}$$

I have represented the term by the Greek letter S and call it the coefficient of power.

For a given aeroplane, the value of % will reach a minimum for a certain angle of incidence in flight, and to that particular value of S will correspond the minimum of power required, and that is why I propose to call that special value S,n the *coefficient of minimum power*.

That coefficient of minimum power is used to calculate the minimum power necessary to maintain in horizontal flight a given aeroplane, and the height of ceiling chosen will fix the nominal power to be provided for the engine. One can therefore see that, should it be possible to reduce in the proportion of two to one, for instance, the value of Sm, then an engine of half the nominal power would be sufficient to reach the same ceiling.

Since I have now clearly shown the way these several coefficients affect the aerodynamical qualities of aeroplanes, I can explain to you how one can design in the future, starting from existing aeroplanes, new ones which should reduce by more

than one half the present rates of aerial freight, and how also, when bringing other improvements which I will specify later on, one can expect to bring down the rates of aerial freight to the value of those now charged in France for first class railway passengers.

An aeroplane of high standard quality now has :—

A fineness equal to 0.12
Its coefficient of minimum power is equal to... ... 0.55
Its propeller efficiency is 0.73

Fuel and oil consumption of its engine at an altitude of 2,000 metres is 290 grammes per horse-power and per hour.

We will, moreover, admit the total weight of that aeroplane to be such as to allow it to climb to 4,500 metres within one and a half hours if the engines are run at full power,* and we will consider an aerial line of 800 kilometres non-stop flights.

If such an aeroplane has a wing surface of 100 square metres, for instance, and a power plant of 600 horse-power, its dead weight will be equal to 2,200 kilogs., and it will be able to carry a total load of 2,100 kilogs. Its total weight will thus be equal to 4,300 kilogs.

Its flying speed at full power at an altitude of 2,000 metres will reach 175 kilometres an hour, and its commercial speed at the same altitude can be reckoned as to be equal to 150 or 155 kilometres an hour.

The weight of fuel and oil necessary in a still atmosphere for a given flight is deduced from the formula (4), which, in the present case, gives the weight as being 568 kilogs.

But practical flying has proved that one must expect to have to fly against a fifty kilometres an hour wind, and therefore it is necessary to have at least a fifty percent. safety margin in fuel and oil. In other words, we shall have to carry in the case under consideration a total weight of fuel and oil equal to 568 x 1.5 = 850 kilogs, whilst the average consumption will only be of about 1.1 times the calculated quantity of 568 kilogs., that is to say, 625 kilogs.f

The crew (pilot and second pilot-mechanic) together represent a weight of about 180 kilogs., and another 70 kilogs. are necessary for various instruments and T.S.F. apparata.

The total weight of fuel and oil, crew and instruments thus reaches eleven hundred kilogs., leaving a clear margin of one thousand kilogs. for passengers and paying cargo.

The present running costs of an aerial line of 800 kilometres long, with the above aeroplanes, are as follows :—

	Francs.
Petrol (820 litres at francs 1.82 for Boo kilom. flown) per kilom.	1.87
Oil (50 litres at francs 3 for Boo kilom. flown)	o. ig

Crew (pilot at francs 0.20 per kilom., second pilot-mechanic
at francs 0.15)* 0.35
• Sinking fund for aeroplane and engine 6.50
Upkeep of aeroplane and engine and aeroport expenses, etc. ... 4.50
General expenses of the company ... ... 4..00
Francs 17.41

Should an aeroplane always fly with full cargo load and without incident or interruption, the cost price per ton and per kilometre would thus be about 17.40 francs. But one has to reckon with trips made with smaller paying loads, or incidentally interrupted, and therefore it is wise to calculate the cost price per ton on flights with half cargo loads as an average, which brings the present cost price per ton and per kilometre to 35 francs. That is about the price at which are now working the best aerial lines. A few companies work on still higher prices, either because the average cargo load is less than one half the maximum, or because they fly over particularly awkward grounds. They then reach such prices as 50 francs or £I 12.s od. per ton-mile.

Should such prices be considered as irreducible they would be practically prohibitive and little chance would be left to commercial aviation, since one would have to charge from eleven to twelve hundred francs per passenger from Paris to London or vice versa, without any profit to the company.

How can these figures be reduced in the near future? We will consider:—

1. —Advantages to be drawn solely from the betterment of aerodynamical qualities of the aeroplanes and of the thermal efficiency of engines.

2.-Advantages resulting from such improvements in the engines and in mechanical parts of aeroplanes as would bring reductions in the provision for sinking funds, upkeep of machines and general expenses.

1.-Advantages to be drawn solely from the betterment of aerodynamical qualities of the aeroplanes and of the thermal efficiency of engines.

Taking, for the sake of demonstration, the same size of aeroplane as already considered, that is to say

Wing area: 100 square metres.
Total weight: 4,300 kilogs. at the start.
Ceiling: 4,500 metres.
And if we suppose that we can bring down
Its fineness to ... ... o.o65 instead of 0.12
Its coefficient of minimum power to ... 0.28 0-55
Its propeller efficiency to ... ... 0.7750.73 The fuel and oil consumption of its
engines per horse-power and per
hour to ... ... 215 ego grams

then such an aeroplane will not require more than 288 horse-power to reach the same ceiling of 4,500 metres instead of 600 h.p.

It is evident that the reduction in power is only due to the betterment of the coefficient of minimum power and of the efficiency of the propeller.

One can thus spare 312 horse-power, which means a saving of 468 kilogs. of dead weight (at the rate of one and a half kilogs. per horse-power for the engine and its appliances).

The quantity of fuel and oil to be carried can be deduced from the formula (4), as has already been done for the first type of aeroplane considered. This gives

p = 230 kilogs.

The weight it is wise to carry up will be taken equal to

230 x 1.5 = 345 kilogs.

and the average actual consumption will be about

230 x 1.1 = 255 kilogs.

The weight saved on fuel and oil with the second type of aeroplane will thus be practically

850 - 345 = 505 kilogs.

and the excess of useful load is thus increased to a total of

468 + 505 = 973 kilogs.

The commercial efficiency of that type of aeroplane will thus be practically double that of the first type, since it will be able to carry 1,973 kilogs. of passengers or paying freight, instead of 1,000 kilogs.

At the same time that aeroplane will cost about 25 percent less than the first, since its nominal power plant will only be half the size of the first, and the value of the nominal power plant now represents about half the price of an aeroplane.

The running cost of the new type of machine will then be as follows:—

Francs.
Petrol (335 litres at francs 1.82 for 8oo kilometres) per kilom. 0.765
Oil (20 litres at francs 3 for 8oo kilometres) ... ... 0.075 Crew ... ... 0.35 Sinking fund (75 per cent. of francs 6.50, since the cost price
of the aeroplane has been found reduced in that proportion) ... ... 4.90 Upkeep of aeroplane and engine and aeroport expenses ... 4.50 General expenses of the company ... ... 4.00 R
Francs 14.59

As the paying load has been raised to 1,973 kilogs., the cost price per ton and per kilometre becomes equal to 7.40 francs, or—if calculated on a half cargo load basis—14.80 francs instead of the present cost price of 35 francs. London to Paris passenger fares can then be brought down to some 450 or 500 francs without profit for the company. Although very high, these last figures are more encouraging and nearly workable.

2.-Advantages resulting from such improvements in the engines and in mechanical parts of aeroplanes as could bring reduction in the provisions for sinking funds, upkeeping and general expenses.

When one can rely on an average life of one thousand hours for aeroplanes and engines instead of the present 200 or 250, much better prices will be obtained. Supposing that. such an aeroplane be bought for the same price as the last one mentioned, but calculating on 1,000 hours life, the sinking fund only calls for 1.10 francs, whilst the upkeep can be reasonably considered as half as expensive since the aeroplanes and engines will be of much better quality and strength. General expenses will also be considerably reduced through the much larger turnover that the companies will then be able to secure.

In such conditions the running costs would be as follows: Petrol ... ... per kilometre, francs 0.765 Oil ... ... 0.075 Crew 0.35

Sinking fund r.r0

Upkeep 2.25

General expenses (estimated) ... ... r.oo

Francs 5-54

That is to say, 5.55 francs for 1,973 kilogs. carried, or 2.82 francs per ton and per kilometre, or 5.65 francs if calculated on the usual half cargo load basis. Then the Paris to London fare will become about 190 francs, or say £4, the present price of the third class railway fare.

When that time comes then the aerial transport companies will be flourishing paying concerns, and no more subsidies will be required from the State, because the time saved in travelling by air from Paris to London, for instance, will certainly be worth a fare of say £6, showing £2 profit on each passenger.

It is worth noting in the last cost price we have given that fuel and oil, although intrinsically very expensive, amount to only fifteen percent of the total cost price, whilst the crew draws 6.4 percent.

On the other side, sinking fund, upkeep and general expenses, which, on the present cost of 35 francs, represent 86 percent of the total cost price, have grown to 92 percent with the second example and come down to 78 percent in the last considered circumstances.

May I therefore state—in opposition to the sayings and writings of certain experts who do not know much about aerial transports—that it is not the cost of fuel or crew which makes aeroplanes expensive machines, but only their present short life, with resulting consequences. But we must expect and hope to see large and strong aeroplanes of the future become as safe as motor cars, steamships and railways, and when that time comes, then we will be able to apply to sinking funds the same coefficient as is now used for steamships, that is to say, about an average life of twenty-five years!

From the example I have taken for the purpose of demonstration of an aeroplane of one hundred square metres wing area and 4,300 kilogs. total weight, you must not infer that I expect the improvements of aerodynamicaI qualities (with the consequences I drew from it) to be realised by such small machines. I believe one can build very good aeroplanes of four to five tons total weight; but I think it would be much nearer to reality to talk of 500 square metres wing surface, twenty to forty tons total weight and fifteen hundred to four thousand horse-power. Such large machines* will most probably have very thick wings. By thick, I mean about six feet, and within these wings will be provided cabins, saloons and every comfort for passengers. It is worth noting that if a large increase of the size of an aeroplane does not improve materially its commercial efficiency, it has nevertheless the great advantage of allowing much more room for passengers and freight, and that can be easily understood when one remembers that whilst the weight, the power, the capacity in cargo and the cost price of an aeroplane vary as the square of its lineal dimensions, the volume to be reserved for passengers will vary as the cube of the same dimensions. In other words, if the weight, surface and power have been increased one hundred times, then the cubic capacity will be one thousand times larger.* Passengers, for instance, will proportionately dispose of ten cubic metres each instead of one cubic metre in the first case, and that shows one of the most important advantages to be drawn from the manufacture of very large machines.

It is not exaggeration to talk of the days when the price of aerial transport will come down to two francs per ton and per kilometre, since an average life of two or three years—or say two thousand hours of flight—for aeroplanes and engines would suffice to bring that result, even with petrol and oil at their present very high prices. It is practically certain that aeroplanes of the future will not burn petrol but rattier heavy oils or other cheap fuels, the cost price of which should be about one-fifth that of petrol.

Now first class passenger fares in France are calculated on the basis of 21.15 francs per one hundred kilometres. Supposing that a passenger with his hand luggage weighs an average of ninety kilogs., we find that the ton-kilometre (passenger) runs to 2.35 francs. That shows that the future prices of aerial transports will be of the same order as the present first class passenger fares in France.

More striking still is the comparison with the fares on steamship lines, since first class passenger nowadays pays about six francs per ton-kilometre, whilst state cabins are charged at the rate of ten francs.

In conclusion, aerial transports are very expensive for the present because they are not yet out of the experimental stage and that the sinking funds, the upkeep and general expenses are very heavy; but one can reasonably say that within ten years these costs should be reduced in the proportion of seven to one, and within twenty years roughly in the proportion of fifteen to one.

Moreover, one must not forget that "time is money," and therefore a saving of four or five days on London to Cairo, for instance, will be of tremendous value to business men. The fares charged will then be of comparatively small importance to them as long as safety and speed are secured, and as aeroplanes will be unbeatable as regards speed, aerial transports are bound to wipe out all other systems of international communications.

We must therefore work hard and steadily, with full confidence in the future of aviation.

DISCUSSION.

The CHAIRMAN said they had listened with interest to M. Breguet's display of an optimism which was well worthy of their respect. He had indicated the steps by which they might compete on equal terms with railways for certain classes of traffic, and if they did not arrive at the whole result they might look step by step at the various factors and see which of them they had failed to bring up to the high level which had been foreseen. He had suggested that the fineness of aircraft could be improved by 50 percent. He had shown the hope that fuel consumption might be reduced, and had discussed similar factors, showing that even if these factors of improvement could not all be obtained *in toto*, he had shown that the sum of the advances obtainable make a fundamental and logical improvement in the whole aeronautical situation. M. Breguet's optimism was legitimate if the moneys spent on research were not reduced. Each specialist could then tackle, in his own sphere, some one of the problems that M. Breguet had exposed, and in such measure as they secured improvement, these would become operative together, and we should approach the competition, on an equal basis of charge, of first class railway fare and travel by aeroplane, with the enormous advantage to the aeroplane traveller that he had saved so much in time. With regard to the author's prophecy of the 40-ton monoplane, he did not suppose that an engineer of the author's distinction would have put that forward entirely at random without having thought it out as a thing thoroughly worth considering as a commercial possibility. The author had shown that the real incoming of aerial transport was not going to be achieved by prophetic letters to the Press nor yet by meetings of the Civil Aviation Advisory Board at the Air Ministry, unless the latter proved themselves competent to understand the technical nature of the problem and secured a sufficient addition of funds for the specialised research which civil transport needed. He agreed that civil transport was the basis for full factories and full factories the basis of military aeronautical operations. Nothing else but the scientific work of men of intelligence and intellect in the laboratory and in the air would solve the technical problems; and nothing but a solution of the scientific problems could make air transport self-supporting. Everyone would agree that that was the solution to be obtained. It was deplorable to realise that the authorities seemed so little capable of realising this, that they allowed the technical and research expenditure to be cut down with a view to national economy; he felt very strongly that this was simply national extravagance. It was killing that which alone could economically keep the aircraft factories in being in the state necessary to provide the fighting machines for aerial defence—Britain's, and indeed any country's, first line of defence.

Mr. F. HANDLEY PAGE said it was very interesting to have M. Breguet to address a meeting of the Royal Aeronautical Society. He had been one of the great pioneers of aviation, and one who had devoted himself not merely to the type of aircraft that they saw flying today, but he believed some of his earliest efforts were in the direction of the helicopter, which, if it had not produced practical results, had at least produced a very lengthy correspondence from the inventors. In having M. Breguet at the meeting the Society was greatly honoured. He (the speaker) was an optimist; his optimism was not based merely on the feeling that the success of air transport depended solely on the research laboratory, which the President had emphasised. It had been very much borne in upon him during the last few days that even with the latest and best of up-to date machines they did not necessarily achieve an air service. An air service was dependent, quite apart from equipment, on the ground organisation that dealt with it. If we were able to make machines that we could run at one-third, or, one-fifth, or even one-fifteenth of the present-day cost, that would not make possible a flight to Paris in thick fog and low clouds, and it would not enable the pilot to know whether he could start now or in an hour's time unless the meteorological service was very good. It was the improvement of the adjuncts to an air service, quite apart from the machine itself, or the skill of the mechanics who looked after it, or the pilots who flew it, that would make development possible. "If it were possible to fly present-day machines in all weathers strictly to scheduled time, and for them to return strictly to scheduled time, no matter what the weather was, costs would be very considerably reduced as well as charges to the public. He had looked with great interest at the formulae in the paper and he did not know whether there was a solution to any of those equations that gave one the value of profits. It seemed to him that if they could determine that accurately by means of an equation it would be an excellent thing for mathematical treatment. As a distinguished mathematician had said, " What comes out of the mathematical mill depends on what you put into it," but there were so many variables in arriving at a result by mathematical methods that it was necessary to study the component factors entering into it before they could arrive at a figure for the profits they were likely to get. He laid stress on the particular item of the ground. Organisation. He was very much interested to see, in the latter part of the paper, M. Breguet's visualisation of the very large aeroplane. The difficulty of structure weight had always seemed to him to be rather insuperable if they went beyond a certain size. In the four-engined machine made by his firm, which weighed 30,000 lbs., it seemed that they were gradually approaching the point where materials had been used to the best possible advantage, and there seemed little possibility of improving the use of those materials and getting over the theoretical disadvantage that was attendant upon increased span. He did not know whether M. Breguet, with his great engineering skill, had thought of any method by which that disability might be overcome. Without a doubt, were it possible to obtain a scale effect with larger sized machines, by which they could fly with greater loadings per square foot and thus decrease the span, such an improvement might be possible. In that direction it was rather interesting to know that in nature some of the bigger birds which, he was assured by Dr. Hankin, flew at the same speed, carried a greater load per square foot, although their landing speed was the same. It would appear that nature had got over structural difficulties by introducing a scale effect. Whether it was possible to utilise that in a very much bigger way in the construction of large machines he did not know. Perhaps M. Breguet could say something about it. He again thanked M. Breguet for his interesting paper, and congratulated him on having read it in English.

Captain GOODMAN CROUCH congratulated M. Breguet on his very interesting and rather optimistic paper, and the Society on having the opportunity of listening to one of the earliest pioneer aviators of France, who was also one of her greatest engineers.

He recalled that he had had the honour of being associated with M. Breguet in aviation some 16 years ago, when he (M. Breguet) put into the air a type of aeroplane which was called a double monoplane, since it was so unlike the usual box kite form of biplane then known. People looked at this curious beast and asked what it was, since with biplane wings it had a fuselage and was almost entirely of metal construction. One had only to consider the machines of a few years later to realise that M. Breguet was a true prophet, for it would be remembered that he alone at that time was the designer working on those lines.

With regard to the air transport costs quoted by M. Breguet, the list of prices shown for running costs of an aerial line of 800 km. length included an item of Frs.6.50 for sinking fund out of a total of Frs. 17.41. This, in his opinion, was a remarkably high percentage. It indicated that in the hypothetical case M. Breguet had taken he had chosen a machine presumably with a far shorter life than that of present-day aircraft, and he believed this item could be considerably reduced. This appeared to be borne out by the length of life assumed by M. Breguet when considering the advantages resulting from such improvements in engines and in mechanical parts, as could bring reduction in sinking fund and upkeep charges. Under this head M. Breguet had assumed the life of present-day machines to be 200 or 250 hours, and predicted the possibility of improving this to 1,000 hours.

Captain Crouch ventured to suggest that even during the war the life of 250 flying hours had been reached, and even surpassed by some of the heavy bombers, and the figure of 1,000 hours was hardly a prophecy since a total of approximately 800 hours had already been reached by a machine on the London-Paris Service.

With regard to the advantages hoped for from the betterment of aerodynamic qualities, M. Breguet's fineness coefficient indicated a figure for *L/D* of approximately 18~. This appeared to be optimistic, but he dare not say much in criticism of the point, since M. Breguet had already shown himself to be a true prophet. Recent aerodynamic tests on a model of a Woyevodski type had given a maximum *L/D* of about 12, and that, as far as he knew, was the highest figure yet reached for a complete model.

M. Breguet's remarks concerning future large machines were teeming with interest, but he felt that M. Breguet was extraordinarily optimistic in assuming that the increase, in volume available for passengers would be so much greater than the increase in weight, power and cost.

Finally, he again thanked M. Breguet for the lecture, which from a technical point of view gave so much food for thought.

Mr. W. O. MANNING said he was sure everybody appreciated the honour M. Breguet had conferred upon them by reading his exceedingly interesting paper. Those who had followed aviation from the early days would remember the large, series of aeroplanes known as the Breguet type, and the brilliant engineering design that invariably characterised them. He endorsed what Captain Goodman Crouch had said to the extent that, although he was not connected with commercial aviation, he certainly expected that the life of aeroplanes and engines today in commercial work was considerably longer than 200 hours. He was not an engine builder and could, perhaps, speak with less bias on that particular point, but he knew he could introduce M. Breguet to one or two English engine builders who could beat that performance. It would give them a great deal of pleasure when they remembered that in the early days of aviation practically the whole of English aviation was dependent upon French engines if they were able now to return the compliment. M. Breguet had done a very great service to aviation by pointing out the enormous importance of improvement in aerodynamical efficiency. One tried to improve the efficiency of the machines, but one did not appreciate, until it had been pointed out so clearly, what a very important matter aerodynamical efficiency was, not only in the saving of engine power, but in increasing the useful load and in cheapening the cost of the machine. With regard to M. Breguet's large machine, he was, of course, up against the dimensional law that the weight went up considerably faster than the area and that there is a definite limit of size for machines of present-day construction and design. But it by no means followed that the limit was the same for other types. It was possible that a very large monoplane, such as that referred to by the Lecturer, presumably with highlift wings, and with the passengers, fuel, engines, etc., distributed along the wings, might be capable of being constructed for a reasonable weight. He again thanked M. Breguet for his interesting paper.

Colonel W. D. BEATTY joined with previous speakers in congratulating M. Breguet upon having read his paper in English. There was one point which had struck him, and that was in regard to the symbols used. The efficiency factor he had assumed corresponded to our English *L/D*. Although there were exceptional cases where the technical experts in the two countries did speak each other's languages, the majority did not, but it was obviously desirable that they should all think in the same mathematical language. With regard to that he was glad to, say that preliminary steps had already been taken, in conjunction with the French Air Ministry, in order to get down to the same basis in England and France. While he did not wish to plunge into the argument as to the possibility or otherwise of the very large machine, he felt rather glad that there seemed to be such hope for the future. We still had a lot to do in the way of building up the traffic necessary to make it commercially practicable.

Mr. O. T. GNOSSPELIUS, after expressing his interest in the Paper, congratulated M. Breguet upon his courage in assuming that what we called *L/D*, or efficiency of the machine, could be improved, because he was quite sure, by his own experiments, that it could be done. They knew that certain experiments had been done at the N.P.L. and other places, and they got certain results, but if one made experiments one's self one got quite a different outlook. He was sure M. Breguet was quite right in saying he could get something like 15 to 1 *L/D*, because he himself had made pieces of wood in the shape of bodies, wings and tails which gave that effect, so that he did not see why the complete machine should not do the same. The trouble was that we did not know much about aerodynamics, and did not know the proper shape to make. It seemed to him that work on that line, was very essential, because 151bs. per h.p. was not practicable; we wanted to turn it into 30. In present machines the figure was more or less 151bs., and he was very glad that M. Breguet had brought forward this sort of figure for efficiency.

Mr. A. P. THURSTON said that the lecture impressed one very much indeed, that famous men, like science, were international. We (in England) more or less regarded M. Breguet as one of ourselves, and felt it a very great honour to receive a lecture from him. He was a pioneer of many things, but it was not realised that over 1,000 of M. Breguet's all-metal machines were actually used in the fighting line during the war. That was a very considerable achievement.

M. Breguet had brought out very clearly that to increase the efficiency of a machine it was necessary to reduce the "useless surface" (surface invisible) to the minimum amount, and the ingenuity of our designers must be utilised in taking, off all extraneous corners and everything which caused waste by increasing that surface. But there was a point which was not, perhaps, brought out quite so clearly, and that was that the efficiency in carrying weight per distance could be increased by actually increasing the speed of the machine and decreasing the lifting area. The great difficulty in this connection was that of landing speed. But there were ways of doing it which would enable them to get a higher speed still in the air with smaller surface, and yet maintain slow landing speeds. In other words, it was possible, as suggested by Mr. Handley Page, to get something of a scale effect by taking advantage—he was not at liberty to say how—of certain properties of the air. He did think that it would be possible to increase the present efficiency of our machines in order to get a greater weight mileage for a certain expenditure either of money or of fuel, and in that way increase the possibilities of commercial aviation. He had once taken the trouble to go through the figures, taking a line to India. Assuming there were a large number of machines, taking the cost of maintenance of grounds, and petrol at 2s. per gallon, assuming the organisation was so perfect that each machine could be flown for 10 hours a day, and each machine would last on an average two years, on that basis he had made out that it was quite possible to maintain a good dividend and charge passengers at the rate of 3d. per mile.

With regard to M. Breguet's remarks about engines, he would like to endorse what was said by Mr. Manning. It was only a few days ago, at Croydon, that a Napier Lion was pointed out which had been running continuously for 450 hours without being taken down. It was possible for British engines to do better still, and attain running efficiencies which would be considerably better than the 220 hours of the French engines.

He also endorsed M. Breguet's remarks as to aviation being the greatest future means of international communication, and in conclusion took the opportunity to thank M. Breguet for the courtesy which he had extended to him (the speaker) when he went through his works.

The CHAIRMAN translated some of M. Breguet's remarks, in which he explained that he was once of Mr. Handley Page's opinion that six tons was the limit at which the weight grew so fast that the area could not be expected to bear it profitably. He had proposed a complete departure in the type of construction, which, although it had not yet actually been put into being, he thought would get rid of the difficulty of the relation of weight to wing surface. He did not claim as an invention at all, but he had made calculations by which, using the thick wing type of machine, burying the engine and load in the wings, and distributing them carefully along the wings, on a 50-ton machine, he hoped to be able to arrive at much the same wing loading and power loading as would be obtained on a smaller craft of 2 or 3 tons. The wings would be 7ft. thick.

A hearty vote of thanks to M. Breguet concluded the proceedings.

NOTES ON M. BREGUET'S PAPER.

Contributed by Captain W. H. SAYERS: I think it is most important and most encouraging to hear so very high an authority as M. Breguet expressing the opinion that very great improvements in the aerodynamic qualities of the aeroplane are not merely desirable, but are also possible. The data given in his Paper are conclusive proof—if proof be needed—of the value of any great improvement in the "fineness"—or in usual English terms—the *L/D* ratio of aeroplanes.

The figures as to costs, etc., given in the Paper relate to French practice and are not directly applicable to British conditions. In certain respects I think British aircraft constructors may rightly claim that they can improve on those figures both aerodynamically and in the equally important matters of the durability and longevity of their aircraft. Such criticisms do not substantially affect the justice of the author's general conclusions, with which I am in entire agreement.

I think, however, that the time has now come to question what have hitherto been regarded as the fundamental bases of aeroplane design-bases which are apparently accepted by M. Breguet for they are implied in his two equations Nos. 1 and 2.

The assumptions are that an aeroplane may be regarded as a heterogeneous assortment of surfaces and bodies, and that the forces on each of the component surfaces or bodies, taken separately, may be added up and will then represent the total of the forces on the aeroplane. Every aeroplane designer knows that these assumptions are in fact inaccurate. No isolated body of good form can be cut in two and have its resistance determined by summing the resistance or the forces on the parts.

That the resistance and lift of present aeroplanes can be determined with reasonable accuracy by this method is, I submit, evidence that present-day aircraft are aerodynamically merely a collection of uncoordinated components. They will continue in this state for so long as designers allow themselves to be limited by a basis of design which is entirely empirical and seriously misleading. It is not true that a given wing has definite lift and drag coefficients at definite angles of attack which are independent of the body, tail and wing bracing structure to which the wing is attached. It is equally not true that the body, tail and other organs which form the complement to wings have force and resistance coefficients which are independent of the wing.

Because existing aeroplanes are so bad that they behave nearly as though these false assumptions were actually true, the designer comes to believe in them. Because he has come to believe in them, he has also come to believe that it is not possible very greatly to improve the aerodynamic efficiency of existing types of aircraft.

I am personally firmly convinced if designers can only be persuaded to forget all about the itemised resistances of the components with which they at present deal, and will regard a projected aeroplane as a single aerodynamic body, and will design it with an eye to its lines as a whole—just as they would design, say, an airship body—that eye will very speedily be found possible to design a complete aeroplane having a *L/D* ratio of 20/1 or over, or—in Nil. Breguet's terms—with a "fineness" of .05 or less.

TRANSLATION OF LETTER FROM MONSIEUR LOUIS BREGUET, DATED 28TH APRIL, 1922, TO THE ROYAL AERONAUTICAL SOCIETY.

Gentlemen, —I return herewith draft copy of the report of the meeting of the 6th instant, and regret that I have been unable, owing to absence, to reply earlier, as promised, to the various speakers who took part in the discussion. I very much appreciate their remarks, for which I thank them.

Replying in the first place to Mr. Handley Page, I agree with him that the Paper had in view only a part of the big problem of the future of aerial transport, but it is quite certain that while it is necessary to have good aircraft, it is equally indispensable to have as perfect a ground organisation as possible, otherwise the use of aircraft will be very uncertain, however perfect they themselves may be.

For instance, let us imagine modern navigation carried out as is actually the case with superb boats, but lacking any organisation of ports, routes, provision of buoys, lighthouses, wireless telegraphy, meteorological service, current charges, etc. The result would be practically negligible and its existence very precarious.

I did not raise this question at the meeting as I am of opinion that if from, the present time until the fact is accomplished, sufficient funds are available, it ascertain that excellent aerial ports, which are more easily and much more cheaply established than seaports, will rapidly come into being.

It is foreseen, however, that the aircraft destined to maintain the big international transport service will have to be of the amphibian type, and they will thus be able to utilise sea routes and have at their disposal the whole existing organisation in the big seaports throughout the world.

From carefully carried out experiments made in various laboratories I am able to state definitely that with the very good coefficients I quoted for "fineness" (indicating *L/D* efficiency), propeller efficiency, and minimum h.p. will certainly be realised in the near future.

I would like particularly to reply to Mr. Handley Page on the subject of large aircraft of the future. I can share his opinion that if aircraft are built on a larger scale whilst remaining geometrically similar, the ratio of wing structure weight to total weight will increase, since, all other things being equal, the weight of the wing structure, i.e., spars, ribs, interplane struts, bracing, etc., increases as the surface to power 3/2. For this reason I was for some time led to think that very large aircraft would not give results of interest, and that no comparison was possible between boats and aircraft, for even given an assured advantage to be gained by increasing the tonnage of ships, rather the opposite would obtain in increasing the size of aircraft. At the beginning of last year, however, I started to give serious thought to a type of monoplane with wings of a section deep enough to house engines, tanks and passengers. Further, by suitably distributing the loads on the wings it is easy to imagine an aircraft in which the dead weight, instead of increasing as the power 3/2 of the area, will only increase directly proportional to the area, and under these circumstances there were no longer any disadvantages in increasing the size of the machines.

I sketched on the blackboard after the discussion how I envisaged such an aircraft. It would comprise three fuselages, one in the centre for the crew, controls, instruments, etc., while the other two on the right and left respectively of the first mentioned, and far enough apart, would be used as hulls or floats. These would contain first class cabins. Finally, the tanks and the float would be distributed inside the wings. This distribution in weights in large aircraft would obviously give them a considerable moment of inertia, but as there would be no need for "stunting," their large lateral moment of inertia would mean a high degree of stability in the air.

With big monoplanes the reduction of parasite resistance can be pushed as far as one likes, and it is to be hoped that results similar to those of plain wings furnished with the tail unit can eventually be reached. It follows that these large machines would eventually have characteristics comparable with those of large birds, and the coefficient which would be applicable to them in that case will certainly be better than those I quoted in the lecture.

To Captain Goodman Crouch I admit that certain British engines have a much longer life than 250 hours, but I ought to say that the average life of the engines used by French companies does not reach this figure.

I am entirely in agreement with Captain Goodman Crouch that in a few years aeroplanes will obtain an average life of 1,000 hours, and for this reason I have every hope of seeing engines reach 2,000 hours.

With regard to Mr. Thurston's remarks, may I say that actually there were more than 6,000 metal machines, and not 1,000, put into service during the war which are still being used.

Finally, I would like to confirm what was the basic point of my paper, i.e., that technical research should be pushed forward without relaxation so that improvements already envisaged may be realised with as little delay as possible as well as those for which as yet one hardly dares to hope.

Yours, etc.,
(Signed) LOUIS BREGUET.

Document 3-5

Captain W. H. Sayers, "The Lesson of the Schneider Cup Race," *Aviation* 15 (5 November 1923): 577-580.

It was clear to many informed observers of the American victory in the Schneider Trophy competition of 1923 held in England that the key to the American success lay in how the designers of the winning Navy Curtiss CR3 aircraft had found ways to limit the amount of what was at the time generally called aerodynamic "resistance," meaning drag. In this short commentary that first appeared in the British magazine *The Aeroplane*, British RAF captain W. H. Sayers emphasized the "very complete way in which the whole detail design [of the Navy Curtiss racer] has been studied throughout with the idea of keeping resistance down to the absolute minimum." Primarily a critique admonishing the British Air Ministry for not providing the type of funds the U.S. government had been giving to winning such international air competitions, Sayers's editorial reported that the American emphasis on "detail design" for the purpose of reducing drag had made all the difference in the recent Schneider Cup race. The Americans had made every effort to make their airplane sleeker and faster. As a result, they had produced an integrated system designed for one purpose: speed.

Aviation historians still debate how influential the air races actually were on the aircraft design revolution of the late 1920s and 1930s and the more sophisticated civil and commercial aircraft that emerged from it. But there is no doubt that the U.S. government's discontinuation of formal sponsorship of international racing efforts left a void and somewhat slowed the pace of experimenting with cutting-edge aeronautical technology.

Document 3-5, Captain W. H. Sayers, "The Lesson of the Schneider Cup Race," Aviation 15 (5 November 1923): 577-580.

THE LESSON OF THE SCHNEIDER CUP RACE

"America Won Because it Entered the Most Perfect Examples Of Racing Aircraft Yet Seen in Europe"

Under the above title W. H. Sayers, (Captain, late Royal Air Force) contributed a very interesting article to our English contemporary The Aeroplane. It is reproduced here not only because of its evident technical value but also because of the clean sportsmanlike manner in which it appreciates the victory of our entries in the Schneider Cup race. – EDITOR.

The American team won the Schneider Cup because they entered for it what are undoubtedly the most perfect examples of racing aircraft that have yet been seen in Europe. It is entirely beside the point to suggest that they won the race on machines that would not have stood up to the Navigability Tests in rough weather.

They stood up to the tests in the weather that actually befell them, and their behavior on the water was of a nature which somewhat upset one's preconceived ideas as to their seaworthiness. Their floats are one believes distinctly heavy, they are certainly extremely strong.

THE CLEANEST THINGS EVER SEEN

As for the rest of the machines they are the cleanest things one has ever seen. The type 29 racing Nieuport biplane was one imagined as clean as a biplane could be. The Curtiss CR3 is a little cleaner in the matter of minor details such as wire fittings, etc., it has no radiator other than the surfaces of the upper plane, and despite the fact that it has an engine of some 500 bhp as against the Nieuport's 320 bhp, that engine is stowed away in a fuselage which is certainly of no greater--and looks to be of distinctly less--cross-sectional area than that of the Nieuport.

So far as the general arrangement of the machine is concerned the Curtiss machines show no surprising features. They use a normal type of thin wing--one believes it to be a "Sloan" section--which looks not unlike a RAF15. There is nothing abnormal about the wing wiring or strutting. The gap/chord ratio is not far from the usual value of 1.

The fuselage is an exceedingly pretty veneer--built affair-made one believes in two halves--and the tail unit has no striking peculiarities.

The floats are of a type which is now practically standardized in America for all float seaplanes. They are of the long type, designed to be stable fore and aft without a tail float, have one shallow step close under the C.G. of the machine, with a very long and fine tail behind it. The bottoms have a fairly steep Vee throughout, and the section above the bottom is practically semicircular throughout.

In the matter of air resistance they are undoubtedly good. On the water--as already remarked--they are surprisingly amenable to the wishes of the U.S. Navy's undoubtedly able pilots.

But it is not the general design of the major components, or the lay-out of the whole machine which accounts for the surprising performance which the Curtiss machines undoubtedly possess. This is due to the very complete way in which the whole detail design has been studied throughout with the idea of keeping resistance down to the absolute minimum.

THE CURTISS ENGINE

The Curtiss D12 engine must be considered to be a most important factor in the whole. It is evidently an engine of the very highest class--but more than this it is definitely a racing engine such as does not exist at present outside of America.

In making this statement one does not refer specifically to its low weight per hp. or its obviously excellent running qualities. The engine is astonishing--considering its great output--on account of its extremely small frontal area and of the absence of any projecting gadgets for which it would be necessary to provide bulges in the cowling.

There are other engines which can cheerfully face comparison with the Curtiss on a weight per horsepower and a reliability basis. One does not know of one of anything like the power which would go into the Curtiss racing fuselage with absolutely nothing sticking out except the airscrew boss and the stub ends of the exhaust pipes. Personally one has no doubt that a big body with nothing whatever sticking out is better for speed work than is a smaller one with an assortment of minor bulges to accommodate odd excrescences which will not go inside the main lines.

The Curtis body is small--and it has not one single bump on it from nose to tail. And it is pretty certain that a small clean body is better than a large clean one when one is trying to push it along at 200 mi./hr. or so.

For those who contemplate the designing of a machine to beat the Americans in the next race for the Schneider Cup it may be as well to remark that it is alleged that the new Wright T3 engine of 700 hp. has an even better frontal-area-to-power ratio than the Curtiss D12, and the reports that the Pulitzer Trophy machines with this engine have achieved speeds of within a mile or two of 250 to the hour seems to be entirely trustworthy.

No English engine maker has been able to afford to design an engine specially for racing purposes, and to that extent we are necessarily handicapped over this matter of body size.

THE REED AIRSCREW

Another factor contributing toward the success of the American machines is the Reed duralumin airscrew. Those used in the race were 8 ft. 9 in. diameter and they were directly driven at 2,300 rpm, giving a tip speed of 1,054 ft. per sec., which was near as no matter the velocity of sound. According to the R.A.E. the efficiency of an airscrew with a tip speed equal to the speed of sound is as nearly as can be zero.

The Reed airscrew at this tip speed is obviously fairly efficient--and it allows the Americans to dispense with a reduction gear on their racing engines. They can thus use a lighter engine--a smaller diameter airscrew,--and keep their undercarriage struts of reasonable length and still have water clearance. All these little things count. A special article on the Reed airscrew will be published as soon as possible.

The engines, radiators, and airscrews are the most striking features of the American machines. According to our authorities to attempt to run an airscrew of this diameter at this speed is to invite complete failure. The Americans have shown that our authorities are wrong on this point, and it is now up to us to find out how it is done.

The wing radiators are pretty certainly a very important feature. To all intents and purposes using this type of cooling system is equivalent to getting one's cooling for nothing whereas with a normal radiator the power absorbed in pushing the radiator of a 500 hp. engine at 180 mi./hr. would not, be much less than 5 hp. There is no novelty about the idea of using wing or body surface for cooling. There are obvious practical difficulties, and for some purposes some disadvantages. There is no disadvantage, for racing purposes at any rate, which can counterbalance an increase of at least 10 percent in the horsepower available for propulsion.

DETAILED DESIGN

These three main items--all concerned with the power plant--would by themselves give the American team ample excuses for having defeated us in the race. Beyond them however there is still something to be learned. The designer of the Curtiss racer was not content with general cleanness of design. He has seen to it that no unconsidered trifle was forgotten in the original lay-out and was afterward permitted to cause a minor irregularity of outline. As a matter of fact there are one or two small fittings for bracing wires on the underside of the top wing which look as though they might have been more carefully kept out of the draught. They are confined to the undersurface, where they have the least effect. It is extremely difficult to make a satisfactory wire terminal inside the wing surface--doubtless the wing radiators add to the difficulty--and there is precious little of these fittings anyway.

Otherwise the machines are as nearly perfect in this respect as they could be. The ailerons--on the bottom wing only--are recessed into the wing so that one could not put a strip of thin paper through the gap. Rudder to fin and elevator to tailplane hinge gaps are covered with rubber sheeting so that there is no gap in fact, and there is not a projecting control lever or wire anywhere on the machines.

The gasoline tanks are in the floats. The hand holes which give access to the filler caps, and those for inspecting the float interiors are recessed slightly into the surface. After these tanks were filled they were covered neatly by a square patch of doped on fabric, varnished as perfectly as the rest of the float and giving an unbroken surface.

The undercarriage struts go clean into the floats--apparently they are built in before the float is planked--and there are no fittings disfiguring their exposed surface. And so on throughout.

HIGH CLASS WORKMANSHIP

Not only is the workmanship and exterior finish of a very high class but it is obvious that the designer has taken as seriously the polishing up the last detail of his design as he took over the general lay-out. In fact he must have taken considerably more.

The merits of the American racers have been dealt with at this considerable length in order to make it quite clear how the Americans have achieved their success. It has been very generally asserted that the explanation is simply that the American Government was willing to spend as much money as might prove to be necessary

in order to win the Schneider Cup, whereas the British Aircraft Industry had no money to spare to defend it.

THE REAL COST OF WINNING

This explanation is accurate enough in its way. It is not however the whole explanation. In the first place it has to be remembered that what has been spent directly for the purpose of financing the Schneider Cup raid is a very small proportion of what has had to be spent to make that raid possible. The Curtiss D12 engine is a direct descendant of the Curtiss-Kirkham engine produced just after the war. Between that engine and the present there are at least three quite distinct varieties of Curtiss 12-cylinder high-performance engine each one an advance toward the ideal racing engine. No English manufacturer has been able to carry on the intensive development of high performance engines to this extent since the war although the engine work actually accomplished in this country under much more severe limitations on expenditure has possibly been of greater practical utility than that accomplished in America.

Over and above engines it may be recollected that since the War the American Aircraft Industry has produced a new batch of special racing machines every year--first of all for in attempt on the Gordon-Bennett trophy and since then for their own Pulitzer Trophy races. Last year alone America built more racing machines than Great Britain has built in her whole history. Thus the actual expenditure which has made it possible to produce the Schneider Cup Racers is extremely large--and almost the whole of it has been provided by the Government of the United States.

But it may be doubted whether the United States despite its large expenditure on this special object has an Aircraft Industry which is financially in a position to overwhelm the French Aircraft Industry in the production of racing aircraft. The Americans beat England--and still more thoroughly France--in the Schneider Cup race because regarded as racing machines pure and simple their Curtiss CR3s were as nearly perfect in every detail as they could be made.

WHAT IS NEEDED TO REGAIN THE CUP

The British Aircraft Industry can produce machines at least the equal of the CR3s. It needs for this purpose a fair amount of money--which at present it does not possess--but it need not expend a tithe of the money which has been spent on this purpose in America during the past five years. For there is not the least doubt that so far as general technical ability is concerned the British Aircraft Industry is ahead of the American, and that much that America has learned in the process of developing racing aircraft we have learned from our general experience.

But we have to learn that racing machines cannot safely be improvised at the last minute. The perfection of detail, the avoidance of every unnecessary compromise are essentials in the design of a successful racing airplane.

In aircraft built for either war or commerce design throughout is a matter of compromise between the conflicting requirements of aerodynamic efficiency practical utility, and cost, and British designers who have been brought up strictly to design for practical utility seem sometimes inclined to under-estimate the aerodynamic importance of detail design on the resistance of the complete machine.

Taking everything into consideration one has no doubt whatever that Great Britain can bring the Schneider Cup back from America--if not next year at least the year following. If we are to do it next year we have to start work at once, and some money has to be raised quickly.

INTER-GOVERNMENTAL SPORTS?

But on the whole the question of whether we are to try for the Cup again seems to be a matter for the Air Ministry to settle up with the Treasury. One had an idea that the Schneider Cup was instituted as a sporting Trophy. Since the advent of the mechanically-propelled vehicle one has had to modify one's ideas on the subject of the connection between sport and commerce far as motor car and airplane racing is concerned.

But the advent of the U. S. Government as a direct competitor in a "sporting" event is somewhat of a startling innovation. Obviously if the American Government has decided that the development of racing aircraft will lead to technical developments of real utility it is perfectly entitled to finance the design and building of such craft and to enter them for International events. And certainly none can suggest that in any detail the American team at Cowes and their auxiliaries have shown themselves to be anything other than sportsmen in the highest sense of the term. But it is pretty obvious that no private individual or corporation can afford to compete in such a test with the Government of the richest Power in the World.

Personally one believes that it would be all to the good were the precedent set by the U. S. Government in this matter followed by others. Inter-Governmental sporting events should have the happiest results on International relations if they were to become normal events but one cannot expect the British Aircraft Industry to compete on level terms with the American Government.

If the Air Ministry agrees with America as to the importance of racing as a method of developing the technique of aircraft design, then it is up to it to accept the perfectly open and honest challenge which America has offered, and to enter a team for the Schneider Cup and the Pulitzer Trophy races either next year or the year following.

THE "SEA LION"

The general characteristics of the "Sea Lion" are already pretty well known, because the machine is actually that which won the Schneider Cup last year at Venice. But certain modifications of detail have been made. The nose of the hull has been modified--the marked "ram" of recent Supermarine hulls has been considerably reduced by bringing the chines in more gradually which probably makes the

hull a bit dirtier on the water but correspondingly reduces the air resistance.

Fairing pieces have been added behind the side of the main step, and wing-tip floats of an elliptical cross section, of reduced buoyancy-- but fitted with bow hydrovanes to give dynamic support on the water have been fitted.

The engine cowling has been cleaned up appreciably and a smaller radiator of the "long tube" type has been fitted. Altogether the effectiveness of the modifications is shown by the increase of some 10 mi./hr. in the average speed attained this year as compared to the last race for the Cup.

In fact the "Sea Lion" did astonishingly well--the American racers ought to have beaten her by more than 20 mi./hr. if their superior cleanliness of line had been all gain, and the result actually achieved would seem to indicate that the flying boat type has intrinsic aerodynamic advantages as against the twin-float seaplane.

Personally one believes that the "Sea Lion" with wing radiators and a totally cowled-in "Lion" could give the CR3s a very good race indeed without further alteration. Unfortunately we shall not again have CR3s with which to compete.

THE CAMS

The two CAMS boats are of very similar design--the only important difference being that the type 36--designed for last year's race is a tractor with the pilot behind the wings, whereas the 38 has a pusher airscrew with the pilot ahead. Both are extremely clean and taking-looking boats. The type 33 is alleged to be some 10 mi./hr. the faster of the two.

The hulls are thoroughly well-made boat-built jobs, roughly rectangular in section forward, with a domed upper surface and the concave bottom which is favored by Signor Conflenti and by Mr. Short. They have but one step, the tail of the hull rising fairly steeply behind it, and the fin and tail plane are built up as part of the hull.

The wings are of the normal single-bay biplane type, but with a smaller chord on the lower wing. The engine nacelle is built up into the upper center section and is very thoroughly streamlined--the airscrew in both tractor and pusher types being fitted with a large spinner.

The engine mounting is used as the central support of the upper wing, thus securing a minimum of strutting at this position.

Both boats are exceptionally clean and given engines of the same class as those against which they had to compete should have made a very good show.

One believes that in regard to seaworthiness these two boats are distinctly good. They make a lot of spray getting off, and if they do not come away cleanly they fall back with a somewhat startling thud. But they probably unstick better in a bit of a sea than they do in a flat calm. They are--so far as one can judge--rather better rough-water craft than the American float machines, and closer approaches to pure racing machines than is the "Sea Lion." They were however outclassed in the matter of engine and in addition their luck was right out.

THE LATHAM

The big Latham boat with Lorraine engines in tandem was the foul-weather hope of the French team. Her flight to Cowes in a full vale was a very fine performance indeed, but one cannot feel very greatly enthused over the design. There is no doubt that for really rough seas one needs a heavily-built seaplane with plenty of engine power. The Latham had these qualifications and perhaps with the limited choice of engines available in France it may be regarded as a very fairly satisfactory attempt at a powerful and reasonably fast seagoing flying boat.

THE BLACKBURN PELLET

The fate of the Blackburn "Pellet" is very greatly to be regretted. All those of the Blackburn Staff and of Mr. Saunders' staff who worked so hard to get the machine ready in time for the race deserve every sympathy with the very bad fortune that befell their efforts.

One sympathizes with them the more because in many respects the "Pellet" was of a distinctly taking design, and because one feels sure that had there been a reasonable opportunity of getting the machine tried out before the race it might have put up a really good performance. .

As it was the machine had no chance. It was designed to make use of an existing hull which in fact proved to be defective in strength and unpleasant on the water under conditions quite different from those for which it was originally designed. Nevertheless one believes that it could have been made to get off and one is certain that in the air it would have been very fast.

But it was an effort to improvise a racing machine--and since the Americans have taken a hand in the game improvisations have a precious poor chance in International Air Races. Mr. Kenworthy's lack of seaplane experience spoiled what little chance remained.

The hull itself was of the Linton Hope type in general design, and of very clean lines. It was however intended for a much less powerful machine than the "Pellet" and was pretty certainly overloaded on the water.

On this hull was mounted a bottom wing of small chord and span, and above it--supported on a steel tube cabane and outwardly-raking N struts a top wing of considerably larger dimensions.

The Napier "Lion" was mounted above the top wing over the central cabane, and drove a tractor Leitner-Watts steel airscrew. Originally tubular radiators recessed into the lower surface of the top wing were fitted. These were not satisfactory, and a single Lamblin, mounted below the engine was later fitted instead.

The machine was undoubtedly distinctly tricky to handle on the water. A hull of relatively small beam--a high C.G., a narrow base for the wing-tip floats, and the torque of the Napier "Lion" made her very prone to immerse a wing-tip on opening up the engine. The hull obviously tended to porpoise badly at low speeds, and this combination of qualities needed a lot of handling.

Document 3-6

John K. Northrop, quoted in Garry R. Pape, *Northrop Flying Wings: A History of Jack Northrop's Visionary Aircraft* (Atglen, Penn.: Schiffer, 1995).

The following comments by Jack Northrop, quoted in a 1995 book detailing his aircraft designs, reflect his affinity for streamlining, but from the viewpoint of his extraordinarily innovative approach to aircraft construction technology. In this fashion, Northrop's abilities to integrate a new type of structure accentuated the aerodynamic capabilities of new airplane design. First tried on the diminutive Lockheed S-1 sport plane of 1919, Northrop's technique of forming a plywood fuselage between a concrete mold and an inflatable rubber bag enabled a manufacturer to build an exceptionally streamlined airplane, and to do so rather economically. As for the wing, Northrop looked for inspiration to Dutch aircraft builder Anthony Fokker's cantilever designs. He went with cantilever even though Lockheed president, Allan Loughead, was against it, because he felt that potential buyers would feel the plane was unsafe without an appropriate amount of bracing struts and wires. A highly intuitive thinker, Northrop reasoned that the streamlined combination of cantilever wing and monocoque fuselage, both without drag-producing struts and wires, could operate at less power and do a better job than aircraft that weighed much more. His gamble proved highly effective, and the new airplane, the Vega, became one of the breakthrough designs of all time.

Document 3-6, John K. Northrop, quoted in Garry R. Pape, **Northrop Flying Wings: A History of Jack Northrop's Visionary Aircraft** *(Atglen, Penn.: Schiffer, 1995)*

NORTHROP FLYING WINGS
QUOTES FROM JACK NORTHROP'S FIRST COMPANY:

A steady program of development and refinement has been underway for the past twenty years until we have at present [1930] a number of carefully designed and comparatively efficient planes embodying streamline fuselages, carefully cowled engines, and 'clean' landing gears with superfluous struts, wires and fittings suppressed to an absolute minimum. It seems quite apparent that our best designs are close to the limit of practical efficiency; yet we find that their maximum over-all L/D (lift-drag) ratio is only about 10, whereas the L/D ratio of the active supporting surfaces of an airplane is normally double this amount.

An analysis of the items adding to parasite drag in the normal design shows that landing gear, power plant, fuselage, interference and bracing, and control surfaces are the major contributors to parasite power loss; the item of control surfaces being by far the smallest. Individual examination of the various units shows that nearly all possible improvement has been made in existing designs.

"We didn't dare to go the whole way and eliminate the tail."

It was obvious that the ideal flying wing was impractical or impossible to construct except in very large sizes. The airplane cannot justify its existence unless it has capacity to carry a comparatively bulky cargo. With conventional wing thicknesses it was impossible, even with very large wing taper, to build a flying wing in sizes of less than 150 or 200 foot span.

The whole objective was to build as clean an airplane as we could possibly conceive in those days. The average airplane had struts or wires or fuselage forms that weren't as smooth or streamlined—with as low a drag as possible. It was pretty obvious, it seemed to me, that a full cantilever wing neatly faired to the fuselage on a perfectly streamlined fuselage would take less power to do the job than some other types. So it was a breakthrough in that we went wholeheartedly into, for the time and at the time, to conceive as clean an airplane as we could. Fortunately, the work in Santa Barbara some years previously had already developed the technique for building a fuselage. It was then just the necessity of designing a full cantilever wing.

Document 3-7

B. Melville Jones, "The Streamline Aeroplane," *Aeronautical Journal* 33 (1929): 358-385.

In 1929, Great Britain's leading aerodynamicist, Cambridge professor Dr. B. Melville Jones, presented what in retrospect must be regarded as the single strongest statement made in favor of the advantages of reducing drag through streamlining that has ever been made in the history of aviation. The paper he read before the Royal Aeronautical Society, entitled "The Streamline Airplane," outlined conclusively how streamlining directly reduced the total drag of an airplane. Jones stressed that such drag reduction would result in higher cruising speed and lower fuel consumption and would consequently increase range and payload. The Cambridge don pointed out the inefficiency of previous aircraft designs, and he cited reduction of form drag as the most important obstacle to increased aerodynamic efficiency.

The aeronautical community received Jones's landmark speech with tremendous enthusiasm, and their reaction to his talk indicated the first widespread conversion of an entire aeronautical community to the benefits of streamlining.

Document 3-7, B. Melville Jones, "The Streamline Aeroplane," **Aeronautical Journal** *33 (1929): 358-385.*

During the past two years Professor Jones has been turning his attention to quantitative work on control. He has recently completed a first stage in a research showing by instrumental records exactly what happens to all the controls and to the aeroplane itself for certain specified movements made by the pilot. The flights were carried out largely by Professor Jones in an aeroplane specially loaned by the Air Ministry to the Cambridge University Air Squadron; the results of this pioneer research work provided a basis for similar experiments on other aeroplanes to be carried out at the R.A.E. and at [Martingham].

About a year ago Professor Jones first drew the attention of the A.R.C. to the great step forward that was possible in the improvement of aeroplane performance by comparing the resistances of an actual aeroplane with those theoretically possible. Much further evidence has been added since that date with the consequence that the A.R.C. initiated a series of researches on the interference of one part of an aeroplane on another. The first results of the interference research, carried out by a sub-committee under his chairmanship, are now to hand and have justified the prediction made by Professor Jones as to the large improvement that was possible.

Professor Jones has been an independent member of the A.R.C. since its appointment in May, 1920, and has assisted in a number of further matters to which that committee has paid attention since that date.

THE STREAMLINE AEROPLANE

BY B. MELVILL JONES, A.F.C., M.A., F.R.A$_{E}$.S.

Ever since I first began to study Aeronautics I have been annoyed by the vast gap which has existed between the power actually expended on mechanical flight and the power ultimately necessary for flight in a correctly shaped aeroplane. Every year, during my summer holiday, this annoyance is aggravated by contemplating the effortless flight of the sea birds and the correlated phenomenon of the beauty and grace of their forms.

We all possess a more or less clear ideal of what an aeroplane should look like; a kind of albatross with one or two pairs of wings—depending on whether we live in Germany or Britain. In our more sanguine moments we even—like Alice and the cat—see the wings without the albatross. But progress towards this ideal, so far as the general purposes craft is concerned is, we must all admit, painfully slow. It has seemed to me that a contributory factor to the slowness of this evolution has been the lack of any generally understood and easily visualized estimate of what could be achieved were the difficulties in the way of realizing the ideal form overcome. There is a natural tendency to decide on one day that the gain—say 20 percent on the total drag, or 7 percent on the speed—to be had by spending endless trouble on improving the undercarriage design, is not worth the trouble; on the next day to come to a similar conclusion about the drag of the engine cooling apparatus; on the next day about the wires, struts and minor excrescences; and on the next about the pilot's view; omitting to notice that if all the improvements were made at once the total gain would not be some insignificant percentage of the whole, but might reduce power consumption to a small fraction of its original value and so extend the range and usefulness of the aeroplane into realms which would otherwise be unattainable.

Considerations such as these led me some time ago to examine the possibility of devising simple formulae for the power required by the ideal streamlined aeroplane, and this lecture is a result of that examination. The very simple formula which I shall discuss is not precise—the present state of aerodynamical knowledge does not allow precision in this matter. It is not possible, for example, to say that lower power expenditures than my estimate might not occur. I am not so bold as to prophesy any limit to progress, but I think that I have made out a case that the power expended on the ideally streamlined aeroplane would not be greater than my estimate. Since this is of the order of one third the power expended on modern passenger carrying aeroplanes, the estimate should suffice, until such time as it more nearly represents actual performance; by which time we may hope that aerodynamic science will have progressed to a stage at which more accurate estimates can be made.

The formula at which I arrive is so simple and obvious that many will consider that I have wasted breath, ink and paper in putting it before you. That may be, but the difficulty lies in the choice of the quantities to be neglected and the argument here bristles with points where the scientist can pick holes. If you had had the job of putting a theoretically leaky argument such as this before a body of scientists, who are of necessity more concerned with detecting fundamental errors in reasoning than in devising engineering approximations, you would understand why I have gone to some trouble to expose, as precisely as I am able, the assumptions upon which the final conclusion is reached.

My lecture therefore deals with the possible reduction of aerodynamic head resistance, or drag, and hence of the power required for flight. At the outset it is perhaps worth noticing that such reductions will not greatly reduce the maximum power necessary for a given service, since maximum power is required for getting off from the aerodrome—an operation in which weight is the predominating factor. Reduction of drag will, however, enable an aeroplane of a given power loading, either to cruise at a higher speed or with a lower petrol consumption. This again will result in increased range or paying load, both factors of the first importance in aeronautical development.

Before the power required to overcome drag can be interpreted in terms of engine power, the airscrew efficiency must be taken into account. Efficiencies as high as 75 percent are practicable on present-day craft, and efficiencies higher than say 85 to 90 percent are unlikely to be achieved in the near future; hence the possible power economies to be obtained from further airscrew development—e.g., through the use of the variable pitch screw—through by no means negligible, are unlikely to be very great. I shall not deal with the airscrew problem further, except in so far as the body-airscrew interference may influence my main argument.

Thanks to the combined efforts of Lanchester and Prandtl we can now isolate from the whole power that part—the power to overcome induced drag—which is expended in supporting the weight on a wing of finite span. This induced power, as it may be called, depends primarily on "*span loading*" that is weight/(span)^2. For a biplane of reasonable proportions the induced power per 1,000 lbs. weight can be expressed as

$$2.80^1\varpi/\sigma V_m$$

where V_m is the speed, with one hundred miles per hour as the velocity unit.
σ is the ratio of the air density to that of standard air, and
ϖ is the span loading in pounds per square foot.

The brake horse-power corresponding to the induced power is obtained by dividing by the airscrew efficiency. Assuming an airscrew efficiency of 75 percent, an average span loading of say 2.2 lbs. per sq. ft., and making σ equal to unity, we get the following table for the b.h.p. required for the induced power in a normal biplane.

B.h.p. per 1000lbs. weight

Speed m.p.h.	For Induced Drag	Total normally supplied	(Ratio) Total Power / Induced Power
90	9.1	35	25%
100	8.2	45	18%
120	6.8	75	9%
150	5.	5120	5%

Although the "induced power" is an important item in the power account at the lower cruising speeds, it is not the predominating factor at speeds above 90 m.p.h. Moreover, since it is clear from theory that no notable reduction in induced power is to be obtained without using much larger wing spans, I shall not in this lecture examine the problem of reducing it still further.

Since no great power reductions are to be obtained either by improving airscrew efficiency or by reducing "induced power," it remains to examine the possibility of reducing that part of the head resistance which arises merely because the aeroplane is being dragged through the air, without reference to the fact that is must support its own weight. Using terms in common use, this part of the whole drag is described as the sum of the wing profile drag and the parasitic drags. The power required to overcome it is seen in the table above to lie between 75 and 95 percent (according to speed) of the total power applied to the modern general purposes aeroplane. Any serious reduction in this item will therefore have an important influence on the total head resistance.

We all realize that the way to reduce this item in the power account is to attend very carefully to "*streamlining*." It is the main object of this lecture to examine how far this item can be reduced by perfect streamlining, and this incidentally will involve a preliminary explanation of what I mean by an ideally streamline aeroplane.

We recall first a proposition relating to that mythical and much abused substance, "the perfectly inviscid incompressible fluid." Theoretically when this hypothetical fluid streams steadily past a body, such as an aeroplane, the forces exerted on the surface of the body are everywhere normal to the surface; no tangential or skin friction forces can arise. The total reaction on the body, the resultant of all the pressures acting normally to the surface, is such that the "*drag*," or down-wind component, will be related to the "*lift*," or cross-wind component, according to the Prandtl theory of induced drag. In other words, Prandtl's induced drag is the sum of the down-wind components of all the normal pressures which would be set up by that steady flow of the hypothetical fluid which gives the required lift. It follows as a particular case of this proposition that the steady flow of the inviscid fluid which gives no lift also gives no drag.

In aeronautical nomenclature a "*streamline body*" is one about which the flow of a real fluid, such as air, approximates closely to a steady flow of the hypothetical inviscid fluid, except in a very thin layer called the "*boundary layer*," surrounding the

exposed surfaces. In such a flow the pressures normal to the solid surfaces are very closely equal to the pressures of the corresponding flow of the hypothetical fluid, but the action of the real fluid in the thin boundary layer causes additional tangential surface forces, or skin frictions, which are not present in the hypothetical flow.

An ideally streamline aeroplane may therefore be defined as one which:—

(a) Generates a flow identical, except in a very thin "boundary layer," with the flow of an inviscid fluid.

(b) Experiences a pressure distribution identical with that due theoretically to the inviscid fluid;

and therefore

(c) Experiences a drag which is the sum of the induced drag and the tangential or skin friction forces resolved in the down-wind direction.

Like all ideals, the ideally streamline aeroplane cannot exist; the boundary layer must have some thickness, so that the flow cannot be exactly the same as one in which there is no boundary layer. If the "*Reynolds' number*" is small, or in other words, if the effective viscosity of the fluid is high, the boundary layer becomes so thick as to make the above definition meaningless, but with the very high Reynolds' numbers, typical of aeronautical practice, the approximation for a good streamline body is very close.

It is, of course, well known that, unless bodies are carefully shaped, they do not necessarily generate streamline flow but shed streams of eddies from various parts of their surface. The generation of these eddies, which are continually being carried away in the air stream, requires the expenditure of power additional to that required to overcome induced drag and skin friction. The power absorbed by these eddies may be, and often is, many times greater than the sum of the powers absorbed by skin friction and induced drag. The drag of a real aeroplane therefore exceeds the sum of the induced drag and skin friction drag by an amount which is a measure of defective streamlining.

Having arrived at the conclusion that the drag of the ideally streamline aeroplane is the sum of the induced and skin friction drags, the next step is to estimate the magnitude of these drags. Methods of estimating the former are well known and an approximate formula is given on page 359. No corresponding theory yet exists for the estimation of skin friction on curved surfaces such as those of the wings and body of an aeroplane. We are therefore forced to adopt some empirical method of investigation. The simplest experiments on skin friction are those upon a thin flat plate edgewise to the wind, for here the resultant, in the down-wind direction, of the surface pressures is necessarily zero. The best experiments, of which I am aware, upon the drag of such a plate at high Reynolds' numbers were made at Göttingen some years ago. They lead to the formula

$$k_F = 0.019\ R^{-.15}$$

where k_F, the skin friction coefficient, stands for (skin friction)/$\rho V^2 E$ and R stands for $\rho Vl/\mu$ where

V stands for the relative velocity of air and plate.

E stands for the total exposed area of both sides of the plate.

l stands for the length of the plate in the wind direction.

ρ and μ are the density and viscosity of the air.

R is thus the Reynolds' number involving the dimension parallel to the wind direction.

The experimental range was approximately from $R = 2 \times 10^5$ to $R = 10^7$.

This expression (1) relates to conditions in which the "boundary layer" is turbulent over the greater part of the plate, that is to say, the air very close to the surface of the plate is eddying—as it were, rolling on the surface. Burgers, of Delft, has shown that near the front of the plate the boundary layer is not turbulent, the separate layers of fluid near the surface of the plate slip over each other smoothly. When the Reynolds' number is small this smooth region extends over the whole plate and the skin friction drag has, in these circumstances, been shown to agree closely with the theoretical expression

$$k_F = 0.66\, R^{-1/2}$$

Thus at very low Reynolds' numbers the drag coefficient is as equation (2), but at high numbers as equation (1). In Figs. 1 and 2 I have plotted curves representing the expressions (1) and (2), above, on the assumption of smooth and turbulent boundary layers respectively. The upper curve in each figure represents expression (1) and the lower expression (2). At medium Reynolds' numbers, where the boundary layer is smooth over the front part of the plate and turbulent over the rear part, the average drag coefficient for the whole plate will lie between the upper and lower curves of Figs. 1 and 2; its exact value depending upon the distance from the leading edge at which the breakdown from laminar to turbulent flow occurs. The curve followed by the drag coefficient in this intermediate condition may be described as a "*transition*" curve, between the lower and upper curves of Figs 1 and 2. I have lightly dotted in roughly calculated transition curves, on the assumption that the critical change from smooth to turbulent boundary layer occurs when the Reynolds' number formed from the distance of the breakdown point behind the leading edge has certain arbitrarily selected values, e.g., 10^5 and 5×10^5.

Burgers has found that for the flat plate the value of the Reynolds' number at this point of breakdown depends on the steadiness of the air in the tunnel before reaching the plate. When the flow was as steady as he could make it the change occurred when $R = 5 \times 10^5$. When the flow was deliberately made unsteady, by bringing the wind tunnel honeycomb nearer to the plate or by placing wire gauze across the tunnel in front of the plate, the break up of the boundary layer occurred

FIG. 1.
COMPARISON BETWEEN PROFILE DRAG OF WELL-KNOWN WINGS AND THE SKIN-FRICTION ON A FLAT PLATE.

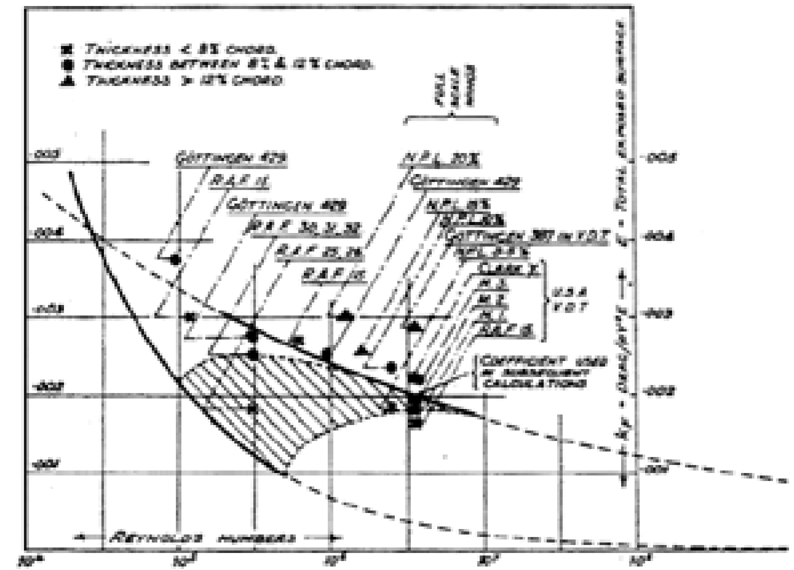
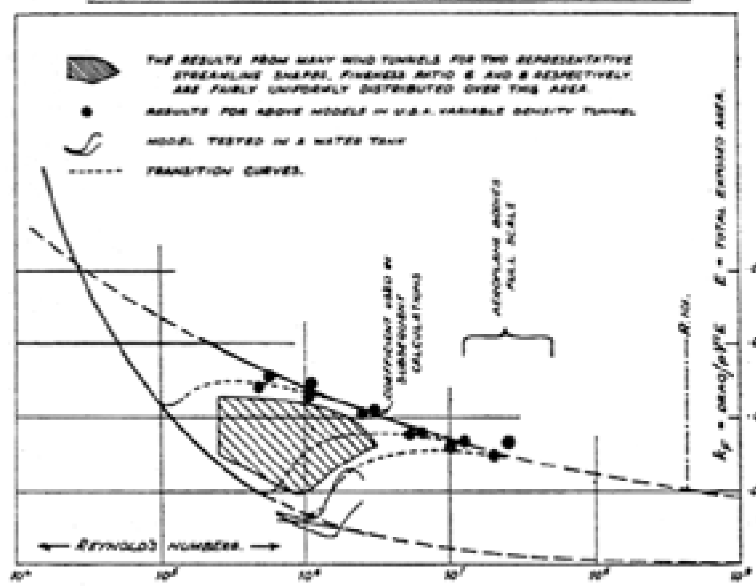


FIG. 2.
COMPARISON BETWEEN THE DRAG OF STREAMLINE SOLIDS OF REVOLUTION AND THE SKIN FRICTION ON A FLAT PLATE.



earlier, $R = 10^5$ approximately. Thus in the former case the drag coefficient of the flat plate should be expected to follow the lower curve until R has increased to 5×10^5 and then follow the transition curve which starts at this point, to the upper curve. In the latter case the change would take place along a transition curve which leaves the lower curve at $R = 10^5$. If it is assumed that the point of breakdown is uncertain between the above limits, the drag of the thin flat plate would be expected to follow the lower curve below $R = 10^5$ and the upper curve above $R = 5 \times 10^6$, but it might be anywhere within the shaded area when R lies between these two values. If the wind tunnel experiment were made on the plate between these two limits of R, the drag would be expected to vary erratically from tunnel to tunnel according to the turbulence of the air in the tunnel.

Our precise knowledge of the drags of very good streamline bodies other than the flat plate is confined at present almost entirely to the results of wind tunnel tests on solids of revolution, such as bare airship hulls, and on isolated wings. The former when moving axially exert no lift, and consequently their drag, if they conform to my definition of "streamline," should be entirely due to skin friction; the latter, when they exert lift should, if streamline, experience induced drag as well as skin friction drag. My first concern, when starting the investigation upon which this lecture is based, was to determine to what extent the drag of the better known streamline solids of revolution and the profile drag (total drag minus induced drag) of the better known wings, could be estimated from the known skin friction on a flat plate. To do this I have expressed the profile drags of certain wing sections and the drags of certain streamline solids of revolution in the form

$$k_F = (\text{drag})/\rho V^2 E$$

where E is the total exposed area. These coefficients are plotted in Figs. 1 and 2, where they can be directly compared with the curves showing similar coefficients for a thin flat plate, as explained above. The Reynolds' number for these wings and streamline solids is of the form

$$R = \rho V l/\mu$$

where l is the maximum dimension of the body parallel to the wind—the "length" of the streamline solid and the "chord" of the wing.

Comparison in Figs. 1 and 2 between the experimental points and curves for the solid shapes and the curves for the flat plate at the same value of R, amounts to comparison between the drags of the solid shapes and of a thin flat plate of the same total exposed area, having a length parallel to the wind equal to the maximum length in this direction of the solid shape. I shall in future describe such a thin flat plate as the "*equivalent plate*."

Figs. 1 and 2 are, I think, striking and significant. In Fig. 1 the points clearly tend to cluster around the upper curve, appropriate to the turbulent boundary layer, but one set of points, those for thin wing sections R.A.F. 25 and 26 at values of R in the neighborhood of 3×10^5, show a tendency to fall towards the lower curve. We may summarize this diagram by the statements that:—

When the thickness of the wing is less than 8 percent of the chord the profile drag is less than that of the equivalent plate. This includes nearly all wings used in Britain before some two or three years ago.

Up to a thickness of 12.5 percent the profile drag is within some 10 percent of that of the equivalent plate. This includes the great majority of wings used in Britain at the present time.

Thicker wings, up to 15 percent or 20 percent, apparently have higher profile drag coefficients—between, say, 15 percent and 50 percent greater than the equivalent plate, according to shape and place of test.

Turn now to Fig. 2. The bulk of the available information here results from extensive trials upon two models of bare airship hulls which were tested in a number of different wind tunnels in the various aerodynamic laboratories of the world, with the primary object of comparing the tunnels. The result was to show that wind tunnel experiments on very low drag models, such as these, are uncertain and depend to a great extent on the local conditions, such as turbulence, etc., in the tunnel. Speaking broadly, it may be said that the various wind tunnels gave experimental results for these models lying anywhere within the shaded area; you can take your choice as to which you are prepared to believe. There are clear signs, however, that as the Reynolds' number rises towards the extreme limit of atmospheric tunnels, the uncertainty becomes less and the tunnels tend to agree in placing the coefficient slightly below that of the equivalent plate. This tendency is somewhat faintly reflected in the shape of the shaded area.

The black circular dots relate to individual experimental results for these same two models in the American variable density wind tunnel. These points, which are carried to much higher Reynolds' numbers than were obtainable in atmospheric pressure wind tunnels, fit the upper or turbulent boundary layer curve with remarkable accuracy, even in the region of the lower Reynolds' numbers, where the majority of the atmospheric pressure tunnels give lower coefficients. The explanation of this is probably that the variable density tunnel employs a fine honeycomb, very close in front of the model, which should result, according to Burgers' experiments, in an exceptionally early break up of the boundary layer from laminar to turbulent flow. Thus under conditions in which, for a flat plate, the boundary layer would be turbulent over the majority of the plate, the drag of two different airship models is found to be closely equal over a very large range of Reynolds' numbers to that of the equivalent flat plate with turbulent layer.

The thin continuous lines near the bottom of the figure, in the neighborhood of

$$R = 10^6,$$

relate to an experiment carried out on a different model in the experimental naval tank of the National Physical Laboratory. Here the fluid—water—was very still and the model was pushed from behind instead of being supported by wires attached at various points on its surface. External disturbances were thus reduced to a minimum. This treatment is seen to result in the coefficient falling very close to the lower curve appropriate to a flat plate with *laminar* layer. The experimental curves, however, begin suddenly to rise at Reynolds' numbers slightly greater than 10^6, in exactly the manner which would be expected if the layer at the rear part of the model were beginning to become turbulent at the higher Reynolds' numbers. That is to say, the curves rise approximately along the theoretical transition curves, which here have a slightly different shape from those in Fig. 1, owing to the tapered tails of the models. This same model was tested with the same method of support in one of the National Physical Laboratory 7 ft. wind tunnels, and produced a curve almost coincident with the lower of the skin friction curves in this figure. It was not, however, practicable in the wind tunnel to reach a Reynolds' number much above 10^6 and no signs of the rise in coefficient was observed. These experiments, both in air and water, were repeated with a thin string loop slipped on to the nose of the model, to form a slight obstruction which, from previous experiments of a similar nature, would be expected to cause the boundary layer behind it to become turbulent. With this addition the drag coefficients both in air and water increased some fivefold and approximated closely to that for the equivalent flat plate with turbulent boundary layer. Thus, in circumstances where the boundary layer, from analogy with the flat plate, may be expected to remain laminar to a relatively high Reynolds' number, the drag of the model is very closely equal to that of the equivalent flat plate with *laminar* boundary, and the rise in coefficient, when it does occur, takes place in exactly the manner which would be expected on a flat plate with tapered rear. When, however, a slight change is made to the surface, which would be expected to break up the boundary layer over the greater part of the surface, the drag approximates closely to that of the equivalent flat plate with *turbulent* boundary layer.

I have examined the drags of other streamline solids of revolution in the same way as above, and I find that so long as the fineness ratio is not less than 4 the coefficients all fall between the upper and lower curves of Fig. 2.

Reviewing the evidence relating to streamline solids of revolution, it seems difficult to resist the rather surprising conclusion that their drag can be estimated with considerable accuracy from the drag of what I have called the equivalent flat plate. If the experiments recorded in Fig. 2 had been conducted upon thin flat plates of the same superficial area as the models and of the same length in the direction of motion as the overall length of the models, they cold not have given results more in conformity with the known behavior of the boundary layer on a flat plate, than the results actually recorded.

We do not yet know to what extent it may be possible to increase Reynolds' numbers whilst retaining a laminar boundary layer, but it seems probably that in

the majority of instances the layer will be mainly turbulent before the Reynolds' number appropriate to aeroplane bodies in flight—say, between 2 and 5 times 10^7—is reached.

For the purposes of the present paper it is sufficient to note that the upper or turbulent layer curve appears to give an upper limit to the drag coefficient of good streamline shapes, whether they be in the form of wings or solids of revolution, provided that the fineness ratios are not less than 8 in the case of wings and 4 in the case of solids of revolution.

The information displayed in Figs. 1 and 2 relates to simple shapes such as isolated wings and solids of revolution. There is as yet little information available relating to good streamline shapes in combinations, such as the wings and bodies of aeroplanes, or to the distortion and interference to which a shape can be subjected without becoming unstremline . Such information as is available suggests that combinations, or minor distortions, can be made without appreciable increase of drag, provided we know how to make them. It is therefore reasonable to suppose, after examining Figs. 1 and 2, that complex bodies such as aeroplanes could, given sufficient knowledge and structural ability, be made to have a drag no greater than the sum of the induced drag and the drag of the equivalent flat plate.

If the drag of the streamline aeroplane is simply the sum of the induced and skin friction drags, the power required to tow it would be obtained by multiplying these drags by the forward velocity V. Let I and F be the powers required to overcome induced and skin friction drags respectively. If the streamline aeroplane is towed by an airscrew of efficiency η, effectively isolated from it so that there is no interference, then the b.h.p. required to drive the screw will be

$$(I + F)/\eta$$

How are we to regard interference between screw and body, when such exists? Interference will alter torque and thrust reactions between screw and engine. The change in torque may call for a redesign of the screw to make it balance engine torque at suitable engine revolutions. The change of thrust is of no interest, except in relation to the size of thrust bearing required, for it may be largely neutralized by change of body drag. Neither change is of direct interest from the present point of view, which is to examine any possible changes in b.h.p. due to interference, assuming always that *the screw is properly designed for the engine*. With this assumption it is not difficult to show that, to a first approximation, the b.h.p. required to propel the *streamline* aeroplane should not be seriously influenced by interference, provided that the interference does not cause the flow to cease being streamline.

We arrive at this conclusion by considering the disturbances left in the air behind the streamline aeroplane. They may be divided into:—

1. The airscrew slipstream.
2. The induced vortices.

3. The small scale turbulence, and possibly temperature rise, due to skin friction on the exposed parts of the airscrew blades and on the aeroplane.

Since, by hypothesis, the flow around the streamline aeroplane is substantially that of an inviscid fluid, except in the very thin boundary layer where the skin friction is applied, the *whole energy* expended—the b.h.p.—is included in the above three items.

The energy in the slipstream is mainly due to the axial velocity of the stream; it is dependent upon the effective diameter of the stream and the net thrust of the screw and body behind it. If, as we may reasonably suppose, these are unaltered by the interference, item (I) will remain substantially unaltered.

The energy *I* in the induced vortices will not be altered by interference, unless the interference appreciably alters the lift distribution across the wing span. If considered necessary, the alteration could be estimated and *I* taken to apply to the induced power associated with the actual lift distribution in the presence of interference.

The energy expended on skin friction on the airscrew blades will not be seriously affected by any reasonable interference.

The energy *F* expended on skin friction on the aeroplane will be affected only on those surfaces which are exposed to the slipstream. This effect will always be small; at high speeds, where *F* is an important item, the slipstream velocity is low, whilst when climbing *F* is but a small part of the power expenditure. To a first order, therefore, this item in the power account will also be unaffected by interference, but if higher accuracy is required *F* must be taken to relate to the estimated skin friction with allowance for increased velocity over surfaces exposed to the slipstream.

I do not maintain that the above arguments are precise, but if they are examined carefully, with due regard to the quantities involved in practicable aircraft, I believe that they will be found sufficient.

We are now in a position to state the main conclusion of the lecture, which is as follows:—

The brake horse-power required to propel the streamline aeroplane horizontally may be estimated as

$$(F + I)/\eta$$

where η is the efficiency to be expected from an isolated screw performing the service required.

F is the power expended in skin friction, which may for the present be taken to be that required to propel the equivalent flat plate.

I is the induced power.

As a first approximation *F* and *I* may be estimated for the aeroplane isolated from the screw. As a second approximation *F* can be altered to allow approximately for the increased velocity over surfaces exposed to the slipstream and *I* to allow for alterations in lift distribution across the wing span due to the slipstream. In the estimates which follow the first approximation is sufficient for my purpose and I have not proceeded beyond it.

When the streamline aeroplane is climbing, the above expression for brake horse-power must include another term *C*, equal to the product of weight and rate of climb. Thus

$$\text{b.h.p.} = (F + I + C)\eta$$

It remains to give numerical expression to the symbols *I*, *F*, *C* and η.

The estimation of *I* presents no difficulty. A simple formula $I = 2.80\ \varpi/\sigma V_m$ horse-power per thousand pounds weight with span loading ϖ in pounds per sq. ft. and V_m measured in hundred-mile-per-hour units has already been given. This formula applies strictly to a biplane or normal gap and aspect ratio and of rectangular plan form, but is easily modified (see footnote on p. 4) to apply to a monoplane or biplane of any desired gap or aspect ratio.

The skin friction power *F* depends upon the skin friction coefficient

k_F = (skin friction drag)/$\rho V^2 E$

and before *F* is estimated some value for k_F must be adopted. The question arises as to what value is to be given to k_F. If it is to be taken from the value for the equivalent flat plate, i.e., from the upper curve of Figs. 1 or 2, its value will depend on the Reynolds' number, and this raises the further question as to how the Reynolds' number for the aeroplane is to be estimated. The Reynolds' numbers of full scale aeroplane wings, based on the chord as a measure of size lie between 4×10^6 and 10^7 and the corresponding value of k_F for a thin plate (see Fig. I) lies between 0.0020 and 0.0017. The Reynolds' number of the bodies of full scale aeroplanes, based on their length as a measure of size, lie between 2×10^7 and 5×10^7, and the corresponding value of k_F (see Fig. 2) lies between 0.00155 and 0.00135. The logical proceeding would be to estimate the wing skin friction drag from Reynolds' number appropriate to the body. But for simplicity and so as to be on the safe side, I propose, for my present purpose, to take an over-all figure for k_F of 0.0020. This should leave us a little in hand to allow us to use moderately thick wing sections—say, thickness up to 12 percent of the chord—in our ideally streamline aeroplane.

Using this figure we have

$$F = 0.002\ \rho V^3 E \text{ foot pounds (using any consistent units).}$$
$$= (27\ \sigma V_m{}^3 E)/W \text{ horse-power per 1000 lbs. weight.}$$

where V_m, is in hundreds of miles per hour units, *E* is the exposed surface in square feet, and *W* is the weight in pounds.

Finally, the climb power *C*, per 1,000 lbs. weight, is easily shown to be given by $C = 0.030\ V_C$ where V_C is the rate of climb in feet per minute.

These three simple expressions for *I*, *F* and *C*, allow an approximate and probably conservative estimate to be made of the power that would be required by an aeroplane in any given circumstance, provided that the flow around it were everywhere streamline and no unnecessary eddies were generated. The difference between the actual power expended and the power so estimated must be regarded as being expended in the generation of unnecessary eddies which might be avoided by more careful attention to external form.

I have thought it of interest to prepare a few curves showing the performance, in level speed and climb, of a streamline biplane in air of standard density near ground level. For this purpose I have taken $E = 3.2 \times S$ where *S* is the conventional wing area, so that $F = 86\,\sigma V_m^{\,3}/\omega$ where ω is the wing loading in pounds per sq. ft.

I arrived at this value 3.2 by computing *E* roughly for a number of well-known aeroplanes and finding that *E*/*S* ranged between 3.0 and 3.5 with 3.2 as an average value. In drawing the curves I have taken σ to be unity and η, the screw efficiency, to be 75 percent for level flight and 70 percent climbing.

Fig. 3 shows four curves giving b.h.p. per 1,000 lbs. weight, for level flight at various speeds for, the following conditions:—

wing loading (ω) 10 and 15 lbs. per sq. ft.
span loading (ϖ) 2 and 2 ½ lbs. per sq. ft.

The individual points, with the names of well-known aeroplanes written against them, refer to the b.h.p. at top speed as given in the 1927 edition of Jane's "All the World's Aircraft." The small circles relate to aeroplanes for which ω is approximately 10 and the squares to those for which ω is in the neighborhood of 15.

The vertical distance between the points and the appropriate curve represents the power being expended on what, from the present point of view, much be described as unnecessary turbulence. Horizontal distances from the curves represent the increased velocity which might presumably be obtained for the same power expenditure in the absence of unnecessary turbulence.

Apparently large commercial aeroplanes, such as the Argosy, the W.10 and the Hercules, would, were they ideally streamline, either fly at the present top speed for one-third the present power, or alternatively travel some sixty miles per hour faster for the same power. Two-thirds of the power used by these aeroplanes is being expended on the generation of turbulence which, from the aerodynamic viewpoint, is unnecessary.

Fig. 4 is constructed on the same lines as Fig. 3 except that the abscissae represent rate of climb and the three continuous lines show the expenditure of horsepower required for a streamline aeroplane, divided up into the three parts: weight-lifting power, induced power and skin friction power. Here the span loading is 2.2 lbs. per sq. ft., which is a good average figure for modern aeroplanes, whilst the wing loading is taken as 10. The airscrew efficiency is taken to be 70 percent.

FIG. 3.

COMPARISON BETWEEN REAL AND STREAMLINE AEROPLANE.
FIGURES FROM 1927 JANE. TOP SPEED.

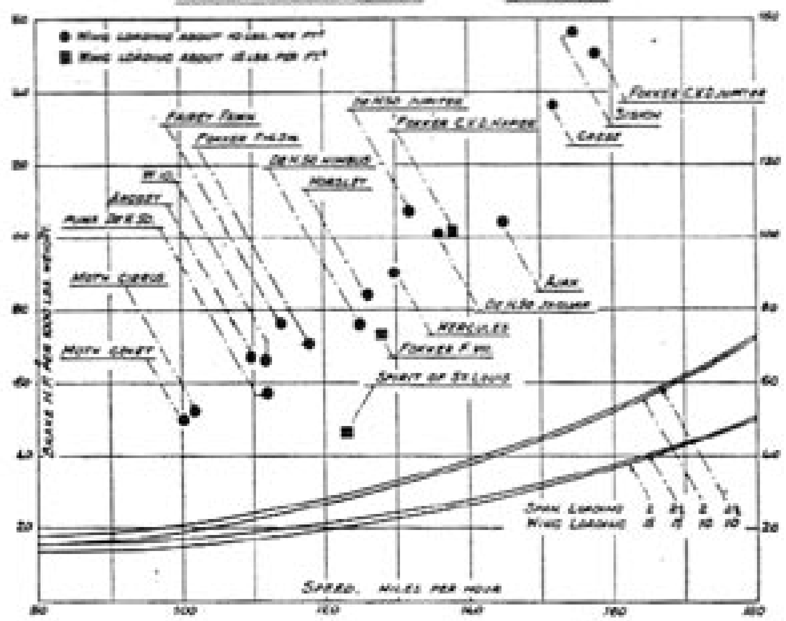
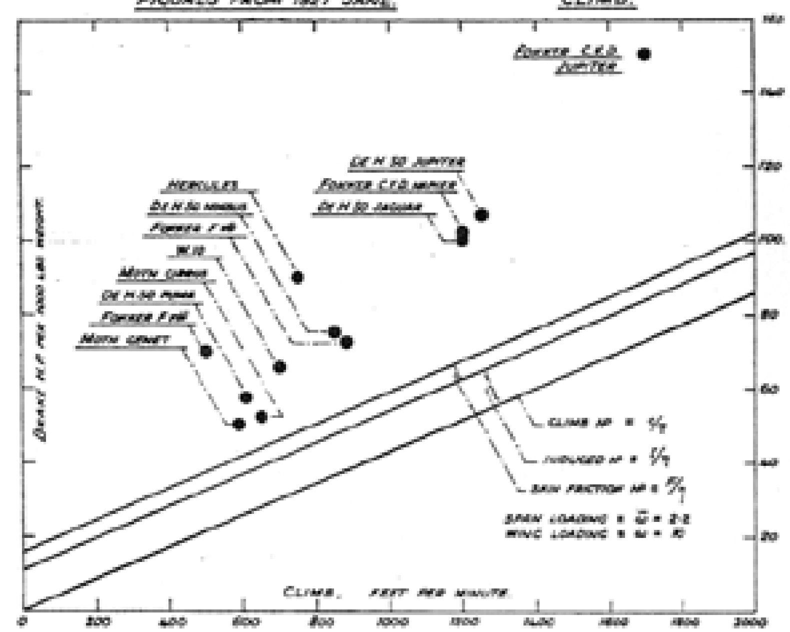


FIG. 4.

COMPARISON BETWEEN REAL AND STREAMLINE AEROPLANE.
FIGURES FROM 1927 JANE. CLIMB.



Though improvements in power consumption for climbing are not so great as for top speed, they are still appreciable. The very high ratio between the power apparently expended in turbulence in some cases and the power lost in skin friction, suggests very high turbulence losses, due probably to severe interference between the slipstream, the wing and the body in these circumstances. Possibly the assumed airscrew efficiency of 70 percent is too high for climbing conditions on modern commercial machines, and this may account for some of the heavy losses indicated in the diagram.

RECAPITULATION

The lecture consists of a search for a simple and reasonably sound way of estimating the power which would be required to drive a perfectly streamline aeroplane. The formula finally reached is very simple and easily visualized; the difficulty lies in defending the approximations by which it is reached.

There are two main steps in the argument: the first is that the power required to tow the ideally streamline aeroplane should be merely the sum of the induced and skin friction powers. This idea suggests the use of a drag coefficient, based on the total exposed area, to estimate that part of the power which is not absorbed in the easily calculable induced drag and in climbing.

A comparison of such drag coefficients for a series of simple streamline shapes, with the skin friction coefficient of a thin flat plate, with turbulent flow in the boundary layer, suggests that the latter provided a convenient and safe estimate for the drag coefficient of any good streamline body.

Finally, a figure of 0.002 is shown to give a conservative estimate of the coefficient for wings and bodies at the Reynolds' numbers of full scale flight.

The second step in the argument is that in the streamline aeroplane, interference between the airscrew and the aeroplane, though it may affect the design of the screw suitable to a given engine, should not greatly affect the over-all power absorbed; hence, when estimating the brake horse-power required for the streamline aeroplane, the screw efficiency may be assumed to be that of an isolated screw.

These two conclusions, if accepted, enable the power required by the streamline aeroplane to be very easily calculated. It is submitted that this should always be done in order to keep before the designer and other people concerned the price that is being paid for defective streamlining.

It is not suggested that it is easy to design a streamline aeroplane which will be also a practicable machine, but the immense saving in power, and therefore in fuel consumption, which would apparently follow such a step, forces me to the belief that design will evolve steadily in this direction and that the ultimate aeroplane will be as well streamlined on the whole of its external surfaces as, say, the bottom of a racing yacht or the externals of an albatross. I am fortified in this belief by surveying the animal kingdom. Those birds and fishes which depend on speed for their existence have long since solved the problem. The compromise with structural difficulty was no doubt as difficult for them as for us, but it has ended in the complete triumph of the external form. We can only hope that it will not take us so long to reach this point as, if we are to believe the comparative anatomists, it took them.

DISCUSSION

The PRESIDENT: Professor Melvill Jones had drawn the attention of the Aeronautical Research Committee a year or so ago to the matters dealt with in the paper; as a result, experiments were carried out, which had in substance proved his contentions. He had set up a valuable standard, and when one considered how far present-day aircraft, both military and civil, were below that new standard, one could hardly cavil about its supposed inaccuracies. He had stated in the paper that his conclusions were based upon leaky theoretical arguments, but one felt that when the resistances of present-day aircraft had been reduced by about 50 percent it would be time enough to consider those leaky theoretical arguments with a view to their revision.

Major F. M. GREEN: He thanked Professor Melvill Jones for having set up not merely an ideal, but an ideal which could be expressed in figures. It meant much more to a designer to be able to say that his aeroplane represented a definite advance towards a definite ideal, than to be able to say merely that it was a little better than its predecessor, because in the latter instance he did not know how much further he had to go. Designers were now aware that a great deal of progress must be made, and the paper would stimulate them to make better aeroplanes. The influence of figures was very great, and designers would be able to express the efficiency of their aeroplenes as a percentage of Professor Melvill Jones' ideal, instead of saying merely that a particular aeroplane was fairly well streamlined or was fairly efficient. With regard to the overall figure of 0.002 for the skin friction drag of planes, he said that was half what was at one time called the minimum profile drag (0.004). The figure would vary, however, with different angles, and with greater angles the figure might be greater. With regard to turbulence, that in the air occurred on a very much greater scale than in a wind tunnel, and he asked whether the results obtained with an aeroplane on a day when there was considerable turbulence would be appreciably different from those obtained on a calm day.

Mr. R. McKINNON WOOD, referring to the use of the wind tunnel, said that for many years it had been thought that the ideal condition of test was that the turbulence of the air in the tunnel should be the minimum attainable, but in the last year or so it had dawned on some investigators—it had dawned on him a few months ago—that possibly the wind tunnel which was regarded as the worst was really the best; because, if there were sufficient turbulence in the air the results obtained would be as indicated by the upper curve exhibited by Professor Melvill Jones, and if one extrapolated along such a curve one should make a fairly good prediction of the full-scale value. If the results lay below that curve—somewhere in the indefinite area—one could not say in the least what the full-scale value might be. He hoped that the paper would be of great service by focusing the attention of designers of aircraft more on aerodynamic considerations. He would not reproach designers for giving, as he considered they did, too much attention to weight, to mechanical, structural and other aspects of their work and too little to the aerodynamic aspect. The reason could be found very simply; one could determine the weight of a machine easily and precisely, but it was more difficult to determine drag and to determine what improvements were effected by small alterations. A question which was continually before those engaged in full-scale test was what improvement was effected by replacing, say, a radiator by a different radiator. The gain in speed effected thereby was probably half a mile or one mile per hour, but the man who was making the tests knew that variations in engine power, up and down currents, and other factors might affect speed to a greater extent than would the changing of the radiator. He believed that this work of Professor Melvill Jones, in that is showed how much better a performance we could look forward to, would have the effect of focusing the attention of designers more and more on the problem of reducing drag.

Mr. A. FAGE: He would like to mention two series of experiments with which he had been connected, and which had a direct bearing on Professor Jones' paper. It was well known that on a large circular cylinder there was a certain range of Reynolds' number (*VD*/*v*) over which the character of the flow underwent a marked change, and which was accompanied by a large drop in the drag coefficient. He had had occasion to explore the boundary layers for these flows and to determine the breakaway points. Denoting the circular distance from the stagnation point to the breakaway point by "*l*," and the velocity just outside the boundary layer at the breakaway point by "*V*," he had found that the range of Reynolds' number (*Vl*/*v*), over which the marked change of flow occurred was from 1.1×10^5 to 4.4×10^5. This was exceedingly interesting, because, as mentioned by Professor Jones, Professor Burgers had found that the critical range of (*Vl*/*v*) for a flat plate (*l* is the distance from the leading edge) over which the flow along a flat plate could break down was about the same order, namely, 10^5 to 5.0×10^5. There was, therefore, from this point of view, a resemblance between the flows in the boundary layers along a flat plate and around a cylinder, and we should expect intermediate bodies such as airship forms and aerofoils to exhibit similar tendencies; Professor Jones had shown that they did. Another point of interest arose from some experiments made to measure the minimum drags (at zero incidence) of a family of symmetrical Joukowski sections of different thickness. If one plotted drag coefficient against thickness one was able to predict the drag coefficient for a Joukowski aerofoil of zero thickness (i.e., a flat plate). The values of Reynolds' number at which the predictions were made were in the critical region, and as would be expected the predicted values of drag coefficient lay between those for laminar and turbulent flows along a flat plate; further, these predicted values agreed fairly closely with Geber's values for a flat plate at the same Reynolds' number. These results gave additional support to Professor Jones' conclusions. A great merit of the paper was that attention was focused on the large amount of power frittered away in driving modern aeroplanes, and the paper should prove a great stimulus to all workers in aeronautics.

Mr. C. C. WALKER: Those concerned with aviation were particularly interested to know what chances there were of recovering some of the lost power and how much of the loss was inevitable. When Professor Jones had first published some of his results, he (Mr. Walker) had made calculations in respect of a number of aeroplanes, taking, instead of approximations, the actual "wetted" surface of each aeroplane and the available h.p. (after multiplying the b.h.p. by the propeller efficiency) and had found that an ordinary commercial aeroplane did attain from 60 to 67 percent of the streamline speed. Both the best and the worst examples among his own company's machines happened to be monoplanes. In a little racing machine which did 197 miles per hour with 133 h.p., a little over 80 percent of the streamline speed was attained. That meant that what had to be recovered amounted to the equivalent of three-quarters of a square foot of flat plate presented normally to the wind, and that had to include the undercarriage, all the bracing, the cooling of the engine, the cockpit, and the effects of the slipstream on the body and wings. The machine must have an undercarriage, and at present it must have some form of cockpit; cooling resistance might be reduced somewhat, but there seemed to be very little margin for recovery in a machine of that sort. In the case of a commercial aeroplane, which must have all sorts of other excrescences, it was difficult to foresee how far one could go towards eliminating the resistance. Such a machine had a radial engine sometimes on the front of the body, the cabin had to be ventilated by means of structures like ships' ventilators, sometimes there was a starting engine mounted outside the fuselage, and it did not matter very much what one did in the way of fairing after that. It would be interesting to know what Professor Jones thought about the amount that should be saved. (Laughter.) Referring to the problem of induced drag h.p., he said that Lanchester, in 1914, had shown how to work it out, and from his book, which was published in 1908, one found that he had put it forward to the Physical Society in 1894. At that time he had called it "aerodynamic drag," but it appeared to be the same as "induced drag." He (Mr. Walker) did not know whether or not Prandtl had worked it out earlier than that, but the point was that if "aerodynamic drag" were the same as "induced drag," and nothing more than a change of name was involved, it was rather a pity that Lanchester should be deprived of the credit due to him.

(*Communicated*): There is an aspect of Professor Jones' criterion of performance which is not free from objection. Presumably, by encasing the various necessary excrescences in large streamline boxes, or by so increasing the fuselage in size as to embrace what otherwise would not be embraced, credit could be taken for the extra surface, and a high streamline efficiency shown.

It could then quite easily happen that of two aeroplanes doing the same job, the slower would show a better figure of merit on this basis than the faster.

In one of Professor Jones' earlier papers, he placed on the credit side the area of the floats of a seaplane—as no credit can be taken for the wheels of the corresponding land machine—the situation mentioned above may be said to have already arisen.

The fact remains that the great virtue of this method is its absolute nature.

For purely comparative purposes, it is perhaps preferable to give the highest figure of merit to that aeroplane which carries a given paying load per h.p. fastest in relation to its landing speed or to use some similar basis. The "streamline efficiency" will then show to what extent this machine falls short of the ideal, but to aim directly and only at this in design would not necessarily produce the best aeroplane.

Mr. W. L. COWLEY: It would appear from his remarks that the wind tunnels had given us fictitious results in the past, but he would like to hear the lecturer explain the fact that, in many cases, excellent agreement had been obtained between model results and full-scale. As far as his personal knowledge went, designers had the greatest faith in wind tunnel work. The host of results upon various wing, strut, body and float forms tested in the past as well as on complete models, airscrews, controls, stability, etc., were made use of daily and no marked discrepancies with full-scale, except in occasional cases such as R.A.F. 19, had been reported. It would be strange if these agreements were purely accidental and still more so if they were but imaginary, and that this fact had escaped the great army of workers that had been engaged upon the subject.

Just before attending the lecture he calculated the drag coefficients of an aerofoil, a body and a gloat that were tested some time ago in connection with a certain machine. The points fell almost exactly upon the turbulent boundary layer curve given by Professor Jones. Now Professor Jones assumed that the drag curves for the airship forms ultimately merged into this turbulent boundary layer curve. If it be assumed that the drag curves for the parts mentioned should also follow this curve, the drag coefficient for the full-scale machine should have been approximately 0.0014 instead of about 0.0022 as the model scale effect curves indicated. The full-scale result appeared to be more consistent with the latter than with the former result. It may be argued that the resistance measured were only partially skin friction. If that was so one would expect the difference between 0.0022 and 0.0014 to be form resistance and the curves of drag coefficients of the models against log Vl/v to follow a transition curve rising up rapidly to a turbulent boundary layer curve parallel to the one given, but having the ordinates greater by an amount equal to this difference. In the tunnel tests mentioned, the variation of drag coefficient with log Vl/v however, was very slight. During recent years tests have been made at the National Physical Laboratory upon several models of complete machines, ranging from single-seater single-engined machines to large three-engined machines. Parts were tested alone and in combination and the whole work has been carried out in direct touch with the designers of the machines concerned. In no case has there been the slightest cause to suspect the results. It should be noted that the scale effect was considered so small that the results at the highest values of Vl/v in the tunnel tests could almost be applied directly to full-scale without correction. Further, the parts were of fairly fine form and the minimum drag coefficients were low. In one machine the model results indicated a higher maximum lift than was expected, but the performance of the machine was found to agree remarkably well with all the model test results.

Reverting to the skin friction curves given by Professor Jones, it would be noticed that the phenomenon of double flow and the transitional region was similar to flow in pipes, but in the latter it was usual to make in the expression log Vl/v equal to the diameter of the pipe and not to a down wind dimension. Now it was implied by Professor Jones that surface area at the rear of the body was affected differently from that near the front on account of the accumulated disturbance produced in the boundary layer by the action of the surface coming before; and the average drag per unit area of the surface of a good streamline form depends only upon the length of the body when the speed, density and viscosity were constant. Now the resistance of a parallel pipe was all skin friction and its drag coefficient appeared to be of the same order as that for the flat plate. One would expect, therefore, similar conditions to prevail. Thus, if for the flat plate, the boundary layer became turbulent at a distance l from the leading edge, then it would be expected that turbulence commenced in a pipe at the same distance from the entry. In other words, turbulence in a pipe commenced at a certain distance from the end irrespective of the diameter, so that, for two pipers a and b using the same fluid, the distances and speeds were related by

$$V_a l_a = V_b l_b.$$

The dimensional theory, however, demanded that, if the conditions were similar, a breakdown in flow would occur at corresponding points when

$$V_a D_a = V_b D_b$$

where D is diameter. In other words, the diameter is all important. It followed, therefore, that the main body of the fluid affected the resistance as well as the surface fluid.

The apparent agreement between the experimental pressure distribution round a body and the pressure distribution calculated from the inviscid fluid theory gave no support to the contention that the integral effect on drag of the flow in the main part of the fluid was negligible. After all the integral of the discrepancies between the pressure distributions, when resolved, was equal to the whole of the drag. One could only conclude that the inviscid fluid theory, in its present form, might be good enough for calculating certain effects, but was useless for any work involving profile drag.

In conclusion, he said that although he regarded the lecture as very interesting and instructive, he thought it was a little dangerous to act upon any deduction made from it at the present stage of our knowledge. It did not justify as yet any loss of faith in wind tunnel work or any change in wind tunnel technique, although he agreed that further research on the lines given by the lecturer might be necessary.

Mr. PYE: Referring to Professor Jones' curves showing the b.h.p. per 1,000 lbs. weight in respect of certain machines for level flight at various speeds, he suggested that one or two spots representing the performance of machines which competed in the Schneider Trophy contest might be added, because the drag had been very materially reduced in the case of those machines. If such information were given, one would be able to make extraordinarily interesting comparisons, because the drag of those machines must be very much nearer to Professor Jones' theoretical limit than it was for any of the machines he had shown.

Dr. DOUGLAS: No doubt in cases where the full-scale flow was turbulent increase of turbulence produced a similar effect to that obtained by increasing Reynolds' number, and a better idea of full-scale value would be obtained if models were tested in a very turbulent tunnel, as suggested by Mr. McKinnon Wood. It was quite possible, however, that on objects, such as struts, the full-scale flow might actually be laminar.

Professor Jones had shown that existing aeroplanes have very much more drag than they need have. Machines were defective both in form and in surface. The latter defect was particularly noticeable on the Schneider Trophy winner displayed in London, and he had been shocked to notice the rivet heads and other excrescences on a machine designed to have the lowest possible drag. The components of a machine of this type have drags little greater than that given by thin plates of similar surface area, and when this standard had been reached it must pay to keep the surface clean. He hoped that Professor Jones' remarks would lead to a better appreciation of the need for reducing drag.

Mr. IRVING: With regard to the point raised by Dr. Douglas, Professor Jones, in arriving at his overall figure for the full-scale drag coefficient, had assumed that one traveled along the upper curve. It was just conceivable, however, that with certain shapes one might possibly keep to the lower curve. The departures from the lower curve had in most cases occurred in wind tunnel tests in which the general flow was turbulent, although in one case, in which tests were made by towing a model in still water, there was also a departure from the lower curve in the direction of the upper curve. Mr. Irving also referred to some tests carried out at the National Physical Laboratory in 1919, in which Mr. Ower and he had measured the skin friction of flat plates of various thicknesses on the balance in the wind tunnel, and extrapolated from different thicknesses down to no thickness. The values of the skin friction coefficient obtained for different sizes of plate at different wind speeds were plotted against *VL*; for the lower values of *VL* the points came actually on the lower curve, but as *VL* increased there was a gradual departure, and at the higher values of *VL* the curve crossed the region between Professor Jones' two curves and almost touched the upper curve. He mentioned this fact because he understood Professor Jones' lower curve was based on measurements of flow near flat planes and not on overall measurements of the skin friction on a balance.

Mr. CAPON: On a previous occasion when Professor Jones had lectured to the Society, he had uttered the dictum that no research could be considered to be competed until it had been reduced to a rule of thumb. One might add that no research should be begun until there was a definite formula to work to, and the great value of Professor Jones' work was that he did provide such a formula. It had been known for a long time that great savings in drag could be effected; probably the reason why so little had been done was that there were a great many small contributions, and nobody felt really convinced about any of them. For example, it had been known for several years that a saving in drag on models could be effected by cowling the cylinders of radial engines. Why were radial engines not cowled? Probably because designers quite reasonably thought that there might be a scale effect on drag or cooling, or both. Again, we really did not know how much the sum of these contributions would amount to. Professor Jones had given a figure of merit to indicate what could be expected, and although there might be some quibbles as to what exactly that figure amounted to—questions such as airscrew interference, and so on, were involved—it was nevertheless a sufficiently definite figure. Professor Jones was to be congratulated, not only upon having produced it, but on having met so successfully, as it appeared, the objections raised by the scientists based on the uncertainty as to the skin friction coefficient to be adopted. His investigations in this direction had apparently led to results of great interest in other connections.

Mr. Scott HALL: It seemed to him that Professor Jones' assumptions with regard to the working of the screw in close proximity to the body were of a very grave nature, for in effect he had assumed that the loss due to increased drag of the body in the slipstream behind the screw was balanced entirely by the extra efficiency with which that screw worked, due to the body behind it. He would have liked to have heard more from Professor Jones on that matter. With regard to the curves showing the performance of various aircraft, he said that the point relating to the "Spirit of St. Louis" was situated a considerable distance from those relating to other machines. The "Spirit of St. Louis" was the only machine dealt with which had no open cockpit, nor openings of any kind, and the fact seemed to indicate that the openings on a streamline body were of very serious practical importance, more so even than had been hitherto supposed.

Mr. BRAMSON: He could not resist the temptation to point out one analogy; in all probability Professor Jones' treatment of the subject of the streamline aeroplane would be regarded as holding the same position in relation to aerodynamics as, for instance, the Carnot cycle held in relation to thermo-dynamics. Professor Jones had put forward an ideal beyond which, without the discovery of new principles, one could not hope to get, and he had given designers a standard by which the qualities of aeroplanes could be judged, a standard which has hitherto been lacking. He asked Professor Jones if he could give, there and then, an actual numerical example of what an aeroplane of reasonable weight, horse-power, and so forth, must do to achieve the ideal. With regard to the curious fact mentioned by one of the speakers, that in the course of experiments he had found that the lift coefficient began to drop at much lower values at low values of Reynolds' number than at high values, Mr. Bramson asked if it were not possible that that was due to the departure from the boundary layer occurring sooner at low speeds, due to the relatively greater effect of the "adverse pressure gradient" near the trailing edge, than at high speeds. With regard to circulation, he said he had heard it stated that the "equivalent circulation" round an aerofoil would never start in the ideal fluid. He asked if that were so, and whether the idea of a circulation around an aerofoil was at all a sensible one. It was difficult to see how, if there were anything which could properly be called circulation, it could go round a sharp trailing edge, for instance, in any intelligible manner.

George H. DOWTY (*contributed*): Following Mr. North's recent lecture, it is possible to compare the ideal aeroplane with present day standards and appreciate the vast improvements which have yet to be made. The lecturer stated that progress towards the ideal streamline aeroplane has been slow and points out that the tendency to belittle minor gains is a wrong policy. The design of racing machines has produced a very clean type of aircraft, and here the designer is prepared to sacrifice practically everything in producing an ideal aerodynamic form. When speed is not the ruling factor, the question of maximum aerodynamic efficiency often takes second place to other considerations and justification is claimed for this because the increase in performance is small. If the existing gap between present designs and the streamline aeroplane is to be bridged then improvements, however small, cannot be neglected. One of the chief items of parasitic drag, and one to which Professor Melvill Jones has drawn attention in R. & M. No. 1115, is the undercarriage. The writer has been engaged on work in this direction for some considerable time, and during the last three or four years has confined his attention to methods for reducing the drag of this unit. Investigations have led to the same conclusions as those given by Mr. North, that the retractable undercarriage is not desirable because of the complicated retracting mechanism and the extra weight involved. Mr. North suggested the use of mechanical launching gear, and from his remarks, it is understood, a form of ski landing gear. This form of undercarriage is open to strong objections because it limits the operation of aircraft to stations equipped with launching gear and such machines would be at a great disadvantage in the case of a forced landing. There is also the question of ground maneuverability and it does not seem reasonable to expect any sacrifice in this direction.

There is fortunately some scope for cleaning up existing forms of undercarriages, and it is on this basis that the writer has been working. The shock-absorbing member is usually located in the slipstream and it will be found that this member gives a resistance at least five times as great as a steel streamline tube carrying the same load. Further, the existing types of connections are very poor, the strut sections being broken at their points of juncture with the body. Such a condition must cause mutilation of the air flow at these points and give rise to additional drag (now termed interference). In order that these disadvantages can be obviated, the writer has designed several types of landing gears where the structure is rigid and the shock-absorbing mechanism lies within or adjacent to the wheel. The wheel with internal springing consists of an oil dashpot shock absorber, compression rubber springing and wheel brakes. This design of wheel has been in existence for two years, but it has only recently been favorably reviewed by wheel manufacturers. The Curtiss Company, of America, have produced a similar type of wheel, and they consider this undercarriage an attractive proposition. The shock-absorbing capacity of these wheels is better than that usually obtained with an oleo leg, because there are no limitations due to angular movements of the structural members. Conservative detail estimates show that the undercarriage drag can be reduced by 25 percent and the weight by 15 percent.

G. T. R. HILL (*contributed*): This paper sets up for the first time a standard by which the performance of any aeroplane may be judged. Considering how far all designers are below that ideal performance, or "Jones performance," as it should now be called, serious objection cannot yet be brought against the standard on account of its being built up with the aid of what Professor Jones calls "a leaky theoretical argument." When the present drag of our military and commercial aeroplanes has been halved, it will be time to set the standard more securely on its base with the aid of aerodynamic knowledge which will then be available.

There appears no doubt that the rate of progress towards the streamline aeroplane is greater than that achieved by Nature in bygone ages in the design of birds and fishes, yet any elation which may be felt over this will be considerably moderated by turning back some eighteen years to 1911, to the remarkable designs of M. Nieuport. There is a good description of these little aeroplanes in the old *Aero* of June, 1911; one of them which flew in the Gordon-Bennett Race of that year was fitted with an engine of only 28 h.p. nominally and with a wing area of about 170 square feet, it is reported to have attained a speed of 75 m.p.h. Looking at the photograph of the aeroplane it might be asked how could its resistance be brought down to the modern standard? It could be said at once that streamline wires could be fitted instead of round cables, and having said this, nearly all has been said.

Turning to the future, the fact cannot be ignored that as the resistance due to some parts of the aeroplane is reduced, the resistance of those parts left unaltered calls more and more loudly for attention. For this reason, it is difficult to foresee clearly the future of the air-cooled engine, in which perhaps four-fifths of the resistance is due to the turbulent air flow around the cylinders and one-fifth to the skin friction which necessarily accompanies the cooling effect required. Already the air-cooled engine is seen to be at a disadvantage in high speed racing aircraft, and in the usual course of events, characteristics of the racing craft of today are exhibited by the general purposes craft of tomorrow. How long will that tomorrow be in coming?

The "Jones ideal performance" stands out as one of the beacons towards which the designer must steer his painful way through the fog of detail work which necessarily surrounds him.

S. J. DAVIES and C. M. WHYTE: (*contributed*): The writers would like to thank Professor Melvill Jones for the excellent way in which he made a highly specialized subject both intelligible and interesting to those who, like themselves, are not conversant with the subject. They were particularly struck by the number of points arising which threw light upon matters which had been obscure to them in an allied subject. It is possible that the following remarks, based on the study of flow through pipes, may in their turn be of interest to aeronautical engineers.

One of the most striking points brought out by the lecturer was that the majority of wind tunnel tests lie within the transfer region between laminar and turbulent flow. This fact must add greatly to the difficulty of interpreting the results, and it is remarkable that reliable figures have been obtained at all. For many years the similar transfer region in connection with pipe flow also gave rise to difficulty and led to much confusion of thought. And in fact it is only within the last few years that any certainty has been reached. The curves from flow in pipes are similar to those given in the lecture and the results of the former may help in interpreting the latter. The work of L. Schiller has played a large part in demonstrating that the amount of turbulence in the fluid as it enters the pipe determines the value of the Reynolds' number at which the transfer takes place. Some of his results, which do not appear to have been published in this country, are shown in Fig. 5. The wide difference between the values of the Reynolds' numbers of the figure and those mentioned in the lecture are due to the fact that in the figure the Reynolds' number is that formed by the linear dimension of the cross section of the stream, while in the lecture the overall length of the body is used. The value of $F/\rho v^2$ in the figure is arrived at by the method used in the lecture, but it should be noted that it does not include the resistance at or near the entrance to the pipe. The various curves were obtained with increasing entrant disturbances, and show that the greater the turbulence at the inlet the smaller is the Reynolds' number at which the transfer takes place. There is, however, a limiting value, and no amount of disturbance will cause the transfer to take place below R = 1160. The relevant conclusion to be drawn from this is that, unless a high degree of turbulence is provided by artificial means, the results will neither be free from the influence of the unknown state of the fluid at entry, nor be consistent among themselves. With artificial turbulence it is possible to obtain points on the turbulent line for flows only slightly in excess of R = 1160. Further tests of Schiller show also that a moderate degree of roughness of the pipe does not influence the transfer.

The vertical transfer curves shown in the figure were obtained only when a length of pipe at least equal to 130 diameters is interposed between the entrance and the testing length. Under other conditions the transfer curve is less definite and becomes rounded in form and very similar to the dotted curve shown by the

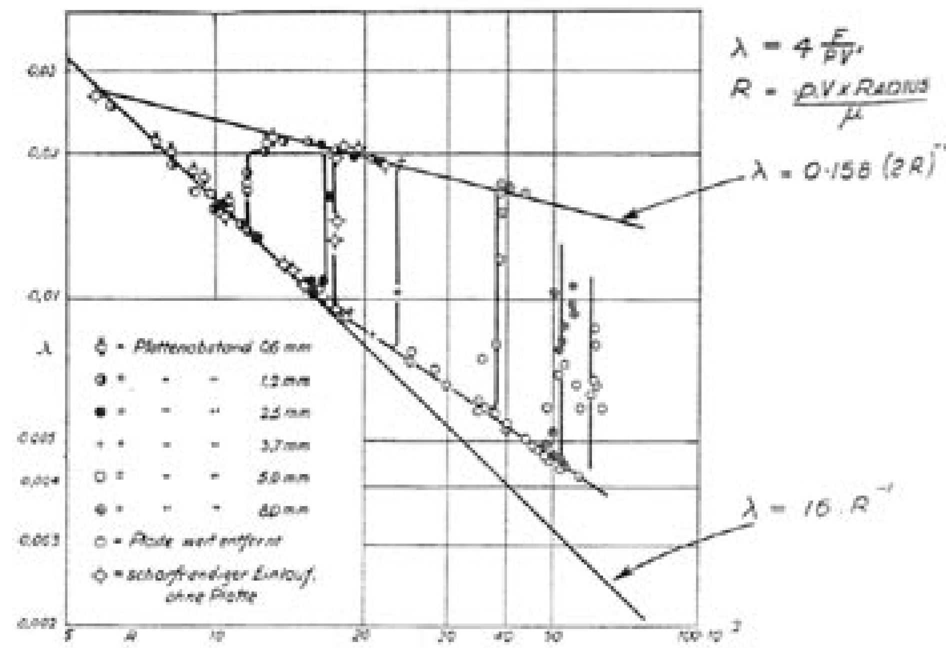


Fig. 5.

lecturer. The value of the Reynolds' number at transfer, however, remains approximately unaltered. The lecturer's method of calculating the form and position of the transfer curve is interesting, but he does not indicate the grounds for his implied assumption that the Reynolds' number, formed by the distance from the leading edge to the breakdown point, is constant during the transfer period. At first sight it might be expected to decrease progressively as the transfer curve is traced out in an upward direction.

The lecturer gave the impression that curvature tends to cause the boundary layer to become turbulent sooner. It would be interesting to know if there is any experimental evidence supporting this view. Curvature in pipe flow, provided that it is slight, appears to be without influence, but, as is shown by some tests about to be published, flow through a curved pipe, of which the radius of curvature is 15 times the pipe radius, is considerably more stable than in a straight pipe, and the transfer does not take place until about four times the Reynolds' number at which it would occur in a straight pipe.

The necessity for carefully regulated conditions when determining the resistance of complicated bodies is well illustrated by tests of a series of very rough pipes carried out under somewhat indefinite entry conditions. These tests show certain striking anomalies. Two pipes, one definitely rougher than the other, were reversed in their resistances when tested over a certain range of Reynolds' number near the transfer region. This behavior was characteristic, in this region, of the majority of the pipes tested, and persisted long after the flow had ceased to be streamline. The conclusion may be drawn that no reliance can be placed on the relative magnitudes of the observed resistances of two models of a complicated form unless the comparison is made at Reynolds' numbers many times as great as those of the transfer region, or, alternatively, unless the state of the fluid is completely known.

In connection with pipe flow the writers have found logarithmic plotting along both axes to be more convenient than the usual method of plotting $F/\rho v^2$ on log. R. Equations (1) and (2) or the lecture would then become straight lines sloping downwards. Plotted as they are, there is a false impression given, owing to the upward concave form of the curves, that they are tending to some constant value of $F/\rho v^2$ at high values of R. There is a further advantage of logarithmic plotting in that inaccuracies of test data of equal percentage are consistently shown at all parts of the diagram by equal displacements, so that undue importance is not attached to isolated tests which happen to fall on parts of the diagram where the scale may be relatively close.

Mr. SIMMONS (*communicated*): Professor Jones has tonight expounded a theory based on the assumption that the skin friction resistance of bodies of fine form follows one law at low values of Reynolds' number and another law at high values. The underlying basis of the theory recalls the methods employed by naval architects for predicting the resistance of ships, founded on the skin friction data of flat plates. He would like to call attention to some results published some years ago by Mr. Baker which he thought pertinent to the present discussion, and lent support to the new theory. These were shown graphically in Fig. 6. It would be observed that below a Reynolds' number of about 4 X 10^6 large discrepancies existed between individual observations made at the same value of VL/v; although at higher numbers the results were more generally consistent. Commenting on the measurements made in air and water on similar models, he thought it was significant that the drag coefficient measured in the turbulent flow of the wind tunnel was higher than the figure obtained in the water experiments. If the initial turbulence in the free stream was a factor which influenced the flow in the boundary and thereby the drag of the model, then its effect appeared to be most marked below

$$VL/v = 4 \text{ X } 10^6.$$

He was, however, a little doubtful whether a stable regime of flow independent of initial disturbances was completely established at this value of Reynolds' number, since the Gottingen results exhibited by the lecturer, and shown by the dotted curve were in excess of the figures derived from tests on the largest planks. Finally, he referred to the similarity existing between the results for bodies of fine form in the transitional region and those obtained with pipes; and he thought it must be more than coincidence that the turbulence curve for flat plates could also be taken to represent the resistance of pipes at high velocities.

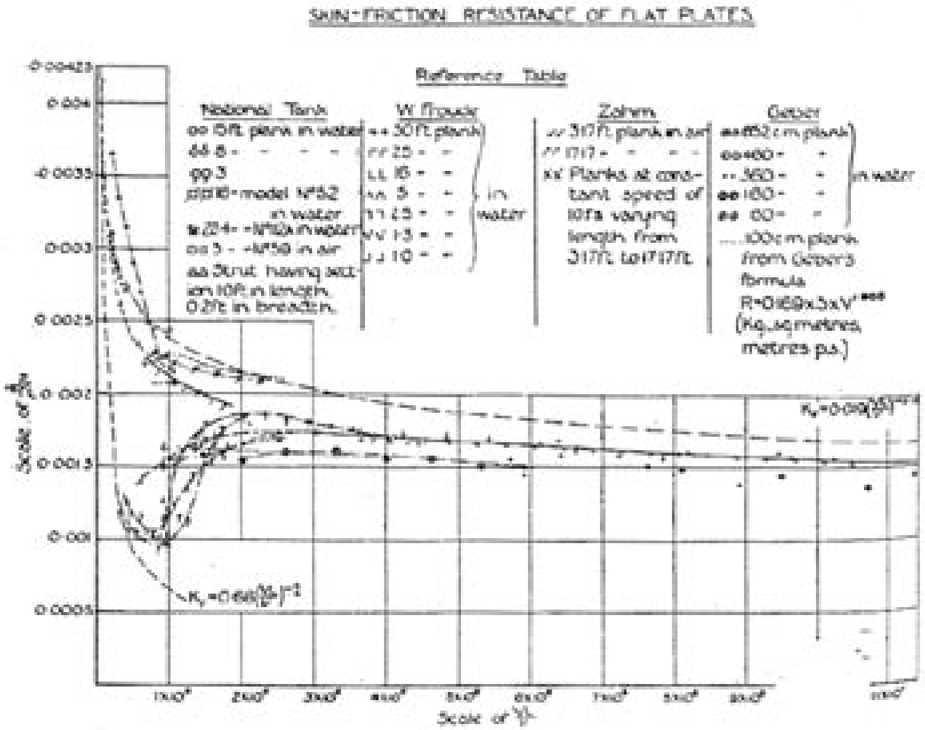


FIG. 6.

REPLY TO DISCUSSION

The discussion has been long and interesting, and I wish first to thank all those who have taken part in it.

In reply to *Major F. M. Green*, the turbulence in the wind tunnel which causes early break up of the boundary layer is of a peculiar kind with a very small scale. I imagine that the scale of the turbulence in the open air is too large to have any influence on the boundary layer and I should not therefore expect differences on different days due to this cause. This opinion is not based on definite evidence. The figure given for skin friction drag coefficient is half the minimum profile drag coefficient, because the area involved in the former is that of both upper and lower surfaces of the planes, whereas the area involved in the latter is one surface only.

With reference to *Mr. R. McKinnon Wood's* remarks, I agree that it is probably that wind tunnels which have been deliberately given a small scale turbulence will be used in the future, but this matter has not yet been clearly thought out so far as I am aware.

Mr. Fage's statement that the Reynolds' number at which the boundary layer breaks up on a circular cylinder is of the same order as that for a flat plate, is most interesting. The effect of curvature on the point of break up of the layer is a matter which requires much further research. I shall be interested to see his results for thin Joukowski sections when they become available.

Mr. Walker's estimate that the speed of his aeroplanes lies between 60 and 67 percent of the streamline speed agrees fairly well with my rougher estimates. Since power varies approximately as V^3, the realized speed of 70 percent of the streamline speed corresponds to an expenditure of about three times the streamline power for a given speed. I am obliged to Mr. Walker for emphasizing the fact that the ratio of actual to streamline power must not be regarded as an overall figure of excellence for the aeroplane. I had a warning to this effect in an early draft of the paper, but inadvertently omitted it in the final text. What the factor does show is how much power is being expended through defective streamlining. I agree with his remarks about Mr. Lanchester and the induced drag theory; all the same, it was Prandtl who threw it into its present practical form.

Mr. W. L. Cowley finds it hard to reconcile my lecture with the available results which have been given by wind tunnels in the past. I do not understand his difficulty. The majority of results which have been used extensively have not been for perfect streamline bodies such as I am discussing. Also it must be remembered that the majority of full-scale results refer only to total brake horse-power, and that scale effects on the various parts may be confused with variation in airscrew efficiency or interference between airscrew and body. Only in a few instances, where research methods have been applied on the full-scale, do we know the drag independent of the airscrew, and even then the whole drag and not that of the parts separately.

There is one way in which apparent agreement can be obtained in spite of the existence of large scale effects; thus, the airship R.101 when tested on the model at a Reynolds' number of 2 X 10^6 gave k_F = 0.0010. This figure was almost exactly that which we should now predict for the full-scale with a wholly turbulent boundary layer at a Reynolds' number of 3 X 10^8. The apparent agreement here is entirely fortuitous, for at intermediate Reynolds' numbers the coefficient is much higher, as would be expected from the theory which I have advanced.

In Mr. Cowley's remarks upon pipes he appears to have forgotten that in a long pipe the boundary layer extends to the middle of the pipe. There is a relationship between the flow in pipes and the flow for a flat plate, but it is not so simple as Mr. Cowley appears to assume; it has been worked out by Professors Prandtl and Von Kármán (See my reply to Messrs. S. J. Davis and C. M. White for references).

I cannot understand Mr. Cowley's statement that the pressure distributions when resolved are equal to the whole drag; so far as I am aware this is incorrect for streamline shapes.

So far from the conclusions of my paper leading to a loss of faith in wind tunnel work, they will, I hope, increase its usefulness through removing some of the anomalies which have been well known for some years.

In answer to *Mr. Pye*, I have not included the Schneider Cup racers because, being seaplanes with floats, they are not comparable with the other aeroplanes in Fig. 3. It would be interesting to see them worked out accurately by someone in the Air Ministry who has the facts at his fingers' ends.

I agree with Mr. Douglas as to the importance of a clean external surface, but it is just possible that small projections may have less influence on the full-scale, where the boundary layer is probably turbulent in any case, than on the wind tunnel model, where the projections may convert a laminar into a turbulent layer.

Mr. Irving's suggestion that the boundary layer may continue laminar to higher Reynolds' numbers in respect of some shapes is very significant. We had already given some thought to this matter at Cambridge, but I left it out of this paper as being too speculative. This, I hope, will be the subject of future research.

His remarks about his experiments on skin friction in 1919, in which the skin friction coefficient fell on the curve for laminar boundary layer, are most interesting and I should like the reference. Dr. Stanton has also done experiments on the skin friction on the thin rings similar to napkin rings, and has found the same agreement. There is no doubt that when the layer is laminar the agreement of the skin friction with Blasius' solution is thoroughly established.

Mr. Capon has clearly emphasized the main reason for the lecture, which was to show that an estimated sum of all conceivable drag reductions is so large as to be worth going for, even if the separate contributions may in themselves appear small.

Mr. Scott Hall has doubts about my screw efficiency theory. I am not surprised at this, as it is at present the weakest part of the paper and is as yet unsupported by crucial experiment. The main conclusions of the paper, however, stand without it. The assumption certainly is, as he says, that the interference of screw on body balances the effect of body on screw, except for the increased power loss due to skin friction in the slipstream. Stated in this way, the assumption is certainly startling, but if my argument is carefully followed I do not see how the conclusion can be avoided. It is to be emphasized, however, that the argument applies only to ideally streamlined machines as defined in the paper.

In reply to *Mr. Branson*, the suggestions in this paper cannot be considered as on the same plane as the Carnot theory of heat engines, but the practical outcome is similar—the provision of an ideal towards which to work. Whereas, however, the Carnot cycle is a precise theorem, my paper is more in the nature of an exercise in approximations.

I agree with *Mr. Dowty* that the landing gear is probably the greatest difficulty in the way of perfect streamlining, and I am interested to hear of his efforts to tackle the problem.

In answer to *Captain Geoffrey Hill*, the air-cooled engine is at present a distinct stumbling block to progress in streamlining, but I am not sure that it will always be so. Recent experiments in cylinder cowling are most encouraging and it should be remembered that, since the temperature of the cylinder is high, scientifically devised air-cooling systems, such as we have not yet got, may give rise to a relatively low resistance.

In reply to *Messrs. S. J. Davies* and *C. M. Whyte*, the relation between resistances to flow in pipes and the Reynolds' number formed from the pipe diameter was

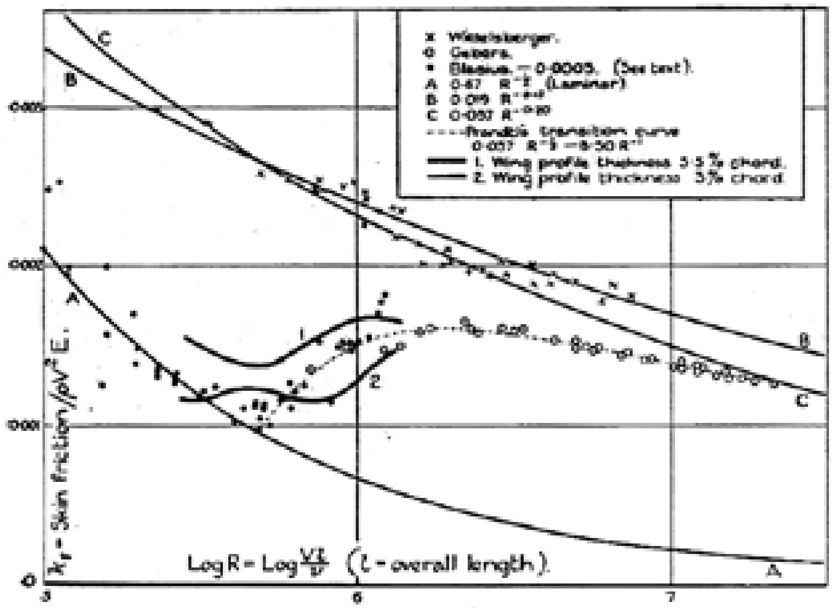


Fig. 7.

Prof. Prandtl's Transition Curve for Skin Friction on a Flat Plate.

Re-plotted from Reports 1 and 7, Ergebnisse der Aerodynamischen Versuchsanstalt Zu Göttingen III. Lieferung.

thoroughly worked out by Stanton and Pannel for both water and air, and a curve showing the relation of skin friction per unit area/ρV^2 to the Reynolds' number, for a very wide range including the critical region, was published in 1914.

The comparison between flow in pipes and the boundary layer on a flat plate has been thoroughly examined by Von Kármán, of Aachen (Abhandlunger aus dem Aerodynamischen Institut an der Technischen Hochschule, Aachen 1921) and by Prandtl (Ergebnisse der Aerodynamischen Versuchsanstalt zu Gottingen, 1927, Vol III). Both these papers have been translated into English, the former by the A.R.C. as Report T. 2219 and the latter by the Air Ministry. In these papers a law, k_F varies as $(l\upsilon/v)^{-0.20}$ for flat plates with turbulent boundary layer is, with certain plausible assumptions, deduced from the law k_F varies as $(l\upsilon/v)^{-0.25}$ which is found to hold experimentally for pipes above the critical Reynolds' number. Fig. 7 is a composite diagram taken from two reports in the Gottingen publication mentioned above and roughly re-plotted to conform with Figs. 1 and 2. The curve $k_F = 0.037(i\upsilon/v)^{-0.2}$ adopted by Prandtl, though it fits Gebers' points at the higher Reynolds' numbers, falls lower than the results from Froude and the N.P.L. given in Fig. 7. Hence for practical purposes I prefer his original formula

$k_F = 0.019(l\upsilon/v)^{-0.15}$, which gives a conservative estimate of skin friction drag for flat plates over the whole known range.

I do not understand the writer's difficulties with the transition curves. The only

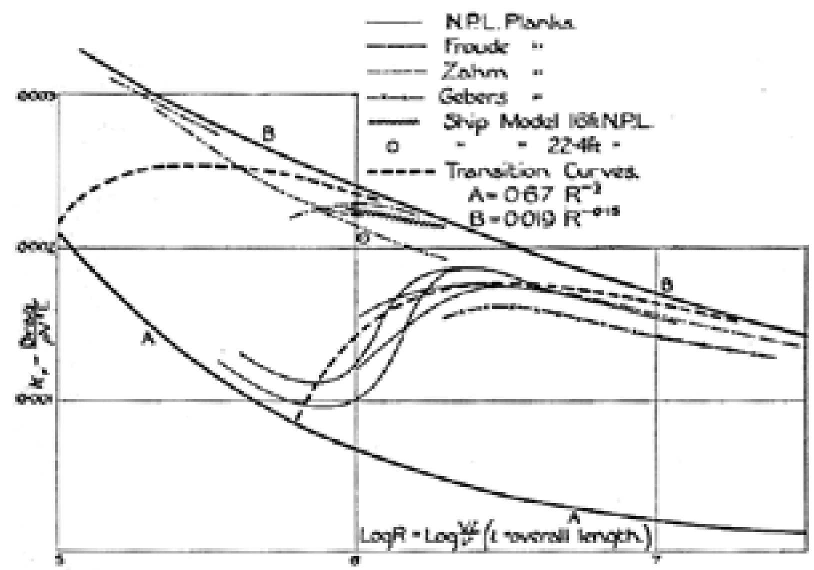


Fig. 8.

Skin Friction Experiments in N.P.L. Naval Tank.

N.P.L. Collected Researches, Vol. XIII., 1916, pp. 103-129, from Plate I. Re-plotted.

assumption regarding the point of breakdown from laminar to turbulent flow is that the point is uninfluenced by the portions of the plate behind it. This assumption must surely be correct for the flat plate; whether or not it is correct for the curved surfaces is shown by comparing the curves for k_F against R for the various streamline bodies with the theoretical transition curves for the flat plate.

To avoid unduly lengthening the paper, I did not give my methods of calculating the transition curves. The difficulty lies in deciding to what extent the laminar layer on the front part of the plate will influence the turbulent layer behind it. If it is assumed not to influence the turbulent layer at all, an upper limit is given for the coefficient of the average drag of the whole plate. If, on the other hand, it is assumed that the turbulent part in the rear behaves as though the whole layer were turbulent, a lower limit is given to the average coefficient. In forming the transition curves in Figs. 1 and 2 I worked out curves on both the above assumptions and took the mean between them. Prandtl, on the other hand, worked on the second assumption only in producing his transition reproduced curve in Fig. 7. The difference between my method and Prandtl's is not great, and I do not know which is nearer the truth.

The question of the effect of curvature on the stability of the boundary layer is still obscure, and will, I hope, shortly be the subject of experimental investigation.

I am aware of the advantage of complete logarithmic plotting, but I thought that on the balance the system which I adopted would be more easily explained to members of the audience who might not be very familiar with logarithmic plotting. The use of logarithms in connection with Reynold's numbers is easily explained as a convenient device for compressing a large range of numbers into a small space.

I am much obliged to *Mr. Simmons* for drawing attention to the available data contained in the figure accompanying his remarks. My attention had been drawn to the existence of this data by Sir Richard Glazebrook a day or two before the lecture, but I had not had an opportunity to consider it. Since the lecture I have secured Mr. Baker's original paper and have re-plotted the information on the same plan as Figs. 1 and 2 though on a larger scale, and the resulting diagram is reproduced herewith (Fig. 8). It is evident, both from Mr. Simmons' figure and from mine, that the boundary layer in the N.P.L. tank experiments was breaking up at about R = 6 X 10^5, and it is clear from my figure that at high Reynolds' numbers the curves of Froude and the N.P.L., which continue up to 4 X 10^7, lie within some 5 percent of the equation $k_F = 0.019(l\upsilon/v)^{-0.15}$. These latter data bring our knowledge of the skin friction coefficient of a flat plate up to a Reynolds' number of 4 X 10^7, that is to say, well into the region of Reynolds' numbers represented by full-scale aeroplane wings and bodies. They show that the formula which I used in my lecture for the skin friction is on the safe side in this region.

Document 3-8

Excerpts from Fred E. Weick and James R. Hansen, *From the Ground Up: The Autobiography of an Aeronautical Engineer* (Washington and London: Smithsonian Institution Press, 1988), pp. 49-61, 66-68, 72.

The organizing thinker and team leader of the NACA's original cowling program at Langley was Fred E. Weick, one of the most remarkable aeronautical engineers in the history of American aeronautics. Born near Chicago in 1899, Weick (pronounced Wyke) developed an avid interest in aviation by the age of 12, attending air meets at nearby Cicero Field and entering model airplane competitions. Upon graduation from the University of Illinois in 1922, he began his professional career as a draftsman with the original U.S. Air Mail Service. After a short stay with the Yackey Aircraft Company (during which time he worked in a converted beer hall in Maywood, Illinois, transforming war-surplus Breguet biplanes into "Yackey Transports"), he started a job with the U.S. Navy Bureau of Aeronautics in Washington, D.C., where, within a matter of months, the NACA's director of research, George W. Lewis (1882-1948), personally recruited him for important work to be done at Langley, some 120 miles to the southeast. (The NACA's Washington office was located in an adjacent wing of the Navy Building, thus facilitating close relations between the NACA and the navy.) Weick arrived at Langley in November 1925 just in time to take over the design and construction of the new Propeller Research Tunnel (PRT)—the job Lewis had specifically asked him to do.

The following is a series of excerpts from Fred Weick's 1988 autobiography in which he recalled the construction of the PRT and the origins of the cowling research program more than 60 years earlier. Readers will find that Weick's recall of these events from long ago was amazing. Perhaps even more amazing was that Weick was such a marvelously clear thinker when it came to technology and how his approach to everything related to engineering was strictly rational. One of Weick's friends and colleagues at NACA Langley in the 1930s (Weick worked at Langley from late 1925 to 1929, then moved to a job with Hamilton Aero Manufacturing Company in Milwaukee, Wisconsin, maker of adjustable aluminum-alloy propellers and steel hubs for both military and commercial aircraft, and then returned to work at Langley from 1930 to 1936) was the distinguished aerodynamicist Robert T. Jones, who became one of the fathers of the swept wing. In the foreword to Weick's autobiography, Jones paid tribute to this former NACA associate specifically in terms of his role in "reinventing the airplane." "Working with Fred," Jones wrote, "I had the feeling that the airplane was being reinvented, as it indeed was. Never mind that the general form and arrangement of the airplane had been well established for many years, Fred felt strongly that every function of the airplane needed to be studied from a logical point of view, without prejudice, so that designers and operators could make whatever changes were necessary to improve those functions" (p. viii).

Following his pioneering work on the NACA cowling, Weick went on to make many other significant contributions to the advancement of aeronautical technology, including development of the steerable tricycle landing gear, the conventional gear used today—even for the Space Shuttle. His most widely recognized achievement, the Ercoupe, has been the favorite airplane of thousands of private flyers since its first production model came out in 1940. And his revolutionary AG-1 and Piper Pawnee set life-saving standards of lasting benefit to both the agricultural airplane and general aviation industries. His autobiography from which these excerpts are taken tells his entire life story in fascinating detail, from his days with the barnstormers, through his navy and NACA years, to his many years in manufacturing for the Engineering Research Corporation (ERCO) and Piper.

Document 3-8, Excerpts from Fred E. Weick and James R. Hansen,* From the Ground Up: The Autobiography of an Aeronautical Engineer *(Washington and London: Smithsonian Institution Press, 1988), pp. 49-61, 66-68, 72.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS, LANGLEY FIELD

The distance by air from Washington, D.C., to Hampton, Virginia, the town nearest Langley Field, is only about 120 miles, but by road through Richmond it is about 175 miles. In the 1920s these roads were surfaced with gravel and often badly rutted; smooth ribbons of concrete were not to be found in rural Virginia. In our Model T roadster, packed to overflowing, it took us all day to make the trip.

The engineer in charge of the Langley Memorial Aeronautical Laboratory at that time, a Californian by the name of Leigh M. Griffith, appeared unhappy with the idea that I had been placed under him from above; in fact, Griffith must have been generally unhappy with his situation at Langley, for he left within the month. He was replaced by Henry J. E. Reid, an electrical engineer who had been in charge of the laboratory's instrumentation. Reid remained the engineer-in-charge until he retired from the National Aeronautics and Space Administration (NASA) in 1960. The lab had a flight research division headed by test pilot Thomas Carroll, a power plant division headed by Carlton Kemper, and two wind tunnel sections, one, the 5-foot or atmospheric wind tunnel (AWT) section headed by Elliott G. Reid, and, the other, the variable-density tunnel (VDT) section headed by George J. Higgins. There was also an instrument shop, model shop, technical service department, and a clerical and property office headed by Edward R. ("Ray") Sharp. The new 20-foot propeller research tunnel (PRT) was being constructed under the supervision of Elton W. Miller, a mechanical engineer who had previously been in charge of the construction of the variable-density tunnel. I was placed under Miller until the tunnel was ready for operation.

By the time I started at Langley, the outer shell of the new tunnel had been completed but work on the entrance and exit cones and guide vanes was still going on. The tunnel, which had been laid out by Dr. Max Munk in Washington, was of the open-throat type then most suitable for testing propellers. My first job was to design and get constructed a balance arrangement that measured the aerodynamic forces on the model and the model's reaction to them. This balance had to support an airplane fuselage, complete with engine and propeller, 25 feet above the floor in the center of the tunnel's 20-foot-in-diameter airstream. All of the pertinent forces, such as drag, thrust, and moments, were to be measured down below by four small and simple beam scales.

Since 1921 Dr. Munk had been holed up in a little office at NACA headquarters in Washington, where he had been turning out excellent theoretical work. Munk had studied under Ludwig Prandtl at the University of Gottingen in Germany and had been brought to this country by the NACA in 1921. His entry into this country required two presidential orders: one to get a former enemy into the country, and another to get him a job in the government. And I guessed this helped him to appreciate his importance.

Without question, Munk was a genius, and, without question, he was a difficult person to work with. In early 1926 he decided on his own that, since Langley laboratory was where all the real action was taking place, that was where he should be. NACA headquarters must have agreed, because it made him the lab's chief of aerodynamics; this put him in charge of the flight research division and the two wind tunnel sections. My boss, Elton Miller, now reported to Munk, and all of my work ultimately had to be approved by him. I had known Munk in Washington and had great respect for his abilities. On the other hand, I did not want my balance design turned down at the last minute; so I had taken the pain to take each detail of design, mostly on cross-section paper, up to Munk to get his approval, and I got his initials on every single one of them. This, I thought, would certainly assure his final approval.

The movable parts of the balance supporting the airplane were supported by a structural steel framework about 12-feet high, 12-feet wide, and 16-feet long. In place of adjustable cables, steel angles ¼ by 2 ½ by 2 ½ inches provided the diagonal bracing.

A couple of days before we expected to try out the balance using a little Sperry Messenger airplane with its 60-horsepower engine running, Munk made an unannounced visit to the PRT building. Just as he walked into the bare-walled 50-foot cubicle that housed the test section, a loud horn squawked, calling someone to the telephone. This sent Dr. Munk into a tantrum, and I immediately had one of my mechanics disconnect the horn. Before he had entirely calmed down, he walked over toward the balance structure and put his hands on the long diagonal braces.

These were fairly flexible, and he found he could move them back and forth a bit. Visualizing the entire structure vibrating to the point of failure and the whole airplane and balance crashing to the ground, the perturbed Munk ordered me to tear down the balance entirely and to design a new foundation and framework for it. He then turned and went back to his office a couple of blocks away.

Naturally I, too, was perturbed. Munk, after all, had approved every detail of my balance design. Not knowing what to do, I waited for some time to give him an opportunity to cool down. Then I went to his office and, as calmly as I could manage, mentioned that I thought the natural frequencies of the long diagonal members would be so low that vibrations would not be incited by the more rapid impulses from the engine and propeller. But mainly I suggested that, inasmuch as all the parts were made and ready to be put up, why not wait a couple of days before tearing it down and make a careful trial using the Sperry Messenger, starting at low speed, gradually increasing it, before dismantling the apparatus. Munk finally agreed, but demanded to be present when the test was made.

I did not like that idea of his presence one iota. To start the engine, the Messenger's propeller had to be cranked by hand from a balloon ladder that was put up in front of the propeller 25-feet above the floor. (A balloon ladder was like a fireman's ladder but its base was attached to a pair of weighted wheels, which permitted it to be "leaned" out into space. At its base there was a "protractor" that told you how far it could be angled without tipping over.) This sweaty business often took some time. It was not the kind of operation I wanted the excitable Munk to watch. Moreover, since no one else in the PRT section had ever started an airplane engine by turning the propeller, I was the one who was going to have to do it.

I brought my problem to Elton Miller, my boss, and to Henry Reid, the engineer-in-charge. Together, we decided that the only thing to do was to make an end-run around Munk and check out the tunnel balance system in his absence. This was easily done, as Munk worked on theoretical problems in his room at a Hampton boarding house every afternoon. We set up the test run and after a bit got the engine started without any difficulty. We then experimented with it until we could start it easily and felt ready for the final trial.

The problem of convincing Munk remained. We could not simply tell him about the successful test, so we agreed to arrange another "first test" for Munk to witness. Engineer-in-charge Reid escorted Munk to the tunnel the next morning. I casually said, "Good morning," clambered up the ladder, and pulled through the Messenger's prop. Luckily, the engine started on the first try. We then moved the ladder away, ran the engine through its entire range with no vibration difficulty, and then shut it down. Now, I wondered, what sort of explosion will we have? I needn't have worried. Munk walked toward me with his hand outstretched and congratulated me on the success of the operation. Everything had turned out all right. The balance system of the PRT operated satisfactorily with engines of up to 400 horsepower into the late 1930s, when it was replaced by a new and better one.

In 1926 Dr. Munk gave a number of lectures on theoretical aerodynamics to a select group of young Langley engineers. I was very happy to learn these things from him. Ever since graduation from the University of Illinois, I had thought about taking some graduate courses in aeronautical engineering. While working for Tony Yackey, I had read in a magazine article about the graduate courses in aeronautics offered at Massachusetts Institute of Technology. I had written MIT for information and had received a letter back from Professor Edward P. Warner, who had been Langley's first chief physicist in 1919 and would later become assistant secretary of the navy for aeronautics, editor of the magazine *Aviation*, and finally president of the International Civil Aviation Organization (ICAO), which continues to coordinate the rules and regulations for aeronautical activities throughout the nations of the world. I had hoped still to find a way to work in some graduate courses even after reporting to work at the Bureau of Aeronautics. But Dr. Lewis had talked me out of the idea on the basis that formal aeronautical engineering education was inferior to what I could learn if I went to work for the NACA at Langley. I guess he was probably right in regard to the aeronautical courses per se, but on occasion, in later years, I sorely missed the extra mathematics and physics that would have been obtained in school.

As mentioned earlier, the power plant for the new PRT consisted of two 1,000-horsepower, six-cylinder in-line diesel engines taken from a T-2 submarine. These engines were located end-to-end with crankshafts connected to a large sheave or pulley between them. This sheave carried forty-four Tex-rope V-belts to a similar sheave on the shaft of the propeller fan that drove the air through the tunnel. The shaft of the propeller fan was 25 feet above the ground, and the two sheaves were 55 feet apart center to center. Because we were concerned that some destructive vibrations might occur in the crankshaft-sheave assembly, we decided that a theoretical analysis of the torsional oscillations should be made, with Dr. Munk outlining the problem and a new man, Dr. Paul Hemke, to work out the solution. As a junior engineer, my assignment was to give the measurements and sizes that I would get from the drawings of the engines and sheaves.

I had no difficulty giving them the measurements, but Dr. Hemke was never able to get the gist of the torsional pendulum problem as described by Munk. This went on for some time with no results being obtained. Finally, I looked into my mechanical engineers' handbook and into a couple of textbooks and found that considerable work had been done on the problem and that the solution was not too difficult. I made the computation myself, coming out with a natural frequency of 312 RPMs. Later on, after the tunnel was in operation, some men came down from the navy shipyard in Brooklyn with equipment to measure the torsional oscillations; they found exactly the same natural frequency as I had computed. Hitting it exactly, of course, was a matter of luck, but it helped give me a good reputation, whether I deserved it or not. The success put me in good with Munk, but unfortunately Dr. Hemke was never able to work satisfactorily with him. A short time later he left the NACA. Hemke later joined the faculty of the U.S. Naval Academy, after holding a prestigious Guggenheim Fellowship for research under B. Melville Jones at Cambridge.

Another problem I helped to solve was the design of the 28-foot propeller fan that was to circulate the air in the propeller research tunnel. This fan needed to have eight blades of normal width. The exact energy ratio of the tunnel was not known in advance, so I desired to have blades that could be adjusted so that the pitch could be set exactly right after trial runs. Aluminum-alloy blades therefore seemed the best choice, but the blades we wanted were too large to be forged in the manner of the aluminum-alloy propeller blades then being manufactured. Fortunately, the propeller was to turn at only 375 revolutions per minute, which meant that the stresses would be very low in comparison even with airplane propellers having large diameters. This gave me the idea that a cast aluminum alloy might be used successfully, which it was.

I arranged with the Aluminum Company of America to cast the blades in their plant at Cleveland, Ohio. Before the large blades were cast, however, the company made two blades for a small ten-foot model that I then took to McCook Field in Dayton, where they were tested by Army Air Service engineers on their propeller whirl rig. This test showed the blades to be sufficiently strong.

During the period that the blades were being manufactured, I made a number of trips to Cleveland. On one occasion, when I had an afternoon with nothing special to do, I visited the Martin aircraft plant in the city's southern suburbs. I went into the door to the main office and told a young lady at the desk that I was an engineer from the NACA at Langley Field and that I'd like to visit the plant. She ushered me into the office of Glenn L. Martin himself, and he spent a couple of hours showing me around. How different from the stilted, bureaucratized conditions existing today in an aircraft factory! Of course, the Martin plant was small then, with only a few hundred employees. Most of his production went to the Navy Department; in fact, while at the Bureau of Aeronautics, I had designed a couple of the propellers used on his airplanes. Because many of his models were seaplanes and nearby Lake Erie was frozen solid in the winter months, Martin was then looking around to find a place farther south where he could manufacture and fly them away directly from the factory all year round. On this account he asked about the conditions around Hampton and Newport News, a neighborhood that he thought might be quite suitable. I told what I could about the area, and later he made some overtures in this direction. But, as I remember it, the local people at Newport News were not interested. Martin finally moved his factory to Middle River, Maryland, near Baltimore, where local authorities gave him a very good deal.

The NACA held its first annual manufacturers' conference at Langley in May 1926. The meeting was attended by representatives from the military air services, Department of Commerce, and aeronautical manufacturing industry. The morning was spent touring the various laboratories and learning about the research work

that was going on in them. The propeller research tunnel was about finished, but Ted Myers, who was in charge of the tunnel's power plant, had not been able to get the diesel engines to run. However, we had the regular starting arrangement by which we turned the engines over by a blast of compressed air until they would start running as diesels. At the demonstration that morning, we ran the tunnel on the compressed air for about one minute; the little Sperry Messenger was up in the test section with its engine running also. In the afternoon, the conference was held at the military officers' club a few blocks away, and suggestions for possible new research were invited. One of the suggestions that was made concerned the cowling of radial air-cooled engines.

When I had started work at the Bureau of Aeronautics, almost all of the army and navy airplanes had had water-cooled engines. The navy, however, was interested in developing radial air-cooled engines. This work had been carried on under the direction of Comdr. Eugene E. Wilson of the bureau's power plant division and had been conducted mostly with the Wright engines designed by Charles Lawrance. The radial engines with their short crankshafts and crankcases and no radiators or water-cooling systems were lighter than the water-cooled engines. But the finned cylinders were cooled simply by projecting them into the airstream, and this caused a high drag. An attempt had been made to reduce the drag by putting propeller spinners over the hubs and cowling the crankcase and lower portions of the cylinders, but the outer ends of the cylinders still extended into the airstream.

During the morning session of the NACA conference, everyone had witnessed the operation of the Sperry Messenger airplane, with its radial air-cooled Lawrance engine running, in the propeller research tunnel. At the afternoon meeting, several people mentioned that tests should be made in the PRT to see how much the cowling could be extended outward without interfering too much with the cooling of the engine. Both the drag and propeller efficiency should be determined, we all agreed, as well as the cooling. During the ensuing months, I laid out a program for these cowling tests.

While studying propellers at the Bureau of Aeronautics, I learned from the propeller work carried out by William F. Durand and Everett P. Lesley at Stanford University the advantages of using a systematic series of independent variables in experimental research. I recognized that the range of variables should extend, if possible, on both sides well beyond the area of greatest interest. One extreme of this series was obviously making use of the bare engine with no cowling at all. The other extreme was to enclose the engine completely. This option had not been anticipated but looked enticing. An engine nacelle would then start with the best airship shape available, and the air could be brought in smoothly at the center of the nose. But how could one get the air out again in a smooth and efficient manner? Elliott G. Reid, who was in charge of the atmospheric wind tunnel at the time, had been making tests on Handley Page wing slots, and he helped me to design an annular exit slot. Together, these forms eventually became the NACA's low-drag cowling.

After I had completed the outline of a tentative cowling test program, the NACA sent it to the military air services and to various manufacturers that had shown interest at the May 1926 conference, and it was approved by all of them. Fortunately, getting their okay took some time, because the propeller research tunnel was at this point in no sense ready to operate.

After establishing that the tunnel was operating satisfactorily, we carried out several series of propeller tests and cowling tests at the same time. Among other things, this enabled us to obtain the effect of propeller-body interference on each cowling design. The various propeller tests were mostly covered in the following NACA reports: TR 306, "Full-Scale Wind-Tunnel Tests of a Series of Metal Propellers on a VE-7 Airplane" (July 13,1928); TR 338, "The Effect of Reduction Gearing on Propeller-Body Interference as Shown by Full-Scale Wind-Tunnel Tests" (March 20, 1929); TR 339, "Full-Scale Wind-Tunnel Tests with a Series of Propellers of Different Diameters on a Single Fuselage" (March 12,1929); TR 340, "Full-Scale Wind-Tunnel Tests on Several Metal Propellers Having Different Blade Forms" (March 18,1929); and TR 350, "Working Charts for the Selection of Aluminum Alloy Propellers of a Standard Form to Operate with Various Aircraft Engines and Bodies" (March 25, 1929).[1]

The goal that we had set for ourselves in the cowling program was a cowled engine that would be cooled as well as one with no cowling whatsoever. This program proceeded easily enough until the complete cowling, covering the entire engine, was first tried. At this point, some of the cylinder temperatures proved to be much too high. After several modifications to the cooling air inlet and exit forms, and the use of internal guide vanes or baffles, we finally obtained satisfactory cooling with a complete cowling. Don Wood was in charge of the actual operation of the testing, and the first of these modifications was made while I was away on a vacation. When I got back, it was obvious to me that the boys were on to something, and from that time on we all worked very hard on the program.

The results of this first portion of cowling tests were so remarkable that we decided that the NACA should make them known to industry at once. In November 1928 I wrote up Technical Note 301, "Drag and Cooling with Various Forms of Cowling for a 'Whirlwind' Engine in a Cabin Fuselage," which the NACA published immediately. The summary of the report was as follows:

The National Advisory Committee for Aeronautics has undertaken an investigation in the 20-foot Propeller Research Tunnel at Langley Field on the cowling of radial air-cooled engines. A portion of the investigation has been completed in which several forms and degrees of cowling were tested on a Wright Whirlwind J-5 engine mounted in the nose of a cabin fuselage. The cowlings varied from the one extreme of an entirely exposed engine to the other in which the engine was entirely enclosed. Cooling tests were made and each cowling modified if necessary until the engine cooled approximately as satisfactorily as when it was entirely exposed. Drag tests were then made with each form of cowling and the effect of the cowling on the propulsive efficiency determined with a metal propeller. The propulsive efficiency was found to be practically the same with all forms of cowling. The drag of the cabin fuselage with uncowled engine was found to be more than three times as great as the drag of the fuselage with the engine removed and nose rounded. The conventional forms of cowling in which at least the tops of the cylinder heads and valve gear are exposed, reduced the drag somewhat, but the cowling entirely covering the engine reduced it 2.6 times as much as the best conventional one. The decrease in drag due to the use of spinners proved to be almost negligible.

I concluded this summary by arguing that use of the form completely covering the engine was "entirely practical" under service conditions, but also by warning that "it must be carefully designed to cool properly."

Having completed the initial round of wind-tunnel tests, we then borrowed a Curtiss Hawk AT-5A airplane from the Army Air Service at Langley Field already fitted with the Wright Whirlwind J-5 engine, and applied the new cowling for flight research. These tests showed that the airplane's speed increased from 118 to 137 miles per hour with the new cowling, an increase of 19 MPH. The results of the instrumented flight tests had a little scatter, and we could have been justified in claiming that the increase in speed was 20 MPH instead of 19, but I wanted to be conservative. I didn't want people to expect too much from this cowling, so we called it 19.

The second part of the cowling program covered tests with several forms of cowling, including individual fairings behind and individual hoods over the cylinders, and a smaller version of the new complete cowling, all mounted in a smaller, open-cockpit fuselage. We also performed drag tests with a conventional engine nacelle and with a nacelle having the new complete design. Though the individual fairings and hoods proved ineffective in reducing drag, we found that the reduction with the complete cowling over that with the conventional cowling was in fact over twice as great with smaller bodies as with the larger cabin fuselage. Data from the AT-5A flight tests confirmed this conclusion.

The first public acclaim of the cowling came in February 1929 when Frank Hawks established a new Los Angeles-to-New York nonstop record (18 hours, 13 minutes) flying a Lockheed Air Express equipped with an NACA low-drag cowling that increased the aircraft's maximum speed from 157 to 177 MPH. The day after the feat, the NACA received the following telegram:

Cooling carefully checked and OK. Record impossible without new cowling. All credit due NACA for painstaking and accurate research. [Signed] Gerry Vultee, Chief Engineer, Lockheed Aircraft Co.

Some time later, the NACA gave me a photographic copy of this telegram, along with a picture of the cowled airplane.

A few weeks before Hawks's record-breaking flight, I had attended the New York Air Show in Madison Square Garden. At the show Chance Vought told me that Germany's Claude Dornier would like to talk to me about the possibility of putting the NACA cowling on the twelve uncowled radial air-cooled engines of his giant DO-X flying boat—which, at the time, was the largest airplane in the world. These twelve engines (British-made Jupiters rated at 550 horsepower each) were mounted back-to-back in six nacelles, each with one tractor propeller and one pusher propeller. Cowling the pushers would, of course, constitute an entirely new problem.

Before finishing this story, it should be mentioned that a great effort was then being made in a number of countries to develop aircraft suitable for airline use across the oceans, particularly the North Atlantic. The aircraft were of two main types: rigid airships of the Zeppelin type and large flying boats like Dornier's. The wing of the DO-X projected from the top of an ample hull with a span of 157 feet and a chord of 30 feet. Lateral stability on the water was obtained by the use of sponsons, or short and stubby winglike structures that projected from the bottom of the hull on each side. Constructed in the late 1920s at Altenrein, Switzerland, on Lake Constance and near Friederichshafen, Germany, the DO-X could accommodate sixty-six passengers comfortably over a range of 700 to 900 miles, but could not lift any kind of payload over transatlantic distances, the minimum such distance being roughly 2,000 miles. On one flight from adjoining Lake Constance, though, one hundred seventy people were crowded into the airplane (I've heard that nine were stowaways), making quite a record at that time.

By this time at Langley lab, we had mounted the low-drag cowling on all three engines of a Fokker trimotor airplane. The comparative speed trials proved extremely disappointing. Separate tests on the individual nacelles showed that cowling the Fokker's nose engine gave approximately the improved performance we expected. Cowling the wing nacelles, however, gave no improvement in performance at all. This was strange, because the wind-tunnel tests had already demonstrated convincingly that one could obtain much greater improvement with a cowled nacelle than with a cowled engine in front of a large fuselage.

Some of us started to wonder how the position of the nacelle with respect to the wing might affect drag. In the case of the Fokker (as well as the Ford) trimotor, the wing engines were mounted slightly below the surface of the wing. The upper surface of the fully cowled nacelle then came very close to the under surface of the wing. As the air flowed back between the wing and nacelle, and the distance between them increased toward the rear of the nacelle, the expansion required was too great for the air to follow smoothly. We tried fairing-in this space, but achieved only a small improvement.

As a result of these experiences I laid out a series of model tests in the propeller research tunnel in which an NACA-cowled nacelle with a power-driven propeller was placed in a number of different positions with respect to the wing. Where it appeared pertinent, extra fairing was put between them. These tests were run by Don Wood and his crew after I had left the NACA to work for Hamilton Standard.

The resulting data on the effect of the nacelle on the lift, drag, and propulsive

efficiency of the Fokker airplane made it clear that the optimum location of the nacelle was directly in line with the wing, with the propeller well ahead of the wing's leading edge. This position had the least overall projected area, and I suppose the result might have been expected. With the complete cowling, the radial engine in this position spoiled the maximum-lift coefficient of the wing. With the cowling, and the smooth airflow that resulted from it, the maximum-lift coefficient was actually increased. After this important information was transmitted confidentially to the army, navy, and industry, most all of the transport and bombing airplanes employed radial wing-mounted engines with the NACA cowled nacelles located approximately in the optimum position.

Document 3-9(a-b)

(a) Western Union telegram, Jerry Vultee, Lockheed Aircraft Co., Burbank, CA, to NACA, "Attention Lieutenant Tom Carroll," 5 Feb. 1929, copy in NACA Research Authorization file 215, NASA Langley Historical Archives.

(b) Fred E. Weick, "The New NACA Low-Drag Cowling," *Aviation* 25 (17 November 1928): 1556-1557, 1586, 1588, 1590.

National attention became focused on the success of the NACA's low-drag engine cowling in February 1929 when celebrated pilot Frank Hawks set a new nonstop speed record from Los Angeles to New York in a Lockheed Air Express equipped with a NACA cowl that increased its top speed from 157 to 177 miles per hour. Gerald "Jerry" Vultee, chief engineer with the Lockheed Aircraft Company, sent a telegram to NACA Langley's chief research pilot, Thomas Carroll, crediting the NACA for the flight's success; this telegram can be found as the first document below.

Not only did the low-drag cowling provide unprecedented performance for new aircraft like the Air Express, it was also a factor in generating public notoriety for how much U.S. aviation was advancing generally. It also bolstered the reputation of the young NACA. Amid a burst of publicity—some of it exaggerated—about the benefits of the NACA cowling, the National Aeronautics Association announced in January 1930 that the NACA cowl had won the Collier Trophy for the greatest achievement in American aviation in 1929.

The second document provides NACA Langley engineer Fred E. Weick's article on the low-drag engine cowling published in *Aviation* magazine in November 1928. This was still early in the NACA's cowling program. Work on advanced forms of cowlings continued throughout the 1930s.

Document 3-9(a), Western Union telegram, Jerry Vultee, Lockheed Aircraft Co., Burbank, CA, to NACA, "Attention Lieutenant Tom Carroll," 5 Feb. 1929, copy in NACA Research Authorization file 215, NASA Langley Historical Archives.

WESTERN UNION

FEB 5, 1929

To: NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

Street and No.: LANGLEY MEMORIAL AERO LABORATORY LANGLEY FIELD VIR

Place:

ATTENTION LIEUTENANT TOM CARROLL LOCKHEED AIR EXPRESS PILOT: FRANK HAWKS WHICH JUST ESTABLISHED NEW LOS ANGELES TO NEW YORK NONSTOP RECORD OF EIGHTEEN HOURS THIRTEEN MINUTES IS EQUIPPED WITH N.A.C.A. COWLING WHICH INCREASED ITS SPEED TWENTY MILES PER HOUR FROM 157 TO 177 STOP COOLING CAREFULLY CHECKED AND OK STOP RECORD IMPOSSIBLE WITHOUT NEW COWLING ALL CREDIT DUE N.A.C.A. FOR PAINSTAKING AND ACCURATE RESEARCH AND GENEROUS POLICY STOP KINDEST PERSONAL REGARDS STOP LETTER WITH DATA AND PHOTOS FOLLOWS.

JERRY VULTEE
LOCKHEED AIRCRAFT CO.

Document 3-9(b), Fred E. Weick, "The New NACA Low-Drag Cowling,"* Aviation *25 (17 November 1928): 1556-1557, 1586, 1588, 1590.

STATIC radial air-cooled engines are claimed by some engineers to possess several advantages over engines of other types, among which are low weight per horsepower, the small number of parts required, and the consequent reliability and low cost of manufacture. They are now widely used and are still gaining favor, both in commercial and military aeronautics. They have had, however, one outstanding disadvantage--their extremely high air resistance, caused by the large frontal area and very poor aerodynamic form. The high drag has been a serious handicap in the field of high speed pursuit planes and single seater fighters, but the low weight of the air-cooled radial has some advantages.

Aircraft designers have attempted to reduce the drag due to the air-cooled radial engine by enclosing varying amounts of it within the nose of the fuselage or nacelle. There has been a wide difference of opinion regarding the best forms and amounts of cowling, and its effect on the drag and the cooling of the engine. Some designers have cowled in almost the entire engine leaving only the cylinder heads and valve gear exposed, while others have been content to leave the engine entirely exposed. Practically no accurate or reliable information has been available on the subject, for until very recently there has been no practical way of obtaining it.

The National Advisory Committee for Aeronautics has made a practice for each of the last few years of inviting the aircraft manufacturers and their representatives to spend a day at the Committee's laboratory at Langley Field, in order that they may become more familiar with the work and facilities, and make suggestions regarding research which would be helpful to them. At the meeting held on May 24, 1927, the manufacturers were practically unanimous in urging that an investigation be made in the new 20 ft. propeller research wind tunnel, then just being completed, on the cowling of radial air-cooled engines. The new tunnel, in which an air speed of 110 m.p.h. can be obtained, is ideal for the purpose. An actual full size airplane can be accommodated except for the wing tips, and the engines can be run with its propeller as in flight. The propeller thrust, airplane drag, and propulsive efficiency can be measured under flight conditions but with laboratory accuracy, so that small differences due to slight changes in cowling are brought out, and thermocouples can be used to obtain the temperatures at a large number of points on the cylinders so that the effect of the cowling on the cooling can be studied.

In working out a program for the cowling tests, it was thought desirable to include not only all of the main conventional forms of cowling, but also to have them arranged in series with various degrees or amounts of cowling. At one extreme of the series, the engine was left entirely exposed except for the rear of the crankcase where it was fitted to a fuselage. For the other extreme, it seemed logical to enclose the entire engine. This involved problems in design, for it was of course desired to have the drag as low as possible, but still have the engine cool satisfactorily. It was easy to design a form enclosing the engine and having a low drag, but there was no information available as to the best means of cooling the engine. It was decided to make the outside of the complete cowling of circular cross-section and smooth form, without individual cylinder fairing such as have been used on a few experimental airplanes, particularly in England. This was done partly for the sake of simplicity and partly because in the case of most American radial engines, and especially the Wright Whirlwind J-5 which was used in this investigation, there is so little room between adjacent cylinders that individual hoods are impractical. It was necessary, of course, with the cowling entirely covering the engine, to separate the air used for cooling the cylinders from the general flow about the body, guide it past the cylinders, and then return it to the outside air again. If the separation and the return could be made smoothly, it seemed likely that a large decrease in drag could be obtained.

It was decided that the cooling air for all of the cylinders could be taken in most satisfactorily at the center of the nose where the air pressure on the body, when in motion, is greatest. This allowed a simple symmetrical design and a smooth separation of the cooling air from the general flow. Regarding the matter of returning the used cooling air to the general flow again, suggestions were obtained from the staff in charge of the five-foot atmospheric wind tunnel of the laboratory, who had done some work on wing slots and boundary layer control. As a result, the new cowling was designed with an annular slot extending entirely around the circumference of the body a short distance behind the engine. In section the slot was similar to some wing slots in which the air passing through is directed tangentially along the surface. Rough comparative tests on two small model fuselages were then made in the six-inch wind tunnel, and these indicated that a substantial reduction in drag and a reasonable flow of air through the nose and out of the slot would be obtained. The flow of cooling air is helped by the fact that the outside air pressure at the nose is the highest and that at the slot about the lowest found over the entire body, when the body is in motion with respect to the air.

A program of tests was drawn up including both extremes of cowling and several conventional intermediate steps, both with and without spinners and on a cabin type and an open cockpit type fuselage. This program was then submitted to the manufacturers for criticisms and suggestions, several of which were adopted. As the tests were finally made, the cooling with each form of cowling was first investigated and compared with that for the uncowled engine. Then the cowling was modified, if necessary, and retested until the cooling was approximately as satisfactory as for the entirely exposed engine. After that, tests were made on the drag and the propulsive efficiency.

The portion of the investigation involving the cabin fuselage has been completed, and tests are now being made with the smaller open cockpit fuselage.

One of the first findings of the tests was the enormous amount of drag due to the uncowled engine. The drag of the bare cabin fuselage with the engine removed

and nose rounded was more than tripled by the addition of the engine, and that of the open cockpit fuselage was increased nearly five times. In fact, the drag of the open cockpit fuselage was about 10 percent. greater than that of the cabin fuselage with the same engine cowling even though the open cockpit fuselage had only half the cross-sectional area of the other. The larger body behind the engine evidently has a beneficial effect on the drag, and the drag of a small fuselage without engine is insignificant compared with that when the engine is added. The conditions with a wing engine nacelle would probably be at least as bad as with a small fuselage. These facts showed plainly that there was an opportunity for great improvement, especially in the cases of small fuselages and engine nacelles.

The next outstanding development of the tests was that the conventional cowlings, in which only the central portion of the engine is covered, had but slight effect in reducing the drag. Even in the extreme case, in which a large spinner was used and the entire engine was covered in except for the tops of the cylinder heads and valve gear, the reduction in drag was comparatively small. Spinners as conventionally used in front of the projecting cylinders of radial engines were found to have a negligible effect on performance.

When the new N. A. C. A. cowling completely enclosing the engine was first tested, an exceptionally low drag was obtained, but the engine ran much too hot. The cowling was modified and retested many times before the engine cooled properly, but finally the cooling was approximately as satisfactory as with the uncowled engine. To accomplish this, it had been necessary to enlarge the hole in the nose, provide cut-outs over the magnetos, enlarge the slot, and guide the cooling air past the hottest parts of the cylinders. In this connection, there is still room for improvement in the effective use of the cooling air, with a possible further gain in performance.

The reduction in drag of the cabin fuselage with the final cowling, which cooled satisfactorily with the engine completely enclosed, was 2.6 times as great as with the best conventional type with a large spinner. A still greater difference is to be expected in the case of a small fuselage or a nacelle, the tests on which are now underway.

Rough calculations show that the power required to drive an average commercial Whirlwind engined cabin airplane at its maximum horizontal speed would be reduced by from 15 to 20 per cent by the use of the new N. A. C. A cowling in place of the best present conventional cowling. For three-engined transports with two wing engines the decrease in power required under similar conditions would be from 20 to 25 percent, and for machines with small open cockpit fuselages as much as 20 to 30 percent.

If the full engine power were used with the N. A. C. A. cowling, the maximum horizontal speed would be increased by from five to ten miles per hour for the average cabin airplane, somewhat more for the three-engined machines, and as much as 20 m.p.h. for small open cockpit planes such as single-seater fighters.

Inasmuch as the drag is less with the N. A. C. A. cowling, the power available for climbing is greater, and the rate of climb and the ceiling will be improved. The fuel consumption will also be reduced, the amount depending on the speed of flight. If the same cruising speed is maintained, as with the old cowling, the decrease in fuel consumption will be approximately proportional to the decrease in power required. On the other hand, if, as is more likely the case, the same engine power will be used in order to cruise at an increased speed, the number of miles obtained per gallon will be increased in proportion to the increase in speed. An increase in range will also be obtained, which is proportional to the increase in the miles flown per gallon.

It is believed that the improved performance with the new cowling makes the air-cooled radial equal to or better than the water-cooled engine in the matter of drag except in the case of pure racing planes on which wing radiators may be used.

The results of the wind tunnel tests were so promising that it was decided to check them in flight. The Army kindly loaned an AT-5A (Curtiss Hawk with Whirlwind engine for advanced training purposes) for the tests. The new N. A. C. A complete cowling was then adapted to the plane by the Flight Operations Section of the laboratory, which had also constructed all of the cowling for the wind tunnel investigation, and the tests were carried out by the chief test pilot, Thomas Carroll, and his two assistants, Messrs. McAvoy and Christopher. The best of the standard Army AT-5A planes was taken from the line and a direct comparison was made between it and the one with the complete cowling, both being flown at the same time. Each test point was checked several times by each of the three pilots.

The plane with the new N. A. C. A. cowling had a maximum horizontal speed at sea level of 137 m.p.h. as compared with 118 m.p.h. for the standard AT-5A, both being attained with the same engine revolutions. This represents a gain of 19 m.p.h due to the new cowling. The reduction of engine drag is probably directly responsible for about 13 or 14 mi. of this gain, the rest being due to the decrease in induced drag and the increase in propeller efficiency at the higher speed.

All of the pilots reported the plane with the new cowling smoother to fly and better in answering the controls than the standard plane. No doubt this can be attributed to the smoother airflow over the fuselage and inner portion of the tail surfaces.

The pilots also reported that with this airplane the new cowling did not alter the range of vision in any useful field. The complete cowling, of course, cuts off whatever view can be obtained between the cylinders. Incidentally, there seems to be a great difference of opinion regarding the usefulness of the vision which can be obtained between the cylinders, some pilots maintaining that it is essential in the case of some planes, such as fighters, and others believing that it is never used to an appreciable extent. It undoubtedly depends to some extent on the contour of the engine and the amount of space between the cylinders. If the complete cowling comes into general use, as these first tests seem to warrant, there may be a tendency toward the development of more compact engines having a smaller overall diameter.

Other engine developments which would improve the effectiveness of this type

of cowling are the placing of all accessories, especially the magnetos, in the rear (this is of course now being done in many power plants), and the provision of greater distance between the plane of the cylinders and the propeller so that a better shaped nose can be had.

The new N. A. C. A. cowling, being simple and smooth in form, is easily constructed. The nose piece or hood used in both the wind tunnel and flight tests was built into a complete ring which was inherently stiff and strong without bracing. It could be easily removed, but it was first necessary to remove the propeller. To avoid this in practice, it would probably be advisable to make the nose piece in two or three quickly detachable sections. When the nose piece is removed the small cowling over crankcase is similar to conventional types, and most parts of the engine requiring frequent attention can be easily reached. No difficulties of maintenance occurred during the many hours of wind tunnel running or in flight tests.

In manufacture, the complete cowling would probably cost no more than a conventional cowling without spinner, except for the nose piece. Since a spinner is not required, it would cost little if any more than the conventional types using a large spinner. The weight of the nose ring used on the AT-5A, part of which was made of 1-16 in. thick aluminum for convenience in working, was 27 lbs.

In the test cowlings, the engine exhaust was directed out of the slot by means of individual stacks on each cylinder. The conventional ring type exhaust collectors could be used behind the cylinders if desired, or if the engine exhausted at the front, the exhaust ring could be made the front part of the nose piece. This latter would provide a very convenient means of support for the rest the nose piece. The complete cowling is well adapted for the use of shutters, which could be made to reduce flow of cooling air over the entire engine if desired. It would seem that this would improve the operation of cooled engines very appreciably in cold climates.

One point regarding the application of this cowling is worth mentioning. The many modifications, which were necessary before proper cooling was obtained with the cowling, show that it must be carefully designed. It is possible that eventually the engine manufacturers will find it advisable to furnish the engines complete with cowling, thus ensuring proper cooling conditions for their products. In that case the exhaust system could no doubt be very neatly incorporated in the cowling.

In appearance, the N. A. C. A cowling is reminiscent of the hoods enclosing the old rotary engines of the war period. It gives the fuselage-engine combination longer and smoother lines with, even on a small fuselage such as that of the AT-5A, are not unpleasant to the eye.

In conclusion, it would seem from the test made to date that a very substantial increase in high speed and all-round performance can be obtained on practically all radial engined aircraft by the use of the new N. A. C. A complete cowling.

Document 3-10(a-c)

(a) H. C. H. Townend, "Reduction of Drag of Radial Engine by Attachment of Rings of Aerofoil Section," British Aeronautical Research Committee *Research and Memoranda 1267* (1929).

(b) United Aircraft and Transport Corporation Technical Advisory Committee, Meeting Minutes, December 1929, Boeing Historical Archives, Seattle, Washington, pp. 213-256.

(c) "The Curtiss Anti-Drag Ring," *Curtiss-Wright Review 1* (December 1930): 16.

The NACA cowling was not the only method of reducing the drag of air-cooled engines. In 1929, Hubert C.H. Townend of the British National Physical Laboratory also developed a low-drag engine cowling. Known as the "Townend ring," this design also reduced drag with little degradation of engine cooling and was widely adopted in Europe and America. Because it completely enclosed the engine, many people in the aviation industry believed that the NACA cowling was inevitably detrimental to engine cooling; therefore, they intuitively favored Townend's design. As indicated in the second document below, members of the United Aircraft and Transport Technical Advisory Committee (curiously of which Fred Weick was briefly a member) reflected this prejudice. Several Boeing aircraft, such as the P-26 "Peashooter" of the early 1930s, utilized the ring cowling. Other manufacturers employed similar structures. One company, Curtiss-Wright, developed its own form of Townend ring, which it called the "Curtiss Anti-Drag Ring," the subject of the third document below.

The history of the NACA cowling-Townend ring rivalry has yet to be written. In the beginning, neither the British National Physical Laboratory nor the American NACA appear to have been aware of the other's cowling work. The NPL published the results of its ring research just before the NACA's cowling reports appeared. To impress American manufacturers with the value of its cowling, the NACA placed its design into some direct competition with the Townend ring. For example, it did so with the Martin B-10 when it competed with the Boeing B-9 for a large army contract in 1932 (see Document 3-19). The overall competitive situation between the cowl and the ring fed the fire of what became a transatlantic dispute and resulted in a long series of patent suits.

Document 3-10(a), H. C. H. Townend, "Reduction of Drag of Radial Engine by Attachment of Rings of Aerofoil Section," British Aeronautical Research Committee* Research and Memoranda *1267 (1929).

AERONAUTICAL RESEARCH COMMITTEE

Report for the year 1929-30

Brigadier-General The Rt. Hon. The Lord Thomson,
P.C., C.B.E., D.S.O., *p.s.c.*, Secretary of State for Air.

June, 1930

My Lord,

The Aeronautical Research Committee beg to submit their report for the year 1929-30.

The Committee wish to draw attention to the stead expansion of activities in aeronautics throughout the world and to the consequent increase in the number of problems awaiting solution which have been brought to their attention in connection with developments within the British Empire.

The speed and size of aircraft continually increase and the number of uses to which aircraft are put grows steadily. New flying boats and aeroplanes, fitted with a number of engines, are projected. The speed of aircraft, especially for service and racing purposes, has increased greatly; the race for the Schneider Trophy in 1929 and the speed record made later over the three kilometer course by officers of the Royal Air Force indicate the extent of this advance. The new airships, R.100 and R.101, have completed their trials during the year and as a consequence of experience with them, the question of larger ships, bringing with it new problems both of design and performance, has naturally come forward. Research requirements demand not only the solution of these new problems but also experiments on larger models at higher values of the Reynolds number, i.e., at higher speeds or in air under pressure; small models do not always reproduce the actual aircraft in sufficient detail. For work at higher values of the Reynolds number a compressed air tunnel is under construction at the National Physical Laboratory, while for models requiring engine details the erection at the Royal Aircraft Establishment of a large wind tunnel with an air jet 24 ft. in diameter has been recommended. In addition, a scheme has been put forward for replacing the obsolescent 7 ft. tunnel No. 1 at the N.P.L., by two open jet tunnels of 8 ft. diameter housed in the existing building. This modernization will materially accelerate the progress of work in the N.P.L. program.

AERODYNAMICS.

When an aircraft is in motion, the disturbance produced in the air, together with the reaction up on the machine itself and its consequent performance all depend ultimately on the nature of the flow over its surface. This "boundary flow" is therefore of great practical importance, and detailed investigations of its characteristics have occupied the attention of the Committee during the year. Already in the previous year, Professor B. M. Jones had drawn attention, in R.&M. 1199, to the large difference existing between the drag of an aeroplane and that estimated from ideal conditions. The coefficient of frictional resistance to the motion of a flat surface through the air is known from experiment to depend on the Reynolds number at which the experiment is made. In the ideal conditions it should be possible to calculate the resistance to an aeroplane from a knowledge of its surface area and of this coefficient of friction, on the assumption that its value does not depend on the curvature of the surface. An enquiry has been started on the curvature of the surface. An enquiry has been started to investigate how far this assumption is justified.

The frictional coefficient depends also on the nature of the flow over the surface. This may be "laminar," in which case the air moves in smooth curves following more or less the shape of the surface, or it may be "turbulent" when a series of eddies is formed. For turbulent flow the coefficient considerably exceeds that found when the flow is laminar. In experiments in a wind tunnel both kinds of flow are observed; the flow over the forward part of a good streamline model is laminar, over the rear it is generally turbulent. As an aid to exploration near the surface of a body, an instrument has been designed which depends on the rate of cooling of a fine electrically heated wire and responds readily to fluctuations in the airflow. When placed near the surface of a model, this instrument can be arranged to indicate by audible means the nature of the flow and the points, if any, at which a change from laminar to turbulent flow takes place.

In some earlier investigations of the same problem, a small pitot tube was moved near to and parallel to the surface of the model. Some difficulties which attended this method have been overcome and the hot wire and pitot tube methods are now in good agreement. In addition to these two methods, the smoke trail from titanium tetrachloride, a chemical very suitable for this purpose, has made details of the flow visible. The first experiments with the chemical have given a good indication of the places on the models where the changes from laminar to turbulent motion occur but the technique of its use must be regarded as still in its infancy.

In addition to the study of the flow past a streamline body, a Joukowski type of aerofoil has been selected for experiments on resistance, for pressure plotting and for measurements of pitot head at distances as small as 2 or 3 thousandths of an inch from the surface. A report on this work is being prepared and will be published at an early date; it has a special interest since the form employed in this type of aerofoil is one for which the characteristics of the flow can be determined theoretically, so that comparison between theory and experiment will be possible.

The flow over airship bodies and aerofoils is generally of a stable nature, whereas the nature of the flow past a circular cylinder is known to vary rapidly at certain speeds. As another means therefore of attack on “critical flow,” the experimental conditions for a cylinder have been changed by setting up artificial turbulence in the airstream and by the alteration of surface roughness. These changes produced orderly responses in the characteristics of the flow and it appears that even in the range of the Reynolds number in which there is a large change in the resistance coefficient these characteristics are quite definite.

The above experiments were all made at normal wind tunnel speeds. In other work carried out at very high speeds, pressure distribution has been measured round a Joukowski section. Up to a speed of half the velocity of sound the force coefficients vary by only a small amount from those found at low speeds but there is an appreciable divergence, when the speed reaches about 0.6 times the velocity of sound. On other wing sections closer agreement with results obtained in a low speed wind tunnel was obtained as regards lift, but as regards drag there was a marked difference even at velocities only half that of sound.

A theoretical study allowing for the compressibility of air has also been made of the conditions under which the flow at high speeds past curved surfaces may exceed the velocity of sound close to a convex surface, while remaining below that speed at some distance from the surface. There appears in the mathematical solution presented to be no indication of any discontinuity of the flow; moreover, speeds just greater than that of sound are attained without the formation of compressibility waves. This work explains why the experiments in the electrolytic tank at Cambridge mentioned in last year’s report, were not successful at speeds above a certain value. Some confirmation of this theoretical work has been obtained in the small high speed jet at the N.P.L., but the matter is not yet completely cleared up.

INTERFERENCE.

While much time has thus been spent on studying flow near the surface, the effects due to the interference of one part of an aircraft on another have not been neglected. Attention had previously been drawn to the fact that aeroplane bodies and wings differing only in the method in which the wings were attached, gave widely different drags. The early experiments to elucidate this matter, described in last year’s report, were purposely made upon a streamline body thicker and shorter than the average aeroplane body, with the object of accentuating the effects to be measured. Selected experiments have been repeated upon another body of proportions more nearly similar to those of the bodies of aircraft and the researches are being extended to include an analysis of the separate forces on wings and bodies. Moreover, a series of experiments on the interference of an engine nacelle and a wing has been commenced in the largest N.P.L. (Duplex) wind tunnel; an airscrew and an aeroplane body will be added later. The effect of changes in the relative position of the body and wing for the cantilever monoplane type of construction is being investigated at the R.A.E.

A cognate research on airscrew body interference, for both tractor and pusher screws using ideally streamline bodies, is well advanced. The experiments on the tractor screws are complete and those on pusher screws are in hand. This will provide a basis for further interference experiments upon airscrew-body-wing combinations.

Concurrently with the general investigations on interference and, indeed, arising out of them, a valuable device known as the Townend Ring has been developed, whose use leads to a substantial reduction of the drag of aeroplane bodies fitted with radial engines (*see* Illustration No. 2). The effect of the ring is to direct the air along the body and lessen the amount of turbulence; the higher the lift coefficient of the cross section of the ring the more efficient is the Townend Ring in decreasing total resistance to forward motion. Moreover, the cooling of the engine is not adversely affected. An account of the experimental work on this Ring has been issued in the Reports and Memoranda Series; since its publication, the results obtained with models have been confirmed by a number of full scale trials. In one case the top speed of a certain aeroplane was increased by eight miles per hour.

The evolution of the Townend Ring affords an example of the valuable practical results that may follow from simple experiments originally intended to throw light on fundamental points. The success achieved in this case has encouraged the Committee to continue their policy of investigating first the simplest cases of body and wing combinations in endeavoring to establish the main principles on which interference depends.

PERFORMANCE.

The variation of the range of an aeroplane with speed and height is of considerable practical interest. Experiments made at the A. & A.E.E., Martlesham, showed that the maximum range of a particular aeroplane increased substantially with height whereas theory indicates that a change in altitude should have little or no effect.

REDUCTION OF DRAG OF RADIAL ENGINES BY THE ATTACHMENT OF RINGS OF AEROFOIL SECTION, INCLUDING INTERFERENCE EXPERIMENTS OF AN ALLIED NATURE, WITH SOME FURTHER APPLICATIONS.

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Summary. Introductory. Some experiments are described in which large, and frequently negative, interference effects are found to be produced by certain objects of streamline or aerofoil form upon the drag of (1) a model of airship form (U.721), (2) model aeroplane bodies having radial engines in the nose, and (3) models in which turbulence is produced by grooves or sharp edges. The evidence provided by the tests shows that the effects produced in cases (2) and (3) are due, not to shielding or fairing of the obstructions, but to the addition of small aerofoils to the models in such a way as to control the airflow in the neighborhood of the obstructions, chiefly by governing its local direction.

In case (1) there were no obstructions on the body, and the results are concerned simply with the interferences between the body (of airship form) and rings of streamline section surrounding it or of streamline struts and aerofoils near it. The effects on the body were very marked, its drag falling to zero when surrounded by a ring of as much as three times its own maximum diameter situated near the plane of the nose. For struts or rings in closer proximity to the surface, the body drag was negative in direction and three or four times its normal magnitude. There is at present no satisfactory explanation to be offered for some of these latter results, through it is hoped that work at present proceeding or projected will help to throw some light on them. In one case of this kind the combined drag of body and ring, when suitably disposed to one another, was less than the sum of the drags of each in free air although the presence of the body might have been expected to increase the ring drag above its minimum value, by making the direction of the local airstream oblique to the ring section.

Applications. The chief result of the experiments has been the development of a method of reducing the drag of radial engines, which consists in placing a ring of aerofoil section round the nose in front of the engine and partly overlapping it. The aerofoil section adopted for the ring may vary widely from a cambered plate to a thick symmetrical section such as could be used for an exhaust pipe or silencer.

The magnitude of the reduction obtained with a given ring increases with the number of cylinders in the engine, at least up to nine. With 14 cylinders in two rows the reduction is practically the same as with 9. In the best case tested (with 9 cylinders) a reduction of drag was obtained equal to 60 percent of that of body and engine only (i.e., $R/R_o = 0.40$).

Full scale tests indicate that the cooling of the engine is usually unimpaired and in some cases improved. Considerable silencing may also be effected when the ring is used as an exhaust collector. The ceiling may be increased (*see* 13). The ring interferes but little with the accessibility of the engine, and involves no modification in the body whatever; in fact, it is probably that in most cases the spinner and in some cases even the crank case cowling may be discarded without appreciably affecting the drag.

The majority of these full scale tests have not been strict comparisons with the model tests reported here, although based on them; exceptions to this statement will be noted in the text.

Further developments. Full scale tests are in hand at the R.A.E. in which measurements are to be made of the effect of two typical rings on the performance of a Bristol Bulldog aeroplane (Jupiter engine).

The rings selected for test on this machine are the full scale equivalents of Ring J and polygonal Ring P_3 shown in Fig. 25 of this report with a slight modification to the angle between the chord and the body axis in the latter case.

The influence on the cooling of the Engine is also to be measured.

The experiments described in this report were commenced in December, 1927. The results include those given in the two earlier reports cited. The report is divided into two parts:

Part I. Interference on the drag of a model airship form (U. 721) caused by the presence near the nose of struts and aerofoils, and of rings of streamline section coaxial with the body, in various positions relative to the nose.

Part II. The reduction of the drag of aeroplane bodies fitted with radial engines in the nose by the addition of rings of aerofoil or streamline section. Some miscellaneous results are also given in this Part.

The two parts will be treated separately but the results of Part II will be presented in greater detail in view of their immediate application to the problem of the drag of the air-cooled radial engine.

PART 1
INTERFERENCE OF STRUTS AND RINGS OF AEROFOIL SECTION ON A MODEL AIRSHIP FORM (U.721).

1. *Introduction.—Origin.*—In the course of a test connected with a proposed investigation into the problem of airscrew body interference it was observed that the drag of a streamline body mounted in a wind tunnel was very considerably affected by the presence of a ring of streamline section surrounding it but independently supported from the tunnel floor. Although the diameter of the ring with which this observation was made was three times the maximum diameter of the body, and its cross section relatively small, the observed effects were large, the changes in drag being much greater than the total undisturbed drag. In view of this it was considered worthwhile to conduct a few experiments aside from the original program to investigate the effect, particularly as the drag was in some circumstances actually reduced—in one case to zero. With this object the following tests were made.

2. *Description of Tests*. (a) *Tests with Rings near a streamline body*.—The body upon which the experiments were made was a model of the airship form U.721 of maximum diameter 6 ½ in. and fineness ratio 4.622, having the low drag coefficient of

$$R/\rho V^2(\text{vol})^{2/3} = 0.007 \text{ approx., } (R/\rho V^2 d^2 = 0.0117)$$

The body was supported on wires from the roof of the (4 ft.) tunnel and from the main bottom balance in the usual way; the ring was mounted on a spindle attached to a large flat metal plate 3/16 in. thick which could be traversed along the tunnel floor. The axes of tunnel, body and ring were coincident.

In the initial experiment the diameter of the ring was 18 in. at its leading and trailing edges, and the chord of its (symmetrical) section 2 in. long. It was expected that the interference of so large a ring would be small; in fact the original tests was made with the object of verifying that it would be so. To accentuate its interference, therefore, the ring was made with a thick section only roughly faired (shown at γ, Fig. 1).

The results obtained with the first ring showed an unexpectedly large interference effect on the drag, a noticeable feature being that when placed in the neighborhood of the nose of the body the drag was *reduced*. The ring was then reversed, that is, placed trailing edge foremost, to make the section somewhat "worse". As this appeared to make the effect of the ring everywhere less, an attempt was made to improve the section by fairing it with plasticine, on the assumption that by so doing the effect would be correspondingly increased. This was found to be the case; so much so in fact that the minimum drag (which occurred when the nose of the body and the leading edge of the ring were coplanar) was reduced to zero (Fig. 1). As these changes were consequent solely upon a change in the section it was decided to test a ring having the section of a good strut of fineness ratio 2.67, but of only ¾ in. thickness (referred to as section α, *see* Fig. 1). The effect of this ring was somewhat smaller, no doubt due to its reduced thickness, but it exhibited the same general characteristics. For the sake of completeness three further rings were tested of decreasing cross sectional area, of the following sections:

(a) rectangular, 1/8 in. X 1½ in.
(b)circular, of diameter 5/16 in.
(c) circular, of diameter 1/8 in.

The results are shown in Fig. 1 where the drag of the body (in lb. at 60 ft./sec.) is plotted against the axial position, x (inches) of the ring relative to the body ($x = 0$ when leading edge of the ring is in plane of nose of body, and is positive when ring is entirely aft of this plane). It will be seen that the last 3 rings produce no perceptible *reduction* in drag anywhere, but that when amidships even the ring of 1/8 in. wire still has an appreciable effect.

The effects of these large rings (18 in. diameter), were observed for all axial positions of the ring relative to the nose of the body. Subsequent smaller rings were only tested in the neighborhood of the nose, where a reduction in the body drag occurs.

In view of the magnitude of the effects observed with rings of such large diameter, particularly when the sections were of streamline form, it seemed possible that interesting results might be obtained, and possible some insight into the cause of the phenomenon by varying

(a) the diameter of the ring;
(b) the orientation of the section of the ring (i.e., its incidence relative to the local streamlines);
(c) the size of the section.

However, to carry out such tests on rings would have been quite out of the question on account of the large number that would have been required, so it was decided to open out the ring, as it were, into a straight strut, which might logically be expected to give results of the same general nature as those obtained with the ring. A few rough preliminary tests showed that this was the case, although it was evident that when close to the body, the rapid change in the incidence of the strut along its length due to the great curvature of the streamlines near the body, as well as the rapid change in the distance of an element from the body surface, would preclude a strict comparison.

The substitution of struts for rings enabled (a) and (b) above to be varied with ease whilst (c) presented no difficulty, and the great resulting experimental simplification was considered to justify the strut tests apart from any interest they might have in themselves. A description of the strut tests is given in section 2.3 (b).

The strut tests suggested that the lowest drags would be obtained when the chord of the ring section (all the sections tested were symmetrical) was roughly parallel to the local direction of the streamlines. The nose of U.721 is of almost exactly the same shape as a 4 to 1 spheroid, and the streamlines and their directions near the nose, were calculated from the appropriate formulae for a spheroid given in Lamb's Hydrodynamics. The results are shown in Table 13 and Fig. 11.

Two rings (A and B) of section α (Fig. 1) were then made with [the] chord lines along the local streamlines when in position $x = 0$, [as] defined previously. These are shown in Fig. 2. The drag of [the] wings themselves was also measured by mounting them on a spindle in the bottom balance and fixing the body on a stand which could be traversed along the tunnel. The forces on rings and body separately for different relative positions are shown in Fig. 3. They are relatively unimportant however, as a result of adding the appropriate curves for body and ring shows that the overall drag is always more than twice that of the body only, but is, generally, considerably less than that of the ring alone, which is perhaps not surprising in view of the angle of the chord line for these rings. More interest attaches to the dotted curves which show the drag of the ring when seven radial cylinders are attached to the body. The modification in the case of Ring A is very marked; this feature is of practical importance and will be referred to in Part II.

2.1 *Effect of Rings on a Body having an annular excrescence*.—After the above tests were made a ring of rubber tubing (0.2 in. outside diameter) was nailed to the body in contact with its surface in the plane $x = 3.8$ in. The effect of the rings A and B on the drag of the body so modified was then measured. The results are not reproduced but may be expressed generally by remarking that the shape of the body drag curve (Fig. 3) with Ring B present is almost unaltered but the curve is raised bodily by about 0.055 lb. at 60 ft./sec. while the drag of the body with ring absent is raised by about 0.075 lb. The effect of ring B is therefore somewhat greater when the excrescence is attached than when it is not. Ring A on the other hand has a smaller effect when the excrescence is attached, the curve being raised to a greater extent than the drag of the body only and being somewhat flattened. The overall drag was not measured.

2.2 *Results obtained with Rings*.—With all rings tested the overall drag is greater than that of the body only, but is frequently less than that of the ring alone, and is almost always less (in the most favorable position) than the sum of the separate drags. This latter fact would be expected in the case of the smaller rings on account of the angle at which the chord line is set. There would also be a local change of pressure between the ring and the body giving rise to axial forces superimposed on the drag, properly so called, and in consequence the forces on ring and body taken separately have little significance. In any case the drag of the ring with the body absent would be high on account of the inclination of the chord to the free stream. It is, however, somewhat surprising that the same effect should also be observed in the case of the 18 in. diameter ring (section α), for in this case the section is already in the position of minimum drag when the body is *absent*, since the chord line is then parallel to the wind. It may be noticed that here the drag of each is reduced simultaneously, implying a reduction in the total turbulence apart from any pressure reactions. The introduction of the body would slightly increase the air speed at the ring, and so tend to increase its drag. No explanation of this effect is offered unless it is to be found in the fact that the ring section is somewhat critical or had its minimum drag at a finite angle of incidence. It would be worthwhile making some further search for the cause of this effect.

2.3 *Description of Tests*. (*b*) *Tests with Struts and Aerofoils*.—The struts under test were mounted on vertical spindles roughly coaxial with their centers of pressure, and were disposed in pairs, symmetrically on either side of the nose of the body. They were capable of being yawed about the axes of the spindles, which passed through holes in the floor of the tunnel. The upper ends of the struts were braced by wires to the walls of the tunnel. Attention was mainly concentrated on those positions of the struts which produced a reduction of body drag. The forces of the struts were not measured.

In Fig. 4 the sections and positions of the struts when at zero yaw, are shown in relation to the nose of U.721, together with the axis of yaw in each case.

It was found that the *change* in drag produced by two struts was almost exactly double that produced by one alone (*see* H and 2H, Figs. 4 and 5) when each strut was only 2 in. from the body axis; most of the tests were therefore made with one strut only.

The strut of section α (A to F, Fig. 4) was 3 ft. long; all the rest were 11 in. Aerofoils G, M and N were of Gottingen 429 section; aerofoils H, K and L were (approximately) R.A.F. 30 section.

A few figures bearing on the above remarks are collected in the following table:—

TABLE

Comparison of Changes in Drag (ΔR) *due to Rings on U.721 with Analogous Tests in 2 Dimensions.*

Centre lines of cylinders 4·0 in. behind nose.

V = 60 f/s.

Position of Ring Section.*			No. of Cylinders.	ΔR.	ΔR. Interpolated for 8 cylinders.
x	*y*	θ degrees.		lb.	lb.
Ring A.					
0·20	3·65	8	7	0·103	0·140
0·30	3·65	8	9	0·178	
Analogue of Ring A in 2 dimensions.			(a) *With Dummy Ends.*		
			No reduction in drag obtained; results critical.		
			(b) *With End Plates.*		
0·30	3·70	14	8	0·119	0·119
Ring E.					
0·65	3·50	11	{ 7 / 9	0·109 / 0·183 }	0·155
Analogue of Ring E.			(a) *With Dummy Ends.*		
0·75	3·60	17	8	0·153†	0·153 †Interpolated between 2 values of *y*.
			(b) *With End Plates.*		
0·75	3·60	{ 14	8	0·204	0·204
		{ 17	8	0·188	0·188
Ring G.					
0·25	3·80	8·5	{ 7 / 9	0·164 / 0·239 }	0·201
Analogue of Ring G.			(a) *With Dummy Ends.*		
0·25	4·00	14	8	0·182	0·182
			(b) *With End Plates.*		
0·25	4·00	14	8	0·212	0·212
0·25	3·90	18	8	0·284	0·284

* *x* = distance of plane of trailing edge of section in front of centre lines of cylinders (ins.).
y = distance of trailing edge from axis of body (ins.).
θ = angle between body axis and chord of section (degrees).

Note.—The rings are not necessarily in the best positions, but in the positions corresponding to the strut results.

2.4 *Results obtained with Struts*.—The results of the foregoing strut experiments are shown in Figs. 5 (*a*) and (*b*), where the drag of the body (lb. at 60 ft./sec.) is plotted against angle of yaw of strut relative to the tunnel axis. The angle of yaw is positive when the leading edge of the strut is nearer the axis of the body than the trailing edge.

It was thought unnecessary to tabulate the large number of readings taken, as the curves were well defined including the critical region near—5° yaw.

The following points may be noticed:

(1) the reduction in drag becomes less as the aerofoil is moved downstream from the plane of the nose.

(2) Large reductions may occur even when the aerofoil is some distance from the body laterally, see A, Fig. 4.

(3) Aerofoils C and G, though of widely different sections and slightly different lengths of chord, produce, in the same position, nearly the same effect.

In addition to the above a few tests were made with a pair of aerofoils of Gottingen 429 section 11 in. long similar to M, Fig. 4, mounted on a stand in such a way that they could be set at any angles of yaw and could be traversed together along the tunnel over a [range] of *x* near the nose.

The axes of yaw, which were situated at ¼ chord from the leading edge of the aerofoils, were spaced 3.35 in. apart transversely. The drag of the body was measured for angles of yaw of both aerofoils of 15°, 25°, 35° and 45° over a range of *x* which included minimum drag.

The results are shown plotted in Fig. 6. The chief points of interest are as follows:

(1) The reduction in drag continues to increase up to quite large angles of yaw.

(2) For a given angle of yaw, the reduction in drag continues to increase as x increases until the aerofoils are quite close to the surface of the body. Minimum drag occurs when the minimum clearance is of the order of 3/16 in. On closer approach the drag becomes positive before actual contact occurs between aerofoils and body. There is therefore a stable relative position, in which the aerofoils, though not touching the body are "towing" it against the wind.

PART II

THE REDUCTION OF THE DRAG OF RADIAL ENGINES

3. *Introduction*.—In paragraph 2.2 (Part 1) tests were referred to in which the interference between a ring and body was negative, i.e., the combined drag was lower than the sum of the separate drags. This effect is not uncommon when the interfering bodies have a high drag, although in such cases the explanation is usually that one of the bodies tends to shield the other. In fact, ordinary fairing is an extreme example of this. In the case of the 18 in. diameter ring of section α already referred to (2.2) the two interfering objects not only did not shield one another but were low drag forms to start with, and yet their mutual interference was negative.

In seeking for some practical example in which advantage might be taken of this effect it was recalled that many aeroplanes powered with radial engines are provided with annular exhaust pipes running round the nose of the machine just in front of or behind the cylinder heads. In normal circumstances, such exhaust rings are made of circular or elliptical cross section and usually add quite considerably to the already high drag of the radial engine. Even when made of streamline section they increase the drag *as normally fitted*.

There was however, in this possible application one serious point of difference from the previous experiments which it was thought might vitiate the application of the results to the case when the radial engine was present, and that was the influence of the cylinders on the air flow; but as the ring had been found to be still effective when an annular excrescence was attached to the nose of the streamline body in the position which would be occupied by a radial engine (see 2.1) it was considered probable that this case also would be amenable to similar treatment, by a suitable modification of an existing exhaust pipe or by the addition of such a pipe when not already fitted. With this objective in view it was decided to make a few preliminary tests.

The results of these tests were very encouraging, and showed at once that appreciable reductions in drag were obtainable. They also disclosed the mechanism by which the ring produced its effect (in the case of the radial engine) and this information was used to design other rings giving much better results.

In order to render the description of the tests more intelligible it may be as well at this point before describing them to anticipate the results, for the purpose of giving an indication of the action of the ring.

3.1 *Function of the Ring*.—The distribution of streamlines around the nose of a streamline body, when it is not fitted with a radial engine is such that the flow continually converges towards the surface of the body as it proceeds from the place of the nose to that of the maximum cross section. When the cylinders of a radial engine are placed in their usual position in the nose they disturb this ideal condition and produce a violent deflection of the airstream away from the surface, this being so not only in the case of air which directly strikes the cylinders, but also of the air which passes between them. This effect can be observed by discharging a jet of smoke in front of the gap between two cylinders.

If by some means this divergence of the streamlines could be obviated it might be supposed that the inevitable disturbance produced by the cylinders themselves would be prevented from expanding to form a large turbulent wake, with a consequent reduction in drag. Now the attachment of a streamline ring is a method of effecting this, since it consists in placing immediately in front of the cylinders a curved aerofoil disposed in such a way with respect to the cylinders and the local direction of the flow as modified by them that the aerofoil section, working at a fairly high lift coefficient, secures control of the air before it is thrown outwards by the cylinders, by exerting a "downwash" directed towards the body axis which prevents the disturbance caused by the engine from expanding radially to produce a large wake. From smoke observations (visual) with and without a ring it was evident that the ring reduced the radial thickness of the wake behind the cylinders by something like 40 percent.

Some further visual experiments were made on a very small (dimensional) model in a water channel, in which the changes in flow were made visible by a jet of dye discharged in front of the model. Photographs of the flow are shown in Fig. 29. In each photograph the jet is in the same position. In the first (*a*) the flow past the body only is shown. In (*b*) two exposures were made on the same plate, the first a repetition of (*a*) and the second with the cylinders in position; the line of ink shows the flow between two cylinders. In (*c*) there are also two exposures on one plate; the first is a repeat of (*b*) with cylinders, and the second is the flow with an aerofoil attached in addition, to represent a ring.

4. *Description of Preliminary Experiments*.—In searching for a typical aeroplane which should have a body similar in shape to the model (U.721) already used for the experiments of Part I, an inspection was made of numerous photographs appearing in "Aviation." It was found that the U.S. Navy "Apache" biplane fitted with a "Wasp" radial engine had a fuselage the shape of which in side elevation was almost identical with that of U.721 up to the maximum diameter. From a few rough measurements of one such photograph seven model cylinders were made and attached to U.721 in the appropriate position. The cylinders were made to fit the surface of the model closely and each was held on by one central pin so that it could be removed and replaced easily. The shape of the cylinders and their situation in the nose are shown in Figs. 2, 13a and 14. They were very simple in outline and were fitted with two dummy cylindrical valves apiece.

An initial attempt to discover the most suitable angle for the ring section relative to the body axis under the new conditions was made by using 4 cylinders only, a pair on each side of the body, each pair being spaced as though forming part of a radial engine. Behind each pair was fixed a segment of a ring of symmetrical streamline section (Section β, Fig. 2). Each segment was attached by two pins (diameter 0.034 in.) to the body, so that by bending the pins the angle of the chord to the body axis could be varied to some extent. The segments were set to various angles and the drag was observed and plotted. It was found that there was a minimum which was appreciably lower than the drag of the body and cylinders alone. When placed just behind the cylinders the best angle of the chord was found to be 3° and when placed in front the best angle was 14°. These angles apply, of course, only to the axial and *radial* positions of the ring section shown as C and D, Fig. 2

Similar tests were made with segments of circular cross-section to imitate the more usual type of exhaust pipe. From photographs, the appropriate diameter was judged to be about 0.58 in. These tests showed that the drag was very considerably increased. The streamline section β was designed to have the same cross sectional area as that of a 0.58 in. diameter circle. The clearance between the segments and the body was about ¼ in. to 3/8 in.

Two complete rings (C and D, Fig. 2) based on the above tests were then made and attached to the body with 7 radial cylinders in the same plane as before. The results agreed closely with expectations based on the segment tests, as did also tests made with rings of 0.58 in. diameter circular cross-section.

Several rings (A, B, C and D) were then tested for drag in the presence of the body (with 7 cylinders), and also the body and cylinders in the presence of the rings. The results (Table 7) are shown in Figs. 7, 8 and 9. The curves for ring and body are added graphically, the sum being shown by the dotted curves, while the points with tails are overall observations made with the rings actually attached to the body. The drag of the rings has been corrected for spindle effect which was measured by means of a dummy and in which there may be slight uncertainty. The important (overall) observations are not subject to this uncertainty. They have been corrected throughout for static pressure drop, and drag of wires and spindle, but errors in these corrections do not affect the comparisons. The forces have not been reduced to coefficients but are shown in lb. at 60 ft. per second wind speed. Scales of R/R_0 (where R is drag of body and cylinders with ring attached, and R_0 = drag of body and cylinders only) are drawn on the right hand sides of the figures.

In addition to the ring of 0.58 in. diameter circular section, rings of circular section were also tested having the same frontal area as that of rings C and D, i.e., of 0.3 in. radial depth, in the same relative positions as C and D respectively. These results are plotted at $x = -3$ and at $x = 0.1$ in Fig. 7.

Some further tests subsequently made on this model with other rings are described later together with the results of more extended experiments.

5. *Description of Extended Experiments*.—As the initial experiments were sufficiently promising to warrant a more thorough investigation, experiments were instituted on larger models in which the details of the engine cylinders were represented more accurately.

Since the circulation around the aerofoil section of the ring associated with the lift would produce a velocity tending to oppose the flow between the cylinders which might be important in connection with the cooling, a few observations of the change of air speed between the cylinders were made with a small pitot tube with various rings in position.

One model was fitted with an airscrew, which enabled measurements to be made of changes in net thrust, torque and efficiency due to the ring.

The models tested were:

(1)U.721 model described already (*see* A, Fig. 13).

(2)¼ scale model of Short Crusader Seaplane (9-cylinder engine) with and without wings and floats (D), Fig. 13 and Fig. 28.

(3)¼ scale model (modified) of body of Bristol Bulldog with 9-cylinder engine, with and without airscrew (C), Fig. 13 and Fig. 27 (*a*) and (*b*).

(4)1/5 scale model of Siskin aeroplane body with Jaguar engine (14 cylinders in 2 rows) (E), Fig. 13 and Fig. 27 (*c*).

(5)1/6 scale model of body with monoplane wings and Lynx engine (7 cylinders) (B), Fig. 13.

5.1 *Two-dimensional Experiments.*—Before commencing the above tests, it was deemed worthwhile to obtain, if possible, some general qualitative information about the effect of varying the chord and section of the ring and the angle of the chord to the body axis, by an adaptation of the "strut" method described in Part I (*b*), in which not only the ring but the body also would be reduced to 2 dimensions. For this purpose a model was constructed of exactly the same sectional shape and size as that of U.721, Fig. 13A, but of approximately 2-dimensional form. A sketch of this, as mounted in a 4-ft. tunnel is shown in Fig. 10. The "span" of that part on which the drag was measured was 10 in., extended by a further 10 in. at each end by dummies attached to the roof and floor of the tunnel and separated from the ends of the model proper by air gaps [1/14] in. wide. It was considered unnecessary to carry the dummies as far as the roof and floor; the upper dummy was slung on radius rods and was capable of being swung out of position to allow of easy angular adjustment of the aerofoils by which the ring was represented. These aerofoils were attached to the model by two flat brass strips provided with a row of holes ¼ in. apart through which screws passed into the ends of the aerofoils. The angle of an aerofoil was therefore adjustable about an axis whose position was itself adjustable by varying the position of the brass strips in the body and by selecting suitable holes in the strips.

The cylinders were represented by the same simple forms as were used on U.721. They were fixed in two rows of four cylinders each, one row on each side of the body in the same position relative to the nose as for U.721. They were separated laterally by a distance equal to their mean circumferential separation in the U.721 case with 7 cylinders.

In order to preserve the interference between the cylinders each row was extended beyond the air gaps by two cylinders at either side and at each end, fixed to the dummies. The aerofoils however were not extended in this manner.

5.2 *Relation between Tests in 2 and 3 Dimensions.*—It was realized that the best angles for the aerofoil sections would not be the same in the 2 and 3-dimensional cases, and some idea of the difference was sought by calculating the slopes of the streamlines at points in the vicinity of the aerofoils for each case on the assumption that the flow near the nose of the body would not be seriously modified by the tail being tapered instead of elliptical. The formulae used were derived from those given in Lamb's Hydrodynamics relating to the stream functions ψ for the elliptical cylinder and ellipsoid respectively.

To illustrate the change in angle the streamlines are shown in Fig. 11 for the two cases—for equal increments of ψ in the case of 2 dimensions, and in 3 dimensions for such values of ψ as make streamlines intersect those for 2 dimensions at points in an axial plane 2 in. behind the nose. The difference in slope between the 2 and 3-dimensional cases is given in Table 13 for various positions near the nose. In the important region the slope in 2 dimensions is about 6° steeper than it is in 3 dimensions. An inspection of the observations given in the tables will show that in cases where the ring and aerofoils correspond closely in other respects the value of θ for minimum drag in 2 dimensions is about 8 or 9 degrees greater than in 3 dimensions. A rigorous test would have required 3 or 4 rings differing only in the angle θ, and this was not considered worthwhile.

5.3 *Drag in 2 dimensions.*—The drag of the 2-dimensional model with and without cylinders was of course very much higher than that of U.721, and therefore the value of R/R_0 has very little significance in this case. It was found however that the *change* in drag (ΔR) obtained by the addition of a pair of aerofoils at their best position corresponded somewhat closely with the change produced in U.721 by the addition of the corresponding ring, the agreement being better than might have been anticipated in view of the inevitable dissimilarity of the two models. This encouraged some confidence in applying conclusions drawn from 2-dimenstional tests to rings with respect to the effects of chord, section, variation in the angle θ and to a lesser degree the value of θ.

A few figures bearing on the above remarks are collected in the following table:

TABLE

Comparison of Changes in Drag (ΔR) due to Rings on U.721 with Analogous Tests in 2 Dimensions.

Center lines of cylinders 4.0 in. behind nose.

V = 60 f/s.

The 2-dimensional analogue of Ring A was tested to determine whether such tests would bear out the results already obtained with this ring on U.721. The result $\Delta R = 0.119$ was considered to be sufficiently close to the value $\Delta R = 0.140$ obtained with U.721 to justify the method; other sections were therefore tested in 2 dimensions and from the results Rings E and G were designed. The subsequent tests with these rings bore out the 2-dimensional results quite closely.

With regard to the angle θ later tests suggest that this should be somewhat smaller (by 3 or 4 degrees) than that obtained by applying to the angle observed in 2 dimensions the theoretical correction previously referred to.

A few further tests were made in 2 dimensions with 2 rows of cylinders, one behind the other, to imitate the "Jaguar" type of engine. In this case the front row consisted of the same 4 cylinders per side as were used before in the same positions, but in addition 3 cylinders per side were added behind the spaces between cylinders in the front rows. Four cylinders only were attached to the dummies, one opposite each end of the front rows of cylinders on the model.

Similar results were obtained with this arrangement as with a single row of cylinders.

6. *Tests of Aeroplane Models*. (*See* Fig. 13.)—6.1. *Crusader (Scale)*.—After the preliminary work on the U.721 model already described, more detailed experiments, the results of which will be discussed together later, were made on scale models of bodies of existing aeroplanes (Fig. 13) in which the details of the engine were accurately represented.

The first such model used was the ¼ scale model of the Short "Crusader" high speed seaplane fitted with a 9 cylinder radial engine ("Mercury"), a model which had been previously tested in connection with the Schneider Trophy Seaplane Race. A photograph of this model is shown in Fig. 28 and a sketch in Fig. 13(D). The nose is shown on a larger scale in Fig. 15. The following tests were made on this model:

(1)Body and engine only, with normal cylinder fairings, cockpit, and pilot's fairings.

(2)Complete machine with wings, floats and tail unit, with normal fairings.

(3)Tests similar to (1) and (2) but with the individual cylinders fitted with dummy helmets. *See* Fig. 13D.

(4)All three tests were made with and without various rings, and in addition to measurements of forces, a few observations were made of velocity between the cylinders.

A visual study by means of smoke was also made of the effect produced by the ring on *the* wake behind the cylinders.

The results (R/R_0) obtained in test (1) with Ring A, agreed closely with the corresponding results for U.721 with 9 cylinders. In fact it became clear as the experiments proceeded that the magnitude of the reduction in the drag obtainable was not sensitive to the exact shape of the body, although the actual *design* of the ring for any particular case was dependent on the shape of the nose and disposition of the engine in relation to it.

6.2 *Aeroplane Body with "Lynx" Engine (1/6 Scale)*.—This was a model of an aeroplane body of circular cross-section fitted with monoplane wings of 5:1 aspect ratio springing from the center of the body. A detailed drawing of the nose and engine of this model is shown in Fig. 14, superimposed upon a sketch of U.721 and cylinders, with which the general shape and size corresponded fairly closely. The nose cap (A, Fig. 14) was removable, the normal outline being shown by the dotted lines, but for the purposes of the present tests it was considered fairer to substitute the nose cap A as representing the form of cowling usually fitted to such engines.

The drag in this condition is taken as standard (= R_0). (For body and engine only it is 7 percent less than that of the shape shown dotted.)

Some previous experiments had been made on this model at the R.A.E. with helmets fitted to the individual cylinders which were designed to give sufficient cooling (*see* Fig. 13B). It was therefore possible to compare the relative merits of helmets and rings for the case of 7 cylinders as well as for 9 (i.e., on the Crusader).

The tests made were:
(1)Body and engine only *
(2)Body and engine and wings *
(3)Same as 1 and 2 but with helmets instead of rings.

* with and without rings.

6.3 *Bristol Bulldog (modified), ¼ Scale*.—The body of this model was a solid of revolution in which the shape from the nose to just behind the engine was the same as the Bristol Bulldog. The outline of the rest of the body was a rough mean between the outlines in plan and elevation of the Bristol Bulldog.

The engine was represented by the same cylinders as used in the Crusader, but the Mercury valve rockers were removed and their places taken by dummy rocker hats of the type used on the Jupiter engine. The cylinders were so adjusted radially that the outside diameter was equal to that of the Jupiter.

Fig. 15 shows the engine in position on the Bulldog model. Superimposed is a sketch of the nose of the Crusader with the position of the Mercury valve rockers shown dotted.

6.4 *Airscrew Tests*.—In the case of the Bulldog, tests were made with the airscrew running. The screw used was a 2-blader which happened to be available and of approximately the correct diameter. The pitch was somewhat low (geometrical P/D approximately equal to 0.66), but this was considered unimportant as it was only desired to ascertain whether the screw would alter, to any appreciable extent, the character of the results obtained with various rings.

The screw tests consisted of the measurement of net thrust and torque. The apparatus used, shown in Fig. 16, was similar to the standard arrangement so far as thrust was concerned, which was measured on a bottom balance. The torque balance was somewhat modified however. The motor was carried at the rear on a cross beam A fixed to the body. At the front it was hung directly from the torque balance B on the roof by means of 2 parallel stranded cables C, attached to the torque arms on the motor casing. The torque arms were completely enclosed within the body. To prevent lateral motion of the motor relative to the body, the nose of the motor was constrained between 2 vertical strips of metal (not shown) attached to the inside of the nose of the body. A slight clearance was allowed between the strips and the motor to avoid torsional constraint. Lateral motion of the body was prevented by the V-wires (E) by which it was slung. These were arranged so that, if produced, they would intersect on the airscrew axis, in order to prevent any lateral forces on the motor from causing the body to roll. Current was led to the motor through mercury cups, M, at the tail of the body and through springs near A (not shown).

In all tests the normal working range of V/*n*D was covered. The motor was controlled on torque, and rotational speed was measured with a chronograph. The rotational speed (*n*) was kept nearly constant over the whole range of V/*n*D at about 43 revs. per second, for most of the tests, and the tunnel speed was varied from 80 f.p.s. to 35 f.p.s.

The chronograph was found to be more satisfactory than a stopwatch for measuring rotational speed. The extra accuracy on *n*, which affects the results virtually in proportion to n^3, was considered worth having; with the chronograph the thrust and torque curves were found to be noticeably smoother than with a stopwatch.

The following tests were made with the modified Bulldog model:

(1)Body and engine only with and without airscrew, with various rings.

(2)Body without engine, with and without airscrew.

(3)Velocity between cylinders. Rough measurements only for comparison between different rings.

6.5 *Siskin Aeroplane Body with Jaguar Engine (1/5 Scale)*.—Through the courtesy of Messrs. Sir W. G. Armstrong Whitworth Aircraft, Ltd., who loaned this model, it was possible to carry out experiments with rings on an engine having two rows of cylinders, the cylinders in the rear row standing opposite to the gaps between the cylinders in the front row. Viewed from the front this engine presents almost a solid disc to the airflow. In spite of this however it was found that a ring was practically as effective in reducing the drag of this engine as of engines having a single row of cylinders.

Details of the model are shown in Fig. 17. The upper half of the figure shows the ungeared Jaguar without rocker hats, whilst the lower half shows the geared model, which was fitted with rocker hats. Two typical rings are also shown in the figure. As this engine was fitted with an exhaust manifold behind the cylinders, no tests were made of this model with rings of the type of Ring A, Fig. 2.

The following tests were made:

(1) Body (with windscreen) and engine only (ungeared), with several rings.

(2) Check tests as (1) on the model with geared engine and rocker hats.

(3) Test with and without spinner and exhaust manifold.

6.6 *Scale Effect on the Drag of Engine Cylinders*.—The drag coefficient of an infinite cylinder is known to undergo a rapid drop in the neighborhood of a certain value of Reynolds number, Vd/v, lying between the model and full scale values for cylinders of the diameter of normal engine cylinders.

It had been suggested by Mr. Relf in Ae. Techl. 399 that though an engine cylinder was very different from an infinite cylinder yet it might be reasonably expected to exhibit some decrease in drag coefficient near the same value of Reynolds number.

As the application of a ring to an engine partakes of the nature of a curve for the turbulence caused by the cylinders it was concluded that any serious difference in the degree of turbulence produced by the cylinders on model and full scale would show itself by a corresponding scale effect on the improvement in drag obtained by adding the ring, which would thus be less effective on full scale than on a model.

A few experiments were therefore made to determine the nature and extent of the scale effect near the critical value of Reynolds number on a very short cylinder projecting from a place surface. The results are quoted below.

Three cases were tested:

(1)8 in. diameter cylinder 10½ in. long in center of 4 ft. tunnel.

8 in. diameter cylinder 10½ in. long with false floor nearly in contact with one end of cylinder.

Document 3-10(b), United Aircraft and Transport Corporation Technical Advisory Committee, Meeting Minutes, December 1929, Boeing Historical Archives, Seattle, Washington, pp. 213-256.

PROCEEDINGS OF TUESDAY AFTERNOON, DECEMBER 3, 1929

The meeting convened at 1:30 o'clock P.M. pursuant to noon adjournment.

CHAIRMAN MEAD: Well, while we are waiting on Colyer and Humphries to come in, Mac has given us a sheet of airplane characteristics and I know Chatfield and the rest of us have been worrying for some time for a way to get this in a standardized form that will be acceptable to everyone. It might be a good idea to pass that around to see if we can get constructive comments.

MR. MONTEITH: Instead of that table of performances, I would rather see curves. It really makes two sheets out of it, but you really stop to plot this thing up in curves anyhow.

CHAIRMAN MEAD: That reminds me,—it may work everybody if we have these days pretty well filled up, but if you can get your gang together in the matter of performance testing of course, I have it down for Friday but we may all of talk by Friday we won't give it the proper consideration,—and see if we can't light on some system that looks reasonable to try out, then we can modify it in six months, but here is Northrop testing down at his place and we are testing in Hartford, and we hope Mac is going to be testing sometime, and it will be nice to get down to earth if we could.

MR. MONTEITH: Well there is not much trouble in the speeds if we get a decent speed course, which we do not have at the present time,—but practically everybody whom I have run into at all in the industry is making his climbs with an altimeter, which is the bunk. I think something we need every place is a good barograph with a calibration apparatus to go with it if we are going to get any decent climb data at all.

CHAIRMAN MEAD: Last night we had a supplementary meeting over at the Hotel and Mr. Sikorsky was putting up a method of measuring landing speed, and that is another thing we are worrying about.

MR. MONTEITH: I just had a letter from Reid down at Stanford. He wants us to loan him some planes: He has a method of testing landing speeds down there by photographic methods. He paints one wheel half white and half black and measures it with his photographic instruments.

CHAIRMAN MEAD: It would be nice if we could get an instrument [that is] not too expensive, but also simple and durable we could use on any of our ships either land or water. Mr. Sikorsky was telling us about a different method that might be worth while if he would explain that again.

MR. SIKORSKY: Certainly, I would be glad to. You see, here is the size we use (indicating on blackboard). This is a box about actual size. This part here is a piece of glass. There is an arm here inside with a visible hand here, and at a place somewhere about here,—of course there is an opening in the top to fix this up,—now here, there is sticking a support on which a disc of twenty-five centimeters diameter is fixed. How, there is existing very reliable data of the pressure on a disc of any dimension may be applied, but it is very easy to graduate it and fairly reliable information is available on the pressure at every speed.

Now the whole thing is to adjust the load here to such an extent as to show your desirable speed. Now, of course, all you can get here would be whether your landing is, say better than 54 or whether it is worse. In other words you have to check it a couple of times and sometimes you have to adjust the load a couple of times until you get the actual thing, but we make a multitude of tests and I would say that I have the full conviction that the thing is accurate within one mile. For instance, when we tested several, or tested the same airplane with several loads then the increase of landing speed went simply mathematical in accord with what it should do.

The thing we tested was the ship actually landing. In this case, of course, a second person must make the observations or it can be tested by the pilot himself. In this case, it is very easy to keep the thing just bouncing back and forth, or even to keep it down. Of course, here it is to keep it down which shows the speed is below a certain limit to which the instrument is adjusted.

The thing is very simply and cheap to construct.

McCARTHY: How about the effect of the angle line on the pressure?

MR. SIKORSKY: Here is the thing: The slight differences, even a good few degrees,—as far as I remember two or three or five degrees make a very little difference for the disc, therefore, of course, you put the disc, to be normal, to the wind and [approximate] your landing speed. Now there the advantage is, you need no correction whatsoever, if you do it [at a] thousand foot altitude the thing will show you,—the correct speed actually may be 63 miles per hour but it will show you 64, just so the corrections are mathematically taken care of.

CHAIRMAN MEAD: The thing seems to me we are interested in landing speed, otherwise we do not appreciate the top speed. If the landing speed is high, the top

speed is not so interesting.

Well, it looks as though we have done about all we could with this matter of transportation. Of course, we would like to analyze this matter of maintenance as we said this morning, and probably we can in the near future in view of what you are doing.

The comparisons of performance for this six months with the last six months we can perhaps make graphically for you when we get the data, and of course you should appreciate that Chatfield and some few people in Hartford are now assigned to help us on this sort of work so as not to make too much of a burden for the individual units. If you can furnish the information, we can sometimes put it in shape and save you some work, but to gain anything out of this data of course it has to be in comparative shape all the time and I think we will find that we are going to be interested in fewer items than we have discussed this morning that we can substantiate those figures in the report so we don't need to take the time to discuss them each time, and we can show graphically on a chart prepared ahead some of these things in a very few minutes.

Well, the next item I have down for discussion is that of power distribution, believing that it was one way to get at the possible improvements in plane performance.

Now, Chatfield had better explain to us his story I think he sent around, and obviously, you can criticize considerably because we have not very much data to work with.

MR. CHATFIELD: I suppose the main objection to this is that based on a small machine, a Sperry Messenger which has only three cylinders, and in order to get it comparable to faster machines, the speed had been stepped up to a speed much higher than this airplane actually had.

The results are obtained by a sort of combination or the NACA reports, the technical report 304 which gave the flight polars for a complete airplane with four complete sets of wings, and technical report 271 which gave the driver of the component exclusive of the wings. The results are nothing more than a combination and reconciliation of these two, and I suppose I might put the percents on the board as being the easiest way of showing them.

(Mr. Chatfield puts tabulated list on blackboard)

This of course, also involves allowance for power lost in propeller so the total figure is not a distribution of drag but a distribution of brake horsepower, and it is break horsepower accounted for in these various ways.

That, I think shows it reasonably well. Of course the propeller is based obviously in propeller efficiency and in this case would be 2 percent.

Of course one surprising thing which probably is exaggerated as I said, in a very low portion which is accounted for by induced drag which might be extreme but you might say only 1.2 percent of brake horsepower is going to hold, the rest of it is all absorbed by various resistances and losses, but as mentioned before I put this account of having jacked up the speed. The induced is normally low and I imagine would be probably twice at any rate, or perhaps somewhat more than that, but still would give the result, the induced drag is a relatively small part of the total.

Of course the most conspicuous item is immediate-interplane bracing and interference which in a sense is the stuff you can't find somewhere else.

MR. MONTEITH: Pardon me, but in that particular ship do you recall that the interplane bracing was made of struts?

MR. CHATFIELD: Yes, the interplace bracing was struts in the particular machine, so possibly that again is somewhat higher than normal.

I might say the only justification for picking this particular airplane was because it was one from which we could get the data; I don't think there is any other argument to be advanced in favor of this set of figures.

Again, due to the engine this addition is undoubtedly abnormally low because it was a three cylinder engine and we don't have many three cylinder engines, and as Mr. Weick has also pointed out, if you went up to nine cylinders not only would the total engine drag be multiplied by the ratio of the number of cylinders, but the drag per cylinder would probably be higher as well on account of the interference.

MR. MONTEITH: Well, there is another feature there, Mr. Chatfield, too that in that particular airplane that was the first air-cooled engine we had you know, and the idea was to put all the cylinders out in the air.

CHATFIELD: It is conventional cowling of the old style with the cowling coming pretty well down to the bottom of the cylinder barrel and not up toward the head as is most common today. Of course, this was all several years ago.

Apparently what goes on inside the engine disc does not make much difference as regards resistance, isn't that the general conclusion?

MR. SHORT: That is what I judge from our tests all right.

CHAIRMAN MEAD: How much improvement do we get?

MR. McCARTHY: You get one mile more an hour high speed with the monoplane than you did the biplane.

CHAIRMAN MEAD: You must have a lot of miscellaneous in this 33.8, otherwise there ought to be a big gain with any monoplane.

CHAIRMAN MEAD: Have we any data in the family which would be useful or can we get it anywhere else which would bring this story any more up to date?

MR. CHATFIELD: Mr. McCarthy has one much more advanced than this.

MR. MONTEITH: I might state that in that particular model we made for the NACA, I was instrumental in building this set of wings for the test. We had one set arranged with internal bracing so we could put the struts in or take them out, but they let Doctor Munk get hold of it finally and he held it so long we never did get the complete test. We kept trying to find out what that interplane bracing interference amounted to on the ship but we never got the data.

MR. SIKORSKY: I would like to have the data concerning this picture. The trouble of course about discussing this thing will be that there would be one equation with quite a considerable amount of uniform factors,—for example, I think the picture here and this figure (33.8) certainly is very correct and probably is much greater, and yet the bracing and interference that is shown here would permit you to save considerable on some other items. Here the induced drag stays as a low item, but if you take a heavily loaded airplane,—if you take a big one, if you consider the case that you are flying with one unit out of commission, in other words, fairly slow speed, in most cases with more multi-engined ships it would be something like 75 or 80 miles per hour, then the figure of induced drag becomes a more considerable one, and to take care of it you need span, in fact nothing can be replaced without span.

In order to give the value of span, I may, for instance, give you the following very accurate information: We built an S-36 amphibian with a gross weight of approximately 6,500 pounds, with lots of bad features dynamically, and this ship was powered with two Wright motors of 200 horsepower each. With one engine dead it showed a loss of altitude of 400 feet per minute, in other words, an enormous lot of altitude.

This ship had 62 feet span. Now we cut the middle part of the wings, added 5 feet on each side and transposed it into [a] 72 feet span airplane, and with the same load, in other words, with greater gross weight than we had, we only showed a loss of 100 feet per minute instead of 400 feet loss previously.

It should be taken for granted that with all other conditions being equal, especially in a big ship, you can afford a bigger span if you use outside bracing than if you will use cantilever sings. This is the thing which to a very large extent permits all of us to profit in the externally braced airplanes, and this makes for the fact, as a general rule,--I am again speaking mainly of the big ships, the clean cantilever monoplane did not show loss of speed or anything more in general than the braced external biplane.

Again, I say this is true for very huge units. In very small ones, it seems logical as the little ships must be given very big preferences.

Now, I hope Mr. Mead will forgive me for the following statement: This is, I believe that what we actually have to experience in dragging across the air the radial engine, of course, the engine does it by itself, we want to get more out of it,—more according to our form of what would be shown by this figure. For example, a very accurate wind tunnel test I made for a very huge engine, the engine nacelle was a little over 5 feet, about 5 ½ feet in diameter. The Jupiter motor was very well streamlined, or rather cowled in so far that the cylinders were sticking [not] much here (indicating). As a matter of fact, if you would use the cross section, the engine would occupy a very inferior part of the circle.

Now in this case, the drag was distributed as follows: This whole business, one-third, and the engine cylinder heads, two-thirds.

Now, again a very large amount of tests, which were entirely reliable and accurate because we have several dozens of tests on our airplane cylinders; they show in general the following things, that the same cylinder which gives us an L.D. of 11 will give us the L.D. 18, so here we have a considerable amount of power going in because in this case it is already the difference of the whole airplane plus the induced drive and everything. Now, however, the windtunnel test showed a considerable improvement due to the cowling or a similar combination. For example, the cylinder which showed L.D. 11—the best lift drag could be pulled to 14 ½ only by specification of the NACA cowlings, or rather similar cowlings because we cannot say on the model what kind of cowlings we put in and how good they would build the actual airplane, so I believe that a very important thing and a very big gain for us would result from a very careful study of these very cowlings. That is where we can save a considerable amount of power.

Again, I think this is more true for exposed engines, but probably it is largely correct also for single engine airplanes, and I believe here in this close corporation with the help of the United facilities, we may be enabled to make a considerable step ahead because this here is quite a big item in which we can save lots of power.

Now, I believe maybe this may be an item which I say is general for all of us, we may expect to use the radial engines on probably most of the designs because they are so much more superior and convenient, and the operating cost is less, and people in those cases want them. The [airline] Pan-American, for instance, simply do not want to talk or to hear about anything except the radial air-cooled engine. That is the situation right now, so it seems a thorough study of all these things may be very justifiable and will do us all some good.

MR. NORTHROP: One thing might be mentioned in what Mr. Sikorsky had to say relative to interplane bracing, and interference with a large span. I have noticed in the high speed fairly small span planes I have had experience with the take-off and climb are not nearly as good in proportion to the rest of the performance as high speed, in other words at points where the induced drag would normally we shall say, the ship is highly efficient over a biplane arrangement, but in take-off and climb it is no better and in some cases, distinctly inferior to biplane arrangement.

CHAIRMAN MEAD: Of course, what interests us most is what sort of improvement we could make in those figures. I wish they were more representative of what one of our present air engines does, then we would know much better about what we are working with.

MR. McCARTHY: Let's put up some figures which will compare with this.

CHAIRMAN MEAD: Have you some there, Mac?

MR. McCARTHY: Yes, I have about five or six different airplanes here.

CHAIRMAN MEAD: Can't we take an average and set them up on the board?

MR. McCARTHY: I can put down about three. (Marking figures on the blackboard).

MR. SIKORSKY: Some of these are water-cooled jobs and some are air-cooled. This one is an XO3-1, that is a two-seater observation plane with a geared 1570 motor on it, and estimated high speed of 182 miles an hour. The total wing drag, I did not separate them, about 35.6.

Interplane struts, wires and interference is only 8.3; fuselage is 14. 1.

The radiator 6.

CHAIRMAN MEAD: Including the engine?

MR. McCARTHY: Yes.

Tail surface 8.7. Landing gear 11.2. Propeller loss 16.1.

Now we designed the same job as a monoplane and at a high speed of 183 miles an hour on the same kind of paper and using the same slide rule the wing drag came out 37.8.

This first (indicating) was really a sesquiplane, the other a monoplane.

Interplane bracing about the same as before. Fuselage 12.2, and radiator 6, tail 8.8, landing gear about the same as before, and we have just as good a propeller.

Now here is an O2U-2, a biplane with the famous Wasp engine, and this is calculated performance and agrees with the actual performance within a mile, 28.9, bracing and interference 15.4, fuselage 23.6.

MR. SIKORSKY: These data are at full speed?

MR. McCARTHY: Yes. If you took it at low speed, your wing drag would go up somewhat more. Now it is interesting that the total of this and this (indicating) agree fairly well with the total drag of the body. The O2U-2 has a large round body with the gas tank in the system, and these two models (indicating) were made with small narrow bodies with the gas tank in the body, so the projected area of these jobs was much less than the O2U-2.

CHAIRMAN MEAD: That seems to bring again the old problem of air-cooled versus water-cooled drag. I wonder if you can get anywhere with a check on these figures on the basis of what a machine does with retractable landing gear?

MR. MONTEITH: That landing gear on the O2U-2 looks awful small. What size wings did you have?

MR. McCARTHY: 30 by 5. The Army test made on a Falcon, wind tunnel test on a model and removing the chassis completely they reduced the drag 14 percent, so that would make the drag on this basis—

MR. MONTEITH: Let's have those figures on the Falcon, put up on the board.

CHAIRMAN MEAD: Have you anything, Monty, we could put up against this as a monoplane with the wheels up?

MR. MONTEITH: We have the overall test with the model 200. The tests are not very accurate with gear in and gear out. We do not figure any performance on it though because we have to have the body with just the blunt nose on it. We were supposed to have the NACA cowling you see, so we simply extended the lines back, so we have not any idea what the body drag is going to be.

MR. McCARTHY: On the Falcon, I have nothing nearly so complete at this. I have the drag, the loss to the radiator is 4 ½ percent for the total drag. You would have to divide that by power efficiency, I suppose, that would make 82 percent,—that would make the radiator 3.7 percent; the landing gear is 11.5. Those are the only two comparable figures I have.

They tried three or four places for the radiator and found the normal position under the body, the old funnel position was the best of all; that was even the best with this Heindrich type.

CHAIRMAN MEAD: I wonder if it is safe to take those and try and build up an average set of figures, and then from those figures what improvement anybody thought they could get for various reasons? That is, propellers could be improved, and engine cowling? Mr. Weick seems to have a lot of dope in his head from his tests of what we might be able to do.

MR. MONTEITH: The thing I am interested in right now is, are we going to be able to use NACA cowling on the geared—

CHAIRMAN MEAD: Well, Ford does.

MR. WEICK: I wouldn't say he did yet. I spent some time there and made some tests on that particular ship. He did not have what you would call NACA cowling on it in the first place, and he didn't know what it did in the second place.

CHAIRMAN MEAD: I know the boys finally got it so it would cool passibly, it does not cool too well; and I was going to suggest it seems to me the McCook Field type cowling would be ever so much better.

MR. WEICK: Well, I think myself a certain amount of development work has to be done on every installation, especially the hard ones like taking a Hornet for instance, and in the extreme case, taking a geared Hornet on a fairly slow ship and cooling it, and I do not think—that is, I think the general idea is to just say NACA cowling is the particular stuff outlined in the report there, but I do not think that is what should be stuck to at all necessarily, I think the air should be guided and used as efficiently as possible especially in the cases where cooling is hard, and in the case of a geared Hornet for instance I think without any doubt in the World it could be made to both cool quite satisfactorily and have a reasonable reduction in drag, but I do not think you can expect to do it the first time you try; I think you have got to work on that to the point [there] with your reduction in drag; you can use a comparatively small amount of air but use it in the right place and get effective cooling, too.

CHAIRMAN MEAD: I am going on the basis that Tillinghast says the cock with Breen's cowling will operate on the ground with the wheels blocked with full throttle for indefinite periods—half an hour at a time—without overheating the engine. Well, that is better than we have often heard of with NACA cowling? I don't mean that as criticism, but it just happens to work that way that the air seems to be better used.

CHAIRMAN MEAD: He has some control, of course, which the other has not.

MR. MONTEITH: On the other hand; the XP-12 which we built here was just exactly like Breen's cowling only we did not pull the skirt of the cowling in, we faired the job out to give it outside diameter of the engine, and it apparently worked all right out here but when he got it back East he had trouble with it overheating. Breen was out here and we laid the the whole thing out with him standing right over us.

CHAIRMAN MEAD: I think it all goes to show that we don't know as much about this job as we ought to know.

MR. MONTEITH: If we use this on the mail line it has to work darn well, not reasonably well. I am wondering [if] it is going to be worthwhile to put it on that ship?

CHAIRMAN MEAD: I think Short can tell some of his experiences, we saw that he had been using the tin shears in Wichita.

MR. SHORT: Now, ours unfortunately thus far have only covered the J-6 300 (horsepower). I hope before the week is over I will get a report on the Wasp.

We started out the first one following very closely to the rule of the NACA cowling, and the changes which we made however on the J-6 was to put the collector ring in the rim of the cowling as the one furnished by the Wright Company is not suitable for strictly NACA cowling.

With that first one and with the propeller the Hamilton Company furnished us we did the admirable high speed of 133.

CHAIRMAN MEAD: Was that in direct comparison with the ship before?

MR. SHORT: I don't know what the ship would do before, but with some slight alternations in the cowling, and with a more suitable propeller on the same ship we did 143.

CHAIRMAN MEAD: In other words, you lose speed with the coowling?

MR. SHORT: With the version of the NACA cowling we had at first.

MR. HAMILTON: You improved the cowling?

MR. SHORT: We made an improvement on the cowling, namely,—it may be interesting to know how we tried it in here (indicating on the blackboard)

MR. HAMILTON: Is that with the same propeller you got the improvement, or with a different propeller?

MR. SHORT: With a different propeller. With that token it is hard to differentiate even though we do know after the first experiment that the first thought on the NACA cowling and the exhaust collector ring was not ideal by any means.
The collector ring came in here (indicating) [as] an attempt to get that effect; that being the outer foil of the outer wrapper, and this was to develop the supposedly air foil appearance on the wrapper.
On cross section this is a collector ring, and that one,—the collector ring was getting quite hot, we were not getting the air through there apparently, and with the propeller and that combination of cowling on the nose we got the 133.

We then changed it to this effect (indicating), bridging over here, and leaving a small gap in there and using this whole portion right in here as a cockpit heater; a hot air heater for the carburetor, and with that 1219 propeller design we did on our course, as I said, 142.7. We figured that was near enough to 143 to swing over.

On our third attempt,—the inner wrapper coming off so fashion (indicating), we have discontinued it from the rest of the cylinders back to a point ahead of that one (indicating). We had a number of experiments and our Organization went through quite a session on it, and we saw no change of speed by removing that inner portion, and saved considerable time on construction of course, and then for maintenance it was ideal.

Now on the first Wasp job we are using some of Captain Breen's ideas, together with the NACA cowling, using a fairly well cowled up nose, a single outer wrapper that is on the Lockheed version like Breen's, toning it in but using—

CHAIRMAN MEAD: (Interrupting) You don't know how much of this increase was due to propeller?

MR. SHORT: No, we have not the opportunity now to try that out we have changed the cowling. We tried it with this portion out (indicating) and got about 130 miles an hour with that arrangement, just using the collector ring setting out here in the open and no outer wrapper.

I think we are safe in saying that on our first ship the NACA cowling did no good at all. The people who came up from Langley Field to see the job at Washington said we did well to get any increase, and we heartily agreed with them after we played with it ourselves a bit, but it brings out Weick's statement that everyone is a separate problem itself, and invariably I think it will happen that the first cut at the cowling is a disappointment.

MR. McCARTHY: How did the one work out that you had done at Langley Field last summer where you had the thing fairing [from] the fuselage?

MR. SHORT: The NACA people reported not so well. We have not gotten a real final report from them on it. That was faired in around a conventional rectangular fuselage with no attempt at fairing in the sides, exhausting through gills on the sides. On our Wasp combination, it points to a very logical arrangement, and as I say, I hope I can tell you what it will do before the week is over. It is a combination of Breen's and NACA, using a nose spinner,—Mr. Mead advised us very timely that we would not get very much engine control over that because the shutter covers only the very lower portion of the cylinder barrels and probably would not control the temperature, but it is getting the air in the inlet and that is the problem if we cowl it up too high.

We did not want to use Breen's Venetian shutter effect in there, the maintenance must be high on that, so we tried to steer clear of that.

MR. NORTHROP: Has anyone any experience in controlling cowling temperatures, that is in taking care of too cold weather by decreasing the gap in the rear of the cowling?

MR. SHORT: We are trying that now with a slipper ring on the end in fact, it will not only control the temperature but it will control your speed, and we thought of making a remote control to the cockpit because you will take off, as Colyer experiences in the mail run, take off from a warm field in Omaha and hit some bad weather before you get to Cheyenne, and you have to keep the motor warm, and you have to pay the penalty with speed so we had a cam arrangement worked out on the outer ring so as you would rotate this outer skirt it would creep back and forth.

MR. NORTHROP: That was a cylindrical skirt in that case?

MR. SHORT: Yes. Well, we made all of ours a perfect circle.

MR. MONTEITH: George, after following up what we said this morning, I would like to point out two things: This discussion of NACA cowling is fine but as far as any NACA cowling itself is concerned it is not only heavier than the normal cowling but also increases the maintenance troubles because of the two sets of cowling to take off.

CHAIRMAN MEAD: Of course, the first thing is to get any gain out of it, Monty, if we can.

MR. MONTEITH: We actually got a gain on P-12. Of course, we had that up to 183 miles an hour with the engine turning 2170.

MR. SIKORSKY: We had a very reliable information concerning the use of the NACA cowling with a sort of ring around the cylinder heads of our amphibians.

In order to have the data as accurate as possible, we made it as follows: We gauged accurately the speed of the ship with the thing on, then we quickly dismounted it and then on the same day, the same pilot, the same engines, checked the speed again with the first test, and we found the following data: The ship actually gained more than five miles per hour at top speed, at least as much in the cruising speed, the difference in the cruising speed appeared to be fairly distinctly visible and very much in favor of the NACA cowling, and of course it was measured with the same amount of cruise.

Now, there was no difference in climb, in other words, I would say that the ship did not lose any in climb, or lost so little that it was impossible to judge it.

Now, it seems that a little negative difference was in the landing speed which was possibly a little bit worse with the cowling than it was without it.

Now, this data was rather accurate and certainly was encouraging from the standpoint of using any kind of an arrangement of that sort, because the one which we used was just simply a first guess which we made, and we tried to be very much on the safe side in order not to overheat the engines, so it was only a tiny ring something like fifteen inches wide just covering the tops of the engine cylinders, and these were the results: The engine did not show at all any signs of overheating, so the cooling was satisfactory, and I believe quite a lot may be gained in this field and it seems to be very advantageous to go on further in some manner of search.

As I said, the data of the wind tunnel test we [did] with wind motor amphibian was still considerably more encouraging because the models with full cowling showed improvement of 3 ½ points, in other words 14 ½ total of drag instead of 18.

CHAIRMAN MEAD: Monty, have you any idea from flying a tri-motored plane with the various combinations what the ultimate situation might be? As far as I understood it the outboard motors do not give you any gain, it that correct?

MR. MONTEITH: That is correct, the center motor gave a gain of 3.1, but the three sets of NACA cowling added about 120 pounds to the ship, that is almost one passenger.

CHAIRMAN MEAD: I wonder if Weick knows from Langley Field whether they have arrived at any conclusions about the relation of cowling and motors to the wings? Isn't that the reason it don't work on Monty's ship?

MR. WEICK: That is the reason that I ascribe to it, that is you have an interference effect there between nacelles and the wings, and so far in just about every case I know of, which is three actual full scale tests, also some wind tunnel tests, the interference between a cowled nacelle and a wing nearby has been very great, in fact, great enough to usually nullify any possible gain due to the use of the cowling on the engines.

The first experience we had with that of NACA was that we cowled the three engines of a Fokker with whirlwind,—tri-motor whirlwind and we got a gain of about 3½ to 4 miles an hour from the nose cowling, and again got no gain whatever from the wing nacelles, and we did not know of course, exactly what to ascribe it to but immediately thought of the possible interference because our wind tunnel test in the twenty foot tunnel had shown just the opposite; it had shown that you get more gain from cowling and small nacelle than from cowling and engine in front of a large fuselage, and we took two methods then of going on to the problem, one was to put strings—small strings a couple of inches long all over the surface on the actual Fokker and on all the surface of the nacelle and the bottom of the wing, and we found that just behind the maximum diameter of the nacelle where the nacelle started to grow small again there was great turbulence in the first place. The nacelle was only about two or three inches from the surface of the wing and the air apparently would not follow through that and down around the nacelle, and most of the strings in that portion actually pointed forward,—going along over 100 miles an hour. It seemed very queer but it showed the condition of the flow.

Then, in the wind tunnel tests we took, in order to get as near as possible to the full schedule figures, we took a section of the Fokker wing and we built up a nacelle just like the Fokker nacelle as near as we could do it, and with a small imitation of a motor. We got about the same drag coefficient for that nacelle as we got for the complete nacelle, so we knew that part was just about right, and we found with the cowled nacelle we had just as much drag when it was next to the wing as we did with the uncowled nacelle, and then we did two things; first we started fairing that into the wing to see whether if by proper fairing we could reduce that interference, and we found in that particular case we could reduce it very materially, and by putting on a large fairing we increased the actual front projected area and appreciably we could reduce the drag very much so that we got almost the entire gain that we had anticipated we might get neglecting interference entirely.

CHAIRMAN MEAD: That is simply from the cowling into the wing?

MR. SHORT: Simply fairing from the nacelle which was already covered with NACA cowling clear to the wing without changing the location of it, and incidentally at that that type of fairing was put on the ship and a total of increase of twelve miles an hour was finally obtained. Also, the nacelle was moved in the model but it was too much of a job to do that full scale, but on the model, the nacelle was moved to several positions above and below the wing and the only one which was moved was the nacelle with the complete NACA cowling, and it was found that by moving it far enough down you could get away from fairing it, but it had to be an appreciable distance below the wing before the interference would be noticeable.

The best results were obtained by putting the nacelle exactly in front of the wing (indicating on the blackboard) with the top of the nacelle parallel to the top of the wing. [It] will just take a small space here (illustrating). Supposing that is the wing (indicating), and the normal nacelle came in about like this, and when it was in that position we got no gain whatsoever, because the air would not flow through here, and having large fillets all around, we got an appreciable gain, but by moving this up so that the nacelle came about in this position (indicating) we got less drag than the sum of the wing drag and the nacelle drag when each was isolated, that is, the total drag of this was less than the sum of the wing drag of the wing and the nacelle when they were not together, so that it showed that we could get an increase in performance by changing the location of the nacelle and down the projected area of the entire works if you had a smooth enough cowling. Of course, if you had an exposed engine in that position you would spoil the lift over a good portion of your wing, and the Ford people with their first tri-motors ran into that problem, they had their f-5 engines right in front of the wing, and they had such high landing speed they had to remove them. They took it at the time, it was due to the fact that the propeller was in front of the wing.

MR. McCARTHY: (Interrupting) You think if they cowled those in they would be all right?

MR. SHORT: Yes, because we did not get any increase in lift by doing that, none whatever. We only did it at low angles of [attack]. I do not know what would happen at high angles of [attack].

MR. HAMILTON: High angles would be interesting as far as your landing speed is concerned, and that is where Ford had trouble.

MR. WEICK: There are no tests giving reliable data in this Country. There have been a few small tests made in Germany, but they also did not give just exactly what you want. Right at the present time,—in fact the last thing I did when I left NACA was to outline a series of tests they are now working on and not in the tunnel yet, which consists of tests on a combination of a wing and a propeller in a nacelle, and the nacelle has forty different positions. Approximately forty different positions with respect to the wing using the propeller as a pusher that includes tests with the propeller entirely above the wing and entirely below the wing and three different positions before and aft, so that it is right as near the wing as it could get clearance, and then some positions fore and aft, and in some cases like that where it is built right into the wing and other cases where the nacelle is suspended above or below the wings.

CHAIRMAN MEAD: Monty, are you going to have NACA cowling on the 200?

MR. MONTEITH: That is what we had planned originally, yes.

CHAIRMAN MEAD: Based on what we know now, the trouble with NACA cowling is heating, isn't it?

MR. MONTEITH: I am still worried about that geared engine though.

CHAIRMAN MEAD: You mean in the 200 you are going to use geared engine?

MR. WEICK: With the cowled nacelle, which is the only thing we had there as I remember it, if you got down close to one engine diameter you could get away from the interference, but that is more than you can ordinarily get in an airplane.

MR. MONTEITH: You mean the space to be one inch in diameter?

MR. WEICK: Supposing the diameter of that engine would be say 45 inches below the wing, that is what I mean.

MR. MONTEITH: On that question of Mr. Egtvedt's here a moment ago, Doctor Raam made some tests four years ago on propellers in front of large wings. The wings were much larger than the ones we are using however.

MR. WEICK: Yes. Well, his tests, I think, were very good and they show one thing too, they show in a case like that, or in any case where the propeller is in front of the wing, you have to put that appreciably in front of the wing or you get a very noticeable loss, and from his tests I got an idea on an ordinary arrangement, we will say a nine-foot propeller, which was what we had on the Fokker that we were working with at the time, if we had put the nacelles up into the wing such as that and then put the engines far enough ahead so that the propeller was approximately 18 inches ahead of the leading edge of the wing instead of just I think about five or six inches as they were in the actual installation, there would have been an appreciable gain all the way through, and it looks to me off-hand as if that is the best condition considering high speed. Now, what that particular condition would do to the lift at high angles or landing speed I do not know.

MR. HAMILTON: There is a Russian reproduction of the Ford tri-motor which I saw in London, where they have the engines out from the wing about better than two feet and it is not cowled. It has a Lynx engine and they claim they have tried the position of the Ford and also this position and the landing speed is no greater in this position than with the Ford,—than with the low wing position. However, their top speed is considerably improved. It seems to bear out the information due to the fact they are I should say almost 30 inches ahead of the leading edge.

CHAIRMAN MEAD: Well, it strikes me one thing we would like to know as soon as possible is the results of these tests in NACA laboratories, with the propeller turnings.

MR. WEICK: It is true, but you won't get those for some time.

CHAIRMAN MEAD: I wondered if there is any chance of you Mr. Chatfield; somebody who knows them well, to get in there ahead of the rest of the gang?

MR. WEICK: Well, there is that possibility—

MR. HAMILTON: (Interrupting) They tell me, just with that idea in mind—

MR. WEICK: (Resuming) Actually, I just did go down and got all the dope they have done on high tip speed so far. Those tests were started by me and they just finished them up after I left and I had no difficulty whatever in getting that stuff because I know the fellows down there and because also I was in on the start of the thing and they realized that I had something to do with them down there.

Now it so happened that I was in on the start of this particular thing and will have no difficulty whatever getting that information by going there, but I can't get it by getting them to write it to me.

CHAIRMAN MEAD: Then if we carry out our present scheme of getting such information to Chatfield he can broadcast it through the news letter and everyone will get it about, as quickly as possible.

MR. WEICK: Only, any such information which comes out before it is published by NACA should be kept within the family because otherwise they, of course, would not let us have anything further if they discovered that we were broadcasting it. It would get them in bad.

CHAIRMAN MEAD: You would not get any more?

MR. WEICK: Yes, that it is, sure.

CHAIRMAN MEAD: Then, as far as I can see at the moment we can't help Monty very much except as to additional sealing in the engine. I would like to know in what regard whether the cylinders themselves are warm, or whether you are just guessing by the oil temperature?

MR. MONTEITH: The cylinders themselves are warm on the transport, up as high as 580.

CHAIRMAN MEAD: How about the barrels?

MR. MONTEITH: The barrels are running in proportion; down around 470.

CHAIRMAN MEAD: I should think Breen's scheme of blocking in between the cylinders may improve that somewhat?

MR. WEICK: I think there is no doubt in the World that some scheme of blocking in between the cylinders and putting the air that you take in right where you want it instead of testing it simply filter through in the easiest possible manner, if it is guided to where it should be that would undoubtedly cool better than even letting the engine stick out in the open, but that does add such things as maintenance troubles which of course are already objectionable.

CHAIRMAN MEAD: Do you think, Monty, we could do you any good in Hartford with the 40-B? Of course we are plumbers when it comes to cowling, but we can patch up something,—it has a geared engine in it,—to try and fix up some installation which will cool there,—help anticipating trouble with the 200, or do you think the ships are so different that we would not get you very much of any valuable information?

MR. MONTEITH: Well, the ship is a little bit slower than we suspect the 200 to be so that will be an additional trouble to overcome, but what I am wondering is whether or not the additional speed we hope to get out of the cowling will overbalance the additional weight and additional cost?

CHAIRMAN MEAD: I wonder what Weick thinks about that? That is a pretty big body. Do you have any information which would check that?

MR. MONTEITH: The body is the same diameter as the engine.

CHAIRMAN MEAD: Well, it is bigger than anything we have had as a single engine ship.

MR. MONTEITH: Well, the over all diameter of the J-5 is approximately the same diameter as the engine, it does not look like it, but it is.

MR. WEICK: The over all diameter of the open-cock fuselage in the 20-foot wind tunnel test was also approximately the same as the J-5 engine used in those tests.

MR. McCARTHY: On the F2U, Monty, the body was almost exactly the diameter of the engine with the NACA cowling they put on it, the top came right directly back and the sides were probed in only a very small amount. We copied Breen's stuff almost exactly; had these deflectors behind the cylinders, and we were right at the danger point as far as cylinder temperature is concerned.

MR. MONTEITH: On the 80-A we tried the NACA deflectors on the cylinders but it made no difference.

CHAIRMAN MEAD: Mac, have you had one of your jobs with NACA on it?

MR. McCARTHY: Yes, the XA2-1.

CHAIRMAN MEAD: I don't see quite why Monty feels he is not going to get gain in speed based on these other tests.

MR. MONTEITH: I don't say we won't gain it or won't get the gain. We have managed to put about 11 miles on the mail plane by both fairing out the body behind the engine and putting the NACA cowling on, and it did run hotter, which from Mr. Colyer's point of view, is not so good. We got an appreciable increase on the XP12-A, and on the Transports, we failed to, except the nosed engines.

MR. MONTEITH: I would like to go ahead with the 200 with the NACA cowling on because we have started out that way, and if we get into trouble we can change to something else.

CHAIRMAN MEAD: We seem to be a long ways from this story, but what I was driving at here is fuselage complete with engine runs 20.18 and 23 which shows apparently that air-cooled and water-cooled do not vary a whole lot. Here is an air-cooled at 23, and water-cooled at 20, and if we should take 20 as an average, which might be safe, how much reduction would we get on cowling in its best possible form? Say I can put 20 in this column of averages, what would we have over there (indicating)?

MR. WEICK: According to our tests you get a noticeable decrease.

MR. McCARTHY: It shows six or seven percent decrease in the fuselage drag,—the total drag.

MR. WEICK: The total drag, which would be, say somewhere between ten and fifteen for that drag.

MR. MONTEITH: Here are three figures which may help you, George:

The equivalent flat plat area of model 83 which was the forerunner of the B-12 figured out to be 6.58 square feet. The B-12 figures 8.34, and XP12-A figures 5.89.

CHAIRMAN MEAD: Just a moment, will you give me those figures again, Monty?

MR. MONTEITH: The 83, 6.58; the P12, 8.34; the XP12-A, 5.89. That is calculated from flight tests from the high speed. Take the wing characteristics which were alike in each case and simply figure out your wing horsepower and parasite horsepower and back.

Now the difference between the 83 and the P12, of course, lies in the wheels, landing gear and streamlines behind the cowling, and little Military stuff like sights and things of that kind.

The difference between the P12 and XP12-A is due to the NACA cowling alone. There is some question about that last figure because I had to estimate what the power of that engine was at 2,170 r.p.m.

CHAIRMAN MEAD: It would be better to run this down then more than we have if you said from ten to fifteen, this rather proves it would be better to be down here at ten, wouldn't it?

MR. HAMILTON: You are dealing now with only top speed, how about climb—rate of climb?

MR. MONTEITH: We did not have it on the XP12-A so we don't know.

MR. WEICK: What you expect, of course, is if you get proper cooling and proper power out of your engine, and if you get the decrease in drag which you expect from your cowling, you would expect it to take slightly less power to drive it through the air at climbing speed and therefore get a little better climb; but it certainly would be a small amount.

CHAIRMAN MEAD: I would like to swing this around on one other track, and that is do we know what that fuselage proof would be with a wing radiator?

MR. MONTEITH: That would depend on what kind of ring radiator you used.

CHAIRMAN MEAD: Air-cooled engines do not look so bad on this method of scoring, but the question is how accurate it is.

MR. WEICK: The three fastest ships at Cleveland apparently had radial air-cooled engines.

CHAIRMAN MEAD: Of course, we get to this top but it certainly looks from Chatfield's figures, which I think Monty has probably checked up by now to a certain extent, that the little engine which can be completely cowled is going to give the big engine something to think about.

MR. SIKORSKY: Yes, I believe so, because you see actually the engine interference enters not to so say one time, but enters in the cube at least because the engine interference and size, which in our case, is to put the wing much higher than we want and therefore have longer struts and so on, and therefore this thing may be of very considerable value because the actual gain would be much more.

CHAIRMAN MEAD: On this item of landing gear, is it going to be correct to assume that is entirely washed out if we can have a retractable gear, or is it going to appear somewhere else in this picture?

MR. MONTEITH: It depends entirely on how you retract it. On the 200, we don't retract it at all, as you saw from the lockup last night.

MR. WEICK: Then, there is another thing, a good many ships you would have to build some special,—you would have to make some special changes to get room to put the landing gear when you retract it.

CHAIRMAN MEAD: That is what I say, if we put it down completely at zero it is going to be there in form.

MR. MONTEITH: If you build a ship with retractable landing gear on it you have to start with the gear and build the ship around it.

CHAIRMAN MEAD: From the looks of those figures, it looks as though 11 would be a fairly decent average for landing gear, and I was wondering if we dared to put down something like 4 or 5 on retractable landing gear on a basis that although that item might be wiped out it might be somewhere else equivalent to that?

MR. MONTEITH: You can wipe out about eight out of eleven,—make it three.

CHAIRMAN MEAD: The next question is,—of course, the big item seems to be this old offender, the propeller.

MR. SIKORSKY: This item is a very interesting item, and I would like to find out actually how many give us the proper full amount of revolutions of 80 percent for, if so, it is too bad because there is no room for improvement.

MR. MONTEITH: If everything was as efficient as the propeller, we would be in fine shape. I think we better leave the propeller manufacturers alone for a while.

MR. WEICK: According to our wind propeller test you can run a propeller up to 950 or 1050 for the tip speed without any depreciable loss, and from then on, the loss is very peculiar, it is almost lineal.

On ordinary installations with direct drive air-cooled engines, you can get efficiencies, that is, propulsive efficiencies, not allowing for propulsion efficiencies, including the effect of the propeller on the body; you can get efficiencies as high as 84 or 85 percent with the highest pitch propeller, and 80 to 85 for any propeller which does not run at too high tip speed and which is on a ship going say 16 miles an hour faster.

CHAIRMAN MEAD: (Interrupting) If you give the propeller the best break and put it in the proper relation to the wing (I don't know what that is myself) and run it at the correct speed what is the very best efficiency anybody dares to figure for propeller?

MR. HAMILTON: Eighty percent.

MR. WEICK: It depends on your figuring, of course—

MR. CAIDWELL: Well, we have made tests of ninety percent.

MR. WEICK: The very best we have ever gotten in the full-scale funnel, that is with a geared propeller which ran at quite low tip speed and which was large with respect to the body, a geared propeller on a J-5 engine; a very high pitched geared propeller, we actually got one case of eighty-nine percent.

CHAIRMAN MEAD: I would hate like the deuce to give you 525 horsepower and have you throw away a hundred just like it did not cost anything.

MR. WEICK: The thing is if you don't want that done, if you don't want us to throw away fifty, then you have to design the engine and airplane to get the most efficient propeller.

CHAIRMAN MEAD: That is what I am talking about. This is our "hope to be" column over here (indicating), and that is what I was wondering, whether you felt that you could do materially better than this; whether it is safe to put down any such figures, say, as ninety percent, which actually is correct, I think for certain high speed motor boats working in the water.

MR. WEICK: Of course, there is one thing, you are talking here about the high speed condition of the airplane which is not necessarily the most important condition at all. The propeller efficiency at take-off is very much lower and the propeller efficiency at climb is also much lower than the propeller efficiency at high speed.

CHAIRMAN MEAD: Aren't we interested from Colyer's standpoint of the propeller efficiency at part throttle?

MR. WEICK: It is going to be almost exactly the same unless there is tip speed loss to start with.

MR. SIKORSKY: What is the practical efficiency for, say around a cruising speed of 110 or 115 miles per hour and a top speed of 135 miles an hour?

MR. WEICK: Well, I will take from those wind tunnel tests,—I will make a guess at somewhere around 77 or 78 percent.

MR. SIKORSKY: 77 or 78? As high as that?

MR. WEICK: Yes. That is cruising at 110 which is just about exactly the same efficiency you would get at full speed if your tip speed was not above a thousand, or to be perfectly safe, 950; that is perfectly safe.

CHAIRMAN MEAD: Well, Northrop has another scheme, or course we would like to hear about from the propeller folks, whether you really think this big gain in putting the propeller behind the wing as he has,—he has buried the engine and has nothing in front of it as he gets the wing thicker he hopes—

MR. NORTHROP: (Interrupting) Our scheme was utilized really to get more efficiency out of the wing rather than the propeller and we plan to try it both ways for that reason. We did not know for sure which way would be the best. We felt the speed of the propeller was such it would be less effective by comparatively smooth flow of the wing than the wing itself would be affected by the turbulence caused by the propeller so close in front.

CHAIRMAN MEAD: Of course, these figures we are putting down here are going to affect something until we get 100 percent again. Incidentally, did they tell you that the Travel Air folks told Short they gained 60 miles an hour with the cowlings?

MR. MONTEITH: I don't believe it.

MR. SHORT: Do you expect any propeller design change due to the cowling on the front?

MR. MONTEITH: No, I do not expect that would make any change [to the] propeller.

MR. SHORT: Don't we in effect have a wall there equal to the outside band to the box the propeller is working in?

MR. WEICK: Yes, but actually it is in a portion which is very close to the hub as far as the whole propeller is concerned and which is comparatively unimportant as far as the whole propeller is concerned, and the average propeller of the present day is designed so that the pitch should reduce in towards the hub anyway because of the short air velocity with any body; that is, an ordinary air-cooled engine without cowling has a great effect in reducing the velocity of the air through the central portion of the propeller, and so had the NACA cowling type, and there is not a very great difference there between one and the other as far as the propeller is concerned.

Incidentally, we have made surveys in the plane of the propeller with both types and the air is actually slowed up more in a sort of uniform manner with the NACA cowling than it is without. Without it, it is slowed up as much but in a different manner. It does not go out to that ring, it goes off in between, but I do not think that just that would bare any appreciable effect on propellers any way. The only effect it could have that I could see would be on the pitch distribution, that is the distribution of blade angles and that is not critical in the first place, and it is not greatly different than what it would be without the cowling in the second place.

CHAIRMAN MEAD: Should we have zero for interplane bracing and interference if we had a monoplane without supports?

MR. MONTEITH: No.

MR. WEICK: The trouble is you would have more profile drag.

MR. MONTEITH: You get a certain amount of interference between the body and the wing. It is a minimum in that case, but it is not wiped out.

CHAIRMAN MEAD: Certainly these figures are much better than those which we had to begin with when we started our investigation, and Mr. Chatfield is going to keep right at that because as fast as we get information we would like to add it to this information and make it as useful as possible.

MR. SIKORSKY: I would like to ask the following question; In a single or multi-engine ship around 500 horsepower, the motor and installation in weather will give you approximately 200 to approximately 250 pounds more weight per each point unit.

Now in the multi-engine, or say any heavy Transport ship we are concerned with the drag from the very beginning, for instance, in the flying boat we are concerned with the drag of the propeller at 25 miles per hour, then with the drag of the propeller to the pull all the way further to the take off speed, then to a certain slow speed like say 75 or 80 miles per hour when we carry very much and about the full efficiency of the propeller as high as possible in order to keep a good flight, and at the present time the operating company always requires us to give a high ceiling with one power unit out of commission and therefore, we have another point where the propeller efficiency is a very high volume. Then finally comes the reducing speed, then finally, most important of all comes the top speed.

Now taking as a reasonable average of all these conditions, what do you gentlemen think would be our best guess for the future? I am speaking now of, say one or two years from now, should we ask Mr. Mead for a direct drive engine of 500 horsepower or 575 horsepower, or should we ask for a geared engine, and if geared, what ratio? Let's see what would be the answer to that?

MR. CALDWELL: I do not think there would be any difficulty to us. Probably that sort of step would be a very big increase in efficiency. At the top speed I believe we figured direct drive Hornet would be about 1100 feet a second which would be beyond the point of good condition for tip speed.

Of course, with a metal propeller we are able to go a little further in tip speed on account of thin sections that it is possible with the wood propeller.

The tunnel tests with rather thick sections of used propellers have an extreme loss of efficiency from 18 percent down to about 42 percent, going up to 1500 feet a second,—but with metal propellers, we can't go very much higher.

MR. WEICK: NACA have just completed several tests they started [when I] was

there, and you get a very noticeable increase; it starts at tip speeds of around 1000 on the average, and of now as, in one case 950, and most of them are between 1000 and 1050, then it goes down fairly rapidly.

CHAIRMAN MEAD: I was getting very discouraged over this gear situation. We finally got some gears which would stand up and you gentlemen over here did not seem to get any gain except in the seaplane, that is, the high speed situation did not improve very much and so on. Lately though, I seem to be considerably cheered up by this noise situation which will probably require propellers whether we get any gain or not.

I do not know how others feel about that, but riding up on the ship the other day, which as I said before was the best transport we ever have been in, its principle deficiency is noise, and certainly we can quiet the exhaust down some but it seems as though a good deal of the noise over turning fifteen or sixteen hundred was from the propeller. I don't know how you feel about it but it seemed to me that one situation was the slowing down of the propeller.

MR. EGTVEDT: I would like to ask one question too: What would be the effect of this problem of Mr. Sikorsky's here with the variable pitch propeller? Now right on that particular problem of gearing as against direct drive with a propeller of that kind—

MR. CALDWELL: (Interrupting) Well, I think the variable pitch will give a decided improvement all right on the static thrust and the efficiency, or rather the power at the take-off. I think it would be intermediate though between the gear and the direct drive—the fixed pitch would probably be lighter; a great deal lighter.

MR. EGTVEDT: It might be possible, for instance with a land plane where the conditions are not quite as severe as has been pointed out for the sea plane, or flying boat, that that would more than off-set our increased weights and other difficulties. On the other hand with a flying boat it is very doubtful whether it would take care of the difference.

CHAIRMAN MEAD: I think we ought to consider this propeller in the most advantageous position as well as the right speed, and we have only tried one experiment in that regard which probably was not conducted very accurately, but there did not seem to be much gain in putting the propeller six inches further ahead, and possibly we should have gone further yet but I think it is worth several pounds in the engine if the propeller efficiency can be stepped up somewhere. We found according to those tests it is one mile an hour, and it cost us nearly twenty pounds in the engine to get it and that did not seem to be very worth while.

MR. HAMILTON: Mr. Mead, it seems to me there is so much involved in this matter of proportion and its effect on future design that I would like to get these propeller experts organized tonight to give you some idea of what we have in mind for next year, tomorrow, and then you ask us a lot of questions and we will try to give you some where near an answer or they will, rather, not me, but the thing always comes back to the propeller I find after the plane is all finished and the design is completed you take it out and expect the propeller men to put on the miles per hour that were laid down on the paper, and I feel that we might be able to contribute, but when they talk about ninety percent efficiency and all that sort of thing I just wonder if these fellows realize that later you are going to be asking for some of those things, therefore I would like to give you an outline tomorrow of what we have in mind.

I was not here yesterday, but we would like to ask some questions about what you want and why you want it, and then we will try to give you some idea as to what can be done with the propeller proposition as far as gearing, lighter weight and all that sort of thing.

I think unless you go at this propeller proposition as one problem, itself, and just have it tied up to this matter of the over all efficiency of the plane, why, we are not going to get much out of it from a propeller point of view at least, I have not gathered much from listening to all this so far; we are just sparring back and forth and I do not see that we are getting much information out of it. We are asking questions now that cannot be answered off-hand intelligently.

CHAIRMAN MEAD: We are just figuring an average of figures, and you all seem to agree that between 80 and 85 percent is where you will land, and that is a good place to begin because we have talked sometimes and thought "if we only had 18 percent". Well, you seem to all agree you will do better than that, and what we intended to do tomorrow was talk transport ships and Military ships and consequent improvements in performance, and from that, try to lay down the program for United as far as research went on all these various items, and I was simply trying to get down here some average which looked reasonable and everyone agreed to, and then of course looking off into the future if anybody was willing to commit themselves as to what possible improvement they might expect.

You see, we have been wondering if you really felt you could get a gain of ten percent, that is, run up from 80 to 90 percent efficiency, why, that was going to help a lot if you honestly feel, as you apparently do, that we can only take up 5 percent, that is something to figure on, and to have to look somewhere else to get a big gain.

MR. HAMILTON: This matter of propulsion is so closely tied up to what is immediately behind the propeller, and according to Mr. Weick's experience in NACA, and also on account of the fact that people cut out a dishpan and put it in front of their engine and think they have an NACA cowling, we have some ideas as far as United is concerned and as far as the industry is concerned.

Now, we have some ideas here, and we wonder whether we can utilize Mr. Weick's experience to the best advantage by undertaking some of this cowling work?

CHAIRMAN MEAD: I think you can't interest the rest of us any more than by taking that job over.

MR. HAMILTON: We are not the least bit unmindful of what is involved in such a nasty mess as to try to assist in cowling.

CHAIRMAN MEAD: What I gave up on, when you hear from around the table none of these ground rules apparently laid down work in each case and you have to change it around, but it is more of a problem than any of us thought; you just can't take some rule of thumb and do it, which seems to indicate to me that we just don't know as much as we ought to about the job.

MR. HAMILTON: I am fairly convinced of that.

MR. WEICK: Incidentally, in connection with that, I got a chance to talk with Mr. North quite a while one evening—he is the party in England who has been doing most of the work along with [Townend] down there, and he said very decidedly—and I was glad to hear him say it—that you could not expect to get any gain out of a Townend ring unless you did a lot of preliminary work. That is, the way he worked it was to put a test—put a model in a wind tunnel and then start putting Townend rings on it and small scale stuff. It was not what might be the best actually in full scale, but it was the best he could do, and he figured that if he could get it in about five or six tries of different Townend rings and different modifications then he could put the results of his work into a full scale job and hope to get some increase, but just taking a clear shot out of the sky you could not tell what you could expect to get, and the same is true of the NACA cowling.

Document 3-10(c), "The Curtiss Anti-Drag Ring," **Curtiss-Wright Review** *1 (December 1930)*

CURTISS-WRIGHT REVIEW
December, 1930

The Curtiss Anti Drag Ring

Greater efficiency—more speed with the same horsepower—is a problem on which the airplane industry is concentrating today.

The most effective way to achieve greater efficiency is by the reduction of parasite, or unnecessary air resistance.

Other things being equal, the air cooled radial type of engine, with its short crankshaft and small crankcase, is lighter than any other type. But when the parts of an airplane which offer an undue resistance to passage through the air are under consideration, the popular radial engine must be considered one of the worst offenders. Hence, a great deal of attention is being given to the problem of cowling this type of engine, so as to make it more efficient from the standpoint of drag. As a practical solution of this problem, the Curtiss Anti Drag Ring has been developed in the Garden City Laboratories of the Curtiss Aeroplane & Motor Company. This device will be manufactured in the Garden City Factory and will soon be offered to the industry for use on all makes of radial engines.

The appearance of the Curtiss Anti Drag Ring is best made clear by the accompanying photographs. It is a short barrel-shaped form of sheet duralumin surrounding the engine cylinders. It has the same contour its the upper surface of the Curtiss C-72 airfoil (wing section).

Experiments first made in England by Mr. Townend had shown the possibility of reducing drag with a ring of this type. The problem then, was to investigate the theory of this type of cowling—how and why it works—and thereafter to find out how to design and install the ring for the best results, both aerodynamically and from the standpoint of maintenance. This development from the Townend ring has resulted in the Curtiss Anti Drag Ring.

To obtain the necessary information, a one-quarter scale wood model of the fuselage of a new Curtiss airplane was built. Models of Wright radial engine cylinders were attached to the fuselage in their proper positions. A number of rings of different shapes were constructed, some spun out of brass and some built up from wood segments. The fuselage model was then set up in the Curtiss seven-foot wind tunnel, and drag tests were made. The wind resistance was measured without any ring and with each ring in place, trying different fore-and-aft locations for each one. In this way the best shape and location for the ring was determined. A large number of other tests were made to find the effects of various changes and to clear up questions of theory.

Air is violently deflected outward away from the fuselage when it strikes the projecting cylinders of a radial engine. This breaks down the smooth flow of air over the entire fuselage and leaves a turbulent wake much larger in diameter than the engine The anti drag ring prevents the turbulence caused by the cylinders from spreading out, and forces the air behind the cylinders in toward the fuselage, ironing out irregularities in the flow. The Curtiss wind tunnel tests showed that a drag reduction of forty-six percent was realized from these effects. It is an interesting fact that there is actually a forward-acting, or anti-drag, force acting on the ring, a force which may amount to as much as two hundred pounds on a fast airplane. This force is due to the angle at which the ring is set with relation to the direction of airflow over the nose of the fuselage.

As finally developed, the Curtiss Anti Drag Ring is simple and light in construction, does not require any special supports, and is easily removed for maintenance work on the engine. It has been used with great success on several Curtiss Airplanes. Speed increases of nineteen miles per hour have been obtained, and it has been found that the cooling of the engine is improved.

Document 3-11(a-b)

(a) United Aircraft and Transport Corporation Technical Advisory Committee Minutes held at the Pratt & Whitney plant, Hartford, CT, 19-23 May 1930, pp. 230-238, in Archive and Historical Resource Center, United Technologies Corporation, East Hartford, CT. [Courtesy F. Robert van der Linden.]

(b) "The Reminiscences of Harold Hicks," August 1951, transcript, pp. 61-69. Henry Ford Museum and Greenfield Village Research Center, Dearborn, Mich.

This pair of documents reflects the U.S. aircraft industry's growing interest for data about the aerodynamic value of engine nacelle placement around 1930. The first comprises an excerpt from the May 1930 meeting of the United Aircraft and Transport Corporation Technical Advisory Committee, held at the Pratt & Whitney plant in Hartford, Connecticut. At the time, no aeronautical organization was larger than the United Aircraft and Transport Organization. Just newly formed in 1930, the organization consisted of four major airplane manufacturers: the Boeing Aircraft Company of Seattle, Washington, which recently had acquired the Stearman Company of Wichita, Kansas, and the Hamilton Metalplane Company in Milwaukee; the Vought Aircraft Company of Long Island, New York; the Sikorsky Aircraft Company of Bridgeport, Connecticut; and the Northrop Aircraft Company of Burbank, California. It also consisted of a leading engine manufacturer, Pratt & Whitney, which had just come out with two excellent new radial air-cooled engines (the Wasp and the Hornet); the largest American propeller manufacturer, Hamilton Standard, which resulted from the merger of Hamilton's propeller company with the Standard Steel Propeller Company of Pittsburgh, Pennsylvania; two airlines, United, which ran from New York through Chicago to San Francisco, following the old air mail routes, and Pacific, which ran from San Francisco up to Seattle. Two other combinations of companies had been formed at about the same time, but United was the largest and most profitable.

The excerpt reproduced below from the minutes of the May 1930 meeting of United's technical advisory committee is extremely interesting from many vantage points. It captures an exchange between United executive George J. Mead; Boeing's Charles N. Monteith, formerly an officer in the engineering division of the air corps at McCook Field in Dayton (he had written a book in 1924 called *Simple Aerody-*

namics and the Airplane); and Fred Weick, who had just moved from the NACA to Hamilton. The conversation definitely highlighted that the industry did not fully recognize the importance of NACA's research to transport design—something that would quickly change over the course of the early 1930s. In fact, operating problems caused by placing engine nacelles under the wing of a multiengine transport, the Ford trimotor, were specifically mentioned during this part of the meeting.

The second document, from the reminiscences of engineer Harold Hicks, the chief designer of the Ford Trimotor airplane, also testifies to the industry's growing concern around 1930 not just for help with proper engine nacelle positioning, but with proper aerodynamic design data overall. The design of the Trimotor has always been portrayed as an empirical and unsophisticated process and a stunning example of the old methods of designing aircraft during the 1920s. Hicks's recollections illustrate that Ford aeronautical engineers were aware of the disadvantages of placing the nacelle below the wing, and they were considering the use of NACA developments to alleviate the aerodynamic disadvantages. The fact that they were willing to incorporate new innovations into a less-than-state-of-the-art design highlights the indeterminacy in design during the period. The interview with Hicks was conducted in August 1951 by Owen Bombard of the Oral History Section of the Ford Motor Company Archives in Dearborn, Michigan, and brings the reader a valuable insight into the design logic behind one of the most well-known aircraft of the period.

Document 3-11(a), United Aircraft and Transport Corporation Technical Advisory Committee Minutes held at the Pratt & Whitney plant, Hartford, CT, 19-23 May 1930.

CHAIRMAN MEAD: Monty, have you any idea from flying a tri-motored plane with the various combinations what the ultimate situation might be? As far as I understood it [N.A.C.A cowling] the outboard motors does not give any gain, is that correct?

MR. MONTEITH: That is correct, the center motor gave a gain of 5.1 [mph], but the three sets of NACA cowling added about 120 pounds to the ship, that is almost one passenger.

CHAIRMAN MEAD: I wonder if Weick knows from Langley Field whether they have arrived at any conclusions about the relation of cowling and motors to the wings? Isn't that the reason it don't work on Monty's ship?

MR. WEICK: That is the reason that I ascribe to it, that is you have an interference effect there between the nacelles and the wings, and so far in just about every case I know of, which is three actual full scale tests, also some wind tunnel tests, the interference between a cowled nacelle and a wing nearby has been very great, in fact, great enough to usually nullify any possible gain due to the use of the cowling on the engines.

The first experience we had at the NACA was that we cowled the three engines of a Fokker tri-motor with Whirlwind engines and we got a gain of about 3 ½ to 4 miles an hour from the nose cowling, and again got no gain whatever from the wing nacelles, and we did not know, of course, exactly what to ascribe it to but immediately in the twenty foot tunnel had shown just the opposite; it had shown that you get more gain from cowling an engine in a small nacelle than from cowling an engine in front of a large fuselage, and we took two methods then of going on to the problem, one was to put strings—small strings a couple of inches long all over the surface on the actual Fokker and on all the surface of the nacelle and the bottom of the wing, and we found that just behind the maximum diameter of the nacelle where the nacelle started to grow small again there was great turbulence in the first place. The nacelle was only about two or three inches from the surface of the wing and the air apparently would not follow through that and down around the nacelle, and most of the strings in that portion actually pointed forward; in other words here we are going along with strings pointing forward, going along over 100 miles an hour. It seemed very queer but it showed the condition of the flow.

Then, in the wind tunnel tests we took, in order to get as near as possible to the full schedule figures, we took a section of the Fokker wing and we built up a nacelle just like the Fokker nacelle as near as we could do it, and with a small imitation of a motor. We got about the same drag coefficient for that nacelle as we got for the complete nacelle, so we knew that part was just about right, and we found with the cowled nacelle we had just as much drag when it was next to the wing as we did with the uncowled nacelle, and then we did two things; first we started fairing that into the wing to see whether if by proper fairing we could reduce that interference, and we found in that particular case we could reduce it very materially, and by putting on a large fairing we increased the actual front projected area appreciably and we could reduce the drag very much so that we got almost the entire gain that we had anticipated we might get neglecting interference entirely.

CHAIRMAN MEAD: That is simply from the cowling into the wing?

MR. WEICK: Simply fairing from the nacelle which was already covered with NACA cowling clear to the wing without changing the location of it, and, incidentally, that type of fairing was put on the ship and a total of increase of twelve miles an hour was finally obtained. Also, the nacelle was moved in the model but it was too much of a job to do that full scale, but on the model, the nacelle was moved to several positions above and below the wing (the only one which was moved was the nacelle with the complete NACA cowling) and it was found that by moving it far enough down you could get away from fairing it, but it had to be an appreciable distance below the wing before the interference was not noticeable.

The best results were obtained by putting the nacelle exactly in front of the wing (indicating on the blackboard) with the top of the nacelle parallel to the top of the wing.

I will just take a small space here (illustrating). Supposing that is the wing (indicating), and the normal nacelle came in about like this, and when it was in that position we got no gain whatever, because the air would not flow through here, and having large fillets all around, we got an appreciable gain, but by moving this up so that the nacelle came about in this position (indicating) we got less drag than the sum of the wing drag and the nacelle drag when each was isolated, that is, the total drag of this was less than the sum of the drag of the wing and the nacelle when they were not together, so that it showed that we could get an increase in performance by changing the location of the nacelle and outing down the projected area of the entire works if you had a smooth enough cowling. Of course, if you had an exposed engine in that position you would spoil the lift over a good portion of your wing, and the Ford people with their first tri-motors ran into that problem, they had their J-5 engines right in front of the wing, and they had such high landing speed they had to remove them. They took it at the time, it was due to the fact that the propeller was in front of the wing.

MR. McCARTHY: (Interrupting) You think if they cowled those in they would be all right?

MR.WEICK: Yes, because we did not get any decrease in lift by doing that, none whatever. We only did it at low angles of attack. I do not know what would happen at high angles of attack.

MR. HAMILTON: High angles would be interesting as far as your landing speed is concerned, and that is where Ford had trouble.

MR. WEICK: There are no tests giving reliable data in this Country. There have been a few small tests made in Germany, but they also did not give just exactly what you want.

Right at the present time, in fact the last thing I did when I left NACA was to outline a series of tests they are now working on and not in the tunnel yet, which consists of tests on a combination of a wing and a propeller in a nacelle, and the nacelle has forty different positions—approximately forty different positions with respect to the wing using the propeller as a tractor, and then there will also be a series of tests made using the propeller as a pusher that includes tests with the propeller entirely above the wing and entirely below the wing and three different positions before and aft., so that it is right as near the wing as it could get clearance, and then some positions for and aft., and in some cases like that where it is built right into the wing and other cases where the nacelle is suspended above or below the wings.

CHAIRMAN MEAD: Monty, are you going to have NACA cowling on the 200?

MR. MONTEITH: That is what we had planned originally, yes.

CHAIRMAN MEAD: Based on what we know now, the trouble with NACA cowling is heating, isn't it?

MR. MONTEITH: I am still worried about that geared engine though.

CHAIRMAN MEAD: You mean in the 200 you are going to use geared engine?

MR. WEICK: With the cowled nacelle, which is the only thing we had there as I remember it, if you got the nacelle away from the wing with a gap down close to one engine diameter you could get away from the interference, but that is more gap than you can ordinarily get in an airplane.

MR. MONTEITH: You mean the space to be once the diameter?

MR. WEICK: Supposing the diameter of that engine would be say 45 inches as it was on the J-5; if you put the top of the engine 45 inches below the wing, that is what I mean.

MR. MONTEITH: On that question of Mr. Egtvedt's here a moment ago, Doctor Zahm made some tests four years ago on propellers in front of large wings. The wings were much larger than the ones we are using however.

MR. WEICK: Yes. Well, his tests, I think, were very good and they show one thing took, they show in a case like that, or in any case where the propeller is in front of the wing, you have to put that appreciably in front of the wing or you get a very noticeable loss, and from his tests I got an idea that on an ordinary arrangement, we will say a nine-foot propeller, which was what we had on the Fokker that we were working with at the time, if we had put the nacelles up into the wing such as that and then put the engines far enough ahead so that the propeller was approximately 18 inches ahead of the leading edge of the wing instead of just, I think, about five or six inches as they were in the actual installation, there would have been an appreciable gain all the way through, and it looks to me off-hand as if that is the best condition considering high speed. Now, what that particular condition would do to that the lift at high angles or landing speed I do not know.

MR. HAMILTON: There is a Russian reproduction of the Ford tri-motor which I saw in London, where they have the engines out from the wing about better than two feet and it is not cowled. It has a Lynx engine and they claim they have tried the position of the Ford and also this position and the landing speed is no greater in their position than with the Ford, than with the low wing position. However, their top speed is considerably improved. It seems to bear out that information due to the fact they are I should say almost 30 inches ahead of the leading edge.

CHAIRMAN MEAD: Well, it strikes me that one thing we would like to know as soon as possible is the results of these tests in NACA laboratories, with the propeller turning.

MR. WEICK: It is true, but you won't get those for some time.

CHAIRMAN MEAD: I wondered if there is any chance of you or Chatfield; somebody who knows them well, to get in there ahead of the rest of the gang?

MR. WEICK: Well, there is that possibility—

MR. HAMILTON: (Interrupting) They tell me, just with that idea in mind—

MR. WEICK: (Resuming) Actually, I just did go down and got all the dope they have done on high tip speed so far. Those tests were started by me and they just finished them up after I left and I had no difficulty whatever in getting that stuff because I know the fellows down there and because also I was in on the start of the thing and they realized that I had something to do with them down there.

Now it so happens that I was in on the start of this particular thing and will have no difficulty whatever getting that information by going there, but I can't get it by getting them to write it to me.

CHAIRMAN MEAD: Then if we carry out our present scheme of getting such information to Chatfield he can broadcast it through the news letter and everyone will get it about as quickly as possible.

MR. WEICK: Only, any such information which comes out before it is published by NACA should be kept within the family because otherwise they, of course, would not let us have anything further if they discovered that we were broadcasting it. It would get them in bad.

CHAIRMAN MEAD: You would not get any more?

MR. WEICK: Yes, that is it, sure.

CHAIRMAN MEAD: Then, as far as I can see at the moment we can't help Monty very much except as to additional cooling in the engine.

Document 3-11(b), "The Reminiscences of Harold Hicks," August 1951, transcript, pp. 61-69. Henry Ford Museum and Greenfield Village Research Center, Dearborn, Mich.

Our position did not at first change when the Ford Motor Company took over Stout. At first, we ran along and did this overhaul work together with cleaning up other ends of the design on other small projects that I was doing at the time, including helping Horton on some stress analysis work.

Along about the first of September, the "Shenandoah" dirigible cracked up in Ohio. Mr. Ford wanted somebody to go there and give him a first-hand report. George Pruden, who was the Stout chief engineer and the man who is really responsible for the designing of the single engine plane, went down on the trip.

Being unfamiliar with the Ford Company way of doing things, he permitted a picture of himself to be taken which was put on the front page of the Detroit Free Press with a caption showing Pruden writing his personal report of the crash to Henry Ford. That apparently didn't suit Henry Ford very well so Pruden was fired.

Then Mr. Ford came to me and asked me to take over the engineering of the airplane. The only instructions that he made to me were very peculiar at that time. He said that I was to get in there, and run it, and to keep Stout out of the design room. He said that for the first time in his life, he had bought a lemon and he didn't want the world to know it. All the work that I did, together with any of the men, the credit would have to be given to Stout.

He was very proud to think that he was a good businessman. Apparently Mayo had led him into something, not fully realizing that Stout was a promoter and not a practical engineer.

At the time when Pruden was released from the Company, they had under construction a three engine plane which was known as the 3 AT job. That had air cooled

engines, the Wright J 4. Three of those were used, one in the nose of the fuselage, the other two in the leading edge of the wing. This was the first development. It had the engine, not in the nacelles beneath the wing, but right in the leading edge.

Pruden had designed the first trimotor, using such people as Tom Towle, John Lee, Otto Koppen and McDonnell who were in the original Engineering Department with Stout. Koppen was in the Stout Engineering Department. He was not an independent outsider brought in to design the flivver plane alone. He was a part of the original group, and I believe there were possibly ten to twelve fellows in the group. When they came over, it was reduced to possibly seven because some of the men were not suited to aeronautical design.

After I took over the Engineering Department, it had to be reorganized. I had as my assistant, Tom Towle. He was an airplane designer and a very good one too. He is now the president of the Church Company that makes baking soda. He married Church's daughter, I believe.

When I took over engineering, Mayo, of course, was the general manager. Stan Knauss had charge of the shop. Hoppin was the treasurer. Shortly after that, they hired a man by the name of Rudolph Schroeder. He took over the flying end and the airport operations.

Harry Russell, I believe, worked for Stout originally as a mechanic. Manning was hired possibly a year or two after that. He was a young fellow that was a pilot and was hired into the Company after it had been fully taken over by the Ford Motor Company.

When I took over, they were producing the 2 AT planes. The 3 AT trimotored plane was being built and assembled. This first trimotor was powered by J 4 engines. It was flown by Schroeder in possibly the late fall, maybe November of 1925. I can remember that there are photographs of that ship. Mr. Ford and Edsel were there.

I can remember when Schroeder brought it in. It landed awfully fast. It landed easily at eighty miles an hour. The reason for that was aerodynamic. We didn't know how to cure it then because NACA had not developed their ring cowls to cover the cylinders and prevent the disturbance from blanketing out the wing area. There was an inadequate wing area on the plane because the wing engines destroyed the air flow behind them; that's why it landed so fast. It was considered unsatisfactory.

The wing section was one of the NACA sections, but it did not have a very effective lift as it was convex on the bottom surface. That was the same type of wing that was used on the single engines.

In his autobiography, Stout says that his original trimotor designed with the engine in the leading edge was an advanced design over that with the pods underneath the wings. He says that the only reason he changed the design was because of the fact that the officials of the Ford Motor Company thought that the plane landed too fast. In lowering the engine and putting it in a pod beneath the wing, they were actually causing a decrease in the performance of the plane.

That is probably so, but at the same time the plane with the engines in the leading edge of the wing without any NACA cowl rings would have been entirely unsatisfactory. It landed too fast, and the top speed of the plane wasn't much either. As I remember, the top speed was only about 110 miles an hour.

So with a top speed of 110 and landing speed of 80, you didn't have any range at all. The take off speed was around 80 miles an hour too.

Schroeder, according to Aviation News, is in Chicago. This was about six months ago. He is writing his autobiography.

However, the very fact that the plant burned down, in my opinion, proved a benefit to the Ford Motor Company and to aviation in general. Plans were immediately made to start a much better factory, one which was built quite quickly. It is now the body building and garage. At least the west half of it was erected very quickly after the fire.

After the fire Mr. Ford wanted to go on. The fire had occurred so early in the Ford experience of producing airplanes that that is probably the one reason why he built it up rather than to cross it off the books entirely.

Document 3-12(a-h)

(a) Harlan D. Fowler to Rueben H. Fleet, 8 January 1929, Folder "Fowler Flap," copy in San Diego Aerospace Museum, CA.

(b) Consolidated Aircraft Corporation to Harlan D. Fowler, 21 January 1929, Folder "Fowler Flap," copy in San Diego Aerospace Museum, CA.

(c) Harlan D. Fowler, "Variable Lift," *Western Flying 10* (November 1931): 31-33.

(d) Harlan D. Fowler to William B. Mayo, 15 August 1932, copy in Accession 18, Box 96, Folder "Fowler Variable Wing," Henry Ford Museum and Greenfield Village Research Center, Dearborn, Mich.

(e) H.A. Hicks to Harlan D. Fowler, 10 September 1932, copy in Accession 18, Box 96, Folder "Fowler Variable Wing," Henry Ford Museum and Greenfield Village Research Center, Dearborn, Mich.

(f) T.P. Wright, "The Application of Slots and Flaps to Airplane Wings in America," *U.S. Air Services* (September 1933): 29-31.

(g) Robert C. Platt, "Aerodynamic Characteristics of a Wing with Fowler Flaps including Flap Loads, Downwash, and Calculated Effect on Take-off," NACA *Technical Report* 534 (Washington, 1935).

(h) Harlan D. Fowler, "Aerodynamic Characteristics of the Fowler Wing," *Aero Digest* 29 (September 1936): 46-50.

Harlan D. Fowler's design of a wing flap in 1924 is one of the least known yet classic stories of invention in the history of American aeronautics. An employee of the army's Engineering Division facility at McCook Field in Ohio, Fowler became interested in the concept of a variable-area wing late in World War I. For the next six years, he developed several unsuccessful prototypes until he came up with the idea of combining a slotted flap similar to the Junkers auxiliary wing with an increase in wing area and camber. In 1929, this notion led him to design what came to be known as the "Fowler flap," a small airfoil housed in the trailing edge of the wing. When needed, the airfoil could be extended backward until there was a slot between it and the main wing, and then hinged downward. Possessing a much heavier mechanism than a slotted or split flap, the Fowler flap made up for the weight with the increase in wing area and greater lift, which improved both takeoff and landing performance. Thus, the basic innovation was to increase lift by combining two effects: increasing the camber or curvature of a wing by deflecting the flap downward, and increasing the wing's surface area by mechanically extending it out downstream of the wing. Used together in such a way, the combination would greatly shorten takeoff runs, lower landing speeds, and increase rates of climb.

The army did not support Fowler's work, which was okay with Fowler as he had always intended his flap as a private venture. He began turning his idea into a practical mechanism in 1926. Working in his spare time and with his own funds, he constructed wings of his own design for various biplanes through the late 1920s. Flight tests revealed that landing speed decreased by two miles per hour and overall top speed increased by ten miles per hour. During this period, Fowler claimed that his design might deliver a whopping 90 percent boost in lift, which few people were prepared to believe.

No one paid attention to the "Fowler Variable Wing" until the NACA started taking a look at it in 1932. Wind tunnel tests at Langley during that year proved that his design did in fact contribute to the overall performance of an airplane. The NACA engineer most involved in testing the Fowler flap was Fred E. Weick, spearhead of the NACA's cowling and engine nacelle placement programs. Weick felt that Fowler's design merited at least some limited wind tunnel testing. In the first report on the Fowler flap published by the NACA in May 1932, Weick reported on "wind tunnel tests of the Fowler variable-area wing" (Technical Note 419). A year later, another report appeared, "Wind Tunnel Tests on model wing with Fowler flap and specially developed leading-edge slot" (Technical Note 459, May 1933), co-authored by Weick and Robert C. Platt.

The NACA's interest and its promising technical evaluations gave Fowler's invention its first true stamp of credibility—one that he really needed as he was

no longer working as an engineer but out of the aeronautics world as a salesman in California. In 1933, he traveled to Baltimore in hope of convincing Glenn L. Martin of the value of his flap. The fact that the NACA had been experimenting with the device was a decisive factor in how Martin responded. He gave Martin a job and put him to work devising flaps for several new Martin aircraft. One of these became the Martin 146 bomber of 1935. Although it was never produced, the airplane did employ Fowler flaps.

By the mid-1930s, the U.S. aeronautics community as a whole had grown extremely interested in the promise of high-lift devices. Airplanes were flying so fast and growing so large that great improvements in lifting capacity and much higher wing loadings were becoming an absolute necessity. Lockheed incorporated Fowler flaps into its new twin-engine airliner of 1937, the Lockheed 14. It was the first production-line airplane to use Fowler flaps. (A few German aircraft with Fowler-type flaps had appeared earlier.) After that, a growing number of planes started to use slotted flaps of various kinds. Fowler became one of the most recognized names in all aeronautical engineering. Even today, his name is still associated with a generic brand of slotted flaps used on many aircraft.

In the string of documents below, one returns to the early 1930s to see how the American aeronautics community first became seriously interested in the Fowler slotted flap.

Document 3-12(a), Harlan D. Fowler to Rueben H. Fleet, 8 January 1929, Folder "Fowler Flap," copy in San Diego Aerospace Museum, CA.

FOWLER AIRPLANE WINGS, INC.
Manufacturer of Variable Area Wings
NEW BRUNSWICK, N. J.
July 8, 1929.
Mr. R. H. Fleet, President,
Fleet Aircraft, Inc.
2050 Elmwood Ave.,
Buffalo, N. Y.

Dear Sir:

The development of the Fowler Variable Area Wing is approaching the stage of practical utility after being successfully used on several types of planes.

A standard type of construction and wing area is now being prepared with the purpose of applying it to the larger majority of types of airplanes now in use giving them very substantial improvements in all around performance, that is, lower landing speed, higher top speed and good climb.

We are approaching you as a manufacturer of high grade airplanes with a proposal involving the use of our wing in place of your standard product for a cost within the range of your own factory cost wings.

If this proposal meets with your approval and you will assure us of your intention to contract for a limited number of wings, then we will install our wing on your plane and obtain complete comparative performance to be used by your company for sales purposes, and cooperate with you in giving demonstrations.

This arrangement will give your products a distinct step in advance of the conventional plane and consequently greatly influence your sales prospects.

We would appreciate learning how this procedure appeals to you and we will be pleased to submit such information as you may desire.

Respectfully yours,

President, Fowler Airplane Wings, Inc.

FOWLER VARIABLE AREA WING

The demand of aircraft operators for improved performance and load carrying capacity to meet the requirements of the public is bringing about a condition which will compel consideration of advanced wing design. Primarily, an aircraft must have sufficient wing lift to provide safe landings and take-offs. This restriction has a direct influence on high speed and load capacity and is an economic loss.

The Fowler Variable Area Wing provides for this condition. The powerful combination of the advantages of change in camber, area, angle of incidence and aspect ratio, simultaneously, has resulted in a wing design of tremendous value to aircraft operators.

As the result of further research and development of the Fowler Wing substantial improvements in performance are obtained. The following comparative data relative to the original PA-3, OXX-6 100 H.P. is interesting:

	Original	Fowler	Wing
Performance	PA-3	No. 1	No. 2
Low speed, normal, M.P. H.	46.2	58.2	57.0
Low speed extended M. P. H.	--	44.5	41.0
High speed, M. P. H.	91.0	101.0	104.0
Cruising	77.0	84.0	87.0
Rare of climb, normal, ft. / min.	515	430	570
Total weight of plane	1936	1990	2000
Wing area, normal, sq. ft.	338	136	145
Wing area, extended, sq. ft.	--	166	186
Wt./ sq. ft. normal	5.72	14.65	13.80
Wt./ sq. ft. extended	-	12.00	10.75
Speed range	1.97	2.16	2.42

The above performances are based on the best propeller design suitable for that type of plane. Performances for the PA-3 and Fouler Wing No. 1 are based on actual flight tests over a one mile course and are the average of several runs. Knowing the high speed of Fowler Wing No. l the parasite resistance was obtained after subtracting the wing resistance. With this parasite resistance still used and with the new Fowler Wing No. 2 substituted the above performance was obtained.

Reference to the above performance reveals a number of possible applications of the Fowler Wing No. 2 as applied to this particular low powered type of plane:

(a) As between the biplane the low speed is reduced almost 5 miles per hour. Between the usual monoplane (normal area) it is 16 miles per hour less in low speed when the extension area is used. Note the difference in wing area.

(b) The high speed of the normal. wing is about 13 miles per hour faster than for the biplane.

(c) The load carrying capacity of the extended wing per square foot area is over 100% greater than for the biplane, and with less landing speed.

(d) Speed range for the Fowler Wing is increased almost 23 per cent over the biplane.

(e) Rate of climb for the Fowler Wing is of a very high order considering its other remarkable features.

(f) The Fowler Wing is only 25 pounds heavier than the biplane with a strength factor 54 per cent greater than the original PA-3.

The evidence presented by these tests indicates possibilities such as:

(a) Pay load increased 100% for equal performances and power.

(b) Same pay load and performance for about once-third less power.

(c) A reduction in wing area 50%. For large planes this is of extreme importance.

Letter Patents have been granted for the design of this device.

Fowler Wing No. 2 is of such area that it can be adopted to 75 percent of the commercial types of planes now in use, giving them an all around improved performance. This will be possible on planes using power up to 225 H. P. and a total plane weight of 3000 lbs. Fowler Wing No. 2 is to be put in production and made available to the industry.

The Fowler Wing is also available to solve any special problems which it may be desired to accomplish.

Fowler Airplane Wings, Inc.
New Brunswick, New Jersey.

Document 3-12(b), Consolidated Aircraft Corporation to Harlan D. Fowler, 21 January 1929, Folder "Fowler Flap," copy in San Diego Aerospace Museum, CA.

January 21, 1929

Mr. Harland D. Fowler
The Miller Corporation
New Brunswick Airport
New Brunswick, N.J.

Dear Sir:

Could you send us information on the typical detail design of your variable area wing? Also, tell us what the span of the PA-3 biplane which you used was, both as a biplane and as a monoplane with normal and standard wings.

Very truly yours,

CONSOLIDATED AIRCRAFT CORPORATION

Asst. to General Manager

Document 3-12(c), Harlan D. Fowler, "Variable Lift," **Western Flying** *10 (November 1931): 31-33.*

November, 1931

VARIABLE LIFT
BY: HARLAN D. FOWLER

In spite of the achievements of the Guggenheim Safe Aircraft Competition, little progress seems to have been made toward the solution of the problem of increasing the lift of wings without sacrificing top speed. The following article is presented with the hope that it will stimulate more thought on the subject. -The Editors.

Time consumed in taking off and landing is a matter of a few minutes, whereas straightaway flying takes hours. Simply because sufficient lift must be available for this landing and take-off, we afflict ourselves with the use of oversized wings. When once in the air, the smallest of wing, consistent with controllability, can be used safely.

Why, then, do we continue to be so far removed from the most important and far reaching development of variable lift wings? As far back as 1910, the subject of utilizing variable lift wings was frequently discussed by engineers. The methods suggested were:

(a) variable camber,
(b) variable area,
(c) variable angle of attack, and later
(d) slotted wings.

Many laboratory experiments have been made on airfoils with the camber adjustable from a streamline section to that of a heavily convexed section, with promises of a wide variation in aerodynamic characteristics. Variable area has presented a mechanical problem of the first order. The variable angle of attack offers the least, if any, improvement, although several airplanes have been tried out using this idea. Perhaps the most successful devices have been the various forms of slotted wings. All four methods have been considered extensively in published articles. However, it is unfortunately true that the benefits obtained from each type alone have not justified its continued development.

THE FOWLER WING PRINCIPLE

It was long recognized by the writer that if the best features of each one could be incorporated into a simultaneous and coordinated alteration of the wing, the fullest advantage would be utilized. This was easier "thought of" than practically solved. Fundamentally and foremost, the basic structure of the wing must not be interfered with.

Hence, the conception of the Fowler Variable Area Wing, which incorporates the following points: (1) A structurally sound basic wing; (2) An increase in area; (3) Variable angle of attack; (4) A variable camber, and (5) The slotted wing.

The lift of the normal or closed wing is increased about 100 per cent by the combined use of these relations. Each feature contributes to the increased lift in the following proportions: Variable camber, 43 per cent; variable area, 28 per cent; recessed camber, 7 per cent; and slots, 22 per cent. And it is all accomplished by the one simple expedient of extending the auxiliary area wing downwardly and rearwardly, which rapidly brings about the simultaneous characteristics of each desirable relationship.

WIND TUNNEL TESTS

Figures 1 and 2 give the characteristics for the normal and extended area. The tests were conducted at the New York University. The maximum Ky normal is .0036 and extended .00556. The normal area is 63 sq. in. and extended 80 sq. in. Viewed on the assumption that the normal wing characteristics are influenced by these alterations by virtue of being self-contained, it will have the equivalent maximum Ky of

$$.00556 \times 80/63 = .00705$$

or

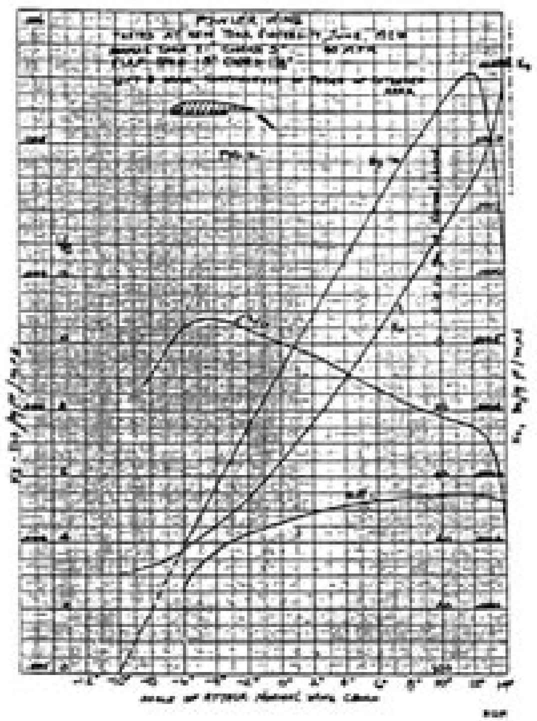
$$.00705/.0036 - 1 = 0.96 \text{ increase}$$

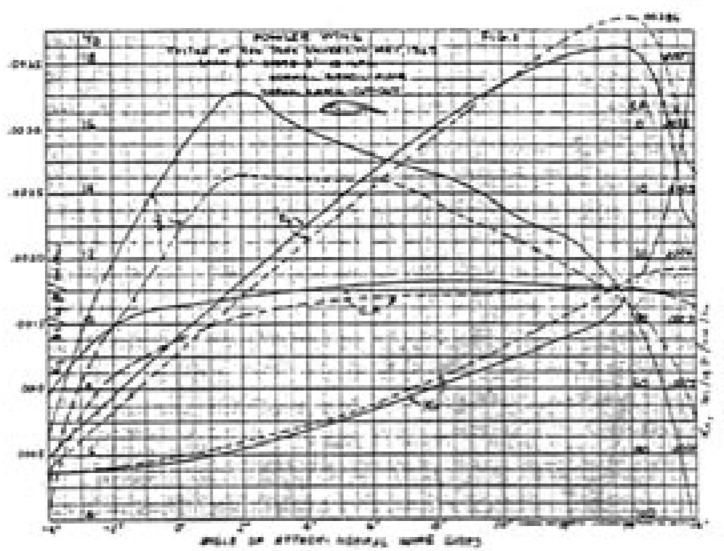
Full flight speed trials at near stall gave a maximum Ky of .0073 as referred to the normal area—the highest lift obtained from any airfoil.

This increase in lift was obtained without impairment of aileron effectiveness, only 70 per cent of the wing span being utilized for the auxiliary wing.

FIG. 1 (below) shows results of wind tunnel test of normal wing with and without recess.

FIG. 2 (right) shows test with wing extended. Max. Ky of .00556 occurs at only 12 deg. angle of attack





FULL FLIGHT TESTS

Performance tests were made with a Pitcairn PA-3 which was originally a biplane of 338 sq. ft. An OXX-6 engine of 100 h.p. and the same wood propeller was used throughout the trials without alterations or overhauling. The following data were obtained:

	Original PA-3	Fowler No. 1	Wing No. 2
Low speed, normal, M. P. H.	46.2	58.2	57.0
Low speed, extended, M. P. H.	---	44.5	41.0
High speed, M. P. H.	91.0	101.0	104.0
Cruising speed, M. P. H.	77.0	84.0	87.0
Rate of climb, ft./min.	515	430	570
Take-off time, seconds	10	11	10
Landing time, seconds	9	11	9
Total weight of plane, lbs.	1936	1990	2000
Wing area, normal, sq. ft.	338	136	143
Wing area, extended, sq. ft.	---	166	181
Wt. per sq. ft., normal	5.72	14.65	13.8
Wt. per sq. ft., extended	---	12.00	10.75
Speed range	1.97	2.16	2 42
Design load factor of wing	5.50	8.00	10.00
Weight of wings, complete, lbs.	377	395	409

Performances for the PA-3 and Fowler Wing No. 1 are based on flight tests over a one-mile course and are the averages of several runs.

Wing No. 2 is an entire new design with a special normal airfoil and aspect ratio of 9. It is designed for a gross-weight of 2850 pounds with a load factor of 7, which for-the 2000-pound plane is equivalent to a load factor of 10.

It will be noted that in spite of using an extended area of less than half that of the biplane, the stall speed was nearly 2 m.p.h. lower.

The stall speed for the normal wing monoplane is 58.2 m.p.h. and represents the typical monoplane. By extending the area, this speed was reduced to 44.5 m.p.h. Thus, the average monoplane can have its stall speed reduced not less than 14 m.p.h.

The high speed was increased from 91 m.p.h. for the biplane to 101 m.p.h. for the normal area Wing No. 1. For the original biplane to have attained 101 m.p.h., at least 136 horsepower would be necessary, resulting in a heavier engine and increased fuel capacity, or an increase in weight of about 185 pounds, using a water-cooled engine. This in turn would raise the stall speed from 46.2 to 48.7 m.p.h. The most important fact is this—the additional cost of a new engine at about $2,000 far exceeds the cost of a set of variable wings.

WEIGHT COMPARISON

Wing No. 2 has been designed according to the strength requirements of the Department of Commerce and approved for installation on planes with gross weight up to 2850 pounds and up to 225 h.p. The actual weight of the wing is itemized as follows:

Main wing, with fittings	242.501bs.
Ailerons	17.001bs.
Five gallons gas tank	8.50 lbs.
Main wing, complete	268.
Extension surface	36.00
Extension surface rails, etc.	24.00
Extension surface controls	6.00
Extension assembly, complete	66.
Fowler Wing No. 2, complete	334.

Struts and wires for installation to plane weigh about 75 pounds, giving a total weight of 409 pounds.

This wing can be designed for a closed cabin without special difficulties.

For comparison with the conventional wings, the following typical data are given:

	Rated H. P.	Gross Weight	Area sq. ft.	Weight Wings	Stall Speed	Load Factor
Fowler Wing	225	2850	181	409	53.0	7.00
“A” biplane	180	2877	351	425	49.0	7.00
“B” biplane	165	2702	289	450	54.0	7.00

Note—Even though Wing No. 2 is lighter than the conventional wings, no attempt was made to resort to expensive light-weight detail construction. With such an excess of lift available, this is unnecessary. However, with design refinement, at least 10 per cent further saving in weight is possible. A and B are well-known airplanes.

APPLICATION TO CANTILEVER WINGS

As shown before, for the same stall speed, the area may be reduced one-half by using the variable area wing. Since the extension feature can be easily incorporated in a cantilever wing, the span can be reduced 25 per cent for the same aspect ratio. Since the gross weight is about the same, the cantilever bending moment is correspondingly reduced. A stiffer and cheaper structure would result from this reduction in size.

From the standpoint of strength, the determination of structural sizes is simple

and straightforward, being governed entirely by conventional design practice. No unusual or tricky supporting members nor articular parts are used in the wing.

For extremely high speed purposes, it is necessary to go into high landing speeds. The Schneider Cup Race planes land at speeds varying from 100 to 125 m.p.h.

Let us assume that with a high speed airfoil, the wing loading is 30 pounds per sq. ft. Substituting the variable area wing, the extended wing loading would be 60 pounds per sq. ft. at 100 m.p.h. stall speed and normal area is 76 pounds per sq. ft. at 145 m.p.h. stall speed. This is a reduction of 45 m.p.h. It is acknowledged that the wing loadings are very high, but the wing could be of a cantilever type and very small in size. The high speed would be greatly improved.

When landing with the wing extended, the glide is steep and the run on the ground short.

WING REDUCES NEED FOR INCREASED POWER

If increased high speed is desired, it is usually the practice to put in a higher power engine. This will not be necessary if the Fowler wing is used.

Let us consider a pure cantilever monoplane with a 420-h.p. engine, wing area 265 sq. ft. and a gross weight of 4500 pounds. The pay load is 600 pounds without including 150 gallons of fuel. Stall speed is 66 m.p.h.

Installation of a 525-horsepower engine would only increase the high speed of this plane from 200 to 215 m.p.h. It is an unfortunate fact that in changing to higher power, the expected increase in speed is rarely obtained. The average loss is about one-third of the theoretical increase. This is largely attributed to the increase in cylinder number and diameter, overall engine diameter, and loss of propulsive efficiency. Therefore, it is very probable that the high speed of 215 m.p.h. for the 525-h.p. engine may be more like 210 m.p.h. or even less, if available data are trustworthy.

The added cost of the larger engine is about $600. The larger gas tank to receive 30 gallons more fuel, propeller, etc., would add at least $100 more, or a total of $700.

A variable wing would cost about 15 per cent or $375 less than the original wing. The total net initial saving would be $1,075. The operating savings on gas consumption, depreciation of engine, and maintenance would also be considerable.

CLIMB AND CEILING

Numerous tests with the extension in various locations between all-in and all-out shore a very definite gain in the rate-of-climb when set about halfway out. This is, then, the best setting for take-off and climb.

With the fully extended wing, the rate of climb is lower, as is to be expected, in view of the lower L/D. Incidentally, for the same reason, the high speed was found to be about 79 m.p.h. This condition is in reality a decided safety measure in that it would be impossible to maneuver sharply. It thus prevents undue strain on the extended surface and supports.

Western Flying

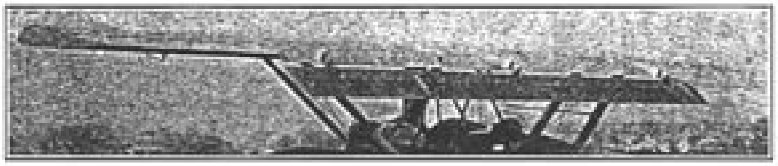


FIG. 3 —Installation of Fowler wing with extension full out. Note slot

The planes on which the Fowler wing was used had fixed stabilizers, and these were not readjusted at any time.

The extension can be operated by the pilot while flying and set at any position desired. The position of the control stick is changed forward when extending the wing, but little change of balance is noted for the two conditions of all-in or all-out.

The plane had adequate control at and beyond stalled position.

DESIGN FEATURES

The normal wing, which is of two halves joined at the center, is of conventional construction, although employing materials in a different manner. The spars are of solid spruce. The ribs are of 3/8 and 7/16-inch spruce. The nose is of solid balsa wood. (Fig. 4.) No internal drag bracing is used because the covering is of plywood which is glued and nailed directly to the spars and ribs.

The auxiliary wing has a single spar to which are secured the solid ribs and balsa wood nose piece. The whole is plywood-covered. This small wing fits snugly under the trailing portion of the main wing. (Fig.4.)

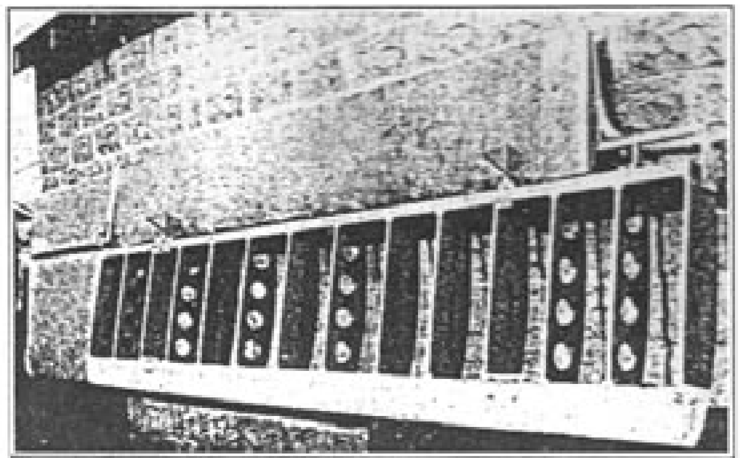


FIG. 4—Showing construction of the Fowler wing in the closed position

Figure 5 is a drawing of the complete combination, showing the supporting rail, trolley and relation of the large and small airfoils. The four supporting rails, which are 3/16 inch thick by 3 1/8 inches deep, are of steel, but may be of duralumin.

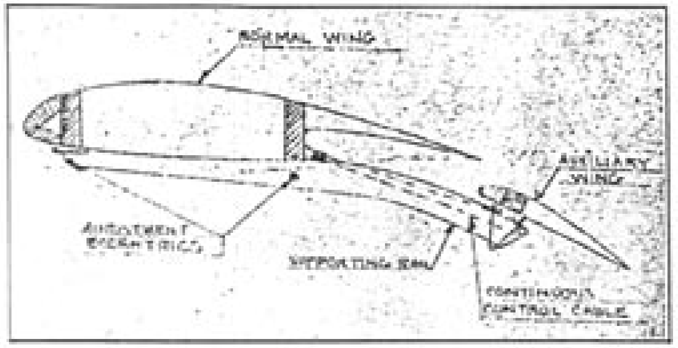


FIG. 5—Cross-section of Fowler wing. Note recess under trailing surface to receive extension

These rails are attachable in up or down movements by eccentrics located at the main fitting attachments so as to provide clearance between the auxiliary wing and the under surface of the main wing when it is closed.

Operation of the extension is by means of a continuous cable wrapping around a drum. To this drum is secured the control shaft and handle reaching down to the pilot who can operate it at his convenience. All control cables, including those for the ailerons, are led along the open face of the rear spar. Nothing is concealed.

COMMERCIAL APPLICATIONS

Due to the high lift of the Fowler wing, it can be applied as follows: (1) Light planes, stall speed 25 m.p.h.; (2) cargo planes, actual payload, 7 pounds per h.p.; (3) optional equipment, substitute for conventional wings, and (4) reduced initial cost of planes and better performance.

Document 3-12(d), Harlan D. Fowler to William B. Mayo, 15 August 1932, copy in Accession 18, Box 96, Folder "Fowler Variable Wing," Henry Ford Museum and Greenfield Village Research Center, Dearborn, Mich.

615 Fifteenth Avenue,
San Francisco, Cal.
July 19, 1932

Mr. Wm. B. Mayo,
Ford Motor Company,
Airplane Division,
Dearborn, Mich.

Dear Mr. Mayo:

With reference to yours of June 28th, I am taking the liberty of sending a copy of the N.A.C.A. report No. 419 (on a loan) so that a study can be made of the Fowler Variable Area Wing.

We have found Position No. 6 to be an all around ideal arrangement and to which the enclosed blueprint of the characteristic curves applies.

It may be to your interest to learn that several other large companies are considering the use of the Fowler Wing. If your research is convincing I shall be pleased to consider a mutual arrangement.

Very truly yours,
Fowler Airplane Wings, Inc.

Document 3-12(e), H.A. Hicks to Harlan D. Fowler, 10 September 1932, copy in Accession 18, Box 96, Folder "Fowler Variable Wing," Henry Ford Museum and Greenfield Village Research Center, Dearborn, Mich.

Sept. 10, 1932.
Mr. Harlan D. Fowler,
120 Webster Street,
San Francisco,
Cal.

Dear Sir:

In reply to your letter of August 15th concerning your variable area wing, we inform you that this company would not be interested in purchasing manufacturing rights at this time.

Yours very truly,

FORD MOTOR COMPANY
(Airplane Division)

H.A. Hicks,
Aircraft Engineering.

Document 3-12(f), T.P. Wright, "The Application of Slots and Flaps to Airplane Wings in America," U.S. Air Services *(September 1933): 29-31.*

September, 1933

The Application of Slots and Flaps to Airplane Wings in America
T. P. WRIGHT
Vice President and Director of Engineering
Curtiss Aeroplane and Motor Company, Inc.

It is the object of this article, within the space limitations set, to present in general terms the objective sought in incorporating slots and flaps on airplane wings and to indicate briefly the application which has been made in this country.

AIRPLANE CHARACTERISTICS

For the purpose of this article it appears desirable to segregate the qualities of the airplane which are affected by these devices into two main groups. These are qualities affecting safety and qualities affecting performance.

Under the heading SAFETY the functions which are affected by changes in wing characteristics are landing speed, susceptibility to spinning, and controllability, particularly beyond the stall. Other things being equal, it appears obvious that the airplane with the lower landing speed, the airplane having freedom from incipient spinning tendencies, and the airplane which maintains lateral control beyond stalling speed will be the safer craft.

Items of performance which are affected by changes in wing characteristics are high speed, rate of climb and ceiling, climbing angle, and angle of descent. Higher and higher speeds are desired each year as aviation progresses so that the advantages of any device tending to increase speed are obvious. Rate of climb and ceiling are only of relative importance, the degree of importance depending, of course, upon the particular type of airplane under consideration. The last two functions, angle of climb and angle of descent, are becoming recognized as being items of major importance more and more as the external cleanness of airplanes increases.

DESCRIPTION OF THE SLOT AND FLAP

Let us now briefly define the slot and flap. The slotted wing is one which has an auxiliary airfoil at its leading edge, either fixed or movable, so that in either case, in its extended position, a slot is formed which induces a smooth flow over the wing at higher angles of attack than are obtainable with the omission of the device. It is important to note that the slotted wing retains the same slope of lift curve as maintains with the unslotted wing. The function of the slot is to increase the angle at which burbling occurs. Therefore, if other airplane characteristics are arranged to conform with the use of a higher lift angle, then the maximum lift of the airplane is substantially increased by the use of the slot.

The flap is a device which has for its essential object the increasing of the camber of the basic wing section to which it is applied. In its simplest form the flap consists of a hinged portion of the trailing edge of the wing, which, when deflected downward, obviously increases the wing's camber. One variation of this simplest form of flap is accomplished by changing the form of the leading edge of the flap, to create a slot at that point, which, as in the case of the slot at the leading edge of the main airfoil above described, gives the beneficial effect of smoothing out the flow over the flap when deflected.

Another form of flap is described as the split trailing edge type whereby only the lower portion of the trailing edge is deflected downward in operation, rather than the whole trailing edge, as in the case of the simple-hinged flap. In a further variation of this type, this lower portion is moved aft at the same time that it is deflected downward, thus to a certain extent increasing the wing area in addition to increasing its camber. A still further variation in flap design is incorporated in the Fowler type in which the lower split flap section is made up into the form of an airfoil and is moved aft through its chord length in addition to its downward angular deflection and is so shaped that when in this final operating position a slot is formed at its leading edge.

The increase in maximum lift due to the type of flaps above described varies but in all cases is substantial. An extensive series of tests has been conducted by the National Advisory Committee for Aeronautics, and the results tabulated, to show the effect on airfoil characteristics of all of these types of flap and of the flap in combination with leading edge slots. It is shown in these tests that, based on basic wing area, lift increases of more than 100% are readily obtainable with accompanying speed range increases of more than 75%. The possibilities of such tremendous improvements in airfoil characteristics are obvious and when airplanes designed with them have other characteristics properly correlated, it is believed that without doubt they will find a substantial application in the majority of types of airplanes.

IMPROVEMENT IN AIRPLANE CHARACTERISTICS OBTAINABLE BY USE OF SLOTS AND FLAPS

Let us now note the possibilities which these devices hold for improving our fundamental airplane qualities, namely, safety and performance. Although the slot can contribute slightly to the lowering of the landing speeds, its chief utility lies in its effect in preventing spins and in permitting lateral control at high angles. It has one other possibility when interconnected with the flap, namely, the supplying of the necessary force for operating the flap, thus relieving the pilot of this operation.

A properly designed auxiliary airfoil when in the unslotted position will increase the wing drag inappreciably and therefore not affect the high speed of the airplane adversely. The high speed of the airplane can, however, be increased for a given landing speed by the use of the flap with its increased lift coefficient and resulting decrease in wing area, although the degree to which this application can be used is contingent upon the allowable resultant characteristics which are injured by the application, namely, rate of climb, ceiling, and angle of descent (perhaps better defined as sinking speed). However, increase in sinking speed or angle of descent to a limited extent is a decided advantage and one which is becoming more and more essential in preventing floating during landing in modern airplanes having ever-increasing fineness. The improved angle of climb obtainable by the use of flaps is also a quality of importance in airplanes of modern design.

In summary, therefore, we find that, with the slot, improved safety is the chief contribution with some possibility of increasing lift and therefore speed range, provided the airplane is otherwise designed to permit of the realization of the high angle of attack necessary. With the flap a very definite increase in speed range is obtainable together with improved takeoff and landing characteristics.

We thus see that it is possible to improve certain performance characteristics of the airplane by the use of slots and flaps. If the basic considerations determining the design of a particular type coincide with the characteristics which are improved by these devices, it then appears that their use is justified. There are certain other types of airplanes wherein the basic characteristics governing the design are injured by the installation of slots and flaps, thereby making their adoption of no value or of questionable value.

TYPES OF AIRPLANES

There are two major classifications into which airplanes may be placed, namely, MIILITARY and COMMERCIAL. Within each group there are subdivisions such as training, fighting, attack, observation, and load carriers, including bombers and transports, in the former; and training, utility, private owner and transport, including mail and passenger, in the latter. Each type demands a special combination of characteristics to permit of the best fulfillment of its functions. It will probably be agreed that the function of safety will be of less importance in military airplanes than commercial, and within the list of commercial types will be of less importance in the mail plane and utility plane than in the case of the private owner plane and passenger transport. This statement therefore in itself simplifies the study necessary in deciding upon the use of slots alone on a given design. The decision on the application of flaps, however, is more difficult, as there are few classes of plane in either broad subdivision which are not susceptible of some improvement by the use of flaps, or flaps in combination with slots.

SPECIFIC APPLICATIONS

In the case of military planes it appears that the attack type, requiring high speed with a lesser degree of climb and ceiling than other types, represents one possible application. This applies particularly to Army planes. An additional problem is involved in the case of the Navy where low landing speed for carrier operation is of far greater importance than in the case of the Army. Therefore in the Navy it appears logical that a wider application may be found desirable.

It is believed that in the Commercial field an even wider application is probable both because of the increased importance of safety and because of the lesser importance, in most cases at least, of the characteristics which are admittedly injured by the use of flaps or flaps in conjunction with slots.

DEVELOPMENT IN THIS COUNTRY

With the above discussion, covering a description of the devices we are considering and of the airplane characteristics which they alter, thereby indicating their possible usefulness in the various types of airplane being developed, before us, let us now see what application has been made in this country. The basic scientific development of the slotted wing was initiated in England and Germany. Apparently the basic idea of improving airflow by means of the Venturi action of a slot was coincidentally and independently worked out by Messrs. Lachmann and Handley Page. Credit for the major engineering development with reference to specific and practical devices is due to Handley Page in England. Important note of this development was first taken in this country in 1927 when the Navy Bureau of Aeronautics sent representatives to England to study the progress made and later negotiated certain license contracts with Handley Page. Shortly thereafter several applications of the slot were made on Naval Aircraft, including Curtiss F7C-1 single seater fighter, a Consolidated training plane, and a Vought observation plane. This application consisted of the installation of slots at the outer portion of the wing, forward of the aileron, only.

The first commercial application seen in this country was on the *Moth* airplane, constructed and sold here in considerable numbers under British license in 1928 and 1929. In this case also the slot at the wing tip only was used.

The first combination of slots along the whole span of the wing, with flaps also on the whole span (floating wing tip ailerons being used in this case for lateral control) appeared on the Curtiss *Tanager*, winner of the Guggenheim Safe Aircraft Competition in 1930. It should be noted that the plane most nearly approximating the *Tanager* performance in the competition also employed slots and hinged flaps, although in this case conventional ailerons were used. This was the Handley Page *Gugnunc*. It is believed significant that the winner and runner-up in this competition were both equipped with slots and flaps, especially as it is considered that the tests set up in the competition correctly represented airplane characteristics essential to safety. Subsequent developed improvements in general airplane design could equally well be applied to the *Tanager*. The *Tanager* development was the result of intensive technical research in the Garden City laboratory of the Curtiss Aeroplane and Motor Company during the period 1927 to 1929. The airplane was delivered to the Guggenheim Committee for tests in October, 1929. It is believed that this theoretical wind tunnel and full flight research was the most extensive carried out to that date in this country. The data determined from this study have been substantially augmented by the results of the very fine program of testing subsequently undertaken and accomplished by the National Advisory Committee for Aeronautics.

Although some work was carried out in 1930 on the application of slots and flaps to commercial, private owner class airplanes, the development was curtailed and then abandoned because of the need for economy at the start of the depression. Undoubtedly during the last three years a great number of successful applications would have been made but for the above economic conditions.

The next application appearing in this country, and the first one applying to a military airplane, was the use of both slots and flaps on the Curtiss XA-8 developed as an attack airplane for the Army Air Corps. The ship is the low, thin-wing, externally braced monoplane type, carrying a useful load about 50% greater than maintains for other classifications of two-seater military plane. The requirement of high sea level speed is of major importance in this class. This airplane flew in the summer of 1931, exceeding requirements substantially. The excelling performance of this plane represented the first large step in high speed increase of Army Air Corps planes since the War as it roughly stepped up speeds from the 150 m.p.h. to 200 m.p.h. bracket. This ship, at the time of its appearance, led the Military Field, when judging excellence on the criterion of load carrying times speed per given horsepower. Subsequently 13 similar ships were constructed and service tested, followed by procurement in a production order of 46 now underway.

Other applications to military developments, both in the Army and Navy, have been made and are being made, the results of which can only be described and their value judged after service testing is completed and official release of information is available.

Commercially, where from basic considerations application should be the most general, slots and flaps have been decidedly neglected at least until very recently, where several applications of the flap have appeared. This has undoubtedly been due to the economic conditions of the country and to the absence of properly charted information on characteristics of airfoils with slots and flaps, now fortunately available in published National Advisory Committee reports.

At the recent conference at the Langley Field Memorial Laboratory of the National Advisory Committee for Aeronautics considerable stress was laid on the possibilities in the use of various types of flap and of these types in combination with slots. The interest in this country, however, in slots continues meager in spite of the quite general adoption of these devices in various forms on a number of planes in several European countries. One other consideration which has undoubtedly retarded general interest in these devices is the fear of additional complexity and weight increase due to their use. The importance of these latter features is fully realized, but nevertheless it is believed that if, as is maintained, the aerodynamic improvements obtainable by their adoption are substantial, and assuming intelligent application in each specific case, the obstacles of complication and weight will be surmounted and a wider use of slots and flaps made in the future.

Document 3-12(g), Robert C. Platt, "Aerodynamic Characteristics of a Wing with Fowler Flaps including Flap Loads, Downwash, and Calculated Effect on Take-off," NACA **Technical Report** *534 (Washington, 1935).*

REPORT No. 534

AERODYNAMIC CHARACTERISTICS OF A WING WITH FOWLER FLAPS INCLUDING FLAP LOADS, DOWNWASH, AND CALCULATED EFFECT ON TAKE-OFF

By ROBERT C. PLATT

SUMMARY

This report presents the results of an investigation in the N.A.C.A. 7- by 10-foot wind tunnel of a wing in combination with each of three sizes of Fowler flap. The purpose of the investigation was to determine the aerodynamic characteristics as affected by flap chord and position, the air loads on the flaps, and the effect of the flaps on the downwash. The flap position for maximum lift; polars for arrangements considered favorable for take-off; and complete lift, drag, and pitching-moment characteristics for selected optimum arrangements were determined. A Clark Y wing model was tested with 20 percent *c*, 30 percent *c*, and 40 percent *c* Fowler flaps of Clark Y section. Certain additional data from earlier tests on a similar model equipped with the 40 percent *c* Clark Y flap are included for comparison. Results of calculations made to find the effect of the Fowler flap on take-off, based on data from these tests, are included in an appendix.

AIRFOIL ORDINATES

CLARK Y

(All values in percent airfoil chord)

Station	Ordinate upper	Ordinate lower	Station	Ordinate upper	Ordinate lower
0	3.50	3.50	40	11.40	0
1.25	5.45	1.93	50	10.52	0
2.50	6.50	1.47	60	9.15	0
5	7.90	.93	70	7.35	0
7.50	8.85	.63	80	5.22	0
10	9.60	.42	90	2.80	0
15	10.68	.15	95	1.49	0
20	11.36	.03	100	.12	0
30	11.70	0			

Leading-edge radius=1.50.

The maximum lift coefficient obtainable, based on original wing area, had a nearly linear increase with flap chord up to 40 percent, but the maximum lift force per unit of total area increased very little beyond the value obtained with the 30 percent *c* flap. The maximum load on the flap occurred very nearly at the maximum lift of the wing-flap combination and was nearly 1½ times the load that would result from uniform distribution of the total load over the total area. In general, the flap appeared to carry a large proportion of the additional lift caused by its presence and to have its center of pressure much nearer the leading edge than it would normally be in free air. The addition of the Fowler flap to a wing appeared to have no appre-

ciable effect on the relation between lift coefficient and angle of downwash. The calculations in the appendix show that, by proper use of the Fowler flap, the take-off of an airplane having wing and power loadings in the range normally encountered in transport airplanes should be considerably improved.

INTRODUCTION

During the past few years the use of flaps on high-performance airplanes as a device for reducing space required in landing has become common. Thus far split flaps have been most generally used, probably because of their simplicity of application and their superiority in giving steep gliding approaches and short landing runs: the features of flaps with which designers have been most concerned. In order to retain satisfactory operation from normal flying fields with fast airplanes, however, the use of high-lift devices that improve take-off as well as landing is desirable. Since drag is unfavorable to take-off, the comparatively large drag of split flaps places them among the least promising of high-lift devices in this respect. The Fowler flap appears to offer a better compromise between these conflicting requirements. For equal sizes it will give higher maximum lift with no higher profile drag than most other flap arrangements and its comparatively low drag at high lifts is favorable to take-off and steep climb. This effect would normally entail some sacrifice of steep gliding ability.

Although sufficient data to form some estimate of the performance to be expected from an airplane equipped with Fowler flaps are available (references 1 and 2), they are inadequate for normal design purposes. The purpose of the tests reported herein is to provide data to form a rational basis for the design of airplanes equipped with Fowler flaps. It appears that for the present the purpose will be attained by making available the following information: effect of flap size on aerodynamic characteristics attainable, aerodynamic loads applied to the flap in various conditions, and effect of the flap on downwash. In addition, a convenient method of estimating the effect of high-lift devices on airplane take-off should prove of assistance in cases where this performance feature merits special attention.

The tests were made in the 7- by 10-foot wind tunnel of the N.A.C.A. (reference 3) at Langley Field, Va., during the summer and fall of 1934.

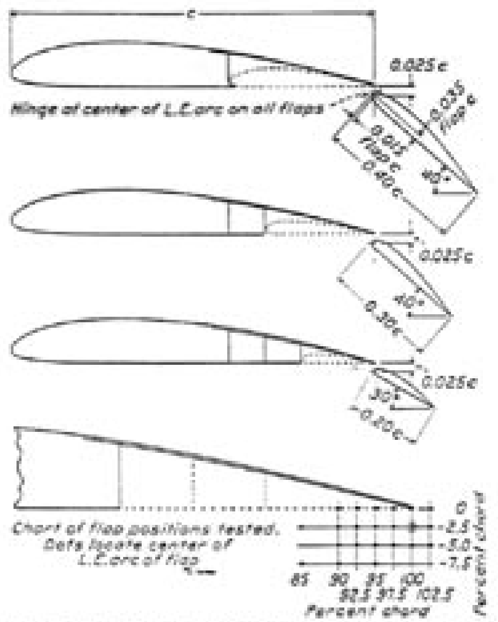


FIGURE 1.—Wing with various Fowler flaps. Flaps shown in maximum-lift conditions.

MODEL

The basic wing was built of laminated mahogany to the Clark Y profile (table I) and had a span of 60 inches and a chord of 10 inches. The trailing edge was cut away and the upper surface replaced by a thin curved metal plate. The lower surface was left open at the rear to serve as a retracting well for the flaps. Blocks were inserted to maintain the correct size of well for each size of flap tested. Figure 1 shows the profile of the wing with the various flaps in place.

The two smaller flaps were made of duralumin to the Clark Y profile and had spans of 60 inches and chords of 2 and 3 inches. The largest flap, which is the one described in reference 2, was made of mahogany and had a 4-inch chord. The flaps were supported on the wing by fittings attached to ribs located in the retracting well. Several sets of attachment holes in the ribs, combined with several sets of fittings, gave the range of flap positions shown in figure 1. The flaps were supported on the fittings by hinges located at the center of the leading-edge arc of the flaps, angular adjustment being obtained by set screws attached to the flap moving in quadrantal slots in the fittings. In general, where the term "flap position" is used, the position of the flap hinge axis is indicated, irrespective of angle, and flap angle is measured between the chord lines of the wing and the flap.

TESTS

Five groups of tests were made in obtaining the data presented in this report. These five groups dealt with maximum lift, optimum flap arrangement for take-off, standard force tests of optimum arrangements, flap loads, and downwash behind the wing with various flap arrangements.

Maximum lift.—The maximum lift coefficients obtainable with the 0.20 *c* and 0.30 *c* flaps at various positions shown in figure 1 were found by tests in which the flap angle was increased from 20° in 10° steps until the peak of the variation of $C_{L_{max}}$ with flap angle was defined for each position. The range of positions in both cases was sufficient to surround the point at which the highest lift coefficient was found, thus isolating an optimum position in each case. Similar surveys had previously been made with the 0.40 *c* flap (reference 2) and were not repeated at this time.

Optimum take-off arrangement.—Lift and drag data were taken at a range of flap angles between 0° and that giving maximum lift for a series of flap positions somewhat more restricted than the range used in the maximum-lift tests. Care was exercised in these tests also to surround what was judged to be the optimum setting, both as regards position and angle.

Standard force tests of optimum arrangements.—A series of final force tests, consisting of lift, drag, and pitching-moment measurements, was made at the flap positions considered to be of special interest. These included tests of the maximum-lift arrangement of each flap, of the optimum take-off arrangement of each flap, and of an arbitrarily selected arrangement representing partial retraction of each flap.

All tests in these first three groups were conducted in accordance with standard force-test procedure as described in reference 3.

Flap loads.—Air loads acting on the flaps were found by supporting the flaps independently of the wing, at the same position and angle as used in the final force tests of the wing-flap combinations, and by measuring the forces on the wing alone in the presence of the flap. The flap loads could then be readily computed. In order to find the center of pressure of the load on the flap, the flap hinge moment was measured by observing the angular deflection of a long slender torque rod required to balance the flap at the angle in question. Similar measurements of loads and center-of-pressure locations on split flaps are more completely described in reference 4.

Downwash.—Measurements were made with "pitot-yaw" tubes attached to the wing by a rigid support. The reference position thus moved in the air stream as the angle of attack was changed but remained the same with respect to the wing, as does the tail of an airplane. The angles of downwash, however, were referred to the initial direction of the free air stream. The apparatus could be adjusted to various horizontal distances behind the wing. The pitot-yaw tubes were ordinary round-nosed pitot tubes with two additional nose holes at 45° above and below the tube axis. Alcohol manometers were used to read the pressures, and the tubes were calibrated in test position in the clear-tunnel air stream.

The wind tunnel is of the open jet, closed return type, with a rectangular jet 7 by 10 feet in size. A complete description of the tunnel, balance, and standard force-test procedure appears in reference 3.

Tests were run at a dynamic pressure of 16.37 pounds per square foot, corresponding to an air speed of 80 miles per hour at standard sea-level conditions. The Reynolds number {AQ3} of the tests, based on the 10-inch chord of the wing without flaps, was approximately 609,000.

PRECISION

The accidental errors in the results presented in this report are believed to lie within the limits indicated in the following table:

Wing data:		Flap load data:		Downwash data:	
α	±0.10°	C_{Nf}	±0.10	ε	±0.5°
C_{Lmax}	±.05	C_{Xf}	±.06		
$C_{me/\lambda}$	±.008	C_{Hf}	±.004		
$C_D(C_L=0)$	±.001	Flap angle	±.25°		
$C_D(C_L=1)$	±.004	Flap position	±.003		
$C_D(C_L=2)$	±.008				
Flap angle	±.25°				
Flap position	±.0015*c*				

Consistent differences between results obtained in the 7- by 10-foot wind tunnel and in free air may be ascribed to effects of the following factors: Jet boundaries, static-pressure gradient, turbulence, and scale. In order that the present results be consistent with published results of tests of other high-lift devices in the 7-by 10-

foot tunnel, no corrections for these effects have been made. Corrections of several sets of airfoil results have indicated that the values of the jet-boundary correction factors, $\delta_\alpha = -0.165$, and $\delta_D = -0.165$, used in the standard equations (cf. reference 5) are satisfactory for a 10-inch by 60-inch wing. The static pressure in the jet decreases downstream, producing an increment in C_D of 0.0015 on normal 12 percent *c* thick rectangular airfoils. Evidence at present available indicates that the effect of the turbulence in this tunnel is small as compared with the other consistent errors.

RESULTS AND DISCUSSION

All test results are given in standard non-dimensional coefficient form. In the case of a wing with a retractable surface, the convention of basing coefficients on the area that would be exposed in normal flight, that is, the minimum area, has been adopted. The coefficients used are then defined as follows:

subscript *w* refers to the basic wing
subscript *f* refers to the flap
$q = 1/2\ \rho V^2$
C_L = lift/$S_w q$
C_D = drag/$S_w q$
C_m = pitching moment/$c_w S_w q$
C_{Nf} = normal force on flap (perpendicular to flap chord)/$S_f q$
C_{Xf} = longitudinal force on flap (along flap chord)/$S_f q$
C_{Hf} = flap hinge moment/$S_f c_f q$
$\in$, angle of downwash, degrees.

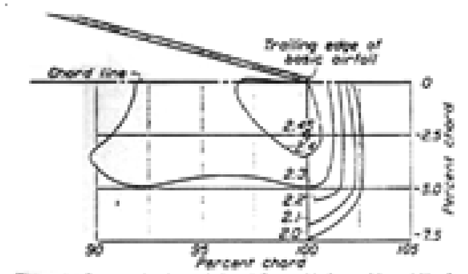


FIGURE 2.—Contours showing variation of $C_{L_{max}}$ with flap position. 0.20 c flap

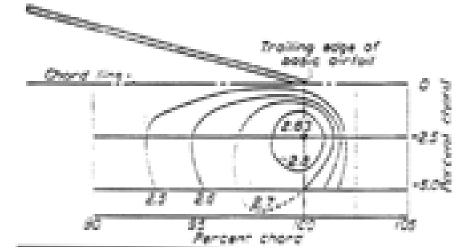


FIGURE 3.—Contours showing variation of $C_{L_{max}}$ with flap position. 0.30 c flap.

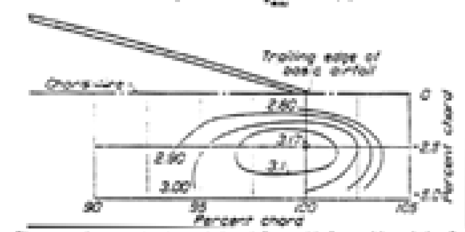


FIGURE 4.—Contours showing variation of $C_{L_{max}}$ with flap position. 0.40 c flap (data from N. A. C. A., T. N. No. 419).

Maximum-lift condition.—The results of the maximum-lift tests are presented as contours showing variations of C_{Lmax} with flap hinge position, irrespective of flap angle. Figures 2, 3, and 4 show contours for the 20 percent chord, 30 percent chord, and 40 percent chord flaps, respectively. Data on the 40 percent chord flap are taken from reference 2, no further tests having been considered necessary on that size of flap after an analysis was made of the data for the two smaller flaps. The optimum position is the same for all three flaps: 2.5 percent of the main wing chord directly below the trailing edge. The optimum angle

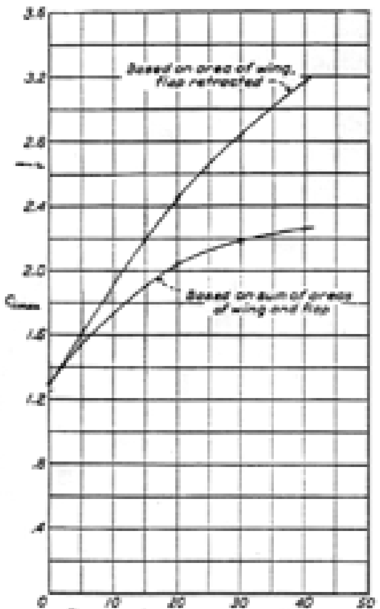


FIGURE 5.—Variation of $C_{L_{max}}$ with flap size. Flap set at optimum position and angle.

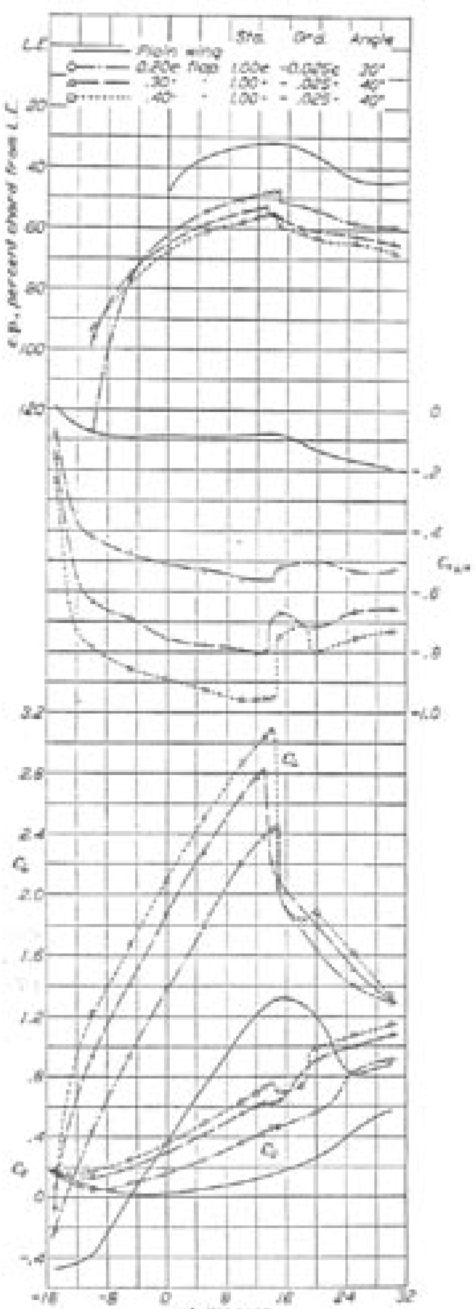


FIGURE 6.—Lift, drag, and pitching-moment coefficients for the maximum-lift condition.

TABLE II

PLAIN WING

(Flap retracted)

α	[illegible]	[illegible]	[illegible]
Degrees			
−15	[illegible]	[illegible]	[illegible]
−10	[illegible]	[illegible]	[illegible]
−5	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
0	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]
10	[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]	
20	[illegible]	[illegible]	[illegible]
25	[illegible]	[illegible]	[illegible]
30	[illegible]	[illegible]	[illegible]

TABLE III

DATA FOR THE MAXIMUM-LIFT CONDITION

(0.20c flap; flap station, 1.00c ordinate, −0.025c angle, 30°)

α	C_L	C_D	$C_{m_{c/4}}$	[illegible]	[illegible]	[illegible]
Degrees						
−15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
−10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
−5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[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]
20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
25	[illegible]	[illegible]	[illegible]			
30	[illegible]	[illegible]	[illegible]			

TABLE IV

DATA FOR THE MAXIMUM-LIFT CONDITION

(0.30c flap; flap station, 1.00c ordinate, −0.025c angle, 40°)

α	C_L	C_D	$C_{m_{c/4}}$	[illegible]	[illegible]	[illegible]
Degrees						
−15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
−10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
−5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[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]
20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
25	[illegible]	[illegible]	[illegible]			
30	[illegible]	[illegible]	[illegible]			

TABLE V

DATA FOR THE MAXIMUM-LIFT CONDITION

(0.40c flap; flap station, 1.00c ordinate, −0.025c angle, 40°)

α	C_L	C_D	$C_{m_{c/4}}$	[illegible]	[illegible]	[illegible]
Degrees						
−15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
−10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
−5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[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]
20	[illegible]	[illegible]	[illegible]			
25	[illegible]	[illegible]	[illegible]			
30	[illegible]	[illegible]	[illegible]			

was 30° for the 20 percent *c* flap and 40° for the two larger flaps.

Variation of C_{Lmax} with flap size is shown in figure 5. The maximum lift coefficient increases approximately in proportion to flap size if the area of only the original wing is considered. This is a reasonably satisfactory basis for comparison of the landing speeds of an airplane with various sizes of flap if a constant maximum speed is maintained. If the maximum lift force that a wing will give at a certain air speed per unit of structural weight is taken as a criterion, it is reasonable to compare the various sizes of flap on the basis of total (wing-and-flap) area. On this basis there is clearly little to be gained by using flaps larger than 30 percent *c*.

Lift, drag, and pitching-moment data for the wing with each of the three flap sizes, with the flap at the setting for maximum lift, are given in figure 6 and in tables III, IV, and V. Coefficients are based on the area and/or chord of the wing alone. The data for the plain wing were obtained with the 20 percent chord flap fully retracted into its well. (See table II.) It is evident that an airplane having a flap of this type would have a much larger range of center-of-pressure travel between various flying conditions than would one with a plain wing. It appears, then, that in a normal type of 2-spar wing the effect of adding a Fowler flap would be to leave the front-spar design load the same as for the wing without a flap but to increase considerably the design loads on the rear spar. If the speed at which the airplane may be flown with flap extended is limited to a value reasonably in excess of its landing speed, it appears likely that the loads with flap extended would be reduced to the same magnitude as the largest loads with flap retracted, with flap sizes not in excess of 30 percent *c*. On this basis it appears that a wing with a Fowler flap as wide as 30 percent *c* could be constructed in which there would be no increase in the weight of the wing structure proper, the only additional weight being due to the flap and its support from the spars.

Take-off condition.—Investigation of wing-flap combinations to determine the flap arrangement most favorable for take-off must involve consideration of performance parameters of the airplane in question as well as of the aerodynamic effects of the lifting surfaces. Concurrently with the tests, a series of take-off computations was made with the purpose of developing a "take-off criterion" for wings based on aerodynamic characteristics and depending on airplane design factors to the minimum extent possible. The application of such a criterion to the data would then serve to isolate the optimum flap arrangement for take-off. The development of the criterion, and associated data, are presented in an appendix to this report.

As the tests and computations progressed, it was found that some general considerations would serve to isolate the optimum arrangement, without recourse to a rigorous criterion. The computations indicated that normal transport airplanes should take off at a lift coefficient greater than 70 percent of the maximum available to achieve the shortest run to clear an obstacle. They also indicated that the principal aerodynamic characteristics affecting take-off, high lift available, and high L/D at the high lift are of nearly equal importance.

The wind-tunnel data, plotted as polar curves, are presented in figures 7 to 10 for the 0.30 *c* flap and in figures 11 to 15 for the 0.20 *c* flap. Comparison of these curves on the basis of the considerations previously stated indicated the flap position 0.025 *c* directly below the trailing edge of the wing, with an angle of 30°, to be the optimum take-off arrangement for both flaps. At this setting each flap has as high ratios of L/D throughout the high-lift region as any other setting tested, within the limits of accuracy of the tests, and has a higher maximum lift coefficient than any other setting having as high ratios of L/D. The 40° setting of the 0.30 *c* flap, at this same position, gives a higher maximum lift and lower ratio of L/D than the 30° angle, the percentage difference in L/D being greater than that in maximum lift. Computations (see appendix) verify the conclusion based on the general considerations, that the 30° angle is better with this flap.

Lift, drag, and pitching-moment data for the wing with each of three sizes of flap, with the flap at the optimum setting for take-off, are given in figure 16 and in tables III, VI, and VII. The choice of the position 0.025 *c* below the wing trailing edge, with a 25° angle, as optimum for the 40 percent *c* flap is based on the relation between optimum take-off setting and that for maximum lift of the 20 percent *c* and 30 percent *c* flaps. Although data for the 40 percent *c* flap are not sufficient for a rigorous selection, comparisons of data that are available (reference 2) indicate the choice to be sufficiently near the optimum for practical purposes.

Partial retraction of flap.—Lift, drag, and pitching-moment data for the wing with the 20 percent *c*, 30 percent *c*, and 40 percent *c* flaps in a partially retracted position are shown in figure 17 and in tables VIII to XI. The settings were chosen by assuming the flaps to move along an arc from the setting for maximum lift or optimum take-off to the fully retracted position. The flap hinges crossed the wing chord line at the 90 percent *c* station, and the angles at this position were 15° for the 20 percent *c* flap, 20° for the 30 percent *c* flap, and 20° and 30° for the 40 percent *c* flap. Comparison of the characteristics at this setting with those at the maximum-lift setting shows that the change of characteristics is in the same direction and of the same order of magnitude as the change of flap setting.

Flap loads.—Curves of normal and longitudinal force coefficients, hinge moments, and center-of-pressure locations of the 20 percent *c*, 30 percent *c*, and 40 percent *c* flaps in the maximum lift, optimum takeoff, and partly retracted settings are shown in figures 18 to 23. The corresponding data appear in tables III to XI. From the magnitude of the load carried by the flap at high lift coefficients of the combination, it is evident that the flap carries nearly 1½ times its proportionate share of the total load. It appears that this type of flap may be regarded as a separate wing, operating in an air stream whose combined velocity and curvature increase considerably the load it carries as compared with the load it would experience in the free air stream. Comparison of load data for a split flap (reference 4) and a Fowler flap clearly shows the fundamental difference in the action of the two flaps. At high lifts, the split flap carries almost no lift and offers large drag; whereas the Fowler carries a large proportion of the total lift, but with less drag.

Although this condition is favorable to airplane performance, it implies a large range of center-of-pressure positions for the complete flight range, with consequent disadvantages in longitudinal-stability characteristics and possibly also in structure. In connection with structural considerations it is interesting to note that a progressive reduction in flap loads occurs with increasing flap size if the maximum angle is kept below 30°.

At flap settings giving high maximum lift coefficients, the center of pressure of the flap itself has little travel throughout most of the angle-of-attack range and is generally nearer the leading edge than it would be on an airfoil in a free air stream. As the flap angle is reduced below 30°, however, the center of pressure moves rapidly backward.

Downwash.—Some representative data from the downwash measurements are shown in figures 24 and 25. Angle of downwash as a function of lift coefficient is shown for two positions behind the wing, with data for the plain wing and for the same flap settings as were used in the flap load tests plotted on each curve. Only small consistent deviations from the mean curve, within the limits of test accuracy, were found for the variety of settings tested. It appears, then, that the addition of a

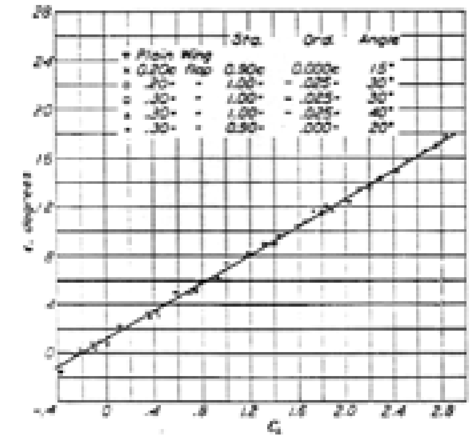


FIGURE 34.—Downwash angle against lift coefficient at a point behind the wing. Position of point: [illegible] behind [illegible] chord point, [illegible] laterally from center line, [illegible] above wing chord.

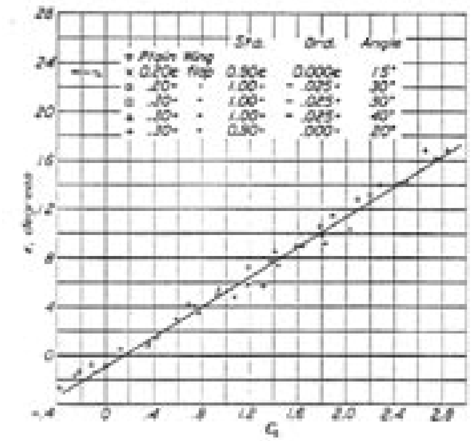


FIGURE 35.—Downwash angle against lift coefficient at a point behind the wing. Position of point: [illegible] behind [illegible] chord point, [illegible] laterally from center line, on

Fowler flap has no appreciable effect on the basic relation between lift, span, and downwash at reasonable distances behind the wing.

The foregoing conclusion is subject to some question owing to the doubtful nature of the jet-boundary effect on downwash in the 7- by 10-foot tunnel. The corrections in this particular case differ considerably from the theoretical corrections, probably on account of the combined effect of static-pressure gradient in the jet and spillage of air over the unflared lip of the exit cone. Different corrections for different positions of the reference point in the air stream might produce greater consistent differences in downwash between the plain wing and flap extended conditions than are indicated by these tests, though this effect would be small unless the variation of the corrections with position is greater than seems likely.

Although the extensive investigation required to establish the corrections might produce results of academic interest, certain effects of combining a variable-lift wing with an airplane fuselage would render the results of small technical value. Since a large difference in angle of attack occurs at the same value of C_L with different settings of the Fowler flap, a large variation of fuselage attitude and lift at a given wing lift coefficient results from changing flap settings. Thus, at a given over-all lift coefficient of the airplane, the lift coefficient and downwash of the wing may be expected to change with flap setting. The use of partial-span flaps produces an effective reduction of span as the flap is extended, causing an additional change of downwash at constant lift coefficient with changing flap setting. It appears that problems involving downwash of variable-lift wings are more susceptible of solution by measurement on the actual design in question, rather than by a fundamental wind-tunnel investigation.

CONCLUSIONS

1. The maximum lift coefficients, based on area of wing alone, found for the three sizes of flap tested were: For the 20 percent *c* flap, 2.45; for the 30 percent *c* flap, 2.85; and for the 40 percent *c* flap, 3.17. The maximum lift coefficient for the wing with flap retracted was 1.31.

2. The location of the flap leading edge for maximum lift was found to be the same in all cases, the center of the leading-edge arc being 2.5 percent *c* directly below the trailing edge of the main wing. The flap angles for maximum lift were 30°, 40°, and 40° for the 20 percent *c*, 30 percent *c*, and 40 percent *c* flaps, respectively.

3. The 20 percent *c* and 30 percent *c* flaps were found to give the characteristics most favorable to take-off with the same leading-edge location as for maximum lift. The optimum angle was 30° in both cases.

4. The maximum normal-force and longitudinal-force coefficients of the 40 percent *c* flap, based on flap area, were 2.89 and −1.25; those for the 30 percent *c* flap were 3.06 and −1.54; and those for the 20 percent *c* flap were 2.80 and −1.20. Center-of-pressure locations corresponding to these coefficients were in each case approximately at the 20 percent *c* flap chord points.

5. At positions normally occupied by the tail surfaces the relation between lift coefficient and downwash angle appears from the present tests to be the same for a wing with or without a full-span Fowler flap.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., April, 26, 1935.

Document 3-12(h), Harlan D. Fowler, "Aerodynamic Characteristics of the Fowler Wing,"* Aero Digest *29 (September 1936): 46-50.

AERODYNAMIC CHARACTERISTICS THE FOWLER WING
HARLAN D. FOWLER

Airfoil design has practically reached its maximum, comprehensive and systematic research by the NACA resulting in such several new highly efficient sections that possibility of further improvement is remote and of comparatively small value, although costly to discover.

Attempts have been made to so design an airfoil that it would develop especially high L/D ratio, better minimum drag at cruising speed, etc. Earliest efforts were devoted to increase maximum lift (to provide safer landing speed), and to increase drag so as to decrease length of the run when landing.

Research conducted by NACA for the Bureau of Aeronautics indicated that an airplane equipped with a Fowler variable area wing could reduce landing speed, decrease landing and take-off runs, and that there would also be indications of improved climb with the Fowler partially extended. This device was first tried in 1927 on a Canuck JN; in 1929 on a Pitcairn; in 1934 at the International Competition at Warsaw, Poland, where a similar device was used by Fieseler and Messerschmitt; in 1935 on a Fairchild F-22 by the U. S. Navy and NACA; and more recently on the Martin Bomber.

Combined use of variable area, camber, angle of attack and of the boundary layer, requires only an auxiliary airfoil that is extended or retracted as the occasion demands. The principle is termed a *fowler* to distinguish it from other flap devices. Individual aerodynamic properties of each of these principles is not sufficiently great to justify its use alone, as for example, the percent distribution of the maximum lift coefficient as contributed by the several features given in Table 1.

Based on area alone C_{Lmax} should vary directly with the fowler chord with it fully extended. However, data available show that with a 20% chord fowler set at -5, fully extended, the increase is slightly higher or about 25% more than for the normal wing. By virtue of the recess cutout under the trailing edge of the normal wing, lift is again increased slightly varying with fowler chord.

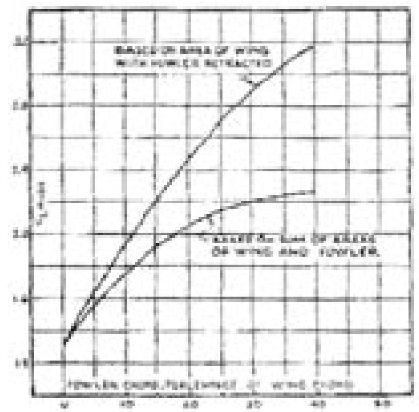
The major individual increase in maximum lift results from the gap, which appears to increase nearly directly with the chord of the fowler. Variable area is the next most effective factor, with camber a close third. However (by the principle involved), the combination of area and camber actually contributes a greater increase than the gap, and it is apparent that all three factors have a powerful influence in contributing to the maximum lift, and increase with enlargement of the flap chord.

PARTIAL SPAN AND LATERAL CONTROL

Distribution of maximum lift along the wingspan has been investigated and checked with actual performance data in cases where the fowler covered a portion of the wing. The loss of lift is greatest near the fuselage and least at the wing tip. On a tapered wing it is hardly worthwhile to extend the fowler beyond 80% of the span as the remaining 20% at the tip represents a loss of about 4% from the full span arrangement. However, if the inner end of the auxiliary wing is not extended over the center 20% span, there will be a loss of about 14% from the maximum.

Considering the small possible gain by extending it to the tip, the question of providing for lateral control means becomes involved. The author maintains that due to the powerful lifting capacity of the device, there is no need to sacrifice good lateral control to attain the last ounce of lift. In this respect, conventional ailerons have been used and the lateral control obtained has been satisfactory, even with the fowler fully extended. Experiments have revealed that rolling moments are substantially higher with it extended than when closed, the ideal condition. In these tests, ailerons occupied from 30 to 40% of the semi-span, the smaller span being adequately effective.

** NACA Technical Report 534 *Aerodynamic Characteristics of a Wing with Fowler Flaps Including Flap Loads, Downwash, and Calculated Effect on Take-Off.*



Variation of $C_{L_{max}}$ with Fowler size. Flaps set at optimum position and angle

Comprehensive research on fowlers of 20, 30 and 40% chord shows that if the maximum angle is kept at or below 30 there is a progressive reduction in flap loads with increasing chord, provided advantage is taken of the corresponding decrease in stall speed. Furthermore, if the high speed with the fully extended wing is kept below twice stalling speed, it is possible to add fowlers having a chord up to 30% to a wing whose spars have already been designed for its normal critical loads (except for wings using an airfoil of constant center of pressure movement) that will be sufficiently strong to take the load from the auxiliary wing without appreciably increasing the main wing weight, particularly the rear spar. Because of the necessity of a recess under the trailing edge of the main wing, ribs are consequently shallower and must be strengthened, although not necessarily with considerable increase in weight, although there will be a weight increase by adding the fowlers and controls.

When the fowler is in its fully extended position, longitudinal force assumes a negative value—that is the force tends to close it. At some intermediate point this force becomes zero then tends towards the positive. The control system is therefore designed not to extend the fowlers but to prevent them from closing. With this arrangement and using an automatic hydraulic pressure relief valve system, should the load become too high, the fowlers will tend to move towards the closed position, thus preventing undue strain on the main wing structure. However, the hydraulic device will hold it at any desired position.

Throughout the flying angles of attack, the center of pressure on the fowler wing is uniformly forward when in the extended position, at about 30% of its chord. Since the main spar of the flap is located at about 20% chord there is no tendency for flutter since the pressure is constantly aft of the point of support. In the case of a twin-engine installation with the propellers directly in front of it, it was found that the extended fowler minimized turbulence, due perhaps to the gap action on the boundary layer over the wing.

CONTROL MECHANISM

There are two methods of operating the fowlers. The original method consisted of fixed tracks, properly curved, attached to the rear spar, with a trolley which is secured to the auxiliary wing, running along the track. Back and forth motion was accomplished either by a continuous cable or by push-pull rods. The second method is the rotating or swinging arm which is pivoted to the rear spar with the fowler suspended at its outer end. The arm swings back towards the trailing edge, thus extending the fowler and automatically increasing its angle, the latter being accomplished by a universal joint. Both systems have been tested and each has merits which the other does not possess. The swinging arm presents a perfectly smooth wing when the fowler is closed. The fixed track has a small portion of its rear end exposed at all times (without causing any appreciable increase in drag) and is less costly to build and lighter in weight than the other method.

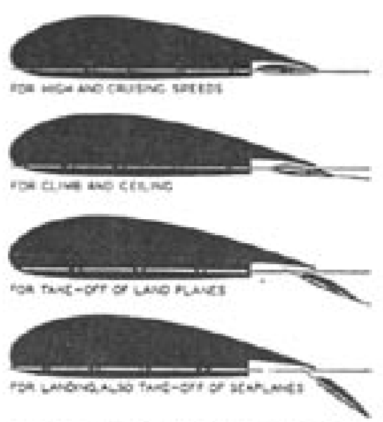
Speed of extension or retraction is obtained in several ways. Using manual crank-operated control, movement is fro m 2.5 to 3 inches to one complete turn of the crank handle. By hydraulic control in one case, movement was accomplished in 15 seconds. There is something to be said about the speed at which fowlers should be operated. They should not be operated too quickly since it gives neither the plane nor the pilot a chance to adjust for the varying conditions. If there is too long an interval, there will be a decided negative influence on landing and take-off, so that a happy medium on speed of operation is important.

Hydraulic and electrical systems are preferable for large planes, the first lend-ing itself to automatic retraction, if the plane's speed becomes excessive. Both systems are dependable and flexible.

** Results obtained from tests conducted on a full scale plane, and published in a confidential report of the U. S. Navy.

PARTIALLY EXTENDED CHARACTERISTICS

Inherent with the extendable feature of the device is the transition or partially extended position. The fowler can be stopped at any intermediate position and several such positions contribute improvement to performance. The accompanying diagram illustrates several positions at which it may be set to give particularly desirable performances, the positions shown being spaced in four locations, the exact positions for the given type of performance varying with airfoil and airplane design.



Performance characteristics with various positions of the Fowler wing

LONGITUDINAL STABILITY AND DOWNWASH

In the normal wing condition, longitudinal stability is as usually obtained on well-designed planes.

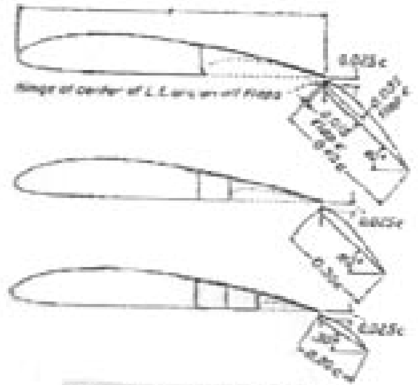
With the fowler device, as it moves outward and to about 2/3 extended position. the change in balance is barely perceptible. In the full out position there is need of more upward elevator movement for landing. Also, due to the increase in

length of the combined wing and fowler chord, tail surfaces should be at a slightly greater distance from the center of gravity, or the horizontal tail surfaces made larger than normal, the area of the elevator being at least equal to one-half the total horizontal tail area. This increase is to be expected because at the very high lift coefficients obtainable with the fully extended fowler, the downwash angle is considerably higher. Combined with the low maximum lift coefficient of tail surfaces, this causes the tail to stall at certain speeds. For this condition large elevator movements are preferable to stabilizer adjustment, especially on large planes. Also, there is no tendency to nose over at the take-off or on landing.

Although not completely affirmed, extensive investigations on downwash angles behind a wing using the auxiliary wing indicate that its addition has no appreciable effect on the basic relation between lift, span and downwash at reasonable distances behind the wing. The downwash angle is a direct function of the lift coefficient, but it appears that some correction must be made for the shifting of the angle at zero lift as between the normal wing and the extended fowler. In other words, the angle of attack for all fowler positions and chord sizes is referred to the basic chord line of the normal wing. As it is extended or increased in chord size, the angle at zero lift becomes more and more negative. Since the setting of the tail surfaces is referred to the zero lift chord of the main wing, this variation must be considered.

LANDING DISTANCES AND RATE OF DESCENT

The maximum lift coefficient obtained by a fowler wing is 3.17, referred to the normal wing area, by using a 40% chord over the entire span. By means of an auxiliary nose airfoil this can be increased to 3.62. At present, for most designs in which the fowlers are used, the maximum lift coefficient is from 2.00 to 2.50, the lower value being attained by using a 20% chord and the latter by using a 30% chord both over 60 to 70% of the wingspan. A 40% chord has been used in one wing.



Wing with various Fowler flaps (From NACA report No. 534)

The accompanying chart (from NACA Technical Report 534) shows the variation of the maximum lift coefficient with fowlers of various percent chords in terms of the basic wing chord. As a high lift device is generally used to increase the maximum speed of a plane keeping a given stall speed, it is proper to consider lift in terms of normal wing area, with fowler retracted.

As an illustration of what has been done in full flight tests, some results obtained at Langley Field by NACA are given in Table 2, which shows minimum rate of descent with the fowler fully extended was about 8.7 ft./ compared to 9 ft./sec.

with the wing closed. Data were obtained on the F-22, results being average of two landings. F-22 has a Fairchild fuselage mounting a specially designed variable area wing. The plane was powered by a 95 hp engine. Gross weight was about 1600 lbs., wingspan 31 ft., normal chord 4 ft. 4 in., normal area 132 ft', fowler area 27.3 ft', total area 159.3 ft.' A 30% chord fowler over 71% of the span was used with conventional ailerons whose area was about 7.2% of the normal wing area. Wing load based on normal area was 12.1 lbs./ft ^{2}, and power loading 16.8 lbs./hp.

Running along the ground for take-off or landing, the proximity of the earth causes a reduction in the angle of attack due to induced lift. Also, the higher the lift, the greater the induced angle of attack of the wing (as this varies directly with the lift), thus allowing a shorter landing gear. The ground angle being smaller, it is possible to use a true stream-line fuselage, with a resultant saving in parasite drag.

TAKE-OFF OF LANDPLANES

Take-off distances for F-22 are in Table 3 which shows a reduction in total distance of 22%.

Theoretical study of the effect of high lift on take-off, with varying power and loading per square foot, showed the fowler wing should be able to reduce total take-off distance by from 30 to 45%, including the clearance of a 50-ft. obstacle.

It should be explained that the fowler is able to contribute to high reduction in take-off run due to the combination of high lift with low drag. The first contributes to low take-off speed, thus favoring propeller thrust. With low drag, the excess thrust is considerably improved.

While the fowler has lower drag and thus less braking effect on landing, the high lift reduces the landing speed accomplishing results similar to the split flap. However, it should be pointed out that due to the high LID ratio with the fowler wing it is necessary for the pilot to use only ordinary flight technique. This is particularly desirable in forced landings.

CLIMB AND CEILING

Wind tunnel research on a complete model indicates that with the fowler extended about 25%, L/D ratio is higher and occurs at a larger lift coefficient. When applied to a given design, service ceiling can be improved. With planes supercharged to high altitudes, the lift coefficient is larger, and with smaller drag the ceiling is bettered. This characteristic will not be detectable near sea level, as compared with the normal wing, but it should appear at altitudes.

Flight tests on F-22 at 2000 ft. indicated that, with the fowler extended 1/3, rate of climb was as good as with it closed, but the angle of climb was higher.

On another plane it was found that at 9000 ft. rate of climb was appreciably higher than for the normal wing, and at low speed the gain was about 10%.

Also, test results seem to indicate the possibility that when one of two engines fails that, by partially extending the fowler, both rate of climb and ceiling can be improved.

SEAPLANE TAKE-OFF

A valuable field of application of the fowler wing is for flying boats, especially those having long range and large payloads. While the controllable-pitch propeller has materially reduced take-off problems for such ships, its combined use with the flap offers further improvements. The problem of a large flying boat is to carry a large fuel load plus passengers, mail and equipment, but this usually results in increasing take-off speed. With the higher take-off speed, water resistance of the hull may become large enough to actually prevent a take-off. With the high lift of the fowler wing, take-off speed is reduced and propeller thrust increased, providing greater excess thrust for acceleration. Even at the full out position, L/D of the wing is high enough to cause a substantial reduction in the total water resistance plus air drag.

The most effective method of using the fowler is to start extending it about 10% below take-off speed, so that it becomes fully extended only at the instant of take-off. Thus the plane starts its run with the normal wing, gets over the hump and speeds on until at some predetermined speed the fowler begins to extend.

Table 4 calculates values for a seaplane of 15,000 lbs. (gross), 1000 ft. normal area and 1000 hp using a 20% chord fowler occupying 62% of the span. In this case the time interval between commencing to extend the fowler to the fully extended position, was about 6 seconds, illustrating the importance of not permitting too long a time for the device to completely open, although a little longer time could be permitted without materially affecting take-off characteristics.

It should also be possible to set the wing in relation to the hull at a lower angle, thus reducing hull drag at cruising speed. Another advantage is that the trim angle of the hull can be maintained nearly constant at get-away because the fowler will pull it off.

The fowler wing can also be utilized to increase fuel load with the same wing area, or alternatively, the same fuel capacity can be kept and the wing area reduced.

Document 3-13

Standard Steel Propeller Company to Ryan Airlines, undated (ca. April 1927), in Charles A. Lindbergh, *The Spirit of St. Louis* (New York: Scribner, 1953; reprint, St. Paul: Minnesota Historical Society Press, 1993), p. 116.

As with all other aspects of the design of the *Spirit of St. Louis*, Charles A. Lindbergh carefully calculated the role of his airplane's propeller before setting off on his historic transatlantic flight from New York to Paris. In the spring of 1927, the Standard Steel Propeller Company of Pittsburgh produced four nine-foot-diameter dural (aluminum alloy) ground-adjustable propellers for Lindbergh's Ryan-built airplane; the company built them according to "specification No. 1519" and sent them on to Ryan Airlines in San Diego. Inspected by Standard Steel's assembly foreman and inspector, Alexander F. Manella, the propellers consisted of twelve pieces designed for use with the Wright Whirlwind J-5C radial engine. Lindbergh and Donald A. Hall, the chief engineer for Ryan Airlines, asked Standard Steel to recommend a specific blade pitch that would help them achieve the range needed to reach Paris. The word received back came in the telegram reproduced below.

What Standard Steel did was simply calculate which propeller blade angle was best, for the propeller itself was essentially "off the shelf." Acting on Standard Steel's recommendation and influenced by urgent time constraints, Lindbergh accepted the compromise setting that favored a setting optimum for cruising conditions. This was a big gamble because it was a pitch setting for the propeller that provided minimum efficiency for takeoff. Still, the metal ground-adjustable propeller offered him a flexibility that wooden and metal fixed-pitch propellers could not. With its propeller blade set at 16.25°, the Wright J-5C engine produced 190 hp at 1,545 revolutions per minute; this generated a static thrust of 700 lbs. The maximum airscrew efficiency of the *Spirit's* propeller rated out at 74 percent.

Roosevelt Field on Long Island, from which Lindbergh lifted off for Paris, was over a mile long and the only suitable place for heavy takeoffs in the New York area. But obstacles surrounded the field, telephone wires and low tree-covered hills, dangers of which Lindbergh was well aware. As he expected, the *Spirit of St. Louis* required almost every inch of the field to lift its 5,000-lb load (mostly fuel) into the air. Years later, Lindbergh recalled his approach to the problem: "I decided to 'feel' the plane off the ground just as I had often done in underpowered planes while barnstorming. If I felt I was not going to get off the ground, my plan was to simply cut the throttle" (quoted in Cassagneres, *Spirit of Ryan*, p. 54). Perhaps more than any other element of risk in an otherwise carefully planned flight, Lindbergh's takeoff threatened failure, even disaster. Fortunately, as it happened, the straining *Spirit* lifted off the ground about 1,000 yards in front of the telephone wires at the end of the field—although the angle of the newsreel pictures made it look a lot closer. Thus, one might call Lindbergh's takeoff the most dramatic and the most decisive event of his entire flight, for as he wrote in his book *The Spirit of St. Louis* (Scribner's Sons, 1953): "My propeller is set for cruising, not for takeoff" (p. 183). This passage perhaps illustrates other innovations as well, especially flaps.

Document 3-13, Standard Steel Propeller Company to Ryan Airlines, undated (ca. April 1927), in Charles A. Lindbergh,* The Spirit of St. Louis *(New York: Scribner, 1953; reprint, St. Paul: Minnesota Historical Society Press, 1993), p. 116.

WESTERN UNION

HOLMSTEAD [SIC]
PENN.

RYAN AIRLINES
SAN DIEGO, CALIF.

15.5 DEGREES SETTING PROBABLY NECESSARY ON YOUR MONOPLANE TO GET TAKEOFF WITH HEAVY LOAD FUEL ECONOMY WILL BE IMPROVED ON HIGHER PITCH SETTING STOP IF TAKEOFF IS SATISFACTORY WITH 15.5 SETTING SUGGEST TRY 16.5 AS THIS WILL IMPROVE FUEL ECONOMY.

STANDARD STEEL PROP. CO.

Document 3-14

C. B. Allen, "Hamilton Standard Wins Collier Trophy for Controllable Pitch Propeller," *The Bee-Hive* 8 (June 1934): 1-2.

In 1933, the National Aeronautic Association awarded its Collier for the year's greatest achievement in American aviation to Hamilton Standard Propeller Company, with particular credit to Frank W. Caldwell, chief engineer, for development of a controllable-pitch propeller that was then entering general use. Caldwell's design controlled its blades via bevel gears that were turned by a drumcam in the propeller hub. Hamilton Standard later went on to refine the design by adding a "constant speed unit" or CSU. This gadget controlled the propeller automatically to permit the desired engine speed. The aircraft industry continued to make improvements. By late in World War II, the controllable-pitch propeller added reversible-pitch settings that further slowed an aircraft for landing. Even as the turbojet revolution gained momentum, aeronautical engineers continued to perfect propeller applications for reciprocating engines. Airplanes such as the Boeing B-29, Boeing B-50, Lockheed Constellation, and Lockheed C-130 Hercules all employed large and sophisticated controllable-pitch propellers of three and four blade sections. Without advanced forms of this type of propeller, piston-engine airliners such as the Douglas DC-6 and DC-7 of the late 1950s and early 1960s could not have achieved effective performance. Without question, the variable-pitch and controllable-pitch propellers made essential contributions to the reinvention of the airplane inherent to the airplane design revolution of the interwar period.

Document 3-14, C. B. Allen, "Hamilton Standard Wins Collier Trophy for Controllable Pitch Propeller," The Bee-Hive *8 (June 1934): 1-2.*

PRESENTATION last month by President Franklin D. Roosevelt to the Hamilton Standard Propeller Company, of East Hartford. Conn., through its chief engineer, Frank Walker Caldwell, of American aviation's most coveted annual award-the Collier Trophy for 1933-has met with wide approval from the industry because of the practical benefits it has enjoyed from the first practical "gearshift of the air."

More than 500 controllable pitch propellers of the type for whose development the award was made are now in everyday service, and their users will have no complaint with the National Aeronautic Association for selecting this device as "the greatest achievement in aviation in America, the value of which has been demonstrated by actual use during the preceding year."

ELIMINATES FAULTS OF OLD MODELS

Essentially the controllable pitch propeller supplies an airplane with a "low gear" for takeoff and climb purposes and a "high gear" for economical cruising. It eliminates the chief faults of the fixed pitch propeller--the fact that its blades "bite" so much air as the plane moves slowly over the ground the engine cannot "turn up" its full rated horsepower or "race" impotently once the ship is in level flight, if the blades are set at a flat angle designed to give a reasonably quick take-off, because they do not get a sufficient grip on the medium through which the whole ship is moving at so swift a pace.

Obviously, such a development always has been highly desirable in aviation, but without it the high-speed transport planes that have made their appearance on America's air lines during the last year would not have been possible. No fixed pitch propeller could be expected to function with any sort of efficiency over the wide range that lies between the take-off and top speeds of these craft, and such devices as the wing-flap "air brake" which enable 200-mile-an-hour transports to land and take off at fifty miles an hour would be pretty much in vain save for the controllable pitch propeller.

"GEARSHIFT OF THE AIR"

Also, the safety features of the multi-motored airplane, especially the two-engine variety, would be greatly impaired without the "gearshift of the air" for the reason that, when one power plant fails, the plane inevitably slows down in the air and only by putting the remaining sound engine in "low gear," where it can "turn up" its full rated horsepower (and in some cases deliver for short periods more power than its normal rating), is it possible to continue flight and maintain altitude--particularly when the failure occurs just after leaving the ground or during flight over high-altitude terrain.

United Air Lines alone has more than 100 Hamilton Standard controllable pitch, propellers in service on the Boeing monoplanes it is operating over its transcontinental and other routes. Some of these have flown 1,500 hours and more--the equivalent of 225,000 miles flying-without failure of any sort.

The device is simple and rugged, a piston, operated by oil pressure from the engine, twisting the blades into "low gear" when the pilot pulls a lever in the cockpit. Once he is in the air and has gained the level at which he wishes to fly, he releases the lever and the blades are automatically pulled into "high" by two counter-weights, which the powerful, outward-pushing oil piston heretofore has thrust and held back.

YEARS OF DEVELOPMENT WORK

Mr. Caldwell designed and patented the controllable pitch propeller in 1928, but years of development work and $200,000 in cash were required before all of its mechanical difficulties had been conquered and its creator was satisfied to put it into production a year ago last January.

There have been three eras in the development of the airplane propellers—the age of wood, which lasted through the World War and seven years beyond, the metal propeller (both with fixed blades and blades that could be adjusted to any desired angle before flight, but not altered in the air), which held sway some nine years and won the Collier Trophy for Dr. S. Albert Reed in 1925, and now the "gearshift of the air" that may be changed at the pilot's will in mid-air.

The 1933 committee of award, appointed by President Hiram Bingham of the National Aeronautic Association, consisted of Rear Admiral Emory S. Land, U.S. Navy: Colonel Edgar S. Gorrell, Air Corps Reserve, and Chief of Staff of the Air Corps in France during the war: Colonel Clarence M. Young, former Assistant Secretary of Commerce for Aeronautics: General Frank Hitchcock, who, as Postmaster General, arranged for the first flight of air mail in America in 1909, and Earl N. Finley, Editor of U.S. Air Services.

NOTABLES AT PRESENTATION

Among the guests who witnessed the presentation were two previous holders: Harold Piteairn of Philadelphia and Glenn L. Martin of Baltimore. Others present included President Hiram Bingham of the National Aeronautic Association; Eugene L. Vidal, Director of Aeronautics of the Department of Commerce; J. Carroll Cone, Assistant Director of Aeronautics; Dr. George W. Lewis, Director of Research of the National Advisory Committee for Aeronautics; Don L. Brown, President of the Pratt & Whitney Aircraft Co.; Ray Cooper, General Manager of the National Aeronautic Association; William R. Enyart, Secretary of the Contest Committee of the N. A. A.; Joseph Edgerton and Bob Ball, newspaper men.

Document 3-15(a-e)

(a) Smith J. DeFrance, "The Aerodynamic Effect of a Retractable Landing Gear," NACA *Technical Note* 456 (Washington, 1933).

(b) Hal L. Hibbard, "Problems in Fast Air-Transport Design," *Mechanical Engineering* 55 (October 1933): 611-617.

(c) "Preliminary Study of Retractable Landing Gears for High and Low Wing Monoplanes," *Air Corps Information Circular* 7 (18 February 1933): 1-9.

(d) Richard M. Mock, "Retractable Landing Gears," *Aviation* 32 (February 1933): 33-37.

(e) Roy G. Miller, letter to editor, *Aviation*, "Retractable Landing Gears," *Aviation* 32 (April 1933), with response from Richard M. Mock: 130-131.

One of the most significant "shelf items" required to reinvent the airplane was retractable landing gear; as essential as it was, it also proved one of the most evasive. The earliest known concept for a retracting mechanism dates from November 1911 and to an obscure aeronautical inventor by the name of F. McCarroll who received a U.S. patent for his invention in November 1915. The first airplane to appear with such an undercarriage was the Dayton-Wright RB-1 of 1920, which also possessed the world's first variable-camber wing. In 1922, the idea of retracting gear got a major shot in the arm as part of Louis Breguet's agenda for aircraft streamlining (see Document 3-4). As discussed in the text, the Verville-Sperry R-3 racer of 1923 brought a lot of attention to retractable landing gear, which it incorporated, when it flew in the Pulitzer Trophy Race of 1923 in St. Louis, winning the race in Dayton the following year.

Systematic testing of the concept did not really begin until 1927, when research engineers at the NACA's laboratory at Langley Field began looking into the relationship between fixed landing gear and aerodynamic drag. The NACA tests, conducted in Langley's PRT on an army-owned Sperry Messenger airplane with its outer wing panels removed, also represented the world's first wind tunnel tests of a full-scale aircraft, not just a scale model or individual components. These tests in the PRT revealed that the resistance of the protruding fixed landing gear amounted to an astounding 40 percent of the airplane's total drag. The tests defined the "real magnitude of the landing gear drag penalty" and provided precisely the kind of empirical data needed to encourage the American aviation industry to devote more resources to the design of landing gear. This proved to be a critical step in the process of reinventing the airplane, with the NACA becoming more and more involved in evaluating the value of retractable landing gear for industry.

The following string of five documents demonstrates the growing commitment to retractable gear. The first concerns NACA tests of the Lockheed Altair monoplane in Langley's Full-Scale Tunnel for the purpose of learning the advantages and disadvantages of the new type of gear and specifically whether or not the gear contributed to the aircraft's excessive takeoff run. NACA researcher Smith J. DeFrance (future director of the NACA's Ames Aeronautical Laboratory in California, which came to life in 1941) found that the retractable landing gear improved performance generally in flight but had negligible effects on takeoff and landing. DeFrance and other NACA engineers understood that, before the industry could wholeheartedly accept retractable landing gear, precise knowledge of the flow of air caused by landing gear when it was extended had to be in hand. When the gear was retracted, the aerodynamics were better, but when the gear was extended, the aerodynamics then became problematic. Until the gear performed more effectively overall, it was difficult to overcome the inertia favoring the certainties of traditional fixed gear, such as that still being put even on innovative aircraft like the Northrop Alpha.

The second document in the string reflects the type of thinking that opposed the use of retractable landing gear. Similar to the objections to using the NACA cowling, many individuals in industry did not feel that retractable landing gear was the most practical solution. One industry representative who thought this way was Hal L. Hibbard, assistant chief engineer of the Lockheed Aircraft Corporation. In 1933, Hibbard presented the following article at the joint meeting of the Society of Automotive Engineers and the American Society of Mechanical Engineers held in conjunction with the 1933 National Air Races in Los Angeles in July. Examining all the components that made up a complete airplane, Hibbard addressed the aerodynamic differences between fixed and retractable landing gear, differences that he considered to be "greatly exaggerated." The major source of drag in landing gear, according to Hibbard, was the aerodynamic interference caused by parts of the landing gear and its relationship with the wing and fuselage. If designers would only carefully streamline their fixed landing gear, then the difference between fixed and retractable gears would be negligible; in fact, the overall advantage could even go to fixed gear. At one point in his presentation, Hibbard referred to "careful wind tunnel tests," which backed up his conclusion. What he was no doubt referring to was a test program conducted at the GALCIT wind tunnel at Caltech on a Northrop Alpha airplane employing streamline coverings known as "spats" or "pants." These were teardrop-shaped fairings around the wheels of a fixed landing gear and enclosing the landing strut and wheels, which helped reduce drag. Spats had become popular with the Lockheed Vega and most fixed landing gear following the Vega used them.

Despite the dramatic benefits that retractable landing gear offered, widespread development and adoption was slow. As late as 1933, as we see in the third document in this string, the U.S. Army Air Corps had no clear idea which forms of retractable landing gear were feasible. The authors of the Air Corps information circular continued to stress the advantages of fixed gear with streamlined wheel fairings even for high-performance aircraft over those possible with retractable gear. The fourth article below is a February 1933 trade journal article that discussed the myriad of variables related to retractable landing gear design. Its author reported on industry's attitudes toward the mechanical difficulties it was facing when trying to integrate retractable gear into aircraft design. The string closes with a letter to the editor endorsing the tangible benefits that retractable landing gear would provide to aircraft operators.

The superiority of retractable landing gear grew more and more obvious as synergistic advances related to power plants, aerodynamics, structures, and stability and control came together through the 1930s, boosting the speed and performance of aircraft to unprecedented levels. By the start of World War II, the advantages of retractable landing gear were clear, and the U.S. aircraft industry had turned retractable landing gear into its standard.

Document 3-15(a), Smith J. DeFrance, "The Aerodynamic Effect of a Retractable Landing Gear," NACA* Technical Note *456 (Washington, 1933).

THE AERODYNAMIC EFFECT OF A RETRACTABLE LANDING GEAR
By Smith J. DeFrance

SUMMARY

Tests were conducted in the N.A.C.A. full-scale wind tunnel at the request of the Army Air Corps to determine the effect of retractable landing-gear openings in the bottom surface of a wing upon the take-off characteristics of a Lockheed Altair airplane. The tests were extended to include the determination of the lift and drag characteristics throughout the angle-of-attack range with the landing gear both retracted and extended.

Covering the wheel openings in the wing with sheet metal when the wheels were extended reduced the drag only 2 percent at a lift coefficient of 1.0, which was assumed for the take-off condition. Therefore, the wheel openings in the bottom

side of the wing have a negligible effect upon the take-off of the airplane. Retracting the landing gear reduced the minimum drag of the complete airplane 50 percent.

INTRODUCTION

A somewhat excessive length of run had been required by a certain low-wing monoplane, a Lockheed Altair, during take-off. This airplane has a landing gear that is completely housed in the wing when retracted; and when it is extended, openings having an area equal to the side area of the struts and wheels are exposed on the lower surface of the wing. It was desired to know whether these openings were causing the detrimental effect upon the take-off characteristics. Consequently, at the request of the Army Air Corps tests were conducted upon this airplane in the N.A.C.A. full-scale wind tunnel to determine the effect of the wing openings upon the lift and drag characteristics.

TESTS AND APPARATUS

The airplane was mounted in the wind tunnel as shown in Figure 1. The lift and drag forces were measured with the wheels retracted, with the wheels extended and wheel wells open, and with the wheels extended and the wells covered with sheet-metal. The tests were conducted at an air speed of approximately 60 miles per hour. Figure 2 shows the landing gear extended and the wheel wells open. A description of the tunnel and balance equipment is given in reference 1.

DISCUSSION OF RESULTS

The primary purpose of the investigation was to determine the effect of the landing-gear openings in the wing upon the lift and drag characteristics during take-off. Assuming an angle of attack for take-off that would give a lift coefficient of 1.0, and comparing the curves on Figure 3 for conditions with landing gear extended and wheel wells both open and closed, it can be seen that closing the wells reduced the drag coefficient only 2 percent. Therefore it can be said that the openings in the wing for the retractable landing gear of the Lockheed Altair have a negligible effect upon the take-off of the airplane.

Because of its retractable feature, the landing gear on the Lockheed Altair is not aerodynamically clean. It is interesting to note, however, that retracting the gear reduces the minimum drag of the complete airplane 50 percent. It is therefore apparent that, if the landing gear proper is streamlined to reduce the drag, the take-off characteristics will be improved; but such a change, if carried to the extreme, would have a detrimental effect upon the landing characteristics and might necessitate the installation of some device to reduce the landing distance required.

CONCLUSIONS

A retractable landing gear of the type on the Lockheed Altair may, when extended, account for 50 percent of the minimum drag of an airplane, but the openings that house the gear in the bottom surface of the wing have a negligible effect upon the lift and drag characteristics when the gear is extended.

Langley Memorial Aeronautical Laboratory, National Advisory Committee for Aeronautics, Langley Field, Va., March 16, 1933.

REFERENCE

1. DeFrance, Smith J.: The N.A.C.A. Full-Scale Wind Tunnel. T.R. No. 459, N.A.C.A., 1933.

Document 3-15(b), Hal L. Hibbard, "Problems in Fast Air-Transport Design,"* Mechanical Engineering 55 *(October 1933): 611-617.

Problems in
FAST AIR-TRANSPORT DESIGN
by Hall L. Hibbard

In 1910 the average speed of the fastest railroad trains in this country was 34.6 miles per hour. In 1920 this average dropped to 34 and in 1930 it was 40.9. Thus, over a period of twenty years, the average speed of the nation's thirty fastest trains increased 6.3 miles per hour. This rather unimpressive change in speed has been due in a large measure to the continuously increasing traffic congestion faced by all surface transportation. Increased speed has been fraught with danger. And here is one of the many advantages that air transport has over all others. Increased speeds, almost without limit, are possible with no attendant dangers and even added safety. Air transport, even during its short existence, has shown increased speeds of 30 to 50 miles per hour, and it has barely started.

It would be impossible in the brief space allotted to this paper to discuss all points of transport design. Therefore, a few, dealing particularly with increasing the speed of transport aircraft, have been chosen.

In connection with the discussion that follows, it will be of interest to have in mind a hypothetical airplane, and to note what effect certain changes have on it. Let us assume, therefore, that this hypothetical airplane has a gross weight of 7500 lb, a horsepower of 700, a wing area of 400 sq ft, a span of 50 ft, giving an aspect ratio of 6.25, a wing loading of 18.75 lb per sq ft, and a power loading of 10.70 lb per hp. Let us further assume that this is a low wing cantilever monoplane with retractable gear, controllable pith propeller, but with no wing flaps.

THE PROPELLER

Before high-speed airplanes became so numerous and slow-speed planes were in vogue, aircraft propellers were fairly satisfactory.The speeds were not so high but that added safety. Air transport, even during its short existence, has shown increased speeds of 30 to 50 miles per hour, and it has barely started.

It would be impossible in the brief space allotted to this paper to discuss all points of transport design. Therefore, a few, dealing particularly with increasing the speed of transport aircraft, have been chosen.

In connection with the discussion that follows, it will be of interest to have in mind a hypothetical airplane, and to note what effect certain changes have on it. Let us assume, therefore, that this hypothetical airplane has a propeller set at a pitch to give best performance at high speed also had satisfactory take-off and climb characteristics. On high-speed planes, however, a propeller with a fixed pitch will not have satisfactory characteristics for both take-off and high speed. One or the other must be sacrificed. The problem has become so acute that in some cases where speed could not be sacrificed the Department of Commerce requirements for take-off have limited the gross weight of the airplane. Such was the case two years ago with the first Lockheed Origin which was equipped with an engine without a supercharger. The take-off was so poor that even though the airplane was capable structurally of carrying a higher gross weight, this was not allowed. Of course, the propeller pitch could have been changed to secure a satisfactory take-off, but tests showed that the cruising speed was so reduced of the planes entered in the present air races. The engine diameter was greater than that of the fuselage, and the cowl was carried straight back. Another cowl was built which was drawn in at the rear. Speed tests were run with both types of cowl and the plane was approximately 15 miles per hour faster, when fitted with the cowl drawn in at the rear. In the case of a plane with a larger fuselage, cowls extending straight back were found to be best.

The first tests completed by the N.A.C.A. indicated that a double nose section in the cowl was beneficial. Later tests, however, showed that increased speeds could be obtained by omitting this inner section of the nose cowl and changing the shape slightly. British tests and some private tests in this country have verified this conclusion, but in spite of this fact, some manufacturers still continue to use the double section which not only reduces the speed but is also more expensive.

For speed and cooling, it is not the quantity of air passing through the cowl that is important but the velocity and distribution. It is a common error to assume that blocking off the air at the nose decreases the drag. Such is not the case. Air must pass through the cowl in order to give the least drag. Tests show that the drag is higher when the nose shutters arc closed than when they arc open. Much is to be learned about the proper distribution of air under N.A.C.A. cowls, and further tests should be conducted along this line.

POWER PLANTS

From the point of view of the airplane designer, the engine diameter should be as small as possible. In this connection it is gratifying to note the progress that is being made along this line with all types of air-cooled engines, including the two-row radial type. Aircraft manufacturers have had the experience of substituting engines of greater horsepower and larger diameter, only to find in almost every case

that the increase in speed was not what it should have been, because of the increase in frontal area.

In single-motor planes, there is but one location for the power plant, namely, in the nose of the fuselage. In multi-motor designs, if the engines are to be placed in the wings, the motors should be placed so that the propeller is located directly ahead of the leading edge of the wing by an amount equal to 2.5 percent of the chord. In this connection it is of interest to note the tests which the N.A.C.A. is at present performing in connection with air-cooled versus liquid-cooled engines with radiators in nacelles. The results indicate a drag of 74 lb with the air-cooled arrangement and drags of 72, and 76 lb, respectively, with two liquid-cooled installations. This translated into cruising speed of one of the later type bimotor transports would mean the same cruising speed for either installation. This was also verified by the Army some months ago in the case of two identical bimotor low-wing bombers, one with air-cooled and the other with liquid-cooled engines. The speeds of the two were almost identical.

Power plants in air transports should be supercharged. Transport airplanes rarely cruise at sea level. Supercharging will give the rated power at altitude and high output in emergencies at sea level for short periods of time.

LANDING GEAR

The gain in the speed of an airplane with a retractable landing gear over one equipped with a well-streamlined gear of the non-retractable type has been greatly exaggerated. A great increase in speed because of retraction of the gear usually means that the original landing gear design was faulty. Furthermore, after retractable gears are installed, there is always the tendency to compare speeds with the gear up and down, which is obviously unfair, as retracted landing gears are never faired or streamlined and arc usually quite unsightly.

Take, for example, the Lockheed Orion. This is the original Sirius model equipped with a retracting gear. The major cause of drag in landing gears is interference. In the Sirius landing gear, all struts arc nicely faired, fairings are placed over the wheels, and all joints to fuselage and wheels are well filleted. But the parts are too close together, angles are too acute, and the gear is close to the underside of the wing.The result is excessively high interference. Thus, with the retractable gear, the increase in speed was more than 2.5 miles per hour.

Careful wind-tunnel tests show conclusively that gears in which the interference has been removed add but little to the drag of the airplane. This type of gear is a pure cantilever type without external bracing of any kind, similar to that pioneered by Northrup. Care must be taken in the design of this gear to use a good streamline shape and it is important that the gear be carefully faired at the top into the wing or fuselage. A cantilever gear of this type will reduce the high speed of the airplane less than 6 miles per hour, which means a reduction in cruising speed of 3 to 4 miles per hour.

Thus it can be seen that there is some question as to the advisability of the retractable gear from the standpoint of speed increase. However, the retractable gear is still recommended as manufacturers will not install the non-interference type gear. They will read this article, or others, be much pleased and relieved to know that gear retraction gives such small increase in speed, and then install on the very next design the old type of landing gear with all its speed-reducing interferences.

When retractable gears first came on the market, rumors were spread about the terrible results that would surely ensue if an airplane was forced to land with the gear retracted. Up to the present, six cases arc known where Lockheed plants have been forced to land with the gear retracted. In no case have there been any injuries to occupants, and in no case have more than minor damages resulted from the landing. The airplane usually slides 150 to 250 ft, depending on the condition of the ground. Because of the very high cushioning effect when the wing is only a foot or so from the ground, the landing is not rough or severe.In other words, instead of being dangerous, retractable gears have become a safety feature and transport operators arc demanding them from that standpoint. It is easy to see that safer ice landings can be made in snow, in marsh lands, and on water; and in mountainous country landings can be made on very small patches of ground.

FUSELAGE AND ACCESSORIES

Fuselages for fast airplanes should be as small as possible, consistent with comfort. There is need for wind tunnel data on fuselage sizes as there is little information on this subject. The British in the Schneider Trophy racers found that decrease in frontal area did more to increase the speed than any other item. On the Super marine racer, the cross-section area was reduced from 8.46 to 8.I8 sq ft, with a resulting increase in speed of 11 miles per hour. This was in spite of the fact that the resistance per square foot of cross-sectional area was higher for the plane with the smaller cross-sectional area. In a comparison of two of last year's racers, it was shown that the drag at 100 miles per hour for the one with the larger fuselage was 89.7 lb, while that for the other was 80.4 lb, notwithstanding the fact that the latter had 30 square feet additional wing area.The straight away speeds of the two airplanes with the same horsepower were 2.47.3 and 2.77 miles per hour, respectively. It would appear then that there is a limit to fuselage size, and from most indications, the smaller the faster.

Another factor which should be taken into account in fuselage design and which has not been given enough consideration is the shape of the fuselage across the wing. Any element, even a flat sheet, placed vertically and parallel to the airstream will interfere with the airflow on the upper surface of a wing. There is a definite flow of air over the upper surface of cantilever wings, such as are being used on present-day transports, which should not be disturbed. It is evident that if a flat sheet affects the airflow, the modern fuselage must make a great disturbance. The fuselage should conform in some degree to the direction of airflow set up by the wing.

Document 3-15(c), "Preliminary Study of Retractable Landing Gears for High and Low Wing Monoplanes,"* Air Corps Information Circular *7 (18 February 1933): 1-9.

PRELIMINARY STUDY OF RETRACTABLE LANDING GEARS FOR HIGH AND LOW WING MONOPLANES

(Prepared by E. H. Schwartz, Materiel Division, Air Corps, Wright Field, Dayton, Ohio, October 29, 1932)

SUMMARY

This report sets forth the results of an investigation made to determine whether or not the use of the retractable landing gear is advantageous in view of the large number of difficulties encountered in its design, operation, and maintenance. The investigation also included cantilever landing gears with streamlined wheel fairing and fixed streamline landing gears. The results of this study indicate that the retractable landing gear can be used advantageously on the multi-engined monoplane with the landing gear retracting into the engine nacelle or wing, and that the cantilever landing gear with wheel fairing is best suited for pursuit, attack, 2-place observation, or single-engine cargo airplanes. These landing gears permit use of monocoque fuselage structure.

A number of retractable, cantilever, and fixed streamline landing gears were examined. The indicated increase in high speed due to retraction of retractable landing gears is misleading, as in all cases it was found that the retractable landing gear was not streamlined, and large wing or fuselage openings prevailed with the landing gear in the down position, giving a low high speed with wheels down. This accounts for the comparatively smaller speed increase obtained from wind tunnel tests on removal of faired landing gears. A study was also made of the weights of the various types of landing gears on present United States Army airplanes for comparison.

The number of retractable landing gears of the fuselage and wing type procured by the Air Corps is small. For this reason, little work has been done up to the present on improving the design of retractable landing gears. Therefore, a study was made of possible retractable landing gears, and, as a result, the landing gears shown in Figures 1 to 10, inclusive, were conceived, and it is believed that they have good possibilities for future designs.

This study also showed that a good installation of a retractable landing gear to an existing airplane cannot be made efficiently or economically without a complete redesign of fuselage or wing.

All weight data on landing gears was obtained from the actual weight statements AN-9102 and AN-9103 furnished the division by the contractors. All airplane weights were taken from the 689 inspection reports of the various airplanes.

All data on the high speed of airplanes and models was obtained from official flight and wind-tunnel tests with the exception of the YlC-17 airplane.

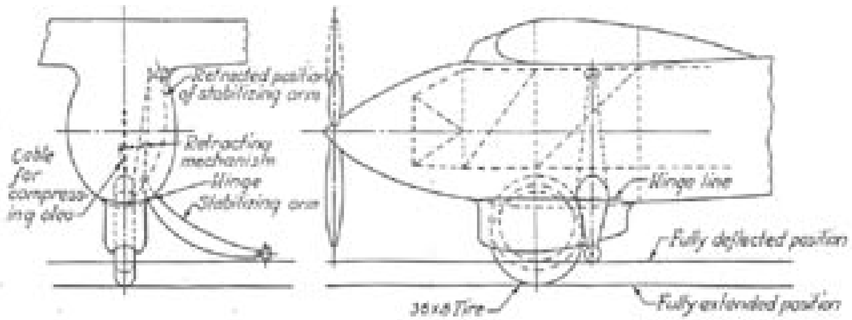
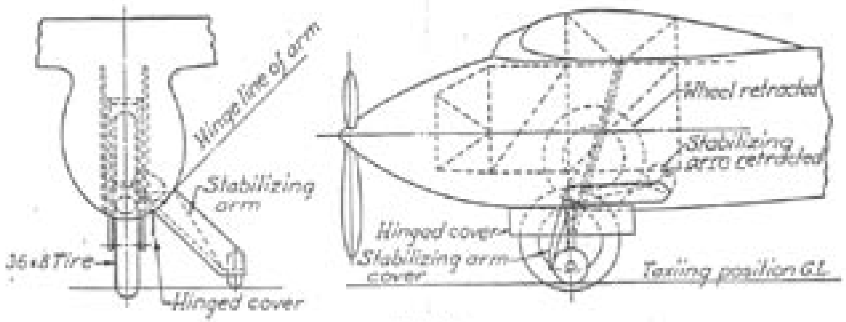


Figure 1



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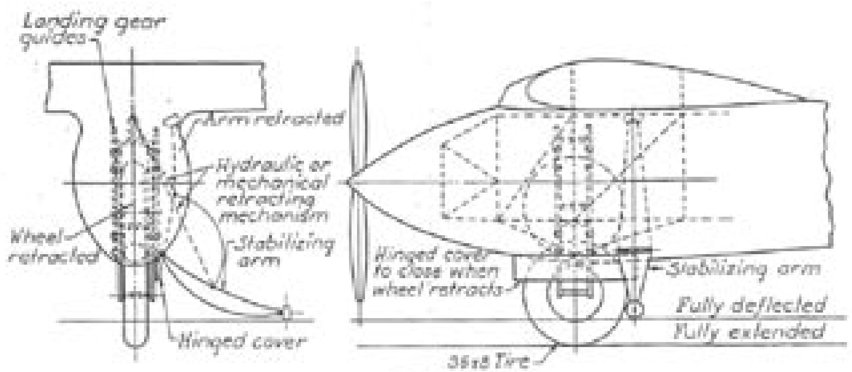

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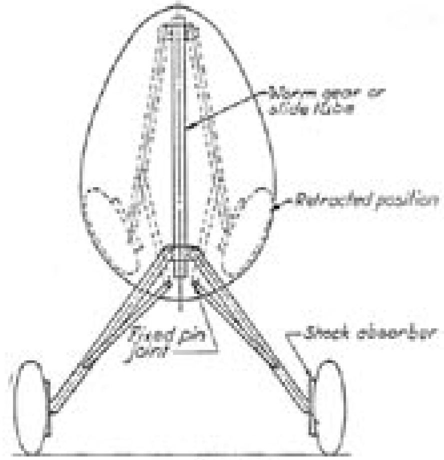

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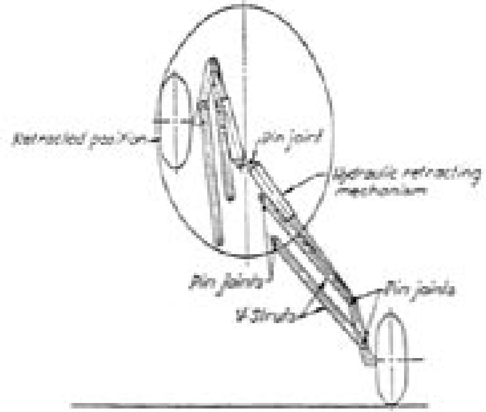

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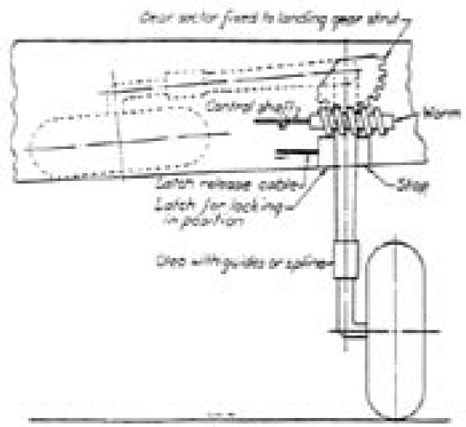

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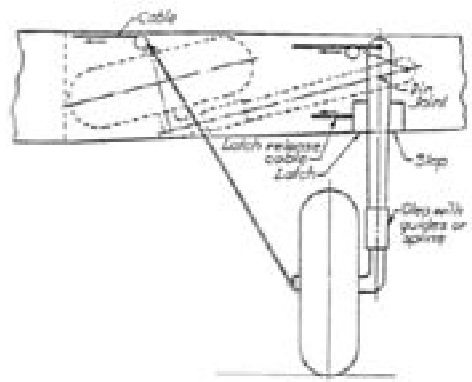

Figure 7

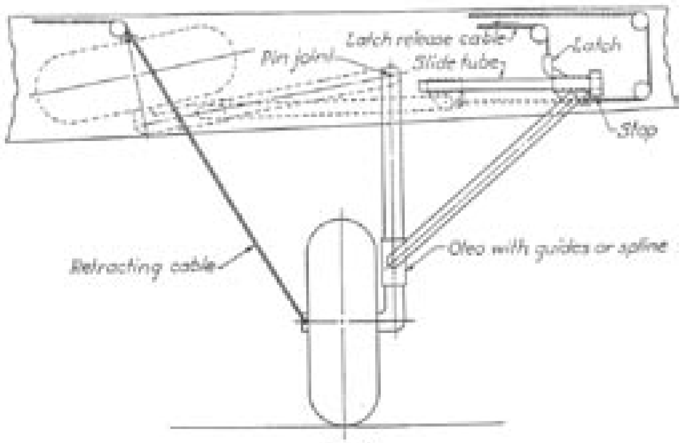

FIGURE 8

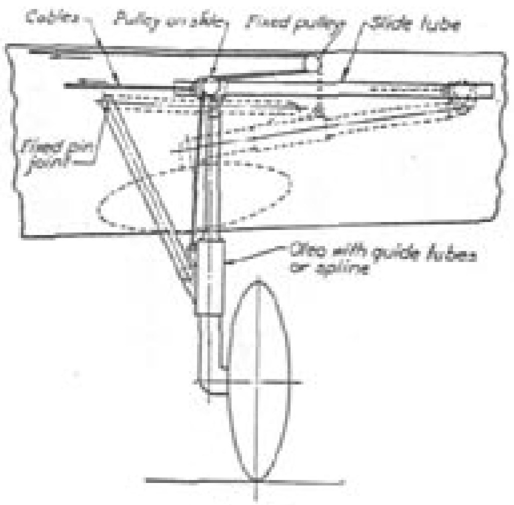

FIGURE 9

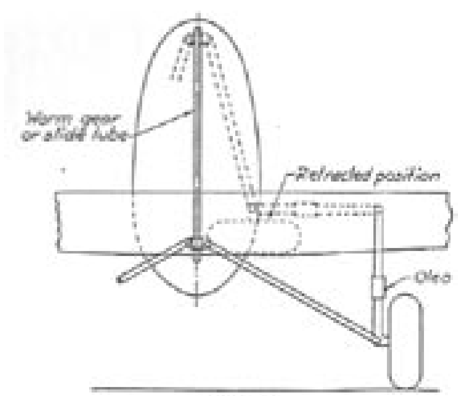

FIGURE 10

OBJECT

The object of this report was to determine whether or not the use of the retractable landing gear is advantageous in view of the large number of difficulties involved in its design, operation, and maintenance, and to determine the type of landing gear which will give the best installation and performance on various types of monoplanes in use by the Air Corps.

DISCUSSION

In this investigation the YlC-12 airplane has been considered as a typical high-wing monoplane for the possible installation of a retractable landing gear. Similarly the YlC-23 or XP-900 may be considered in the same class for low-wing monoplanes. (Gross weight 4,000-5,000 pounds.) XO-35 or XB-9 considered typical of engine nacelle type landing gear.

It must be realized that the application of a retractable landing gear to an existing airplane will involve considerations and result in decisions that would differ somewhat from those considerations involved at the time of layout of a new design, for in the latter case fuselage shape, bulkhead locations, spar locations, wing thickness, etc., can be readily laid out or altered to best suit a retracting mechanism.

At the start of the investigation certain governing factors must be recognized, namely

(1) That the landing angle of the airplane be as large as possible, of a magnitude to enable the airplane to develop not less than 90 percent of its maximum lift coefficient in landing. A decrease in landing angle will result in an increased landing speed.

(2) That the angle in side view between a line passing through the center of gravity of the airplane and the center of the wheels, with the airplane in the level landing attitude, and the vertical must not be less than 12° for airplanes without brakes and must be 20° for airplanes with brakes.

(3) That the angle in the front view between the vertical and a line joining the center of gravity and the point of contact of either wheel and the ground shall not be less than 25°.

(4) That the propeller clear the ground by at least nine (9) inches with the airplane in either a flying or landing position.

The foregoing requirements are taken from the Handbook of Instructions for Airplane Designers, Volume I.

The purpose for which the airplane is to be employed may establish other requirements, such as:

(1) That the landing gear in its retracted position offer no interference with the pilot's location.

(2) That the cargo or bomb space remain intact in cargo or bomber airplanes.

(3) That certain space in the vicinity of the center of gravity, or elsewhere, be reserved for military equipment, etc.

(4) That the fuselage section be as small as possible to give the best vision possible.

There are other general requirements to be met by retractable landing gears, again possibly subject to alteration in the case of special-purpose airplanes:

(1) That the handling of the airplane on the ground be as simple as possible (compared with a 2-wheel landing gear with swiveled tail wheel).

(2) That the retracting gear and movement of parts be such as to permit a structure capable of carrying the fuselage design loads, and that this structure preferably be determinate and simple.

(3) That the retracting mechanism be reliable and incapable of jamming in any intermediate position.

(4) That the landing gear itself be capable of absorbing the prescribed landing loads without damage to the fuselage or airplane.

(5) That maintenance of the landing gear be readily accomplished.

(6) That the landing gear be lowered or dropped with reasonable speed.

(7) That the wing or fuselage openings be closed by means of doors, fairing, etc., on retraction of the landing gear.

Retractable landing gears may be classed as follows:

(1) Fuselage type, with landing gear retracting into the fuselage and the mechanism housed within the fuselage.

(2) Wing type, with landing gear folding up into the wing and the mechanism located in the wing.

(3) Engine nacelle type, with landing gear retracting back into the wing, engine nacelles, or both, of multiengine monoplanes with the engines located outboard of the fuselage.

The fuselage type of landing gear may be either a single-wheel or a 2-wheel landing gear. The single-wheel landing gear does not require as wide a fuselage as the 2-wheel on retraction; but requires for stabilization the use of two small auxiliary wheels, which must also be retracted into the fuselage. This requires the use of two retracting mechanisms-one for the main wheel and one for the two auxiliary wheels. This means excess weight and more fuselage cut-outs.

The fuselage type is best suited for a high-wing monoplane. The distance from the wing to ground on a high-wing monoplane prohibits the use of the wing type, since wing cut-outs and length of retracting mechanists depend on the landing gear length. This would give a very poor and inefficient installation. The fuselage-type landing gear occupies useful and valuable space at an important section of the fuselage near the center of gravity of the airplane. In cargo or bomber airplanes cargo or bomb space is valuable near the center of gravity. In other types of airplanes this place is important for the fuel tank and military equipment location. A large fuselage section is necessary in order to house the landing gear and mechanism. The size of the fuselage section depends on size of wheels, landing gear length, and length of retracting mechanism. The length of retracting mechanism is dependent on the length or travel of the landing gear. The landing gear length must be such so as to meet the requirements of the Handbook as stated on page 1. This type landing gear is unsuitable for pursuit, attack, or 2-place observation airplanes, since fuselage space is very limited and since a small fuselage section is most important for vision and performance. Due to the large cut-outs on the sides and bottom of a critical section of the fuselage, an inefficient structure must be used to carry the required loads. An inefficient structure means an excess structure weight. The large cut-outs necessary for retraction of this landing gear prohibits the use of a monocoque structure.

The wing type of retractable landing gear is best suited for a low-wing monoplane, which requires only a short landing gear, since the length of landing gear determines the size of cut-outs and space needed for retracting mechanism and retracted landing gear. In order to house the retracted landing gear and retracting mechanism, a thick wing section is necessary. For this reason, on a tapered wing monoplane the landing gear is retracted in close to the fuselage to make use of the maximum wing thickness available. This eliminates the use of outboard wing fuel tanks. On this type of airplane the landing gear cannot be retracted into the center section of the wing, due to the large cut-out necessary in the wing at the wing attachment fittings, which are at a critical section of the wing. With this type of retractable landing gear it is most important to close tip the wing openings on retraction by means of doors, plates, or fairing. An excess weight is added due to addition of the doors, plates, or fairing for closing the wing openings, due to an inefficient wing structure necessary to house the retracted landing gear and due to the addition of the retracting mechanism. Due to the wheels being forward of the front spar, the axis of rotation or hinge line must be at an angle to the chord line in order to fold the landing gear up between the spars. Where a slide tube or screw is used, unless the spars are far enough apart, ball and socket joints must be used on the struts to prevent interference with the rear spar, due to the landing gear swinging at an angle to the chord, since, with pin joints, the retracting mechanism must be in a plane perpendicular to the axis of rotation or hinge line. This type of retractable landing gear permits the use of monocoque fuselage.

The engine nacelle type of retractable landing gear is restricted to monoplanes with multi-engines located outboard of the fuselage. The engine nacelles are used advantageously to wholly or partially house or fair-in the retracted landing gear. This landing gear on a low-wing monoplane swings about the fitting on the front spar back into the wing in front of the rear spar. The wheels of this type landing gear cannot be fully retracted into the wing due to the size or diameter of the wheels and the depth of the wing section in front of the rear spar, for example, the YB-9, XB-907, and YO-27. In a high-wing monoplane with the engines located below the wing, as on the XO-35, the landing gear swings back behind the engine. The protruding wheels on the high and low wing monoplane installation are used to advantage for protection of the airplane against possible failure of retracting mechanism and possible failure of pilot to drop the landing gear. The design is such that

TABLE 1.—*Landing-gear weights*

FUSELAGE TYPE, RETRACTABLE

Airplane	Total weight: Landing gear (pounds)	Total weight: Landing gear (per cent of gross weight)	Weight of landing gear chassis (pounds)	Weight of wheels, brakes, brake mechanism (pounds)	Weight of wheel fairing (pounds)	Weight of retracting mechanism (pounds)	Gross weight of airplane (pounds)	Landing load factor	Remarks
YO-40	294.8	6.2	136	26	....	82	4,828	6	Retracting mechanism, cable operated, second-class.
WING TYPE, RETRACTABLE									
XP-900	272.6	6.2	133.4	105.7	....	34.5	4,360	7	Cable operated mechanism, second-class.
ENGINE, NACELLE TYPE, RETRACTABLE									
YO-27	399	3.6	221	198	....	80.0	10,020	6	Cable operated mechanism, second-class.
XO-21	511.5	5.0	229.8	170.1	....	101.2	10,204	6	Hydraulic mechanism.
YB-9	572.8	4.5	220.5	300.9	....	131.1	12,811	5	Positive acting mechanism, screw type.
XB-907	844	6.1	346.7	218.5	....	78.8	13,780	5	Cable operated mechanism, second-class.
CANTILEVER									
XP-22	255	7.6	137	78	40	....	3,354	7	Cantilever with streamlined wheel fairing.
XP-6E	244	6.0	118	84	42	....	3,392	7	Do.
YO-31	279	3.8	129	104.9	35.2	....	4,024	6	Do.
NONRETRACTABLE									
P-6	194	5.5	100	84	....	....	3,172	7	Split-axle type.
XP-16	222.4	6.3	95.4	104.5	12.8	....	3,566	7	Do.
O-25C	227	4.8	120.7	101.3	....	....	4,656	6	Do.
YO-13	259	5.6	125	117	22.0	....	4,615	6	Split-axle type with wheel fairing.
XP-28	211	7.5	132	84	....	....	3,224	7	Split-axle type.
XA-8	458	8.0	169	179	113	....	5,708	6	Low-wing landing gear with streamlined fairing.
Y1C-12	191.6	4.6	90.1	55.5	....	....	4,171	5.5	Split-axle type.
Y1C-17	294.2	5.7	145.0	90	30	....	5,172	4.5	Wire-braced landing gear.

the exposed part of the wheel strikes the ground first, thus protecting the airplane against serious damage. For this reason the retracted wheels are not fully faired, thus saving the added weight of streamlined fairing. This landing gear is best suited for heavy cargo, bombing, or 3-place observation monoplanes and does not take up any valuable fuselage or wing space. Only small wing cutouts are necessary. Due to its short length, this landing gear is not heavy, and its weight compares very favorably with the non-retracting landing gear. It permits use of monocoque fuselage. For comparison of the retractable landing gear with the non-retractable landing gear the following table is given:

Retracting mechanisms may be classed as follows:

(1) Positive acting, as the screw or gear type.

(2) Cable operated for retraction and lowering.

(3) Cable operated on retraction only, but dropping by gravity.

(4) Hydraulic or oleo action.

The first group is positive in action and is very suitable for heavy airplanes. The screw has the advantage of self-locking the landing gear in any position. It can be readily adapted for any speed, but means must be provided for lowering the landing gear fast and retracing the landing gear with a reasonable speed. The screw type requires a long screw, which in turn requires much fuselage or wing space. The gear-

TABLE 2.—*High speed of airplanes with various types of landing gears*

Airplane	High speed: Wheels up or with fairing (miles per hour)	High speed: Wheels down or without fairing (miles per hour)	Increase in high speed (miles per hour)	Increase in per cent of high speed	Engine: Type	Engine: Horsepower	Remarks
YO-40	193.8	157.4	36.4	24.4	SR-1820E	650 at 1,900 r. p. m.	Wheel fairing flight tests; speed increase due to retraction of landing gear.
XP-900	214.1	165.6	46.5	27.6	V-1570C	600 at 2,400 r. p. m.	Same as above.
Y1C-23	181.6	133.6	48.0	36.2	R-1340D	450 at 2,100 r. p. m.	Do.
YO-27	184.8	158.1	26.4	16.7	GIV-1570C	2 at 600 at 2,450 r. p. m.	Do.
XO-31	174.2	163.6	10.2	6.1	do	do	Do.
XB-9	188.0	172.5	15.5	9.0	SR-1860B	2 at 575 at 1,950 r. p. m.	Wheel fairing flight tests at 6,000 feet, speed increase due to retraction of landing gear.
XB-907	194.6	153.6	41.0	26.6	GIR-1820	2 at 600 at 2,200 r. p. m.	Wheel fairing flight tests; speed increase due to retraction of landing gear.
XB-907	195.6	173.0	22.6	13.2	do	do	Wheel fairing flight tests; increase due to retraction, with landing gear sheathing off.
XP-22	202.4	No data available without fairing			V-1570C	600 at 2,400 r. p. m.	Wheel fairing flight tests; cantilever landing gear.
Curtiss	P-6E, 194.5 at 5,000 feet.	P-6A, 176.8 at 5,000 feet.	17.7	10.0	do	do	Wheel fairing flight tests; speed increase due to use of cantilever landing gear on P-6E instead of split-axle landing gear on P-6A.
YO-31	182.5 with fairing.	178.5 without wheel fairing.	4.0	2.2	GIV-1570C	600 at 2,450 r. p. m.	Wheel fairing flight tests; speed increase due to use of wheel fairing on cantilever landing gear.
XP-16	196 with landing gear off.	182 with landing gear on.	14.0	7.7	V-1570C	600 at 2,400 r. p. m.	Wheel fairing wind tunnel tests; speed increase due to removal of landing gear.
YO-60	145.5 with wheel fairing.	142.5 without wheel fairing.	2.9	2.0	V-1150E	435 at 3,200 r. p. m.	Wheel fairing flight tests; speed increase due to use of wheel fairing on split-axle type landing gear.
XP-20	188.8 with wheel fairing.	187.0 without wheel fairing.	1.8	1.0	SR-1820E	575 at 1,800 r. p. m.	Do.
XA-8	213.8 with landing gear off.	194.8 with landing gear on.	19.0	9.8	V-1570C	600 at 2,400 r. p. m.	Wheel fairing wind tunnel tests; speed increase due to removal of landing gear.
Lockheed	Y1C-17, 191.0	Y1C-12, 178	13.0	6.3	Y1C-17, SR-1340E. Y1C-12, R-1340C.	Y1C-17, 500 at 2,000 r. p. m. Y1C-12, 450 at 1,900 r. p. m.	Y1C-17 high speed not official; increase in high speed due to wire-braced landing gear, wheel fairing, and supercharged engine.

sector type does not require much space; but means must be provided for locking in position and stops must also be provided.

The second group makes use of cables and pulleys for retraction and lowering of landing gear. Cables are easily adapted to an airplane, but the system of pulleys and cables must be complicated due to the necessity of cables for releasing lock on landing gear for retraction as well as the double system for lowering and retracting landing gear. Tension must be maintained on the free cable on lowering to prevent over-running of cable on drum and snagging of cable on parts of the airplane. Stops and catches must be provided to lock the landing gear in down position and to take the required loads on landing. Care must be used in this installation to prevent chafing of the cables. The double system of cables insures more positive locking of landing gear in lowering against any air resistance, as it does not rely on gravity. Frequent inspection of the cables is necessary.

The third class depends on cables for retraction and on gravity for lowering. It is essential to have tension in the cable at all times on dropping of landing gear to prevent the slack cable from snagging or overrunning the drum. This type gives a lighter installation than the second type. The cable system must also include means of releasing the lock or catch on retraction. Air loads on some landing gears may be such as to resist the dropping of the landing gear and prevent the locking of it in place. For this reason the single cable system is not recommended.

The fourth class, that is, hydraulic or oleo type, gives a good installation due to the absence of moving parts. The tubes from the cockpit to the cylinder can be easily located to suit the airplane. A long cylinder is required to obtain the desired travel of landing gear. For this reason the use of this type is limited to space available for the installation. With the tubes properly fastened and supported and with frequent inspection of tubes and connections, there is little danger of tube breakage which would render the retracting system useless. This type is easily adapted for any weight of landing gear and is positive in action in either lowering or retraction of landing gear. An excess weight is added due to the addition of pump, valves, hydraulic unit, and tubing.

Table 1 shows the actual weights of various types of landing gears as used on present Army airplanes. The retractable landing gear weights are grouped in their proper class. The retractable landing gear weights of the fuselage or wing type do not offer a fair comparison with the other types of landing gears, as the retractable landing gear weights of these two classes do not include the excess weight necessary in the inefficient structure of the wing or fuselage due to cut-outs, nor the excess weight due to a larger fuselage or thicker wing section necessary to house the retracted landing gear and retracting mechanism. The retractable landing gear weights of the engine nacelle type with landing gears attaching to engine mount do not include the heavier engine mount or the weight of added cowling which is charged to the engine. In using the figures of Table 1 the design landing load factors must be taken into consideration.

Of the six Army airplanes using retractable landing gears, four employ the use of cables for retraction and lowering of the landing gear. The XO-35 uses the hydraulic system for retraction, and at first glance seems rather light in weight; but, due to the engines being located below the wing, the landing gear is very short. However, the landing gear is very simple, and the only added weight is the oleo unit, tubes, valve, and pump. It is very accessible and provides for easy maintenance.

The YB-9 uses the screw type mechanism for retraction. It is heavier than the XO-35 landing gear, due partly to the wing location with respect to the ground, requiring a longer landing gear. However, it is lighter than the landing gear of the XB-907, using cables for retraction.

The cantilever landing gears from Table 1 seem to be heavier than the retractable landing gears at first glance, but the retractable landing gear weights do not include excess fuselage or wing weight. The cantilever landing gear weights are true, so they may be easily compared with split-axle type landing gear weights. Both monoplanes and biplanes using cantilever or non-retractable landing gears are listed in Table 1, but they may be compared directly, as these landing gears attach directly to the fuselage and are independent of wing location or the type of wing. The P-6 and XP-6E are good examples for comparison as they are almost identical, with the exception of the landing gear, and have same load factor. The weight of the P-6 split-axle landing gear is 5.8 percent of the gross weight, and the weight of the XP-6E cantilever landing gear is 6.9 percent of the gross weight, or an increase in weight of 1.1 percent due to the installation of the cantilever landing gear with streamlined wheel fairing. The 0-25C and the YO-31 also form a good comparison, as their gross weights are practically equal and their design landing load factors are the same. The 0-25C split-axle landing gear weighs 4.8 percent of the gross weight, and the YO-31 cantilever landing gear weighs 5.8 percent of the gross weight, which is 1.0 percent heavier due to the use of wheel fairing and cantilever landing gear.

The YO-1G uses a split-axle type of landing gear and streamlined wheel fairing. The weight of this type of landing gear is 5.6 percent of the gross weight compared to 5.2 percent for the same airplane without the wheel fairing, or an increase of 0.4 percent due to the addition of wheel fairing.

The weight of the XA-8 fixed streamline landing gear, which is attached to the wing, is very heavy, that is, 8 percent of the gross weight. This is due to the weight of the fairing (50 pounds) and the provisions for synchronized guns, etc.

Table 2 shows the high speed of various airplanes and models with retractable landing gears, with landing gears removed, with cantilever landing gears, with low-wing monoplane landing gears, and with split-axle type of landing gears. The figures show a very high increase in high speed due to the retraction of the landing gears. In the cases of the XP-900, XO-40, XB-907, and YlC-23, the retraction of the landing gear increases the high speed about 30 percent. These retractable landing gears have an exceedingly high drag when lowered, due to the large fuselage or wing openings, due to no streamline fairing of the struts or wheels, and due to exposed fairing or doors for closing the openings being open.

Flight tests of XB-907 were made for high speed with and without landing gear shielding with landing gear down and with landing gear retracted. The high speed with wheels retracted was the same (195.8 miles per hour) without landing gear shielding as with landing gear shielding, but with wheels down the high speed increased 23 miles per hour by removing the shielding. On this airplane the shielding is a detrimental clue to the excess weight and increased drag with wheels down requiring a longer distance for take-off.

These speed increases are not true indications of the actual gain in speed of a retractable landing gear over a well streamlined non-retractable landing gear. Wind tunnel tests on the XA-8 and XP-16 models show an increase of only 9.8 and 7.7 percent, respectively, for the removal of these streamlined landing gears. This is the ideal condition of retraction, but it is never realized in practice since perfect closing up of openings is not possible and since changes must be made in the fuselage or wing to accommodate the retractable landing gear and its mechanism. It is safe to assume that the actual speed increase of a retractable landing gear is not greater than 6 percent over the split-axle type or low-wing monoplane landing gears.

A good comparison of high speed can be made between the cantilever and split-axle type of landing gears by taking the P-6A and P-6E airplanes which have same engine. The P-6E with a cantilever landing gear weighing 6.9 percent of the gross weight has a high speed of 194.5 miles per hour at 5,000 feet, and the P-6A with split-axle type of landing gear weighing 5.8 percent of the gross weight has a high speed of 176.8 miles per hour at 5,000 feet, or a gain of 10 percent in high speed due to the use of cantilever landing gear which weighs 1.1 percent of the gross weight more than the split-axle type.

From actual flight tests on the YO-31 with cantilever landing gear a high speed increase of 2.2 percent was obtained by use of wheel fairing with an increase of 0.8 percent in gross weight. From flight tests on the O-1G (split-axle type landing gear) a high speed increase of 2.0 percent was noted due to the use of streamlined wheel fairing, which increased the gross weight by 0.5 percent. The high speed increase of the XP-20 (split-axle type of landing gear) obtained from the flight tests was 1.0 percent by the use of wheel fairing. This data indicates that streamlined wheel fairing is essential for high performance of airplanes with non-retractable landing gears, as a large increase in high speed results from a small increase in landing gear weight due to wheel fairing.

Table 2 shows that the YlC-17 with wire-braced landing gear and wheel fairing is 6.3 percent faster than the YlC-12 with split-axle type of landing gear with an increase in landing gear weight of 1.1 percent of the gross weight. Since the high speed on the YlC-17 is not official and since the engine of the YIC-17 is 50 horsepower greater than that of the YlC-12, no information can be gotten from these figures.

Figures 1 to 3, inclusive, show several possible methods of retracting a single wheel landing gear. These landing gears use two small auxiliary wheels for stabilization on the ground. The landing gear of Figure 1 does not fully retract, only by the amount of oleo travel. It employs the use of a good streamlined fairing for the wheel. The stabilizing arms are retracted vertically into the fuselage and are so shaped to close up the fuselage openings on retraction. Figures 2 and 3 show two different methods of retracting the auxiliary wheels in addition to showing the retraction of the large wheel. In Figure 2 the large wheel retracts up and back in the fuselage to permit more room in the fuselage for the retracting mechanism. The auxiliary wheels swing back into the fuselage and fairing is so shaped to close up the fuselage openings. Figure 3 shows the large wheel retracts vertically into the fuselage as well as the stabilizing arms, which also close up the openings in the fuselage. The landing gears of Figures 2 and 3 use a hinged cover to close up the opening in fuselage when the main wheel is retracted. Any one of the retracting mechanisms may be used, depending on the fuselage space available. These types of landing gears do not require as wide a fuselage as a 2-wheel landing gear. The use of a 3-blade propeller can be used advantageously to lower the fuselage, thereby shortening the landing gear length.

The landing gear shown in Figure 4 is very suitable for a high-wing monoplane, and does not require a complicated mechanism, but has the disadvantages of Class I landing gears as stated on page 2. It is positive in action and has good mechanical advantage throughout its entire travel. The use of cables and slide tube or screw mechanism is recommended for this landing gear.

The landing gear of Figure 5 is also of the first class. The struts form a parallelogram and the wheels are kept in a vertical plane in any position. A hydraulic mechanism is used for retraction. This landing gear requires a wide fuselage and large fuselage cut-outs. However, it does not require a deep fuselage.

Figures 6 to 9, inclusive, are landing gears of the second-class retraction into the wing. Figure 6 shows one of these landing gears using a worm gear and gear sector for retraction. A stop and catch or locking device must be used to prevent landing loads being taken out by the mechanism. Means for releasing the locking device must also be provided for retraction. This mechanism does not require a thick wing section. Figure 7 is similar to Figure 6, except cables are used entirely for retraction and lowering of the landing gear. Figure 8 shows a landing gear which uses a slide tube and cables for retraction. A latch, or locking device, and a stop is also necessary to take the landing loads. This mechanism does not require a thick wing section. It also has a good mechanical advantage in any position of the landing gear. The landing gear shown in Figure 9 has good possibilities. The pull of the cable on retraction is changed from the slide to the landing gear proper to the best advantage as the slide pulley passes the fixed pulley. Thus the first pull of the retracting cable breaks the slide loose and as the slide passes the fixed pulley the cable leaves the slide pulley and the landing gear is lifted directly, thereby giving a straight and direct pull on the landing gear. This landing gear requires a thick wing section. All of these landing gears must swing about an axis or hinge line which is at an angle to the chord line in order for the landing gear to retract between the spars. For this reason, where the landing gears are not far enough apart to permit the landing gear to swing in the same plane as the mechanism, ball and socket joints must be used.

The landing gear shown in Figure 10 comes in neither the first or second class landing gear, but is a cross between the two. The landing gear folds up into the wing and the retracting mechanism is housed in the fuselage. It has a good mechanical advantage throughout its travel. It has the disadvantage of cut-outs at a critical section of the wing; that is, the point of attachment of the wing to the fuselage, and also eliminates the use of fuel tanks in the center section of the wing. This landing gear does not require a wide fuselage section nor does it require a thick wing section, as it retracts into the thickest section of the wing.

CONCLUSIONS

As the result of this study, it was found that a good installation of a retractable landing gear to an existing airplane cannot be made efficiently or economically without a complete redesign of fuselage or wing.

The wing and fuselage types of retractable landing gears in present designs are complicated, heavy, and unsatisfactory in operation. For these reasons the retractable landing gears shown in Figures 1 to 10, inclusive, are proposed and show good possibilities for future designs. The fuselage type of retractable landing gear does not readily permit the use of monocoque fuselage structure.

As a result of the study of the nacelle type of retractable landing gears, it is believed that this landing gear will give far better high-speed performance than a cantilever or split-axle type of landing gears for multiengine monoplanes such as bombers, cargo, or 3-place observation airplanes. This type of retractable landing gear does not interfere with use of monocoque fuselage structure. The use of a cantilever landing gear on these airplanes would require a heavy landing gear and would increase the drag of the airplane. The use of a screw or hydraulic retracting mechanism gives a reliable and good installation for the engine nacelle type of retractable landing gear.

It was also found that fairing or shielding on the nacelle type of retractable landing gear may not increase the high speed with wheels retracted and that it may decrease the high speed materially with wheels down. Thus the excess weight of fairing or shielding is of no advantage, but a detriment due to increased drag with wheels down, requiring a longer distance for take-off.

The results of this investigation also show that the cantilever landing gear with streamlined wheel fairing gives the best installation for monoplanes or biplanes in the single-engine class, such as pursuit, 2-place observation, attack, or light cargo airplanes. This installation permits the use of a small fuselage, which is of vital importance in a pursuit, attack, or observation airplane for vision and high-speed performance; and it requires no fuselage or wing space, which is valuable in these airplanes for fuel tank or military equipment locations. This landing gear can be easily adapted to existing airplanes without any major changes or alterations, including monocoque fuselage structures.

It is believed that the cantilever landing gear with wheel fairing will give a better high-speed performance than the low wing monoplane landing gear and the wire braced landing gear with a lighter installation.

This study proves conclusively that the use of streamlined wheel fairing is important for high-speed performance for non-retractable landing gears with only a small increase in gross weight.

Document 3-15(d), Richard M. Mock, "Retractable Landing Gears,"* Aviation *32 (February 1933): 33-37.

Though retractable landing gears for landplanes have only come into popular use in the last few years, the idea is by no means new. In 1876 Penaud and Gauchot patented a design of an airplane which had a front landing chasses of the wheel, all retracting into the fuselage to reduce the air resistance. However, as far as can be learned the idea never took a practical form until after the War, when Dayton-Wright built a high wing cantilever monoplane for the 1920 Gordon Bennett race with the wheels retracting flush in the sides of the fuselage. The year before Lawrence Sperry built an amphibian flying boat which is believed to have had the first practical retractable gear.

However, these were special purpose planes. On normal civilian and military planes of that time the drag of the landing gear compared with the total drag of the airplane was not sufficient for a retractable gear to give enough increase in speed to warrant the additional complication. For the next ten years the problem received little attention. Today most high speed planes are "cleaner," so that the landing gear drag is a greater proportion of the total. Thus, the gain by the elimination of landing gear drag is likely to be greater, though the value of tail wheel retraction is still doubtful.

As a rule, where the genera arrangement allows a reasonably efficient retractable landing gear it has been found that, compared with a similar design with fixed wheel type undercarriage, the speed is increased only 3-4 per cent at 130 m.p.h. Because faster planes are generally cleaner the increase grows to 6-7 per cent at 150 m.p.h. and at 165-170 m.p.h. to about 10 per cent. One well known low wing design had a high speed of about 175 m.p.h. with a streamlined external gear, while with the landing gear fully retracted the speed was increased some 25 m.p.h., or 14 per cent. It is possible that as much as 20 per cent increase in speed might result at 185-195 m.p.h. from retracting the landing gear on a very clean design. On designs where the wing bracing is combined with a streamlined landing gear, as on may low wing racers or the Bellanca Airbus, the gain due to retraction would of course be debatable.

At the speeds achieved today the exact relative merits of the streamlined external gear (whether or not it is part of the wing bracing) and the retractable type depend much upon the ingenuity of the designer and the purpose, type and size of the airplane.

SPACE

On some type insufficient space is available in the wing or fuselage to retract the landing gear. Fundamentally, for high speed flight it is believed better to increase the frontal area slightly to provide the needed space. Thus all parts are concentrated into one mass that can be given the best possible shape, rather than have a number of separate units with the accompanying interference between them and the possible disturbances where they meet. This problem is closely tied in with problems of where to house the wheels and will be discussed later.

WEIGHT

An increase in speed with the same power means less flying time, hence less fuel and oil required for a given flight distance. The saving in weight of fuel and oil goes to offset the additional weight of the retracting mechanism, linkages and accompanying increase in structural weight.

An example might help to illustrate this point. Assuming an airplane having 8,000 lb. gross weight, 3,000 lb. useful load, and cruising at 150 m.p.h., the addition of a retractable mechanism might increase the weight empty 60 lb., and reduce the useful load by the same amount. The fuel consumption might be assumed to be 35 gal. and oil consumption 3 gal. per hour, or a total of 230 lb. per hour. A 10 per cent increase in speed would reduce the time for a given flight 9.1 per cent, saving about 21 lb. of fuel and oil per hour (neglecting that slightly smaller tanks could be used.). Therefore for a 450 mile flight, if this increase in speed is achieved, the additional weight of the retracting gear would have no net effect on the pay load. This result is typical, whatever the size of the plane.

In general a fixed landing gear weighs 6-9 per cent of the empty weight of the airplane or 10-14 per cent of the useful load, though this may vary as much as 7-17 per cent. A retractable landing gear increases the landing gear weight 10-20 per cent, reduces the useful load 1-3 per cent. Airplanes of about 10 lb. per hp. Loading use 7-11 per cent of their useful load per hour in fuel and oil. Thus, with a three hour range the additional weight would be offset by the fuel and oil saving if the speed were increased 5-7 per cent. For a two hour flight, a 10-13 per cent increase would be sufficient.

COST

Outside of the greater value of a faster service, an increase in speed often means that fewer planes are needed to keep a given frequency of schedule. In addition, the flying time to cover a given distance is less, meaning a reduction of all costs proportional to flying time, such as fuel and oil, flying crews pay and maintenance and overhaul of airplane and engine.

Consider a conservative approximation of the additional expense due to a retractable gear. Assuming that the initial cost of the retractable landing gear is $500-$1,500, depending on the size, type and purpose of the plane, there will be an increase in cost of depreciation of 10 cents to 30 cents per hour based on 5,000 hours for the life of the airplane. Though some operators claim a retractable gear is cheaper to maintain than a fixed gear, with streamlining, assume an additional maintenance cost of 3 cents to 10 cents per flying hour making a total additional expense of 13 cents to 40 cents per flying hour.

Though in most instances the insurance costs would not be increased, it seems reasonable to assume a possible increase of 1 to 2 per cent in both crash and passenger liability insurance. From the Post office Department figures, insurance represents 6.5 per cent of the total operating expense. Crash and passenger liability are assumed to constitute about 40 per cent of the total insurance or 2.6 per cent of the total flying expense. If this were increased 1 to 2 per cent due to the retractable gear the total increase in operation expenses would be only 0.026 to 0.052 per cent.

Using the most probably figures within the above range in each case, and adding an imaginary plane of strictly up to the minute design and correspondingly lowered operating costs, the following table shows the increase in cost due to the addition of a retractable gear. (Only a portion of the "direct operating expenses" are directly proportional to flying time so only 30 per is used.)

An increase of 5 per cent in cruising speed, however, would mean that a flight of a given distance could be made in 4.8 per cent less flying time and hence at a saving of 4.8 per cent minus the added costs just tabulated. A 15 per cent increase would cut the time 13 per cent. It is thus apparent that in a typical case the provision of a retractable gear ought to reduce the operating expenses by from 3 to 12 per cent of the direct flying costs, or from 1.0 to 3.6 per cent of the total cost, depending upon the gain in speed. For a transport carrying from 8 to 12 passenger and crusing at 160 m.p.h., a retractable gear ought to cut total costs about $1-$2.50 per hour or 0.625—1.56 cents per mile.

DANGER OF FAILURE

Another factor to be considered is the danger of the landing gear not being in the proper position at the time of landing. This may happen from any one of four reasons: (1) A structural failure of a landing gear part or the actuating mechanism, due to faulty design, materials or workmanship; (2) fouling of the wheel bracing linkage, or actuating mechanism by ice or mud; (3) pilot's neglect to lower the wheels, which an be eliminated by proper warning devices; or (4) a mechanism that is too slow to allow the wheels to be lowered in a forced landing

As far as can be determined there has been no instance of a personal injury due to a retractable landing gear functioning improperly. In a forced landing in a small or bad field, especially with passengers a "wheel up" landing is definitely an advantage as the speed is slightly lower, the run considerably shorter and the possibility of nosing over practically eliminated. One of the leading operating companies has found it desirable to make forced landings with wheels retracted, as the expense of subsequent repairs is usually less than if the wheels were completely or partly down. In the past two years a great number of wheel up landings have been made with various privately and commercially operated planes, and invariably they resulted in less than $1,000 damage and more often $300 or less. The greatest damage usually experienced is when the wheels are in a partly retracted position. The extent of the damage due to a wheel up landing is usually limited to the propeller and the bottom covering of the fuselage.

To insure proper functioning of a retractable landing gear the mechanism should be designed to be simple, easy to service and maintain, and well protected against being fouled by foreign material thrown up by the wheel during take off. With the wheel opening in the bottom of the wing or fuselage the mechanism should not be exposed to mud, which might freeze solid after the gear has been retracted. In planning the disposition of the landing gear members, care should be taken to prevent struts from being forced into the cabin if a landing is made with partially retracted wheels. The actuating mechanism, especially cables, should not take any landing loads and the linkage must be so laid out that it never approaches dead center closely enough to require great operating force. The mechanism should not be reversible as the "down position" is approached (unless sole dependence is to be placed on a lock to hold the wheels in landing position).

WHEEL LOCATION

The best method and location for housing the landing gear varies with the type of plane. The gear can be retracted into one of five places :into the wing, the fuselage, and engine nacelle of a muti-engine design, an external fairing, or an exposed position where the frontal area or interference drag is reduced. In deciding which one to use, the aerodynamic effect of the wheel opening and the partly retracted gear during take off and landing immediately invites consideration. A disturbance of the flow by the opening might affect the stability, while a wing opening might affect the airfoil characteristics. These aerodynamic effects seem to be negligible however in most designs. Recent full scale wind tunnel tests by the N.A.C.A. on a Lockheed monoplane show that a wheel opening in the lower surface of the wing does not affect the flying characteristics when the wheels are extended. (Reference 2)

Until a year or two ago, practically all American air planes were biplanes or high wing monoplanes. As these types have inherently less drag than the low wing monoplane their general arrangement should be more desirable. (References 3, 4 and 5) The ease of retracting the gear in the low wing monoplane is apparently one of the main reasons for its increasing popularity. It is interesting that with the same power and loading a low wing monoplane, which gained 14 per cent in speed by fully retracting the landing gear, was only 3-4 per cent faster than a high wing version of the same plane with a fixed streamline, single strut, tie rod braced gear indicating that the high wing model would have been considerably faster with a retractable gear. However, as it is exceptionally difficult to retract the landing gear into the wing of a high wing type the fuselage is a more promising location for single engine designs.

There have been many successful designs with the wheels retracting either flush into the sides of the fuselage or into the bottom. An interesting mechanism adaptable for retracting the wheels into the sides of the fuselage is shown in the illustration taken from a patent held by L. R. Grumman. A deviation from a true parallelogram is made to provide "toe in" for landing and taxing. Another type of parallelogram mechanism was used on the Great Lakes amphibian of 1929. The member parallel to the wheel was an oleo carrying bending from the axle. A diagonal strut hinged at the top of the oleo went downward and inward to a point in the hull. By raising the inner end of this member the wheel was raised and swung inward into a recess in the side of the hull.

To have sufficient tread and ground clearance on a high wing monoplane with the wheels retracting into the bottom of the fuselage it is usually necessary to either build out small stubs as on the Stinson R-3 or to have a wide fuselage as on the Burnelli. The mechanism of the Stinson is illustrated herewith. Burnelli uses a sort of curved track to give a specific path to the upper end of one member of a tripod strut arrangement. There are an infinite number of other variations with shortening or retracting struts, folding struts, etc.

To retract the wheel into a thin wing as on a biplane or an externally braced monoplane would usually necessitate and increase in wing thickness to house the

Retracting mechanism on Stinson Model R-3. There are two parallel beams in stub wing. Side brace member lies in place of rear beam and has its upper end raised vertically by a cable actuated by a winch and worm gear. The worm gear is self locking preventing gear from falling if cranking is stopped. Gear may be "cranked" down or dropped by releasing a clutch, and locks in down position automatically. Operation of hoisting crank releases lock mechanism before actually beginning lateral movement of strut. Hydraulic arresters eliminate shock in working parts. It is stated that the gear is raised in 30 seconds and lowered in two.