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Fundamentals of Aerodynamics

Seventh Edition

McGraw Hill

John D. Anderson, Jr.
Christopher P. Cadou

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John D. Anderson, Jr.

Fundamentals of Aerodynamics

Seventh Edition

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FUNDAMENTALS OF AERODYNAMICS

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ABOUT THE AUTHOR

John D. Anderson, Jr., was born in Lancaster, Pennsylvania, on October 1, 1937. He attended the University of Florida, graduating in 1959 with high honors and a bachelor of aeronautical engineering degree. From 1959 to 1962, he was a lieutenant and task scientist at the Aerospace Research Laboratory at Wright-Patterson Air Force Base. From 1962 to 1966, he attended the Ohio State University under the National Science Foundation and NASA Fellowships, graduating with a PhD in aeronautical and astronautical engineering. In 1966, he joined the U.S. Naval Ordnance Laboratory as Chief of the Hypersonics Group. In 1973, he became Chairman of the Department of Aerospace Engineering at the University of Maryland, and since 1980 has been professor of Aerospace Engineering at the University of Maryland. In 1982, he was designated a Distinguished Scholar/Teacher by the University. During 1986–1987, while on sabbatical from the University, Dr. Anderson occupied the Charles Lindbergh Chair at the National Air and Space Museum of the Smithsonian Institution. He continued with the Air and Space Museum one day each week as their Special Assistant for Aerodynamics, doing research and writing on the history of aerodynamics. In addition to his position as professor of aerospace engineering, in 1993, he was made a full faculty member of the Committee for the History and Philosophy of Science and in 1996 an affiliate member of the History Department at the University of Maryland. In 1996, he became the Glenn L. Martin Distinguished Professor for Education in Aerospace Engineering. In 1999, he retired from the University of Maryland and was appointed Professor Emeritus. He is currently the Curator for Aerodynamics at the National Air and Space Museum, Smithsonian Institution.

Dr. Anderson has published 11 books: *Gasdynamic Lasers: An Introduction,* Academic Press (1976), and under McGraw Hill, *Introduction to Flight* (1978, 1984, 1989, 2000, 2005, 2008, 2012, 2016), *Modern Compressible Flow* (1982, 1990, 2003), *Fundamentals of Aerodynamics* (1984, 1991, 2001, 2007, 2011), *Hypersonic and High Temperature Gas Dynamics* (1989), *Computational Fluid Dynamics: The Basics with Applications* (1995), *Aircraft Performance and Design* (1999), *A History of Aerodynamics and Its Impact on Flying Machines,* Cambridge University Press (1997 hardback, 1998 paperback), *The Airplane: A History of Its Technology,* American Institute of Aeronautics and Astronautics (2003), *Inventing Flight,* Johns Hopkins University Press (2004), and X-15, The World's Fastest Rocket Plane and the Pilots Who Ushered in the Space Age, with co-author Richard Passman, Zenith Press in conjunction with the Smithsonian Institution (2014). He is the author of over 120 papers on radiative gasdynamics, reentry aerothermodynamics, gasdynamic and chemical lasers, computational fluid dynamics, applied aerodynamics, hypersonic flow, and the history of aeronautics. Dr. Anderson is a member of the National Academy of Engineering, and is in *Who's Who in America*. He is an Honorary Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is also a fellow of the Royal Aeronautical Society, London. He is a member of Tau Beta Pi, Sigma Tau, Phi Kappa Phi, Phi Eta Sigma, The American Society for Engineering Education, the History of Science Society, and the Society for the History of Technology. In 1988, he was elected as Vice President of the AIAA for Education. In 1989, he was awarded the John Leland Atwood Award jointly by the American Society for Engineering Education and the American Institute of Aeronautics and Astronautics "for the lasting influence of his recent contributions to aerospace engineering education." In 1995, he was awarded the AIAA Pendray Aerospace Literature Award "for writing undergraduate and graduate textbooks in aerospace engineering which have received worldwide acclaim for their readability and clarity of presentation, including historical content." In 1996, he was elected Vice President of the AIAA for Publications. He has recently been honored by the AIAA with its 2000 von Karman Lectureship in Astronautics.

From 1987 to the present, Dr. Anderson has been the senior consulting editor on the McGraw Hill Series in Aeronautical and Astronautical Engineering.

Christopher P. Cadou earned his undergraduate degrees (BS in Mechanical Engineering and a BA in History) from Cornell University in 1989 and went on to graduate school at the University of California Los Angeles where he studied fluid mechanics and acoustically excited flames using laser-induced fluorescence imaging techniques. Dr. Cadou graduated with a PhD in 1996 and moved to the California Institute of Technology as a post-doctoral scholar where he studied boundary layer instabilities associated with SCRAMJet inlet unstart using time-resolved Schlieren imaging and taught a course in air breathing propulsion at UCLA. This was an important time because he learned that he liked both research and teaching. Two years later he took another post-doctoral position at the Massachusetts Institute of Technology to help develop the combustor and turbomachinery of a tiny gas turbine engine being constructed using the same technologies used to make computer chips. However, his interest in teaching remained and he left MIT in 2000 to join the University of Maryland's Aerospace Engineering Department as an Assistant Professor. He has taught compressible flow at the graduate and undergraduate levels to more than 1,000 students, authored one book on micro-scale energy conversion systems, and published more than 100 scholarly papers in the areas of micro-scale combustion, supersonic film cooling, laser diagnostics, smart materials-based actuators, and hybrid turbine/fuel cell energy conversion systems. He is a fellow of the American Society of Mechanical Engineers and an Associate Fellow of the American Institute of Aeronautics and Astronautics.

CONTENTS

PREFACE TO THE SEVENTH EDITION

FUNDAMENTALS OF AERODYNAMICS

This book follows in the same tradition as the previous editions: it is for students—to be read, understood, and enjoyed. It is consciously written in a clear, informal, and direct style to talk to the reader and gain their immediate interest in the challenging and yet beautiful discipline of aerodynamics. The explanation of each topic is carefully constructed to make sense to the reader. Moreover, the structure of each chapter is highly organized to keep the reader aware of where we are, where we were, and where we are going with the flow of new and important ideas and concepts.

This edition continues with the same instructional and learning features introduced in the previous editions, such as preview boxes at the beginning of each chapter, road maps to keep the reader focused on the flow of new ideas and concepts, and end-of-chapter integrated work challenges that help to consolidate the important concepts in the minds of the readers. It also continues with such features as an introduction to computational fluid dynamics as an integral part of the modern study of aerodynamics, a chapter devoted entirely to hypersonic aerodynamics which has applications to new vehicle designs, and historical notes placed at the end of many of the chapters (a unique tradition that started with the first edition of this book, and that has carried on through all of the subsequent editions). Due to the extremely favorable comments from readers and users of the first six editions, virtually all the content of the earlier editions has been carried over intact to the present edition.

The major new feature of this edition is the addition of a valuable co-author, Dr. Christopher Cadou, Keystone Professor of Engineering at the University of Maryland. Dr. Cadou has contributed new worked examples and many new end-of-chapter homework problems which constitute most of the new content to this Seventh Edition, and which in fact greatly enhances the learning power of the new edition.

This book is organized along classical lines. It deals first with inviscid incompressible flow, then progresses to inviscid compressible flow, and then viscous flow in sequence. The material nicely divides into a two semester course, with Parts 1 and 2 in the first semester and Parts 3 and 4 in the second semester. The entire book has been used in a fast-paced first semester graduate course intended to introduce the fundamentals of aerodynamics to new graduate students who have not had this material as part of their undergraduate education. The book works well in such a mode.

Thanks go to the McGraw Hill editorial and production staff for their excellent help in producing this book, and to the legions of students over the years for many stimulating discussions that have influenced the development of this book. Special thanks go to both families of the two authors; families who have been patient and understanding about the time devoted to the preparation of the book.

As a final comment, aerodynamics is a subject of intellectual beauty, composed and drawn by many great minds over the centuries. Fundamentals of Aerodynamics is intended to portray and convey this beauty. Do you feel challenged and interested by these thoughts? If so, then read on, and enjoy.

John D. Anderson, Jr.
Christopher P. Cadou

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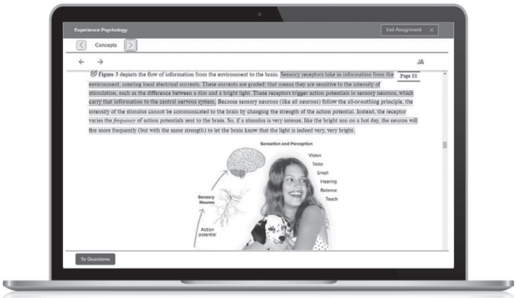

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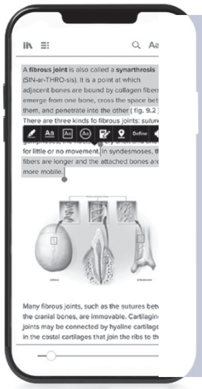

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PART 1

Fundamental Principles

In Part 1, we cover some of the basic principles that apply to aerodynamics in general. These are the pillars on which all of aerodynamics is based. ■

CHAPTER 1

Aerodynamics: Some Introductory Thoughts

The term "aerodynamics" is generally used for problems arising from flight and other topics involving the flow of air.

Ludwig Prandtl, 1949

Aerodynamics: The dynamics of gases, especially atmospheric interactions with moving objects.

The American Heritage Dictionary of the English Language, 1969

PREVIEW BOX

Why learn about aerodynamics? For an answer, just take a look at the following five photographs showing a progression of airplanes over the past 70 years. The Douglas DC-3 (Figure 1.1), one of the most famous aircraft of all time, is a low-speed subsonic transport designed during the 1930s. Without a knowledge of low-speed aerodynamics, this aircraft would have never existed. The Boeing 707 (Figure 1.2) opened high-speed subsonic flight to millions of passengers beginning in the late 1950s. Without a knowledge of high-speed subsonic aerodynamics, most of us would still be relegated to ground transportation.

Figure 1.1 Douglas DC-3 (*NASA*).

Figure 1.2 Boeing 707 (*CSU Archives/Everett Collection/Alamy Stock Photo*).

Figure 1.5 Lockheed-Martin F-22 (*U.S. Air Force Photo/Staff Sgt. Vernon Young Jr.*).

Figure 1.3 Bell X-1 (*Library of Congress, Prints & Photographs Division [LC-USZ6-1658]*).

Figure 1.6 Blended wing body (*NASA*).

Figure 1.4 Lockheed F-104 (*Library of Congress, Prints & Photographs Division [LC-USZ62-94416]*).

The Bell X-1 (Figure 1.3) became the first piloted airplane to fly faster than sound, a feat accomplished with Captain Chuck Yeager at the controls on October 14, 1947. Without a knowledge of transonic aerodynamics (near, at, and just above the speed of sound), neither the X-1, nor any other airplane, would have ever broken the sound barrier. The Lockheed F-104 (Figure 1.4) was the first supersonic airplane point-designed to fly at twice the speed of sound, accomplished in the 1950s. The Lockheed-Martin F-22 (Figure 1.5) is a modern fighter aircraft designed for sustained supersonic flight. Without a knowledge of supersonic aerodynamics, these supersonic airplanes would not exist. Finally, an example of an innovative new vehicle concept for high-speed subsonic flight is the blended wing body shown in Figure 1.6. At the time of writing, the blended-wing-body promises to carry from 400 to 800 passengers over long distances with almost 30 percent less fuel per seat-mile than a conventional jet transport. This would be a "renaissance" in long-haul transport. The salient design aspects of this exciting new concept are discussed in Section 11.10. The airplanes in Figures 1.1–1.6 are six good reasons to learn about aerodynamics. The major purpose of this book is to help you do this. As you continue to read this and subsequent chapters, you will progressively learn about low-speed aerodynamics, high-speed subsonic aerodynamics, transonic aerodynamics, supersonic aerodynamics, and more.

Airplanes are by no means the only application of aerodynamics. The air flow over an automobile, the gas flow through the internal combustion engine powering an automobile, weather and storm prediction, the flow through a windmill, the production of thrust by gas turbine jet engines and rocket engines, and the movement of air through building heater and air-conditioning systems are just a few other examples of the application of aerodynamics. The material in this book is powerful stuff—important stuff. Have fun reading and learning about aerodynamics.

To learn a new subject, you simply have to start at the beginning. This chapter is the beginning of our study of aerodynamics; it weaves together a series of introductory thoughts, definitions, and concepts essential to our discussions in subsequent chapters. For example, how does nature reach out and grab hold of an airplane in flight—or any other object immersed in a flowing fluid—and exert an aerodynamic force on the object? We will find out here. The resultant aerodynamic force is frequently resolved into two components defined as lift and drag; but rather than dealing with the lift and drag forces themselves, aerodynamicists deal instead with lift and drag *coefficients*. What is so magic about lift and drag coefficients? We will see. What is a Reynolds number? Mach number? Inviscid flow? Viscous flow? These rather mysterious sounding terms will be demystified in the present chapter. They and others constitute the language of aerodynamics, and as we all know, to do anything useful you have to know the language. Visualize this chapter as a beginning language lesson, necessary to go on to the exciting aerodynamic applications in later chapters. There is a certain enjoyment and satisfaction in learning a new language. Take this chapter in that spirit, and move on.

1.1 IMPORTANCE OF AERODYNAMICS: HISTORICAL EXAMPLES

On August 8, 1588, the waters of the English Channel churned with the gyrations of hundreds of warships. The Spanish Armada had arrived to carry out an invasion of Elizabethan England and was met head-on by the English fleet under the command of Sir Francis Drake. The Spanish ships were large and heavy; they were packed with soldiers and carried formidable cannons that fired 50 lb round shot that could devastate any ship of that era. In contrast, the English ships were smaller and lighter; they carried no soldiers and were armed with lighter, shorter-range cannons. The balance of power in Europe hinged on the outcome of this naval encounter. King Philip II of Catholic Spain was attempting to squash Protestant England's rising influence in the political and religious affairs of Europe; in turn, Queen Elizabeth I was attempting to defend the very existence of England as a sovereign state. In fact, on that crucial day in 1588, when the English floated six fire ships into the Spanish formation and then drove headlong into the ensuing confusion, the future history of Europe was in the balance. In the final outcome, the heavier, sluggish, Spanish ships were no match for the faster, more maneuverable, English craft, and by that evening the Spanish Armada lay in disarray, no longer a threat to England. This naval battle is of particular importance because it was the first in history to be fought by ships on both sides powered completely by sail (in contrast to earlier combinations of oars and sail), and it taught the world that political power was going to be synonymous with naval power. In turn, naval

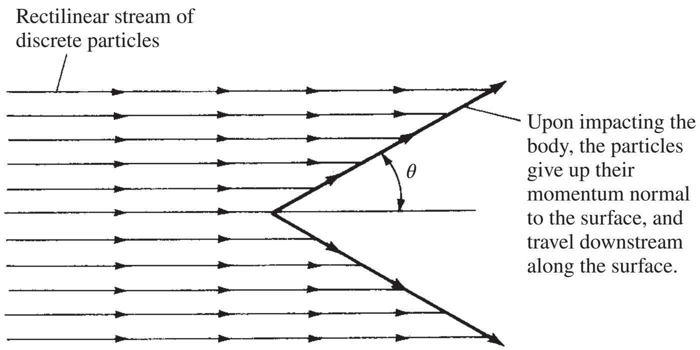


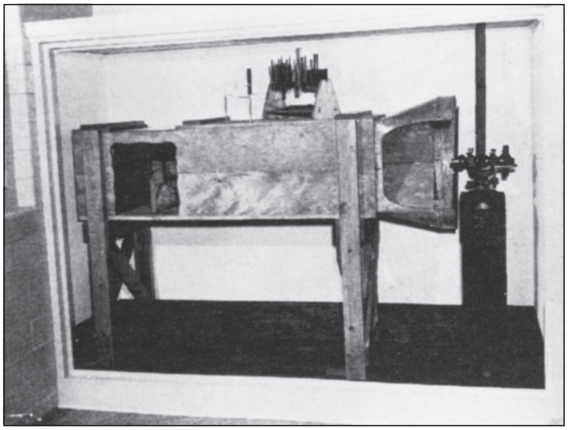
Figure 1.7 Isaac Newton's model of fluid flow in the year 1687. This model was widely adopted in the seventeenth and eighteenth centuries but was later found to be conceptually inaccurate for most fluid flows.

power was going to depend greatly on the speed and maneuverability of ships. To increase the speed of a ship, it is important to reduce the resistance created by the water flow around the ship's hull. Suddenly, the drag on ship hulls became an engineering problem of great interest, thus giving impetus to the study of fluid mechanics.

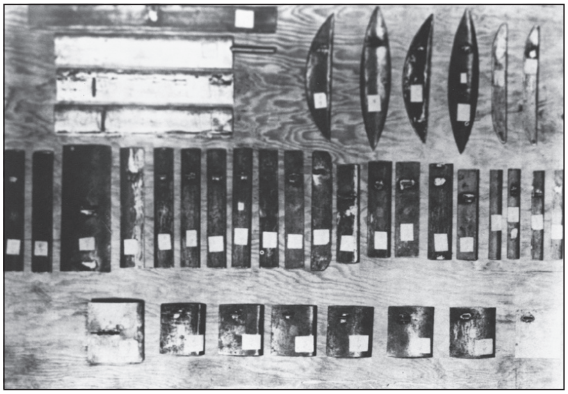
This impetus hit its stride almost a century later, when, in 1687, Isaac Newton (1642–1727) published his famous *Principia,* in which the entire second book was devoted to fluid mechanics. Newton encountered the same difficulty as others before him, namely, that the analysis of fluid flow is conceptually more difficult than the dynamics of solid bodies. A solid body is usually geometrically well defined, and its motion is therefore relatively easy to describe. On the other hand, a fluid is a "squishy" substance, and in Newton's time it was difficult to decide even how to qualitatively model its motion, let alone obtain quantitative relationships. Newton considered a fluid flow as a uniform, rectilinear stream of particles, much like a cloud of pellets from a shotgun blast. As sketched in Figure 1.7, Newton assumed that upon striking a surface inclined at an angle θ to the stream, the particles would transfer their normal momentum to the surface but their tangential momentum would be preserved. Hence, after collision with the surface, the particles would then move along the surface. This led to an expression for the hydrodynamic force on the surface which varies as $\sin^2 \theta$. This is Newton's famous sine-squared law (described in detail in Chapter 14). Although its accuracy left much to be desired, its simplicity led to wide application in naval architecture. Later, in 1777, a series of experiments was carried out by Jean LeRond d'Alembert (1717–1783), under the support of the French government, in order to measure the resistance of ships in canals. The results showed that "the rule that for oblique planes resistance varies with the sine square of the angle of incidence holds good only for angles between 50 and 90° and must be abandoned for lesser angles." Also, in 1781, Leonhard Euler (1707–1783) pointed out the physical inconsistency of Newton's model (Figure 1.7) consisting of a rectilinear stream of particles impacting without warning on a surface. In contrast to this model, Euler noted that the fluid moving toward a body "*before* reaching the latter, bends its direction and its velocity so that when it reaches the body it flows past it along the surface, and exercises no other force on the body except the pressure corresponding to the single points of contact." Euler went on to present a formula for resistance that attempted to take into account the shear stress distribution along the surface, as well as the pressure distribution. This expression became proportional to $\sin^2 \theta$ for large incidence angles, whereas it was proportional to $\sin \theta$ at small incidence angles. Euler noted that such a variation was in reasonable agreement with the ship-hull experiments carried out by d'Alembert.

This early work in fluid dynamics has now been superseded by modern concepts and techniques. (However, amazingly enough, Newton's sine-squared law has found new application in very high-speed aerodynamics, to be discussed in Chapter 14.) The major point here is that the rapid rise in the importance of naval architecture after the sixteenth century made fluid dynamics an important science, occupying the minds of Newton, d'Alembert, and Euler, among many others. Today, the modern ideas of fluid dynamics, presented in this book, are still driven in part by the importance of reducing hull drag on ships.

Consider a second historical example. The scene shifts to Kill Devil Hills, 4 mi south of Kitty Hawk, North Carolina. It is summer of 1901, and Wilbur and Orville Wright are struggling with their second major glider design, the first being a stunning failure the previous year. The airfoil shape and wing design of their glider are based on aerodynamic data published in the 1890s by the great German aviation pioneer Otto Lilienthal (1848–1896) and by Samuel Pierpont Langley (1834–1906), secretary of the Smithsonian Institution—the most prestigious scientific position in the United States at that time. Because their first glider in 1900 produced no meaningful lift, the Wright brothers have increased the wing area from 165 to 290 ft^2 and have increased the wing camber (a measure of the airfoil curvature—the larger the camber, the more "arched" is the thin airfoil shape) by almost a factor of 2. But something is still wrong. In Wilbur's words, the glider's "lifting capacity seemed scarcely one-third of the calculated amount." Frustration sets in. The glider is not performing even close to their expectations, although it is designed on the basis of the best available aerodynamic data. On August 20, the Wright brothers despairingly pack themselves aboard a train going back to Dayton, Ohio. On the ride back, Wilbur mutters that "nobody will fly for a thousand years." However, one of the hallmarks of the Wrights is perseverance, and within weeks of returning to Dayton, they decide on a complete departure from their previous approach. Wilbur later wrote that "having set out with absolute faith in the existing scientific data, we were driven to doubt one thing after another, until finally after two years of experiment, we cast it all aside, and decided to rely entirely upon our own investigations." Since their 1901 glider was of poor aerodynamic design, the Wrights set about determining what constitutes good aerodynamic design. In the fall of 1901, they design and build a 6 ft long, 16 in square wind tunnel powered by a two-bladed fan connected to a gasoline engine. A replica of the Wrights' tunnel is shown in Figure 1.8*a*. In their wind tunnel they test over 200 different wing and airfoil shapes, including flat plates,



(*a*)



(*b*)

Figure 1.8 (*a*) Replica of the wind tunnel designed, built, and used by the Wright brothers in Dayton, Ohio, during 1901–1902. (*b*) Wing models tested by the Wright brothers in their wind tunnel during 1901–1902. [*(a) NASA; (b) Courtesy of John Anderson*.]

curved plates, rounded leading edges, rectangular and curved planforms, and various monoplane and multiplane configurations. A sample of their test models is shown in Figure 1.8*b*. The aerodynamic data are taken logically and carefully. Armed with their new aerodynamic information, the Wrights design a new glider in the spring of 1902. The airfoil is much more efficient; the camber is reduced considerably, and the location of the maximum rise of the airfoil is moved closer to the front of the wing. The most obvious change, however, is that the ratio of the length of the wing (wingspan) to the distance from the front to the rear of the airfoil (chord length) is increased from 3 to 6. The success of this glider during the summer and fall of 1902 is astounding; Orville and Wilbur accumulate over a thousand flights during this period. In contrast to the previous year, the Wrights return to Dayton flushed with success and devote all their subsequent efforts to powered flight. The rest is history.

The major point here is that good aerodynamics was vital to the ultimate success of the Wright brothers and, of course, to all subsequent successful airplane designs up to the present day. The importance of aerodynamics to successful manned flight goes without saying, and a major thrust of this book is to present the aerodynamic fundamentals that govern such flight.

Consider a third historical example of the importance of aerodynamics, this time as it relates to rockets and space flight. High-speed, supersonic flight had become a dominant feature of aerodynamics by the end of World War II. By this time, aerodynamicists appreciated the advantages of using slender, pointed body shapes to reduce the drag of supersonic vehicles. The more pointed and slender the body, the weaker the shock wave attached to the nose, and hence the smaller the wave drag. Consequently, the German V-2 rocket used during the last stages of World War II had a pointed nose, and all short-range rocket vehicles flown during the next decade followed suit. Then, in 1953, the first hydrogen bomb was exploded by the United States. This immediately spurred the development of long-range intercontinental ballistic missiles (ICBMs) to deliver such bombs. These vehicles were designed to fly outside the region of the earth's atmosphere for distances of 5000 mi or more and to reenter the atmosphere at suborbital speeds of from 20,000 to 22,000 ft/s. At such high velocities, the aerodynamic heating of the reentry vehicle becomes severe, and this heating problem dominated the minds of high-speed aerodynamicists. Their first thinking was conventional—a sharp-pointed, slender reentry body. Efforts to minimize aerodynamic heating centered on the maintenance of laminar boundary layer flow on the vehicle's surface; such laminar flow produces far less heating than turbulent flow (discussed in Chapters 15 and 19). However, nature much prefers turbulent flow, and reentry vehicles are no exception. Therefore, the pointed-nose reentry body was doomed to failure because it would burn up in the atmosphere before reaching the earth's surface.

However, in 1951, one of those major breakthroughs that come very infrequently in engineering was created by H. Julian Allen at the NACA (National Advisory Committee for Aeronautics) Ames Aeronautical Laboratory—he introduced the concept of the *blunt* reentry body. His thinking was paced by the following concepts. At the beginning of reentry, near the outer edge of the atmosphere, the vehicle has a large amount of kinetic energy due to its high velocity and a large amount of potential energy due to its high altitude. However, by the time the vehicle reaches the surface of the earth, its velocity is relatively small and its altitude is zero; hence, it has virtually no kinetic or potential energy. Where has all the energy gone? The answer is that it has gone into (1) heating the body and (2) heating the airflow around the body. This is illustrated in Figure 1.9. Here, the shock wave from the nose of the vehicle heats the airflow around the vehicle; at the same time, the vehicle is heated by the intense frictional dissipation within the boundary layer on the surface. Allen reasoned that if more of the total reentry