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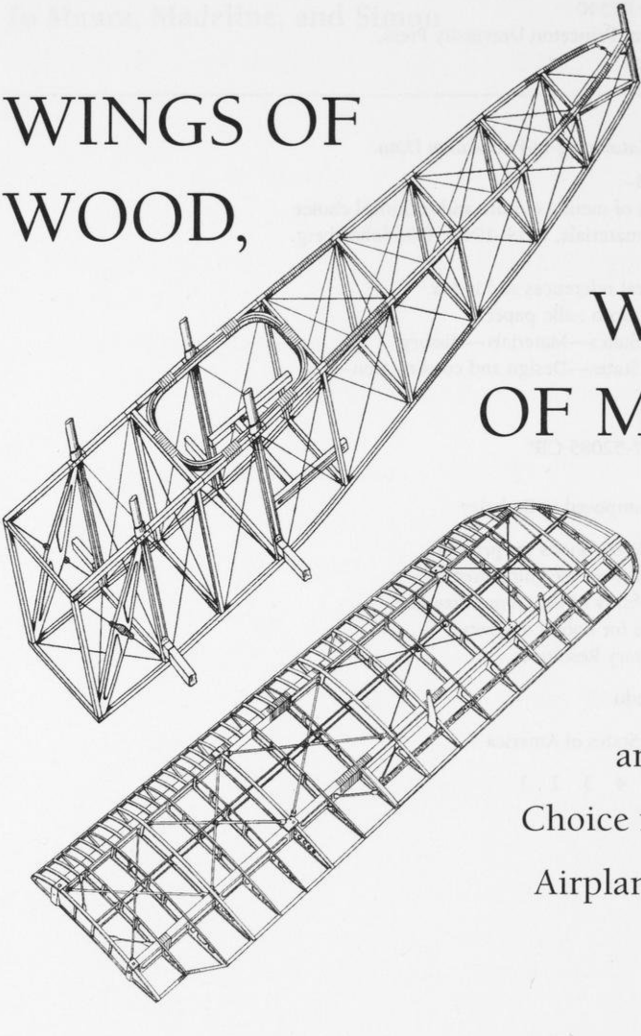

Culture and Technical Choice in American Airplane Materials, 1914–1945

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To Maura, Madeline, and Simon

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Acknowledgments

HISTORICAL RESEARCH AND WRITING are solitary activities, making it easy to forget that the generation of historical knowledge, like all knowledge, is a social process. This book is no exception, and I have benefited tremendously from the many people who have willingly shared their expertise, whether or not they agreed with my argument.

When, as a graduate student, I first delved into aeronautical history, I received invaluable advice from numerous well-established aviation historians, among them Tom Crouch, David Lewis, Walter Vincenti, Alex Roland, and especially Richard K. Smith. Walter Vincenti's studies of aviation history, with their detailed analyses of the process of technical change, were an important inspiration for me. William F. Trimble shared with me drafts of his work on the Naval Aircraft Factory and also provided well-grounded criticisms of my argument. I spent a summer as a graduate fellow at the Aeronautics Department of the National Air and Space Museum, where I learned a great deal from the historians, curators, and librarians there, among them Dominick Pisano, Ron Davies, Peter Jakab, and especially Howard Wolko. The late aeronautical engineer Nicholas J. Hoff shared with me some of his vast knowledge of aeronautical history. Another aeronautical engineer turned historian, Mark Levinson, has strongly encouraged me from the early days of this project. Mark also provided valuable comments on the final manuscript.

I owe special thanks to Robert Friedel, who drove up to Philadelphia from Maryland to hear the first public presentation of what became the thesis of this book. After the talk, Robert mentioned that he had written an unpublished paper that made essentially the same argument more than a dozen years earlier. Robert not only shared his own paper with me but strongly encouraged me to focus my research on the shift from wood to metal airplanes. If priority matters in history, Robert certainly deserves credit as the first professional historian to recognize the ideological character of the debate over wood and metal airplanes. I have continued to benefit from Robert's insightful analysis of the role of materials in the history of technology.

The book owes much to the creative intellectual environment I encountered during my graduate studies at the University of Pennsylvania's Department of History and Sociology of Science. I had the great fortune to work with Thomas P. Hughes, under whose guidance I began this book in its earlier life as a dissertation. Tom's own work provided me with a model of scholarship that is both innovative and rigorous, and his prudent advice gently steered me in suitable directions while allowing me to develop into an independent researcher. I also received encouragement and advice from Judith McGaw and Robert Kohler; it was in one of Rob's seminars that I first took up research in aviation history. The conceptual framework that led to this book was influenced by a short seminar I took with Donald MacKenzie when he visited the university in the spring of 1985; Donald gave me my first rigorous introduction to the sociology of technology. At about the same time, I was also very taken with David Noble's *Forces of Production*. Noble's analysis of the "road not taken" in automated machine tools primed me to recognize the wooden airplane as an alternative path.

In this project's metamorphosis from dissertation to book, I have received support from numerous colleagues in the history of technology, including A. Michal McMahon, Jonathan Zeitlin, and Helmut Maier. Dr. Maier shared early versions of his work on the history of aluminum; his arguments on the symbolic significance of aluminum as a "scientific metal" parallel the arguments made in this book. My introduction was much improved through the helpful comments of Mark Shields. Mark also supplied an insightful critique of my theoretical argument, raising deep conceptual issues that will require more than an introduction to resolve. Jeffrey Meikle kindly let me see a typescript copy of his book *American Plastic*. My research assistant, Julie Levinson, helped bring order to massive amounts of published material I had collected, and Libbie Freed helped check the quotations. Lee Bowman compiled the index. Finally, I cannot imagine a better intellectual home than the Department of the History of Science at the University of Wisconsin-Madison, where my colleagues have provided me with the friendly, supportive, and stimulating environment that I needed to complete the book.

This book depends heavily on archival sources and would have been impossible without the help of dozens of dedicated archivists. I have relied especially on the records of the National Archives in Washington, D.C., that great but underfunded repository of the nation's history. The overworked archivists there helped me tremendously, especially John Butler, David A. Pfeiffer, Clifford L. Snyder, Will Mahoney, and Barry Zerby. I received wonderful assistance in my research on Canadian wooden airplanes from Paul Marsden at the National Archives of Canada, Tim Dubé at the Department of National Defence, and Ralph Leonardo, formerly with the National Aviation Museum.

I have received financial support from many sources in researching and writing this book. As a graduate student, I began this project with help from a National Science Foundation Postdoctoral Fellowship, a Smithsonian Institution Ten-Week Graduate Fellowship, the American Historical Association's Aerospace History Fellowship, and a Dean's Fellowship from the University of Pennsylvania. I wrote much of chapter three while a postdoctoral fellow at the Center for the History of Electrical Engineering at Rutgers

University. At the University of Wisconsin, I have received funding from the Wisconsin Alumni Research Foundation and the National Science Foundation. This funding supported my work on chapters one, nine, ten, and eleven. An earlier version of chapter three appeared in my article "Ideology and Technical Choice: The Decline of the Wooden Airplane in the United States, 1920–1945," *Technology and Culture* 35 (1994): 34–69, copyright 1994 by the Society for the History of Technology.

Authors traditionally thank their families; after completing my first book, I now understand why. The unwavering enthusiasm of my parents, Paul and Tobalee Schatzberg, helped sustain me to the end of this project. My father read every chapter, provided me with valuable feedback, and caught German spelling errors. I could not have a better intellectual partner in life than Maura Whelan, who was always willing to help me work through difficult conceptual issues. Her sharp editorial pencil did much to improve the final manuscript. Finishing the book will mean the most to Madeline and Simon, whose father will no longer feel so torn between the demands of scholarship and the joys of his children.

WINGS OF WOOD, WINGS OF METAL

1

Materials, Symbols, and Ideologies of Progress

In 1989 the *Ripley's* Sunday comic strip featured the British Mosquito combat airplane (figure 1.1), which

> during World War II . . . was one of the fastest planes in existence. The photographic reconnaissance version of this aircraft . . . was able to fly non-stop over Europe so high it was neither seen nor heard. **It was constructed entirely of wood**.
>
> Believe it or not![1]

Ripley's claim is accurate and even understates the Mosquito's success in combat against metal aircraft.[2] *Ripley's* does not seek to provide historical instruction, however, but rather to evoke surprise and disbelief. Why should a successful airplane with a wood structure evoke surprise and disbelief? The reason lies in the symbolic meanings that our modern technological culture associates with different materials. Wood symbolizes preindustrial technologies and craft traditions, while metal represents the industrial age, technical progress, and the primacy of science. The airplane is one of the defining technologies of the twentieth century, the age of science-based industry. The wooden airplane is thus a symbolic contradiction, representing both science and craft, modernity and tradition.

A simple argument lies at the heart of this book. The symbolic meanings of airplane materials influenced more than just cultural perceptions; they also shaped the technical history of the airplane, promoting the shift from wood to metal between the world wars. Wood remained the dominant material for airplane structures throughout World War I, although a few metal airplanes did appear near the end of the war. After the armistice, advocates of metal airplanes challenged the hegemony of wood, advancing technical arguments for replacing wood with steel and aluminum alloys. But at the same time, these advocates also elaborated new cultural meanings for airplane materials. Proponents of metal drew upon existing symbolism to link metal with progress, modernity, and science, while associating wood with backwardness, tradition, and craft methods.

These symbolic associations gained their significance from a set of beliefs deeply embedded within the aviation community—the ideology of technological progress. This ideology posited the inevitable progress of technology

Figure 1.1. The wooden airplane in popular culture: a symbolic contradiction. ©1997 Ripley Entertainment Inc., registered trademark of Ripley Entertainment Inc.

for human betterment, but it did not indicate which specific technical changes would be deemed progress. By linking metal with modernity and wood with tradition, advocates of metal laid claim to the rhetoric of progress, constructing a narrative that predicted the inevitable replacement of wood by metal in airplane structures. These beliefs constituted a specific form of the ideology of progress, which I term *the progress ideology of metal*.

The progress ideology of metal was widely accepted within the culture of aviation between the world wars. But culture alone cannot explain the ultimate triumph of metal. Metal also benefited from its links to power, most importantly the power of the military to shape the technical development of the airplane. In the United States and abroad, air forces doggedly supported the development of metal airplanes, despite discouraging early results. Without military support, metal would have never succeeded in dominating high-performance airplanes by the start of World War II. Thus, military influence supplies the second major theme for this book.[3]

Culture and power are not independent variables, however. Without the military's power to command scarce resources, symbolic meanings could never have provided the technical and financial support that metal airplanes needed. Yet without the cultural authority provided by these symbolic meanings, military personnel would have found it difficult to justify their persistent support for the new technology. In the shift from wood to metal airplanes, culture and power were intertwined.[4]

The shift from wood to metal did not occur solely on a terrain of meanings but also in the material world. This world did not always conform to the meanings imposed on it. Metal airplanes, for example, did not prove as cheap, durable, and fireproof as proponents originally claimed. When discrepancies arose between meanings and the material world, sometimes the meanings yielded, as when engineers finally acknowledged that airplanes cost more to produce with metal than with wood. At other times the material world proved more malleable, transformed by the ingenuity of engineers, designers, and scientists. In some instances, the discrepancies between meanings and the material world persisted, as in the case of fire safety, which was repeatedly invoked as an advantage for metal despite considerable evidence that aluminum airplanes were no safer than wooden ones.[5]

My account of the shift from wood to metal airplanes, therefore, involves interactions among culture, power, and the material world. By focusing on the role of culture and power, my account differs fundamentally from the standard technical histories of the airplane, which portray the shift to metal as a key step in the technical progress of aviation. The standard histories are classic exercises in Whig historiography, judging the past in terms of its contribution to the present. The heroes of this standard story are the pioneers and prophets of the victorious path that led to the all-metal stressed-skin airliners developed in the United States during the early 1930s. In effect, the standard account accepts at face value the arguments advanced by proponents of the victorious path. These technical histories do little more than codify the aviation community's own mythology, and thus cannot evaluate the basic assumptions of that community.[6]

Constructing this new account involves more than just reinterpreting existing historical data with greater sensitivity to nontechnical factors; it also requires work to uncover the lost history of unsuccessful airplanes. In the history of technology, failed machines and abandoned projects far outnumber the successes, but these failures are for the most part obliterated from the historical record, left ignored in dusty archives like old cars in an abandoned junkyard. The progressivist history of technology discourages attention to failed alternatives, focusing instead on the steps leading directly to the successful technology, making the victorious technology appear as the inevitable outcome of prior developments. Yet any satisfactory explanation of technological change requires as much attention to failure as to success. It is only through attention to failures that historians can isolate the factors that led to the successful alternative.[7]

In telling this story of both failure and success, technical details matter. These details are necessary to understand the struggles of engineers trying to make airplanes conform to the metallic ideal, struggles that reveal the influence of ideology on technical choice. At times, this influence is directly apparent in the rhetoric of engineers, airplane designers, manufacturers, and military officers, who openly expressed their prejudices against wood. More often, though, I have had to uncover this influence through the careful analysis of technical arguments about airplane structures, manufacturing methods, durability, and strength of materials. I have done my best to make this analysis accessible to nontechnical readers. At the same time, I have tried to include enough detail to satisfy aviation experts, though in general I have leaned toward accessibility.

My account centers on a specific technical community, that of American aviation.[8] Although all the major aviation powers participated in the shift to metal, American manufacturers developed the first truly successful airplanes using all-metal, stressed-skin structures, which became the dominant form of metal construction by World War II. This American lead was not very great, however. Aviation technology was thoroughly international in the interwar period, in part because of its military potential, which encouraged governments and manufacturers to keep close tabs on technical developments in other countries. Furthermore, there was no shortage of enthusiasm for metal in Germany, France, and Britain. Nevertheless, I have chosen to focus on a specific national community because the problems involved in the choice of airplane materials differed from country to country. These differences arose in part because of variations in resource endowments: Britain, for example, had little aircraft timber, limited domestic sources of aluminum, but ample supplies of steel. At the same time, the meanings of materials also varied with national context, as demonstrated by Canadian support for wooden airplanes during World War II (see chapter ten). I have, therefore, only examined the experience of other countries when it directly influenced events in the United States, or when it provides contrasts that elucidate American developments.

From Wood to Metal

This book examines the displacement of wood by metal as the dominant material for airplane structures between the world wars. No heroic inventions explain the shift, although numerous small innovations contributed to the success of metal. Nevertheless, in the twenty-seven years from the end of World War I to the end of World War II, metal almost completely replaced wood. During World War I, the major combatants built approximately 170,000 airplanes, almost all using wooden construction.[9] During World War II, the major powers produced roughly 750,000 airplanes, the vast majority with metal structures.[10] A comparable shift to metal occurred in commercial aircraft. Only in small, private airplanes and military trainers did wood retain its place as a structural material through World War II.

Wood remained unchallenged as the dominant material for airplane structures until late in World War I. In the typical airplane of the war, wood comprised all major structural elements, with metal used only for fittings and tension wires (figure 1.2). The wings consisted of two spruce spars running the length of the wing, with wooden ribs placed crosswise to give the wing its shape. Strong steel wire braced the resulting grid of spars and ribs, creating a framework to support the linen cloth that formed the wing surface. A similar rectangular frame of wooden struts, also wire braced, formed the fuselage. Even the landing gear was likely to be of wood.[11]

Despite the dominance of wood, early airplane designers had not ignored metal. Even before the Kitty Hawk flights, airplane pioneers Maxim and Langley had experimented with metal structures. The French airplane builder Breguet began using steel in 1910, and other designers experimented with the metal monocoque fuselage as early as 1912.[12] Nevertheless, on the eve of World War I no airplane in production had a metal structure.

Like many developments in aviation, the metal* airplane was a child of World War I. Chapter two recounts these wartime origins, and the postwar enthusiasm that ensued. Germany was the first nation to make widespread use of metal in aircraft structures. Over a thousand German warplanes used the welded steel-tube fuselage developed by Anthony Fokker. But a much more potent symbol was the all-metal airplane of Hugo Junkers. Junkers' first airplane used sheet iron, but in later models he switched to duralumin, a high-strength alloy developed shortly before the war. By the end of the war, Junkers and other German manufacturers had developed numerous metal designs, and a few metal airplanes even made it into combat. The U.S. Army also experimented with metal aircraft during the war, though with less success than the Germans.

* In discussing the use of metal in aircraft, one needs to distinguish between all-metal construction and the partial use of metal. The aeronautical community did not apply a consistent terminology. "All-metal" generally referred to airplanes that used metal almost exclusively for both the internal structure and the external covering, while the term "metal airplane" also included aircraft with internal metal structures but fabric or wood covering. I follow this usage in the book when referring to "all-metal" and "metal airplanes." Many airplanes, however, used both wood and metal structures, for example a metal fuselage and wood wings. Such airplanes were sometimes referred to as metal, at other times as wood, and sometimes as "composite." In this book, "wooden airplane" or "wooden construction" refers to any airplane in which a major part of the structure was made of wood.

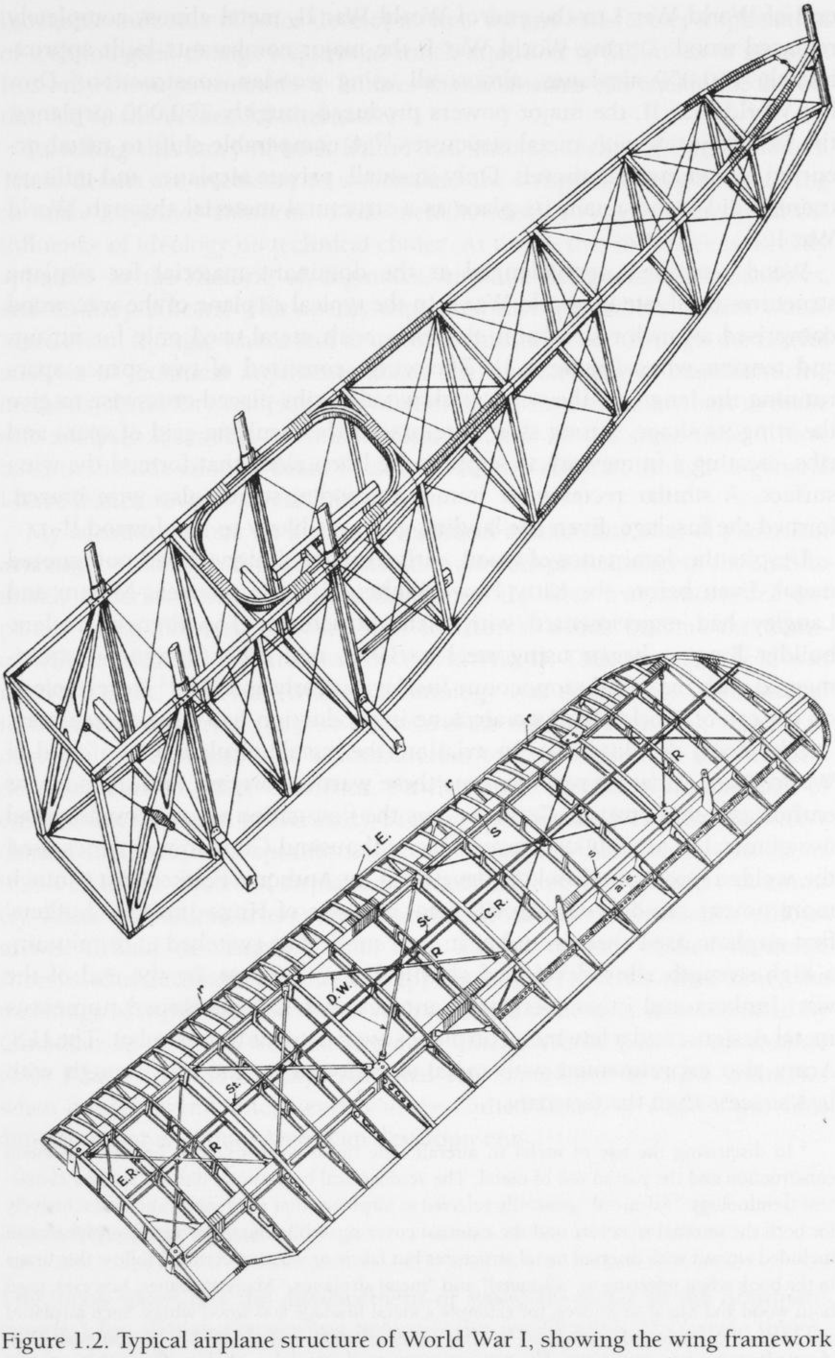

Figure 1.2. Typical airplane structure of World War I, showing the wing framework and fuselage. The entire structure is wood, with metal used only for tension wires and fittings. A. J. Sutton Pippard and J. Laurence Pritchard, *Aeroplane Structures* (London: Longmans, Green, 1919), figs. 12, 16.

After the war, news of the German metal airplanes generated tremendous excitement among the Allies, especially in the United States. American aviation engineers quickly applied themselves to the design and construction of metal aircraft, with substantial support from the army and navy. Yet despite the optimistic predictions of metal's supporters, wood remained widespread in aircraft structures into the early 1930s.

Chapter three examines the technical reasons behind this continued use of wood, along with the cultural factors underlying the strong support for metal. This chapter presents the heart of my argument. Advocates of metal made a strong case for its advantages over wood, yet in practice metal failed to fulfill expectations. This failure resulted from what I call the technical indeterminacy of the choice between wood and metal. Experience with metal airplanes in the 1920s showed that the claims made by metal's proponents for fire safety, durability, lightness, and lower production costs were uncertain at best. Metal indeed had definite advantages, but it also faced serious problems not present in wood construction. No accepted criteria existed for balancing these advantages and disadvantages. Neither technical arguments nor practical experience could convincingly demonstrate the superiority of metal.

Support for metal did not, in fact, draw its strength principally from technical arguments, but rather from symbolic meanings as articulated in the progress ideology of metal. Chapter three concludes with an examination of this ideology. Metal's supporters expressed this ideology quite openly, insisting that the shift from wood to metal was an inevitable aspect of technical progress. They argued that the airplane would repeat the shift to metal undergone by prior wood-using technologies such as shipbuilding and bridge construction. This ideology provided more than just useful rhetoric to supporters of metal: it also inhibited public expressions of support for wood while insuring that metal received a disproportionate share of funds for research and development.

Chapters four and five examine early attempts to develop metal airplanes after World War I for military and commercial use. The military led the way in the early development of metal airplanes, as discussed in chapter four. The army and navy officially endorsed metal construction in 1920 and doggedly supported metal airplane projects despite repeated failures. The armed forces gave contracts to favored manufacturers for experimental metal types, while also underwriting research in government laboratories on the problems of metal construction. When researchers discovered a serious corrosion problem with aluminum airplanes in 1925, the navy orchestrated a concerted federal effort to find a solution. After 1925, metal also spread to commercial aviation, when Henry Ford started building metal airliners. Chapter five details Ford's venture into metal aircraft production, which ended as a multi-million-dollar failure. Ford's failure notwithstanding, his support for metal construction encouraged other manufacturers to develop metal commercial airplanes.

Despite the strength of the progress ideology of metal, the technology of wooden airplanes did not remain static in the 1920s. Chapter six describes one such development, the plywood stressed-skin airplane. This form of construction demonstrated its viability in the Lockheed Vega, the fastest single-engine commercial airplane of the late 1920s. The streamlined, stressed-skin Vega anticipated the sleek metal airliners of the 1930s. Nevertheless, the progress ideology of metal inhibited development of airplanes like the Vega. The federal government provided only minimal support for research on wood construction while vigorously supporting research on aircraft metals. In the late 1920s, the federal government began eliminating support for research on wood glues, even though the majority of commercial aircraft still relied on glued joints. In 1931 deterioration of glued joints contributed to the crash of a Fokker trimotor that killed football coach Knute Rockne.

Meanwhile, the military continued to support development of metal airplanes, despite the repeated failures of the early 1920s. In the early 1930s, both the army and navy finally developed all-metal airplanes suitable for combat use. Chapter seven recounts these developments. In parallel with the military's continued support for metal construction, a number of private firms sought to develop comparable designs for commercial aircraft. These all-metal, stressed-skin airplanes had limited success until after the Rockne crash in 1931, when the airlines turned decisively in favor of all-metal construction. After the introduction of the Boeing 247 in 1933 and the Douglas DC-2 in 1934, all-metal airplanes became standard for scheduled air travel in the United States. Chapter eight describes the triumph of these all-metal airliners and the role of military support in their development.

Innovation in wooden construction continued, however, even after the apparent triumph of metal. In the late 1930s, a few creative designers developed molded plywood airplanes using new resin adhesives based on thermosetting plastics. These new adhesives eliminated the worst problems of traditional wood glues, especially the tendency to deteriorate when damp. Chapter nine describes the development of these "plastic" airplanes in the late 1930s and their failure to gain military support before World War II.

Mobilization for World War II dramatically reversed the decline of wooden airplanes in the United States, a story told in chapter ten. When a serious aluminum shortage developed in late 1940, the army launched a major program to increase the use of wood in noncombat airplanes. The military could not reverse two decades of neglect overnight, however, and in 1943 army officers pronounced the wooden airplane program a failure. In contrast to the United States, other countries had considerably more success with wooden airplanes. The most striking example was Britain's all-wood

Mosquito, one of the best combat airplanes of the war, which convincingly demonstrated the untapped technical potential of wooden construction. Nevertheless, the wartime revival of the wooden airplane proved temporary; wood found few places in the postwar world of jet aircraft and guided missiles.

The book concludes with an epilogue on the recent development of nonmetallic materials for airplanes structures. These "composite" materials have recently emerged as major challengers to light alloys in airplane structures. Composites have more in common with wood than metal and in a very real sense represent a continuation of the alternative path started by molded plywood airplanes. The origins of composite materials lie in research on fiber-reinforced plastics during the 1930s, research directly linked to studies of resin-bonded wood veneers. The new nonmetallic composites have long lost any association with wood, but symbolic meanings still play a role in the competition between composites and metal. Until the mid-1960s, "fiber-reinforced plastics" had been the accepted technical term for the materials now called "composites." The shift in terminology represents a clear attempt to control the symbolic meaning of the new materials, to disassociate "composites" from the negative connotations of "plastics."

Materials and Symbolic Meanings in History

The progress ideology of metal arose in the early 1920s as a response to specific problems of airplane design. This ideology was local to the community of aviation at this particular historical moment, yet it was not without a broader history, having emerged from a synthesis of two related aspects of modern industrial culture. The first aspect concerns the symbolism of industrial materials that preceded the airplane, in particular the tendency to characterize historical periods by specific materials. But these symbolic meanings only assumed their significance within another aspect of industrial culture, the ideology of technological progress that arose in the nineteenth century.

The symbolism of materials plays a role in every technological artifact. According to Robert Friedel, artifacts convey cultural meanings not just through their form but also by their materials. Different materials have different symbolic meanings, or 'values' in Friedel's terminology. These values are in no sense inherent in the material themselves but are relative to a specific cultural context. Even the functional characteristics of materials are culturally relative, for function is, according to David Pye, nothing more than collective agreement about the proper use of a thing. Friedel notes, furthermore, that the values associated with materials are distinct from the values associated with an artifact, although they obviously influence each other.[13] This distinction is crucial to understanding the historical emergence of the progress ideology of metal, for while the form of early airplanes represented modernity, their use of wood symbolized tradition.

The specific linking of metal with modernity and wood with tradition was the product of nineteenth-century industrialization. But the connection between materials and the march of history was not new. The classical Greek tradition had its Gold, Bronze, and Iron ages; nineteenth-century archaeology converted these ages into a progressive schema by substituting stone for gold. By the late nineteenth century, industrial civilization had become increasingly characterized by a shift from the organic to the inorganic. Writing at the turn of the century, Werner Sombart gave this idea formal expression in his *Moderne Kapitalismus*. Sombart viewed the displacement of wood by metal as part of the general trend "toward the economic emancipation of men from the limits of organic nature." Lewis Mumford continued this line of analysis in the early 1930s, using materials and power sources to identify three major epochs in the history of technology: the Eotechnic age of wood and water power; the Paleotechnic age of coal, iron, and steam; and the Neotechnic age of synthetic materials and electricity.[14]

With the growing use of iron and steel in bridges, buildings, and ships, wood became increasingly identified as a traditional material antithetical to the onward march of the industrial age (figure 1.3). Aesthetic critics of industrialism like John Ruskin and William Morris praised the virtues of wood and stone while condemning the new techniques for mass-produced ornament, such as cast iron. Anticipating Sombart, Ruskin also saw in the industrial age a shift from the organic to the inorganic, a shift Ruskin condemned.[15] Emerson, in contrast, welcomed the new materials as harbingers of material progress: "Who would live in the stone age or the bronze or the iron or the lacustrine? Who does not prefer the age of steel, of gold, of coal, petroleum, cotton, steam, electricity, and the spectroscope?"[16] The utopian literature of the late nineteenth century reflected this association of new materials with progress. Aluminum was one of the most prominently featured technologies in utopian fiction, along with high-speed trains and electricity. Aluminum forged an especially durable link with progress, first through its identification with scientific chemistry and later by virtue of its dependence on the magical power of electricity, another powerful symbol of progress.[17]

The symbolic connection between inorganic materials and progress intensified in the early twentieth century. Wood had no place in machine-age aesthetics. Modernist architects turned Ruskin on his head, rejecting traditional materials as unsuited to "machines for living." Le Corbusier was typically strident on this issue, praising the influence of industry on materials of construction. The first step in the industrial transformation of buildings, claimed Le Corbusier, was "the replacement of heterogeneous and unreliable natural materials by homogenous artificial materials subject to

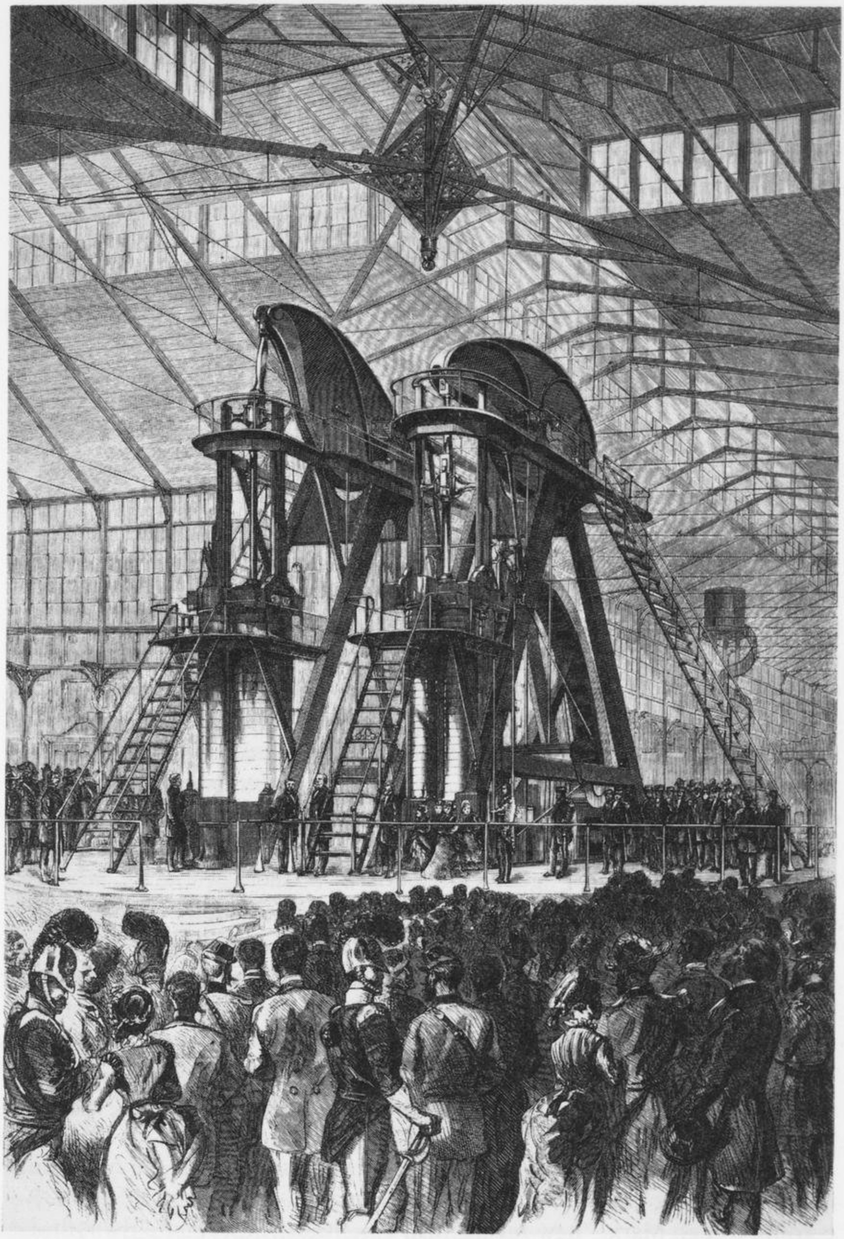

Figure 1.3. Metallic modernity: The Corliss engine at the Philadelphia Centennial Exposition. Metal structures and metallic machinery defined modern technology, as demonstrated by this famous illustration of President Grant and Dom Pedro starting the great Corliss steam engine at the Philadelphia Centennial Exposition of 1876. *Harpers Weekly* 20 (May 27, 1876): 421.

laboratory tests."[18] This language was remarkably similar to contemporary criticisms of wooden airplanes made by English, German, and American engineers (see chapter three). Even Mumford praised the shift from wood to metal and argued that even more progress would be achieved by substituting aluminum for iron.[19]

The identification of industrial progress with a shift from the organic to the inorganic, and from wood to metal, contains a grain of truth. In other words, it is mostly false. The increased use of iron during the nineteenth century resulted from changes in the relative prices of iron and timber, due largely to improved methods for smelting and refining iron. In countries with ample supplies of timber, such as the United States, wood played a much larger role in industrialization. Wood, furthermore, did not disappear, especially as a structural material, where it found continued use in bridges and buildings. As Gregory Dreicer has argued, wood remained the preferred material for innovative designs in nineteenth-century truss bridges.[20] Wood itself became an industrial product, cut into standardized shapes, peeled or sliced into thin veneers by massive machines, and steamed into curved forms for quantity production. In the 1920s, Frank Lloyd Wright acknowledged this industrial basis of wood, a material whose "finer properties . . . have been emancipated by the machine." Wright argued for a new aesthetic of wood suited to modern civilization, but he remained largely alone in his understanding of wood as a machine-age material.[21]

The dichotomy of wood versus metal mirrored the opposition of tradition and modernity. This opposition has been a fundamental tenet of the idea of progress since the Enlightenment. Inspired in part by dramatic changes in science and technology, the Enlightenment inaugurated the very concept of modernity itself, along with the orientation toward the future that is the hallmark of the modern age.[22] Our modern technological civilization depends on this orientation toward the future, because rapid change requires a willingness to challenge ideas and practices based upon tradition. But this orientation toward the future, this faith in progress, comes at a cost, becoming a "prejudice against prejudice," to use Gadamer's phrase. This prejudice against prejudice, this critique of tradition that denies the role of tradition in critique, turned the Enlightenment's orientation toward the future into the ideology of progress, the unquestioned faith in the unending improvement of human civilization.[23]

The Enlightenment ideology of progress was modified in the nineteenth century by the great technological transformations of industrialization. According to Leo Marx, "new mechanical inventions," especially the railroad, "had the effect, as nothing else did, of certifying the reality of progress." American popular culture seized upon the machine as undeniable evidence of human progress. By the late nineteenth century, most Americans came to define progress in material and technological terms, thus displacing earlier moral and spiritual conceptions.[24] In a preface to the American edition of

J. B. Bury's classic study of the idea of progress, Charles A. Beard chided Bury for neglecting the role of technology. "Technology is the fundamental basis of modern civilization, supplies a dynamic force of inexorable drive, and indicates the methods by which the progressive conquest of nature can be effected."[25]

Beard's clear articulation of the ideology of technological progress was a response to growing criticism of "machine civilization."[26] Such criticism had little influence within the engineering profession, where faith in technological progress provided an essential element of professional identity. In speech after speech, argues Edwin Layton, engineers claimed "that their group had a unique and vital role to play in social progress." At the same time, engineers wrapped themselves in the mantle of "science," in part to distinguish their expertise from the traditional knowledge of craft workers. Science and progress thus formed a central part of the professional identity of the engineer.[27]

Engineers proved particularly receptive to the rhetoric linking metal and progress. For mechanical engineers especially, "wood was anathema to the ideals of precision, power and production" that defined the profession and clearly distinguished engineers from millwrights and carpenters. Craft skills remained essential for working with metal as well as wood, but metal's uniformity made it attractive to engineers designing tasks for less-skilled workers, especially in mass-production industries. For civil engineers, the highly visible monuments of Victorian engineering, especially the great metal bridges, created prominent symbols linking metal with technical progress.[28] When American engineers entered aviation in large numbers during World War I, displacing the self-taught designers who had previously dominated the fledgling industry, they brought with them their prejudices against wood in engineering structures.

It was these engineers, faced with the clash between the modernity of aviation and the traditionalism of wood, who clearly articulated the progress ideology of metal. This ideology provided aviation engineers with an interpretive framework that made sense of the contradictory symbols of the wooden airplane, while resolving the indeterminacy of the choice between wood and metal. These engineers decided, in effect, that the future of airplanes lay with metal, and they took the necessary steps to make this future a reality.

Indeterminacy, Symbolism, and Ideology: Theoretical Implications

My account of the shift from wood to metal airplanes raises a number of methodological issues of broad significance to the history of technology. Most centrally, my interpretation seeks to bring culture into hardware history, that is, to show that cultural factors directly shape the details of technical change. The relevance of culture has been obscured by the dominant assumption that technology is a form of instrumental rationality, a process of matching means to given ends. But instrumentalism fails to provide an adequate account of technical choice, because technical choice always possesses significant indeterminacy with regard to technical criteria. This indeterminacy opens technical change to the influence of culture, most notably culture conceived in terms of symbolic meanings that play a direct role in technical choice. But symbolism is not neutral; it can become linked with systems of power in a way that distorts understanding and restricts human choices. In such cases, symbolic systems become ideologies, and these ideologies can exert a powerful influence on technical change.

Over the past thirty years, historians of technology have become tremendously more sophisticated in producing hardware histories, the detailed accounts of changes in technological artifacts and processes. Unlike the old hardware history, epitomized by Robert Woodbury's *Studies in the History of Machine Tools*, this "new hardware history" is thoroughly informed by contextualist historiography, situating the development of specific artifacts within larger institutional and social contexts. The new hardware history has produced nuanced accounts of invention and engineering design, revealing clearly the ambiguous role of scientific knowledge, the uncertainties accompanying technical choices, and the social processes involved in technical change. Historical research inspired by the sociology of scientific knowledge has taken this process even further, convincingly demonstrating the indelibly social and political character of the most recondite and scientific modern technologies.[29]

Yet despite this theoretical and empirical sophistication, most hardware history remains marginal to mainstream history and social theory. This marginality is rooted in a powerful presupposition contained within the very concept of technology itself, instrumentalism. According to sociologist Mark Shields, this "instrumentalist presupposition" consists of the premise that technologies are rationally determined means applied to given ends. In this view, technology is governed by a utilitarian logic in which categories like efficiency and profitability determine the course of technical change. Successful technologies are therefore those best adapted to the ends they serve. Although the purposes of technology may vary with time and culture, technology as means is merely the expression of a universal logic of practice, constrained only by limitations in knowledge and resources.[30]

As a first approximation, the instrumentalist premise provides a reasonable explanation for most technological change. After all, instrumentalism reflects the official doctrine of the technical professions, which insist upon their ability to match means to ends within an area of expertise.[31] Furthermore, questions of technical efficacy remain central to understanding past technologies.

As an unexamined assumption, however, instrumentalism imposes considerable burdens on the history of technology. More than anything else, the instrumentalist assumption separates technology from other domains of human endeavor. In instrumentalist terms, a technology is judged solely by its efficacy in serving specific ends and not as a product of meaningful human action.[32] By isolating technology from the sphere of meaning, instrumentalism also separates technology from culture, exiling culture to the periphery of technical change, where it speaks only to ends while remaining silent on means.

There are two basic arguments for demonstrating the inadequacy of instrumentalism, one "strong" and the other "weak." The strong argument asserts that symbolism is implicated in all human action, including technical action. In this form of the argument, purely instrumental action is impossible because the very criteria used to determine if an action is instrumental, criteria like efficiency and efficacy, are themselves symbolic constructs whose meaning varies with time and place.[33] The weak argument, in contrast, starts from within the concept of instrumental reason itself, demonstrating that the process of technical choice is itself indeterminate. This concept of technical indeterminacy means simply that an artifact or technical process is only in part determined by the application of technical knowledge to particular human purposes. Even given clearly specified objectives, the requisite empirical data and relevant scientific theories, a designer still has considerable freedom to choose the form of the artifact. Although I subscribe to both forms of the argument, I prefer the version based on technical indeterminacy. The argument from indeterminacy encourages a more direct engagement with the technical arguments themselves while also creating a basis for dialogue with defenders of instrumentalism.

The concept of technical indeterminacy has received support from sociological theories of technical change, most importantly the approach termed "social construction of technology."[34] Using arguments derived from the sociology of knowledge and the post-empiricist philosophy of science, the social constructivists make the idea of technical indeterminacy a key premise. In a seminal article, Trevor Pinch and Wiebe Bijker focus on the "interpretive flexibility" of artifacts, which means "not only that there is flexibility in how people think of, or interpret, artefacts, but also that there is flexibility in how artefacts are *designed*." Donald MacKenzie describes the same concept as "contingency of design." By emphasizing the indeterminacy of design, the social constructivists have opened up technical change to a variety of explanatory strategies, including those that focus on competing interest groups, state power, gender relations, and power struggles on the shop floor.[35]

The concept of technical indeterminacy predates the work of Pinch and Bijker, however, and can be demonstrated without recourse to the sociology of knowledge. Historians of technology have long argued that technical change involves a creative, artistic component that cannot be reduced to a set of propositional rules.[36] More directly, the organizational theorist Donald Schön has argued that technical indeterminacy results from inevitable uncertainties in the design process, uncertainties produced by incomplete knowledge.[37] Design theorist David Pye arrives at the same result from the opposite direction. While Schön suggests that the design process is underdetermined due to incomplete knowledge, Pye argues that the process is overdetermined due to inevitable conflicts among the technical criteria. According to Pye, the desirable characteristics of any designed object are incompatible. Since the requirements are incompatible, the object cannot be "the logical outcome of the requirements." The designed object represents a compromise among the conflicting requirements, which implies that the designer has to choose which requirements will fail to be met and the extent of the failure.[38]

Airplane engineers and designers recognized the inevitability of conflict among design requirements and the resulting necessity for compromise. According to T. P. Wright, the chief engineer of the airplane division of the Curtiss Aeroplane & Motor Company:

> It sometimes seems that there exists no element of design which does not conflict directly with every other element. Conflicts, requiring compromises, exist between such important elements as weight saving and structural strength; between weight saving and low production cost; high performance and commodious fuselage size; high cruising speed and low landing speed; high power loading and low operating expense; and many others.

Other aeronautical engineers echoed Wright's observations.[39]

Technical indeterminacy reveals the insufficiency of the instrumentalist premise. Technical criteria cannot by themselves dictate the choice among alternatives. On what basis, then, do engineers and designers choose? They are neither efficiency-maximizing automatons nor passive pawns of social forces. Rather, designers base technical choices on an interpretive understanding of the design criteria and context, an understanding mediated by culture, where culture is defined as a system of symbols and practices that people use to make sense of their world.[40]

The concept of technical indeterminacy opens the door to culture, but culture still needs to be invited inside. Recently, a number of scholars in science and technology studies have proposed doing just that, broadening the social-constructivist approach by integrating culture into accounts of scientific and technological change.[41] In a review article on the history of technology, John Staudenmaier identified an emerging theme in the history of technology based on such an approach, one that he termed the "symbolic construction of technology." According to Staudenmaier, works falling under this rubric argue that a technology succeeds "in part because it has achieved . . . compelling symbolic status within the culture's affective and cognitive frames of reference."[42]

Staudenmaier's analysis points to symbolism as a key concept linking culture with technical choice, based on the recognition that technologies have symbolic meanings as well as material effects.[43] Indeed, cultural historians have not ignored the symbolic dimensions of technology. Over the past three decades, they have produced a substantial literature that focuses on the cultural significance of technologies from sewers to airplanes.[44]

For the most part, however, this attention to culture has not influenced the study of technical choice itself. Most cultural historians treat technologies like the stars, whose rich symbolic meanings have not changed their material characteristics. Technologies are not natural objects, however, but rather the products of human choices. These choices involve more than rational calculation or the play of social forces. Like all human choice, technical choices are the result of interpretations shaped by systems of symbolic meanings. In this way, symbolism directly influences technical change.[45]

Symbols form systems of meaning, interpretive frameworks that guide human action.[46] Such frameworks provide the preconditions necessary for all understanding and are not necessarily distorting. Symbolic systems can, however, become sources of distortion when linked to relations of power and forms of domination. In this context, symbolic systems become ideologies. While the classic type of ideology is political, the symbolic meanings of technology are also subject to ideological distortion as much as symbolic meanings in the political sphere. As symbolic systems, ideologies of technology shape technical choice just like more "neutral" design traditions. But in contrast to design traditions, which merely direct attention toward certain types of solutions, ideologies of technology promote the active suppression of particular alternatives.[47]

David Noble provides a paradigmatic example of such influence in his analysis of the development of numerically controlled machine tools after World War II. In Noble's account, the Air Force, MIT, and General Electric favored the development of complex, digitally programmed devices that tended to remove expertise from the machinist on the shop floor. At the same time, these organizations repeatedly rejected the alternative record-playback technology, despite its promise to provide cheaper, user-friendly devices better suited to the vast majority of small machine shops. Record-playback systems did not fail because of technical inadequacies, according to Noble. Within the ideological framework of the military-university-industrial complex, the record-playback system did not represent an acceptable solution, in part because it permitted too much control to remain with the machinist on the shop floor. But as Noble and Harley Shaiken have shown, the successful numerical control technology also failed to live up to its ideological billing, as manufacturers often found it necessary to continue employing skilled machinists on the new machines. Although Noble does not use the concept of symbolic meaning, in effect he shows that the success of numerical control depended as much on what it symbolized as on what it achieved in practice. In other words, numerical control succeeded because it symbolized the ideals of total control, technical elegance, and de-skilling that were central to the ideology of the military-university-industrial complex.[48]

Aside from Noble, only a few scholars have explicitly addressed the role of ideology in shaping technical change.[49] In part, this neglect results from the dominant instrumentalist view of technology as an exemplar of rational action. But leaving technology aside, the concept of ideology itself has come under attack from a variety of intellectual directions. Critics argue that the word has taken on so many divergent meanings as to make it practically useless. In traditional usage going back to Marx, ideology implies irrationality, dogmatism, and a lack of objectivity. This pejorative sense, critics contend, makes ideology more a weapon of political rhetoric than a tool of intellectual analysis. In other contexts, in contrast, the concept of ideology has evolved into a neutral term, one that has expanded to cover all human ideas and cultural systems. In this all-encompassing sense, ideology loses all utility as an analytical concept.[50]

Yet despite these apparently conflicting definitions, the concept of ideology remains essential, especially for making the moral judgments implicit in the practice of history. But to retain ideology as a useful analytical as well as evaluative tool, the historian needs to combine both types of definition, the pejorative and the neutral. Paul Ricoeur achieves such a synthesis by drawing on Marx, Weber, and Geertz to define three levels of ideology: integration, legitimation, and distortion.[51]

Following Geertz, Ricoeur insists that at its deepest level ideology must be understood as a symbolic system not as a set of ideas. According to Geertz, ideology functions as an explicitly articulated symbolic system that helps define a community and provide a common program of action. In this integrative role, ideology allows a community to make sense of situations in which myth and tradition prove inadequate, as they so often do during periods of rapid social change.[52] At the same time, argues Ricoeur, ideologies provide legitimation, ensuring at least some degree of consent from the governed, consent that is necessary to sustain every system of power, however tyrannical. At this level, ideologies do not necessarily sustain systems of domination: they can legitimate both just and unjust structures of power. But legitimation always involves an element of distortion, and distortion is central to the concept of ideology. As systems of distortion, ideologies limit choice by suppressing alternatives, making specific choices seem inevitable and natural. In this way, ideologies present the contingent as necessary and the particular as universal.[53]

Within the community of American aviation, the progress ideology of metal operated primarily on the first and third levels. First, this ideology helped the aviation community define itself as part of the technological vanguard, as the bearer of the most exciting technology of the new century. For aviation engineers in particular, working with wood was incompatible with this self-definition. At the same time, the progress ideology of metal also functioned as a system of distortion by representing the shift to metal as a necessary and universal stage in airplane design. This ideology did help identify the technical potential of metal airplanes, but it blinded aviation engineers to the advantages of wood structures, preventing them from appropriating the useful and valid aspects of the wood tradition. The American aviation community worked hard to solve the problems of metal construction. At the same time, this community systematically ignored arguments and evidence that supported wood, while actively discouraging research and practical efforts to improve wooden airplanes.

2

Engineering Enthusiasm: World War I and the Origins of the Metal Airplane

ACCORDING TO MOST aviation historians, the trend toward all-metal airplane structures began in Germany during World War I. Indeed, German engineers designed and built the first metal airplanes produced in quantity and used in service. German engineers also built several all-metal airplanes with stressed-skin structures, anticipating what became the dominant system of airplane design. Yet the precise German contribution to all-metal construction remains ambiguous. The first truly successful airplanes with stressed-skin, all-metal structures were American not German.[1]

Yet Germany contributed more than technical advances to the development of all-metal airplanes. German work in metal construction, when it became known after the end of the war, generated a wave of enthusiasm for metal airplanes among Germany's former enemies, especially the United States. Americans had also worked on metal aircraft during the war, but this work sparked none of the excitement that greeted the first German all-metal airplanes in the United States.

German Metal Airplanes of World War I

Germany began World War I with some 450 warplanes, compared to 600 for the French and just 160 for the British. Initially the combatants used airplanes only for reconnaissance, but they soon developed techniques for air-to-air combat, tactical ground support and strategic bombing. As expectations of a short war proved unfounded, air power assumed an increasingly important role in the conflict, and the major powers launched programs to produce airplanes on a large scale. These programs transformed fledgling companies into massive enterprises supported by government-run research and engineering establishments. In a long war, Germany had no hope of matching the Entente's capacity for aircraft production. German industrial inferiority placed a premium on the search for technological superiority. Germany's wartime development of metal airplanes was part of this search for technical advantage, a search that grew increasingly desperate as the war dragged on.[2]

The use of metal in German aircraft during the war took two paths. One proved useful on a wide scale, while the other had a much stronger symbolic impact. The first and more practical development was the substitution of steel tubing for wood in fuselage structures. The more symbolic development was the construction of military aircraft made entirely of metal.

The steel-tube fuselage first achieved widespread success through the work of Anthony H. G. Fokker (1890–1939). Fokker, a flamboyant Dutchman working in Germany, was already a well-known flyer and airplane builder before the war. In early 1914 he developed a new model, the M5, patterned after a French monoplane, the Morane-Saulnier. Instead of copying the French airplane's wooden fuselage, Fokker had Rheinhold Platz, a skilled welder who would later become Fokker's chief engineer, design and build a fuselage framework of welded steel tubing. Platz had already built a steel-tube fuselage for an earlier, unsuccessful Fokker design, the M2 of 1913. The M5 proved successful, and Fokker quickly adopted the welded steel-tube fuselage for all his designs, while continuing to use wood for his wings. Fokker's airplanes found favor with the German military, and the German army purchased over a thousand Fokker fighters with steel-tube fuselages.[3]

The M5 fuselage designed by Platz was simple, light, and easy to manufacture. In form, the Fokker fuselage followed the wood structures of the period (figure 2.1). Four tubes called longerons ran the length of the fuselage, forming the edges of a long, roughly rectangular box. The longerons converged somewhat toward the tail, giving the fuselage a tapered look. The longerons were connected by vertical struts, also of steel tubing, which were butt-welded to the longerons. Steel wire provided the diagonal bracing that kept the rectangular structure rigid. Fokker used tubing of mild steel, which was easy to weld. The heat of welding sometimes distorted the longerons, which were easily trued by a little hammering. The completed framework was covered with fabric or plywood.[4]

While Fokker was busily building his steel-tube airplanes for the German army, other German designers were experimenting with a more radical departure from current practice—building airplanes entirely of metal. Not only did these designers extend the use of metal from the fuselage to the wings, but they also went one step further, replacing fabric or plywood coverings with sheet metal. The most important of these designers were Hugo Junkers and Claude Dornier.[5]

Hugo Junkers (1859–1935) was a successful inventor, industrialist, and engineering professor at the Aachener Technische Hochschule. Junkers became involved in aircraft design in 1909 when he collaborated with fellow professor Hans Reissner in designing and building an airplane called the *Ente* (Duck). Reissner's *Ente* had a monoplane wing covered with corrugated aluminum. Junkers soon became convinced that the ideal airplane would be one approaching a "flying wing," an airplane consisting almost

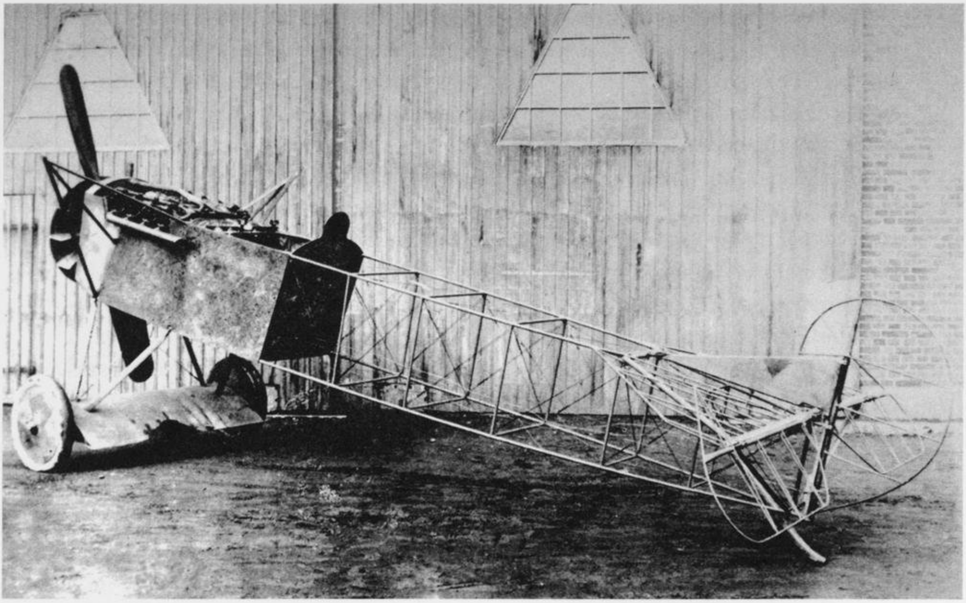

Figure 2.1. A 1918 Fokker V-37 steel-tube fuselage structure. National Air and Space Museum, Smithsonian Institution (SI neg. no. A 43641-10).

entirely of a large hollow wing enclosing engines, cargo, and passengers, with no external bracing. Junkers received a German patent for this idea in 1910. In 1912 he left the Technische Hochschule to devote himself full-time to his inventive work, financed by profits from his patented "geyser" bath-water heater, still common in European kitchens and baths.[6]

Junkers was no theorist, and he had a strong sense of the practical, as demonstrated by his numerous successful inventions for home and factory. Yet when it came to airplanes, Junkers became a visionary. He was driven by two *idées fixes*: devotion to the unbraced monoplane and an unwavering commitment to all-metal construction. Both these obsessions were clearly foreshadowed in Reissner's *Ente* and Junkers' 1910 flying-wing patent. In 1914 Junkers began the serious work required to translate these ideas into practice, to make the impractical practical. The result was the J1, an all-metal fully cantilevered monoplane fighter (figure 2.2).*

Early in 1915, Junkers moved from Aachen to Dessau, site of his bath-heater factory, where he established a laboratory to develop his all-metal airplane. The army gave Junkers a contract for a prototype of the J1 after visiting his laboratory in May. Construction of the J1 began in August. The

* *Fully cantilevered* wings, also termed *unbraced* or *internally braced*, lacked the external struts common in the 1920s. These struts added strength but increased aerodynamic drag.

Figure 2.2. The unsuccessful J1, 1916. Hugo Junkers' first all-metal airplane was made from sheet iron. National Air and Space Museum, Smithsonian Institution (SI neg. no. 96-15636).

J1's structure prototype embodied a number of novel features. Junkers designed the wings of the J1 using a principle he called the "supporting cover," in which "all tensile, compressive and shearing forces are taken up by the wing cover." This principle anticipated the stressed-skin designs that have dominated metal airplane construction since the 1930s. Junkers built his wings of soft sheet iron (*Eisenblech*), between 0.5 and 1 mm thick. Junkers stiffened the thin iron sheets by welding a second, corrugated sheet to the inside surface, using the new process of electric resistance welding. The wing was assembled from these stiffened panels.[7]

Flight testing of the J1 began in December. The airplane was not well received by the military authorities, despite its impressive top speed of 106 mph with a 120-horsepower motor. Junkers attributed this poor reception in part to "the prejudice against metal construction" and also to the mistrust of unbraced wings by pilots. In fact, as Junkers himself later admitted, the J1 was heavier than a comparable wooden airplane and had a very poor rate of climb. A good rate of climb was essential for combat, so the army made additional orders conditional on its improvement.[8]

The failure of the J1 led Junkers to make fundamental changes in his approach to metal construction. His most important step was the substitution of duralumin for sheet iron. Duralumin was a high-strength aluminum alloy developed in 1906 by Alfred Wilm, a German metallurgist. About 1908 Wilm granted an exclusive license for the German production of his alloy to the Dürener Metallwerke, which marketed it under the trade name Duralumin, often shortened to *dural*. Duralumin consisted of aluminum alloyed mainly with copper, with smaller amounts of magnesium and manganese. The key to duralumin's strength was its heat treatment. Heat treatment involves the controlled heating and cooling of a metal in the solid state to produce desired characteristics, such as hardness or ductility. One common type of heat-treatment, quenching, is used to increase the strength and hardness of steel by rapidly cooling the red-hot metal in water or other liquids. Wilm was experimenting with similar processes for aluminum alloys, but his alloys did not behave as expected. Instead of increasing in strength and hardness immediately upon quenching, Wilm's heat-treated alloy gained strength through a process known as age (or precipitation) hardening, in which the quenched alloy gradually hardens over a period of several days. Age-hardened duralumin has the tensile strength and ductility of mild steel, with just over one-third the weight. Like heat-treated steel, duralumin and related alloys also lose strength when welded, making rivets the preferred joining technique.[9]

In addition to switching from iron to duralumin, Junkers abandoned the supporting cover because of its excessive weight. He then developed a new type of all-metal wing and fuselage structure using a duralumin-tube framework covered by dural sheet, which was corrugated to improve its stiffness (figure 2.3). The corrugations ran in the direction of flight to avoid excessive air resistance, which prevented the cover from carrying any of the main bending loads of the wings, although it did contribute to the torsional strength of the wing.[10]

Junkers' first success using this new structural system was the J4 armored biplane of 1916. The army had insisted on the biplane wing, despite Junkers' preference for the monoplane. The J4 was designed for ground observation and combat directly above the trenches. Such an airplane required neither a good rate of climb nor high speed but rather ruggedness of construction and resistance to ground fire. The all-metal airplane proved well-suited to this task. The J4 became the first all-metal airplane to enter production. In all, 227 were manufactured, although the Armistice arrived before many of these saw combat. Junkers also built a few all-duralumin monoplane fighters near the end of the war.[11]

The second major pioneer of German all-metal aircraft construction was the engineer Claude Dornier (1884–1969). Dornier had experience in metal aircraft structures through his work for the Luftschiffbau Zeppelin beginning in 1910. This company was formed in 1908 to build rigid airships, also know as zeppelins, for Count Ferdinand von Zeppelin. In contrast to non-rigid airships (blimps), rigid airships use internal metal structures to se-

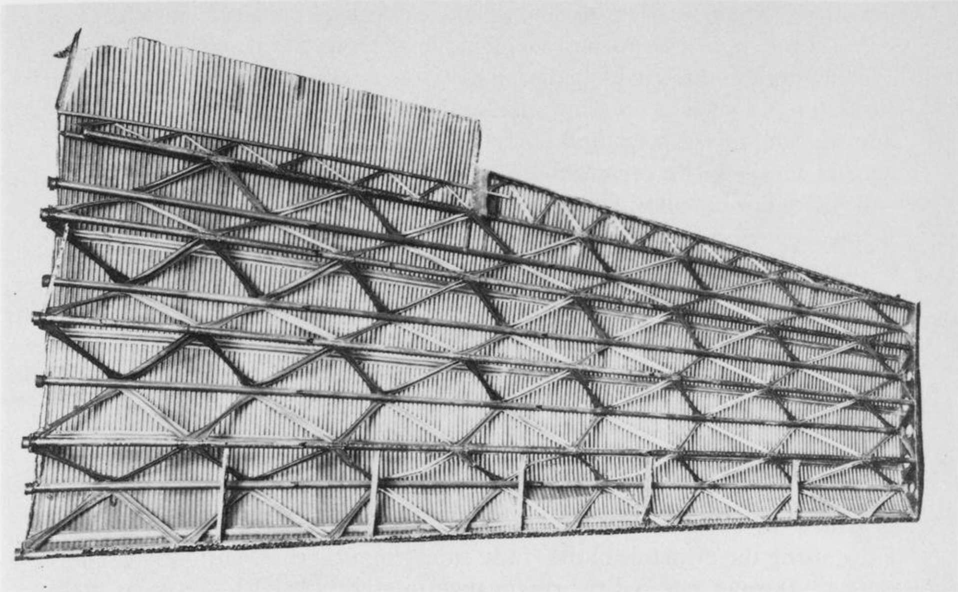

Figure 2.3. Typical Junkers wing construction. This wing assembly, probably for the J9, is typical of those developed after Junkers switched to duralumin. National Air and Space Museum, Smithsonian Institution (Wright-McCook photo no. 9419).

cure the gas bags and maintain the airship's exterior shape. Such structures allowed rigid airships to reach huge dimensions, which gave the zeppelin a flight range and load capacity far superior to any airplane before World War II. In 1914 the Zeppelin company began using duralumin for its airship structures, which created a large demand for the alloy and gave the Zeppelin engineers invaluable experience in using the new material. Spurred on by the fanatical nationalism of Count Zeppelin, the German military invested considerable resources to turn the rigid airship into a military weapon, using it for dramatic but ineffective bombing raids on British cities.[12]

At the beginning of the war, Count Zeppelin became convinced of the need to complement the airship with large, long-range bombing airplanes. In mid 1914, Zeppelin organized a company at Staaken to build these planes, which became known as R-planes (for *Riesenflugzeuge*, or giant airplanes). The Staaken organization turned out R-planes using conventional mixed wood-and-metal construction, similar to Fokker practice. However, Count Zeppelin also believed in the ultimate superiority of all-metal airplanes, and in late 1914 he placed Dornier at the head of a separate project to build all-metal seaplanes in the town of Seemoos on Lake Constance.[13]

There, Dornier built a line of metal seaplanes for the German navy. Dornier's seaplanes used a mix of alloy steel and duralumin. In contrast to

Junkers, Dornier was less dogmatic about all-metal construction and the unbraced monoplane. Dornier covered all his seaplane wings with fabric and supported them with external bracing. Steel was used for highly stressed parts, such as the wing spars and fuselage structures, while duralumin was employed in the hull covering and wing ribs. Despite the experience of the Zeppelin organization with duralumin, it remained an exotic and unpredictable alloy, which convinced Dornier to avoid duralumin for highly stressed parts. For example, one of Dornier's engineers reported that duralumin sheet "had the unpleasant tendency to disintegrate in spots to a white powder." Dornier's seaplanes followed Zeppelin airship practice, with the main structure consisting of truss or lattice beams fabricated from riveted steel strip rolled into special flanged shapes. Dornier built four large seaplanes during the war, only one of which saw military service.[14]

Dornier also tried his hand at an all-metal design, developing a biplane fighter with dural-covered wings, the D1, in early 1918. Dornier achieved in duralumin what Junkers had attempted in iron, producing an all-metal wing in which the smooth skin contributed substantially to the strength of the wing, using the principle of the "fully supporting cover" (*volltragende Außenhaut*). Dornier rejected the corrugated duralumin used by Junkers, and instead borrowed from his experience with smooth metal coverings for flying boat hulls. In his metal boat hulls, Dornier stiffened the duralumin hull by riveting U-shaped channels to both sides of the hull covering, placing the external channels in the direction of the air flow while the internal channels ran at right angles to those on the outside. Dornier's fighter used a similar system for its fuselage and wings, although the rear portion of the wing remained covered with fabric to facilitate production and reduce weight (figure 2.4). The D1 performed well in a competition for new fighters held in the summer of 1918, despite a crash due to wing failure that killed the commander of the Richthofen squadron. However, Dornier's experience with the D1 convinced him that metal-covered wings increased both weight and production costs, and he returned to fabric covering in his postwar designs.[15]

Whether one judges the German all-metal airplane program a success or failure depends on the criteria used. In narrow technical terms, the all-metal airplanes were impressive demonstrations of engineering ingenuity. On the other hand, German metal aircraft played a minimal role in combat and certainly failed to demonstrate any advantage over all-wood or mixed wood-and-metal structures. In addition, the development of metal airplanes diverted technical talent from other pressing wartime needs, in particular the quantity production of combat-worthy airplanes. The Fokker steel-tube fuselage was well adapted to production, but the same was not true of the all-metal designs. For example, the Junkers J4 armored biplane required

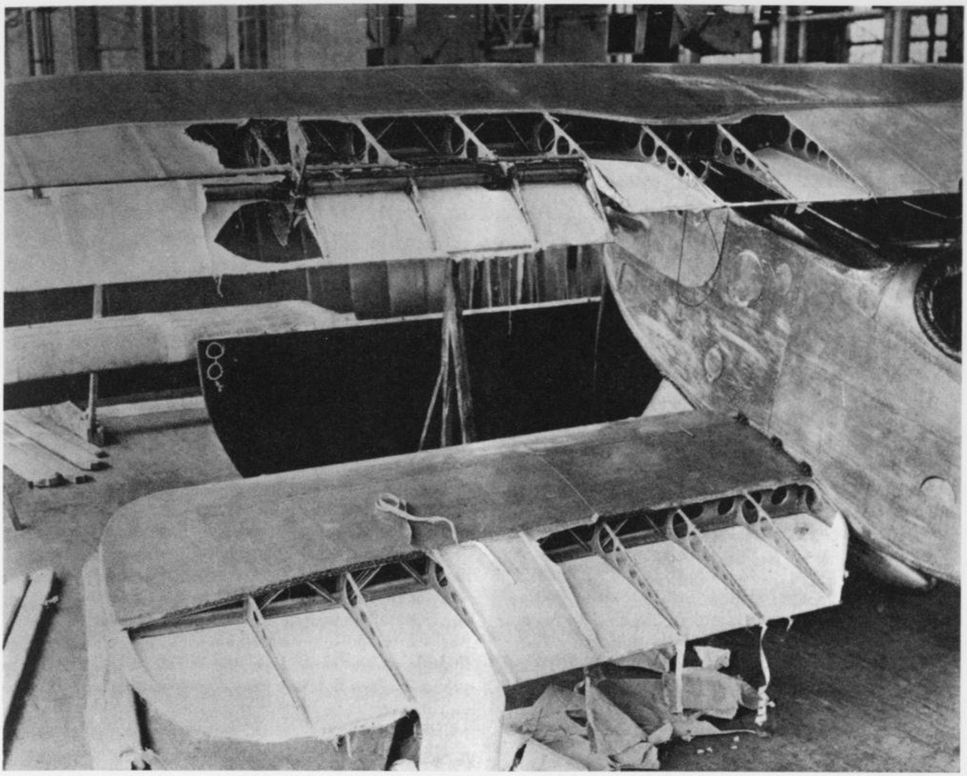

Figure 2.4. Dornier D1 metal wing construction, with fabric removed from trailing edge to reveal the metal-covered box spar. Official Navy photo in *U.S. Air Services* 10 (March 1925): 14.

four times as much labor as standard designs. Fokker, who had been forced into a merger with Junkers in 1917, later criticized Junkers for his impractical commitment to all-metal construction despite the pressing demands of wartime production. In any case, by the spring of 1918, metal shortages had become severe enough to preclude large-scale production of metal airplanes like the Dornier D1.[16]

German metal airplanes remained little known during the war, gaining prominence only after the Armistice, when they inspired tremendous enthusiasm in France, Britain, and especially the United States. But before Americans learned of German developments, the U.S. government launched its own program to develop metal structures for military airplanes. This program achieved modest success but generated none of the enthusiasm that would later greet German developments.

Wartime Metal Airplane Work in the United States

While European aircraft production expanded massively at the beginning of World War I, American aircraft production remained minuscule in comparison, increasing from 49 airplanes in 1914 to only 411 in 1916 (see table 1). When the United States declared war in April 1917, the nascent airplane industry was ill-prepared for wartime demands. The industry consisted of dozens of small firms, most of which had never produced more than ten airplanes. Congress quickly appropriated tens of millions of dollars for aircraft purchases, and the military deluged the industry with orders for thousands of airplanes. When the war ended eighteen months later, the American aircraft industry had delivered 13,894 aircraft and 41,953 engines. It had achieved a peak annual production rate of twenty-one thousand airplanes. Unfortunately, American production came too late to influence the war, and most of the aircraft produced had become obsolete before they were delivered. Massive waste pervaded the program, prompting bitter congressional investigations that blackened the public image of the industry for years.[17]

When the United States entered the war, little was known about German work on metal airplanes. At that time all American airplanes were built of wood, with the exception of a few models designed by Grover Loening of the Sturtevant Airplane Company.[18] The army concentrated on producing large numbers of proven designs, rather than developing new types. Nevertheless, the army and other federal agencies undertook a number of projects to develop new types of aircraft, including a project to substitute metal structures for wood in existing airplanes.

Shortly after declaring war, the United States embarked upon a massive program to build twenty-nine thousand airplanes for the Allies. This program required huge increases in the production of airplane lumber. Large stands of virgin Sitka spruce in the Pacific Northwest provided the main source for the high-quality, straight-grained wood most favored by airplane builders. Much of the U.S. war effort was hampered by supply bottlenecks and a lack of coordination, and spruce production was no exception.[19] A few months after the declaration of war, spruce shortages began to hinder the aircraft program. In September of 1917, the National Advisory Committee for Aeronautics (NACA) urged the president to exempt spruce workers from the draft due to "a disastrous shortage of labor" hampering spruce logging and milling.[20] Continuing problems led the federal government to establish the Spruce Production Corporation, which assumed control of aircraft lumber production. By spring 1918, this organization was able to supply the massive amounts of spruce demanded by the United States and its allies.[21]

TABLE 1
Aircraft Produced in the United States, 1920–1939

	Total	*Military*	*Other*
1913	43	14	29
1914	49	15	34
1915	178	26	152
1916	411	142	269
1917	2,148	2,013	135
1918	14,020	13,991	29
1919	780	682	98
1920	328	256	72
1921	437	389	48
1922	263	226	37
1923	743	687	56
1924	377	317	60
1925	789	445	344
1926	1,186	478	708
1927	1,995	609	1,386
1928	4,346	847	3,499
1929	6,193	779	5,414
1930	3,437	836	2,601
1931	2,800	853	1,947
1932	1,396	500	896
1933	1,324	331	993
1934	1,615	393	1,222
1935	1,710	336	1,374
1936	3,010	858	2,152
1937	3,773	858	2,915
1938	3,623	925	2,698
1939	5,856	921	4,935

Source: U.S. Bureau of the Census, *Historical Statistics of the United States: Colonial Times to 1956* (Washington, D.C.: U.S. Department of Commerce, 1960), 466.

Note: "Military" figures are airplanes for the U.S. Army and Navy; military exports are included in "Other."

Before spruce production had reached adequate levels, the federal government also began research on substitute materials. One of these projects concerned the development of metal airplane structures. This project was supervised by the NACA, a federal agency established in 1915 to advise the federal government in matters pertaining to aviation. During the war the NACA took an active role in coordinating aeronautical research through a system of technical committees devoted to specific problems and broad research areas. Members of the technical committees came primarily from government agencies involved in aviation, including the NACA itself. The

NACA had no research facilities of its own but rather provided advice and technical supervision for projects undertaken by other federal agencies. Under the NACA's guidance, the army and the Bureau of Standards launched a joint program to develop metal airplane structures. The program began in September 1917, when the NACA asked the Bureau of Standards to examine the possibility of making wing spars of metal. Calculations and tests at the bureau suggested that commercially available steels and new aluminum alloys might be practical alternatives to wood.[22]

Soon after starting the program, the Bureau of Standards found a private manufacturer eager to participate in the development of metal aircraft, the Empire Art Metal Company of College Point, New York, which advertised itself as a manufacturer of "hollow steel doors and interior trim, etc." This background was not as irrelevant as it might seem, because metal aircraft production required skill in forming complex shapes from sheet metal.[23] The company did not, however, have any experience in designing airplane structures. In November 1917, it unveiled a metal structure for the Curtiss JN-4, the army's mainstay wood-and-fabric training airplane. The entire structure was fabricated from low-carbon steel. Empire's initial effort demonstrated skillful fabrication techniques and excellent detail design, but the structure came nowhere near matching the strength of the JN-4's wooden airframe. The Bureau of Standards then sent staff scientist H. L. Whittemore to the Empire plant to assist the company's engineers in solving the structural design problems.[24]

Experiments at the Empire company in the fall of 1917 revealed that mild steel could not compete with spruce in terms of weight. The Bureau of Standards and the army then turned to other types of steel and aluminum alloys. Metallurgists of the time could produce a variety of steels with markedly different properties. Low-carbon steel, though easy to weld and available in a wide variety of shapes, developed a relatively low tensile strength of sixty thousand pounds per square inch. For steel to compete with spruce, army engineers believed that they needed steel with a tensile strength of more than one hundred thousand pounds per square inch. The strength of steel could be increased through various techniques, including heat treatment and the addition of alloying substances. Experiments with alloy steel at the Empire factory proved disappointing, but heat-treated steels showed more promise. However, they proved difficult to form and lost their strength when welded. In an attempt to solve these problems, the Bureau of Standards developed methods for heat-treating steel structures after fabrication, but the procedures remained experimental.[25]

At the urging of the army and the Bureau of Standards, the Empire company began experimenting with duralumin, the metal of the German zeppelins. At this time, the U.S. Army knew nothing of German use of duralumin in airplanes. Moreover, before the war no American company had produced duralumin. Beginning in 1916, the navy urged the Aluminum Company of America (Alcoa) to develop a duralumin-type alloy for a rigid airship. Later that year, Alcoa received duralumin samples from a German zeppelin that had crashed in France. After the United States entered the war, Alcoa gained access to German patents seized by the U.S. government. The secrets of producing high-quality duralumin remained elusive, however, and Alcoa found it difficult to move from experimental to quantity production. Through the end of the war, duralumin remained an experimental metal available only in limited quantities.[26]

The Empire company received its first delivery of duralumin from Alcoa in February 1918. Initial tests suggested that duralumin wing spars would be competitive with spruce. That spring, the Empire company built two more sets of wings for the Curtiss JN-4, this time with duralumin spars, steel ribs, and fabric covering. These wings were delivered to the army's aircraft engineering center at McCook Field near Dayton, where they received strength and flight tests.[27]

The strength or "static" tests were relatively simple, but nevertheless essential for designing new airplanes. To test a small component like a rib or spar, the engineers fixed the test item in a jig and hung weights that simulated the loads expected in flight. More weights were added until the part failed. A metal component was considered equal in performance to a wood part when it sustained an equal or greater load but weighed no more than the wood part. If the metal part supported a larger load but weighed more, the results were ambiguous.[28] Static tests of complete wings followed a similar procedure. The wings were attached upside down in a jig, and then loaded with sand bags to simulate the distribution of air pressures on the wing in flight. The engineers increased the load until the wing collapsed (figure 2.5). The maximum load sustained without failure determined the load factor, a measure of airplane strength that consisted of the maximum load divided by the normal load in steady flight. As with ribs and spars, the metal wing was superior to the wood wing only if it sustained at least as great a load but weighed less.[29]

The Empire company's first metal wings were not competitive with wood. These wings, built in spring 1918, included the set with duralumin spars and steel ribs, as well as two all-steel designs. The army performed static tests on each design at McCook Field. It also tested a set of standard wood JN-4D wings for comparison. The wings with duralumin spars were significantly weaker than the wood wings, supporting 17 percent less load than wood wings of nearly equal weight. The steel wing also failed to match the strength of the wood wing, while weighing significantly more. Late in 1918, McCook Field received and tested another all-steel wing from the Empire company. This wing used alloy steel, heat treated after fabrication. It weighed 425 pounds, 7 percent more than the wood wing, but it supported

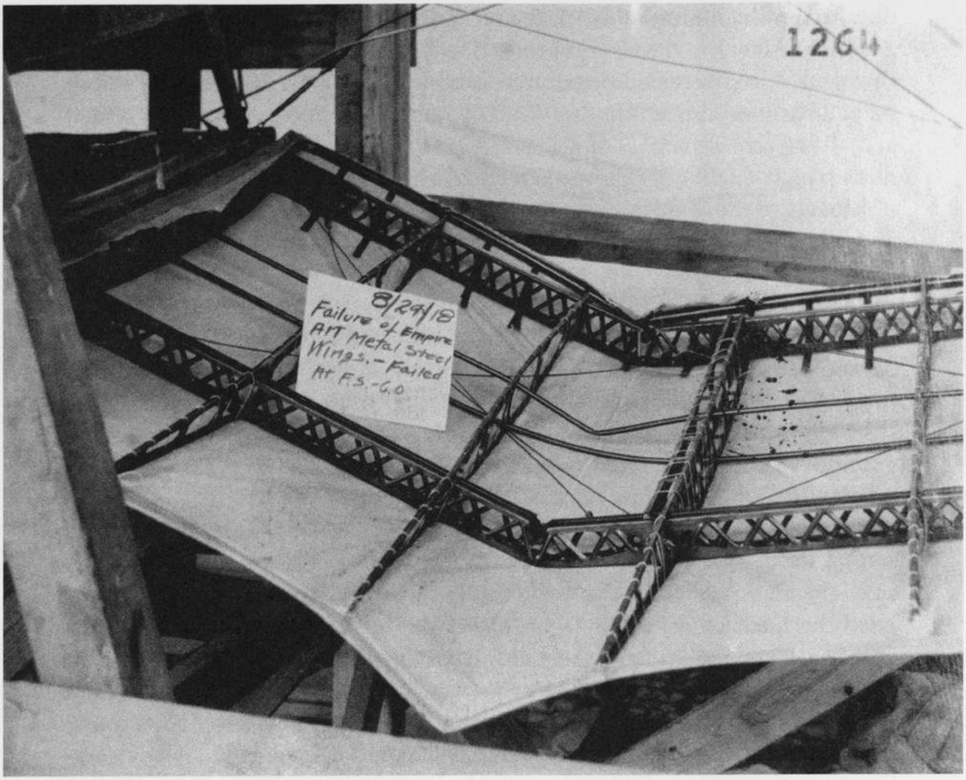

Figure 2.5. Results of a static test of the JN-4 metal wing structure, 1918. From K. M. Lane and Alexander Klemin, "Sand Load Test of JN-4 (Art Metal) Steel Wings," n.d., box 193, Klemin Papers, Department of Special Collections, University Research Library, UCLA.

a load of 13,160 pounds without failure, a 19 percent advantage. The engineers concluded that "by reducing the weight of the steel wings slightly they could be made quite as light and strong as the wood wings."[30] By this time, of course, the war was over, and metal airplanes would make no contribution to the U.S. war effort.

Three months after the Armistice, the army's Airplane Engineering Division at McCook Field published a detailed (but still confidential) account summarizing the wartime program in metal construction. In this report, army engineers cautiously endorsed metal wing structures. Metal had certain advantages in quantity production, they argued, and offered greater uniformity than wood. In certain cases metal structures had greater strength than wood for equal weight, although this required "an entirely new type of construction." The McCook field engineers remained pessimistic about prospects for all-metal airplanes, however, and insisted that metal was not suited to fuselage construction. The army had received some design proposals for all-metal airplanes that "even go so far as to suggest light sheet-metal coverings on the wings and control surfaces," but the engineers argued that such designs were "certain to be very much heavier than the standard type." The engineers remained unimpressed by the information they had received on German all-metal airplanes, claiming that "none of them proved very successful." All-metal construction might be suitable for some warplanes, the report concluded, especially those used for close combat support, but "for commercial planes, wood will always play an important part."[31] This sober assessment appeared quite justified in light of the modest results achieved. In little more than a year, however, such sober engineering judgments would be completely submerged in a wave of enthusiasm for metal airplanes.

Postwar Germany and the *Neue Stil*

During the revolutionary turmoil that followed the signing of the Armistice in November 1918, the German aircraft industry contracted sharply. The German army continued to buy a few aircraft, but it could furnish no new orders. With the collapse of the military market, German aircraft builders sought to apply wartime technical developments to a market that did not yet exist—commercial air transport. Builders of metal aircraft stood at the forefront of this postwar movement. They applied themselves eagerly to the design and construction of new aircraft suited to carrying passengers and freight, preferably at a profit. After January 10, 1920, the Versailles treaty forbade military aeronautics and severely restricted commercial aviation, but many German aircraft companies continued production abroad while maintaining design bureaus in Germany. Despite these restrictions, German designers pushed ahead with the development of all-metal, fully cantilevered monoplanes, designs that came to symbolize the modern airplane.[32]

Junkers and Dornier, the wartime leaders in metal construction, were at the vanguard of commercial metal aircraft design. As soon as the Armistice was declared, Junkers assembled his engineering staff and announced that the company would henceforth focus on commercial air transport. In early 1919, Junkers began work on a purely commercial model based on his wartime experience with metal. The prototype passed its government certification tests on June 25. This airplane became known as the F13 (figure 2.6) and closely followed the structural practice and aerodynamic layout of Junkers' 1918 monoplane fighters. The F13 was an all-metal, low-wing, unbraced monoplane, constructed almost entirely of duralumin. It had an enclosed cabin and cockpit, with room for five passengers. A single 185-horsepower motor powered the F13, giving it a top speed of 106 mph and a

Figure 2.6. Junkers F13 all-metal passenger monoplane, marketed in the U.S. as the JL-6. National Air and Space Museum, Smithsonian Institution (SI neg. no. 96-15637).

cruising speed of about 87 mph. This airplane retained the corrugated duralumin wing and fuselage covering used in Junkers' wartime designs, as well as the duralumin-tube framework. Only a few were built in 1919, but in 1920 production of the F13 increased to seventy-three aircraft.[33]

Meanwhile, Dornier applied his experience at Seemoos to the design of commercial flying boats based on scaled-down versions of the navy R-planes. His first model, the GSI, was an eight-passenger monoplane flying boat, powered by two 260-horsepower engines, giving it a top speed of 112 mph. The plane had originally been ordered by the German navy, but its design was modified for civil use after the Armistice. Like Junkers, Dornier closely followed his wartime design practice, using steel for highly stressed parts, duralumin for the hull and other lightly stressed components, and fabric for the wing covering. In 1921 Dornier built the *Delphin* (Dolphin), his first single-engine boat designed purely for civil aviation, and two land planes. On May 5, 1921, the Allied powers issued the London Ultimatum to force the Germans to comply with the aeronautical provisions of the Versailles treaty. The ultimatum halted production of the Dornier airplanes, although Dornier did continue some production abroad.[34]

The most widely noted addition to the ranks of German metal aircraft designers was Adolf Rohrbach (1889–1939), a Zeppelin engineer who had worked with Dornier at Seemoos during the war. Shortly before the Armistice, Rohrbach was sent to the Zeppelin R-plane plant at Staaken to begin building all-metal R-planes. The end of the war halted this work. Rohrbach

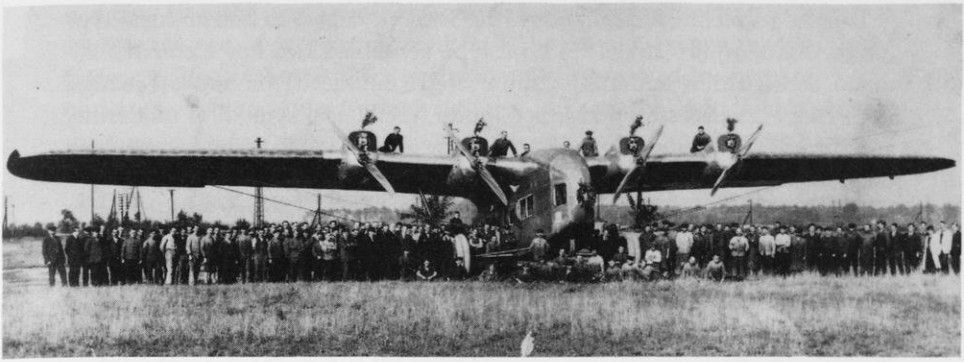

Figure 2.7. The huge Staaken E4/20 all-metal passenger monoplane, ordered destroyed by the Allies in 1922. National Air and Space Museum, Smithsonian Institution (SI neg. no. 76-17370).

then designed a large all-metal passenger airplane, probably based on wartime plans for an all-metal bomber. Construction of the airplane, known as the Staaken E4/20 (or E.4.250), began in May 1919, but was not completed until September 1920 (figure 2.7). The Staaken E4/20 was probably the largest passenger transport of the period. Its four 240-horsepower engines were buried in the leading edge of a thick monoplane wing. The structure was formed almost entirely from flat duralumin sheet, including the fuselage skin and most of the wing. Specially shaped "stringers" riveted to the inside of the skin provided additional stiffness, similar to Dornier practice. The plane had a top speed of 144 mph, and could carry up to eighteen passengers. However, its load-carrying efficiency was quite low, with its useful load amounting to only 28 percent of its gross weight, and it had a very high landing speed of 80 mph. After its test flights, the Inter-Allied Aeronautical Control Commission judged the Staaken E4/20 to have military value, which contravened the Versailles treaty. The commission ordered the aircraft destroyed, and it was scrapped in November 1922.[35]

Many aviation historians portray Rohrbach's work, and the Staaken E4/20 in particular, as forerunners of the modern all-metal airplane.[36] Indeed, the Rohrbach airplane anticipated the main features of seminal designs like the DC-1 of 1933, namely the unbraced monoplane with a stressed-skin structure built primarily of aluminum-alloy sheet. Yet the Staaken was far from an efficient airplane. Rather, it embodied technological enthusiasms nurtured by war, its grand size deriving more from German desire for long-range bombers than any realistic appraisal of civilian air transport, and its esoteric material a byproduct of another wartime excess, the military zeppelin. No airplane of its size would prove successful in civil aviation before the 1930s. The Allies were indeed justified in ordering the airplane destroyed, for it was more appropriate for military than civilian purposes.[37]

Despite its technical limitations, the Staaken helped define an ideal type for the modern airplane. This ideal type contained two key elements: all-metal construction and fully cantilevered (unbraced) monoplane wings. Both elements had strong abstract appeal, metal as a symbol of modernity and the unbraced monoplane as an approximation of the flying wing, which theoretically eliminated most parasitic drag. In 1924, C. W. Erich Meyer, editor of the *Deutsche Motor-Zeitschrift*, made this ideal type explicit in an article on recent German airplanes. Meyer termed the new design trend the *neue Stil* or *neue Schule* (new style or school), in contrast to the *alte Stil* (old style) represented by wood-and-fabric biplanes. As examples of the new and old styles, Meyer juxtaposed photographs of two airplanes. Representing the *alte Stil* was an Italian Caproni triplane flying boat, a massive, cumbersome assemblage of wood and cloth criss-crossed with steel wires. For the *neue Stil*, Mayer presented the three-engine Junkers G23, an all-metal unbraced monoplane. The boxy Junkers with its corrugated covering was poorly streamlined even compared to the metal airliners of the mid-1930s, but next to the Caproni it seemed a striking exemplar of sleek modernism. But perhaps more striking was the nature of Mayer's argument, which in essence made an aesthetic claim about the style appropriate for a modern airplane.[38]

Not all proponents of metal adhered to the *neue Stil*. More often than not, however, support for metal went hand in hand with advocacy of the internally braced monoplane. Proponents of this ideal type rarely clarified the necessity of the connection between metal and the monoplane but saw both as necessary elements for efficient air transport. The evocative power of the *neue Stil* in part explains the enthusiastic reception of the German postwar airplanes in the United States.

The German metal airplanes revealed many aspects of the future of metal construction. All-metal airplanes raised difficult design problems, which could only be solved with considerable support from the military. All-metal structures tended to weigh more than comparable wood-and-fabric airplanes, and they proved difficult to manufacture. Despite the engineering ingenuity of these designs, the best type of airplane structure had yet to be decided. But most importantly, the German metal airplanes revealed the tremendous enthusiasm that metal construction inspired, an enthusiasm that soon infected Germany's former enemies.

Enthusiasm Triumphant: Postwar Response to German Metal Aircraft

Although the Allies knew of German metal airplanes during the war, these airplanes generated little concern among military authorities, probably because metal airplanes did not afford the Germans any clear advantage in combat. After the war, however, German metal airplanes attracted attention completely out of proportion to their technical achievements. Among the former Allies, enthusiasm for metal aircraft blossomed in the early 1920s in direct response to the German designs. In France, Britain, and especially the United States, metal construction became one of the hottest topics in aviation.

At the end of World War I, all the belligerents drastically slashed orders for military aircraft.[39] Despite these reductions, technical change in aviation continued at a fast pace in the immediate postwar years, propelled by the momentum of wartime research. During the war, all major powers had established military air arms and aeronautical research facilities, and these did not disappear at the end of the war. The war created real aircraft industries out of prewar workshops, complete with well-equipped factories, test facilities, and experienced designers. Faced with a superabundance of technical expertise as well as excess capacity, the aircraft industries in Germany, France, Britain, and the United States turned enthusiastically toward commercial aviation, hoping to exploit the substantial experience gained with wartime aircraft. These efforts went largely unrewarded, since air transport remained unprofitable without substantial government subsidies, and surplus military equipment satisfied the needs of most sports flyers.[40]

Information on German metal airplanes emerged slowly after the Armistice. During the war, Allied military authorities obtained some data from German airplanes that landed or crashed in Allied territory, but this information remained sketchy. During the revolution and counterrevolution in Germany following the Armistice, little additional information became available. The Germans did their best not to cooperate with Allied authorities in implementing the Armistice agreement.[41] Details about the German designs only became available after the Versailles treaty went into effect in January 1920.

Even before 1920, however, confidential military reports revealed a growing excitement about German metal airplanes among the officers who had a chance to inspect them. In early 1919, the Paris office of the American Expeditionary Force reported on a Junkers single-seat monoplane fighter abandoned in Belgium. The report praised the Junkers as "in some respects the most remarkable of all the Airplanes built by the Germans." According to the report, the all-metal construction made the Junkers "absolutely weather-proof, and also less liable to destruction by fire."[42] As later events would tragically demonstrate, aluminum construction in fact offered little protection against airplane fires. In July the British Air Ministry produced a detailed, printed report on the same Junkers model. This report found the structural design to be of "great importance," and claimed that Junkers had "separated himself completely from the influence due to the use of the wood spars and ribs that are almost universally employed in a non-metal wing." The British report also argued that the all-metal Junkers resisted the effects of weather better than wood-and-fabric construction, despite evidence that the duralumin covering had become brittle.[43] This brittleness provided a hint of the severe corrosion problems that would become apparent a few years later.

As information on German metal airplanes became more widely available, it generated tremendous enthusiasm among the French and British. The designs of the Junkers and Zeppelin organizations particularly impressed the French. In a January 1921 report on German aeronautics, the French undersecretary of state for aviation concluded that the Junkers F13 was "the craft of the future." The report of the Inter-Allied Aeronautical Control Commission, a French-dominated agency charged with enforcing the Versailles treaty, waxed poetic about German metal airplanes, and described Hugo Junkers in almost mythic terms. With encouragement from the French Air Ministry, French designers quickly produced a variety of duralumin aircraft as early as 1920. A 1923 American report on French aviation noted that "all-metal construction is the fashion of the hour and the constructors follow the leader like so many fashionable dressmakers."[44] Like the French, the British also promoted metal aircraft in the postwar period, but they preferred high-strength steels to duralumin, due in part to the absence of domestic supplies of bauxite. By 1924 the British Air Ministry had gained enough confidence in metal construction to require that all "vital parts" of new military aircraft be built of metal.[45]

American interest in German metal aircraft remained muted until early 1920, in part because of the paucity of information available to the public.[46] In the spring of 1920, the British Air Ministry released descriptions of captured Junkers and Dornier models, descriptions that were widely reproduced in the American technical press.[47] But such technical data failed to generate much interest in the American aviation community. American enthusiasm for metal construction was finally stimulated not by technical data but rather by the demonstration of an actual all-metal airplane in the United States, the Junkers F13 transport.

The F13 owed its presence in the United States to the promotional efforts of John M. Larsen. Before he took up aviation, the Danish-born Larsen had worked in the dairy industry, introducing Danish butter-making techniques to the United States and selling his own brand of industrial ice-making machinery.[48] In late 1919, Larsen went to Europe to look for financial opportunities in postwar aviation. He later claimed that he had intended to sell American airplanes in Europe but was so impressed by the Junkers that he immediately obtained a license to build them in the United States. However, it appears more likely that he had heard of German metal airplane work and sought to profit from its introduction into the United States, as he had previously done with Danish dairy technology. Larsen obtained a license from Junkers to build the F13 in the United States. He also bought eight F13s directly from Junkers, followed by fifteen more before the end of the year.[49]

In May and June, Larsen launched a widespread effort to promote the F13, which he marketed in the United States as the JL-6 (for "Junkers-Larsen"). The all-metal Junkers generated tremendous excitement in the military and among manufacturers. Larsen took special pains to interest the army, demonstrating the airplane to influential officers in the Army Air Service, including Maj. William C. Ocker. After a brief flight in the JL-6, Ocker sent a report on the JL-6 to Gen. Charles T. Menoher, chief of the Air Service. In this report, Ocker praised the JL-6 as "the airplane of the future" and recommended its purchase for further study. Such endorsements convinced Menoher, himself not a flyer, to embrace the metal airplane. In early June, Menoher wrote Larsen that "there can be no question that the all-metal plane is here and it behooves the rest of us to get busy in the near future if we hope not to be left entirely behind in the race." Larsen continued his promotional efforts in June, staging a number of flights to publicize the passenger-carrying capability of the F13. On June 12, two army officers raced a pair of JL-6 airplanes from Washington to Long Island with full passenger loads at an average speed of 102 mph for the faster plane. Col. W. K. Wilson, who piloted the winning plane, heralded the JL-6 as introducing "a new era in aviation."[50]

Such hyperbole typified the reception of the JL-6, as demonstrated by reporting in the *New York Times*:

> Aircraft design and construction will have to be completely revolutionized as the result of the success of an all-metal aircraft, the product of German genius, in the opinion of prominent American aircraft manufacturers and Army Air Service officials. . . . It was said on good authority that one American company was going out of business, realizing the futility of continuing to manufacture planes along the present lines of construction.[51]

This favorable publicity paid off for Larsen, who sold eight of the Junkers to the U.S. Air Mail at $25,000 each, quite a high price for the time, and six more to the army and navy.[52]

The JL-6 drove no American company out of business and did not revolutionize American aviation. However, the excitement generated by the JL-6 directly inspired a movement to develop metal airplanes in the United States. This movement first found programmatic expression in the 1920 annual report of the NACA.

At the end of World War I, the NACA still had not found a clear role within the federal government. During the war, the army, the navy and the Bureau of Standards established centers for aviation research, but the NACA did not gain its own research facilities until the opening of the Langley laboratory in 1920. In the mid-1920s, the NACA would become the leading

American institution for research in aerodynamics. In 1920, however, the NACA remained just one of several federal agencies competing for influence over the federal aeronautics establishment.[53] By supporting research in metal airplanes, NACA staff hoped to position the agency at the forefront of aviation technology, insuring the NACA a central place in postwar aviation.

The NACA showed some interest in metal aircraft construction before 1920, but it only developed a real enthusiasm for metal after the arrival of the Junkers transports.[54] In July, Leigh M. Griffith, the senior engineer at Langley, visited the Engineering Division of the Army Air Service at McCook Field, which had just received the army's first JL-6. The Engineering Division continued McCook Field's wartime role as a development and test center for new military aircraft. The Engineering Division proposed to spend $250,000 to develop all-metal airplanes, but, reported Griffith, the army engineers had no clear program for spending this money. Griffith believed that the NACA "could become an important factor in the direction of this all-metal development" if it submitted a well-defined program for research on metal construction.[55]

Griffith's proposal for a research program was received favorably at NACA headquarters in Washington.[56] In a clear lapse of institutional memory, discussions of the proposed program contained no reference to the metal airplane work of the Empire company, whose results justified only cautious support for metal. Instead, discussions of the program revealed the powerful though unarticulated influence of the *neue Stil*, which combined metal construction and the fully cantilevered monoplane in a single aesthetic construct. In a memo to the executive committee on the proposed program, NACA executive officer George Lewis shifted back and forth between problems of metal construction and internally braced wings, with no justification for their inclusion in a single program. A major component of the draft program involved aerodynamic research regarding the properties of thick wings, which at that time were a necessity for fully cantilevered construction. The program also proposed research into the properties of duralumin and the most effective types of metal structures.[57]

In the end, the NACA technical committees failed to agree on a comprehensive research program. Nevertheless, enthusiasm for metal airplanes found voice in the NACA's annual report for 1920, which contained a ringing endorsement of all-metal construction. The report discussed airplane materials in what appeared to be sober, technical language:

> All-metal construction of airplanes has received the careful attention of airplane manufacturers in Europe, with the result that apparently successful models have been constructed. The war was fought with machines constructed of wood, which from many standpoints is most unsatisfactory. . . . Wood has a nonhomogenous structure, is uncertain in strength and weight, warps and cracks, and weakens

> rapidly when exposed to moisture. The advantages of using metal construction for airplanes are apparent, as the metal does not splinter, is more homogeneous, and the properties of the material are much better known and can be relied upon. Metal also can be produced in large quantities, and it is felt that in the future all large airplanes must necessarily be constructed of metal.[58]

The dispassionate tone of the report deceptively presented the superiority of metal as an established technical fact, yet this "fact" depended on the very research that the NACA was proposing to undertake.

The excitement generated by the JL-6 and the NACA's endorsement of metal helped stimulate a burst of activity in the design and construction of metal airplanes. The Army Air Service and the Navy Bureau of Aeronautics quickly established major metal aircraft programs. Both services let contracts with manufacturers for experimental all-metal aircraft. The navy developed duralumin fabrication techniques at the Naval Aircraft Factory, and actively transferred these techniques to airplane manufacturers. By 1922 four firms were using duralumin for navy airplanes. In 1924 William Stout produced the first American all-metal commercial airplane. As early as 1923, some advocates of metal construction felt enough confidence to conclude that the "problem today is not the choice between wood and metal but rather how best to design and fabricate metal parts."[59]

This confidence proved premature. Although Fokker's welded steel-tube fuselage became standard by the mid-1920s, all-metal aircraft remained the exception. Beginning in 1925, Henry Ford put his skills and money behind Stout's all-metal airplanes, but few imitators followed.[60] Statistics of U.S. commercial aircraft demonstrate the continued dominance of wood wing structures. In 1930, there were 130 types of commercial aircraft certified by the federal government for use in interstate commerce. Of these 130, 107 used wood wing spars while fifteen used metal spars. Only seven of these fifteen also used metal covering, and four of these metal-covered airplanes were Fords. Thus in 1930, all-metal construction accounted for only 5 percent of the types of commercial aircraft in production.[61]

The persistence of wood wing spars into the early 1930s seems surprising in light of the NACA's unequivocal statement in 1920 on the advantages of metal. However, the aeronautical community's endorsement of metal was not the result of a careful consideration of its practical advantages. These advantages would only arise at the end of a long period of development, and even then the relative merits of wood and metal remained open to debate. During the 1920s, the choice between wood and metal remained highly indeterminate.

3

Metal and Its Discontents

Why did the aviation community so enthusiastically embrace metal airplanes in the early 1920s? The achievements of German designers hardly seem to justify the reaction; their wartime metal airplanes demonstrated no particular advantages over traditional construction, while suffering from some obvious drawbacks. American wartime research provided even less evidence in favor of metal. Nevertheless, French, British, and American engineers began advocating metal construction before they had a chance to study German airplanes in detail.

One certainly expects sellers of consumer goods to tout every new variation in their products as revolutionary, but engineers are supposed to be swayed by hard technical arguments that allow them to match available technical means with desired ends. Indeed, advocates of metal did advance technical arguments to support their position. Yet when examined in detail, these arguments prove equivocal. Throughout the 1920s, neither theory nor experience could demonstrate the superiority of metal for airplane structures.

Technical criteria cannot explain the enthusiastic support for metal construction in the 1920s. Rather, this support derived from the culture of the aeronautical community, its traditions, prejudices, and symbols. Within this culture, metal symbolized progress and science, while wood represented stasis and craft practices. When combined with the period's powerful faith in technological progress, these symbolic associations shaped the judgments of engineers and airplane designers, justifying their belief in the innate superiority of metal over wood and encouraging them to view the triumph of metal as inevitable.

Technical Indeterminacy: Experience versus Rhetoric

Advocates of metal airplanes did not see any ambiguity in the choice. After World War I, they launched a widespread campaign against wood in the technical press, characterizing it as impermanent, imprecise, and unreliable, having all the undesirable characteristics of organic products of nature. To metal they ascribed all the permanence and precision of the inorganic materials that formed the basis of modern material culture. The technical arguments advanced by these advocates were fairly uniform, whether published in Germany, France, Great Britain, or the United States. These arguments claimed a multitude of advantages for metal in fire safety, weight efficiency, manufacturing costs and durability. Yet in each of these four areas, practical experience with metal airplanes in the 1920s failed to confirm metal's purported superiority.[1]

During and after World War I, fires caused many airplane accidents. A major benefit of metal, according to its advocates, was increased safety from fires. For example, Samuel W. Stratton, head of the Bureau of Standards, declared the early Junkers airplanes to be "incombustible." An army pilot who examined the Junkers JL-6 in June 1920 told the *New York Times* that "fireproof" metal construction had a "big advantage" over wood. Larsen himself argued that "these metal machines eliminate the aviator's greatest fear—fire."[2]

Yet when the fire safety of the JL-6 was put to the test, it proved to be tragically exaggerated, to the detriment of the U.S. Air Mail. The Air Mail purchased eight JL-6's from John Larsen in the summer of 1920 for $200,000. Unfortunately, the JL-6 had serious defects in its fuel system. Less than one month after the Air Mail began using the JL-6 that August, one pilot narrowly escaped death when his feet were suddenly enveloped in flames that burned through the metal floor. The next day two pilots were killed when their Junkers caught fire in flight. The Junkers were grounded, but they soon returned to service. On September 14, just two weeks after the first fatal accident, another JL-6 burst into flames while flying over Ohio, killing its two crew members. Despite extensive changes to the fuel system, another Junkers was destroyed in a fatal crash in February 1921, probably as the result of a fire. After this incident, the Post Office sold the four remaining JL-6s for a mere $6,044.[3]

As the Air Mail's experience with the JL-6 demonstrates, the chief fire danger for airplanes in the 1920s came from combustible fuels, not structural materials. Thin sheets of aluminum provided little protection against fuel fires. Aluminum alloys melt at about 1000 degrees F., roughly half the melting point of steel. Additional experience in the 1920s confirmed that metal offered little protection against airplane fires. In 1930, MIT professor Joseph Newell observed that crash fires "completely consumed" the structures of aluminum airplanes, leaving "no more evidence of . . . [the] original shape than would a spruce structure." Although wood-and-fabric airplanes also provided little protection against fire, chemical retardants could dramatically increase their fire resistance. In one demonstration, a specially treated wooden airplane was flown with burning gasoline-soaked rags attached to its wings.[4]

However questionable the initial claims for metal's superiority in fire resistance, this issue was minor when compared with metal's greatest liability: weight, or more precisely, weight in relation to strength. As designers began accumulating experience with metal wing construction during the early 1920s, they discovered that it was very difficult to build a metal wing as light as a wood structure. Neither theoretical comparisons, laboratory tests, nor practical experience could demonstrate a clear advantage in weight efficiency for either wood or metal.

No theme is more central to the history of airplane design than the struggle to control weight. "Without doubt," argued T. P. Wright, a prominent airplane designer, "weight and weight distribution, or balance, are of more importance in airplane design than in any other branch of engineering." To be useful, an airplane had to carry, in addition to its own weight, a "useful load" consisting of passengers, freight, gas, oil, and crew. The weight of the airplane itself was termed "weight empty." The sum of weight empty and useful load, the total weight carried in flight, was called "gross weight."[5]

Within the boundaries of gross weight, variations in weight empty and useful load are a zero-sum process. Every ounce eliminated from weight empty adds to the useful load, and conversely every item added to weight empty reduces useful load by an equal amount. These principles gave designers of aircraft structures a clear goal—to create structures of minimum weight while maintaining adequate strength, as specified by government safety regulations. Aeronautical engineers therefore had to negotiate a treacherous path between two sources of failure, excess weight and inadequate strength. These engineers pushed the limits of structural design, developing amazingly light structures that supported huge loads. Aeronautical engineers, noted aviation pioneer Grover Loening, thought it "nothing extraordinary" to build a six-hundred-pound wing structure, "really a bridge," that could support more than twenty tons. Quite often, however, airplane designers found it impossible to keep airplanes within their estimated weights while meeting strength requirements. According to Jerome C. Hunsaker, the navy's top aeronautical expert, designers "risk their reputations with weight estimates." An overweight airplane was an unsuccessful airplane, unable to carry the useful load specified in the design.[6]

In the early postwar years, many airplane designers hoped that metal structures would prove lighter than wood. A few well-publicized cases seemed to confirm these hopes, most notably a set of metal wings designed for the navy in 1922 by Charles Ward Hall, an experienced civil engineer turned airplane designer. However, Hall's success remained exceptional.[7] More typical was the army's unsuccessful program to develop metal aircraft in the early 1920s. As part of this program, the Army Air Service in late 1920 contracted with the Gallaudet Aircraft Company for a monoplane bomber with metal-framework wings and an all-metal fuselage, named the DB-1.

The company promised the army an airplane with a weight empty of 3,800 pounds and a useful load of 3,250 pounds, including bombs. As delivered in late 1921, the prototype DB-1 exceeded the estimated weight empty by more than a ton, which reduced the useful load to about one thousand pounds. After deducting the weight of fuel and crew, this useful load was barely enough for a hand grenade.[8]

Although the weight excess of the DB-1 was extreme, by the mid-1920s even supporters of metal construction admitted to weight problems, especially in wing structures. "Metal wings are undoubtedly heavier than those of wood and fabric," reported an army spokesman in a 1925 article hailing the advantages of metal. In a 1929 textbook, Alexander Klemin, a leading aeronautical engineer, estimated that metal wings weighed on average from 25 to 36 percent more than wood wings. Klemin did admit that some engineers could produce metal wings lighter than their wood counterparts, but such designs were possible "only in special cases and after long experience."[9]

One might think it relatively easy for engineers to determine which material would give the lightest structure: they could simply choose the material with the greatest ratio of strength to density. Such simple comparisons are inadequate, however, because no single measure of strength suffices to describe the behavior of a material. Materials exhibit different strength properties when subject to compression, tension, shear, torsion, and bending. A material might prove superior according to one criterion but inferior according to another. In addition, some materials, such as wood, are highly anisotropic, meaning that their properties vary with direction. For example, Sitka spruce has almost twenty-eight times more tensile strength parallel than perpendicular to the grain. Materials also fail in a multitude of ways, making comparisons difficult. Materials fracture, crumple, crush, crinkle, buckle, rupture, tear, deform, or creep, to use some of the terms current in interwar aeronautical engineering. All these differences make material properties an imperfect indicator of weight efficiency in complete structures.[10]

Despite these difficulties, engineers did publish theoretical and empirical analyses of the relative weight efficiencies of aircraft materials, though the results often proved difficult to interpret. In a 1927 paper, Air Corps engineer J. A. Roché compared the weight efficiency of wood and metal using several different criteria. For parts of equal ultimate tensile strength, spruce was lighter than all but the strongest heat-treated alloy steels, and even these had only a 2-percent advantage over wood. Airplane parts were more likely to fail in compression than in tension, however, a fact that limited the significance of the tensile strength comparison. When comparing compressive strength, Roché's data showed a definite advantage for metal. For short blocks of equal strength, army tests demonstrated that aluminum alloy weighed 13 percent less than spruce, while heat-treated alloy steel weighed 24 percent less.[11]

These comparisons offered no clues to the greater weight of metal wing structures; in fact they ignored metal's greatest liability. The key problem lay not in the compressive strength of short, thick parts, but rather in the strength of the long, thin parts common in aircraft structures. A completely different type of failure determined the strength of such parts—compressive buckling. The nontechnical reader can understand buckling by experimenting with a sheet of paper. If one grasps opposite edges of the sheet and pulls, the paper will resist a moderate amount of force without tearing. However, if the edges are pushed toward each other, the paper provides almost no resistance, usually bending in the middle of the sheet. This bending is compressive buckling.[12] Whenever a structure relies on thin sheets or long slender parts in compression, the possibility of buckling exists. In metal airplanes, the high density of the material necessitated thin cross sections compared to wood. For sheets of equal weight, aluminum is one-fifth as thick as spruce plywood, while steel is only one-fourteenth as thick.[13]

Curiously, aeronautical engineers did not publish quantitative comparisons of the relative buckling strength of wood and metal before the late 1930s, even though the comparisons are relatively straightforward. The mathematical treatment of buckling goes back to Leonhard Euler, who in 1744 analyzed the elastic buckling of long slender columns. Aeronautical engineers knew Euler's analysis well, often referring to long slender parts in compression as "Euler struts."[14] Most buckling failures in metal aircraft were not those of the Euler strut, however. Designers rarely used columns so slender as to fail in the Euler range, because of the low stresses they could support. Buckling failures in metal airplane members usually occurred in small areas where the thin metal experienced high compressive stresses, for example the top of the wing spar. Such buckling could then cause the failure of the entire member, weakened by buckling at one point. In effect, part of the area under compression would behave as an Euler strut, losing its ability to carry large compressive loads (figure 3.1). Engineers commonly referred to such failures as local buckling or crinkling. Practical experience with local buckling first arose with the new wrought-iron bridges in the mid-nineteenth century, specifically the Britannia Bridge over the Menai Straits in Wales. In experiments connected with the design of the bridge, Eaton Hodgkinson established that the buckling load of a thin plate varied as the cube of its thickness, a result in accord with Euler's analysis.[15] For flat plates of equal weight, thickness varies inversely with density, giving less dense materials like wood a great advantage in buckling strength.

Quantitative comparisons of buckling strength appeared in the late 1930s, when new plastics rekindled interest in the relative weights of air-

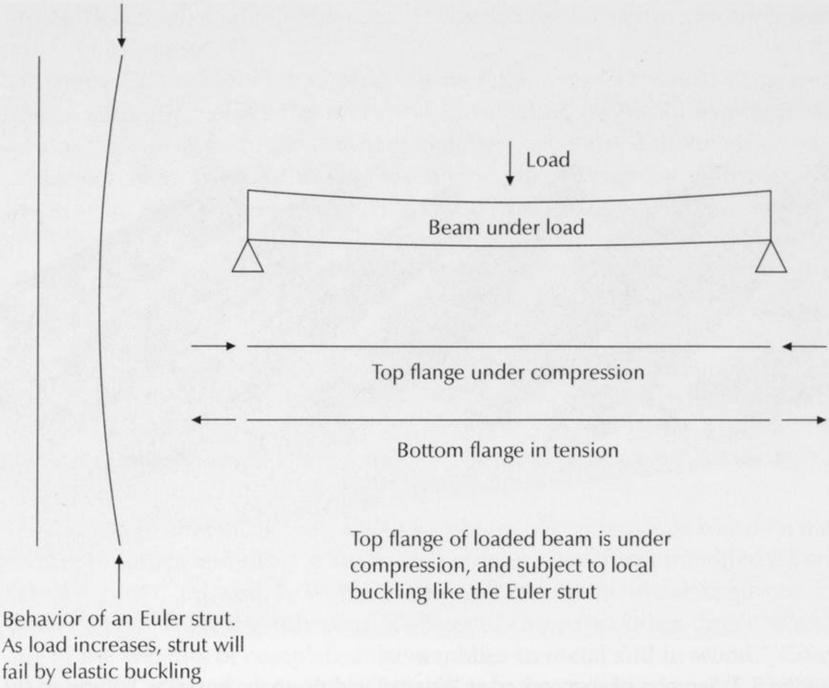

Figure 3.1. Elastic buckling, showing the analogy between an Euler strut and the compression flange of a beam in bending. Adapted from Nathan Rosenberg and Walter G. Vincenti, *The Britannia Bridge* (Cambridge: MIT Press, 1978), 20.

plane materials (see chapter nine).[16] These comparisons showed how great a handicap metal had to overcome in structures limited by buckling strength. In a 1942 textbook, engineering professor John Younger estimated the relative weights of wings of equal buckling strength, calculated on the basis of flat plates. According to Younger's calculations, if a plywood wing weighed 100 pounds, an aluminum wing of equal strength would weigh 255 pounds, and a steel wing 500 pounds. These calculations show why buckling was the most serious problem faced by metal airplane designers. Such calculations provided some of the strongest arguments in favor of wood. For these same reasons, proponents of metal usually preferred aluminum to steel, since aluminum was only one-third as dense.[17]

An army project to develop metal wing spars illustrates the difficulties that compressive buckling posed for designers of metal structures. In 1925 McCook Field requested bids for metal wing spars designed for identical ten-ton loads; bids for thirty different spars were accepted. The Air Corps also tested some standard wood spars for comparison (figure 3.2). The

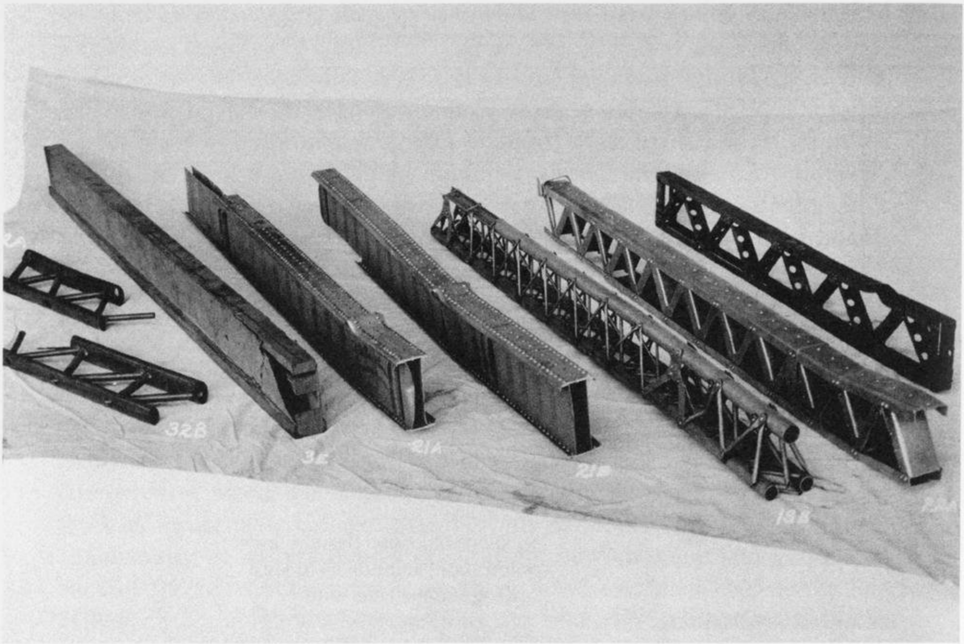

Figure 3.2. Samples of spars tested at Wright Field. Note the buckling failures in the top flanges of the metal spars at center left. A. S. Niles, "Tests on 6¼ Inch Metal Spars," *Air Corps Technical Report*, no. 2895, Oct. 1, 1927, 35, copy in Library of Congress.

initial results, published in 1927, showed that no metal spar performed as well as the best wood spars. According to the report, the principal cause of failure was "the liability of [metal] spars to fail by lateral buckling of the compression flange. The wood spars did not show the slightest tendency to buckle." The authors attributed the poor showing of metal not to any inherent deficiency but rather to the designers' lack of experience with metal construction. Neither did they see any inherent advantage in metal, ascribing relative merit to the skill of the designer not the material.[18]

Some advocates of metal, aware of the buckling problem, believed metal better suited to large airplanes. Buckling became less serious as airplanes increased in size, because the buckling strength of thin parts increased with the cube of thickness. Although this relationship was only dimly perceived at the time, many proponents of metal were also advocates of large airplanes. However, no one in the 1920s could predict how big airplanes had to become before buckling ceased to be a serious concern. Even in 1930, the largest American passenger airplanes revealed no clear advantage for metal in terms of weight efficiency.[19] The historical record presents very little evidence that airplane designers turned to metal to meet future requirements for large airplanes.[20]

After 1930 another design trend, the increasing use of stressed-skin structures, more than offset the reduction in buckling promised by larger airplanes. In a stressed-skin (or monocoque) structure, the covering contributes a large part of the structure's strength, in contrast to framework structures, whose strength depends primarily on a skeleton of structural members (see chapter eight). Stressed-skin structures solved two problems at once, providing a streamlined external surface for the airplane as well as a load-bearing structure. At the same time, stressed-skin structures made buckling failures more likely. In a framework structure, most of the material is concentrated in a few major members with relatively thick cross sections, whereas a stressed-skin structure spreads its material over a large area, resulting in relatively thin cross sections. For all-metal stressed-skin structures, preventing buckling failures became the designer's most vexing task.[21]

Many engineers recognized the unreliability of comparisons based on material properties and insisted that only complete structures provided a basis for judgment. Edward P. Warner, a prominent aeronautical engineer, argued in 1927 "that the only possible basis of comparison is a direct balancing of the weights of complete subassemblies in metal and in wood." Comparisons of material properties did not give due credit to metal, claimed Warner, since they neglected its ability to be formed into more efficient shapes, like tubing. Unfortunately, the comparison of complete structures was also not decisive. Warner admitted that the efficiency of a complete structure depended as much on the skill of the designer as on the choice of material.[22]

Advocates of metal had always assumed that ingenuity would solve the buckling problem, and by the late 1920s this assumption proved justified. By the end of the decade, several firms were building metal-winged airplanes with weight efficiencies comparable to wooden-winged airplanes.[23] However, preventing buckling led to a new problem: metal structures cost much more to produce than equivalent wood structures.

Designers of metal airplanes relied on two main techniques to prevent buckling, both used widely in German metal airplanes during World War I. The first technique involved complex curved shapes, such as the corrugated coverings favored by Junkers. Curving a flat sheet greatly increases resistance to buckling perpendicular to the radius of curvature, as one can demonstrate by pressing on the ends of a rolled sheet of paper. The British took this technique to extremes with elaborate shapes for steel spars. Curved shapes, however, only increase buckling strength in one direction. To increase buckling strength in all directions, engineers attached reinforcing "stringers" to the metal sheet, breaking it up into small panels, as visible in the Dornier and Rohrbach designs. These stringers kept the edges of each panel rigid, preventing buckling as long as the stringers themselves did not buckle.[24]

Although these techniques improved the weight efficiency of metal airplanes, they had a price, quite literally. All-metal designs required a massive amount of riveting and a large number of different parts, which greatly increased labor costs. Initial costs are typically high in the early stages of most innovations, and metal airplanes proved no exception. But even as manufacturers gained experience, all-metal airplanes still remained far more expensive than composite airplanes built with wood wings and steel-tube fuselages.

Proponents of metal admitted that wood had some advantages for building experimental designs and small quantities, but they insisted that these advantages would disappear with quantity production. Metal, argued Hugo Junkers, was essential for "modern methods of manufacture, such as . . . interchangeability, standardisation, [and] wide application of machine work." William Stout asserted, with characteristic hyperbole, that small metal airplanes could be produced at even lower cost than cars or trucks, given an equally large market. A 1930 survey of American airplane manufacturers found that "many [manufacturers] consider general use of metals or alloys as necessary to attain mass production," a goal "of vital importance to the progress of the . . . industry."[25]

Despite the supposed advantages of metal in production, early metal airplanes cost considerably more than those built with composite structures. In 1924 Admiral William A. Moffett, head of the Navy Bureau of Aeronautics, reported that the "high cost of this type of construction" continued to limit the navy's use of metal airplanes; the following year Comdr. H. C. Richardson reported to Congress that metal flying boats were costing the navy five to six times more than comparable wooden types.[26] The development costs of metal airplanes were particularly high, as demonstrated by the army's DB-1 metal bomber. The first DB-1 prototype cost Gallaudet $148,000, which included a $43,000 loss on the fixed-price contract. The Air Service paid Gallaudet another $150,000 to redesign the DB-1, but the new model also proved unsatisfactory. The DB-1 was among the most costly development projects undertaken by the Air Service in the early 1920s; only the huge Barling NBL-1 bomber cost more.[27]

The widespread faith that metal airplanes would ultimately prove cheaper to build than wood airplanes helped sustain support for metal construction during the 1920s. Yet subsequent experience proved this faith unfounded. Metal airplanes remained more costly than mixed wood-and-metal types throughout the 1930s, even though costs gradually decreased as airplane manufacturers gained experience with metal. A 1930 German study, which examined both European and American airplane construction, found "all-metal construction . . . much more expensive than mixed construction." In 1932 the plant manager of the Boeing Airplane Company reported that all-metal fuselages cost Boeing twice as much as fabric-covered types when produced in the same quantities. Preliminary studies at Boeing indicated that all-metal wings would also cost twice as much as those built of wood and fabric. As late as 1939, large metal airplanes still required twice as many hours of labor per airframe pound as typical wood-and-fabric biplanes of 1922, despite the widespread application of machine tools to metal airplane production during the 1930s. Large-scale production in World War II lowered these costs considerably, but even then all-wood designs like the de Havilland Mosquito cost no more to produce than comparable metal airplanes.[28]

Metal failed to live up to expectations for cheaper production because these expectations rested on two demonstrably false premises: first, that wood was unsuited to quantity production, and second, that airplanes would follow the paradigm of mass production in the automobile industry. From the early nineteenth century, inventors and entrepreneurs had applied specialized machinery and systematized procedures to the large-scale production of wooden products. Woodworking machinery provided the foundation for the first system approximating the modern concept of mass production, the Royal Navy's pulley-block factories at Portsmouth. This well-publicized system had a daily production capacity of 1,420 wooden pulley blocks, all manufactured with steam-powered machines that produced interchangeable parts using little skilled labor. In the 1850s the Austrian firm Thonet Brothers was building fifty thousand pieces of bentwood furniture annually at a single factory, and in the early 1880s the Singer Manufacturing Company was manufacturing nearly one million plywood sewing-machine cabinets each year. More complex structures also proved amenable to "mass" production. By 1895 Studebaker Brothers had become the largest manufacturer of wagons and carriages in the United States, with an annual output reaching seventy-five thousand vehicles. In the 1920s, a British manufacturer applied mass-production methods to wooden railroad cars, reducing manufacturing time from six weeks to six days.[29]

The natural variability of wood may indeed have limited the rigorous application of Fordist mass production methods. But airplanes never had any prospect of being produced in quantities comparable to automobiles, except in the delusions of aviation enthusiasts. Annual production of Ford's Model T peaked at 1.8 million units in 1925, while the entire U.S. airplane industry produced only 45,201 airplanes of all models in the twenty years from 1920 to 1939. Even during World War II, production runs for military models rarely exceeded ten thousand for the entire war, and Fordist mass production remained a chimera. Mass production was even more unrealistic for commercial aircraft. For manufacturers in the 1920s, "quantity production" meant "an order for fifty or one hundred machines." Passenger airlines promised no large market; in 1924 E. P. Warner estimated future American demand for commercial transport aircraft at seventy airplanes per year. Warner's estimate was actually a bit high. In 1938 the industry produced for domestic use only fifty-three multiengine airplanes, the dominant type for airline travel, while domestic air carriers needed a total fleet of only 260 airplanes to serve the largest air travel market in the world. For civil aircraft, by far the largest market was for small, privately owned, single-engine models, precisely the types dominated by wood-and-fabric construction.[30]

Advocates of metal repeatedly invoked fire safety, weight efficiency, and production costs as arguments in favor of metal, even though practical experience proved equivocal. But another issue provided the most potent argument for metal—durability. Durability was one of the most frequently cited advantages of metal. Wood, said Junkers, "is subject to . . . fire and decay, and splinters when breaking; it bursts and warps from the effect of humidity . . . and the glued joints split; finally it is attacked by insects. . . . Metal is free from all such drawbacks."[31] Indeed, metals are in general more durable than wood, but both deteriorate when left unprotected. Wood rots, steel rusts, and aluminum corrodes. In the 1920s, only practical experience could determine metal's true advantage in durability, ideally through studies involving comparable wood and metal airplanes operating under similar conditions. If such studies were ever done, they were never made public. In any case, practical experience soon demonstrated that duralumin too had durability problems, problems comparable in severity to those of wood.

In the early postwar years, airplane operators had little information on durability, but soon discovered that heat and humidity were very hard on wood-and-fabric. Airplane operators quickly recognized that maintenance varied considerably with climate and type of service. Wood-and-fabric airplanes deteriorated much faster in tropical than in temperate climates. As early as 1920, the U.S. Navy found that its wood airplanes in Panama rotted "very quickly," even when kept in hangars. Colonial airlines in French Guiana and the Belgian Congo became convinced that "all-metal seaplanes are an absolute necessity in the tropics" due to the warping, rot, and alignment problems experienced with their wood-and-fabric ships.[32]

Proponents of duralumin were initially very sanguine about its durability.[33] As the use of duralumin spread, however, reports of corrosion problems began to accumulate, and by 1925 evidence of an especially insidious type of corrosion began to appear—intercrystalline embrittlement. In common types of corrosion, chemical reactions eat away the surface of the metal while leaving the properties of the underlying material unchanged. Intercrystalline embrittlement, on the other hand, produces little change on the

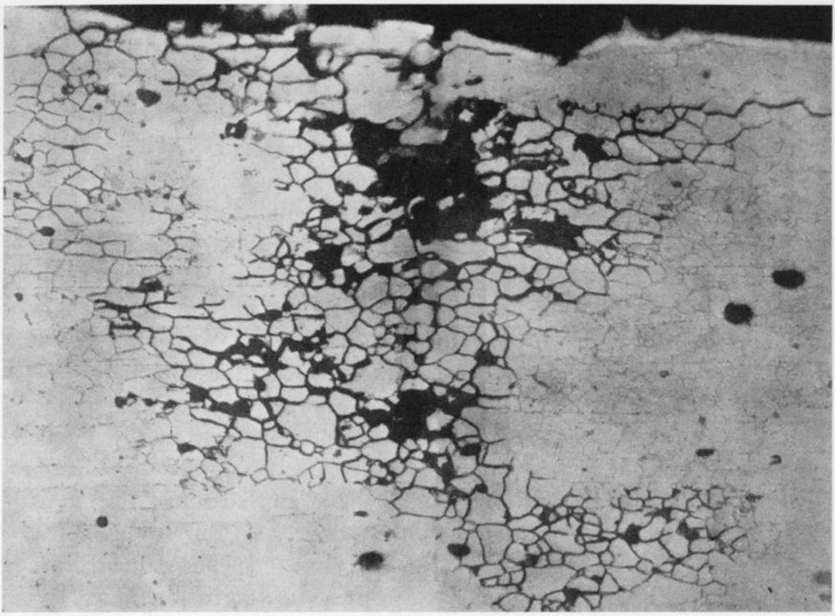

Figure 3.3. Intercrystalline corrosion. The magnified cross-section of an aluminum alloy sheet shows penetration of corrosion into the sheet. Henry S. Rawdon, "Corrosion Embrittlement of Duralumin, II," *U.S. NACA Technical Note* no. 283 (April 1928).

surface, but instead proceeds into the metal along the grain boundaries of the alloy's crystalline structure (figure 3.3). This process changes the physical structure of the metal, producing a marked reduction in ductility and tensile strength. Embrittled duralumin gives little warning of impending failure, which made it especially dangerous to airplanes in flight.[34]

The effects of intercrystalline embrittlement were observed for several years before the cause was identified. Salt water and tropical conditions proved as hard on duralumin as on wood. In the early 1920s, a German airline using Junkers seaplanes in Colombia found that duralumin parts deteriorated rapidly in the high heat and humidity, sometimes needing replacement in a matter of weeks. In the United States, a Post Office JL-6 began showing evidence of embrittlement after only two months of service. In late 1924, after two years' exposure on a Virginia seashore, the wing covering of a retired navy JL-6 had become so brittle that it could easily be pierced by a finger. This covering had originally been strong enough to walk on.[35]

In late 1924, materials scientists at the Bureau of Standards finally diagnosed the problem as intercrystalline embrittlement. Further tests showed the problem to be widespread. The bureau's findings caused considerable concern in the federal aeronautics establishment. When the navy airship *Shenandoah* (the ZR-1) crashed in September 1925, the Bureau of Standards found widespread intercrystalline corrosion in parts of the wreckage. Although the corrosion did not contribute to the accident, the bureau's study gave further publicity to the embrittlement problem.[36]

These corrosion problems led a number of engineers to conclude that metal airplanes were not very durable. Duralumin corrosion was especially troublesome for the navy, because the salt environment accelerated corrosion. In 1930 Lt. Lloyd Harrison of the Navy Bureau of Aeronautics summarized his years of experience with metal airplanes: "We have found that wood . . . was much more reliable than metal during the same period, with regard to the main structural elements." In another context, MIT professor Joseph Newell repeated with approval a comment made to him by the chief engineer of "one of our most progressive airplane companies. . . . 'For durability and dependability I'll have my all-metal airplanes made of wood.'" Newell admitted, however, that a recently developed duralumin product, known as Alclad, promised improved corrosion resistance, and Harrison thought that the navy's problems with duralumin corrosion were "in the way of being solved."[37]

The aviation community did indeed mobilize its resources to solve the duralumin corrosion problem, most successfully through the development of Alclad, an aluminum alloy bonded to a coating of pure aluminum. Alclad was the result of a concerted effort by the federal government and the Aluminum Company of America (Alcoa) to solve the problem of intercrystalline corrosion (see chapter four). No similar efforts were undertaken to solve the durability problems of wood airplanes (see chapter six).

Thus neither theory nor experience seem to justify the enthusiastic support given to metal airplanes during the 1920s. In fire safety, weight, production costs and durability, metal failed to demonstrate any marked advantage over wood. Nevertheless, support for metal construction enabled it to spread despite its problems, so that by the mid-1930s wood had been completely eliminated from major classes of American aircraft, including multimotored passenger airplanes and all U.S. combat aircraft.

Given the indeterminacy of the technical case for metal, how can one explain its success? Metal did appear to offer advantages for certain specific applications, such as flying boats, due to the considerable weight in moisture absorbed by wooden hulls.[38] But advantages in specific applications cannot explain the nearly universal support for metal structures in all types of aircraft. In most applications, the technical criteria did not clearly favor metal.

Because of the indeterminacy of the technical criteria, instrumentalist explanations that rely solely on technical factors are clearly inadequate. Historians of technology have, however, gone far beyond such technological determinism and now employ a variety of more sophisticated approaches, using concepts such as systems, presumptive anomalies, social construction, and entrepreneurial strategies. Each of these recent methodological innovations suggests possible explanations for the shift from wood to metal airplanes.

One of the most powerful is the systems approach pioneered by Thomas P. Hughes, who argues that technological change is shaped by the need to overcome "reverse salients" that limit the growth of functionally integrated sociotechnical systems. Civil aviation did indeed become a large-scale technological system during the interwar period, but the problems with wood did not constitute a reverse salient preventing the continued expansion of the system. Commercial aviation grew rapidly in the late 1920s, in no way inhibited by the use of wood structures.[39] Nor was support for wood the result of far-sighted engineers who recognized "presumptive anomalies," inherent limits in the continued improvement of particular technologies. Although one can persuasively argue that modern large airplanes would be impractical with the wood technology of the interwar period, there is no evidence that interwar engineers based their support for metal on any clear conception of future requirements.[40]

Other possible explanations can be derived from the social construction approach, which focuses on the role of competing social groups in shaping technical change. Although social construction is in principle compatible with attention to symbolic meanings, in practice this approach has focused on economic interests, bureaucratic politics, and other struggles for power between social groups. In any case one would be hard pressed to correlate support for metal with identifiable social groups; this support came from established companies and independent inventors, private enterprise and government bureaucracies, college-educated engineers and autodidacts.[41]

Finally, one cannot explain the success of metal through the entrepreneurial strategies of supplier firms and the interaction of these strategies with market structures. Suppliers of aircraft metals, in particular Alcoa, did have more market power and better research facilities than suppliers of aircraft lumber, and in theory were better positioned to offer airplane companies the materials they needed. Yet all the evidence suggests that the metals suppliers were followers rather than leaders, responding to the aeronautical community's enthusiasm for metal aircraft.[42]

None of these possible explanations explicitly addresses the phenomenon central to understanding the shift to metal airplanes: the symbolic meanings of airplane materials. No explanation that posits utility-maximizing rational actors nor any approach that limits itself to an objective logic of markets, firms, or other social structures can adequately explain the victory of metal airplanes.[43] To understand the aviation community's support for metal airplanes one must go beyond such explanations and examine the culture of the aeronautical community along with the specific ideology that helped justify support for metal.

Metal and the Ideology of Progress

The clue to the aviation community's support for metal lies in the symbolic meanings that the aviation community associated with various materials. For this community, wood symbolized pre-industrial technologies and craft traditions, while metal represented the industrial age, technical progress and the primacy of science. These symbolic meanings were not just vague, implicit assumptions. Leading figures in the aviation community made their beliefs quite explicit, articulating these symbolic associations into a specific ideology of technical progress, a progress ideology of metal. According to this ideology, the shift to metal was an inevitable consequence of technical progress, part of the shift of engineering from art to science. This ideology was a key factor in the demise of wooden aircraft.[44]

The idea that ideology shapes technical choice conflicts with the dominant conception of technology as an archetype of rational discourse and action. For many people, ideology implies irrationality and dogmatism. This view centers on a definition of ideology as distortion. Although the progress ideology of metal did blind the aviation community to the technical potential of wooden construction, the concept of ideology as distortion does not explain its enduring power. Like all ideologies, the progress ideology of metal also had integrating and legitimating functions. At the level of integration, ideologies are explicit symbolic frameworks that help define communities by providing a common program of action. Ideology guides action by allowing people to make sense of a situation when myth and tradition prove inadequate, as they so often do with rapidly changing technologies.[45] The progress ideology of metal represented an attempt by the aviation community to make sense of the symbolic contradiction inherent in the wooden airplane, the clash between the modernity of aviation and the traditionalism of wood. The belief in the inevitability of metal helped resolve this contradiction by defining the wooden airplane as a transitional technology in the path to metal construction.

Two themes dominated the progress ideology of metal, the first linking metal with progress and the second associating metal with science. In the early 1920s, proponents of metal were especially vocal in their insistence that the shift to metal was the inevitable consequence of technical progress. "All the history of engineering relates the gradual displacement of timber by lighter and more durable structures of steel," argued John D. North, a prominent British advocate of metal construction. In 1925 Lt. Corley McDarment, an army spokesman, expressed the same view: "Just as the trend of engineering has always been toward replacing wood with metal, so has the new branch . . . followed tradition. . . . The use of metal in aircraft construction is therefore only a natural consequence in the growth of engineering." J. B. Johnson, the army's chief materials expert at McCook Field, echoed these sentiments: "There is little doubt that the future airplane will be built entirely of metal on account of its uniformity and permanency."[46]

Proponents of metal supported this claim of inevitability by making historical analogies with past triumphs of metal. French designer M. E. DeWoitine argued that the replacement of wood by metal was a repeating pattern in new technologies, which the airplane was destined to recapitulate. Wood dominated early airplanes because "wood is by nature essentially a material for new industries . . . ideal for the inventor, who . . . obtained results with but little design and calculation." As the technology advanced, metal would become dominant, just as it had in other industries. "I cannot conceive that the ultimate airplane can be in anything else but metal," concluded DeWoitine, "in the same way that metal ships today completely replace the wooden ships of days gone by." The analogy of the wooden ship also inspired William Stout: "In a comparatively few years from now [1922], wooden airplanes in the air will be scarcer than wooden ships on the sea."[47]

Two navy engineers invoked a very specific historical analogy, that of the steel railway coach, as an object lesson in the "struggle between metal and wood."

> At first it was a question of sacrificing low structural weight to satisfy the public demand for a safe vehicle; but later when the standard structural shapes gave way to special shapes developed for the purpose and when designers became more experienced and specialized[,] the steel railway coach became lighter than the wooden coach.

Thus, even though the first metal planes might be heavier than comparable wood designs, as indeed they were, this shortcoming would soon pass with the progress of metal construction.[48]

This use of historical analogies was rather ironic given the devotion of metal's supporters to creating novelty through technical progress. Nevertheless, these analogies made rhetorical sense because they created the myth of a broad, autonomous historical process, one that operated by substituting new materials for old. Proponents of metal credited this process with numerous great achievements, all viewed by the engineering community as symbols of technical progress. Metal's supporters thus rested their case for the future progress of aviation on the past triumphs of metal over wood.

The second aspect of this progress ideology concerns the "scientific" character of metal. This theme was rarely fully articulated but found expression in the argument that metal permitted greater accuracy in stress calculations than did wood.[49] Design in metal was considered more scientific because metal better met the assumptions of the theory of elasticity, assumptions that included a linear relationship between stress and strain and also the absence of time-dependent plastic deformations like creep. However, highly refined calculations were of little use in design, because safety standards were based on ultimate (breaking) load, which occurred when stresses had passed far beyond the elastic limit. Due to the limitations in structural theory, designers assumed elastic behavior when calculating ultimate loads, thus limiting any advantage to be gained from increased accuracy in the elastic range.[50]

The "scientific" argument for metal derived its force from the assumption that technological progress involves a trend from art to science. This assumption was made explicit in a semi-official article written by Corley McDarment, a lieutenant in the War Department's information division. Although "flying started as an art," argued McDarment, "aviation is now crying out to science" to solve its problems. Aviation must wait a while "before the pure art in airplane construction gives way to pure science." Nevertheless, continued McDarment, science has already assumed a major role in airplane design and has promoted the shift to metal. "It was the finger of science that pointed to metal in airplane construction." Wood and fabric construction do not "enable a manufacturer to say: 'This is true, and that is true.'" Metal, on the other hand, permits accurate predictions, claimed McDarment, who was presumably referring to stress calculations. "The scientific mind likes to build upon the most reliable figures obtainable. And these are certainly to be found among metal workers." According to this logic, the ineluctable movement of engineering from art to science dictated the use of metal.[51]

"Science" in this context did not refer to a logically coherent system of ideas or an epistemological method. Rather, science was an attribute of a technological style, one that valued the use of theoretical models, complex calculational procedures, and extensive, systematic empirical research. The belief that metal was more scientific than wood was itself a cultural prejudice. "Science" did not adhere to specific materials; its techniques and ethos were as applicable to wood as to metal. In fact, wood had as much if not more to gain from the application of science, because scientists had devoted less effort to wood research and because wood's mechanical properties are more complex than metal's.[52]

The preference for "science" in technology over nonscience was another cultural prejudice, a central legitimating ideology for engineers in the early twentieth century. The techniques subsumed under the concept of science did offer some practical advantages, but the legitimating, ideological functions of science often exceeded its instrumental role in engineering design. Most aviation engineers understood the limited utility of science, and argued persuasively that airplane design involved much more than applied science. Nevertheless, science as a cultural concept had symbolic power, which the advocates of metal appropriated to their cause.[53]

Some engineers recognized the ideological character of support for metal, noting the nontechnical factors influencing the debate. In 1923 A. P. Thurston, a British engineer and an early supporter of metal, noted a "tendency to make all-metal construction a fetish, that is, . . . to construct every part of the machine of metal whether metal is the most suitable material or not." Edward P. Warner saw engineers' support for metal as partly "psychological." Defenders of wood were fighting a losing battle, said Warner. "One of the reasons is psychological . . . and is by no means unimportant. We who work directly with airplanes may have fallen under the spell of the peculiar virtue that is supposed to inhere in a material so generally used in other engineering structures." The German airplane designer Heinrich Focke encountered the same attitude among engineers on the other side of the Atlantic. "The preference for metal construction does not rest on purely technical (*sachlichen*) grounds. The engineer feels a certain reluctance about working with an unfamiliar material such as wood." These psychological factors, this reluctance, and the fetish for metal were all manifestations of progress ideology.[54]

The progress ideology of metal was no mere epiphenomenon but had demonstrable effects on the aviation community as a whole. Its first effect was to define the terms of the debate over aircraft materials. Second, this ideology inhibited the public defense of wooden construction, producing a one-sided debate in the aviation press. Third, it undermined the arguments in support of wood that did appear, since even wood's defenders acknowledged the inevitable triumph of metal.

The very terms of the debate about aircraft materials reveal the influence of the progress ideology of metal. Airplane designers did not simply decide to use "metal" or "wood," but rather selected specific materials, such as Sitka spruce or 17ST aluminum alloy. Nevertheless, most debates about airplane materials posed a choice only between two broad classes of materials, wood and metal. Within each of these categories were hundreds of materials with an extraordinary range of physical properties. Although some advocates of metal favored steel and others duralumin, they almost invariably framed the debate in terms of the dichotomy between wood and metal. Partisans of steel or duralumin supported their favored materials with none of the passion reserved for the question of wood versus metal. This passion for metal over wood reflected, as Robert Friedel has observed, "a general attraction to the use of the inorganic over the organic." This preference for the inorganic was deeply embedded in the culture of engineering.[55]

Given the almost universal use of wood in American aircraft until the late 1920s, one would expect to find vigorous advocacy of wood in some quarter of the aviation community. But the case for wood was never made. Progress ideology tends to stifle debate by making certain choices appear inevitable. The paucity of support for wood in the aeronautical literature reveals the strength of this ideology in aviation. Not a single article appeared in the American aviation press in the 1920s in defense of wooden construction.[56] Lieutenant McDarment noted this absence in 1925: "The wood and fabric people . . . are not doing much talking in defense of these materials." There were occasional spirited defenses of wood against the claims of metal's advocates, but these never appeared in the aviation press. One such article appeared in the *Journal of Forestry* in 1924, hardly standard reading for aeronautical engineers. In 1930 wood expert George Trayer published another well-argued defense of wood in the journal *Southern Lumberman*, in which he advocated continued research on wooden aircraft construction. Yet such arguments were almost never heard within the aviation community, despite the continued widespread use of wood in both military and civilian airplanes well into the 1930s.[57]

Even when manufacturers were willing to defend wood in public, progress ideology structured the debate in a way that handicapped the supporters of wood. A publicity newsletter for the Fokker Aircraft Corporation illustrates this point. The company's founder, Anthony Fokker, was one of the most successful and innovative designers of American transport aircraft in the interwar period.[58] But his company's progressive image seemed threatened by its continued use of wood wings. The 1926 newsletter, entitled "Why Are There No Fokker 'All Metal' Airplanes?" is written in a defensive tone. The newsletter acknowledged the historical trend from wood to metal, as evidenced by ships, railroad cars, and automobiles. It accepted the logic of those who "feel that the airplane is bound some day to go through this same process. . . . Against the eventual prospect of such development *nothing can be said.*" If Fokker airplanes continued to use wood, this indicated not conservatism but "that all is not well with all[-] metal construction." The newsletter enumerated these disadvantages, arguing against metal wings on the grounds of safety and ease of repair. At the same time, the newsletter defended Fokker's reputation as a technically progressive company, despite its continued use of wood. "In the Fokker factories, both in the United States and abroad, the spirit of progress, of constant improvement, dominates."[59]

The Fokker company's defense of wood actually served to undermine its continued use. The argument for metal was based not on technical comparisons alone, but also on historical analogies shaped by the progress ideology of metal. The newsletter accepted the logic of this argument, which dictated the inevitable triumph of metal. The Fokker company merely quibbled over the timing. It argued, in essence, that metal suffered from a few teething problems, which made the continued use of wood necessary for the time being. This defense of wood actually helped justify the concentration of research and development work on metal construction, and the subsequent neglect of wood. And this newsletter appeared in 1926, when every American commercial airplane in production used wood except for the Fords.

The progress ideology of metal involved more than empty rhetoric; these debates were not sideshows to the real decisions being made in the engineering departments of airplane firms. This ideology provided a cognitive framework that encouraged basic research and practical efforts to improve metal construction, while discouraging attempts to solve the problems of wood. The dominant belief in the inevitable triumph of metal directly undermined the planning and research necessary for the continued use of wood.

4

An Old Role for the Military: Government Support for Metal Airplane Construction

MILITARY SUPPORT was essential to the success of American metal airplanes. Between the world wars, the army and navy promoted metal airplanes financially, technically, and ideologically. Beginning in the summer of 1920, the air arms of both services launched major programs to develop metal airplanes suitable for military use. These programs produced multiple failures; by 1925 neither service had acquired metal airplanes suitable for operational squadrons. Despite these failures, the army and navy persisted with efforts to develop metal airplanes, finally achieving success at the end of the decade.

The centrality of military support to the development of metal airplanes should come as no surprise. Warfare has shaped technical change from the beginning of human history, while military needs played a key role in the emergence of Western technology during the Early Modern period. In the nineteenth century, the military provided essential support for a number of important new technologies, including interchangeable parts, railroads, and steel. In the twentieth century, military influence rose to a new level, creating entirely new industries that served both civilian and military purposes, including nuclear power, radar, space flight, computers, and microelectronics.[1] But the first such industry was aviation. Without military support, the airplane would have remained little more than a curiosity suited to entertaining crowds at county fairs.[2]

As David Edgerton has argued, the airplane's dependence on military support clashes with the liberal ideal that technologies should develop naturally from forces operating within civil society. From the perspective of this liberal ideal, military influence is an artificial distortion of the normal, market-driven process of technical change. The standard technical histories of aviation all reflect this view, attributing major advances to commercial factors.[3] A few members of the aviation community accepted this liberal myth, and argued that military influence was inimical to civil aviation. Promoters like William Stout dreamed of producing airplanes that could support themselves financially as well as aerodynamically, without any need for government assistance. Fortunately for the industry, no one took Stout's rhetoric seriously. If market discipline had ever been imposed on the industry, it would have collapsed immediately. Most commentators acknowledged the military as the engine of aeronautical progress, even in the United States, which had the world's largest civilian air transport market. As the Aeronautical Chamber of Commerce stated in its 1923 annual report, "the problems of military and commercial aviation are inseparable."[4]

Military dominance of aviation derived in part from the sheer size of government purchases. According to a 1940 financial analysis by George S. Armstrong & Company, "long before the present conflict had started," aviation's "close integration with military demands and service" distinguished it from "practically all other industries." Only the ordnance industries devoted a larger proportion of their output to the military.[5] Available statistics on American aviation sales show that the dollar volume of military purchases exceeded civilian sales by a wide margin between the world wars, despite tight military budgets. Military dominance was almost total in the first half of the 1920s, when commercial production was negligible. From 1920 through 1923, the military spent roughly $40 million to buy aircraft and engines. During this same period, the industry produced only 213 airplanes for civilian and export markets, a figure that represented less than $1 million in sales. Although civilian sales exceeded military sales by a wide margin in 1929, that year proved anomalous; in most years military purchases continued to outpace commercial sales. The proportion of sales devoted to military production increased in the late 1930s even before the United States began preparing for war; in 1936 and 1937, military sales accounted for two-thirds of the total market.[6]

Aviation differed from other industries by more than just proportion of output consumed by the military. According to the Armstrong report, aviation was also distinguished "by the extent to which developments and improvements in design, function and manufacturing . . . have been stimulated and supported by governmental appropriation as dictated by transcendent national policy."[7] Military demands for improved performance controlled the pace and direction of technical change. Most civil aircraft were small, low-powered "puddle-jumpers," while the military dominated the market for larger, faster planes. Designers of commercial transports always kept one eye on military requirements, and almost invariably attempted to sell their equipment to the army or navy. At the same time, manufacturers of commercial planes borrowed heavily from military designs. The military air arms spent millions annually on research and development, transferring the results of successful projects to industry for production. Both of the military services maintained large civilian engineering staffs that dwarfed the technical capabilities of private manufacturers. In 1924 the Army Air Service's Engineering Division maintained a staff of more than one thousand civilians at an annual cost approaching $2 million, while the Naval

Aircraft Factory at Philadelphia employed thirteen hundred civilians. The military also exerted considerable control over the aeronautical research agendas of other federal agencies, especially the Bureau of Standards and the National Advisory Committee for Aeronautics (NACA).[8]

Military domination of technical trends was particularly evident in the development of metal construction. Both the army and navy designed and built their own prototype metal airplanes in the early 1920s and then contracted with private manufacturers for production versions. These projects gave military engineers valuable experience in the design problems of metal airplanes, experience that was then applied to airplanes developed under contract. The army and navy let contracts for numerous metal airplanes in the early 1920s when there was little civil demand for conventional airplanes, let alone novel types. In addition, the military repeatedly issued statements in support of metal construction, which encouraged manufacturers to develop metal airplanes even in the absence of government contracts. Thus while military support was essential for the success of metal construction, the industry did not receive a free ride with regard to development costs. Airplane manufacturers shared the military's enthusiasm for metal and were willing to invest their own funds in developing metal airplanes.[9]

Military contracts served as the principal means for the military to shape the technical development of the airplane. The contracting process for new airplanes remained quite flexible, despite periodic attempts by Congress to impose a rigid system of competitive bidding. At one extreme, companies sometimes developed new airplanes as speculative ventures, with no assurance that the army or navy had any interest in the type. The military often encouraged such ventures by lending the manufacturer engines, armament, and other equipment under a bailment contract. At the other extreme, the military often negotiated contracts for experimental airplanes directly with a single manufacturer, without even the pretense of competition, sometimes providing partial payments before delivery of the airplane to help keep the firm in business. Most experimental contracts, however, fell between these extremes, following standard procedures that included both negotiation and competition.[10]

Within the army, development of new airplanes was the responsibility of the Army Air Service, established by President Wilson in May 1918. The Army Reorganization Act of June 4, 1920, recognized the Air Service as both a combatant and a supply organization. In its combat role, it had a status similar to the artillery, tactically subordinate to field commanders. More importantly, the Air Service controlled the development and supply of its own equipment. Within the Air Service, responsibility for these supply functions fell to the Engineering Division at McCook Field, Ohio. In 1926 Congress reorganized the Air Service as the Air Corps, and the Engineering Division became the Materiel Division. In 1927 the Materiel Division moved to larger quarters at nearby Wright Field, now Wright-Patterson Air Force Base.[11]

By the early 1920s, the Engineering Division had developed a standard process for procuring new airplanes. Within the division, responsibility for new airplanes fell to the Airplane Section. Other sections were responsible for the development of power plants, equipment, and armament. A new airplane generally began with a detailed performance specification, developed in conjunction with tactical personnel outside of the Engineering Division. The specification stated the loads, armament, and equipment to be carried, as well as performance. The performance data included figures for high speed, ceiling, rate of climb, and range. Occasionally the Engineering Division required a specific type of construction, such as a monoplane or a steel-tube fuselage, but in general the division left these decisions up to the manufacturers. It then issued the specification in a circular proposal to the industry, which responded with preliminary designs and bids. Price was rarely the decisive factor in choosing among manufacturers at this stage.[12]

In the next step of the procurement process, the Engineering Division negotiated a contract with the chosen manufacturer for two or three airplanes, sometimes requiring extensive changes in the manufacturer's design based on the division's own experience and calculations. The Engineering Division continued to offer technical advice to the manufacturer throughout the life of the contract. Most contracts required the manufacturer to supply a wind tunnel model, which was tested at McCook Field to check performance predictions, and a detailed stress analysis showing that each structural member and fitting would develop the required strength. In most cases, the first airplane produced was used for static testing and consisted only of the airframe. Assuming that the airplane passed its static test, the next one was used for flight tests. If the division and operating personnel judged the performance satisfactory, the manufacturer received an additional order, typically for about ten airplanes, which were sent to the airfields or tactical units for "service" tests by army pilots. The Engineering Division did not control the service tests, which in effect gave the pilots veto power over new designs. If the plane passed its service tests, it could be adopted as a standard Air Service type and possibly ordered in quantity. The entire procedure, from the development of a specification to the adoption of the airplane as standard equipment, could take two or more years.[13]

Enthusiasm and Failure: The Army's Early Experience with Metal

American enthusiasm for metal airplanes was ignited by the arrival of the all-metal Junkers JL-6 in mid-1920 (see chapter two). John Larsen, the able promoter of the JL-6, wisely focused on military officials in his efforts to sell the airplane, and the military proved highly receptive to his sales pitch. But Larsen's influence far exceeded the half-dozen metal airplanes that he managed to sell to the army and navy. More importantly, Larsen's sales campaign prompted the army to embark on a vigorous program to develop metal aircraft construction. This program, however, proved less than a stellar success. The army completed three major metal airplane projects in the first half of the decade; none produced a satisfactory airplane. This experience confirmed the difficulty of producing metal airplanes comparable to wood structures in weight, strength, and cost.

The army's interest in metal airplanes remained muted until late in the spring of 1920, when Larsen's lobbying campaign reached senior military officers.[14] By mid-June, Larsen had built up considerable support among these officers. Not one of them had made a detailed technical inspection of the JL-6, nor had any independent tests verified Larsen's claims for the airplane. Yet based on these officers' cursory examination of the JL-6, both the army and navy jointly endorsed the development of metal airplanes as a major goal for each service's air arm. In a rare instance of interservice cooperation, this endorsement was made by the Aeronautical Board, a committee created in 1920 by the army and navy to eliminate duplication of effort between the services.[15]

The endorsement of metal came at a meeting of the Aeronautical Board's Technical Committee on June 18 at McCook Field. The five army and five navy officers present adopted a resolution recommending "that the acquisition and construction of all-metal airplanes be considered at once by both the War and Navy Departments." The resolution also urged the purchase of existing all-metal types for testing and evaluation. The committee specifically recommended buying six JL-6 airplanes, three for the army and three for the navy, with metal pontoons for the navy planes to permit operation on water. The proposed program for the JL-6 included the study of construction methods, performance, flying qualities, and durability. The full Aeronautical Board approved the recommendation of the Technical Committee and urged the rapid development of all-metal airplanes by both services.[16]

The Aeronautical Board's endorsement of metal construction did not commit the Air Service to any particular strategy for investigating the new technology, except to buy and test the JL-6. In fact, the resolution did not insist that the army and navy actually adopt metal airplanes at all, only that each service consider such adoption. The Air Service faced a choice between two divergent approaches to fulfill the Aeronautical Board's mandate, one restrained and the other aggressive. In the more restrained approach, the Air Service would merely sample existing technologies and gently encourage manufacturers to adapt them to existing military requirements. Such an approach did not satisfy the enthusiastic advocates of metal construction.

These advocates urged the Air Service to plunge headlong into metal construction, aggressively developing all-metal airplanes in the *neue Stil*.

The Engineering Division began formulating its strategy for developing metal airplanes in mid-July. Initially, the Division proposed spending $250,000 for "development work" related to metal airplanes. Capt. Virginius E. Clark, then chief engineer at McCook, advocated some restraint, favoring a two-step approach to the problem. The first step would involve adapting metal construction to current Air Service types, namely externally braced biplanes with fabric covering. After making some progress in the first step, the Engineering Division would then concentrate on internally braced designs of the Junkers type. Despite the element of conservatism in Clark's two-step program, he retained "the greatest faith in the ultimate successful development of the all-metal internally braced machines," that is, airplanes of the *neue Stil*.[17]

Clark's caution was soon swept aside by enthusiasm for metal construction. In August of 1920, the Engineering Division proposed an ambitious $10 million budget for fiscal year 1922 (which began July 1, 1921), double the appropriation for the previous year. Metal airplanes figured prominently in the proposed expenditures. Out of the $840,000 budget for "Airplane Research and Development," research in metal construction accounted for $235,000. This research program included studies of internally braced duralumin wings, fuselages of tubular and sheet dural construction, metal tail surfaces, and sheet-metal wing and fuselage coverings. These figures did not include civilian pay, which totaled $2.6 million for all projects. Even more ambitious was the proposed purchase of fifty-nine experimental airplanes at a cost of $2,665,000. These airplanes represented new models for each of the fifteen different service types desired by the Air Service. Of these fifteen, seven were specified as all-metal, with metal suggested as an option for an additional three types.[18]

These plans were wildly optimistic in an era of presidential and congressional parsimony unmatched in this century. The public's bitter aftertaste of World War I prompted especially sharp reductions in military spending. War Department expenditures were cut by more than half between 1921 and 1922, from $1.1 billion to only $458 million. The Engineering Division did not fare badly in this climate, obtaining an appropriation of $4.3 million in fiscal year 1922, down from $5 million in the previous year. Nevertheless, this restricted appropriation prevented the Air Service from taking a headlong plunge into the new metal technology.[19]

This enforced caution proved fortuitous for the Air Service, for each of its initial forays into metal construction ended in failure (with the exception of work on the welded steel-tube fuselage). The first fiasco was with an observation plane built by the Empire company, which the army had ordered in late 1919, before the arrival of the JL-6. This metal-frame, fabric-covered biplane embodied the experience gained by the company in metal construction during the war, and was also its first attempt at the design and manufacture of a complete airplane. Empire delivered its first airplane to McCook by October 1920, and army engineers began subjecting it to static tests. In almost every single test, the airplane failed to support the required load factors. In November the Air Service reported laconically that "the structural strength was unsatisfactory, and the development of this airplane has been abandoned."[20]

This single setback did not deter the Engineering Division, which had firmly committed itself to developing metal airplanes. In September 1920, the Engineering Division requested submissions from manufacturers for a design competition covering five different airplane types. In a design competition, the Air Service asked for preliminary designs and made small cash awards for the best submissions. If the Engineering Division found a particular proposal promising, it would negotiate a fixed-price contract with the manufacturer for the construction of experimental airplanes from the company's design. The September design competition required at least partial metal construction in all five specifications.[21]

Also in September 1920, the Engineering Division started designing its own all-metal internally braced monoplane. This airplane, designated the CO-1 (for *Corps Observation*), was the Division's own attempt to produce an airplane of the *neue Stil*. The CO-1's structure consisted primarily of duralumin, except for some heat-treated alloy steel in highly stressed parts of the Pratt-truss wing spars. Following Junkers's practice, corrugated duralumin covered both the wings and the monocoque fuselage (figure 4.1). The CO-1 was powered by a four-hundred-horsepower Liberty engine, a reliable workhorse developed during the war. Construction of the CO-1 began at McCook Field in early 1921, and the first airplane was finished by November. The initial flight of the CO-1 took place in March 1922. J. A. MacReady, chief of the Engineering Division's Flying Section, reported favorably on the airplane's flying qualities. MacReady found the CO-1 to be a "far easier 'plane to fly than . . . the JL-6," but noted its poor side visibility due to the location of the wing, a serious drawback in an observation plane.[22]

In April 1922 the Engineering Division began negotiations with manufacturers for production of the CO-1. William Stout, who was then building an all-metal torpedo bomber for the navy, refused to manufacture the CO-1 unless he could redesign it to his liking. The Engineering Division had better luck with the Gallaudet Aircraft Company of East Greenwich, Rhode Island. This company was founded in 1910 by Edson Fessendon Gallaudet, a Yale graduate with a physics doctorate from Johns Hopkins. Gallaudet was a moderately successful contractor to the Air Service, supplying airplanes worth more than $600,000 during the 1920 and 1921 fiscal years. Gallaudet had recently received two contracts from the Air Service to produce metal airplanes of Gallaudet's own design, making the firm a logical choice to

Figure 4.1. Army CO-1 observation plane, McCook Field's first attempt at all-metal construction. National Archives at College Park, Record Group 18-WP, photo no. 12332.

produce the CO-1. In June 1922, Gallaudet began working on a $110,000 contract to build three CO-1s.[23]

Meanwhile, tests of the CO-1 continued during the first half of 1922. The Engineering Division completed a second CO-1, and performed additional flight tests. Despite MacReady's favorable initial report, subsequent test pilots developed a strong dislike for the airplane. They reported poor combat visibility, annoying vibrations, and insufficient maneuverability. One pilot thought the CO-1 "absolutely worthless as a military 'plane." The final flight test report concluded that "this airplane lacks so much in flying qualities . . . that it does not fulfill the requirements of a military airplane for corps observation work." Finally, a July report on the static tests revealed that the CO-1, like the Empire airplane before it, failed almost every strength requirement. The report recommended a substantial redesign of the structure.[24]

Despite these negative reports, the Engineering Division permitted Gallaudet to proceed with production of the three CO-1s. Gallaudet delivered the first CO-1 in early 1923. Unfortunately, this single airplane cost

Gallaudet almost the entire amount allocated for all three airplanes under the fixed-price contract. The company requested the Engineering Division to cancel the order for the remaining two airplanes, and the Division agreed. In March the Air Service ordered Gallaudet to stop work on the contract, and an audit found that Gallaudet was entitled to almost $89,000 for its work on the one airplane. The Air Service had already spent nearly $185,000 at McCook field on engineering, building, and testing the CO-1, for a total cost approaching $274,000 for three unsatisfactory airplanes.[25] Thus ended the Engineering Division's own attempt to design an all-metal airplane of the *neue Stil*.

The CO-1 was not Gallaudet's first venture in metal airplane construction for the army nor its first failure. When Gallaudet began working on the CO-1 in mid-1922, it already had two army contracts for metal airplanes, one for a bomber and the other for a pursuit plane. Gallaudet began designing the bomber in the fall of 1920 in response to an Air Service competition for a single-engine day bomber. Gallaudet's design was for an internally braced monoplane with a metal structure. The day before Christmas, the Engineering Division signed a contract with Gallaudet to build three of these bombers, known as the DB-1 (for *day bomber*).[26]

Like the CO-1, the DB-1's development was also fraught with problems. The initial performance and weight estimates looked very promising. Gallaudet had promised to deliver an airplane with a gross weight of 7,050 pounds, a useful military load of 3,250 pounds, including 600 pounds of bombs, and a high speed of 141 mph. When Gallaudet delivered the first DB-1 in December 1921, almost one year after receiving the order, the Engineering Division found the airplane seriously overweight. The original design estimated the weight empty at 3,800 pounds, but the DB-1 as delivered weighed 5,969 pounds, exceeding the estimate by more than a ton. Roughly 280 pounds of the weight increase was due to the engine, over which Gallaudet had no control, but most of the increase resulted from the metal structure. As delivered, the DB-1 had a monocoque fuselage and fabric-covered wings, built primarily of duralumin with some steel in the wing spars and landing gear (figure 4.2). At about the same time as Gallaudet delivered the first DB-1, the Engineering Division received results of the wind tunnel tests conducted at MIT. The test report revealed disappointing aerodynamic efficiency for the airplane, as measured by a poor lift-to-drag ratio of 6.6. Using the wind-tunnel data and the higher weight, the Engineering Division reduced its estimate of the DB-1's top speed to only 115 mph, 36 mph below the original estimate.[27]

The Division completed static tests on the DB-1 at the end of December 1921. These tests revealed weakness in the wings and problems with the controls. The wing failed at a load factor of 4.5 by buckling in the upper flange of the front spar, below the required load factor of 5.5. In addition,

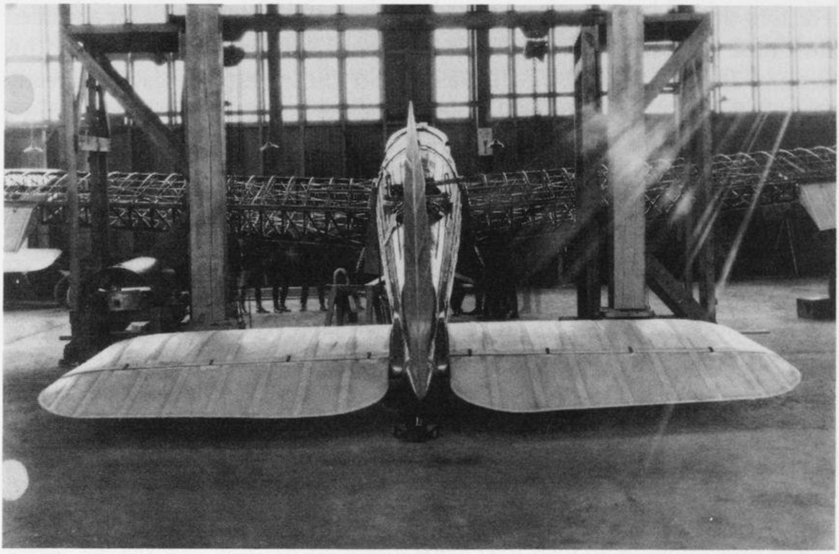

Figure 4.2. Gallaudet DB-1 metal bomber. This first version shows the wing structure and monocoque fuselage. National Air and Space Museum, Smithsonian Institution (Wright-McCook photo no. 11304).

the elevator controls would not work properly. The elevator control wires passed over pulleys attached to the fuselage skin, which buckled slightly under load, interfering with operation of the elevator. Civilian engineer D. B. Weaver, author of the static-test report, recommended a major redesign of the structure and control system. Weaver concluded that the monocoque fuselage was especially overweight, and that its redesign would produce a significant reduction in weight.[28]

In addition to weight and performance problems, the DB-1 was plagued by excessive costs. Shortly after delivery, E. F. Gallaudet began complaining of losses under the fixed-price contract. Gallaudet claimed that the airplane had cost him $45,000 more than the $103,000 that the Air Service was paying for it. The disappointing results led the Engineering Division to question the entire DB-1 project. On January 4, 1922, the officers involved in the project met to discuss the changes that needed to be made to the DB-1. They decided that Mr. Gallaudet would bear "the burden of proof" to demonstrate that he could build a metal airplane of satisfactory weight. If not, the Air Service would consider canceling the contract.[29]

After receiving detailed advice from the Engineering Division in January 1922, Gallaudet agreed to a series of changes that constituted almost a completely new design for the DB-1. These changes were incorporated into a new cost-plus contract for the second airplane, now designated the DB-1B.

The new design abandoned the monocoque duralumin fuselage for a welded steel-tube structure, and also used a standard Air Service wing section instead of one developed by Gallaudet. Wind tunnel tests indicated a greatly improved lift-to-drag ratio of 9.1, and static tests on a sample spar indicated sufficient strength. When delivered in May 1923, the DB-1B weighed 5,348 pounds, a reduction of 621 pounds. With an increase in gross weight, this reduction gave the DB-1B the desired useful load of 3,500 pounds, including a 600-pound bomb load. When flight tests started in August, however, the DB-1B was found to have very poor control characteristics. The most serious problem was a pronounced tendency to roll to the right at speeds above 120 mph. Lt. Ernest Dichman, an engineering officer at McCook Field, concluded that the control problems would "have to be corrected before this airplane can be considered in any degree successful." But after spending $253,000 for two unsatisfactory versions of the DB-1, the Engineering Division decided to abandon the project.[30]

The Air Service undertook another metal airplane project in the early 1920s that repeated the failures of the CO-1 and DB-1. This project involved a contract with Gallaudet for three all-metal pursuits designated the PW-4. Gallaudet designed a partially cantilevered biplane with a duralumin monocoque fuselage, with ribs fashioned from duralumin sheet, and spars of heat-treated steel and duralumin. Unlike the DB-1, the PW-4's wings were covered by duralumin instead of fabric. Gallaudet delivered the first airplane on January 30, 1922. In static tests of the PW-4 that spring, the tail surfaces and controls proved unsatisfactory. The Engineering Division postponed a decision on the PW-4's future pending static tests on a Dornier D1, which shared many structural features with the PW-4. (The army had obtained the D1 from the navy, which had purchased the airplane in Switzerland.) In September 1922 the Air Service canceled the contract for the remaining two planes and abandoned further development of the PW-4.[31]

The Engineering Division had more success in promoting the welded steel-tube fuselage developed by Anthony Fokker. As part of the metal airplane work begun in the fall of 1920, McCook Field designed a pursuit plane with a welded steel-tube fuselage, the PW-1; at about the same time, the Engineering Division also ordered another pursuit with a steel-tube fuselage, the Curtiss PN-1. Neither airplane entered production. The Air Service also bought twelve Fokker monoplane fighters from Holland; these were designated the PW-5 and gave the Air Service experience with both the steel-tube fuselage and monoplane wings. The Engineering Division slowly gained confidence in the Fokker fuselage, and in February 1923 the Air Service gave Boeing a contract to remodel three wooden DH-4s with welded steel-tube fuselages. The results proved satisfactory, and the Air Service gave Boeing a contract for fifty more DH-4s. In the next fiscal year, 1924, the Air Service awarded Anthony Fokker's new American company a contract to remodel one hundred DH-4s with steel-tube fuselages, and Boeing received a contract to remodel another 127. The new fuselages for the DH-4s cost on average only $2,400 per airplane, a fraction of the cost of duralumin monocoque fuselages. By fiscal year 1924, the Air Service had begun placing production orders for new airplanes using the steel-tube fuselage, including twenty-five Curtiss PW-8 pursuits and twenty TW-3 training planes. At the end of the fiscal year, welded steel-tube fuselages had become standard for almost all new airplanes procured for service use.[32]

The steel-tube fuselage provided the only success in the Air Service's program to develop metal airplanes in the early 1920s. The steel-tube fuselage was a significant improvement over the wooden frameworks it replaced, but this development failed to spark the enthusiasm that accompanied all-metal aircraft. The steel-tube fuselage still required fabric or plywood covering, and it failed to eliminate pre-industrial wood from the wings.

Except for the steel-tube fuselage designs, every metal airplane that the Air Service attempted to develop between 1920 and 1923 ended in failure. These failures illustrate two of the problems with metal discussed in chapter three, weight and cost. In the early stage of a new technology, one would expect costs to be high and difficult to predict. The weight and strength problems were more serious, however. In particular, American airplane designers found it very difficult to predict the strength of metal airplane structures, due largely to the prevalence of buckling failure. Major H. S. Martin, chief engineer at McCook Field, made this point explicitly in a discussion of the stress analysis of the DB-1. Stress analysis techniques of the time were moderately accurate for certain types of structures, such as pin-jointed trusses and simple beams in bending. The methods were less accurate for complex structures, however, especially those that failed by buckling. Martin had little faith in the predictive power of the stress analysis for metal airplanes. He criticized the presence of a thin projecting lip in the DB-1's metal spars, which Martin thought "likely to crinkle." "It is impossible to say," concluded Martin, "whether or not the section would develop the required strength." Indeed, the spar did not develop the required strength, and failed by buckling.[33]

The Retreat from Enthusiasm

The repeated failure of the army's metal airplane projects changed the attitude of the Engineering Division toward metal construction. Although the Air Service never repudiated the goal of the all-metal airplane, the Engineering Division adopted a more conservative approach. This new approach rejected immediate attempts to acquire airplanes of the *neue Stil* in favor of the evolutionary development of metal structures. Instead of all-metal fully-cantilevered monoplanes, the Air Service decided to stick with fabric coverings and externally braced biplanes. Already in 1922, the Engineering Division had become wary of metal wing coverings. In a memo regarding a design competition for an "all-metal" bomber, Maj. L. W. McIntosh, acting chief of the Engineering Division, noted that the specification permitted fabric coverings. McIntosh believed that fabric would save weight and ease inspection and repairs. In addition, the division had also grown wary of the monoplane. Although the design specification permitted a monoplane, wrote McIntosh, "this division believes a monoplane undesirable."[34]

The appearance on the American market of another German all-metal airplane of the *neue Stil* revealed the reasons behind the new attitude of the Air Service. This airplane, a single-seat pursuit known as the Dornier-Wright WP-1, was introduced to the American market in 1923 by the Wright Aeronautical Corporation, a major military supplier of aircraft engines. The WP-1 was structurally similar to the wartime Dornier D1 (see chapter two). Dornier built this airplane in Switzerland to circumvent the Versailles treaty's prohibition against the manufacture of military aircraft in Germany. The WP-1 had a duralumin monocoque fuselage and an internally braced monoplane wing mounted on struts above the fuselage in the "parasol" arrangement. The wings consisted of heat-treated steel spars, stamped duralumin ribs, and a partial duralumin covering.[35]

The Wright company worked hard to sell the WP-1 to the Air Service. In a letter to Maj. Gen. Mason M. Patrick, chief of the Air Service, Wright company president Frederick Rentschler reiterated the standard arguments in favor of metal construction. Rentschler insisted "that the airplane of the future would be of all metal construction," arguing that metal would increase "durability and reliability," and eventually reduce production costs. Rentschler admitted that "almost prohibitive" production costs had inhibited the development of metal airplanes and that it appeared "seemingly impossible" for metal airplanes to match the performance of wood-and-fabric types. The WP-1, claimed Rentschler, had solved these problems. The Wright company offered to build the WP-1 in the United States, presumably under license from Dornier, but only if it could obtain a production order from the Air Service.[36]

General Patrick instructed the Engineering Division to report on the Dornier-Wright airplane. The Engineering Division did not receive the WP-1 with open arms, in sharp contrast to the embrace of the Junkers JL-6 less than three years earlier. The intervening experience with metal construction had cooled the enthusiasm of the army's aviation experts. Although the McCook Field engineers acknowledged the skillful construction of the WP-1, they reported emphatically that the Dornier design "is *not* the type which is desired for service use." The division's engineers objected to both the monocoque fuselage and the metal-covered wing. The monocoque fuselage made maintenance and inspection difficult in comparison to steel-tube construction. "One has only to put this airplane [the WP-1] beside the Curtiss [probably the PW-8] to see that the steel frame structure with fabric covering and removable cowling offers marked advantages for a military airplane." The WP-1's gas and oil tanks, mounted internally in the fuselage, could only be accessed through the cockpit, "a decidedly poor arrangement, but one that is almost imperative in a monocoque fuselage." The metal fuselage covering also prevented inspection of the joints between the wing struts and the fuselage. Deterioration of this joint could cause loss of the wing during the violent maneuvers required of pursuit airplanes. The report on the WP-1 questioned the use of duralumin for any structural parts that could not be easily inspected.[37]

The Engineering Division also objected to the WP-1's fully cantilevered monoplane wing. It had concluded that internally braced monoplane wings were undesirable for pursuit planes. Writing for division chief McIntosh, A. H. Hobley complained of "too frequent" structural failures with this type of wing. Hobley mentioned the crashes in a recent Spanish exhibition of two monoplanes, one wood and the other metal. These accidents confirmed the army's own experience with monoplane pursuits, which included the death of an army test pilot in a Fokker monoplane due to wing flutter, and persistent flutter problems with the Fokker PW-5 pursuit. This distrust of the WP-1 wing proved justified when one of the wrecked Spanish monoplanes turned out to be a Dornier-Falke pursuit similar to the WP-1. This airplane crashed when the wing failed after experiencing wing flutter at full speed in level flight. This information reinforced McIntosh's recommendation against the Dornier-Wright WP-1, and led him to denounce the "reprehensible" behavior of foreign designers, by implication Fokker and Dornier, who failed to inform the Air Service of safety problems in airplanes being tested at McCook Field.[38]

The Dornier-Wright plane gave the Engineering Division the opportunity to make explicit its ideas about the proper path for the development of metal construction. The division believed that the best fuselage consisted of a rigid steel-tube structure covered with fabric aft of the metal-cowled engine compartment. The "most desirable" wing would have a metal framework, covered with fabric, "closely akin to the conventional wooden wing." Such wings could be stored uncovered and then closely inspected before being covered with fabric and placed in service. Metal wing coverings made such a procedure very difficult. A 1925 Air Service publication made the preference for fabric explicit: "It is now the policy of the Air Corps, in practically all of the service types of airplanes, to insist, as far as possible, on a wooden or metal structure covered with fabric."[39]

The Engineering Division's more conservative approach was reflected in the draft chapter on aircraft materials for a book titled *Airplane Design*. The authors, civilian engineers at McCook Field, incorporated the lessons learned from the unsuccessful attempts to develop all-metal airplanes. The McCook engineers acknowledged the complexity and uncertainty involved in the choice of materials:

> The problem [of choice of materials] cannot be solved by the simple method of subjecting test specimens of the various possible materials to tension, bending, and compression tests and selecting the material which gives the best ratio of strength to weight; but many other factors must be considered, some of which are incapable of being expressed mathematically. . . . Tests may show that a new material is stronger in every way tested than some other material that has been used successfully for a long time, yet when the new material is substituted for the old, it proves to be entirely unsatisfactory due to some property not indicated by the tests.[40]

This statement was an implicit rebuke to the categorical claims made by advocates of metal construction. Practical experience could provide the only clear test for the suitability of a particular material.

The Engineering Division's first opportunity to implement its more cautious approach was provided by a design competition for a night bomber. The competition, which closed in February 1923, called for an "all-metal" airplane, with fabric covering permitted, having a top speed of 110 mph and a useful load of 2,770 pounds, about five hundred pounds less than the DB-1. Most of the major airplane builders submitted designs. None of the proposed designs satisfied the structural engineers at McCook Field. Alfred S. Niles, writing for the structures unit, judged all of the designs "highly experimental" because of the requirement for metal construction. Niles was then a twenty-nine-year-old structural engineer with a bachelor of science in civil engineering from MIT; he later became a professor at Stanford and a leading expert on aeronautical structures. According to Niles, "the members of the structures unit are unanimous in feeling that it would be inadvisable to build any of the proposed designs at the present time with our very limited knowledge of metal construction." Instead, Niles proposed a more modest approach. Rather than complete airplanes, he suggested the purchase of parts of the designs, such as fuselages, ribs and wing spars, from each of the manufacturers. These parts would be tested under uniform conditions, allowing the Engineering Division to evaluate a variety of structural types at a much lower cost than that required for complete airplanes.[41]

Limited funding made Niles's proposal especially attractive. The Engineering Division had already spent close to $578,000 on the three Gallaudet contracts and the McCook Field CO-1, without receiving a single satisfactory airplane. Meanwhile, the Engineering Division's budget had continued to shrink. Its fiscal year 1923 appropriation fell to $3.5 million, down from $4.3 million in fiscal year 1922. In a draft of the 1923 annual report, Major

McIntosh complained bitterly that "the continued decrease of appropriations permit [*sic*] only the solving of the more important problems at hand in the quickest manner possible." Despite McIntosh's protests, the shortage of funds actually forced the Engineering Division to develop a long-range strategy for the development of metal structures, a strategy based on Niles's proposal for testing metal components.[42]

At the end of March 1923, the Engineering Division launched the first study inspired by the new strategy. The division asked manufacturers who had submitted designs for the all-metal day bomber to provide price quotes on metal ribs, spars, and fuselages, all designed for the same loading conditions. A tight budget precluded orders for the fuselages, which cost up to ten times more than the spars and ribs combined. Most manufacturers were willing to supply two spars and six ribs for between $2,000 and $3,000, a bargain compared to the cost of a complete airplane. A number of established manufacturers received orders, including Boeing, Douglas, Aeromarine, and LWF.[43]

This first metal spar study did not yield any definite results about the best type of metal construction, but it did provide a glimpse of the difficulties that compressive buckling would pose for spar designers. By the end of the project, the Engineering Division had tested seven metal spars, and also one wood spar for comparison. The initial results of the spar tests indicated that the wood spar was "a little more efficient" than the metal spars.[44] The tests also revealed "the marked tendency of such [metal] spars to fail by buckling or crinkling of the compression members." However, most of the failures also involved failures of fittings, making it "impossible to separate the effect of the fitting from that of the spar construction." These problems prevented the engineers from reaching any broad conclusions about the relative merits of different types of construction.[45]

The interim results were sufficiently encouraging to convince Niles of the need to broaden and extend the tests. Niles proposed a "continuing study to cover several years" to develop metal spars superior to those of wood. This study would follow the lines of the original project, involving contracts with a variety of manufacturers for metal spars subjected to identical tests at McCook Field "in competition with wood spars." Niles made it clear that the comparison with wood was not intended to evaluate the relative merit of the materials. Rather, the goal was to help develop metal spars more efficient than existing wood spars. Niles thought metal spars "of great importance for the future of airplanes," and he believed it possible "eventually to develop metal spars lighter than wood for nearly every case." This confidence was not misplaced, in part because McCook Field had abandoned all projects related to improving the design of wood spars. Still, Niles counseled patience, and warned that superior metal spars "should not be expected for some time."[46]

Niles's proposal became the basis for an extensive study of metal spars designed for the requirements of a single-bay observation biplane. The study began in earnest in early 1925, when the Engineering Division requested bids from the industry for metal spars, 6¼ inches deep and 7 feet long, all required to support identical loads. Most of the spars were supplied by major manufacturers and independent engineers, while others were designed and built at McCook Field. By August 1926 the McCook engineers had tested forty-one spars, including thirteen different types of metal construction; six months later they had tested twenty-three more. The variety and complexity of the metal spars is striking, comprising almost every major type of metal construction. The spars included box beams, channel trusses, tubular trusses, plate girders, hourglass sections, dumbbell trussed webs, and tube frameworks. Most designers used duralumin; a few employed steel. All received detailed data from the Engineering Division on the tests of their spars, including an analysis of failure at ultimate load. Designers used this information to improve subsequent spars of the same type, with as many as five different variations being tested.[47] In effect, the spar study served as a training program to diffuse the knowledge needed for metal airplane construction to a large part of the aviation industry.

A progress report on the study was prepared in August 1926, partly in response to widespread interest from manufacturers. The report demonstrated the inconclusive nature of even the most straightforward experiments, at least with regard to questions of design. The test results revealed the superiority of the wood spars (see chapter three), which proved somewhat embarrassing, since Niles had championed the study as a means for developing better metal spars. The results clearly implied that wood was the better material for spars in terms of weight efficiency, at least with regard to the hypothetical observation airplane under consideration.[48]

However, the results were also open to an interpretation that led in a different direction. Rather than granting any innate advantage to wood, Niles and his coauthor E. C. Friel attributed the superior performance of the wood spars to their greater refinement in design. Niles and Friel argued that European reports of better strength-to-weight ratios for metal spars did not apply to American conditions. "The development of the wood spar has not progressed as far in Europe as in the United States, while in Europe that of metal has progressed much further." When both wood and metal spars had achieved equal levels of development, argued Niles and Friel, the relative merit of designs would depend more upon the skill of the designer than the choice of materials.[49]

Niles and Friel's analysis of relative levels of development certainly contained some truth, but it was also a well-worn strategy for defending a new technology that failed to perform as expected. The concept of equal levels of development is much less precise than strength-to-weight ratios. The metal spars in the study represented the best efforts of American aeronautical engineers, who were well informed about European developments. Engineers in the American airplane industry had been working on metal construction since 1920. Furthermore, wooden wing spars remained relatively simple, both in design and construction. An observer comparing wood and metal spars would not have concluded that the wood spars were more highly developed. Existing test data did make wood spars easier to design than metal, but this reflected the greater simplicity of most wood spars, which made such test data easy to obtain. The real problem with metal spars was the low buckling strength of the metal, which increased the complexity of the design process. Designers of wood spars could usually ignore buckling. In other words, the problem with the metal spar was not its low level of development but its need for a higher level of development before it could compete with wood.[50]

Although Niles had explicitly designed the study to advance the cause of metal construction, some of the more vigorous advocates of metal found fault with his conservative approach. They attacked the basic premise of the study, insisting that the hypothetical two-spar, fabric-covered wing was not suited to metal construction. Some engineers argued that the Junkers multispar design or the Rohrbach single-box spar should serve as the model for development. Niles and Friel countered by noting that the two-spar framework "was taken from analogy to metal structures like steel-truss railroad bridges." They pointed out that steel framework structures had completely superseded the hollow-box ("tubular") designs of early English iron railroad bridges like the Britannia bridge, which were analogous to the Rohrbach-type stressed-skin wing. Niles and Friel argued that until all-metal wings "can show a superiority they have not yet proved," development should focus on open frameworks.[51]

In tests conducted during the winter of 1927, one metal spar finally proved superior to at least some of the wood spars. The Douglas Aircraft Company designed the spar, which was of dural box construction with a corrugated web. The spar surpassed the strength-weight ratio of the wood I-spars, but remained slightly inferior to the best wood box spar. The weight difference between the Douglas spar and the best wooden spar amounted to only one pound over its seven-foot length. These results finally demonstrated that an acceptable metal spar could be designed for observation airplanes, at least in terms of weight-to-strength ratios.[52]

Dogged Persistence: The Navy's Support for Metal Airplanes

The U.S. Navy played a major role in developing metal airplanes, a role at least as important as the army's, despite the navy's smaller budget. The navy found metal airplanes just as troublesome as the army did and encountered similar problems with weight and cost. But the navy's metal airplanes proved somewhat more successful than the army's, managing to get past the prototype stage and into service tests. In service, these airplanes revealed another difficulty, expensive maintenance costs, especially when aluminum alloys came into contact with salt water.

The navy made its first contribution to metal construction by convincing Alcoa to begin U.S. production of duralumin-type alloys. The navy's interest in duralumin began well before the postwar enthusiasm for metal airplanes. By 1916 Germany's use of military zeppelins had sparked the navy's interest in rigid airships. Rigid airships promised to provide the navy with long-range scouting ability far in excess of anything that airplanes could provide. In July 1916, Adm. David W. Taylor, chief constructor of the navy, asked Alcoa to develop a high-strength aluminum alloy similar to that used in German zeppelins. For additional assistance, Taylor brought in the Bureau of Standards, which had considerable expertise in nonferrous metallurgy.[53]

Alcoa succeeded in producing a duralumin-type alloy in laboratory quantities not long after the American declaration of war in April 1917. Alcoa's laboratory success was aided by research at the Bureau of Standards, where metallurgist Paul Merica discovered the fundamental chemical mechanism of precipitation hardening in aluminum alloys. But Alcoa metallurgists found it hard to translate their laboratory success into commercial production, experiencing considerable difficulty producing duralumin sheet of a quality acceptable to the navy. Production problems continued even after December 1919, when Alcoa accepted contracts to deliver duralumin for the navy's first rigid airship, the ZR-1.[54]

Under constant prodding from the navy, Alcoa worked hard to develop reliable production methods for this new alloy, named 17S by Alcoa. The navy did its best to help Alcoa, even engaging in industrial espionage to discover the production secrets of European firms. Not until spring 1921 was Alcoa able to deliver sufficient quantities of 17S for construction of the ZR-1. By late 1922, Alcoa was finally able to produce 17S consistently, even exceeding the strength and uniformity of German duralumin. Alcoa certainly deserves credit for overcoming the difficult technical problems involved in producing duralumin. But without the technical assistance of the U.S. government and the determination of navy officers to have a domestic supply of duralumin, Alcoa would have had little incentive to become a commercial supplier of aluminum alloys for aircraft structures.[55]

Aside from encouraging the domestic production of duralumin, the navy did little to promote metal airplane construction before the summer of 1920. After the official endorsement of metal construction by the Aeronautical Board in June 1920, the navy too began letting contracts for metal airplanes. The army and navy did little to keep each other informed about their metal airplane projects, despite the call for cooperation by the Aeronautical Board. If navy engineers had kept abreast of the army's contracts, they would have found distressing parallels with their own experimental airplanes, which repeatedly proved too costly, too heavy, and too difficult to maintain.

The navy's first all-metal airplane had much in common with the Galludet DB-1. This airplane, designated the ST, was a torpedo bomber designed and built by Stout Engineering Laboratories of Detroit. William Bushnell Stout, the company's president, was an engineer, publicist and inventor. Stout had much in common with professional inventors of the late nineteenth and early twentieth centuries, men like Thomas Edison and Elmer Sperry. These inventors clearly understood that a successful invention depended on effective promotional skills as well as technical achievements. Stout had taken the importance of public relations to heart; all that separated Stout from Sperry and Edison was his lack of technical ability.[56]

Stout's career demonstrates how far enthusiasm can compensate for such shortcomings. Stout was born in Quincy, Illinois, in 1880, the son of a Methodist minister. He obtained a degree in mechanical engineering from the University of Minnesota in 1904, after which he made his living designing toys and writing do-it-yourself articles. Stout founded an aviation journal in 1914 and then joined the aircraft division of the Packard Motor Car Company in 1917. In 1918 he began building airplanes on his own. Stout's first airplane was a small monoplane with a fully cantilevered plywood-covered wing, ordered by the army near the end of World War I. This airplane, known as the "batwing" because of its long wing chord, suffered from very poor visibility, which convinced the army to abandon the project. After the armistice, Stout returned to Detroit, where he built a commercial version of the batwing. He found no buyers, probably because of the plane's poor control during landings.[57]

Stout was an early enthusiast of the fully cantilevered monoplane but a later convert to metal construction. In April 1920 he began discussing a possible design for a plywood torpedo monoplane similar to his earlier designs. Later that month, Stout caught wind of the duralumin JL-6, and he immediately embraced the new material. In early June he wrote Col. Thurman Bane, chief of the Engineering Division, about the JL-6: "I have just been up in a German Junker [*sic*] plane at Mineola, and am sore all over that the Germans should have beaten us to it on our own ground."[58] Henceforth, Stout became an advocate of the *neue Stil*, the all-metal, fully cantilevered monoplane. He doggedly pursued this goal until he finally produced a successful airplane of the *neue Stil*. The navy provided a large part of the support Stout needed to reach this goal, but it derived little benefit from Stout's eventual success.

Stout's conversion experience coincided neatly with the navy's decision to build metal airplanes. In late June, Lt. Comdr. Jerome C. Hunsaker approved Stout's new plan to build the torpedo plane in metal. Hunsaker, a

1908 graduate of the Naval Academy, was perhaps the most technically astute officer in American military aviation. After Annapolis, Hunsaker received advanced training in naval architecture from MIT, earning his master's degree in 1912. In 1913 he returned to MIT to establish the first American degree program in aeronautical engineering. He received MIT's first doctorate in aeronautical engineering in 1916 and then joined Admiral Taylor to head the Aircraft Branch at the navy's Bureau of Construction and Repair.[59] Despite Hunsaker's technical credentials, he failed to perceive the risk he was taking with Stout.

Stout quickly negotiated a $170,000 contract for three all-metal, twin-engine monoplanes designed to carry a 1,650-pound torpedo at 110 mph, with the first plane due on January 1, 1921. Stout promised an empty weight of 4,600 pounds and a useful load of 4,000 pounds, quite optimistic figures at that time. Stout soon exhausted his available capital, and in November the navy agreed to provide him with progress payments, a departure from the standard practice of withholding payment until delivery of an acceptable airplane. On December 7, with the first airplane due in twenty-four days, Stout asked for his first of many extensions. By October 1921, Stout had spent almost the entire contract amount without finishing the first airplane. Stout demanded substantial additional funding to complete the contract, insisting that he had created "an organization for the development of metal structures second to none in the world," while offering no specific proposals to solve the many problems that plagued his work under the contract.[60]

The navy had already paid Stout $92,000, even though he had not delivered a single airplane. Despite Stout's failure to fulfill the contract, the navy's engineers seemed ready to accept Stout's every excuse, so thrilled were they by the allure of the all-metal airplane. In May 1921, Taylor had told the secretary of the navy that "from all information available, [Stout] leads other aircraft manufacturers in this country in skill in all-metal airplane construction." Meanwhile, navy inspectors reported on the poor organization of the engineering and manufacturing work, which contributed heavily to Stout's excessive costs. Stout had also failed to install an adequate system of weight control to keep the airplane near its design weight; such systems were fundamental to airplane manufacturing. In assessing the project for the Bureau of Construction and Repair, Lt. Comdr. Garland Fulton lamented Stout's lack of an experienced technical staff, whose expertise could have saved the project thousands of dollars. Still, insisted Fulton, "this is too big an investment to throw away." Fulton refused to condemn Stout, insisting that the project "must be considered from an engineering standpoint and an appreciation of the pioneer and research character of the work Mr. Stout has done." The navy canceled the existing contract in late October, paying Stout $141,000, and gave Stout a new contract to complete the three torpedo planes.[61]

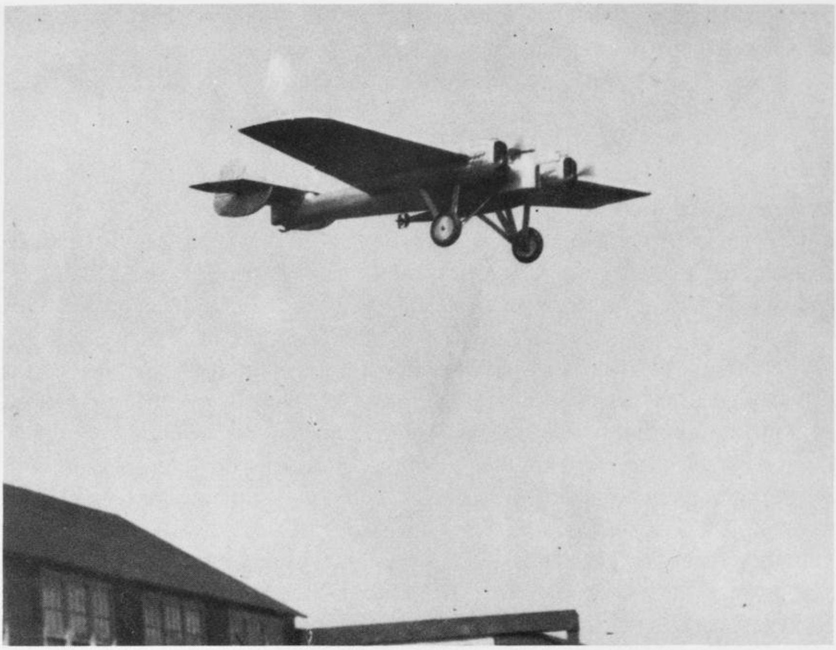

Figure 4.3. Stout ST-1 all-metal torpedo bomber in flight, May 31, 1922. Note the torpedo under the fuselage. National Air and Space Museum, Smithsonian Institution (SI neg. no. 96-15638).

The new contract did little to improve Stout's engineering skills. By early December it appeared that the first airplane would be a thousand pounds over its contract weight, much like the DB-1. After spending another $75,000 of the navy's money, Stout finally delivered the first airplane in the spring of 1922 (figure 4.3). Flight tests began in late May and showed the plane to be longitudinally unstable. Adm. William A. Moffett, Chief of the navy's new Bureau of Aeronautics, reported the test results to Stout. "Frankly," wrote Moffett, "I do not feel justified in asking our test pilots to fly a plane of the characteristics indicated in the trial board's report." Correcting the instability would have required a complete redesign of the airplane. According to Moffett, the navy had spent $216,000 with "very little to show for this expenditure." Moffett canceled the contract, ending Stout's relationship with the navy.[62]

In November 1922, the secretary of the navy appointed a board of engineering officers, among them Jerome Hunsaker, to report on Stout's accomplishments. The board's report was filled with backhanded compliments, though it contained little direct criticism of Stout. The officers concluded that the knowledge gained was of considerable use to Stout but of little value to the navy. In an accompanying memo to files, Hunsaker revealed his true assessment of Stout's contribution. Stout had not developed a single technique, process, or tool superior to those used elsewhere, claimed Hunsaker. Stout's methods compared unfavorably with those at the Naval Aircraft Factory (NAF), which Hunsaker visited to prepare the report on Stout. NAF engineers had produced numerous manufacturing innovations for building the duralumin girders of the airship ZR-1; these techniques were readily applicable to duralumin airplane construction. Many of the basic techniques for working with duralumin were developed in England by Vickers; Hunsaker himself had helped transfer those techniques (in part through industrial espionage) to Alcoa and the NAF. The NAF's manufacturing techniques were in general much simpler than Stout's, whose methods tended to be "unnecessarily elaborate and costly." Stout did manage to produce an excellent set of metal pontoons for the torpedo plane, but only after Stout's young chief engineer, George Prudden, consulted closely with NAF engineers who had already designed successful metal pontoons. Hunsaker noted with disdain that Stout's lack of real achievement did not prevent him from claiming "astonishing success with his metal fabrication."[63]

Although the navy gained little from Stout, Stout benefited tremendously from his work for the navy. In just two years, Stout milked the navy for what amounted to a $200,000 training program in metal construction, despite his almost complete lack of relevant expertise. Stout's real prowess lay not in his technical skills but in his ability to manipulate the symbols of progress to obtain financing for his airplane work.

The navy also funded several other metal airplane projects in the early 1920s, projects supervised by engineers with far more technical ability than Stout. Yet these projects too proved unsuccessful, demonstrating that the problems of metal construction stemmed from something more than the competence of the individual designer.

The first project involved the design and construction of metal wings for the Curtiss HS-2 flying boat, the navy's standard single-engine patrol boat during the early postwar years. In May 1920, the navy signed a $35,600 contract for two sets of HS metal wings to Charles Ward Hall, a skillful structural engineer with a Cornell degree in civil engineering. Hall intended to use duralumin sheet and tubing in his design, but Alcoa proved unable to supply him with dural tubing, so Hall used mild steel instead. Hall delivered the first set of wings, without their fabric covering, in January 1922. In terms of meeting the contract specification, the wings proved a tremendous success. Hall's metal wings had no trouble supporting the required load factor of six, and they also weighed some 28 percent less than the wooden HS-2 wings, a savings of about 366 pounds from the 1,320 pounds of the wood wings. Of course, this comparison did not take into account possible savings that could have been achieved by a more skillful redesign of the

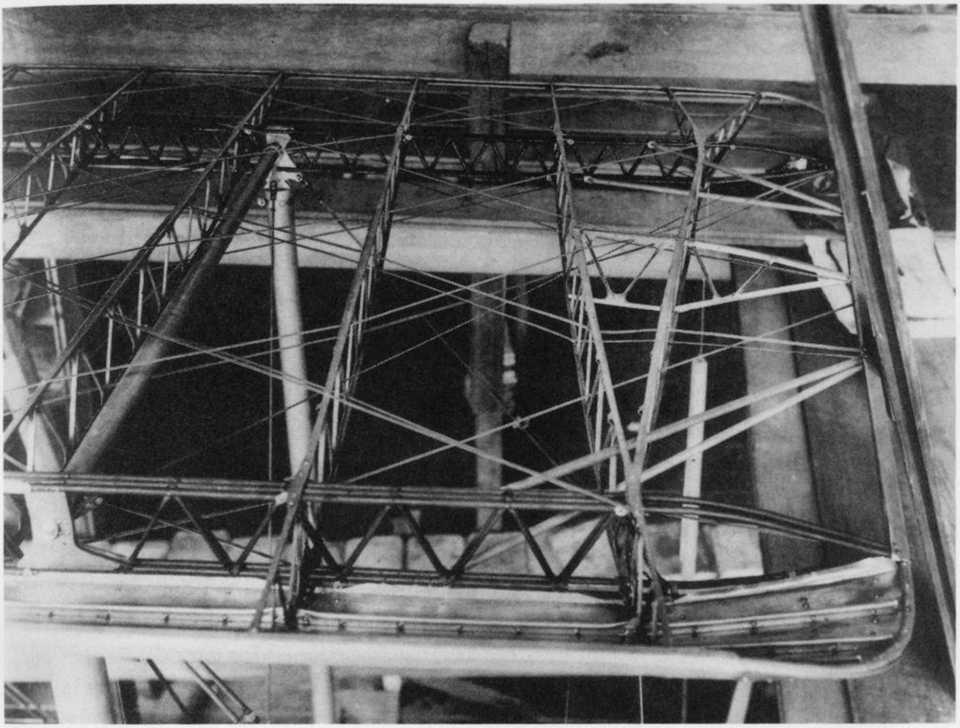

Figure 4.4. Delicate structure of C. W. Hall's metal HS-2 wings. National Air and Space Museum, Smithsonian Institution (Wright-McCook photo no. 29890).

HS-2 wings in wood; such a redesign could have "undoubtedly" reduced their weight by 10 percent or more, according to an internal navy report. More seriously, the numerous small fittings and delicate pieces in the Hall wings made them too fragile for service use and too complex for economical production (figure 4.4). Although the wings performed well in flight tests, they were easily damaged by ground crews and rough seas. During a test flight in 1923, waves seriously damaged the Hall wings when the pilot made a forced landing in the Chesapeake Bay; the pilot claimed that "the standard HS-2 wing would have suffered no damage in such a sea." The navy decided that the wings were not worth the estimated $9,300 repair cost, and it abandoned the project.[64]

The navy was encouraged by early results with the HS-2 wings. Not long after delivery of the metal wings, the navy asked Hall to redesign an entire airplane in metal. The navy chose the new TS-1 biplane fighter, its first airplane designed to operate from an aircraft carrier. The navy rejected Hall's bid of $179,000 for the three small airplanes, which Curtiss was building in wood for less that $12,000 each. Instead, the navy urged Hall to cooperate with Curtiss to reduce costs. In early 1923 Hall signed on as a subcontractor to Curtiss. Curtiss then received a $105,000 contract for two metal versions of the TS-1, which received the navy designation F4C. When delivered in September 1924, the F4C weighed a substantial 233 pounds less than the 1,242-pound TS-1, with most of the savings achieved in the wings. Even so, this comparison was "somewhat unfair" to the wooden TS-1 wings. Hall had designed the F4C using the gross weight of the land plane version of the TS-1, which was 10 percent less than the gross weight of the seaplane version that the TS-1 wings were designed to support. Despite the F4C's weight reductions and acceptable performance, the navy decided not to produce the design because the structure's numerous small parts made it expensive to produce and difficult to repair.[65]

The navy developed two more metal airplanes in the early 1920s, both built by the Glenn L. Martin Company. Glenn Martin was a successful aircraft manufacturer, though with modest technical training. To launch his firm into metal construction, he enticed Dr. Georg Madelung to come join his company in Cleveland. Madelung was an experienced German aeronautical engineer who had worked with Junkers during the war. In 1922 the Bureau of Aeronautics awarded Martin contracts for two metal seaplanes, the MO-1 and MS-1. The MO-1 was a three-seat, single-engine monoplane for observation work; the diminutive MS-1 was designed for easy disassembly to allow its use aboard submarines. The navy ordered thirty-six MO-1s and six MS-1s. Both airplanes had fabric-covered structures, with steel-tube fuselages and fabric-covered duralumin wings, although the MO-1 wings used wooden ribs.[66]

When delivered in 1923, neither plane proved successful. The MS-1 handled poorly in the water, requiring nearly calm seas for safe takeoffs and landings. The MO-1 performed sluggishly, and suffered from severe vibration, raising fears of fatigue failures in the metal structure. Both airplanes experienced serious maintenance problems, especially with corrosion. The metal pontoons of the MS-1 leaked at the seams, and the duralumin struts corroded on the inside. One officer criticized the MS-1 for its "poor design, material and workmanship," and recommended removing the airplane from service. Despite attempts to correct the problems with the MO-1, flying officers continued to oppose the airplane. In October 1924, an investigative board heard testimony regarding the suitability of the MO-1 for use on ships. Lt. Comdr. Karl F. Smith, an aircraft squadrons engineering officer, recounted the airplane's flaws, giving special attention to the corrosion problems, which Smith had observed while the airplanes were still in the factory. If the MO-1 were installed on ships, insisted Smith, it would "do more to give aviation in the Fleet a 'black eye' than any other one act."[67]

By 1925 the army and navy had spent almost $2 million to develop or purchase complete metal airplanes, without receiving a single acceptable model.[68] These projects demonstrated that metal construction was tremendously expensive, that most metal airplanes weighed more than wood designs, especially when using metal coverings, and that metal airplanes were not necessarily more durable than wood. These projects did not fail due to the idiosyncrasies of individual designers. Well-established firms like Gallaudet and brash upstarts like Stout, creative structural designers like Hall and German-trained aeronautical engineers like Madelung all proved equally inept at metal construction.

The disappointing results with early metal airplanes seemed to falsify the claims of prometal advocates, who had insisted that metal airplanes would be cheaper, lighter, and especially more durable than those of wood. These results should have provided strong arguments in favor of wood construction. Yet the repeated failure of metal airplanes did not revitalize the debate over airplane materials; instead these failures remained buried in the lower levels of the military bureaucracy, almost completely ignored by the trade press and all but lost from aviation history. After such a string of failures, it is amazing that the army and navy continued to provide any support at all for metal construction. Yet the military engineers were not dissuaded; they merely made a strategic retreat into research, convinced that the true potential of metal construction had yet to be realized. This conviction was indeed correct, but it could not be justified on technical criteria alone. The military's continued support for metal drew strength from progress ideology, which posited metal construction as a necessary step in the historical development of aviation. This ideology allowed military engineers to interpret failures as learning experiences, minor detours in the search for the true path to the metal airplane.[69]

Military Sponsorship of Metal Research

The category of "research and development" is a modern one, reflecting the conceptual subordination of engineering to science after World War II. The intimate linking of these two terms implies that the development of specific technologies is based upon prior scientific research. In recent years, historians of technology have done much to rehabilitate the concept of development, which they define as the process of transforming a design concept into a physical artifact suited to the needs of specific users. In this view, development becomes a highly creative process that is not subordinate to research but instead uses research as one of many resources needed to produce a successful technology.[70]

The military's metal airplane projects all fall within the modern category of development, although the military did not use this term in the early 1920s. The army classified its exploratory work as "experimentation and research," which included everything from laboratory experiments to the purchase of airplane prototypes. In addition to development projects, the army and navy also supported projects that in modern terminology would be called applied research. In the interwar period, the military viewed this research not as a necessary prior step in developing new technologies but rather as an ancillary process to help resolve the more intractable problems uncovered in design and operation. This research proved crucial to the development of metal aircraft, providing essential design data and solving major problems that inhibited the widespread use of metal airplanes. Airplane manufacturers were in no position to support this research themselves, because their small size and the vigorous competition between firms limited research spending.[71]

Following World War I, most aviation research was performed by four entities, the NACA, the Bureau of Standards, and the two military air services.[72] The NACA coordinated this research through its system of technical committees. These committees always had representatives from the army and navy, along with participants from other federal agencies involved in aviation. In practice, the military set the agenda for federal aviation research. The military air arms did some research in their own facilities, but most of their research was performed at other federal agencies. The army and navy sometimes sent research requests directly to these agencies; at other times they would first consult with the relevant NACA committee, which would then direct a request to the appropriate agency. In general, the army and navy provided funds to support this research, but the NACA often contributed as well.[73]

In the division of labor that developed in federal aviation research after the war, the Bureau of Standards performed most of the work on aircraft metals. Its role in aircraft metals developed naturally from its expertise in metallurgy and testing and from its supervision of metal airplane development during the war. This role made the Bureau of Standards the single most important agency for aviation research in the early 1920s, until eclipsed by the NACA later in the decade. The bureau devoted some of its own budget to aviation, but most of the funding came through transfers from the army and navy. Between 1917 and 1925, the army, the navy, and the NACA transferred a little more than $1,231,000 to the bureau for aviation projects, while the bureau itself allotted about $393,000 of its own funds.[74]

As airplane designers began using the new aluminum alloys, they found little reliable information on basic properties of the materials. Alcoa provided data on ultimate tensile strength and elongation (a measure of ductility), but much remained unknown. In particular, airplane designers knew little about the fatigue strength or corrosion resistance of the new alloys, information essential for designing safe airplanes. Under navy sponsorship, the Bureau of Standards took the lead in research on duralumin, providing design data on duralumin fatigue and discovering a solution to the dangerous problem of intercrystalline corrosion.

Fatigue refers to the failure of a material when subjected to repeated stresses at loads less than its ultimate strength. For example, a piece of steel loaded to three-fourths of its ultimate load has a 25 percent margin of safety, but the steel can still break if this load is removed and applied repeatedly, say one hundred thousand times. This number may seem large, but an aircraft engine operating at two thousand revolutions per minute produces 120,000 oscillations per hour.[75] Any time a metal part is subject to vibration, aeronautical engineers worry about fatigue.

Fatigue failures give little warning, making them especially dangerous in airplane structures. "They simply happen and, from a flying standpoint, that is of vital importance," noted a McCook Field engineer. When airplane designers began using duralumin in the early 1920s, little was known about its fatigue properties. Engineers had a fairly good empirical understanding of fatigue in steel but not in aluminum alloys. Most steels have an "endurance limit"; at stresses below this limit, an infinite number of repeated loadings will not cause failure. In steel the endurance limit is about one-half the ultimate stress. Early studies of duralumin could not find an endurance limit, and indeed modern research has found no such limit. Early duralumin airplanes also had problems with fatigue in practice. In the fall of 1920, an NACA memo noted the "serious difficulty [that] has been experienced with the failure of duralumin due to fatigue," while Jerome Hunsaker remarked that "designers are at sea as to the fatigue resisting properties of duralumin." Hunsaker urged the NACA Committee on Materials to initiate a study of duralumin fatigue. The Materials Committee complied, assigning the research to the Bureau of Standards.[76]

To mimic service conditions, the Bureau of Standards developed special machines to test flexural fatigue, the most likely type of fatigue in metal airplane structures. These tests constituted the first extensive study of flexural fatigue in thin sheet metal and continued for three years with navy funding. Some dural samples were subjected to 200 million repetitions, which for one sample required 389 days of continuous testing. The study confirmed the absence of an endurance limit in duralumin, which meant that dural could fail by fatigue even at very low stresses, given enough repetitions. At 100 million repetitions, for example, dural had only one fourth its ultimate strength. The bureau's data allowed designers to make rough estimates of the life of duralumin parts; for example, the bureau calculated that the structure of the airship *Shenandoah* (the ZR-1) would last at least forty years. The apparent precision of such calculations was deceptive, however; fatigue failures often occurred much sooner because of unforeseen vibrations, variations in service conditions, and stress concentrations caused by rivet holes and sharp corners. Extensive research in fatigue has continued in the post–World War II era, but fatigue failures still pose a threat to present-day airplanes.[77]

The navy also took the lead in initiating research on duralumin corrosion at the Bureau of Standards, research that would eventually uncover the dangerous phenomenon of intercrystalline embrittlement. Intercrystalline embrittlement was an especially insidious form of corrosion (see chapter three), penetrating into the material along the grain boundaries while leaving the surface almost unchanged. At early stages, this corrosion produced a measurable reduction in strength, ductility, and resistance to fatigue; at advanced stages the corroded sheet would disintegrate into little jagged pieces.[78]

The navy had always worried about the corrosive effect of salt water on duralumin. The navy began exposure tests as soon as the material became available from Alcoa. In 1919, the navy brought in the Bureau of Standards to supplement the exposure tests with laboratory experiments. Initial results seemed encouraging but inconclusive, in part due to the lack of standardization and inconsistent quality of duralumin.[79] Despite this inconclusive research, proponents of duralumin were quick to declare the material immune from attack by sea water, even after evidence of duralumin corrosion began to mount. In 1924, Lt. F. O. Carroll, an engineering officer at McCook Field, insisted that duralumin was "not affected by salt-water or atmospheric conditions." Carroll appeared completely ignorant of the navy's experience with corrosion in duralumin airplanes like the MS-1 and MO-1, illustrating the lack of communication between the Army Air Service and the Navy Bureau of Aeronautics.[80]

The progress ideology of metal may have encouraged the aviation community to overlook mounting evidence of intercrystalline corrosion. Many early tests reported the presence of a fine white powder on the surface of the metal, sometimes accompanied by pitting. Later studies identified these characteristics as clear signs of intercrystalline corrosion, but researchers at the Bureau of Standards and elsewhere missed their significance. The bureau also overlooked more compelling evidence of intercrystalline corrosion. In the fall of 1920, after a mere two months of service, the duralumin covering of a Post Office JL-6 began to disintegrate on one of its tail surfaces. The Post Office sent the offending material to the Bureau of Standards, which subjected it to careful analysis. The sheet showed "extreme brittleness," with several inches missing from the original edge of the sheet, "leaving a ragged edge with cracks extending into the sheet." Microscopic examination revealed a "network of very fine intercrystalline cracks throughout the alloy," direct evidence of intercrystalline corrosion. The bureau's report downplayed the problem, describing it as sporadic, and suggested that it had probably resulted from variations in quality of the German duralumin in conjunction with chemical or electrolytic action.[81]

By 1924 enough additional evidence had accumulated to force the navy to act. Its JL-6 airplanes had not stood up well in service, and in 1922 it retired one of the airplanes to the Hampton Roads Navy Yard for exposure tests near salt water. In July 1924, a navy report concluded that the JL-6 wings were still "in excellent condition" after two years of exposure. A mere two months later, however, another inspection produced a startling discovery: the corrugated wing covering had become so brittle that holes could easily be kicked through it. Even more disturbing was the visual appearance of the material. The surface showed no evidence of serious corrosion, and would even take a shine, although "practically all of the physical strength of [the] duralumin has disappeared."[82]

The navy immediately sent samples of the JL-6 wing covering to the Bureau of Standards, along with other duralumin parts that had been subjected to a variety of exposure tests. By December, the bureau had uncovered the cause of the problem—intercrystalline corrosion. The bureau's report cautioned against panic, noting that the results were from a single sample. But analysis of additional samples showed the problem to be widespread. In early 1925, the navy sent the bureau samples of material used for girders on the airship *Shenandoah*. When the tests revealed intercrystalline corrosion in this material, the navy and Bureau of Standards began mobilizing resources to find a solution.[83]

The navy and the bureau coordinated their efforts through the NACA's Committee on Materials, which was chaired by George Burgess, director of the Bureau of Standards. On April 16, the Materials Committee held a special meeting at the Naval Aircraft Factory devoted almost entirely to duralumin corrosion; this meeting asked the Bureau of Standards to prepare a research program on the protection of duralumin from intercrystalline corrosion. The bureau worked closely with the navy to map out the research strategy. The navy insisted that the bureau first concentrate on an "engineering solution," that is, an empirical study of protective coatings and other measures "to enable the confident use" of duralumin by airplane manufacturers. The bureau responded with a comprehensive program to test the influence of almost every conceivable variable on the problem. The program involved accelerated corrosion tests in which dural samples were sprayed with a mist of salt water and hydrogen peroxide. The bureau received funding from the navy, the army, and the NACA for this research, at a cost of $10,000 for the first year alone, a relatively large allotment for this type of project. Maj. Leslie MacDill, chief engineer at McCook Field, readily agreed to supply the $2,500 requested by Burgess, adding that the project was "of sufficient importance to justify furnishing additional funds if necessary."[84]

The insidious nature of intercrystalline corrosion made it an obvious threat to aviation safety, a threat that might have undermined support for metal construction in the aviation industry. Except for a few isolated individuals, however, advocates of metal never lost faith. The navy, the NACA, and the Bureau of Standards remained optimistic, both in public and in private, insisting that intercrystalline corrosion was a solvable problem. In September 1925, the crash of the airship *Shenandoah* brought public attention to intercrystalline corrosion because of its presence in the airship's structure, even though this corrosion had not contributed to the accident. This publicity sparked an extraordinary discussion at the February 1926 meeting of the NACA Materials Committee. Starr Truscott, a civilian materials expert at the Navy Bureau of Aeronautics, demanded that the NACA publicly endorse the "suitability of duralumin for aircraft construction" in order to counteract the negative publicity appearing in the popular and technical press. The navy, Truscott revealed, hoped to obtain funding for two more rigid airships and feared that the critical reports would threaten the projects. After much discussion in favor of duralumin, the Materials Committee complied with Truscott's request and endorsed the release of a supportive statement.[85]

The NACA's endorsement of duralumin was clearly premature. The bureau's research had yet to produce a clear solution to the problem, and in any case the preliminary laboratory results would require confirmation through long-term exposure tests. The NACA's technical experts were eager to endorse duralumin before learning the results of the very research they were sponsoring; such eagerness blatantly contradicts the purported objectivity of technical experts. Nevertheless, the NACA's optimistic assessment of duralumin made perfect sense in the interpretive framework provided by the progress ideology of metal.[86]

Fortunately for the members of the Materials Committee, the Bureau of Standards delivered the results they had optimistically predicted. Within a year of starting the study, the bureau had discovered a fundamental solution to intercrystalline corrosion: coating the duralumin with a layer of commercially pure aluminum. The bureau had proposed testing such a coating in its June 1925 proposal for the corrosion study. At the May 1926 meeting of the NACA Materials Committee, Dr. H. W. Gillett, the bureau's lead scientist on the study, reported that aluminum-covered dural samples appeared unharmed in the accelerated corrosion tests. The following month Gillett wrote up a draft patent application, which he hoped would forestall any private firm from laying claim to the discovery. The patent application described a variety of methods for bonding the pure aluminum coating to the underlying alloy. Gillett favored a metal vapor process, but the draft patent described a variety of other techniques, including pouring molten aluminum around an ingot of duralumin before rolling it into sheets.[87]

One year after Gillett had presented his findings on aluminum-coated duralumin to the NACA Materials Committee, Alcoa announced its solution to the intercrystalline corrosion problem—Alclad. Alclad consisted of duralumin bonded to a thick coating of pure aluminum, which was applied to the duralumin ingot before it was rolled into sheets, precisely as described in Gillett's patent application. Alcoa announced Alclad in a paper presented by Edgar H. Dix, an Alcoa metallurgist, to the annual aircraft conference held at the NACA's Langley laboratory on May 24, 1927. Dix's paper did not acknowledge the work of the Bureau of Standards. In a clear attempt to assert Alcoa's priority, Dix claimed that Alcoa had conducted unsuccessful experiments with pure aluminum coatings as early as 1921. These experiments had nothing to do with intercrystalline corrosion, however, since the problem was not identified until three years later. H. W. Gillett and other researchers at the bureau clearly felt slighted by Dix. In a letter written three days after the announcement of Alclad, Gillett and his colleague H. L. Whittemore wrote to the NACA, insisting that the bureau had done the "fundamental work on the adaptability of aluminum coatings for duralumin." They credited Alcoa with solving the "second step, the working out of the commercial difficulties."[88]

The bureau's scientists appear justified in their priority claim. Zay Jeffries, head of metallurgical research at Alcoa, was a member of the NACA Materials Committee and had been an active participant at the May 1926 meeting where Gillett announced the results of his aluminum coating tests. The Materials Committee received updates on the bureau's work at every meeting, giving Alcoa privileged access to this research. Dix himself admitted in an internal Alcoa memo that Gillett's experiments had helped inspire Alclad. Nevertheless, Alcoa did its best to present Alclad as a triumph of industrial research. In reality, a direct line runs from the military to Alclad. It was the product of federal research at the Bureau of Standards, research initiated and funded by the military.[89] As chapter six will show, the government's support for this research bore almost no relation to the contemporary importance of duralumin in aviation; this support was based almost entirely on faith in the future role of metal.

In the early 1930s, Alclad would provide an essential element for the development of commercial airplanes with all-metal structures. But even before the development of Alclad, airplane manufacturers attempted to develop metal airplanes for commercial use. These attempts foundered on the same shoals that sunk the military's metal airplane projects. Without substantial military support, even the wealthiest corporations in America proved unable to turn metal airplanes into a profitable business.

5

Metal and Commercial Aviation I: Henry Ford Takes Flight

ALTHOUGH THE MILITARY was the dominant force behind the development of metal airplanes in the 1920s, manufacturers of commercial airplanes also made key contributions. Many proponents of commercial aviation were even more enamored of metal than their military counterparts. The military contribution was larger simply because its resources far exceeded those of commercial firms.

Commercial aviation in America developed directly from military technologies. After World War I, American commercial airplanes differed little from military aircraft in materials and structures. In the early postwar years, metal proved just as unsuitable for commercial as for military use, with the exception of the steel-tube fuselage, which was adopted for commercial models as soon as it became standard for military planes. A number of airplane firms attempted to build commercial metal airplanes in the early 1920s, but few finished more than a single vehicle.

Developing a metal airplane was an expensive and frustrating process, one that proved just as difficult for private firms as for the military. Few firms could combine the capital and expertise needed to produce metal airplanes for an air transport market that remained almost entirely hypothetical. Nevertheless, a number of small companies gave it a try; one of these was the Stout Metal Airplane Company, established by William Stout after his unsuccessful navy contracts.[1] When Stout joined forces with Henry Ford, the richest industrialist in America, advocates of metal airplanes gained the most powerful ally possible. Yet even Henry Ford's vast wealth and talented engineers could not turn metal airplane production into a profitable business.

American Air Transport in the 1920s

Before 1925, there was little demand for commercial aircraft. Immediately following the war, American manufacturers developed a number of promising passenger and freight airplanes to supply dozens of proposed airlines. Most of these new airlines were stillborn, however, in part due to the 1921 recession but also because of the inability of scheduled routes to succeed without government subsidies. Manufacturers had even less success than operators, because the few commercial operations that did survive relied primarily on converted war-surplus equipment. From 1919 to 1924, American manufacturers produced less than one hundred airplanes annually for customers other than the American military (table 1).[2]

Commercial airplane production began to increase in 1925. The depletion of war surplus stocks encouraged this trend, but far more important was the contracting of the U.S. Air Mail to private carriers. Before 1925 the Post Office ran the Air Mail as a government operation using war surplus DH-4 observation planes. Under government operation, the Air Mail became the largest air transport enterprise in the world and the first to engage in regular night flying.[3] With the passage of the Kelly Act in February 1925, the Post Office began letting airmail contracts to private operators. The prospect of mail contracts brought a surge of private capital into air transport. At the same time, the Kelly Act created a market for new transport airplanes to replace the Post Office's obsolete DH-4s. By 1927 private carriers had taken over all of the federally operated airmail routes. Post Office payments to the private carriers exceeded Air Mail revenue by a considerable amount, thus providing American aviation with a camouflaged subsidy.[4]

Contracting the Air Mail also helped create a market for passenger travel by air. Prior to 1925, all of the pioneer airlines ended in financial failure. The Kelly Act helped create a structure of privately owned, regularly scheduled air transport that formed the backbone of an emerging passenger network. The contract mail carriers established the ground facilities needed to keep their planes in the air, and they gained experience with maintaining regular schedules. Mail loads rarely filled the planes to capacity, and many mail contractors began to carry a few passengers along with the mail. In addition, the Air Commerce Act of 1926 established federal regulation of interstate air commerce, which helped improve public confidence in air travel by licensing pilots and establishing safety standards for airplanes. Lindbergh's transatlantic flight in May 1927 further boosted enthusiasm for aviation. Airlines expanded passenger capacity at a rapid rate, adding larger airplanes designed for increased passenger comfort. Between 1928 and 1929, the number of passengers on U.S. airlines surged 335 percent, pushing the United States from third to first place in air travel worldwide. The number of passengers more than doubled again in 1930, to almost 375,000, which earned the airlines $7 million. Although passenger travel in 1930 still produced only half as much gross revenue as air mail payments, air travel had become an essential component of the emerging air transport system.[5]

Markets and Technical Choice

Superficially, commercial operation of airplanes appears to allow much less room for the influence of ideology on technical choice than does the peacetime military. The true test of military technology comes only during wartime, while commercial technology must prove itself on a daily (or at least quarterly) basis, judged by the objective criterion of profitability. Even if ideology might bias engineers in the commercial sector toward a particular technology, market competition would prevent its adoption if there were a more cost-effective alternative. Market mechanisms apparently insure the adoption of the most effective technology among the available alternatives. According to this logic, metal was clearly superior to wood by virtue of the success of the all-metal airliner. If metal had not been superior, manufacturers and airlines that switched to metal would have gone out of business due to competition from firms that retained wood construction.[6]

The argument that market mechanisms insure technical progress is one part of what David Noble has characterized as the dominant "Darwinian" view of technical change. According to Noble, this view posits three successive "filters" that supposedly insure the survival of only the fittest technologies. First is the "objective technical filter" based on scientific rationality, second the "pecuniary rationality of the hard-nosed businessman," and third the rationality of the competitive market. As I argued in chapter one, technical indeterminacy removes much of the selective power from the first filter. The rationality of individual firms also fails to insure selection of the fittest technologies, as discussed below. Noble dismisses the third filter, the competitive market, as a myth "too easily overwhelmed by the force of monopoly and the state." But even when competitive markets do exist, they fail to select the "best" technology, as some recent work in economic theory and history demonstrates.[7]

The idea that competitive markets insure technological progress rests implicitly on neoclassical economic theory, which has proved thoroughly unsuited to the task of explaining technical change. In essence, neoclassical theory treats changes in technological knowledge as a consequence of "exogenous variables," that is, factors external to economics. Within the existing range of technological knowledge, firms supposedly choose among a range of alternatives according to the relative prices of the inputs to the production process, which include labor, capital, and materials. However, new technologies do not, like Athena, erupt on the economic scene fully grown. As historians of technology have repeatedly demonstrated, the transformation of an invention from idea to practical product involves a long and expensive process of development and innovation. This development process occurs predominantly within profit-motivated business firms.

Only the most dubious assumption could consider the development process as economically exogenous.[8]

As soon as one attempts to account for technological development, however, one finds that it violates basic precepts of neoclassical theory. In general, neoclassical theory cannot adequately account for the learning processes that occur in the course of economic activity. Such learning processes are a central facet of technical change. Observers have frequently noted that, as more and more people adopt a new technology, it becomes better and cheaper. In other words, not only do improvements in a technology entice more people to adopt it, but the very act of adoption directly lowers the costs to subsequent users. Economists label this phenomenon "increasing returns to adoption."[9]

The phenomenon of increasing returns is a direct result of learning processes and other facets of technical change ignored by neoclassical theory, in particular technical interrelatedness, economies of scale, and "learning curve" effects. Interrelatedness means that an individual or firm will develop new devices that fit into the existing technological complex or system, even if the resulting complex is suboptimal, in an economic sense, with regard to alternative arrangements. For example, a high-efficiency light bulb that could only operate at 220 volts would be of little use connected to the standard American outlet of 110 volts. Technical interrelatedness also insures that manufacturers design their products to fit existing skills, as in the keyboard manufacturers who continue to produce the QWERTY keyboard despite numerous studies that demonstrate its inefficiency compared to alternative arrangements of the keys. Technical economies of scale are clearly evident in electric utilities, where a large customer base decreases the variation between daytime and nighttime load, thus improving the utilization of invested capital. Finally, new technologies benefit from the learning curve, an empirical phenomenon ubiquitous in manufacturing. The learning curve results from the simple fact that the longer one does something, the better one gets at it. In manufacturing, this process reduces the cost of production with each additional unit of output, even though the basic technology and capital invested remain constant. The classic example of learning curve was discovered in the production of airframes during the 1930s.[10]

A number of economists have produced relatively simple models of technical choice that incorporate the hypothesis of increasing returns. These models try to predict what happens to two new technologies competing in a particular market. Four interesting results emerge. The first result is that one technology will eventually eliminate or "lock-out" the other, despite the continued presence of users who initially prefer the unsuccessful technology.[11] Second, these models suggest that the successful technology is not necessarily the best in terms of long-run economic potential. Even though "every agent acts rationally, . . . an inferior technology can dominate the market."[12] Third, the path of technical change affects future choices. Initial advantages can be crucial, and small events can have a major, long-term impact.[13] Fourth, these models predict that expectations of success tend to be self-fulfilling, reducing the time required before a single technology locks out its rivals. According to economic historian Paul David, this type of analysis suggests that "a particular system could triumph over rivals merely because the purchasers . . . expected that it would do so."[14] Among manufacturers of commercial aircraft, the choice of materials was indeed shaped by such expectations of success.

Just as markets do not insure the success of the optimal technology, neither do the attempts of business firms to act rationally. Firms make investment decisions based on predictions about the potentialities inherent in a given technology, but these predictions are characterized by uncertainty rather than risk. Risk involves known probabilities, as in an honest game of blackjack, whereas uncertainty involves unknown probabilities. When dealing with risk, one can make rational economic calculations, but with uncertainty the scope for such rationality is limited. Uncertainty is inherent in development and innovation; one can never be certain that a desired novel result is technically feasible, and one can never be sure what markets will exist for a new technology. The development process can be viewed as a means for converting uncertainty into risk, but this process requires that investments be made before the risks are known. In other words, it can cost a firm more to obtain the information needed to act rationally than the firm would save by acting rationally. As a result, firms continue to live with uncertainty, allowing technical decisions to be guided by other forms of persuasion, in particular the technological enthusiasms of people with control over the development process.[15]

Air transport operators in the early 1920s faced great uncertainty with regard to the air transport market they were trying to create. The aeronautical community could not even agree on what qualities were desirable in a commercial airplane. At one point *Aviation* editorialized on the need for speed in commercial aircraft, since "the principal factor which marks the aircraft as superior to other means of travel is high speed." A few years later the same journal argued for low power loadings, which meant the ability to carry a large load with low horsepower, which could only be achieved at the expense of speed. Given this uncertainty, manufacturers remained reluctant to develop airplanes to meet the "as yet largely hypothetical requirements of air transport."[16]

Although uncertainty regarding operating costs waned as transport operators gained experience, the air transport market remained mysterious through the end of the decade. As late as 1930, the technical committee of the United Aircraft and Transport Corporation (UATC) reported that "the relative ability of various sizes and types of airplanes to produce income is still not well established." The UATC was the largest and most integrated of the aviation conglomerates of the late 1920s and included some of the most important transport operations and manufacturers of the time. The technical committee consisted of top managers in the UATC's subsidiaries, who collectively possessed as much experience as any group of aviation experts. Despite this experience, the committee still found it impossible to predict the most profitable trend in airplane design.[17]

Operators of the pioneering airlines of the early 1920s recognized the uncertainty of cost predictions. One of these operators was Earl D. Osborn, a former employee of Aeromarine Airways, which prospered briefly in the early twenties by ferrying drink-deprived Americans from Miami to Nassau and from Key West to Havana. In 1923 Osborn summarized his experiences with measuring airline operating costs:

> The most perfect system of cost accounting . . . will give misleading results if the industry to which it is applied is unstable. Nobody has yet claimed that air transportation has gone beyond that stage. . . . The system chosen for a given industry and its application must be the result of long experience.

Osborn found depreciation estimates particularly difficult. Depreciation formed a large percentage of total costs and had to be calculated, yet there was "really no empirical rule in this matter." Operators had not gained enough experience to determine how much use an airplane could endure. An airplane appeared more likely to become useless through technological obsolescence than from deterioration.[18]

The economic uncertainties inherent in new technologies leave gaping holes in the supposedly rational process of technical change, holes through which culture and ideology cannot help but enter. These uncertainties clearly existed in commercial airplane design, and the resultant holes in technical rationality readily accommodated the progress ideology of metal.

William Stout, Henry Ford, and the Maximalist Strategy

Within the commercial aviation community, advocates of metal fell into two groups, each supporting a different strategy for reaching their common goal. The first group, the maximalists, included those engineers and designers inspired by the Junkers JL-6. They sought the immediate development of airplanes of the *neue Stil*, all-metal fully cantilevered monoplanes. The most successful member of this group was William Stout, who built the first American commercial airplane of the *neue Stil* and then convinced Henry Ford to manufacture airplanes based on this design. But aside from Stout and Ford, the maximalists had very few adherents until the late 1920s. Almost the entire remainder of the aviation community fell into the second group, the gradualists. This group favored the piecemeal substitution of metal frameworks for wood, starting with the fuselage. Anthony Fokker's steel-tube fuselage exemplifies the gradualist strategy, despite Fokker's continued use of wood wings, because Fokker too professed belief in the eventual transition to metal.[19]

William Stout was the leading American advocate of the maximalist strategy. In mid-1922, when the navy canceled Stout's contract for the all-metal torpedo bomber, Stout turned his attention to the development of an all-metal passenger airplane. By then, Stout was an experienced airplane designer—experienced in failure. He had produced three prototype airplanes, two in wood and a third in metal, but none had acceptable flying qualities. Despite Stout's repeated failures, he continued to succeed in business, adeptly exploiting the symbolism of metal to persuade investors to finance his next prototype.[20]

On November 6, 1922, Stout formed the Stout Metal Airplane Company to develop his ideas for an all-metal commercial airplane. Stout located the new company in Detroit, which proved strategic, for he was able to tap the industrial wealth emerging from the automobile industry. Stout funded his new company by obtaining $1,000 investments from a large number of individual stockholders, as well as a substantial infusion of cash from R. A. Stranahan, president of the Champion Spark Plug Company, who had funded some of Stout's earlier projects. In his mimeographed prospectus, Stout wryly guaranteed potential investors that they would never see their money again, given the dim commercial prospects of his venture. Stout succeeded in attracting many automobile industrialists, among them Walter P. Chrysler, R. E. Olds, Harvey Firestone, Paul W. Litchfield, Charles F. Kettering, William S. Knudsen, Albert Champion, and others. Eventually, Stout obtained 138 stockholders, mostly prominent industrialists and bankers.[21]

These 138 men did not invest in Stout's company primarily for financial gain. Rather, the symbolic power of Stout's rhetoric proved as persuasive as the prospect of speculative returns. In Stout's rhetoric, metal provided an essential link between the airplane and mass production, due to the widely held belief that wood was unsuited to quantity production. Stout artfully constructed analogies between the airplane and the automobile, arguing that mass production would bring the same benefits to the aviation industry that it had to automobile manufacturers.[22] Stout's arguments struck a responsive chord among Detroit industrialists, including their most prominent member, the father of mass production himself—Henry Ford.

Ford's involvement with aviation went back to World War I. In the summer of 1917, he proposed using his facilities to build 150,000 airplanes using mass production methods. Airplanes, claimed Ford, could be built in the thousands, just like automobiles. Ford had little government support and soon dropped this project. Instead, he helped to produce aircraft engines for the American war effort. Ford's direct involvement in aviation ended with the Armistice, but he continued to follow aeronautical developments. In part Henry was spurred on by his son Edsel, who had a keen interest in aviation.[23]

Stout's route to the Fords was through William B. Mayo, a top Ford Motor Company engineer nominally in charge of aviation activities. Mayo was one of the original subscribers in Stout's metal airplane company, and it did not take Stout long to begin exploiting this connection to the richest industrialist in America. With funds from his first thirty investors, Stout had built a small four-seat metal airplane, the Air (or Aerial) Sedan. With the first flight of the Air Sedan in February 1923, Stout immediately began soliciting additional investments. In March he wrote Mayo to seek help from the Fords. Mayo forwarded Stout's letter to Edsel, recommending that he and his father make a small investment in Stout's company. In December Edsel invested $2,000 in Stout's company. He also became a director.[24]

Stout's Air Sedan differed significantly in structural design from his unsuccessful torpedo bomber. Much like Junkers before him, Stout abandoned the smooth metal covering in favor of corrugated duralumin. Stout found it easy to imitate Junkers, in part because of the opportunity he and his chief engineer George Prudden received in January 1921 to examine a JL-6 at the Anacostia Naval Station, while Stout was still working on his navy contract. Except for the corrugated covering, the Air Sedan resembled Stout's earlier Batwing designs with its bulging fuselage and long wing chord (figure 5.1). With its ninety-horsepower engine, the Air Sedan proved overweight and underpowered. Substitution of a 150-horsepower engine improved its performance. Still, the Air Sedan was too expensive for private flyers yet too small for profitable commercial use. In addition, there are no independent reports of the airplane's flight characteristics; given the previous performance of Stout's designs, its flying qualities probably left much to be desired.[25]

In mid-1923, Stout recognized the need for a larger airplane. He decided to build an eight-passenger model around the four-hundred-horsepower Liberty motor, a reliable and inexpensive war-surplus engine. George Prudden later claimed credit as the principal designer of this airplane, a claim supported by the recollections of other engineers who had worked with Stout. Stout named this new model the "Air Pullman," and punningly dubbed it the *Maiden Detroit*. The *Maiden Detroit* took its first flight in April 1924. With this airplane Stout (or more likely Prudden) abandoned the long-chord Batwing design and instead adopted a high-wing layout reminiscent of the Fokker transports, which had a reputation for excellent flying qualities. The Air Pullman continued to use the corrugated covering, making it look like a cross between the Junkers and Fokker designs (figure 5.2). The wing consisted of three dural spars, cross-braced and covered with

Figure 5.1. Stout Air Sedan. William Stout stands at far left, beside his first all-metal passenger airplane. National Air and Space Museum, Smithsonian Institution (SI neg. no. 80-4504).

Figure 5.2. Stout Air Pullman. William Stout's first successful airplane served in the U.S. Air Mail. National Air and Space Museum, Smithsonian Institution (SI neg. no. 96-15639).

0.014-inch corrugated dural sheet. A boxy metal framework formed the fuselage, which was also covered in corrugated dural.[26]

In 1924 there was still little private demand, so Stout tried to sell his new model to the military and the Air Mail. Both the army and the Post Office were favorably impressed. In May Stout invited representatives from the Air Service's Engineering Division to Detroit to inspect the Air Pullman. Stout claimed publicly that he had made no attempt to follow military design, but he told the inspectors from the Engineering Division that he had followed the structural requirements of the Air Service Handbook. The inspectors pronounced the Air Pullman's flying qualities "far superior to the Junker [*sic*] JL-6." The Engineering Division invited Stout to bring his plane to McCook Field for tests. Meanwhile the Post Office also took an interest in the Air Pullman. In April, Paul Henderson, chief of the Air Mail, commented favorably on Stout's new airplane, which was then purchased by the Post Office.[27]

The Air Pullman was received with considerable enthusiasm by the aviation community, but a closer examination of the data shows that its performance was not remarkable. Comparisons are difficult for commercial airplanes built before the Civil Aeronautics Act of 1926, which legislated federal regulation of airplane safety. These regulations established procedures for determining gross weight, which was the maximum weight at which the airplane could safely take off, fly, and land. Given a long enough runway and a good head wind, a heavily overloaded airplane could get airborne and fly safely, as long as the pilot avoided any abrupt maneuvers. The permissible gross weights of military aircraft were limited by the army and navy design handbooks, but commercial airplanes faced no such restrictions before 1927. In addition, other performance characteristics, such as maximum speed, depended significantly on test conditions. A lightly loaded plane could fly faster than one with a full load, and top speed also varied with altitude. Even seemingly simple data like weight empty could vary significantly. Many passenger airplanes were convertible to freight transports, and the absence of passenger accommodations produced a considerable savings in weight. To be comparable, weight empty figures had to refer to similarly outfitted aircraft.[28]

With these caveats in mind, one can compare the performance of the Air Pullman with other transport planes of the time. During a one-month period shortly after the first flight of the Air Pullman, Stout provided three different sets of figures for the weight of the airplane. Alfred Verville, a civilian engineer at McCook Field, drew up a table comparing the performance of the Air Pullman with three existing army transports, using the earliest (and most favorable) figures provided by Stout (table 2). All four airplanes used the same Liberty engine, leaving variations in performance to differences in the airframes. Even with the more favorable figures, the Stout transport

TABLE 2
Comparative Performance of Four Liberty-engine Transport Planes, 1924

	Fokker	*L.W.F.*	*Stout (original)*	*Stout (revised)*	*Douglas WC*
Gross weight (lbs.)	7,993	7,016	6,000	5,708	9,162
Weight empty (lbs.)	5,030	4,317	3,575	3,638	4,433
Useful load (lbs.)	2,963	2,699	2,425	2,070	4,729
Load efficiency factor[a]	37	38	40	36	52
Wing area (sq. ft.)	958	759	600	600	565
Top speed (mph)	100.8	94.63	116	110	103.68
Landing speed (mph)	68	52	62		60
Climb at sea level (ft./min.)	400	315	700		450

Sources: Except for the "Stout (revised)" column, these figures are from a blueprint accompanying A. V. Verville to C. W. Pyle, "Stout All-metal Transport," 29 Apr. 1924, USAF/SCC, RD3135, 452.1-Stout Metal Air Transport/1924. I have used penciled changes where present on the original document. Except for top speed, the "revised" column is from L. W. McIntosh to C/AS, "Stout All-Metal Transport," 20 May 1924, AAF/E166, box 985, 452.1-All Metal Planes. The top speed of 110 mph is from John T. Nevill, "Ford Motor Company and American Aeronautic Development," *Aviation* 27 (1929): 44.

[a] Load efficiency factor equals useful load expressed as a percent of gross weight (UL/GW × 100).

did not stand out, appearing somewhat superior in top speed but inferior in load carrying ability. The later, more realistic figures did even less to recommend the Air Pullman. In terms of structural efficiency, measured as the ratio of useful load to gross weight, the Air Pullman finished last at 36 percent, slightly below the Fokker and far below the Douglas World Cruiser biplane, with its impressive 52 percent efficiency. The Air Pullman also had the smallest useful load, meaning that it could carry less fuel and cargo than the other airplanes. The Fokker's useful load exceeded the Air Pullman's by 43 percent. To its credit, the Air Pullman was the fastest of the group by 6 mph, which probably was due to its lower gross weight. For a given engine, top speed varies inversely with weight. Compared with the other airplanes, the Air Pullman sacrificed load for speed, which was not an unreasonable design choice. More significantly, the Air Pullman demonstrated that there was no mystery to the German all-metal airplanes; American engineers could also produce airplanes comparable to the JL-6.[29]

After the McCook Field engineers inspected the Air Pullman in May, the army began negotiations with Stout over a possible order. Despite the favorable initial report, doubts remained. The Engineering Division expressed concern about the airplane's structure, which was designed using assumptions "of doubtful accuracy." The Division insisted that the Air Pullman undergo extensive structural testing before being accepted by the Air Service. The recollections of John G. Lee demonstrate the wisdom of this cautious approach. Lee was an MIT-trained aeronautical engineer hired by Stout in 1925 to redesign the wings of the Air Pullman. Decades later, Lee recalled the structural design of the Air Pullman as "perfectly awful," violating all he had learned at MIT and the Curtiss Aeroplane Company. "The truth was, nobody knew where the loads went, or what they were, or how strong the structure was." Stout apparently realized that the airplane would probably not pass muster at McCook Field, and in June wrote the chief of the Engineering Division, rejecting the division's conditions. The army, said Stout, could take it or leave it: "Until this plane is developed to a point it is worth buying on regular purchase orders, on the same basis as trucks, motor cars, or soap, then we are not interested in selling it" to the military.[30]

The Engineering Division's doubts remained private. Meanwhile, the favorable public reception of the Air Pullman gave Henry Ford the confidence he needed to become significantly involved with aviation. During the construction of the Air Pullman, William Mayo had kept tabs on Stout's operations through visits to the Stout plant. Early in the summer of 1924, Henry Ford invited Stout to Dearborn to help him pick a site for an airport to be built on nearby Ford company property. Construction began immediately, and soon thereafter Ford offered to build a factory for Stout next to the new airport. Ford's involvement with Stout was formally announced in the *Ford News* on July 15. Ford explained that he was aiding aviation with a view toward the mass production of aircraft, so that planes could be built "by the thousands or by the millions."[31]

The Stout Metal Airplane Company moved into the new factory in January 1925, and began building a second Air Pullman, dubbed the *Maiden Dearborn*. Ford's support was essential for keeping Stout's company afloat, since Stout had received no additional orders for the Air Pullman after the sale of the prototype to the Post Office. Ford purchased the *Maiden Dearborn* in April and started a scheduled air transport service between Detroit and Chicago for company business, primarily freight. Ford's entry into the air transport business generated great publicity in the popular press. In the mid-1920s the Ford phenomenon was at its zenith; the Ford Motor Company was still producing Model Ts by the million, making "Fordism" synonymous with mass production. Ford had yet to stumble, as he would in the late 1920s, when the company switched to the Model A. Meanwhile, Ford remained Stout's only customer, ordering four more Air Pullmans for the company airline.[32]

Soon after starting the company airline, Henry Ford moved to become directly involved in airplane production. He offered to buy Stout's company at twice the original price, provided that Ford could obtain all of the stock. By mid-1925, Stout had obtained $185,000 from individual investors and $150,000 in cash from Stranahan. These sums were huge by the standards of the time; even the military could not afford $300,000 to develop a new airplane. Under an agreement negotiated by Mayo in July, Ford also paid Stout more than $500,000 for his interest in the company. On July 31, 1925, the Stout Metal Airplane Company became a division of the Ford Motor Company. Ford retained most of Stout's staff, but in practice Mayo ran the company, and Henry Ford retained ultimate control. Stout remained on as a vice-president with an annual salary of $20,000.[33]

The public viewed Ford as a shrewd businessman as well as a brilliant engineer. Despite this reputation, Ford's entry into airplane manufacturing owed more to a hubristic belief in the universality of his mass production methods than to actual knowledge of the requirements of air transport. Ford too believed in the unsuitability of wood for mass production, so his commitment to mass production led directly to his enthusiasm for metal airplanes. In the spring of 1925, just before Ford bought Stout's company, Henry and Edsel held discussions with Clement M. Keys, owner of the Curtiss Aeroplane and Motor Company. Keys was organizing an air transport company to fly between New York and Chicago, and he sought the Fords' participation in the venture. According to Keys, the Fords were "all 'hipped' on metal ships," although they admitted their lack of knowledge and appeared willing to take advice. The Fords declined to participate in Keys' new venture but continued to discuss possible cooperation with Curtiss. Months later, after Ford had completed the purchase of Stout's company, Keys still found Ford quite naive about aviation, proceeding "in about the same frame of mind that Curtiss was in when he built his first motor or first airplane." Subsequent events would demonstrate the validity of Keys's assessment.[34]

With the sale of Stout's company complete, Mayo directed Stout to begin work on a three-engine version of the Air Pullman. Trimotors, as such planes were called, became popular for passenger aircraft after 1925 due to their ability to keep flying if one engine failed. Both Junkers and Fokker developed trimotor versions of their monoplane transports in the first half of 1925. Mayo became convinced of the need to produce a trimotor Air Pullman after a July meeting with Post Office officials, who were worried about the safety of single-engine airplanes for the Air Mail's night-flying operations. Stout immediately set to work designing the new trimotor. Unfortunately, Stout was soon deprived of his most skilled engineer, George Prudden, who was fired in early September for talking to the press at the crash site of the *Shenandoah*, where he had been sent to prepare a first-hand report for Henry Ford. Without Prudden's help, Stout designed a monstrosity. Two air-cooled engines were bolted directly to the front wing spar, with a section of the leading edge removed from each wing to make space (figure 5.3). The engines created turbulent flow across the wings, destroying lift for the portion of the wing behind the engines.[35]

When the new airplane first flew in November 1925, its performance proved abominable. The test pilots were furious at Stout. The airplane

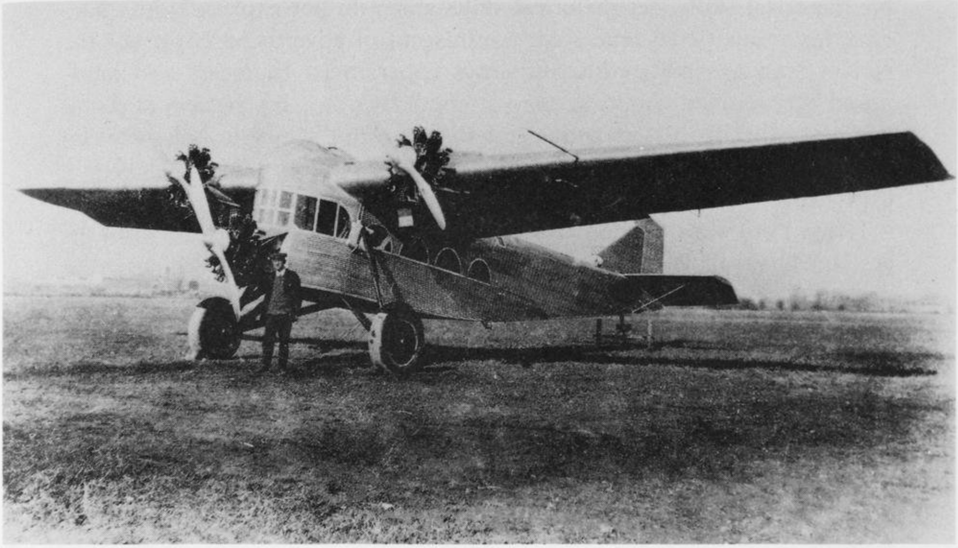

Figure 5.3. William Stout's disastrous first trimotor, 1925. National Air and Space Museum, Smithsonian Institution (SI neg. no. A-42247).

landed at a dangerously high speed and proved extremely difficult to control. An enraged Henry Ford relieved Stout of design duties and placed Harold Hicks in charge of airplane design. According to Hicks, Ford instructed him "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 about it." Ford also told Hicks that Stout would continue to receive credit for all the design work performed by Hicks and his staff.[36]

The failure of Stout's trimotor ended his influence on the technical development of American aviation. However, the fact that he had any influence at all dramatically illustrates the role of the progress ideology of metal in aviation history. Ample evidence attests to Stout's incompetence as an airplane designer. Other prominent designers have had their technical ability questioned, for example Glenn Martin and Anthony Fokker, but at least these men knew how to employ competent subordinates and could distinguish between sound ideas and poppycock. These men also had many successful airplanes to their credit, unlike Stout, who could claim at most one success out of the six major airplane projects he had supervised. Despite his repeated failures, Stout coaxed investments and contracts worth hundreds of thousands of dollars from the army, the navy, and Detroit businessmen. If one includes Ford's payment to Stout for the metal airplane company, Stout received more than $1 million for his metal airplane work. Stout's "success" was not based on technical accomplishments but rather on his rhetorical skills. Yet rhetorical skills alone do not explain Stout's success; his promotional letters are reminiscent of advertising copy, not the sort of language that ordinarily sways experienced engineers and hard-nosed businessmen. Stout's greatest strength lay not in his mastery of rhetoric, but rather in his recognition of the powerful symbolic link between metal airplanes and aviation progress, a link he reinforced and shamelessly exploited.[37]

Henry Ford was not going to let Stout's incompetence drive him from the airplane business. Hicks assembled a talented group of young airplane engineers and set them to work completely redesigning a new trimotor with no interference from Stout. In January a fire destroyed Stout's prototype trimotor along with the entire Stout factory building, giving Ford a clean slate for the new trimotor. Many insiders were convinced that someone close to Henry Ford set the fire to erase all evidence of Stout's bungling. Ford soon had the factory rebuilt, and the new trimotor, named the 4-AT, had its first flight on June 11, 1926. The 4-AT followed the same general layout as the Air Pullman, retaining the corrugated duralumin covering and dural framework, and provided room for eight passengers and a crew of two (figure 5.4). The 4-AT proved quite successful as a passenger and mail transport and was bought by numerous airlines. Ford sold a total of seventy-eight 4-ATs, making it the first commercial metal airplane produced in quantity in the United States. In 1928 Ford's aircraft division enlarged the 4-AT and installed more powerful engines. This new model was designated the 5-AT, of which 116 were produced through 1932. The Ford trimotors were among the most common large transports of the late 1920s and early 1930s.[38]

The success of the 4-AT and 5-AT seemed to vindicate Henry Ford's faith in metal airplanes. Yet the Ford Motor Company's venture into airplane production did not last. Ford's airplane activities peaked in 1929, when the company sold a record eighty-six trimotors. Production reached a pace of four planes per week over the summer of 1929, and the workforce totaled 1,850 men. At the same time, Ford launched a major expansion in factory space, with a planned production capacity of one plane per day. Even before the October stock market crash, however, aviation journalist John T. Nevill noted the limited growth potential in the market for large transport planes, which were more analogous to railroad coaches or buses than to automobiles. Under normal circumstances, Ford would have had trouble keeping his expanded factory busy producing trimotors. But with the onset of the Depression, sales plummeted to only twenty-six planes in 1930 and twenty-one in 1931. Meanwhile, Junkers had initiated patent litigation against the Ford trimotors, which limited Ford's access to foreign markets. By 1932 Henry Ford faced rapidly mounting losses, weak domestic demand, restrictions on exports, and few prospects for military sales. In addition, his automobile business was losing tens of millions of dollars, and development of

Figure 5.4. Ford 4-AT. This successful trimotor has been wrongly attributed to William Stout. National Air and Space Museum, Smithsonian Institution (SI neg. no. A-46899H).

the new V-8 auto engine demanded his undivided attention. Ford had no time for the aircraft division, which sold only three trimotors in 1932. That July, Henry Ford laid off all but a skeleton staff at the aircraft division. He ceased all operations the following year.[39]

Ford's involvement in airplane manufacturing was never profitable, even when sales reached their peak. Despite the Ford company's vast skill in production engineering, metal airplanes did not prove cheaper to build than composite wood-and-metal types. The Ford trimotors competed directly with the Fokkers, which had plywood-covered wood wings and fabric-covered, welded steel-tube fuselages. The Ford 5-AT and the Fokker F-10A used the same Pratt & Whitney engines and had almost identical weights, performance figures, and sale prices, and they sold in similar quantities. In 1927 Fokker claimed that the Ford company provided a subsidy of $40,000 to $50,000 per plane due to the high costs of all-metal construction. Fokker had good reasons to exaggerate, but his estimate was not too far off the mark. Ford's accounting practices make it almost impossible to disaggregate costs, but total losses from Ford's aviation activities were staggering. Between 1925 and 1931, Ford sold just over $11.1 million in airplanes and airplane parts; losses amounted to more than $5.6 million, not including depreciation and an unsalable inventory of $1.27 million. If one excludes operations of the Ford company airline, and includes depreciation and unsold inventory, total losses on airplane production amounted to at least $5 million, or roughly $25,000 for each airplane. Even in robust years, sales of the Ford trimotors barely covered productions costs; only the year 1929 showed a profit on manufacturing operations alone, due largely to Ford's practice of excluding unsold inventory from operating costs.[40]

The financial problems of Ford's aircraft division were due in part to its lack of involvement in the military market. The Depression provided the immediate impetus for Ford's decision to abandon the aircraft business. However, a number of manufacturers with lesser financial resources survived the Depression, most notably Douglas, Curtiss-Wright, and Boeing (as part of United Aircraft and Transport). All of these firms had substantial military contracts. Ford initially had no interest in producing military aircraft, although the company did sell twenty-two trimotors to the army and navy. In 1931, after the collapse of the commercial airplane market, Ford entered a converted trimotor in an army bomber competition, but the airplane's performance was far inferior to the twin-engine Boeing B-9 prototype. The modifications to the trimotor interfered with its aerodynamics, resulting in "semi-dangerous" flying qualities. In addition, the army's trial board found placement of the armament unacceptable. With no experience in designing combat aircraft, Ford engineers proved unable to produce a remotely acceptable military airplane. Despite entreaties from Mayo, neither the army nor navy was willing to spend money to keep Ford in the airplane business.[41]

Both the popular and technical press had heralded Ford's entry into aviation as the start of a new era, but in practice Ford had little direct impact on the technical course of airplane design. Despite frequent refinements in the design of the trimotors, Ford did little to change the structural practices first used by Stout on the 1923 Air Pullman, in particular the use of corrugated coverings. Corrugation was the easiest way to give compressive strength to thin sheet metal. In the late 1920s, however, American designers of metal airplanes began to abandon corrugated coverings in favor of stiffened flat sheet (see chapter seven). Corrugated skins created manufacturing problems, being more difficult to shape and attach to the structure than smooth skins. In addition, corrugated wing coverings were not suited to the faster airplanes of the early 1930s. To prevent excessive wing drag, the corrugations had to run in the direction of flight, but even so, the corrugated skin significantly increased drag. The corrugations also prevented the skin from contributing much strength to the structure. Corrugated sheet has little strength perpendicular to the corrugations, tending to fold up or expand like an accordion. A corrugated wing covering could not resist the primary bending forces on the wing. Flat sheet, in contrast, could be stiffened internally to resist these bending stresses.[42]

In retrospect, the Ford Motor Company's involvement in commercial aviation was clearly a failure. The company lost millions while contributing little technically to the all-metal stressed-skin construction that came to dominate passenger airplanes after 1933. Henry Ford viewed the problem primarily in terms of production, but even here his engineering expertise and vast financial resources proved unable to bring the construction costs of metal airframes down to the level of composite types. Ford built nearly two hundred trimotors, but even this push down the learning curve failed to make metal airplanes a profitable business. Ford's failure resulted directly from the progress ideology of metal, which blinded him to the difficult problems involved in the efficient production of metal aircraft structures.[43]

Despite his eventual failure, Henry Ford's involvement in airplane production did much to advance the cause of metal, especially in commercial airplanes. The Ford company advertised its airplanes heavily, stressing the advantages of all-metal construction. THIS IS THE DAY OF METAL, proclaimed the headline of a 1928 Ford advertisement, which insisted with standard prometal rhetoric that "all the experience of the past points to the necessity of metal construction in vehicles for transportation." These advertisements even repeated the oft-falsified claim that metal construction was fireproof. The Ford advertisements argued that metal created the impression of safety needed to attract paying customers, an important consideration in the early days of air travel. Even at the time, observers recognized the significance of Ford's prometal advertising. The authors of a 1930 investment analysis, for example, refrained from endorsing either wood or metal construction. Nevertheless, they noted that "the Ford advertising has created considerable popular preference for metal airplanes. The factor to decide this question may be advertising." Although Ford's advertising did not decide the question, it did popularize the progress ideology of metal, cementing the association between metal and progress and easing the way for other firms to develop commercial metal airplanes.[44]

And metal airplanes did indeed benefit from the association between metal and progress. While Henry Ford, the army and the navy were putting millions into metal airplanes, a few manufacturers continued to develop innovative wooden airplanes. But these innovators received very little help from the federal research establishment, in sharp contrast to the tremendous support received by developers of metal airplanes.

6

Neglected Alternative I: Plywood Stressed-skin Construction

No ideology ever dominates completely. Regardless of the social glue that holds particular communities together, individuals can always make room for alternative visions and strategies that conflict with dominant ideologies. Such alternative strategies did exist within the American aviation community of the 1920s. Despite the strength of the progress ideology of metal, a number of firms worked to improve wood airplane structures, and one federal agency received funding for serious research related to wooden airplanes. These efforts produced, among other things, the Lockheed Vega, the fastest single-engine commercial airplane of the late 1920s.

The "airframe revolution" of the early 1930s contained three main elements: all-metal construction, the fully cantilevered monoplane, and stressed-skin structures. Both contemporary observers and historians have viewed these elements as related. In the early 1920s, the idea of the *neue Stil* firmly linked metal with the unbraced monoplane, while later in the decade designers and researchers conceptualized stressed-skin structures almost entirely in terms of metal. In the early 1930s, the military and commercial airlines adopted stressed-skin structures and all-metal construction at the same time.

There was, however, no inextricable link between metal and stressed-skin structures. Stressed-skin structures were particularly susceptible to buckling failures (chapter three). This susceptibility provided a strong argument in favor of plywood, which possessed superior buckling strength compared to aluminum or steel. The advantage of plywood was not merely theoretical. A number of manufacturers in the 1920s developed successful wooden airplanes with stressed plywood coverings, demonstrating the viability of plywood structures as an alternative to metal stressed-skin airplanes. These manufacturers also benefited significantly from federal research, although at a level far below that devoted to metal construction. Belief in the inevitability of metal construction led the aviation community to neglect wood research, even in problems widely recognized as critical, limiting the ability of plywood to compete with the new metal structures. Despite the promise shown by plywood stressed-skin airplanes and the clear utility of wood research for airplane designers, the progress ideology of metal undermined further developments along this alternative path.

Early Stressed-skin Plywood Structures

Plywood was the key to using wood in stressed-skin structures. Plywood consists of several layers of wood veneer, arranged with the grain of adjacent layers at right angles and held together with glue. Although woodworkers have used veneer for centuries, plywood is an industrial product, dependent on the machinery used to cut large thin layers of wood from logs. Plywood offers several advantages over standard forms of lumber. By crossing the grains of the veneers, plywood compensates for the highly directional properties of wood, giving the sheet strength in two directions instead of just one. This property permits the use of plywood in thicknesses that would be impossibly fragile with single veneers. Plywood also reduces the variability of wood by allowing adjacent layers to compensate for small defects and variations. The thin veneers are also easier to inspect for defects than solid lumber. In addition, plywood can be more easily formed into curved shapes than solid wood.[1]

One of the earliest uses of plywood in airplane structures was for monocoque fuselages. The monocoque fuselage initially attracted the interest of airplane designers who sought a well-streamlined body with unobstructed interior spaces. The first technically successful application of plywood monocoque construction was in the Deperdussin racing plane of 1912. Fuselages of the Deperdussin type were built in three layers, with each layer consisting of strips of tulip-wood veneer wound spirally around a temporary frame. The workers first tacked a layer of veneer in place, and then glued a layer of linen over the veneer. The linen was followed by a second layer of veneer wound in the opposite direction, so that the grain of the two layers of veneer crossed at right angles. Another layer of fabric was added, followed by the third layer of veneer wound opposite to the second layer. When the glue had dried sufficiently, the framework was collapsed and removed from the shell.[2]

The monocoque Deperdussin won the prestigious Gordon Bennett race in 1912, and a number of designers in France and elsewhere imitated its construction. Manufacture of the Deperdussin-type fuselage was difficult, however, and involved much skilled hand labor. Furthermore, drying time for the glue lengthened the production process. Each fuselage shell required about seven days before it could be removed from the temporary frame.[3] These disadvantages in production outweighed the advantages in streamlining. Until the adoption of the steel-tube fuselage in the early 1920s, most manufacturers continued to build wooden framework fuselages covered with fabric or plywood.

When the United States entered World War I, army engineers at McCook Field decided to take another look at the monocoque fuselage. These engineers recognized that the difficult manufacturing process of the Deperdussin fuselage was not an inherent characteristic of wood monocoque structures, and they launched a study to simplify the production of wood monocoques. This study focused on semimonocoque structures, which in general weighed less than "true" monocoques. Semimonocoques used bulkheads and longerons (or stringers) to reinforce the inside of the wood shell, while the true monocoque derived all of its strength from the shell itself. The army brought in two plywood manufacturers and a furniture maker to design and build experimental semimonocoque fuselages. These firms investigated a number of methods to speed the production process. All of the methods involved molding flat sheets of plywood to the required shape, in contrast to the Deperdussin process, which relied on the pliability of individual veneer strips.[4]

Two of the firms developed similar methods for molding large sheets of plywood. One firm was the Haskelite Manufacturing Company, a plywood manufacturer located in Grand Rapids, Michigan. In the Haskelite process, a plywood sheet was first boiled for several hours to make it pliable. Metal clamps then gripped the edges of the sheet, holding it above a cast-iron die. A hydraulic press forced the die into the plywood sheet, producing the desired shape. Steam pipes heated the mold to speed drying. When dry, the curved plywood was glued and nailed to the longerons and bulkheads. Using the Haskelite process, the entire covering of the twenty-five-foot fuselage comprised only five pieces.[5]

Neither of the large-panel methods proved successful before the Armistice. The McCook Field engineers found that the best results were obtained when the face grain (the grain of the outer layers of veneer) ran parallel to the longitudinal axis of the fuselage. However, the Haskelite molding process only worked on plywood with the face grain running circumferentially. A third process, involving smaller panels formed directly onto the framework, permitted the use of plywood with longitudinal face grain. This method demonstrated its practicality, but the Armistice ended the project before production could begin.[6]

At the end of the study, the McCook Field engineers were quite optimistic about the potential of the wood monocoque. They concluded that wood monocoques could be built lighter than framework types, and that they were "an excellent production proposition." Designers could easily obtain a well-streamlined shape with a monocoque fuselage. In addition, plywood veneers could be cut from timber rejected as unfit for standard aircraft construction, thus easing concerns over wood shortages. Monocoque structures also needed less maintenance, since they did not require the frequent adjustments necessary to maintain the alignment of wire-braced wood frameworks. These opinions led Lt. Col. Jesse G. Vincent, wartime head of McCook Field, to endorse further development of the plywood monocoque over the metal fuselage.[7]

Development of the wood monocoque fuselage continued after the war, building on the work at McCook Field. Not long after the Armistice, Alfred Verville, a civilian engineer at McCook, designed a racing monoplane based around a monocoque fuselage of the Deperdussin type. Verville simplified the Deperdussin process by building the fuselage in two half shells. The army entered the Verville racer, designated the VCP, in the 1920 Pulitzer Air Race, the most important aerial competition in the United States. The VCP won the race with an average speed of 178 mph. Not to be outdone, the navy decided to compete in the 1921 Pulitzer race, and it turned to the Curtiss Aeroplane and Motor Company. Following Verville's example, the Curtiss company designed the first of a series of biplane racers with plywood monocoque fuselages. Army and navy variants of the Curtiss racers dominated American racing through 1925.[8]

After the Armistice, Curtiss and other manufacturers also designed plywood monocoques for new commercial models. Unfortunately, manufacturers could sell few new airplanes of any type in the early postwar years due to the glut of war-surplus airplanes. In 1919 Curtiss developed two commercial airplanes for the anticipated postwar market, the Oriole and the Eagle. Both models had plywood monocoque fuselages. The Oriole was a three-seat, open-cockpit biplane, while the Eagle carried six to eight passengers in a comfortable enclosed cabin. Little is known about Curtiss production methods for its monocoque fuselage, but Curtiss engineers obviously believed that their methods would allow them to meet the expected robust demand. The production potential of the Curtiss fuselage was never tested, however. Curtiss built only a few Eagles, while sales of the Oriole amounted to a few dozen at most.[9]

More interesting from a production standpoint was the Loughead S-1 of 1919. Brothers Malcolm and Allen Loughead had established the Loughead Aircraft Manufacturing Company in 1916. The S-1 was a single-place sport biplane, designed to serve the demand expected from thousands of demobilized army pilots for a small, low-cost airplane. Anthony Stadlman, Loughead's head of production, worked out a plywood molding method for the S-1 superior to those developed for McCook Field during the war. Malcolm Loughead applied for a patent on this process in 1919.[10] The S-1 fuselage skin was formed in halves in a concrete mold cast in the precise shape of the fuselage. Workers placed three layers of spruce veneer strips in the mold, each layer well coated with glue. A layer of cloth separated each veneer layer, as in the Deperdussin fuselage. All the layers were assembled at one time. A cover was then clamped over the mold, and a rubber bag inside the cover was inflated, placing uniform pressure on the shell. This pressure was maintained until the glue set. Workers then glued the completed half-shell to the bulkheads and stringers.[11]

The Loughead brothers spent almost $30,000 on the S-1 prototype, but they failed to sell a single airplane due to the postwar collapse of the airplane market. In 1921 the company suspended operations, and the Lougheads temporarily abandoned the airplane business.[12] Nevertheless, the S-1 fuselage bore fruit a few years later in the Vega of 1927.

In December 1926, Allen Loughead established a new company to produce a single-engine passenger monoplane based around a monocoque fuselage similar to the one developed for the S-1. Allen Loughead named the new firm the Lockheed Aircraft Company, using the phonetic spelling of the family name. Aircraft designer John Northrop, who had previously worked on the S-1, was the chief engineer for the Vega, as the new airplane was called. Northrop laid out a closed-cabin, fully cantilevered monoplane. The Vega's careful streamlining was more reminiscent of a racing plane than of the commercial airliners of the day, a resemblance that Lockheed emphasized in its descriptions of the Vega. The Vega was powered by the reliable Wright Whirlwind, the same engine that took Charles Lindbergh across the Atlantic. The Vega carried from four to six passengers at a cruising speed of 110 mph, with a top speed of 135 mph. It flew faster than competing airplanes of similar size and power, such as the Fokker Universal, which had a top speed of 118 mph, or the Stinson SM-1, with a top speed of 125 mph.[13]

The speed and load-carrying efficiency of the Vega made it well suited for record-breaking flights. The first Vega disappeared during a race from Oakland to Hawaii in August 1927, while in April 1928 explorer George W. Wilkins took the third Vega on a 2,200-mile exploration flight across the Arctic from Alaska to Norway. That August, a Vega with a 420-horsepower Pratt & Whitney Wasp engine became the first airplane to fly nonstop from Los Angeles to New York. With an advertised top speed of 170 mph, guaranteed to within 5 percent, the Wasp-powered Vega was the fastest commercial airplane of the late 1920s able to carry more than two passengers.[14]

The addition of the NACA engine cowl further increased the performance of the Vega and its variants. The first commercial airplane to use the new NACA cowl was the Lockheed Air Express, a modified Vega designed for combined mail and passenger transport. The cowl increased the top speed of the Air Express from 157 to 177 mph. In February 1929 the cowled Air Express set a new nonstop record from Los Angeles to New York. The reduction in drag produced by the NACA cowling was especially advantageous when combined with the streamlined monocoque fuselage, producing a smooth contour from propeller to tail. With an NACA cowl, the top speed of the Vega increased to 180 mph. Amelia Earhart owned such a Vega, and used it in 1932 to become the first woman to fly solo across the Atlantic (figure 6.1).[15]

The performance figures and record-setting flights of the Vega brought Lockheed numerous orders. The ease of producing the molded monocoque fuselage helped Lockheed meet this demand. Manufacture of the Vega fuselage followed the procedure developed for the Loughead S-1. The reinforced

Figure 6.1. Amelia Earhart's wooden Lockheed Vega with NACA cowling. National Air and Space Museum, Smithsonian Institution (SI neg. no. A-45812D).

concrete molds were relatively inexpensive and easy to make. The fuselage shell itself consisted of three layers of spruce veneer with the face grain longitudinal. Each layer was first assembled from veneer strips and held together with paper tape. This method permitted each layer to be handled as a unit, reducing the time required for handling and applying the glue. Using the pre-assembled layers, it took only twenty minutes to assemble a complete shell in the mold. When all three layers had been covered with glue and placed in the mold, a heavy cover with a large rubber bag on the inside was bolted onto the mold. The bag was inflated to twenty pounds per square inch, placing the fuselage shell under uniform pressure. The shell remained under pressure for eight hours before being removed for drying (figure 6.2). When dry, the completed shell was glued and nailed to the framework of longerons and laminated-spruce rings.[16]

The wooden Lockheeds sold well until the 1929 stock-market crash and were used by many airlines. The Wasp-powered Vega was priced under $20,000, costing no more than competing models while providing substantially greater speed. With its monocoque fuselage and plywood wing, the Vega seemed to provide a clear advantage in performance with no increase

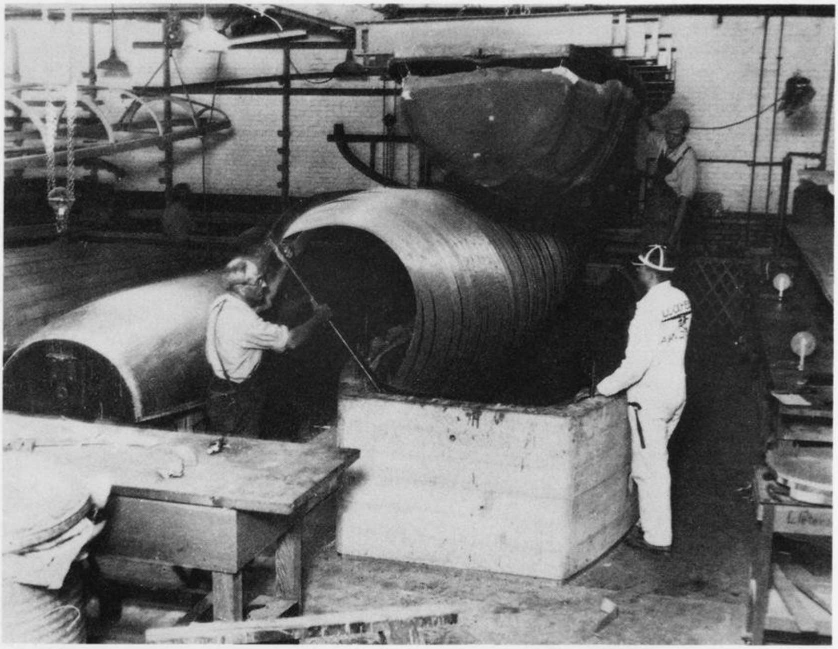

Figure 6.2. Molding the Vega's plywood fuselage. A completed fuselage half-shell is being removed from the mold. National Air and Space Museum, Smithsonian Institution (SI neg. no. 83-332).

in production costs. Sales of the Vega grew from thirty-one in 1928 to sixty-eight in 1929, which compared well with the eighty-six Ford trimotors sold in 1929. Even though the Ford carried twice as many passengers as the Vega, the two planes had roughly the same cost per seat-mile, according to estimates made later by E. P. Warner.[17]

Lockheed's success with the Vega made it an attractive target in the great merger wave that swept over the airline industry in the late 1920s. In 1929 the Detroit Aircraft Corporation bought the Lockheed company and in 1930 developed a metal monocoque fuselage for the Vega. The metal fuselage did not help the company's profitability, however, and in 1931 both Lockheed and its Detroit parent were in receivership. In 1932 Lockheed found new owners, who built a few more wooden Lockheeds while developing a new twin-engine all-metal airliner. Even with the decline in sales after 1929, more than 180 wooden Lockheeds were built between 1927 and 1934.[18]

The Vega was not only a prime example of the plywood monocoque fuselage but also of the stressed-skin plywood wing. Most airplanes in the 1920s used fabric wing coverings, which did not contribute to structural strength. The Lockheed wing, on the other hand, had a covering of $^3/_{32}$-inch spruce plywood, which increased both the strength and rigidity of the fully canti-

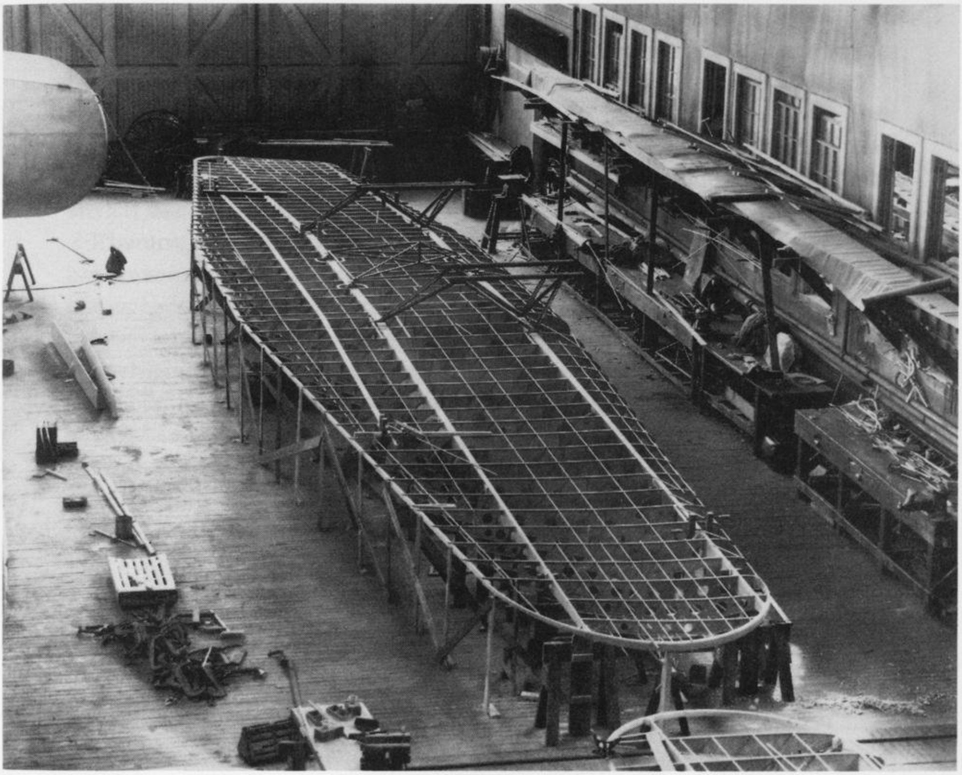

Figure 6.3. Internal structure of a Fokker F-10A wooden wing, which was later covered with plywood. National Air and Space Museum, Smithsonian Institution (SI neg. no. 96-15634).

levered wing. Lockheed's initial advertising for the Vega credited Anthony Fokker with the development of the fully cantilevered plywood-covered wing.[19] Fokker first used plywood-covered wings on the V-1 experimental monoplane fighter of 1916, the first of his airplanes to use a thick, fully cantilevered wing. A subsequent design of this type went into production near the end of the war as the D-VIII fighter. After the war, Fokker built a series of passenger airplanes with plywood-covered monoplane wings and steel-tube fuselages. The standard Fokker wing was based around two tapered box spars. The spars were deepest at the wing root, where the largest loads occurred, and became thinner toward the wing tips to correspond with decreasing loads. The flanges (top and bottom) of the spar consisted of solid or laminated spruce, joined by plywood on the sides to make a hollow rectangle. Solid plywood ribs connected the two spars, and a plywood skin covered the whole wing assembly (figure 6.3).[20] The Vega wing structure followed Fokker's twin-box-spar design, but with truss ribs instead of solid plywood. Due to the large number of parts and extensive gluing, assembling a Vega wing took ten experienced woodworkers about a week.[21]

Aside from Fokker and Lockheed, few American airplane manufacturers used plywood wing coverings. The Curtiss racers provide the main exception. The wings of the Curtiss racers employed multiple spars and a special two-layer spruce plywood, called Curtiss-ply. This form of construction had been suggested in 1921 by Armin Elmendorf, a consulting engineer for the Haskelite company. To take advantage of the plywood covering, noted Elmendorf, one needed to redesign the wing spars "so as to throw stresses into the covering." He suggested replacing the spars with longitudinal plywood webs spaced fairly close together, giving a typical wing roughly six webs. Curtiss appears to have followed this design in its racers and on early versions of the PW-8 fighter developed from the racers. On the PW-8, the spars and ribs were spaced to create square cells, which were then covered by the Curtiss-ply, giving the structure rigidity. Curtiss referred to this wing as "cellular," clearly anticipating the multicellular metal wing on the Northrop Alpha (chapter eight).[22]

The Neglect of Wood Stressed-skin Construction

Despite the impressive performance and commercial success of the Lockheed Vega, the stressed-skin plywood structure found few imitators among American manufacturers. By the mid-1930s, wood monocoque fuselages and plywood-covered wings had almost completely disappeared from American military and commercial airplanes.[23] These plywood structures clearly anticipated the stressed-skin metal airplanes of the early 1930s, yet they had little influence on the development of metal stressed-skin construction (see chapter eight). The reasons for the decline and neglect of plywood are complex. In the early 1920s, plywood suffered due to the general mistrust of permanent coverings, whether of wood or metal. Airplane builders and operators preferred fabric coverings, which needed periodic replacement, allowing inspection of the internal structure. But plywood structures faced a more serious impediment in the late 1920s, when interest in stressed-skin construction blossomed. Within the framework provided by the progress ideology of metal, the only acknowledged advances in airplane structures were those that involved a shift to metal. As a direct result of these beliefs, practically all stressed-skin research and development was performed on metal structures.

Several factors limited the success of the plywood monocoque fuselage in the early 1920s. Both the army and the navy's preference for fabric coverings discouraged further development of plywood monocoques, in view of the military's complete dominance of the airplane market in the early 1920s.

Despite earlier experiments with wood and metal monocoques, by early 1923 the monocoque fuselage had clearly fallen into disfavor among McCook Field engineers, who preferred the easier maintenance permitted by the fabric-covered welded steel-tube fuselage (see chapter four). When Curtiss developed the new PW-8 pursuit for the army in 1923, it abandoned the wood monocoque that had proven so successful on its racing planes, and settled instead on a welded steel-tube fuselage.[24]

There was nothing irrational in the army's preference for the higher drag but lower maintenance of the boxy steel-tube fuselage. The aerodynamic advantages of the monocoque fuselage remained limited for the relatively low-speed airplanes of the time. Most airplanes of the early 1920s suffered from high levels of parasitic drag. The reduction in drag provided by a monocoque fuselage was small compared to the remaining drag due to struts, bracing wires, landing gear, open cockpits, and especially the exposed cylinders of air-cooled engines. In addition, these other drag-producing elements directly interfered with the smooth airflow over the fuselage, making it impossible to realize the theoretical improvement in drag as measured on the fuselage alone. Only when various sources of drag were reduced together would the advantages of the monocoque fuselage become apparent.[25]

Concern over the durability of plywood also influenced decisions in favor of the welded steel-tube fuselage in the 1920s. For example, in the mid-1920s, Boeing engineers rejected the plywood monocoque fuselage in favor of welded steel tubing for a new mail plane, based on their belief that the wood monocoque was insufficiently rugged for hard service. Experience with the Lockheed Vega, however, including its use for Arctic exploration, suggests that the plywood monocoque could withstand very rough handling indeed. The Boeing decision does not appear to have been based on any actual operating experience with plywood monocoques.[26]

For similar reasons, stressed plywood wings also remained the exception in the 1920s. The army's objection to permanent fuselage coverings applied equally to wings. In addition, the increased stiffness produced by the plywood skin was of greater advantage to fully cantilevered monoplanes than to the more common biplanes and braced monoplanes. External bracing added considerable stiffness to the wings, lessening the benefits of a stressed skin. The advantage of stressed coverings only became apparent in the late 1920s with the growing interest in high-speed, fully cantilevered monoplanes. By this time, however, stressed-skin development was conceived entirely in terms of metal.

As with metal structures, the difficulty of making stress calculations also inhibited the adoption of plywood airplanes. Stress calculations were much more difficult to make for stressed-skin than for framework structures, due to problems in predicting buckling failures. Without a theoretical basis for calculating the strength of stressed-skin structures, designers had to rely heavily on empirical testing. As Walter Vincenti has argued, engineers routinely develop rational design methods in the absence of theory by means of systematic parameter variation. This process involves tests on representative components, and the reduction of test results to a series of equations or tables applicable to a range of expected design conditions.[27] In airplane design, such data depended on the materials tested, and one could not safely use data from one material to design structures in another.[28] Extrapolation from metal to wood was especially problematic, given wood's anisotropic properties and its very different mode of compression failure.

Designers of plywood monocoques clearly recognized the need for extensive testing as early as 1920. According to Armin Elmendorf of Haskelite, tests on monocoque and semimonocoque fuselages showed that "failure does not take place in compression . . . *until after collapse due to buckling*. The engineer must therefore design the monocoque fuselage so as to get maximum buckling strength." Unfortunately, engineers had no reliable equations telling them how to design a fuselage skin for maximum buckling strength, especially with regard to plywood, where stiffness varies with direction. Given the limits of calculation, engineers had to rely on extensive testing to design an optimal monocoque fuselage. The Haskelite company did perform a series of such tests, but the company apparently abandoned this research as interest in plywood monocoques declined.[29]

In the late 1920s, growing interest in stressed-skin construction led to a resurgence in research on the strength of thin-walled structures. Plywood found almost no place in these studies. The navy initiated this research in 1927, when it asked the Bureau of Standards to conduct a study of the strength of flat metal plates under edge compression, information important for the design of flying-boat hulls. This research relied heavily on parameter variation, and was performed entirely on metals. The bureau tested sheets of four different metals in six thicknesses and six widths, for a total of 144 tests. McCook Field engineers were also interested in this study because of its possible application to wing coverings, but in early 1927 they did not consider stressed coverings important enough to justify an extensive research program. Within a few months, however, the Materiel Division changed its tune and began planning its own study of stressed-skin structures, beginning with tests of corrugated metal in compression. All the proposed tests involved metal components. By early 1928, Capt. Carl Greene and John Younger of McCook Field had begun a study to develop a metal "skin stressed wing," with some of the research to be performed by Alcoa. As part of this project, the army engineers first tested the torsional strength of box beams with thin plywood sides, and then extended the tests to duralumin. Plywood structures, however, were not themselves a subject of research but merely a means to help develop an all-metal wing. The plywood tests were completed in 1928, but the army did not publish the results. Until the late 1930s, the NACA, the army, and the navy showed no interest in studying wood stressed-skin structures.[30]

By 1930 the term *stressed-skin construction* referred almost exclusively to metal in the eyes of researchers in federal agencies, universities, and airplane companies. In 1929 MIT aeronautical engineering professor Joseph Newell, formerly of McCook Field, began a study of reinforced plates under edge compression. This study focused on duralumin, but some plywood panels were tested. By 1931 the tests indicated that corrugated dural gave the best weight-to-strength ratio, but also that reinforced plywood was superior to stiffened flat duralumin sheet. Nevertheless, most of Newell's research focused on flat dural sheet, and he did not mention the plywood results in his journal articles, which gave useful guidelines for designing metal stressed-skin structures. Newell was one of the few engineers to express doubts about the wisdom of all-metal construction, making his omission of the plywood data even more striking.[31] Other researchers and designers working with stressed-skin structures did not even consider wood as an alternative material. When New York University professor Alexander Klemin polled industry and government engineers in 1930 about stressed-skin design, both his questions and the answers were framed exclusively in terms of metal construction.[32]

Military and civil interest in stressed-skin structures continued to grow in the early 1930s. In May 1931, the NACA established a temporary subcommittee on monocoque design to oversee research at the Bureau of Standards and the NACA's Langley Laboratory. The subcommittee defined its scope entirely in terms of metal, claiming that research on stressed-skin structures was "a result of the present trend toward all-metal airplane construction." The experimental studies supervised by the subcommittee were almost exclusively conducted with duralumin and stainless steel. Much of the research concerned practical design questions, such as the proper spacing of rivets.[33] Such practical research provided significant benefits to designers of metal stressed-skin structures, benefits not available to designers of wooden airplanes.

The limitation of stressed-skin research to metal clearly demonstrates the power of the progress ideology of metal to promote a particular developmental path. There was absolutely no technical reason to restrict stressed-skin research to metal; in fact, the shift to stressed-skin structures created new opportunities for low-density materials like plywood. With their high densities, metals exacerbated the buckling problems inherent in all thin-walled structures, a fact easily demonstrated in the 1920s using elementary equations for buckling strength (see chapter three). Yet if engineers noticed that stressed-skin construction provided an argument in favor of wood, they did not think it worthy of mention. A 1927 French report briefly noted that the continued use of wood might aid the transition to monocoque structures, but such observations were extremely rare. Typical discussions of stressed-skin construction simply ignored wood. For example, a 1932 article on "The Monocoque Fuselage" stated simply that "comparison [of metal] with wood construction is not warranted," without giving any justification.[34] Because aviation engineers viewed monocoque design as an aspect of all-metal construction, most of them ignored the potential benefits of wood monocoques.

NACA Wood Research and the Durability of Glues

Another factor that discouraged the development of plywood stressed-skin structures, and of wooden airplanes in general, was distrust of glued joints. Gluing provided by far the strongest joints between wood parts, far stronger than screws or nails, and so was indispensable to wooden airplane structures. Critics of wood construction correctly identified glued joints as the place where deterioration began in wooden airplanes. Researchers in wood structures had long recognized the need to improve the durability of glues, yet the widespread belief in the inevitable triumph of metal discouraged the aviation community from pursuing such research. Instead, aviation research remained focused on problems of metal construction, despite the widespread use of wood in airplane structures into the 1930s. This neglect of wood research is strikingly demonstrated by the NACA's lukewarm interest in the durability of glues, especially when contrasted with the NACA's vigorous response to intercrystalline corrosion in aluminum alloys. These radically different responses clearly bear the imprint of the progress ideology of metal.

By 1920 airplane builders had made considerable progress with woodworking glues, especially with glues for making plywood. Before World War I, the structural use of plywood was hindered by the lack of water-resistant glues. Traditional hide and bone glues produced strong joints but remained water soluble, making their use unwise in structures exposed to the weather. By World War I, however, manufacturers were gluing veneers with blood-albumin and casein glues, both of which became insoluble after setting. Albumin glues required heat to set, whereas casein glues could be applied cold. Widespread use of these glues in the United States was a direct result of military demand for water-resistant plywood during World War I. During the war, the Forest Products Laboratory (FPL) developed tests for the water resistance of plywood glues. These tests included boiling a plywood sample in water for twenty-four hours and soaking a sample in cold water for two weeks. By 1918 McCook Field engineers had identified over a dozen commercial plywood glues that could survive these tough tests.[35]

After World War I, the cold-setting casein glues became the most popular adhesive for airplane construction. Unfortunately, the long-term durability of casein glues remained uncertain, especially under moist conditions. FPL research during World War I had revealed the weakening of casein glues when wet, but the brief FPL tests did not uncover the tendency of casein to deteriorate when kept in prolonged contact with moisture. Casein glues softened in the presence of moisture, and after prolonged exposure behaved like soft cheese. They also made good food for various microorganisms.[36]

Supporters of metal construction often cited the impermanence of glues as an argument against construction in wood, plywood in particular. In 1925, an Air Service officer told a congressional committee that plywood structures on army airplanes deteriorated more rapidly than those of solid wood. William Stout claimed that after six months any airplane built of plywood would suffer from "veneer-eal" disease, a problem that "none of you can overcome no matter how you build it." Both army and navy officers in the mid-1920s agreed that the deterioration of airplane structures began in the glued joints.[37]

Nevertheless, properly maintained wooden airplanes could last for many years. Dutch studies in the 1920s showed that plywood-covered Fokker wings retained their strength after years of service, even in tropical conditions. The Royal Dutch Airlines (KLM) successfully used Fokker plywood-covered wings in the tropics and on the Holland to Java route through the mid-1930s. Many Lockheed Vegas remained in hard airline service until the late 1930s. One Vega flew scheduled routes in Alaska into the 1950s, finally ending its career when it crashed after running out of gas. Other wooden Lockheeds served Mexican routes from the early 1930s into the 1940s.[38]

Given the acknowledged problems with glued joints and their near ubiquity in airplane structures, one would expect to find concerted research to insure the durability of wood glues. For a variety of reasons, no such efforts were made. Within the federal government, research on wooden airplanes, including glue research, was coordinated through the NACA's Subcommittee on Woods and Glues, established in 1920 as a subcommittee of the Committee on Materials for Aircraft.[39] The FPL, a part of the Forest Service within the Department of Agriculture, performed most of this research. The FPL maintained a well-equipped research facility in Madison, Wisconsin; in 1921 the FPL employed 220 "engineers, wood technologists, chemists, manufacturing specialists, and assistants." During World War I, the FPL had played a major role in airplane research, especially in the development of water-resistant airplane glues.[40]

Most of the FPL's funding for airplane research came from the army and navy. However, these funds were sharply curtailed at the end of World War I. For fiscal year 1920, which began July 1, 1919, Congress slashed the War Department's request for aircraft research at the FPL from $100,000 to

$25,000, which was hardly enough to continue ongoing projects. In fiscal year 1921, the Air Service increased its funding of FPL projects to $50,000. But by the summer of 1920, enthusiasm for metal airplanes had enveloped the army, which soon began to limit funds for research in wood structures. In August 1920, Thurman H. Bane, the chief of the Air Service Engineering Division, recommended against transferring additional funds to the FPL:

> It is desired to devote as much money as possible during the current fiscal year to the investigation of metal, in connection with airplane construction. If metal construction proves feasible, which in the opinion of the undersigned it will, the work at the Forest Products Laboratory will become less important in connection with airplane engineering, as it is hoped that we will get away almost entirely from wooden construction.

Thus as early as 1920, before the army or anyone else had made a serious study of the merits of the metal airplane, research in metal construction was displacing wood research.[41] Bane used the expected success of metal construction to deny wood researchers the funds they needed to help wood compete against metal. This rationale would be repeatedly invoked throughout the 1920s.

Despite constraints on funding, researchers at the FPL did attempt to develop more durable and water-resistant glues. As early as April 1920, the NACA Subcommittee on Woods and Glues noted that "development of a waterproof glue is urgently needed."[42] By February 1921 the FPL had begun research to develop such a glue. The problem of glue durability, reported the FPL in 1921, "is of great importance in the construction of aircraft, where the value of glues that will stand indefinite exposure to water or high humidity without weakening is obvious."[43] As part of this study, FPL researchers tested the effectiveness of preservatives in increasing the durability of casein glue. This research continued at a low level through 1925, largely supported by navy funding.[44]

In 1925 the FPL's glue research encountered a funding crisis. George Trayer, a senior FPL researcher and the new chairman of the NACA Subcommittee on Woods and Glues, detailed this crisis in an October 1925 memo to the subcommittee. The army and navy funded specific short-term projects at the FPL, explained Trayer, but did not support the long-term research needed to study the durability of glues under prolonged exposure to moisture. According to Trayer, "the future status of wood in aircraft construction" depended on a comprehensive understanding of the durability problem. Beginning that summer, however, the army and navy ceased to provide funds for glue research. To save the program, Trayer appealed to the NACA to fund a long-term study on the durability of wood glues.[45]

The NACA's Committee on Materials was willing to support Trayer's proposal. At its October meeting, the committee requested NACA funds for a three-year study at the FPL on the durability of glued joints. The NACA did not treat the matter with any urgency, however, and a year later the FPL had still not received authorization to begin the study. Eventually, the NACA's Executive Committee approved a "Study of the Resistance of Glues to Prolonged Exposure to Damp Conditions," and provided the FPL with $2,500 annually for three years (fiscal years 1927–1929), with additional funding provided by the FPL and the navy. The study continued for another two years without support from the NACA.[46]

Trayer correctly perceived the importance of the glue study to the continued use of wooden airplanes. Nevertheless, the FPL was under no pressure from the NACA or the military to generate practical results. The laboratory proceeded at a leisurely pace, carefully developing experimental protocols before investigating practical methods to improve the durability of glues. During the first year of the study, FPL researchers focused on techniques for testing the mechanical properties of thin films of glue. They also began a series of long-term tests in the "fungus pit" to measure the effectiveness of antifungal agents on casein and albumin glues.[47] Research continued in this scientific vein the following year, focusing on "new methods for studying the essential physical and chemical properties of glues." The FPL scientists carefully studied the chemistry of casein glues, and began investigating the microbes that attacked different adhesives. Large-scale exposure tests of glued joints began only after the FPL had spent almost two years examining the fundamental properties of existing animal, casein, and blood albumin glues. These tests exposed glued joints to a wide variety of natural and artificial environments. The researchers hoped to find connections between the exposure tests and the fundamental properties of glues.[48] The exposure tests, however, required several years to yield useful results.

Unfortunately for the FPL glue study, the NACA began losing interest in wooden airplanes well before the study yielded practical results. George Lewis, the NACA's director of research, had long been a supporter of metal construction. As the pace of metal airplane development quickened in the late 1920s, Lewis grew increasingly unfriendly to research on woods and glues. In 1928 the FPL asked the NACA to publish a manual on aircraft gluing practices that the laboratory had prepared for the navy a few years earlier. NACA publications provided the single best route for communicating research results to the aircraft industry. Lewis refused, however, insisting that "such a report is not as important as it was several years ago" due to the "steady increase in the use of metal in the construction of aircraft." Metal construction was already "practically standard" for fuselages, claimed Lewis, and was now spreading to the wings. Although there was some truth in Lewis's claim about the spread of metal construction, the fact remained that the vast majority of aircraft in service and in production used wooden wings. Even the army, which had recently renewed its strong support for metal construction, had only two combat types with metal wing structures, the Thomas-Morse O-6 and the Curtiss B-2.[49]

Carlile P. Winslow, director of the FPL, was clearly miffed at this dismissive response from the NACA. In his reply to Lewis, Winslow correctly pointed out that "wood is still being used in most commercial planes." Winslow also noted "the rapid growth of commercial aircraft," which insured "that the [gluing] manuscript would still serve a very useful purpose," despite the increased use of metal construction. Winslow, in fact, had a much more realistic view of the place of wood in the aircraft industry than Lewis. Unlike Winslow, however, Lewis was in a position to influence the funding of aeronautical research and thus to make his views self-fulfilling. The FPL finally managed to get its aircraft gluing manual published in 1930 as a technical bulletin of the Department of Agriculture, but in this form it was unlikely to receive wide distribution in the aircraft industry.[50]

Lewis's decision on the FPL gluing manual was symptomatic of the NACA's increasing reluctance to support research on wood construction. The 1928 NACA annual report reflected this attitude, stating that the trend toward metal construction rendered additional studies of woods and glues unnecessary, despite the fact that "wood will undoubtedly be used for some time to come." The Subcommittee on Woods and Glues would henceforth initiate no new research, according to the report, but would rather focus on completing projects already under way at the FPL.[51] This declining support for wood research closely reflected military priorities. As the 1929 NACA annual report revealed, the army and navy had "practically ceased to initiate activities regarding woods and glues."[52] By 1929 both military services had committed themselves to developing all-metal air forces, and were focusing their research efforts on metal construction. This research, however, applied more to a desired future than the practical needs of the present. In 1929 Edward P. Warner conducted a survey of the aircraft industry; this survey found that 92 percent of commercial airplanes then being built used wood for the wing spars and other structural parts. In other words, all but 8 percent of commercial airplanes then in production could have benefited from practical research in wood structures, especially research to improve the durability of wood glues.[53]

Despite the lack of new projects, the FPL still had considerable unpublished data from prior research. In 1929 Trayer convinced the NACA to publish the results of this research. The FPL's aeronautical activities over the next two years consisted primarily in preparing these reports for the NACA, although work on the glue durability study did continue at a reduced pace. By March 1931, the FPL had completed the last of five reports based on previous research. The results of the glue durability study, however, were never published.[54]

On April 6, 1931, George Lewis recommended replacing the Subcommittee on Woods and Glues with a Subcommittee on Miscellaneous Materials. In justifying his decision, Lewis again overstated the importance of metal in aircraft production, while revealing the NACA's bias toward military needs. He claimed that "practically all military and naval airplanes are all-metal, although many commercial airplanes are still being built with wood as part of their structure." In fact, *most* commercial aircraft continued to use wooden wings, although metal had become common on large aircraft. A survey of airplane types published about six weeks prior to Lewis's memorandum found that more than 83 percent of all models in production used wooden wing spars. While it was true that most army planes under development had metal structures, the majority of army planes in service used wooden wing spars, and the army was still buying new wooden-winged pursuits (see chapter seven).[55]

If the aircraft industry had been indifferent to the results of wood research, the demise of the Subcommittee on Woods and Glues would not have affected the future course of airframe design. The industry, however, remained very interested in the FPL's research. The decision to disband the Subcommittee on Woods and Glues was approved at a meeting of the Executive Committee on April 23, 1931. At this same meeting, George Burgess, chairman of the Committee on Materials, reported that the new FPL reports published by the NACA "have been very much in demand by those interested in the design of aircraft."[56] At the same time, the FPL was fielding requests from airplane designers for information related to the strength of plywood stressed-skin structures. Some manufacturers undoubtedly recognized the advantage of plywood in buckling strength, and logically turned to the FPL for help. Unfortunately, the FPL had done no studies of plywood stressed-skin construction. Just one month before the disbanding of the Subcommittee on Woods and Glues, George Trayer brought up the question of the buckling strength of plywood sheets at a meeting of the Committee on Materials, noting the inquiries that the FPL had received from the aircraft industry. Trayer expressed the FPL's willingness to study the topic if the committee considered it important for aircraft design. The ensuing discussion noted Fokker's continued use of plywood-covered wings, but in the end the committee referred Trayer to the Subcommittee on Aircraft Structures, which was just beginning its study of monocoque design. This research was conceived exclusively as a problem in metal construction.[57]

The NACA's lukewarm pursuit of the glue study contrasts sharply with its vigorous response to the intercrystalline embrittlement of duralumin (see chapter four). The NACA first became aware of the problem of dural embrittlement in a February 1925 letter to George Lewis from George K. Burgess, head of the Bureau of Standards and chairman of the NACA

Committee on Materials. Immediately upon learning of the dural problem, Lewis instructed Burgess to make the problem a top priority. Burgess quickly mobilized support from the army, navy and private companies, including Alcoa. In April the Committee on Materials convened a special session at the Naval Aircraft Factory in Philadelphia, bringing together users and producers of duralumin for a discussion of the embrittlement problem. By the summer of 1925, the Bureau of Standards had launched a major study on the prevention of intercrystalline corrosion. This study included basic research into the corrosion mechanism as well as extensive testing of a wide variety a protective coatings. If the basic research had proved unfruitful, the exposure tests would still have provided practical guidance to airplane manufacturers. By 1927 the NACA-sponsored research had yielded practical results in terms of recommendations for protective coatings. Alcoa's involvement in the research also proved fruitful that same year, when the company introduced Alclad, Alcoa's solution to the embrittlement problem. By 1928 the NACA had published a comprehensive series of reports detailing the theoretical and practical aspects of intercrystalline corrosion.[58]

The FPL glue study, in contrast, was conducted with no sense of urgency. The FPL proceeded in good scientific fashion, first undertaking basic research before attempting to find a practical solution. After three years, the FPL study had produced no results of practical use to the aircraft industry. The NACA never once urged the FPL to step up the pace of its research, nor did it encourage cooperation between the FPL and airplane manufacturers.

The contrast between the intercrystalline corrosion and glue studies could not be sharper. The NACA responded to the corrosion problem as if it posed an immediate threat to the aviation industry, while it treated glue durability like an issue of incidental academic interest. In fact, almost the reverse was true. In the mid-1920s duralumin was of little importance to the American aircraft industry, and only one major manufacturer, Ford, had committed itself to duralumin airplanes. On the other hand, the overwhelming majority of aircraft depended for their safety on the reliability of glued joints. By discouraging research on the problems of wood, the belief in the inevitable triumph of metal became a self-fulfilling prophesy.

The Knute Rockne Crash

Lack of research on wood glues undoubtedly helped accelerate the decline of wooden airplane construction. In 1931 wood wings were on the wane among new military models and the largest commercial airplanes. Yet wood still remained the most important material in the wings of commercial airplanes. But one fatal accident in 1931 also proved fatal to the wooden airliner. On March 31, a three-engine Fokker F-10A crashed in Kansas, killing all eight occupants, including famed Notre Dame football coach Knute Rockne.

The crash made front-page news throughout the country, and would have been the lead story but for a thousand people killed by an earthquake that devastated Managua that same morning.[59] Department of Commerce investigators immediately began searching for the cause of the accident. Witnesses had reported hearing the engines sputtering and seeing a wing break off before the crash. Ice on the wing appeared to be a major factor. But when inspection of the interior of some Fokker wings revealed serious deterioration of the glued joints, apparently due to moisture that had accumulated inside the wing, the Department of Commerce ordered the planes removed from passenger service. The order only applied to F-10s and F-10As built in 1929, but it still grounded thirty-five aircraft, hampering operations on most of the major airlines. These Fokkers were permitted to fly again only after federal inspectors had examined the wing structure of each airplane. Most of the planes resumed passenger service after seven weeks, while a few returned later after reconditioning. The Department of Commerce also ordered periodic inspections of the interiors of Fokker wings, which required the removal of the plywood covering, a costly procedure. Although the investigators failed to establish a definitive link between the glue deterioration and the Rockne crash, the public and the industry lost confidence in Fokker's wooden wings. After 1931 few Fokkers remained in service on U.S. airlines.[60]

General Motors, which controlled the Fokker Aircraft Company, moved quickly to shift the company to all-metal construction. In July, General Aviation, the parent company of Fokker Aircraft, replaced Fokker's chief engineer, Albert A. Gassner, with Herbert V. Thaden, a designer of all-metal airplanes. Thaden had become part of General Aviation when it bought Thaden's firm the previous February. Shortly after Gassner's departure, Anthony Fokker resigned as engineering director of Fokker Aircraft under an agreement that permitted him to retain the rights to the Fokker name. In August, General Aviation renamed its Fokker subsidiary the General Aviation Manufacturing Company. Anthony Fokker returned to the Netherlands to continue building airplanes under his own name.[61]

Because the aeronautical community accepted the logic of the progress ideology of metal, the Rockne crash was interpreted as revealing a fundamental flaw in wood construction. The *New York Times* editorialized that the new inspection requirements signaled the end of wooden aircraft.[62] Wood did remain in fabric-covered wings, where frequent inspection was possible, but the Rockne crash inhibited further development of wood stressed-skin structures until the end of the decade. Yet these consequences did not follow ineluctably from the technical circumstances of the Rockne crash. Both metal and wood airplanes had suffered accidents due to the deterioration of materials, but in metal these failures served to locate problems to be solved. Engineers could have reached similar conclusions with regard to the glue deterioration in the Fokker wings, seeing it as a solvable problem in an otherwise sound design. Had the NACA pursued research on glue durability with as much vigor as research on duralumin corrosion, perhaps the gluing problems in the Fokker planes could have been avoided. By 1932 the FPL was reporting "remarkable results" from its long-term exposure tests, but these results came too late to help Anthony Fokker or Knute Rockne.[63] Even if the FPL research had not been able to prevent the Rockne crash, a better understanding of airplane glues might have given manufacturers enough confidence to continue with wood construction.

In a 1938 retrospective lecture, E. P. Warner, MIT aeronautics professor and former editor of *Aviation*, questioned the consequences of the Rockne crash:

> The condemnation [of wooden structures] may have been too hasty and too severe, for it is quite possible that protective treatments and water-proof adhesives can yet be found that will overcome the liability to deterioration that is wood's weakest point.[64]

In 1938, such improvements were more than just a possibility. Several manufacturers were already developing new wooden airplanes based on synthetic resin adhesives. Nevertheless, the aviation community's persistent prejudice against wooden airplanes inhibited the widespread application of these innovations (see chapter nine).

The long-term consequences of the Rockne crash are difficult to gauge. The general trend to metal construction in commercial aircraft clearly predates the Rockne crash. However, this single accident did force Anthony Fokker from the American aviation scene, and thus removed the last powerful advocate of wood in large passenger aircraft. In addition, the Rockne crash eliminated dozens of Fokker aircraft from airline service, creating an immediate demand for new equipment. Wood had no place as a structural material in this new generation of passenger airplanes. But without continued military support for metal construction, airplane manufacturers would have been unable to provide these new all-metal airliners.

7

Persistence Pays Off: Military Success with Metal Airplanes

By the mid-1920s, the military's vigorous support for metal construction had failed to produce a single metal airplane suitable for service use. Both the army and navy had cooled in their enthusiasm for all-metal airplanes, and each service seemed resigned to purchasing airplanes with steel-tube fuselages and fabric-covered wooden wings, at least temporarily. Despite this more pragmatic attitude, the earlier efforts to develop metal airplanes had generated considerable momentum, both in the military and among private manufacturers.[1] The military's continuing pronouncements in favor of metal construction encouraged private manufacturers to risk their own funds on new prototypes, even when military contracts were not forthcoming. Military projects also helped diffuse the skills needed to design and build metal airplanes throughout the aviation industry. The army's metal spar study provided many airplane companies with experience in designing metal structures, while the duralumin fabrication techniques developed at the Naval Aircraft Factory were freely transferred to any company with a navy contract (see chapter four). In time, this momentum began to yield success. By the late 1920s and early 1930s, both the army and navy were purchasing metal airplanes as standard service types.

The army and navy pursued somewhat different strategies for meeting their goal of all-metal construction during the second half of the 1920s. Both services continued to support some metal airplane projects, though at lower funding levels than in the early 1920s. The army used the momentum for metal construction to convince manufacturers to contribute substantially toward development costs. This strategy led to the Thomas-Morse O-6 observation plane, the army's first metal airplane successful enough to undergo service tests, and its successor, the Thomas-Morse O-19, the army's first metal airplane to be procured in quantity. In contrast to the army, the navy vigorously pursued the development of large metal flying boats at its own facility, the Naval Aircraft Factory (NAF). NAF personnel designed and built a series of experimental airplanes to perfect the metal flying boat; in the late 1920s the NAF transferred these designs to industry for production. Meanwhile, the Air Corps had become concerned about a potential shortage of aircraft timber, which provided an excuse for increased efforts to obtain suitable metal airplanes. At the same time, the army began losing its aversion to metal coverings. It began encouraging the development of monocoque metal fuselages and research on all-metal stressed-skin construction. By 1933, the army had adopted metal airplanes as standard equipment for all of its combat types.

The Army's Renewed Development of Metal Aircraft

Despite the conservative approach adopted by the Engineering Division in 1923, the army never abandoned the goal of all-metal construction. In a 1924 letter to an airplane company working on metal designs, Maj. Leslie MacDill, the chief engineer at McCook Field, agreed that "we will eventually need some type of metal construction." Brig. Gen. William Mitchell, then assistant chief of the Air Service, was also a strong supporter of metal construction. Although Mitchell had no direct command over technical matters at the Engineering Division, he did have influence over the types of airplanes selected. In a 1924 conference with the section chiefs of the Engineering Division, Mitchell stated that "we should build nothing but metal" as soon as adequate designs became available. Mitchell's shrill advocacy of an independent air force soon cost him his post as assistant chief of the Air Service. Nevertheless, his views on metal aircraft were accepted even by high-ranking army officers, whom most flying officers viewed as hostile to the Air Service. In a January 1925 article prepared by the army's Information Division, a part of the General Staff, Lt. Corley McDarment wrote that "one can scarcely doubt that the future airplane will be of metal construction." McDarment's article could not have been published without official review and clearly reflected the thinking of high-ranking staff officers concerned with aviation.[2]

The Air Service also felt pressured to do more regarding metal construction as a result of congressional hearings begun in late 1924 by the House Select Committee of Inquiry into Operations of the United States Air Services, headed by Rep. Florian Lampert of Wisconsin. The Lampert Committee's primary mandate was to investigate charges of collusion between the military and a supposed "aircraft trust" organized around the Manufacturers Aircraft Association. This association administered a patent pool established during World War I at government insistence. During the hearings, committee members repeatedly grilled Air Service officers about procurement policies. An early witness was Brigadier General Mitchell, who claimed that the United States lagged in metal construction. When Air Service chief Mason M. Patrick testified, Rep. Frank R. Reid demanded an explanation for "the delay in developing an all-metal ship." General Patrick acknowledged the desirability of all-metal construction but argued that the industry had failed to solve the problems associated with it. When Patrick mentioned German all-metal construction, Reid asked rhetorically: "These foreigners are no better inventors than we are, are they?" Reid suggested that the continued use of wood was due to the aviation industry having "fallen down in developing an all-metal plane," a charge Patrick denied.[3]

Not long after General Patrick's testimony before the Lampert Committee, the Air Service renewed it efforts to obtain a satisfactory metal airplane for service use. This airplane would eventually be produced by the Thomas-Morse Aircraft Company. Thomas-Morse was an experienced manufacturer of military aircraft, having received more than $1 million in Air Service contracts in fiscal year 1920 alone, primarily for its pursuit airplane. The company soon turned to metal construction and provided the army with three all-metal racing planes, designated the R-5. The R-5 had a corrugated metal covering on the fuselage and tail surfaces. In the 1922 Pulitzer Race, the R-5 proved no match for airplanes of wood construction, especially the Curtiss racers with their wood monocoque fuselages (see chapter six). Thomas-Morse continued to develop duralumin military airplanes, building four different prototypes through 1924. McCook Field supported some of these projects by lending the company engines and instruments, but it found none of the completed airplanes sufficiently promising to justify orders or contracts for further development.[4]

In April 1924, Thomas-Morse began threatening to cease operations if no government orders were forthcoming. In a report to the company's board of directors, company vice president B. Douglas Thomas complained of the conservative attitude of the Engineering Division to new forms of construction. Thomas-Morse had taken up metal construction, he said, due to "persistent encouragement from Washington and McCook Field to abandon wooden construction for either steel tubing or duralumin." While other companies took up steel-tube construction, Thomas-Morse turned to duralumin, in part because European designers appeared far ahead of Americans in duralumin airplane design. Thomas attributed the division's conservatism to its limited funds, which made it reluctant to take risks on airplanes with novel features. However, insisted Thomas, his company had proven "that duralumin airplanes are perfectly practicable." Thomas defended the company's most recent design, submitted for an observation plane competition, against Engineering Division criticism of its dural monocoque fuselage. The company had begun construction before the competition was announced, and the plane was already two-thirds complete. Thomas-Morse faced a dilemma. Either it should complete the airplane despite Engineering Division criticism, or it should "abandon the project and disband our organization."[5]

Thomas's complaints elicited a surprisingly sympathetic response from the Engineering Division. Chief Engineer MacDill replied that he was "loathe to see such pioneer work in metal construction . . . come to naught."

MacDill noted that resistance to the monocoque fuselage came from the tactical units, which objected to its inherent maintenance problems. MacDill refused to rule out the monocoque fuselage for future airplanes. A few months later, the Engineering Division accepted an offer from Thomas-Morse to sell the Air Service a prototype training plane at cost. The division wanted to use this airplane for service tests of the durability and maintenance requirements of the monocoque fuselage. Although the airplane did not meet the required factors of safety, the division argued that it could be flown safely as long as stunting was avoided. Unfortunately for Thomas-Morse, Air Service chief Patrick rejected the request to purchase the airplane, citing fiscal constraints.[6]

Thomas-Morse continued to press for army funding of its development efforts and renewed its threats to close if no contracts were forthcoming. Engineering Division chief John F. Curry urged General Patrick to help Thomas-Morse stay in business. The failure of Thomas-Morse would constitute a "serious setback" to American efforts to develop metal airplanes. Curry acknowledged the difficulties involved in procuring metal airplanes, noting that metal airplanes were costly to develop, especially those with metal coverings, due to the impossibility of accurate stress calculations. This difficulty required the purchase of two versions of the prototype, one for flight tests and another (without an engine) for static tests. According to Curry, new metal airplanes presented a two-fold risk in addition to their high cost. To be successful, both the airplane's structure and its aerodynamics had to prove satisfactory. An airplane with unsatisfactory flying qualities could not provide a fair test of metal construction. As a solution, Curry suggested that Thomas-Morse be invited to reproduce in metal a wooden airplane of proven aerodynamics. The metal airplane would follow in general the dimensions of the steel-tube and wood plane, allowing for a side-by-side test of the two types of construction.[7]

General Patrick endorsed Curry's proposal for Thomas-Morse to build a metal version of a proven army airplane. In late 1924, the Engineering Division chose the Douglas O-2 observation plane to replace the aging DH-4Bs. The O-2 was a single-bay biplane of standard composite construction. The division was extremely pleased with the performance and flying qualities of the Douglas airplane and asked Thomas-Morse to reproduce the O-2 in metal. On April 21, 1925, the company signed a contract to deliver five metal observation planes and one static test model at a cost of $128,490. The Air Service designated this airplane the XO-6, with the *X* indicating an experimental model. The Materiel Division dropped the *X* prefix when an airplane was released for service tests.[8]

The O-6 was not entirely successful, but it came closer to meeting military requirements than did any of the army's previous metal airplanes. The airplane had a dural monocoque fuselage with a corrugated skin, character-

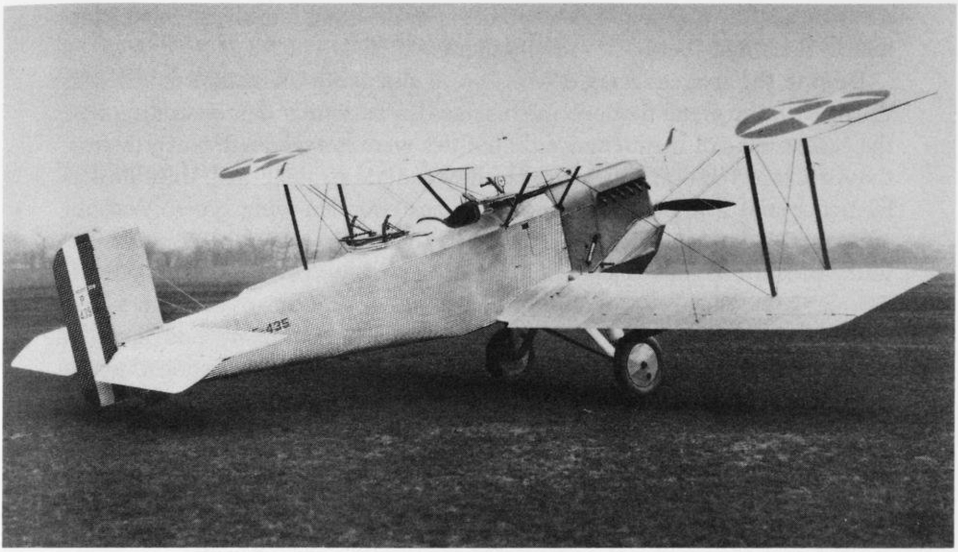

Figure 7.1. Thomas Morse XO-6, the U.S. Army's first successful metal airplane. National Archives at College Park, Record Group 18-WP, photo no. 30473.

istic of Thomas-Morse designs since 1921 (figure 7.1). The wings used extruded dural spars, which Thomas-Morse had spent several years developing. The wings also had an interesting combination of fabric and metal coverings, with corrugated duralumin on the top surfaces and fabric on the bottom. The airplane easily passed its static tests, but flight tests of the prototype, delivered in April 1926, revealed control problems. Correction of these problems delayed completion of the contract until the first half of 1927.[9]

The O-6 performed respectably but not well enough to justify the increased cost. Despite Thomas-Morse's accumulated experience with the design and construction of metal airplanes, the company's costs exceeded the contract price by a considerable margin. In January 1927 Thomas-Morse renewed its threats to go out of business as a result of losses on the O-6 contract and the absence of new orders. The company had already spent $80,000 more than the revised contract price of $135,220, and the contract was not yet complete. Thomas-Morse claimed that the weight and performance of the O-6 was comparable to the latest model of the O-2, but General Patrick disputed this claim, insisting that the plane was overweight and had unsatisfactory performance. By mid-1927, Thomas-Morse had corrected the control problems, and the Materiel Division (successor to the Engineering Division) released the five airplanes for service tests to determine "the practicability of aluminum alloy construction." After a year of service tests, the O-6 proved acceptable in terms of maintenance, but performance remained "below . . . requirements."[10]

Despite the inadequacies of the O-6, it did serve to familiarize the Air Corps with the metal monocoque fuselage, in particular demonstrating that the earlier fears of maintenance difficulties were exaggerated. Nevertheless, the Air Corps remained unwilling to buy a metal airplane with inferior performance and a higher price than standard wooden-wing types. Without additional orders, further development of the O-6 appeared in jeopardy due to the precarious finances of the Thomas-Morse company. In January 1927, Thomas-Morse made a direct plea for additional support to Assistant Secretary of War F. Trubee Davison, insisting that the company had invested large sums of money to develop metal airplanes "in direct response to the expressed desires of the Government." Thomas-Morse claimed to have spent a total of $743,000 on metal airplane work since 1921, for which it had received only $238,000 from the army. In reply to an inquiry from Davison, Brig. Gen. William E. Gillmore, chief of the Materiel Division, defended the Air Corps' progress in acquiring metal airplanes. Gillmore used the ambiguous terminology of metal airplanes to his advantage, including wooden-winged types with steel-tube fuselages in his list of metal airplanes purchased by the army. In fact, Gillmore's list showed that the army had only two metal-winged airplanes under development, the Curtiss XB-2 and the Huff-Daland XHB-1 bombers. Meanwhile, Gillmore advised General Patrick against giving Thomas-Morse more work until it had completed the O-6 contract.[11]

Thomas-Morse did not disband after completing the O-6 contract, despite the company's threats. In 1927, Thomas-Morse took the experience gained from the O-6 back to the drawing board, and produced an improved version at its own expense. The flying qualities of this airplane impressed the engineers at the Materiel Division, and in fiscal year 1928 the army bought three additional test versions of the airplane, designated the O-19. With the O-19, the Air Corps had finally acquired an airplane with performance comparable to, but not better than, existing wooden-winged types like the Curtiss O-1E and the Douglas O-2H. The Air Corps adopted the O-19 as a standard type in fiscal year 1930, giving Thomas-Morse an order for 70 of the O-19B version. The Air Corps bought 180 of the O-19 and its variants through fiscal year 1931, making the O-19 the first metal airplane procured in quantity for the U.S. Army.[12]

The success of the Thomas-Morse O-19 was not due to the inexorable progress of superior technology. Rather, the O-19's success resulted from the slow accumulation of experience in metal design by an aircraft company familiar with military requirements. Although the army provided significant financial support for this learning process, Thomas-Morse supplied the bulk of the funding itself. Thomas-Morse proved willing to invest heavily in these projects because the company shared the Air Corps' belief in the inevitable triumph of the metal airplane.

In-House Development: The Navy's Metal Flying Boats

Like the army, the navy never abandoned the goal of metal airplanes, despite the unsuccessful designs of the early 1920s. Unlike the army, which continued to rely almost entirely on private contractors for the design of prototype metal airplanes, the navy turned to the Naval Aircraft Factory for development of a new generation of metal flying boats. The NAF was in many ways comparable to McCook Field, being a large organization dedicated to the development of military airplanes and their equipment. Unlike McCook Field, however, the NAF retained significant design and manufacturing capabilities. In addition, the Engineering Division at McCook (later the Materiel Division at Wright Field) had primary responsibility for airplane procurement, a function that the navy retained in Washington at the Navy Bureau of Aeronautics. The NAF often operated like an outside contractor to the Bureau of Aeronautics, even bidding on competitive contracts let by the bureau.[13]

The NAF developed considerable expertise in duralumin structures during the design and construction of the airship *Shenandoah* in the early 1920s. By 1924, after Stout, Martin, and Hall had failed to produce metal airplanes suitable for regular military use, the NAF assumed the leading role in developing metal airplanes for the navy. The NAF had been closely involved in metal airplane work since 1920, when the factory tested the Junkers JL-6. The NAF continued to keep close tabs on German metal airplanes, testing the Dornier D1 fighter and CS-2 flying boat in the early 1920s. In 1922 the NAF began designing an all-metal biplane, the NM-1, in open imitation of Dornier and Staaken practices. This project had its origins in late 1920, when Admiral Taylor requested that the NAF build an "experimental plate wing." When completed in late 1924, the all-metal NM-1 closely resembled the Dornier D1. Although the NM-1 passed its tests at the NAF, the Bureau of Aeronautics chose not to continue the project. According to H. C. Richardson at the Bureau, "the plate duralumin all metal construction is not advantageous from a weight standpoint." In both weight and cost, the NM-1 compared unfavorably to the old DH-4 observation plane. These results convinced the NAF to focus on a simpler and lighter type of wing construction.[14]

Another line of development at the NAF proved more fruitful for metal airplanes: flying boats. These had always been important for naval aviation, since they allowed airplanes to operate safely over the open ocean in close cooperation with surface vessels. But the design of flying boats presented some of the most vexing problems of any airplane type. Flying boats had to be both seaworthy and airworthy, and their designers needed experience in both naval architecture and aeronautical engineering. Hull design was particularly troublesome, forcing compromises between the requirements for taxiing, take-off, landing, and flight. Furthermore, all of these requirements had to be met while keeping weight to a minimum.[15]

Metal construction offered some very real advantages to designers of seaplane hulls. The traditional wooden boat construction used in seaplane hulls was already rather heavy. Plywood was not used extensively due to its limited durability in wet conditions. Furthermore, all the waterproof coatings available in the early 1920s were of limited effectiveness, allowing large increases in weight from water soakage. These increases could be considerable. Some published reports claimed that soakage could amount to as much as 10 percent of a seaplane's weight. Typical soakage probably amounted to half that amount, but a 5 percent increase in weight empty still posed a major liability for wooden hulls. Metal hulls eliminated the soakage problem.[16]

Metal seaplane work at the NAF began in 1921 with the design of duralumin floats for the Curtiss N-9. The metal floats proved much lighter than the original wooden ones, even before accounting for soakage. But like much early metal airplane work, the seaplane floats were tremendously more expensive than their wooden counterparts, roughly \$7,000 versus \$900 per wooden float. Commander H. C. Richardson, a senior engineering officer at the Bureau of Aeronautics, hoped that the superior durability of the metal float would justify the increased cost, but experience proved otherwise. In 1922 the NAF sent several sets of metal floats to the Pensacola Air Station for service tests. Two years later, the Bureau of Aeronautics received a strongly worded letter from Pensacola complaining that the metal floats corroded, were easily damaged, and were very difficult to repair. Although the Pensacola letter acknowledged that the lower weight of the metal float did improve performance, "all things considered . . . it is not believed that the adoption of duralumin floats at this time is justified." Next to this sentence, someone at the Bureau of Aeronautics had boldly penciled "Wrong."[17]

Complaints like the ones from Pensacola did not dissuade the navy from developing metal boats but rather served to focus the NAF on problems that needed to be solved. The NAF worked methodically to improve the durability and lower the production costs of metal structures. In August 1923 it began work on a metal hull for its new PN-7 flying boat, which had a traditional wooden hull and fabric-covered wooden wings. The hulls were completed in 1925 and provided significant weight savings. Before the end of the year, two of these new airplanes, designated the PN-9, were used in an attempt at a first-ever flight from San Diego to Hawaii. One turned back early in the flight. The other ran out of fuel two hundred miles from Hawaii. The second PN-9 and its crew spent nine days sailing in heavy seas without major damage to the duralumin-covered hull, an impressive demonstration of the robustness of the new construction. Meanwhile, the NAF had begun work in 1925 on fabric-covered duralumin wings for the PN-type boats. The new type was designated the PN-10, but design changes, fabrication difficulties, and slow delivery of materials delayed completion of the metal wings until mid-1927. The PN-10's structure met expectations, but its liquid-cooled Packard engine proved troublesome. In 1927 the NAF began work on a new flying boat, the PN-11, intended to embody all the lessons learned from the earlier models. When completed in 1929, the PN-11 became the NAF's "definitive" metal flying boat.[18]

Admiral Moffett's vision for the NAF did not include production of standard types. With the experimental work on the metal boats complete by the late 1920s, the Bureau of Aeronautics began letting contracts for the construction of flying boats based on the PN designs. Contracts were let to four manufacturers for five different flying boat types, all derived from the PN-10 and PN-11. These four—Douglas, Martin, Hall, and Keystone—all benefited from close cooperation with the NAF. For example, the navy lent Martin a PN-12, a modified PN-10, for use in the design of the Martin PM-1. Private manufacturers also received detailed design drawings and help with manufacturing techniques.[19]

The NAF spent well over $1.5 million on the PN series, patiently working out the problems of metal design that would have bankrupted any private manufacturer. By transferring these government designs to private industry, the navy provided a significant boost to metal construction in general.[20] In particular, Douglas and Martin both became major producers of all-metal airplanes in the early 1930s, Douglas with commercial transports and Martin with army bombers.

The Wood Supply and the Army's Support for Metal

While the navy made slow but steady progress in its development of metal flying boats, the army's support for metal airplanes remained muted through the mid-1920s. Although the Air Service never abandoned its goal of a metal air force, the sense of urgency ebbed after the expensive failures of the early 1920s. Aside from the metal spar study and the Thomas-Morse O-6, the Air Service sponsored no major metal airplane projects from 1924 through 1927. In 1928, however, fears of timber shortages prompted the Air Corps to reassert the goal of acquiring metal airplanes.

Advocates of metal often claimed that insufficient timber supplies favored the adoption of metal. Concern over the wartime supply of aircraft timber was one of the original motivations behind support for metal aircraft construction during World War I. As supply problems eased after the war, engineers tended to emphasize the supposed technical advantages of metal rather than its value as an ersatz material.[21] Nevertheless, fears of wartime timber shortages continued to trouble military leaders throughout this period. In response, the army buried its collective head in the sand, ritually invoking the inevitable triumph of metal construction as the solution to potential problems with wartime wood supplies. These problems were potentially very serious; but the army made no plans to solve them. Neither did it plan for possible shortages in aircraft metals. When the army began mobilizing for World War II, the shift to metal airplanes was almost complete, and timber shortages presented few problems. Instead, the army found its production program limited by shortages of aluminum (see chapter ten).

As early as 1921, the army began using the prospective shift to metal construction as an excuse to avoid planning for spruce production. Spruce was the wood most favored for aircraft structures because of its straight grain, low density, and high ratio of strength to weight. Memories remained fresh of the bottlenecks and disorganization that plagued the early spruce production program during World War I. The federally owned Spruce Production Corporation was still in the process of disposing of the sawmills and other property that it had used to meet the demand for aircraft lumber during the war. Late in the spring of 1921, the Seattle Chamber of Commerce wrote to Secretary of War John W. Weeks, urging planning for spruce production in case of a military emergency. Washington State had the largest and highest quality reserves of aircraft spruce in the continental United States, and orderly exploitation of the resource clearly concerned Seattle's businessmen. The secretary's response, drafted by the Air Service, rejected the advice of the Chamber of Commerce. Weeks declined to support planning for spruce production, suggesting that the trend to metal construction rendered such plans unnecessary. "Wherever possible," wrote Weeks, "spruce and other woods are being replaced by metal. . . . We all hope that the next war will be far in the future and it is entirely probable that very little, if any spruce will be required." Yet in the very next sentence Weeks admitted that "a large quantity of spruce is essential for the construction of the types of aircraft now in service" and that "we must prepare for any emergency." This sentence directly contradicted Weeks's rejection of the Chamber's advice, yet no one seemed to notice the logical inconsistency. The presumed future triumph of metal provided an excuse for complacency, even with regard to the present.[22]

Such complacency was not universal within the Air Service. In late 1922, Maj. Oscar Westover took exception to the lack of postwar planning for spruce production. Westover had spent twenty-two months in the early 1920s helping the Spruce Production Corporation dispose of its property. This work had familiarized him with the production of aircraft lumber, which required skills and equipment not found in commercial sawmills. Westover was convinced that commercial mills could not be relied upon to produce sufficient quantities of aircraft spruce in the event of an emergency. Given the wholesale dismantling of the government's spruce production capability, Westover lamented the lack of planning and urged conservation of the Sitka spruce stands that provided the best aircraft lumber. He took his case over the heads of his superiors directly to the secretary of war. Westover responded directly to the argument that the prospective shift to all-metal aircraft rendered planning for spruce production unnecessary. He did not deny the eventual triumph of metal construction, but accurately predicted that aircraft spruce would continue to be needed for another ten years to meet wartime requirements.[23]

Westover's pleas fell upon deaf ears, and the army continued to avoid planning for spruce production. The greatest threat to supplies of aircraft timber was the depletion of the virgin Sitka spruce stand in the Pacific Northwest. There, huge trees grew to between twelve and fifteen feet in diameter with very straight grain, providing the long, unblemished lumber required for wing spar construction. Using the best methods, only about 10 percent of the lumber from these trees was suitable for aircraft use. But Sitka spruce was also favored as a source of pulp by paper mills, and commercial logging was rapidly depleting the best stands. Instead of conserving, however, the army continued to invoke metal aircraft as a solution to potential spruce shortages, and the shortages in turn bolstered the argument for metal construction.[24]

Despite the optimistic predictions of metal's advocates, in 1926 the army still depended on wooden wing structures for all of its standard service types. This continued dependence stimulated renewed concern over spruce supplies. In mid-1926, the Materiel Division estimated a current need for 1 million board feet of aircraft spruce annually, based on a survey of major airplane companies. Most of this spruce was used for wood wing spars, which new airplanes would continue to use "for several years at least," according to Maj. Ira Rader, who prepared the estimate. In case of mobilization, the Air Corps would require almost 34 million board feet of aircraft spruce in the first 24 months. This figure represented an almost immediate fifteen-fold increase in the production of aircraft spruce, and the Air Corps had taken no steps to insure that such a supply would be available. Rader's estimate clearly demonstrated the need to plan for emergency spruce production. In response, the Materiel Division hired Charles Van Way, a retired army officer who headed the U.S. Spruce Production Corporation, to conduct a study of the problem.[25]

Van Way did not complete his study until early 1928. His report urged action to insure adequate spruce supplies for mobilization. He noted that commercial logging had already depleted much of the old-growth timber that had been available for aircraft production during World War I. Van Way estimated the remaining supply of aircraft lumber available under commercial conditions at 139 million board feet. Although this amount appeared sufficient for the immediate future, Van Way expected much of this readily available spruce to be logged in the next six to eight years. Spruce would still be available, but only through selective logging, an expensive alternative to commercial practice. Van Way proposed that the Army establish a reserve of 4 million board feet of cut aircraft spruce to meet the requirements of the first few months of mobilization. Properly dried and stored, this reserve lumber would last indefinitely. Van Way predicted that this reserve could be purchased in peacetime for one-half its wartime cost. Total cost of the reserve would be about $1.2 million, including shelter and handling.[26]

Van Way's report passed first through Materiel Division chief Gillmore, who refused to endorse the proposed spruce reserve, insisting that metal aircraft offered an alternative. The Air Corps would be unprepared for war in the next few years, argued Gillmore, whether the war were fought with metal or wooden-winged airplanes. Gillmore suggested that progress in metal wing structures might render a spruce reserve unnecessary by the time funds for it could be appropriated. He also repeated the widely held belief that the excessive cost of metal airplanes would disappear in wartime, once quantity production began. Gillmore presented Maj. Gen. James E. Fechet, the new chief of the Air Corps, with two alternatives, either spend more than $1 million dollars on a spruce reserve, or "expedite the development of all-metal airplane structures." Gillmore endorsed the latter alternative, which incidentally promised a great deal more engineering work for the Materiel Division.[27]

Fechet initially decided to reject Gillmore's recommendation against the spruce reserve. Fechet was somewhat less certain than Gillmore that rapid progress in metal construction would provide adequately for the nation's defense. However, the Materiel Division continued to argue in favor of increased support for metal, directly lobbying Assistant Secretary of War C. B. Robbins, who was responsible for deciding the issue. Jacob Fickel, writing for the Materiel Division, noted that metal fuselage and empennage construction had already reduced spruce requirements by 40 percent. He mentioned the metal-winged Curtiss B-2 bomber then under procurement, and the new Thomas-Morse observation plane undergoing service tests. Additional metal airplane projects were scheduled for fiscal year 1930. Fickel also demonstrated the flexibility of technical rhetoric in an interesting twist on the relative durability of wood and metal wings. The principal problem with metal wings, argued Fickel, was the lack of durability sufficient to ensure a five-year service life. But this lack of durability was "not a war problem, for wings can be built now of all metal construction which would meet war conditions." In other words, lack of durability, seen as a major defect in wood construction, was not a defect when ascribed to metal, at least for airplanes in wartime.[28]

In the end, the Materiel Division's view prevailed. In March 1928, Secretary Robbins rejected Fechet's request for a spruce reserve. Instead, Robbins pledged "to support any reasonable program of the Air Corps in research and experimental development of the all metal plane." The NACA appears to have had some influence on this decision. Robbins had written the NACA asking advice on the spruce reserve. NACA Chairman Joseph Ames declined to endorse any particular policy, but he did highlight the NACA's research on metal construction, and proclaimed that "the general trend of development in airplanes . . . is definitely toward the more widespread use of all-metal construction." In April 1928, one month after Robbins had rejected the spruce reserve, Fechet reversed himself and endorsed the assistant secretary's decision.[29]

It took several more years to develop satisfactory metal pursuits and bombers, but the decision against the spruce reserve closed the door on significant new designs in wood. The army had firmly decided to fight the next war with metal airplanes. No sensible manufacturer would have continued to focus on developing better wooden warplanes.

Upon closer examination, the army's fears of spruce shortages appear excessive. Van Way's estimate of 139 million board feet represented roughly a one-hundred-year supply at current consumption levels in the aircraft industry. Conserving this resource by limiting less essential uses was certainly conceivable, although perhaps impractical given the political climate of the late 1920s. Furthermore, there was little danger of a complete exhaustion of spruce resources. Van Way's estimate only covered Sitka spruce available under commercial conditions; a vastly greater amount would have become available during wartime, although at a higher cost. The estimated stand of Sitka spruce in the United States in 1929 amounted to 29.5 billion board feet, of which 11.5 billion were in Washington and Oregon and the remainder on the southern Alaskan coast. Considering only the Washington and Oregon spruce and assuming conservatively that only 4 percent of each tree was suitable for aircraft lumber, the potential yield amounted to almost half a billion board feet. This figure represented enough spruce for

920,000 small planes or 92,000 large planes using existing construction methods. Nor would the higher cost of this less accessible spruce have been prohibitive. The cost of wood in the late 1920s accounted for only a tiny fraction of the price of an airplane; even a doubling of wood prices would have caused roughly a 7 percent increase in selling price. Finally, a number of alternative species appeared suitable for aircraft use, greatly expanding the potential supply.[30]

Aside from the potential supply of Sitka spruce, alternative types of wood construction promised to expand vastly the amount of wood suitable for aircraft use. Experiments conducted by the Bureau of Standards during World War I showed that wing spars of laminated wood were as strong as spars cut from solid stock. These laminated spars consisted of several layers of wood glued together, allowing the use of smaller pieces, thus reducing the importance of the massive Sitka spruce trees needed for large pieces of aircraft lumber. Fokker wing spars had successfully used laminated wing spars for years (see chapter six). For similar reasons, aircraft plywood was even less dependent on Sitka spruce. During World War I, the army built experimental plywood fuselages using woods rejected as unfit for use in standard aircraft.[31]

Although the army's concern with the adequacy of wood supplies was quite sensible, this concern did not extend to metal. Military planners seemed simply to assume that adequate resources and production capacity would be available to meet wartime requirements for airplane metals. Figures on iron ore reserves and steel production capacity supported this assumption for steel, but aluminum was a different matter. In early 1924, McCook Field conducted a survey of worldwide supplies of metals used in aircraft construction. This study indicated potential supply problems with domestic sources of bauxite. Using 1922 figures, the report concluded that "there is considerable doubt whether the domestic high grade bauxite alloys can last more than twenty years at the present rate of production." In 1922, bauxite imports amounted to only 10 percent of domestic production, but from 1925 on imports generally supplied over half of the total U.S. consumption. Dependence on foreign supplies for crucial materials usually induces severe anxiety among military planners. However, no such concerns arose in the development of an air force built predominantly of aluminum.[32] After the Japanese attack on Pearl Harbor, aluminum production was severely threatened when German submarines in the Caribbean attacked U.S.-bound bauxite transports from South America, which cost many merchant seamen their lives (see chapter ten). The imprint of the progress ideology of metal is clearly evident in this dramatic contrast between the exaggerated concern over spruce supplies and the lack of attention paid to the corresponding problem in metal.

The Army Adopts the Metal Airplane, 1929–1933

The April 1928 decision against a spruce reserve marked the beginning of a shift at Wright Field toward more support for experimental metal airplanes. Still, limited funds kept the "metallization" program modest. The decision against a spruce reserve did not create a sense of urgency, largely because of the remoteness of any military threat. The Materiel Division's annual report for fiscal year 1928 remained cautious concerning metal, insisting that "a definite and favorable answer to all problems . . . should be obtained before metal construction is generally adopted for peacetime use." The only evidence in the annual report of the decision to expedite metal construction was a commitment to purchase sample metal airplanes of all types for service tests, "in order that there need be no fear of a shortage of spruce in event of emergency."[33] After 1928, though, metal airplanes received the bulk of the funding devoted to new types of aircraft.

The most important change in technical direction with regard to the army's metal program in 1928 involved the shift in structural research at Wright Field from framework to stressed-skin structures. The new experiments involved tests on a series of box-beam wings, "similar to the Adolph Rohrbach construction." This type of wing consisted of a single box spar of roughly rectangular shape, covered on all four sides with aluminum alloy. The top and bottom of the box conformed to the wing profile, and thus provided an external covering while contributing to the structural strength of the spar. With the addition of leading and trailing edge sections, the box spar became a complete wing. The Materiel Division also began a more general program of research into stressed-skin construction, including theoretical and experimental work on flat and corrugated sheets.[34]

The pace of the Materiel Division's metal airplane work began to increase in fiscal year 1929. Research into stressed-skin wings continued, but it was hindered by the loss of experienced personnel to private industry, a consequence of the booming commercial market and the higher salaries available in the private sector. The most important new metal airplane was the Thomas-Morse O-19. The division also planned to purchase the Douglas O-22, a wooden-winged observation plane with a metal monocoque fuselage, indicating the Materiel Division's acceptance of monocoque construction. The Division also bought ten of the metal-framed Curtiss B-2 twin-engine biplane bombers, whose prototypes had proved satisfactory in tests the previous year. The B-2 had welded steel-tube wing spars and duralumin ribs. These metal wings were the result of Curtiss's work with Charles Ward Hall on the Navy F4C, providing a clear example of the diffusion of expertise on metal structures. The division also purchased the P-12 pursuit,

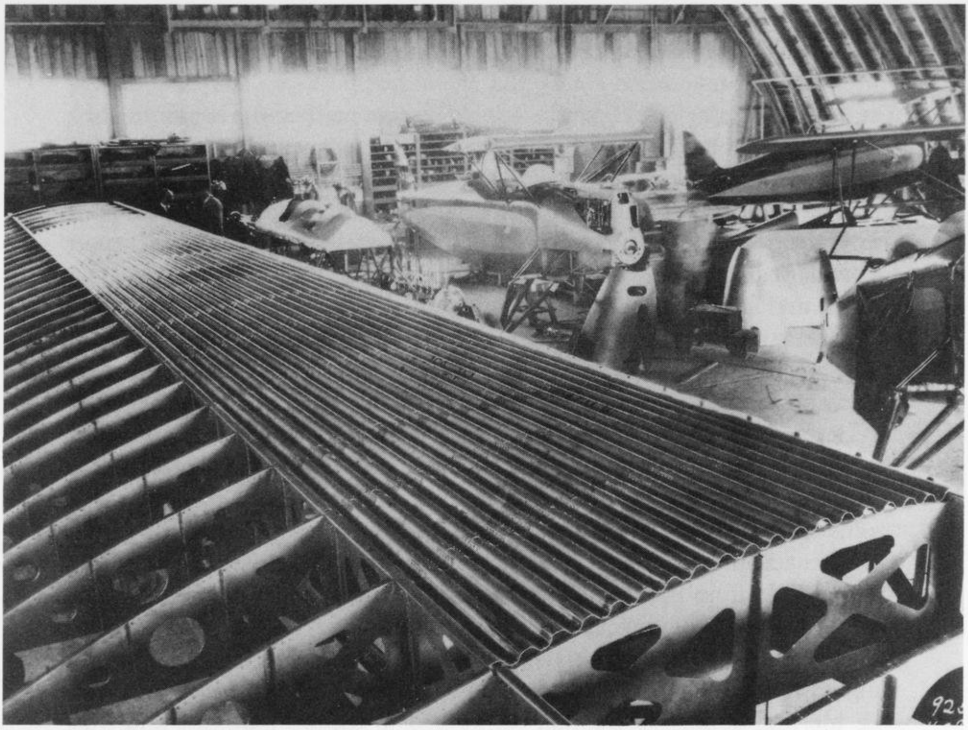

Figure 7.2. Materiel Division fifty-five-foot metal wing. Note the corrugated upper flange of the box beam, which will later be covered with smooth dural sheet. National Air and Space Museum, Smithsonian Institution (Wright-McCook photo no. 39681).

developed as a speculative venture by Boeing. Derived from Boeing's PW-9, the P-12 retained the wooden biplane wing while replacing fabric with corrugated duralumin on the tail and control surfaces, and also substituting dural tubing for steel in the fuselage. More importantly, in May 1928 Wright Field moved ahead with plans to develop a metal fighter, ordering the XP-9 from Boeing, the leading producer of fighters for the Air Corps. The XP-9 was to have a dural monocoque fuselage and fabric-covered metal wings. Unlike the Thomas-Morse fuselages, the XP-9 had a smooth rather than corrugated skin. Various problems delayed completion of the contract by more than a year. Boeing finally delivered the XP-9 in September 1930, but performance proved disappointing.[35]

The Air Corps' adoption of metal construction gathered momentum in fiscal year 1930, despite the failure of the Materiel Division to obtain increased funding for metal airplane work.[36] During fiscal year 1930 the Materiel Division continued to study stressed-skin structures and to buy metal airplanes. Stressed-skin experiments included the construction of two box-spar wings, one with a twenty-seven-foot and another with a fifty-five-foot span (figure 7.2). The division also produced a lengthy report on metal wing construction. Many industry engineers visited Wright Field to discuss this structural research, which undoubtedly encouraged designers to incorporate metal stressed-skin structures into new military models. After successful service tests of the Thomas-Morse O-19, the Air Corps gave the company the order for seventy airplanes. The Materiel Division purchased a few more metal-frame types as experimental models, including its first metal pursuit since 1922, the Berliner-Joyce XP-16. In addition, the division ordered two Douglas metal types for delivery the next fiscal year, the XO-31 and the twin-engine XO-35, which was also purchased in a light bomber version, the XB-7. These Douglas models had corrugated dural monocoque fuselages similar to the Thomas-Morse O-19, and fabric-covered metal wings.[37]

By mid-1931, metal airplanes dominated the new models being developed for the Air Corps. Even the Fokker Aircraft Corporation, long a proponent of wooden wing construction, developed a metal-winged attack monoplane, the XA-7. Excluding training planes, which continued to use wood construction, and transport planes, which were versions of commercial airplanes, the Materiel Division had ordered or was considering for purchase nineteen new airplane types, of which all but five had metal structures. Both attack planes under consideration used metal-framework wings, as did two out of three light bombers. All three heavy bombers employed all-metal construction, in which metal replaced the fabric wing covering. Of the three airplanes under consideration for the single-engine observation type, all had metal monocoque fuselages and metal wings. The division also ordered twenty-five of the Berliner-Joyce P-16 two-place metal pursuits. The main exception in the trend to metal was the single-place pursuit category, where the two new airplanes under contract were based on the wooden-winged Curtiss P-6. The Materiel Division also ordered five wooden-winged, twin-engine Fokker XO-27 observation planes for service tests, while awaiting delivery of the metal Douglas O-35.[38] The use of metal even increased in existing standard types. In March 1931 the Air Corps ordered 135 P-12Es, a new version of the wooden-winged Boeing P-12 pursuit with a dural monocoque fuselage in place of the fabric-covered metal-framework structure.[39]

In mid-1931, the Air Corps was well on the way to a metal air force, even though most of its standard airplanes in service still had wooden wing spars. Among the new airplanes being considered for purchase in 1931, dural monocoque fuselages and fabric-covered metal wings predominated, with a clear trend to monoplanes instead of biplanes. Meanwhile, the Materiel Division continued its research program in all-metal, stressed-skin wing structures, indicating the division's desire to replace fabric coverings with

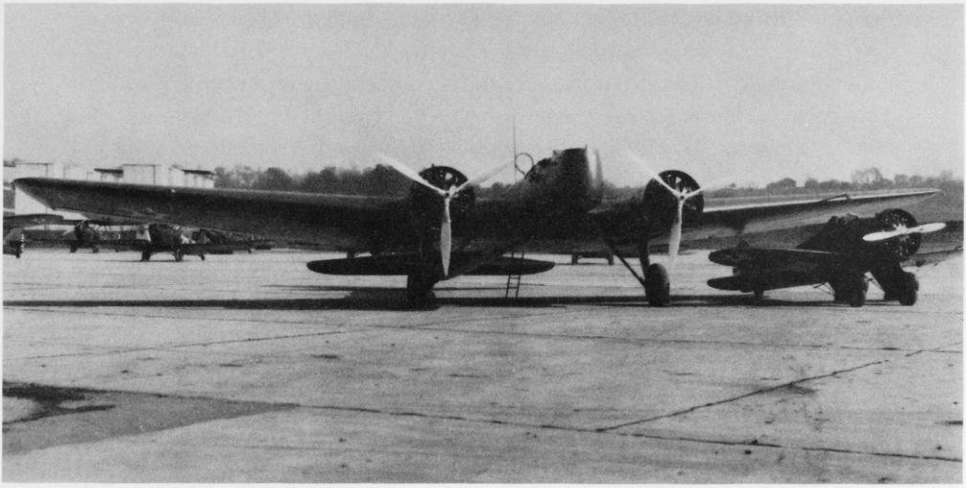

Figure 7.3. Boeing all-metal YB-9 bomber and P-26 pursuit. National Archives at College Park, Record Group 18-WP, photo no. 45258.

metal.[40] Two new airplane projects, both under way by 1931, would finally succeed in producing all-metal, stressed-skin models suitable for standard army types. Boeing developed both airplanes, the YB-9 bomber and the P-26 pursuit.

Boeing began work on the YB-9 bomber in 1930 after the Air Corps issued a circular proposal for an advanced heavy bomber. Boeing was one of three manufacturers in 1931 to compete in this category by building prototypes at their own expense for army tests. The YB-9 was a sleek all-metal monoplane with a retractable landing gear and two cowled, air-cooled engines faired into the leading edge of the wing (figure 7.3). Ford also developed a bomber for this competition, but the Ford's boxy framework and corrugated duralumin covering was clearly outclassed by the Boeing design (see chapter five). The YB-9 first flew in April 1931, and its speed was impressive, better than most pursuit airplanes then in service. In August the army purchased the first two prototypes and ordered an additional five for service tests, designated Y1B-9A, which Boeing delivered between July 1932 and March 1933.[41]

Boeing based the twin-engine YB-9 on its much smaller single-engine Model 200, the Monomail, a low-wing commercial monoplane designed for mail transport (figure 8.2). The Monomail first flew in May 1930, and was Boeing's first all-metal airplane. Although little is known about the motives behind the Monomail's production, its development clearly reveals the influence of military support for metal construction. According to Harold

Mansfield's somewhat fanciful account, Boeing executives Claire Egtvedt and Eddie Hubbard conceived the Monomail in September 1928, five months after the contract for the XP-9. The Monomail's smooth-skinned monocoque fuselage closely followed that of the XP-9. The most radical structural departure in the Monomail was its all-metal stressed-skin wing. The Boeing engineers designed this wing with help from an Army report on internally braced wings by E. C. Friel, an engineer at Wright Field. The Monomail wing had two Warren-truss spars of square dural tubing and Warren-truss ribs, covered with an interior layer of corrugated dural. This corrugated dural was then covered with flat dural sheets to create a smooth wing exterior. The Monomail wing, with a span of 59 feet, followed many of the design details of the Materiel Division's fifty-five-foot cantilever wing, designed during 1928 and 1929. The YB-9, built soon after the Monomail, closely followed the design of the Monomail's fuselage and wing structures.[42] Thus even though the YB-9 was derived from a commercial airplane, this commercial airplane was itself heavily dependent on prior military support.

The Air Corps' second major step to all-metal construction was the Boeing P-26, a one-seat monoplane pursuit (figure 7.3). In mid-1931, the Materiel Division began working with Boeing on the design of a new all-metal pursuit that would incorporate the company's growing expertise with metal stressed-skin construction. Boeing signed a bailment contract in December, and the first model flew in March 1932. After tests, the Army bought the two prototypes in June and assigned them the designation XP-26. Following brief service tests, the Air Corps gave Boeing a contract for 111 P-26As in January 1933, at a total cost of $1.2 million including spare parts and design data.[43]

With the P-26, metal construction appeared to have overcome its severe cost disadvantage in comparison with composite construction, although in real terms the metal airplane remained more costly. The unit cost of the P-26A airframe was only $9,999, compared to $10,644 for the Boeing P-12C pursuit, a wooden-winged biplane with a framework fuselage, ordered in 1930. Both models were produced in similar quantities, implying that metal construction had ceased to impose a cost burden. However, price deflation between 1930 and 1933 obscures the cost comparison between wood and metal construction, and the shift from biplane to monoplane reduced costs regardless of the choice of materials. The wholesale price index for intermediate manufactured goods decreased by 20 percent between 1930 and 1933, as did wages in manufacturing. These decreases more than accounted for the 6 percent price drop from the P12-C to the P-26A. In addition, biplanes generally cost more to manufacture than monoplanes of the same size due to the biplane's greater number of parts and fittings. Nevertheless, the price increase in real terms of the P-26 (about 14 percent) was quite reasonable considering its all-metal construction and substantially increased performance.[44]

Quantity orders for the P-26 gave the Air Corps an all-metal fighter, but the Air Corps had yet to decide on an all-metal bomber, even though all signs pointed to the Boeing YB-9. Unfortunately for Boeing, the YB-9 was just a little before its time. In 1931 the Glenn L. Martin Company began work on a prototype for a light bomber, planned as a twin-engine monoplane with a metal monocoque fuselage and fabric-covered metal wings. By the time the Martin bomber was delivered to the army in March 1932, about a year later than the Boeing YB-9, it had an all-metal stressed-skin wing like the YB-9. Testing at Wright Field led to major changes in the airplane, whose gross weight increased by almost two thousand pounds, giving the Martin plane a useful load about equal to the YB-9. The Martin bomber was also 19 mph faster than the Boeing and had better structural efficiency, with a ratio of useful load to gross weight of almost 42 percent, as opposed to under 38 percent for the Y1B-9A. The Martin prototype was purchased by the Air Corps as the XB-10 in January 1933. At the same time, the Air Corps ordered forty-eight additional Martin bombers at a cost of $2.44 million.[45] Together, the production orders for the P-26 and B-10 firmly established all-metal stressed-skin monoplanes as standard construction for the Air Corps' combat airplanes.

The army's new all-metal airplanes performed better than the composite wood and metal models they replaced, but this improvement did not represent the logical triumph of an inherently superior technology. As the military's adoption of metal demonstrates, the "success" of metal airplanes was as much the result as the confirmation of claims for metal's superiority. This success was only achieved after a long struggle to overcome the problems associated with metal construction. In the shift to metal airplanes, little attention was paid to other materials and forms of construction that could have met the same requirements. In fact, new forms of wood construction offered considerable promise for airplane design, yet the military systematically neglected these new developments (see chapter nine).

By the early 1930s, the momentum toward all-metal airplanes seemed almost unstoppable. This momentum influenced commercial as well as military airplane design. Commercial designers did not stand still to await the definitive military metal airplane. Although strongly influenced by the military, designers of commercial airplanes increasingly developed their own metal airplanes in the late 1920s and early 1930s. After the Rockne crash in 1931, these trends ushered in a new generation of commercial airplanes, the all-metal, stressed-skin airliners.

8

Metal and Commercial Aviation II: The Triumph of the All-metal Airliner

THE SUCCESS of metal airplanes in the early 1930s was not limited to the military. Wood structures also disappeared from the most highly developed type of commercial airplane, the multimotor passenger transport, or airliner. These airplanes carried most of the passengers in the booming air travel market of the interwar years, and much of the mail as well. Beginning in the late 1920s, a handful of manufacturers followed Ford's lead and developed metal airplanes for the passenger market. These new metal airliners benefited from military research and borrowed freely from military designs. After 1929 manufacturers of transport airplanes followed the military trend to stressed-skin construction, adopting a smooth exterior covering instead of the corrugated sheet favored by Ford and Junkers. Despite the trend toward metal, wooden-winged Fokkers retained a large share of the market for multimotor airliners. But after the 1931 crash of a Fokker trimotor that killed Knute Rockne, the airlines turned decisively in favor of all-metal, stressed-skin construction. With the introduction of the Boeing 247 in 1933 and the Douglas DC-2 in 1934, the all-metal airliner assumed its modern structural form, a form that remained basically unchanged for half a century.

Metal Transport Airplanes of the Late 1920s

For two years Ford stood as the only significant builder of metal commercial airplanes in the United States, but starting in 1927 other manufacturers entered the field. Some followed the maximalist path, producing all-metal planes similar to the Ford trimotor, while others pursued the gradualist strategy, developing fabric-covered metal structures patterned after military designs. The maximalists were all new entrants into airplane construction. Established firms, on the other hand, chose the gradualist strategy. These firms typically had close ties to the military and were able to borrow metal wing structures directly from their military models.

Within a few years of Ford's decision to build metal airplanes, three smaller companies introduced all-metal transports patterned after the Ford designs, although none of these models sold well. The first of the new designs appeared in the spring of 1927. It was a monoplane built by the Hamilton Metalplane Company of Milwaukee, whose president, Thomas Hamilton, also headed a successful propeller company. The Hamilton plane was openly imitative of Stout's Air Pullman, even down to the name of the prototype, the *Maiden Milwaukee*. As in the Air Pullman, the Hamilton wing consisted of three spars, with corrugated dural on the wings and fuselage. About six months after the Hamilton monoplane was announced, George H. Prudden came out with a smaller version of the Ford trimotor. Prudden had worked as Stout's chief engineer during design of the first metal transports, a position he briefly retained when Stout's company became part of the Ford Motor Company (see chapter five). When Prudden was fired in September 1925, he moved to San Diego and founded a company to develop his own trimotor. The Prudden transport followed the general outline of the Ford trimotor, including the corrugated covering. In November 1927, soon after the new trimotor's first flight tests, Prudden announced the start of production at an improbable rate of two planes per week. In fact, Prudden built only one trimotor in 1927 and had no sales until February 1928, when a sightseeing company bought one plane for aerial tours of Yosemite National Park. That same month a third all-metal commercial plane was announced, the Thaden T-1, designed by Herbert V. Thaden, founder of the Thaden Metal Aircraft Company of San Francisco. The T-1 was a single-engine, strut-braced monoplane, carrying up to six passengers. Like the Prudden and Hamilton designs, the Thaden was covered in corrugated duralumin. Its wings differed from Stout's in the use of a Rohrbach-type box spar instead of truss spars. Thaden's planes also failed to sell well, and in 1929 the company was bought for $100,000 by a Pittsburgh holding company. The renamed Pittsburgh Metal Airplane Company produced only a few airplanes before being sold in 1930 due to heavy losses.[1]

While Ford and his smaller imitators were following the maximalist path, other firms pursued the gradualist strategy, developing fabric-covered metal wing structures. Among the first was the Russian aviation pioneer Igor Sikorsky, who emigrated to the United States after World War I. In 1924 Sikorsky tested his first American airplane, the S-29, a ten-passenger twin-engine biplane with a fabric-covered steel and dural structure. Sikorsky built only one S-29. Over the next few years, he built nine more airplanes in eight different models, most with duralumin-framework wings, until finally achieving commercial success in late 1928 with the eight-passenger S-38. The S-38 was a twin-engine amphibian, a flying boat with a retractable landing gear that enabled it to fly from both land and water. Aside from the Fords, the S-38 was the first metal-winged commercial airplane to be built in large numbers in the United States, with fifty-five completed by the end of 1929 and a total of 114 built through the early 1930s.[2]

Two other firms introduced metal-framework passenger planes in the late 1920s, Curtiss and Boeing. In contrast to Sikorsky, both were large military contractors, and their military experience directly influenced the design of their commercial airplanes. The first airplane to appear was the Boeing 80, a twelve-passenger trimotor biplane that first flew in August 1928. The Boeing 80 had a steel and duralumin-tube fuselage, dural-tube wing-spar trusses, and duralumin ribs. The wings were fabric-covered except for wood wing tips. The wings of the model 80 were based directly on an unsuccessful navy model, the PB-1, a long-range flying boat that Boeing built in late 1924. Like the model 80, the PB-1 employed truss-type wing spars and wooden wing tips. Although published details on the PB-1 are lacking, the airplane's metal wings were undoubtedly designed in close cooperation with engineers at the NAF. Boeing produced only four model 80s before introducing the model 80A, which used larger engines, increasing passenger capacity to eighteen. Boeing built a total of sixteen model 80s, including all variants.[3]

The military influence was even more direct on the Curtiss transport, the Condor. The Condor was converted from the Curtiss B-2 twin-engine bomber, first flown in 1927 but not ordered in quantity until 1929. The B-2 wings used welded steel-tube wing spars and duralumin ribs with fabric covering. In 1928 the Army permitted Curtiss to develop a commercial version of the B-2. The first Condor transports differed from the B-2 primarily in the fuselage, which was modified to accommodate eighteen passengers. The first three Condors followed the B-2 design down to gunners' cockpits behind the engines, which were merely faired over in the transport. Curtiss built only three more Condors, although without the gunners' cockpits.[4]

Before 1930 the shift to metal among commercial airplanes was little more than a trickle. Of the 130 types of American airplanes certified for use in passenger service in 1930, 88 percent used wood for the main wing structures. Of the 12 percent with metal wings, only the Ford and Sikorsky models came close to commercial success. Nevertheless, by 1930 metal types had become the majority for multimotor passenger airplanes, a trend that would intensify in the early years of the decade.[5]

Despite the trend to metal in large passenger airplanes before 1930, these aircraft did not incorporate the type of metal structures that would come to dominate the most successful metal airliners. The new airplanes would be based neither on the corrugated-skin all-metal types nor the fabric-covered metal frameworks. By 1930 a few firms were working on another form of all-metal construction that would come to define the modern airliner, and displace all other types of structures for large commercial aircraft.

Stressed-Skin and Commercial Metal Airplanes

One type of structure dominated the new generation of all-metal airliners that emerged in the early 1930s—stressed-skin construction. These new metal airliners shared common roots with their military cousins and benefited from the same government-funded research. The first successful metal stressed-skin airliners appeared in 1930, the Boeing Monomail and the Northrop Alpha. These two small airplanes paved the way for the "modern airliner"—the all-metal, twin-engine planes that replaced the Fokker trimotors after the Rockne crash.

Until the early 1930s, most American passenger airplanes had framework structures, which derive their strength from a skeleton of members arranged to resist the loads imposed on the structure. These structures derive little strength from their coverings, even rigid coverings like the corrugated duralumin or plywood that sheathed the framework fuselages of the Fokker and Ford transports.

Even in the 1920s, framework airplanes faced competition from another type of structure, one that derived much of its strength from its smooth, load-bearing skin. Engineers have used a variety of terms to describe this type of structure, among them *stressed-skin*, *monocoque*, *shell*, and *thin-walled*. All refer to structures in which the covering contributes a large part of the structures' strength. In the 1920s, the most common term was *monocoque*, but after 1930 the term *stressed-skin* became widespread. *Monocoque* usually referred to fuselage construction, though it was occasionally used for wings as well. The term was first applied to the wooden Deperdussin racer of 1912 (see chapter six). Its fuselage was a "true" monocoque, with no vestige of a framework.[6] True monocoque fuselages were rare, however, due to the low buckling strength of the thin shell, especially when using metal. Most practical monocoques were reinforced, usually with longitudinal "stringers" and transverse rings. These structures were sometimes referred to as semimonocoque. In semimonocoque structures, the grid of stringers and rings resembled a framework, somewhat blurring the boundary between monocoques and frameworks and creating some terminological confusion.[7] For this reason, *stressed-skin* provides a more useful rubric than *monocoque*, clearly encompassing all aircraft structures that use the covering as a load-bearing element.[8]

Stressed-skin construction proved attractive to airplane designers because it solved two problems at once, providing an external surface as well as the load-bearing structure. Monocoque fuselages also appealed to designers seeking to reduce drag. The monocoque fuselage provided a well-streamlined shape with a circular or oval cross-section, while the framework fuselage had a rectangular cross-section that requires external fairings to produce a streamlined shape.[9]

Despite these advantages, a number of factors hindered the spread of stressed-skin construction after World War I. One was the difficulty in predicting the strength of such structures. Monocoque structures generally failed by compressive buckling, which proved much less amenable to calculation than typical failures in beams and framework structures. Aeronautical engineers received little help from other technical fields, except perhaps naval engineering. Due to weight requirements, airplanes had much thinner sections than other engineering structures. This difference rendered "all experience gained in machine or bridge construction . . . practically inapplicable to airplanes." Although mathematical analysis of stressed-skin structures became a major field of aviation research in the 1930s, the design of these structures remained thoroughly empirical.[10]

Problems of weight also limited the appeal of stressed-skin structures, especially for metal wings. Junkers abandoned the stressed-skin wings used in his first all-metal fighter due to their excessive weight. As Junkers himself admitted, his construction "allowed only to a small degree the utilisation of the compressive strength of the material." In the early 1920s, American attempts to design airplanes with fully stressed coverings, for example the Stout ST and Gallaudet DB-1, also proved unsuccessful, largely due to excessive weight caused by the low buckling strength of thin metal coverings.[11]

Maintenance problems created further obstacles to the widespread adoption of monocoque structures. The army rejected metal coverings in the early 1920s in large part because of difficulties in maintenance. Stressed coverings prevented the inspection of the structure for deterioration and greatly complicated the removal and installation of equipment. To meet these objections, designers had to provide removable panels for access and inspection, which increased the complexity of the structure.[12]

Despite these problems, a number of factors began to work in favor of stressed-skin construction later in the decade. Most importantly, stressed-skin found an important ally in the progress ideology of metal. Advocates of metal airplanes sought not only to eliminate wood structures but also fabric coverings, since fabric also suffered from an association with pre-industrial materials. However, even the thinnest practical dural sheet weighed six times more than doped and painted fabric. Simply replacing fabric with metal would have produced a prohibitive weight increase. Metal covering could only be justified by putting it to work, that is, by making it bear part of the wing and fuselage loads, thus permitting a reduction in the weight of the internal structure.[13]

By itself, the progress ideology of metal cannot explain the shift to stressed-skin construction. The symbolism of fabric had little evocative power compared to that of wood, and many designers happily continued to use fabric-covered metal wings. In the United States, the question of monocoque versus framework structures was not even clearly formulated until the late 1920s. Stressed-skin construction only became a recognizable topic in the late 1920s when the army and navy began supporting research on stressed metal coverings.

A number of factors encouraged this military support. Advocates of stressed-skin designs argued that monocoque structures could be pierced by bullets and shells without failing, a clear military advantage. A more direct stimulus was the navy's interest in improving the design of metal flying-boat hulls, improvements that depended on better information about the behavior of metal plates. In early 1927 the Bureau of Standards began research for the navy on the behavior of thin metal sheets in compression. The results of this research, published in 1930, stimulated the development of some of the first practical design formulas for metal monocoque structures.[14]

In fiscal year 1928, the army took up stressed-skin research when Wright Field engineers began a major, multiyear project to develop an all-metal stressed-skin wing. This project focused self-consciously on wings of the type used by Adolph Rohrbach in his all-metal flying boats and involved a theoretical analysis of the stresses in this type of wing, as well as the design and testing of experimental wings. The Rohrbach wings were based around a single "box" spar, a tapered structure of rectangular cross section that ran the entire length of the wing. The sides of the "box" consisted of lattice girders fashioned from sheet duralumin, while the top and bottom consisted of dural sheet, with U-shaped stringers riveted to the inside of the sheet parallel to the spars. The Rohrbach wing had no traditional ribs but rather widely spaced bulkheads that maintained the shape of the box. The wing was made complete with the addition of the leading and trailing edges, separate structures that were bolted to the front and back of the box (figure 8.1).[15]

The reasons for Wright Field's interest in stressed-skin wings are unclear. Peter Brooks has suggested that Adolph Rohrbach directly sparked the renewed American interest in stressed-skin construction during the late 1920s, arguing that to "Rohrbach . . . must undoubtedly go much of the credit for the form of construction adopted by the Americans for the 'modern' airliner." Brooks claims that Rohrbach influenced American designers through a paper presented to the Society of Automotive Engineers and published in January 1927, a claim repeated by many historians of aviation. There is, however, little evidence that Rohrbach's paper had sufficient impact to shift the course of American airplane development. Rohrbach devoted most of his paper to manufacturing problems of a rather mundane variety. His discussion of the box-spar wing amounted to only half a page, with little information on its technical merits. American publications had described the Rohrbach wing structure in some detail as early as 1921, and Rohrbach's paper provided little new information. Both the army and navy were already quite familiar with Rohrbach's designs, the navy having built a Rohrbach-type wing for the NM-1 in the early 1920s (see chapter seven). The army's interest in box-spar wings was not the result of trans-Atlantic technology transfer but rather a reconsideration of a previously rejected design in light of new conditions.[16]

The real impetus behind the development of stressed-skin structures was the pressure for increased speeds, coming initially from the military. Grad-

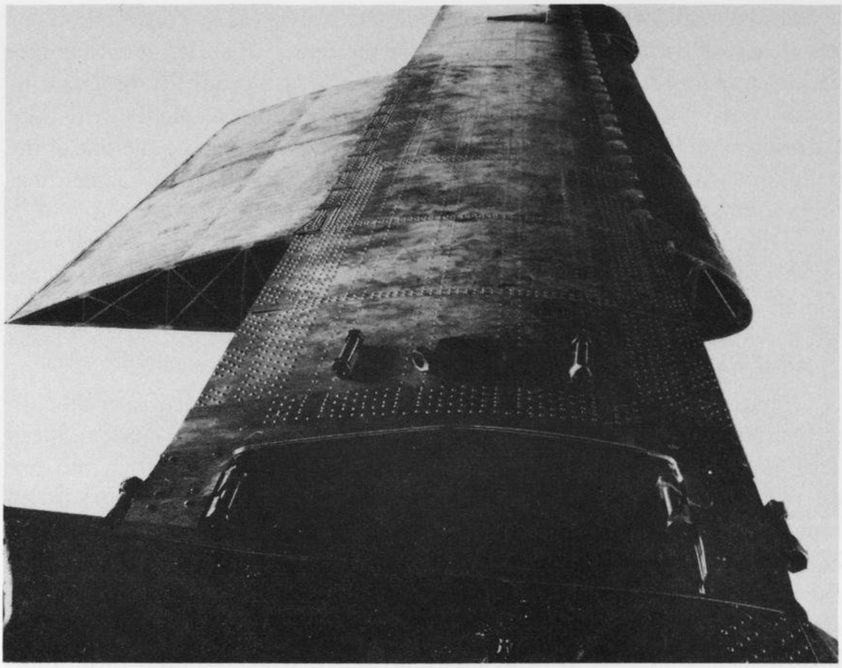

Figure 8.1. Rohrbach metal box-spar construction, c. 1927. Note the central box beam with detachable leading and trailing edges. National Air and Space Museum, Smithsonian Institution (SI neg. no. 92-13553).

ual improvements in the power and weight efficiency of aircraft engines permitted the army to demand higher speeds for new combat planes. For example, in fiscal year 1929 the army contracted with Boeing to produce an experimental all-metal monoplane pursuit with a top speed of 225 mph (the XP-9).[17]

Higher speeds favored stressed-skin construction on a number of counts, most directly by putting pressure on designers to minimize drag. Higher speeds reduced the proportion of drag attributable to unavoidable "induced" drag, the resistance created by the lift of the wing. The remaining "parasitic" drag resulted from disturbances to the flow of air past the airplane and also the friction of the air on the airplane's skin. This parasitic drag could be reduced by careful streamlining to insure a smooth flow of air. Such streamlining was easier for a monocoque fuselage than a framework structure. Designers did streamline framework fuselages by using external fairings, but at the expense of increased complexity and weight. The monocoque fuselage, in contrast, provided a well-streamlined shape with little fairing, while permitting full utilization of the enclosed space without the obstructions present in framework structures.[18]

The demand for higher speeds promoted stressed-skin construction for wings as well as fuselages. Beginning in the late 1920s, designers became willing to accept the disadvantages of higher wing loadings in order to increase speeds. Wing loading refers to the weight of the airplane divided by the wing area. Higher wing loadings lowered drag by reducing the size of the wing, but with the drawback of increased landing speed. At the same time, higher wing loadings increased the force per unit area that a stressed-skin wing had to absorb, thus permitting the use of thicker skins, which were more resistant to buckling. These more concentrated forces reduced the weight disadvantage of the stressed-skin wing in comparison to the framework wing. At the time, however, aviation engineers apparently did not understand this relationship.[19]

General adoption of the unbraced monoplane also favored stressed-skin structures but by a more circuitous route. Unbraced monoplanes reduced drag by eliminating all exposed parts of the wing structure that did not contribute to lift, such as bracing wires and the interplane struts used with biplane wings. A monoplane wing has much less torsional stiffness than an equivalent biplane wing, making the monoplane wing more susceptible to the problems of divergence and flutter. In divergence, a wing develops a significant twist at high speeds, which can tear the wing from the fuselage. Insufficient stiffness also contributes to flutter, large-amplitude vibrations that can literally shake a wing to pieces at high speeds. Stressed-skin wings proved significantly stiffer than framework structures of equal weight.[20]

The army's research at Wright Field confirmed the stiffness advantage of stressed-skin wings, both theoretically and experimentally. In 1929 John E. Younger, a civilian engineer at Wright Field, developed a theoretical analysis of the contribution of stressed coverings to torsional stiffness. Two years later a series of tests by the Air Corps demonstrated that stressed-skin wings had superior torsional stiffness. This research helped convince the army to buy airplanes with stressed-skin wings, starting with the Boeing XB-9 in August 1931 (see chapter seven).[21]

Even before the army began buying airplanes with stressed-skin metal wings, several commercial models appeared using stressed-skin structures with smooth metal skins. The most influential were the Boeing Monomail and the Northrop Alpha. Although they were direct antecedents to the two airplanes that established the dominance of the all-metal airliner, the Monomail and Alpha received only moderate attention when they first flew in the spring of 1930. Both models broke with the design practice of Junkers-type all-metal airplanes, substituting a smooth, internally stiffened dural skin for the corrugated covering. Both were fully cantilevered low-wing monoplanes, driven by a single well-cowled air-cooled engine. With these models, the ideals of the *neue Stil* finally achieved realization in a commercially viable form.[22]

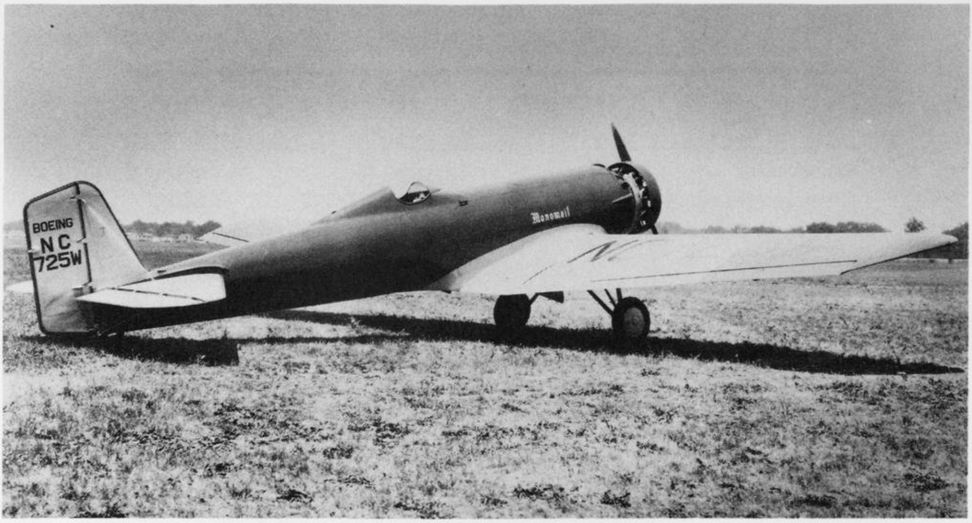

Figure 8.2. Boeing Monomail all-metal mailplane. National Archives at College Park, Record Group 18-WP, photo no. 38781.

The Monomail, also known as the model 200, was designed as a fast mail carrier with no provision for carrying passengers (figure 8.2). Its design was directly influenced by the army's metal airplane work (see chapter seven). The Monomail represented a profound shift in design philosophy for Boeing, which had previously followed the gradualist strategy with regard to metal airplanes. The new philosophy proved successful in the Monomail, in terms of performance if not profits. The Monomail performed substantially better than Boeing's model 40, the single-engine, wooden-winged biplane that launched Boeing as a successful contract airmail carrier. Table 3 compares the Monomail with the Boeing 40-B of 1928. With only fifty more horsepower, the Monomail flew 26 mph faster than the 40-B and carried over seven hundred pounds more useful load. On the other hand, the Monomail's ceiling was a thousand feet lower than the 40-B's, and it could barely get airborne from some of the high-altitude airfields along the Seattle-Chicago mail route.[23]

Although the Monomail represented a real advance over the previous generation of mail transports, it did not provide clear evidence for the superiority of metal construction or of the *neue Stil* in general. The Monomail involved so many changes from the model 40 that the factors responsible for its improved performance are difficult to isolate. The path from the 40-B to the Monomail involved a shift from biplane to monoplane; framework to stressed-skin; and wood, steel, and fabric to duralumin. In addition, the Monomail was one of the first commercial airplanes to employ a retractable

TABLE 3
Comparative Performance of Single-engine Mail Planes, 1930

	Boeing 40-B	*Monomail*	*Carrier Pigeon II*
Horsepower	525	575	600
Gross weight (lbs.)	6,079	8,000	7,600
Weight empty (lbs.)	3,542	4,758	4,235
Useful load (lbs.)	2,537	3,242	3,365
Load efficiency factor[a]	42	41	44
Wing area (sq. ft.)	547	535	550
Wing loading (lbs./sq. ft.)[b]	11.1	14.9	13.8
Top speed (mph)	132	158	150
Service ceiling (ft.)	15,000	14,000	14,200

Sources: Peter M. Bowers, *Boeing Aircraft since 1916*, 2d ed. (London: Putnam, 1968), 112, 176; Peter M. Bowers, *Curtiss Aircraft, 1907–1947* (London: Putnam, 1979), 195–96.

[a] Load efficiency factor equals useful load expressed as a percent of gross weight (UL/GW × 100).

[b] Wing loading equals gross weight devided by wing area.

landing gear to reduce drag. In any case, the Monomail's performance does not seem remarkable compared to a contemporary mail plane of standard construction, the six-hundred-horsepower Curtiss Carrier Pigeon II of 1929. This traditional wooden-winged biplane was slower than the Monomail by 8 mph, but it carried 123 additional pounds of useful load with a weight efficiency of 44 percent (table 3). In terms of performance, the *neue Stil* had yet to demonstrate any clear advantage.[24]

Boeing gained more from the Monomail in experience than in revenues. Even before it was completed, the Monomail served as the basis for design of the YB-9 twin-engine bomber for the army. But the Monomail itself never went into production. Boeing built only one additional Monomail, the model 221, with a fuselage modified to carry passengers in addition to mail.[25] The published record does not reveal why the Monomail did not enter production. Given the history of metal construction, it probably suffered from excessively high manufacturing costs.

The second successful example of the *neue Stil* to appear in the spring of 1930 was the Northrop Alpha, designed by John K. Northrop, who had previously designed the wooden Lockheed Vega. Like the Monomail, the Alpha was a low-wing all-metal monoplane using stressed-skin construction and a smooth skin (figure 8.3). Northrop left Lockheed in 1928 and founded the Avion Corporation to develop metal airplanes. In 1929 Avion became the Northrop division of the United Air & Transport Corporation (UATC), which also owned Boeing and Pratt & Whitney. Although William Boeing

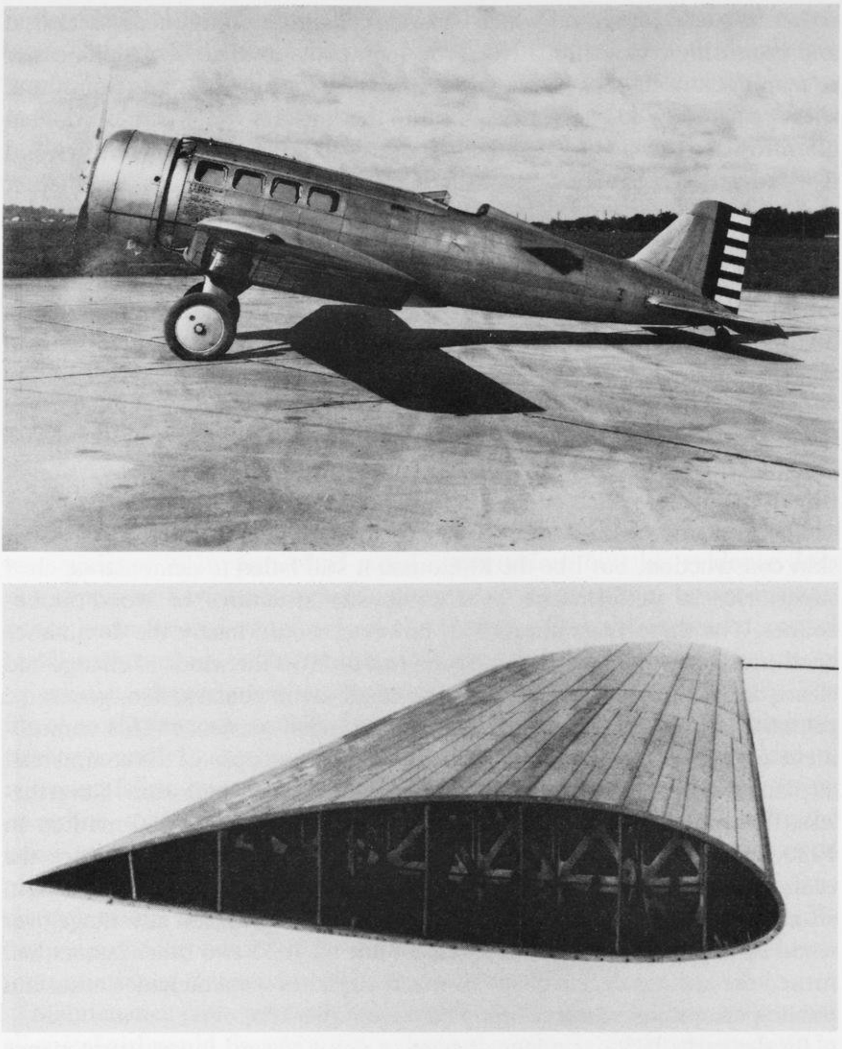

Figure 8.3. (Top) All-metal Northrop Alpha (Army Y1C-19). (Bottom) A cross-section of the "multispar" wing. National Air and Space Museum, Smithsonian Institution (top, USAF photo no. 167068; bottom, SI neg. no. 96-15635).

played an active role in acquiring Northrop's company for the UATC, the Alpha does not appear to have influenced the Monomail project, which was already well under way when Northrop became part of the UATC.[26]

In many respects the Alpha was a metal version of the Vega. Like the Vega, the Alpha carried six passengers and reached a top speed of 170 mph. It was not the Alpha's aerodynamics that drew attention, however, but rather its metal structure, which *Aviation* magazine pronounced "a radical and promising innovation." Northrop took pains to make the Alpha easier to manufacture than previous metal airplanes, forming all parts from dural sheet rather than costlier extrusions and castings. Its wings employed what Northrop termed a multicellular structure, harking back to the plywood stressed-skin wings used in the Curtiss racers of the early 1920s (see chapter six). The Alpha's wing structure had multiple spars spaced roughly twelve inches apart, and intersecting ribs at twenty-four-inch intervals, thus creating rectangular cells. Flat duralumin sheet was riveted to the spars and ribs, forming the external wing surface. The spars took the shear loads in bending, while the upper and lower wing coverings carried the compression and tension loads, which in a normal spar would have been absorbed by the flange. The wing covering was reinforced by stringers running parallel to the spars, as in Rohrbach practice, preventing the covering from buckling under the main bending loads. Northrop produced about ten of the first version of the Alpha, five of which entered service for TWA in 1931.[27]

The Alpha provided good evidence for the viability of all-metal, stressed-skin construction, but like the Monomail it still failed to demonstrate clear superiority in performance over composite structures or wood monocoques. The three years after 1930, however, would insure the dominance of all-metal transport airplanes. By the end of 1930 the winds of change had clearly begun to blow in the direction of all-metal construction, generated primarily by the military's commitment to metal airplanes. This commitment assumed even greater importance with the collapse of the commercial airplane market as the industry sank deeper into the Depression. Nevertheless, the military could not dictate designs for the commercial market. In 1930, metal construction still cost more than wood, especially since the economies expected from mass production never materialized. In addition, all-metal construction did not appear to have any significant advantage over wood in terms of structural efficiency.[28] But by 1933 two other factors had turned the airlines decisively to all-metal airplanes—maintenance costs and public perceptions of safety.

By the early 1930s, evidence began to point toward lower maintenance costs for all-metal construction. Maintenance accounted for a large part of an airliner's direct operating costs, typically 20 to 25 percent, roughly half of which was attributable to the airframe.[29] Proponents of metal had always asserted that metal airplanes cost less to maintain than those of wood and fabric, but practical experience during most of the 1920s contradicted this claim. However, by about 1930 some airlines concluded that metal coverings cost significantly less to maintain than fabric or plywood. Fabric needed regular replacement, typically after every 750 to 1,000 flying hours. As early as 1926, Adolf Rohrbach had argued that eliminating the periodic replacement of fabric offset the increased cost and weight of metal coverings. Unfortunately, the corrosion problems experienced with duralumin negated any theoretical savings. The balance in maintenance costs appears to have tipped in favor of metal with the widespread adoption of Alclad beginning in 1928, although the evidence remained inconclusive for several years. Alclad was used on the corrugated skin of the Ford trimotors, which saw extensive service on many airlines, permitting the airlines to make comparisons with other types of wing coverings. In 1930 a preliminary study of maintenance costs for the airlines of the UATC concluded that metal coverings were preferable to wood and fabric. This result corroborated a similar study by Pan American, which found that metal coverings "quite definitely" had lower maintenance costs than wood or fabric. A survey of the maintenance chiefs of all major airlines produced similar results in 1932, although the consensus still held that fabric-covered airplanes weighed less than those of metal and that fabric offered advantages for emergency repairs.[30]

The lower maintenance costs of metal-covered airplanes supplied important evidence in support of all-metal construction, but this evidence does not appear to have been a major stimulus to its adoption. Lower maintenance costs favored metal only if the savings offset the increased cost of metal construction. Such comparisons depended on the assumptions used to calculate depreciation, assumptions that remained fairly arbitrary. The life of an airplane was usually determined by obsolescence rather than deterioration, and obsolescence was extremely difficult to estimate. In addition, replacing fabric represented a very small part of the total cost of operating an airline, so the advantage of metal was unlikely to be decisive. Finally, the lower maintenance costs of metal coverings were not inherent; improved plywoods in the late 1930s reduced the relative advantage of metal (see chapter nine). Nevertheless, evidence on maintenance costs undoubtedly swayed some airlines toward purchasing all-metal designs, and helped promote continued development of metal airplanes.[31]

Maintenance costs were not responsible for the final, decisive shift to the all-metal airliner in the early 1930s. Instead, it was Knute Rockne's death in the 1931 crash of a Fokker trimotor that spelled the end of the wooden airliner (see chapter six). In 1931 Fokker was the only major manufacturer still producing large, wooden-winged, multimotor passenger airplanes suitable for airliner service. The accident led to discovery of glue deterioration in the wings of several Fokker F-10As. The Aeronautics Branch of the Department of Commerce first grounded the suspect Fokkers and then required the airlines to undertake costly periodic inspections of the returning airplanes. But even with the new inspection procedures, the airlines had lost confidence in the Fokker construction. Not long after the Fokkers returned to service, Pan American Airways retired its seven F-10As, and over the next three years other major airlines gradually withdrew their Fokker trimotors from service. Anthony Fokker was forced from the company he had founded, and his chief engineer, Albert Gassner, was replaced by Herbert V. Thaden, a strong advocate for metal airplanes. Anthony Fokker returned to Holland, and the United States lost its most important advocate for wooden airplanes.[32]

The Triumph of the Twin-Engine Metal Airliner

The gradual withdrawal of the Fokkers from airliner service created a demand for new airplanes as air travel continued to grow despite the Depression. With Ford no longer producing airplanes, development of new models fell to the remaining major airplane manufacturers. The resulting twin-engine, all-metal monoplanes revolutionized air transport, completely replacing the trimotors that had formed the backbone of passenger air travel. These new designs sharply increased flying speeds, reduced costs, and facilitated a rapid rise in passenger traffic with fewer airplanes. In 1931 the domestic airline fleet consisted of 490 airplanes, mostly Fords and Fokkers. By 1938, the domestic airline fleet had declined to only 260 airplanes, consisting almost entirely of the new twin-engine models. Yet this transformed airline fleet carried more than twice as many passengers and twice as much mail as the airline fleet of 1931.[33]

The rise of the twin-engine, all-metal monoplane airliner in America is an oft-told story, beginning with the Boeing 247, the first "modern" airliner, and culminating with the Douglas DC-3. This story has become an essential element of the mythology of aviation, based primarily on recollections of participants and information from public-relations departments of airplane manufacturers. Accounts of these events exaggerate the connections to German developments in metal aircraft while minimizing the direct contributions of the American military. These accounts uncritically view the shift to metal as an example of technical progress, which thus requires little explanation.[34] As I have argued throughout this book, the rise of metal airplanes requires considerable explanation and cannot be understood without reference to the technical prejudices of the engineering community and the influence of the military on design trends. When the metal airliner finally came of age in 1933, it owed its success to more than a decade of development inspired by these prejudices, with funding and technical direction from the army and navy.

The first of the new models to appear was the Boeing 247. Boeing engineers first considered developing a twin-engine transport based on the YB-9 bomber in early 1931, while the YB-9 was still under construction, but this initial proposal was shelved due to insufficient single-engine performance. Then came the Rockne crash at the end of March, and the successful first flight of the YB-9 in April. The new bomber proved to have excellent performance, with a top speed of more than 170 mph. In September Boeing began working seriously on a twin-engine all-metal transport patterned after the YB-9. The new airliner was intended to supply the recently formed United Air Lines, a consolidation of the transport operations of the UATC, Boeing's parent company. In November, United Air Lines agreed to buy sixty of the new airplanes, designated the Model 247. With an initial price estimated at about $41,000 (later rising to $68,000), this was the largest single commercial aircraft order ever received by an American manufacturer. Production of the 247 began in earnest in March 1932, though the first plane was not ready for flight tests until February 1933. When it finally flew, the 247 exceeded expectations, with a maximum speed of 182 mph and a cruising speed of 161 mph. The 247 entered airline service with United at the end of March. Using the 247, United established a transcontinental schedule of just under twenty hours, seven hours faster than TWA's competing time using Ford trimotors.[35]

As far as the Air Corps was concerned, the 247 relied so closely on the design of the YB-9 that its early sale abroad would have constituted a security breach. While the first airplane was still under construction, the Air Corps received word of Japanese interest in buying the 247. Brig. Gen. H. Conger Pratt, chief of the Materiel Division, warned Boeing against such a sale. The Air Corps' policy was not to hinder the export trade unless it compromised military secrets. In Pratt's opinion, that was precisely what foreign sales of the 247 would do: "In this instance the commercial transport in question is a direct development of a military type which is still in a Service Test stage, and it incorporates structural and design improvements that are directly the result of developments of both your company and the Materiel Division." Boeing promised not to sell the airplane abroad without government permission.[36]

The corporate connection between Boeing and United Air Lines sparked the development of a rival airplane that was to make the 247 obsolete—the Douglas DC-1. When Boeing began working on the 247 for United, other airlines got wind of the project. With a projected cruising speed of over 150 mph while carrying ten passengers and mail, the 247 promised to give United a major advantage over its competitors. Transcontinental and Western Air (TWA), a major trunk-line competitor to United, approached Boeing about purchasing the 247. Boeing was willing to sell to TWA, but the UATC board in New York refused to allow the sale until Boeing had filled United's order for sixty airplanes. TWA was unwilling to wait and also reluctant to become dependent on the products of a manufacturer allied with a rival airline. So, on August 2, 1932, TWA submitted a terse, two-page

Figure 8.4. Douglas DC-1 prototype with TWA markings, March 6, 1934. Courtesy Douglas Products Division, Boeing Company, Long Beach, Calif., photo no. SM5807.

letter to five manufacturers requesting bids for an airliner to rival the 247. This letter specified a trimotor monoplane, preferably of all-metal construction, with a twelve-passenger capacity and a cruising speed of 150 mph. The Douglas Aircraft Company responded with a proposal for a twin-engine, all-metal airliner, the DC-1.[37]

TWA accepted the Douglas proposal for a twin-engine design instead of a trimotor after Douglas gave firm guarantees on single-engine performance. Douglas received a $125,000 contract for the DC-1 prototype, with an option for purchase of another sixty at a unit price of $58,000. The DC-1 prototype first flew on July 1, 1933, only 11 months after TWA first expressed interest in the project and little more than eight months after Douglas received its contract (figure 8.4). In performance the DC-1 significantly outpaced the Boeing 247, reaching a top speed of 210 mph and a cruising speed of 190 mph at eight thousand feet, while carrying twelve passengers. TWA placed an initial order for twenty-five of the new airliners, modified to carry fourteen passengers, at a price of $65,000 each. This airplane became known as the DC-2 and began service for TWA in May 1934, a little over a year after the 247. In 1935 Douglas widened the DC-2 fuselage and substituted more powerful engines, increasing passenger capacity to twenty-one with only a slight increase in operating costs. This new plane, the DC-3, entered service in 1936.[38]

The DC-2 proved tremendously successful, and the DC-3 even more so. By the spring of 1935, Douglas had received orders for 102 DC-2s, and would eventually produce 220. Douglas built about six hundred DC-3s for civil use, and thousands more for the military during World War II. The DC-3 quickly came to dominate the fleets of U.S. airlines. By the end of 1941, 270 of the 350 planes in the domestic airline fleet were DC-3s, and another thirteen were DC-2s. Together these two Douglas models accounted for 87 percent of all available airline seats.[39]

The story of the DC-1, -2, and -3 is one of the central myths of the popular history of aviation. According to this myth, Douglas was "a small, struggling firm in Santa Monica" with little background building commercial airplanes and not "one iota of experience in designing a metal airplane." However, in airplane design heroics are a poor substitute for practical experience, especially in metal monocoque construction, where engineers lacked well-developed design criteria and instead relied on extensive testing of components and assemblies. Rather than heroics, the success of the DC-1 was largely dependent on Douglas's position as a major military supplier.[40]

In the first sentence of its announcement of the DC-1, *Aviation* magazine noted that "the output of the Douglas plant . . . has to date been definitely militaristic." Between 1921, when Donald Douglas began building airplanes, and the end of 1933, when production of the DC-2 began, the Douglas company built 1,100 airplanes, almost all for the U.S. military, primarily the army. In 1930, with the Depression battering commercial aircraft producers, Douglas sales rose to more than $4 million, more than 10 percent of all sales by domestic aircraft manufacturers ($34 million, excluding engines). Douglas sales fell some during the next three years due to reductions in military aircraft purchases, but the company remained profitable while other firms suffered heavy losses or closed down completely. As late as 1934, when sales of the DC-2 were increasing rapidly, Douglas earned 84 percent of its gross income from sales to the U.S. government, mostly the army.[41]

Douglas Aircraft's close relationship to the military aided the development of the DC-1 in two ways, financially and technically. Its strong military sales gave it sufficient capital for the development of the DC-1. Development costs of the DC-1 totaled $307,000, which probably exceeded that of any previous commercial airplane. Engineering costs alone approached $83,000, of which the largest part was undoubtedly for stress analysis. Another reason for the high development cost was the need for extensive static tests, both for design of the structure and to insure that the completed airplane met strength requirements. More than four hundred separate tests were performed on the DC-1 and its structural components. The contract with TWA gave Douglas only $125,000 for the DC-1, resulting in a net loss of $182,000. Losses continued when production began. The first twenty-five DC-2s sold to TWA produced a net loss of $266,000, for a total loss of roughly $450,000. Douglas would never have been able to absorb this loss if it had been dependent on commercial sales.[42]

However significant the financial contribution of the military to Douglas's ability to build the DC-1, the military's technical contribution was perhaps more important. The direct contribution of military designs to the DC-1 is difficult to uncover without access to internal company documents. Nevertheless, the available evidence shows that Douglas's close relationship with the army and navy gave the company the technical background necessary to build the DC-1. Almost all of the airplanes that Douglas produced for the army during the 1920s were fabric-covered biplanes of composite construction, with welded steel-tube fuselages and wooden framework wings. Douglas did, however, follow the army in its gradual adoption of metal construction. As early as March of 1923, Douglas submitted a design to the Air Service for an all-metal bombing plane. Douglas participated in the army's first metal spar study beginning in 1923, which gave Douglas experience with duralumin design and fabrication. In 1927 Douglas produced the first metal spar that exceeded the performance of a wood spar in the army's spar study (see chapter four). When Thomas-Morse finally convinced the army of the benefits of the corrugated metal monocoque, Douglas followed with its own metal designs. The first was the XO-31 monoplane in 1930, with fabric-covered metal wings and a corrugated monocoque fuselage like that of the Thomas-Morse. Douglas also benefited from the Navy's work on metal flying boats, receiving a $1.5 million contract at the end of 1929 to produce twenty-five PD-1 metal flying boats patterned after the NAF's PN-12.[43]

Meanwhile, Douglas had begun to investigate smooth metal monocoques, guiding a research project at Stanford and supplying the necessary test specimens. Caltech conducted similar research under contract from Douglas. When the Air Corps purchased five service test models of the O-31, Douglas converted the fuselage to a smooth dural monocoque. A similar process occurred with two twin-engine army models, the O-35 and the B-7, both built originally with corrugated monocoques and then redesigned for smooth monocoques. Thus when TWA's request for an all-metal airliner arrived in August of 1932, Douglas had already designed and built army models with smooth metal monocoques. Finally, Douglas engineers working on the DC-1 were undoubtedly familiar with the army's work on stressed-skin metal wings.[44]

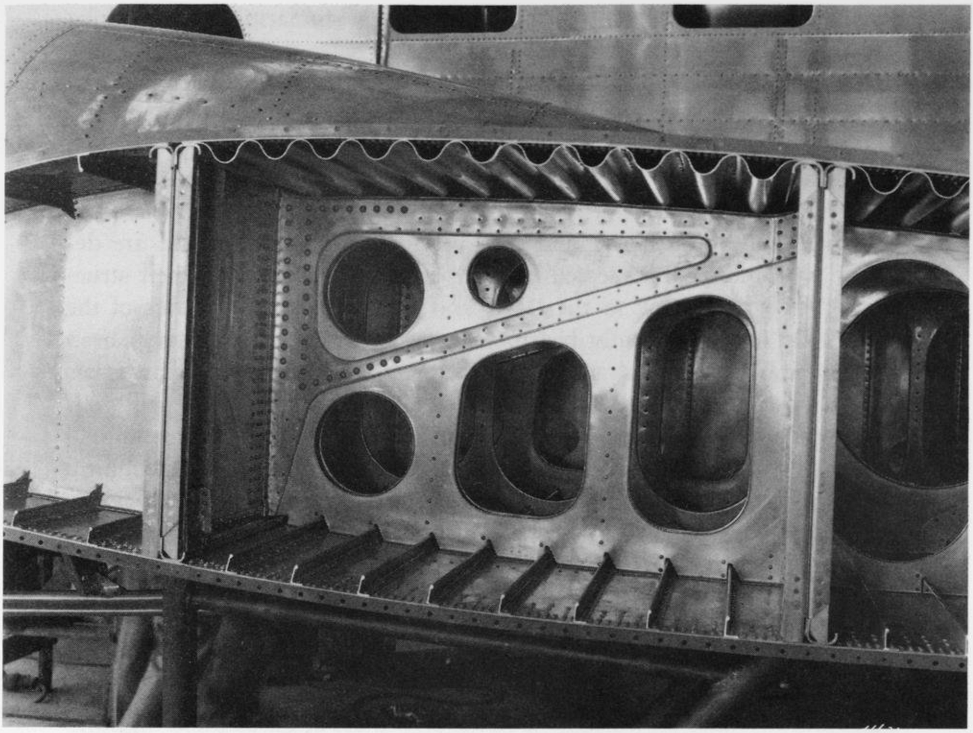

Figure 8.5. DC-1 inner wing section, May 11, 1933. Note the corrugated upper flange, similar to that of the Wright Field metal wing. Courtesy Douglas Products Division, Boeing Company, Long Beach, Calif., photo no. SM4638.

One aspect of the DC-1 mythology links its wing design to the multicellular metal wing that John K. Northrop used on his Alpha transport. Northrop left the UATC in 1931 and established a new company in early 1932 as a Douglas subsidiary. This subsidiary built single-engine, all-metal airplanes similar to the Alpha. Supposedly, Douglas thus gained access to Northrop's experience in metal construction. The DC-1 did incorporate elements of the Northrop wing, including multiple spars and the use of the wing covering to support most of the main bending loads. In addition, Douglas publications followed Northrop in referring to the DC-1's wing construction as multicellular. This link to Northrop suggests a civilian antecedent for the DC-1 wing, since Northrop had little involvement with the military. However, the inner section of the DC-1 wing, the part containing the engine nacelles, used corrugated sheet inside the upper surface of the wing, reminiscent of the experimental army wings and the Monomail (figure 8.5) rather than the Alpha. Northrop also had no direct role in the design of the DC-1 according to Arthur Raymond, chief engineer on the DC-1 project.

The Douglas company's emphasis on the DC-1's similarities to the Alpha was a useful sales strategy, since it permitted the sales staff to argue that the DC-1 wing structure had already proven reliable in airline service with the Alpha.[45]

The success of the DC series marked the arrival of metal construction as a mature technology. Decades of refinements brought no fundamental changes to the airframes of commercial airplanes. Today's jet airliners use improved aluminum alloys and new production techniques and are designed with more sophisticated methods of stress analysis, but their structures clearly hark back to the DC-1 and other all-metal airplanes of the mid-1930s.[46] Only recently has metal's hegemony in large airliners been challenged by a new generation of composite materials; these new materials have more in common with wood than metal (see the epilogue).

The triumph of the metal airliner in the 1930s suggests that metal had clearly proven its superiority to wood, at least with respect to the technical practices then available for airplane construction. In a sense this superiority was quite real, especially once metal became dominant and thus benefited from an accumulation of practical experience in design, manufacturing, and maintenance. Perhaps the success of the metal airplane resulted simply from the inherent technical superiority of metal over wood. As this and earlier chapters have shown, however, the "inherent" technical characteristics of metal only emerged as the product of sustained human efforts to transform the material world. Due to the prejudices of the engineering community, as embodied in the progress ideology of metal, metal construction benefited from a considerably higher level of effort than wood in the realization of its supposedly inherent characteristics. Still, the aeronautical community never completely abandoned wood, and a number of firms continued to improve wood construction even after the triumph of the metal airliner. These efforts gained renewed vigor with the introduction of synthetic resin adhesives in the early 1930s.

9

Neglected Alternative II: Synthetic Resin Adhesives

FOLLOWING KNUTE ROCKNE'S DEATH in the crash of a wooden-winged Fokker trimotor in 1931, the fortunes of wood reached their nadir. The army and navy finally began ordering all-metal combat airplanes in quantity and soon eliminated all vestiges of wood in new combat models. The largest airlines committed themselves to buying all-metal, multi-engine airliners, and manufacturers got busy creating the airplanes to fit the bill. Wood remained dominant in the wings of "puddle jumpers," sport planes, and small transports carrying less than five passengers, but these structures remained simple and the technology static. Even the manufacturers of these small airplanes began developing all-metal types. Federal research in wooden aircraft ceased completely. Although George Trayer of the Forest Products Laboratory (FPL) remained a member of the NACA's Subcommittee on Miscellaneous Materials, wood disappeared from the subcommittee's agenda, and the FPL's research in aircraft woods quickly evaporated due to lack of funding.

The progress ideology of metal relied on an image of metal as a dynamic material, capable of improvement, while wood was seen as static, fixed by nature. But in fact no material is fixed by nature; all are capable of improvement through human intervention.[1] In the aircraft industry, demands for improved materials provided a major incentive for the development of new alloys, while also stimulating advances in basic metallurgy. These demands did not have a comparable effect on the technology of wood, because wood research was discouraged by expectations of the shift to metal. Nevertheless, the application of human ingenuity to wood technology could produce major advances, as developments in the 1930s demonstrated. Plastic resins provided the key to these improvements. These resins were suitable for more than just radio cabinets; they also made excellent wood adhesives, eliminating the worst problems of traditional glues. Synthetic resin adhesives served as a link between wood and plastics, connecting some of the oldest materials of human culture with some of the newest, both physically and symbolically.

Resin Adhesives and the Renaissance of Wood Engineering

Resin adhesives were a direct application of the material that launched the plastic age—Bakelite, the first synthetic polymer plastic. Bakelite, invented in 1907 by the Belgian-born American chemist Leo Baekeland, was the trade name for a class of thermosetting plastics made from phenol-formaldehyde resins. These resins remained soft until molded under heat and pressure, when they formed a hard, durable, waterproof, fire-resistant material. Through the efforts of Leo Baekeland, Bakelite soon became widely used in the electrical and automobile industries. During the interwar years, phenolic plastics became common in a wide variety of consumer products.[2]

As a structural material, pure Bakelite had its limitations. Although Bakelite was reasonably strong in compression, it was also quite brittle and relatively weak in tension. With the addition of reinforcing materials such as cotton fabric or wood pulp, the strength properties of Bakelite improved dramatically. By varying the number and orientation of reinforcing fibers (known as "fillers"), engineers could design materials with strength characteristics and densities suited to particular applications.[3]

Bakelite also proved viable as a wood adhesive, which was to have tremendous significance for airplane structures. Unlike casein or albumin glues, Bakelite formed a water-resistant, durable bond, immune to mold and fungi. It did not take Leo Baekeland long to discover the affinity of Bakelite for wood; in fact, he had been searching for an improved wood preservative when he first synthesized Bakelite.[4] In 1912 Baekeland patented a method for using phenolic resin as a plywood adhesive, but his method of applying the resin proved too expensive for commercial use. In 1919 a Westinghouse employee, John R. McClain, patented a method for applying the resin in the form of a dry film, eliminating the problems associated with the solvents. In McClain's process, the film consisted of paper or fabric impregnated with a carefully controlled amount of phenolic resin. These sheets were then inserted between individual layers of veneer, and the assembled layers were compressed by a heated press, which transformed the resin into its hardened state.[5]

At first, American plywood manufacturers showed little interest in phenolic resins, but by the early 1930s the new adhesives were creating quite a stir in the plywood industry. Commercial production of phenolic glue films started first in Germany, where the Essen firm of chemist Thomas E. Goldschmidt introduced the Tego film in 1926. American plywood made with Tego film became available in 1930.[6] Shortly thereafter American firms developed new methods using dry resin powders and colloidal suspensions, and by 1933 American manufacturers were producing resin plywood using all three methods: film, dry powder, and colloid.[7]

Proponents of resin plywoods quickly proclaimed their development "revolutionary."[8] The moisture resistance of the new plywoods made them suitable for building exteriors, boat hulls, and seaplane pontoons.[9] Test data demonstrated the superiority of resin-bonded plywood, especially with regard to durability in damp conditions. For freshly made plywood, the resin bond tested a bit stronger than the best traditional glue. This advantage became dramatic when plywood samples underwent accelerated exposure tests. Resin-bonded plywood remained completely unaffected by exposure in a "mold pit," whereas the traditional plywoods lost all shear strength after two to seven weeks. In addition, the phenolic resins considerably reduced the rate of moisture absorption.[10]

The new plywoods quickly found uses in a number of demanding environments. The steamship *Washington*, which, upon completion in 1933, was the largest ship ever built in the United States, used 425,000 square feet of resin-plywood bulkheads. These bulkheads consisted of a layer of asbestos paper under attractive hardwood face veneers, all bonded to a balsawood core, making a stiff, lightweight and practically fireproof structure that also provided excellent thermal and sound insulation. The manufacturing process relied on a phenolic resin developed by General Plastics in cooperation with the Haskelite Manufacturing Company, which had been a major supplier of aircraft plywood (see chapter six)[11]

The new adhesives and other advances in wood engineering produced a minor renaissance in wood structures during the 1930s, with considerable assistance from the Forest Products Laboratory in Madison. In the mid-1930s, FPL engineers developed a new system of prefabricated housing that used resin-bonded plywood panels designed according to stressed-skin principles developed for wooden aircraft. This system received a fair amount of publicity, some of it during a visit from Eleanor Roosevelt, and by 1939 five companies were assembling prefabricated houses based on the FPL's designs. The FPL also did pioneering research in laminated arch construction. Using improved gluing practices to join small pieces of lumber, wood engineers could create solid arches "of practically unlimited size." These arches provided an alternative to steel framing in structures requiring large open spaces, such as school auditoriums and churches. The introduction of improved timber connectors, first developed in Germany, also helped revive wood structures. By the late 1930s, these connectors were being used to build timber roof trusses with two-hundred-foot spans and wooden radio towers up to six hundred feet high.[12]

Outside of aviation, proponents of wood construction used these developments to try to break the symbolic link between wood and traditional technologies. The new techniques clearly demonstrated that wood too could be progressive, that wood, like metal and plastic, could benefit from scientific research. Progress in wood structures, claimed proponents, gave lie to the idea that "to design in timber is to be old fashioned." Modern research could increase the "rational use" of wood. Popular journals publicized the FPL's "practical research triumphs," which helped dispel the notion of wood as a traditional craft material. Modernist designers, who had ignored wood "because of its strong traditional associations," found creative uses for the new plywoods, using molding techniques to produce prize-winning furniture designs.[13]

Neglect of Resin Adhesives in Aviation

Despite these improvements in wood engineering, the American aeronautical community remained remarkably blind to the benefits of new wood technologies, a blindness that was particularly striking with regard to resin-bonded plywoods.[14] By drastically reducing the problem of deterioration, the new resins eliminated the most serious objection to the use of plywood in airplanes. Even Alexander Klemin, usually an astute observer of aviation trends, remained oblivious to the benefits of the new adhesives. In a 1935 article, this influential aeronautical engineer argued that "wood, and the glue which is almost an unavoidable concomitant of it, are organic materials, subject to bacterial and other types of decay." This factor, among others, made metallization "inevitable," so that "today there can be no further argument on the topic Metal vs. Wood."[15]

Klemin's comments were particularly remarkable because they appeared in the same issue of *Aero Digest* as an article by T. C. Bennett, who used the advantages of resin adhesives to argue for the wider use of plywood in airplanes. Bennett, a 29-year-old engineer at the Naval Aircraft Factory, insisted that wood for airplanes was "not so much a dead material as . . . an unfashionable one." While Klemin proclaimed the conclusive triumph of metal over wood, largely due to problems with glues, Bennett presented data on the excellent strength and durability of Tego-film plywood. In addition to praising resin adhesives, Bennett also reopened the question of the relative weight of wood and metal. He noted that plywood had a clear weight advantage over duralumin on the basis of "crippling" (i.e., buckling) stress. Bennett's comments represent the first instance in the U.S. technical press in which a defender of wood clearly appealed to wood's superior buckling strength. Bennett noted the considerable advantages of this superior buckling strength for stressed-skin structures, though he made no attempt to quantify his argument.[16]

Given the difficulty in keeping up with numerous technical fields, Klemin's ignorance of the new adhesives is perhaps excusable. But Klemin was not alone; neglect of resin plywoods was widespread in the aviation community, extending even to the NACA, which had a federal mandate to evaluate and coordinate aviation research. In the case of the NACA, this neglect involved more than passive ignorance, but rather an active rejection of research on the new adhesives, as demonstrated by the work of the Committee on Aircraft Materials.

This committee had the principal responsibility within the NACA for evaluating research on aircraft materials. The committee included representatives from all government agencies engaged in research in the field, including George Trayer of the Forest Products Laboratory. Trayer, former chairman of the NACA's disbanded Woods and Glues Subcommittee, had remained a member of the Materials committee despite the NACA's declining interest in wood research (see chapter six). At the March 1934 meeting of the committee, Trayer reported excellent results from FPL tests of resin plywoods, and he distributed samples showing no evidence of glue failure after nearly three years of severe exposure. Trayer's presentation generated not a single comment, in contrast to lively discussions of topics related to metal.[17] The following year, Trayer explicitly asked the NACA to support the FPL's research on resin plywoods, but the request was rejected "in view of the fact that wood is being superseded by metal in modern aircraft construction."[18]

Wood Meets Plastic: German Research in Aviation Materials

After more than a decade of constant propaganda in favor of metal, wood had too little currency in the aeronautical community to compel its reconsideration, whatever the potential of the new adhesives. Instead, wood reentered the debate through its link with plastics, one of the most potent symbols of technological progress in the interwar period. Popular enthusiasm for plastics blossomed in the 1930s. Plastics directly illustrated the benefits of modern science, specifically the science of synthetic organic chemistry, which promised to create a world of material abundance filled with wondrous new products. The image of phenolic materials differed considerably from that of the first widely used plastics, such as celluloid, which were generally perceived as cheap substitutes. Durable, impervious, and fireproof, Bakelite had the qualities needed to compete directly with other materials in industrial settings. During the 1930s, the chemical industry quite self-consciously worked to counter the ersatz image of plastics inherited from celluloid, using all the tools of public relations to link plastics with modern, machine-age aesthetics. The popular press was soon heralding the arrival of a utopian "Plastic Age."[19]

Phenolic resin adhesives blurred the boundary between wood and plastics, rhetorically as well as materially. The trade press abetted this process by using the term "plastic plywood" for resin-bonded veneers. Researchers also undermined this boundary by exploring novel ways of combining wood veneer and thermosetting resins. Among the first to investigate this fuzzy boundary were German materials scientists, who conducted pioneering research on plastics for airplane structures beginning in the late 1920s. In 1928 Otto Kraemer, a research scientist at the Deutsche Versuchsanstalt für Luftfahrt (DVL, the German counterpart of the NACA), began investigating commercially available phenolic plastics combined with fibrous fillers like wood pulp or cotton cloth. These plastics developed good strength/weight ratios, but compared poorly to wood in terms of stiffness, calculated as the ratio of elastic modulus to density. Insufficient stiffness could cause an airplane structure to flap itself to pieces at high speeds, so stiffness was an important characteristic.[20]

By 1933, Kraemer's search for a stiffer plastic had led him back to wood. Instead of paper or fabric, Kraemer began using very thin birch veneers (from 0.1 to 0.3 mm) impregnated with phenolic resin and then laminated into sheets about 1 cm thick consisting of fifty to a hundred layers of veneer. For a given weight, the strength and elastic characteristics of this material were equal or superior to those of solid birch. According to Kraemer, his tests demonstrated that laminated "wood-plastics" (*Holzkunstharzstoffe*) had significant advantages over normal wood without the low elastic modulus of other plastics. In principle, suggested Kraemer, complex structures could be molded from this improved wood in a single operation, offering considerable advantages in production.[21]

Unfortunately, the resin-impregnated wood proved very difficult to glue because the pores of the wood were already completely filled with resin, preventing the glue from penetrating far enough to form a strong bond. To obtain a gluable material of lower density, the DVL researchers returned to using the phenolic resin as an adhesive only, though they retained thin veneers (0.4 mm), laminating forty-five to fifty veneers with Tego film to produce a single sheet. This material had most of the advantages of the impregnated wood while being easy to glue.[22] In particular, one type of laminated beech developed a ratio of compressive strength to specific gravity of 20,500 pounds per square inch, 55 percent higher than solid beech and about 9 percent higher than aluminum alloy. For equal weight, natural wood has a lower compressive strength than aluminum alloy when buckling is not a factor, so this improvement was quite significant. Although the laminating process significantly increased the density of the beech, its specific gravity remained only one third that of aluminum.[23]

This German research revealed how plastics could provide a pathway linking wood with the ideology of progress. There was a close affinity between research in wood and in reinforced plastics, at least when researchers did not erect artificial boundaries. This affinity is clear to some present-day materials scientists, who describe wood as a natural fiber-reinforced plastic, consisting of cellulose fibers embedded in a lignin resin.[24] Phenolic plastics were often strengthened with wood flour or paper made from wood pulp. The boundary between the categories "wood" and "plastic" was thus not at all clear, though these two categories carried quite different symbolic associations. By blurring the boundary between "natural" wood and "artificial" plastics, the German research demonstrated the possibility of significantly improving wood as a structural material, in direct refutation of those who insisted that the characteristics of wood were fixed by nature. The DVL scientists achieved these results with a fairly modest research program. In Germany, as in the United States, aviation researchers focused on metallic materials, giving "comparatively little notice" to the new synthetic adhesives.[25]

Back in the United States, the NACA was slow to investigate plastics for aircraft structures, despite promising results from German and British research.[26] When the NACA did begin to examine plastics in the mid-1930s, it ignored the links with wood already established by the Germans. The NACA first took up plastics in 1936, when it approved a literature review that was not completed until late 1937. In mid-1938 the NACA approved a $6,500 project at the Bureau of Standards to develop a "reinforced plastic" suitable for airplane structures, despite skepticism from navy representatives. Discussions of this program made no mention of wood, though the NACA did propose to examine a variety of "reinforcing agents," which might have included wood veneers.[27]

Synthetic Resins and Molded Airplanes

Although the NACA ignored the links between wood and plastics, a number of American engineers had already begun developing airplanes based on the new plastic plywoods. These projects involved methods for building airplanes from large sections of molded, synthetic-resin plywood. By 1938 commercial developments had already surpassed the NACA-sponsored research. When the NACA's Miscellaneous Materials subcommittee discussed the plastics research program in 1938, George Lewis, the NACA's research director, recommended that the Bureau of Standards examine a commercial material called "Duramold."[28] Duramold was indeed one of the most significant applications of phenolic resins to aircraft structures, and hence a suitable topic for plastics research. But Lewis appeared unaware that Duramold consisted mainly of thin wood veneers, and thus was one of those materials on the boundary between wood and plastics. By taking advantage of Duramold's association with plastics, the developers of Duramold helped put wood back on the agenda of aviation research in the United States.[29]

Duramold was a direct outgrowth of dissatisfaction with all-metal construction in the mid-1930s. Around 1935, Sherman Fairchild, president of the Fairchild Engine and Airplane Corporation, began to have doubts about the suitability of the newly dominant all-metal construction for quantity production and high-speed flight. The key problem, according to Fairchild and his vice-president for engineering, Virginius E. Clark, was the lowly rivet, necessitated by the difficulty of welding duralumin-type alloys, and required in huge numbers to fasten the intricate network of reinforcements to the external metal skin. Even a small all-metal airplane could require more than fifty thousand rivets at a cost of five cents each, while the rivets in a medium-sized metal airplane could exceed half a million.[30] As Clark put it a few years later, "any type of structure which demanded such a multiplicity of reinforcing parts and so many thousands of rivets did not constitute the best final answer for rapid and inexpensive production."[31] In addition, rivets made it very difficult to obtain the extremely smooth external surfaces needed by high-speed airplanes. Although engineers developed various methods of flush riveting to deal with this problem, smooth riveted surfaces remained difficult and expensive to manufacture.[32]

Fairchild assigned the task of eliminating the rivet to Clark, an experienced and creative aircraft engineer most famous for developing the widely used Clark-Y airfoil during World War I. *Scientific American* described Clark as a "well-girthed, patient voiced gentleman . . . with kind manners, an abstracted air, and blue eyes as cold as calculus." Born in 1886, Clark began his professional life as a naval officer, graduating from the Naval Academy in 1907. From 1914 to 1915 he attended MIT's postgraduate engineering course in aeronautical engineering, the first formal program in aeronautical engineering in the United States. He then served as the army's chief aeronautical engineer from 1915–1920, receiving a commission as an army officer during World War I. After leaving the army, Clark worked for a series of airplane manufacturers as vice-president or chief engineer before landing at Fairchild in the 1930s.[33]

Clark's search for a rivetless construction quickly led him to molding techniques using resin-bonded plywood. In addition to his success as a designer of metal airplanes, Clark also had a background in plywood molding, having supervised the development of a molded plywood fuselage at McCook Field during World War I (see chapter two). Clark had himself obtained a patent on a molded wing structure in the early 1920s.[34] With support from Fairchild, Clark began working with the Haskelite Manufacturing Corporation and its head, George Meyercord, "one of the most fertile minds . . . in the plywood field." It was quite natural that Clark and Fairchild would turn to Haskelite, given the company's experience with aircraft plywood and its role in developing resin-bonded plywood. The Fairchild and Haskelite companies jointly developed a bag-molding technique for producing airplane parts of phenolic plywood, termed "Duramold" by Clark.[35]

Figure 9.1. Fairchild F-46 with Duramold fuselage. National Archives at College Park, Record Group 18-WP, photo no. 62546.

In 1937 Clark designed a five-place commercial airplane with a Duramold fuselage, the Fairchild F-46, which completed its first flight on December 5, 1937 (figure 9.1). The F-46 had excellent performance characteristics, but it failed to sell and only the prototype was completed. Costs of the project began to mount even before the first flight of the F-46, so Fairchild created a wholly-owned subsidiary, the Duramold Aircraft Corporation, to take over the project. With Clark in charge, the new subsidiary took over marketing of the F-46 and further development of the Duramold process.[36]

The Duramold process represented a synthesis of two lines of development in wood products: molded plywood and resin-bonded "improved" wood. Bag-molding techniques were not new to airplane construction, having been used quite successfully on the Lockheed Vega. But in contrast to the casein-glued Vega fuselage, Duramold required molding pressures as high as 100 pounds per square inch and temperatures up to 280 F., which made the molding equipment more complicated. The Duramold process initially used a pressure bag placed over a steam-heated convex cast-iron die, which was similar to Haskelite's unsuccessful approach to molding fuselage panels in World War I (except for the pressure bag). Duramold also differed from earlier molded plywoods in its use of phenolic resins and thin veneers of $^1/_{48}$ in. (0.5 mm) to $^1/_{20}$ in. (1.3 mm) thickness, reminiscent of Kraemer's work at the DVL. These thin veneers were easily bent into the compound curvatures needed for streamlined surfaces.[37]

The Duramold process permitted dramatic increases in speed of production, even allowing for exaggerated claims. The F-46 fuselage consisted of two half-shells molded on the same die and then assembled with casein glue. Due to the high buckling strength of Duramold, the fuselage required very few internal stiffeners, simplifying assembly. Meyercord estimated that a single die could turn out a complete fuselage shell in two hours. Later reports claimed that it had taken nine men at Haskelite only a single hour to produce the first fuselage half-shell. According to Clark, assembly of the fuselage at Fairchild required just five hours and twenty minutes, although he did not specify the number of workers and did not include interior furnishings.[38] Even with this incomplete data, the Duramold fuselage clearly required just a fraction of the labor needed for a comparable all-metal fuselage, which could require up to six person-months to complete.[39]

Despite the promising results of the prototype and the confident claims of Duramold's developers, the process was far from ready for quantity production. Duramold differed so much from ordinary plywood that it was in effect an entirely new airplane material. The application of any new material to airplane construction involves considerable difficulties, as demonstrated by the early problems with metal construction. Even with help from plywood manufacturers or resin suppliers, no airplane manufacturer had the financial and technical resources to develop an entirely new system of airplane construction. Only the federal government could provide the necessary support to continue development of the Duramold process, a fact that Virginius Clark understood very well. So, like practically every innovator in airplane technology since the Wright brothers, Clark turned to the military, specifically the Army Air Corps.

Clark was an almost legendary figure in the history of army aviation. He had personal ties with many pioneers in army aviation, including H. H. Arnold, who in early 1938 was assistant chief of the Air Corps. But despite Clark's credentials and connections, persuading the Air Corps to buy Duramold airplanes would prove a difficult task, given Wright Field's antipathy to wood. Clark's strategy was quite explicit: he would portray Duramold as plastic rather than wood. Clark understood quite clearly that the success of Duramold depended not only on its technical characteristics but also on its symbolic meanings.

In early January, Clark began a vigorous campaign to sell the Duramold process to the Air Corps. He started at the top, writing directly to Oscar Westover, chief of the Air Corps. Arnold, then acting chief, responded positively, informing Clark that "the Air Corps is extremely interested in this development." With this endorsement from Arnold, Clark began the hard work of convincing the Materiel Division at Wright Field. Clark began by submitting a ten-page letter, emphasizing Duramold's suitability to quantity production in wartime. Clark had no illusions about the negative reputation of wood in aviation circles, and he did his best to disassociate Duramold from wood. The material was based on wood, he admitted, but "we prefer, insofar as possible, to avoid the use of this word because of the unpleasant associations resulting from most unhappy experiences with 'wooden' airplanes in times past." According to Clark, he named the new material

"Duramold" in order to emphasize the vast difference between it and more common forms of wood.[40]

Unfortunately for Clark, his letter was not the first communication received at Wright Field concerning Duramold. In late 1937 Meyercord had written a letter to an army officer in Chicago describing the advantages of the new process in general terms but providing few technical details. Meyercord emphasized the advantages of Duramold for quantity production and its complete reliance on domestic materials, all important attributes in wartime. His letter found its way to J. B. Johnson, longtime head of the Materials Laboratory at Wright Field and the army's chief expert on aircraft materials. Johnson, a metallurgical engineer by training, had no time for wood. In an internal memo, Johnson gave a point-by-point rebuttal of Meyercord's letter in a tone ranging from dismissive to hostile. The Haskelite material, he insisted, was "simply" plywood glued with a synthetic adhesive, which would not improve its strength properties significantly. The plywood might be more moisture resistant, but the outer layers would still deteriorate. Johnson did not fear wartime shortages of metals, insisting that "the supply of raw materials for emergency production appears to be sufficient" in light of the Air Corps' use of welded steel-tube fuselages in training airplanes. Johnson also dismissed the argument that plywood airplanes might offer an alternative raw material and additional production facilities during wartime, claiming that the potential supply of aircraft plywood "is not abundant." In effect, Johnson rejected the argument that Duramold represented a new material, full of promise and ripe for development. Instead, he insisted on classifying Duramold as plywood, a discredited material in the eyes of the technical staff at Wright Field.[41]

Despite Johnson's negative assessment, Arnold's support for Clark forced Wright Field to take Duramold seriously. Clark supplied samples of Duramold for testing, and arranged through Arnold to have the F-46 prototype flown to Wright Field for examination. After a January 13 conference with Clark at Wright Field, senior officers at the Materiel Division recommended support for "reasonable development of this process."[42] Nevertheless, Lt. Col. Oliver P. Echols, acting chief of the Materiel Division, balked at the proposed $225,000 figure, insisting that a "costly" program to develop a Duramold airplane "should not be undertaken at this time."[43]

Westover and Arnold were not dissuaded. They were impressed by Clark's offer to build one thousand training planes in less than one year at a price of only $2,520 each, after completion of the development contract then under discussion.[44] In mid-February Westover asked for a $500,000 increase in the fiscal year 1939 Air Corps budget to fund research and development relating to "plastic" airplanes. Westover emphasized the possibility of "rapid and low cost production," and noted the support for this goal expressed by members of the House Appropriations Committee in a recent hearing on the military budget. Westover framed his request in terms of plastics, never mentioning that wood was the primary constituent of the materials he proposed to develop. However, the secretary of war was not convinced, and he directed that the proposal be rejected on the grounds that "the present highly satisfactory all-metal airplane is the result of a long period of development at considerable expense. We should concentrate on the perfection of metal airplanes."[45]

In many respects this response was quite justifiable, given the limited development funds available to the War Department. But such reasoning would also have justified the rejection of research in metal airplanes in the early 1920s, given the need to perfect the wood-and-fabric airplanes developed during World War I. In addition, by 1938 the rising threat of a European war might have given the army cause to think twice about the need for rapid production of airplanes. The European arms race had already begun to worry President Roosevelt, who in late January requested from Congress almost $17 million in additional funding for the army "in the light of the increasing armaments of other nations." In addition to $9 million for antiaircraft weapons, this request included more than $6 million for "aids to manufacture," showing that mobilization for war production had become a serious concern.[46]

For the six months following the rejection of Westover's request for additional funds, Wright Field continued trying to negotiate a more modest contract with Clark. During the interwar period, airplane manufacturers typically took a loss on such "experimental" contracts, hoping to make up the difference on later production orders. But with no other orders or contracts, the Duramold company was not in a position to take such a loss. In early 1938, continuing losses on the project prompted the Fairchild company to sell a majority share of the Duramold subsidiary to a group of outside investors, who renamed the company Clark Aircraft Corporation. Even with the additional funds these investors provided, the company remained unable to absorb a big loss on an experimental contract.[47] The cost of the steam-heated, cast-iron molds remained the biggest stumbling block. Clark estimated that the costs for even a single basic-training airplane would amount to $132,000 for the molds alone, along with more than $100,000 in strength tests and engineering work. Meanwhile, Wright Field had begun negotiating with Eugene Vidal, who was developing a rival method of plastic plywood construction. General Robins, chief of the Materiel Division, advised against any contract with Clark, insisting that the same information could be obtained from Vidal for only $32,000.[48] Vidal's research, however, was several years behinds Clark's, and Vidal's process relied heavily on thermoplastic resins, which the NACA had already rejected as unpromising for airplane structures.[49]

In the end, neither Vidal nor Clark received a contract for an experimental plastic-plywood airplane in fiscal year 1939, though Vidal did receive a small contract to provide a molded wing assembly to Wright Field for testing.[50] By failing to give significant support to molded-plywood projects, the Air Corps lost a major chance to develop an alternative method of airplane construction before World War II. In mid-1939 Clark Aircraft was sold back to the Fairchild company, where it once again became a wholly owned subsidiary and returned to its original name. Sherman Fairchild financed this purchase by selling Howard Hughes the rights to use the Duramold process for large airplanes, a transaction that would lead to the most infamous wooden airplane project of World War II. Clark left the Duramold company and was soon working as a consultant for Hughes. The original F-46 continued flying into the 1970s, with its owners reporting "virtually nil" maintenance for the Duramold fuselage.[51]

Meanwhile Arnold, who became chief of the Air Corps in September 1938, apparently decided that Duramold was more wood than plastic. During congressional testimony in early 1939, Arnold dismissed the new materials because they were "not the true plastic," that is, they could not be used "to pour airplanes . . . just as you pour concrete now." Rather than plastic, Arnold described these materials as "impregnated wood," which despite showing some promise was "not a step in the right direction." Clark's attempt to connect Duramold with plastics had apparently failed to convince Arnold. As long as Duramold remained linked to the symbolism of wood, it could not represent "a step in the right direction."[52]

War Jitters and Wooden Airplanes

Arnold's dismissal of molded plywood seems rather surprising in light of FDR's proposal little more than two weeks earlier for a dramatic expansion in military aviation. In a message to Congress on January 12, 1939, President Roosevelt called for a $525 million increase in defense spending, of which $300 million was earmarked for army aviation. FDR's proposal was a direct response to rising German belligerence and especially the Munich crisis of the previous September, when French and British negotiators agreed to dismember Czechoslovakia to appease Hitler. Observers at the time attributed Hitler's success in Munich to the strength of the Luftwaffe, an assessment that FDR embraced.[53]

More than anything else, it was this threat of war that revived public interest in wood airplanes. By itself, the technical promise of synthetic adhesives could not overcome the opposition to wood rooted in the progress ideology of metal. Proponents of synthetic adhesives did get some attention by invoking the symbolism of plastics, but this strategy could not prevent critics from pointing out that materials like Duramold consisted mainly of wood veneers. The prospect of war, however, brought problems of production to the foreground. Wood offered potential solutions to some of these problems, in particular shortages of metals, labor, and production facilities. Furthermore, the issue of production gave defenders of wood an opportunity to air a whole range of technical arguments concerning choice of materials, in particular arguments regarding buckling strength. In the late 1930s and early 1940s, defenders of wood airplanes presented a stronger public case than they ever had in the 1920s and early 1930s.

Renewed interest in wood first emerged in Europe, where the growing threat of Nazi Germany was most keenly felt. In November 1938, the British journal *Aeroplane* published an article defending wood by F. G. Miles, a designer of small commercial airplanes and military trainers. Miles insisted that metal airplanes had "not lived up to early expectations" for quantity production. Wood airplanes, he claimed, offered a number of advantages over metal in design and production. They could be designed more quickly, and they could take advantage of skilled labor in the wood-working trades. Miles predicted that costs would be lower and the supply of material greater. He insisted that, except for large aircraft, wood airplanes could meet the same demanding specifications as metal airplanes with regard to speed and durability.[54]

In the United States, the developers of Duramold renewed the debate over wood airplanes when they began publicizing the process, focusing on Duramold's advantages for quantity production and its links to plastics. Fairchild and Haskelite had kept quiet about Duramold while Clark was negotiating for an army contract, no doubt to avoid alerting potential competitors. This situation changed in early 1939, when George Baekeland, son of the inventor of Bakelite, described the Duramold process in testimony before Congress. In his testimony, Baekeland emphasized Duramold's production advantages, particularly for wartime, claiming that an entire wing or fuselage could be molded in only two hours. Baekeland never mentioned the use of wood, referring only to "plastics in combination with some other materials." Although Baekeland's discussion of Duramold occupied barely three out of twenty-five pages of his testimony, newspapers and popular magazines seized on the theme of "plastic" airplanes.[55]

Baekeland's testimony helped revive discussion of plastic plywood airplanes in the technical press, where advocates of wood reopened the old debate over the relative weights of airplane materials. As if struck by revelation, these advocates suddenly discovered the advantage of low-density materials in buckling strength. Virginius Clark made the case most effectively in a paper on Duramold that he presented at an engineering conference in May. He cleverly started by discussing the relative merits of aluminum and steel. In aircraft structures, compressive stresses posed the toughest design problem. Designers did not prefer aluminum because of its inherent ratio of compressive strength to weight; alloy steels were in fact superior to aluminum by this measure. Rather, argued Clark, aluminum's superiority was a result of its lower density, which permitted aluminum parts to be almost three times thicker than those of steel for the same weight, giving a buckling strength 7.65 times greater than steel for an unreinforced flat plate. But even aluminum alloy sheets were too thin to take compression stresses without extensive reinforcements. These reinforcements were responsible for the continued high production costs of all-metal airplanes, despite progress in labor-saving methods. The answer, said Clark, lay in a low-density material like Duramold, which combined the good mechanical properties of wood with the reliability and durability of thermosetting plastics. According to Clark's calculations, a Duramold cylinder five feet in diameter could support 80 percent more force in compression than a reinforced aluminum alloy cylinder of the same weight.[56]

Throughout 1939 and into 1940, a flurry of articles in American periodicals highlighted the new opportunities created by resin adhesives and plywood molding techniques. In most cases, wartime production advantages received more attention than buckling strength, even before the German invasion of Poland. For example, in an article in *Scientific American*, journalist Forest Davis pronounced molded plywood airplanes of "tremendous wartime significance." Airplanes were "a machine-age paradox," argued Davis, still largely made by hand while "automobiles roll off the assembly line like shelled peas into a basket." Duramold provided the solution, making possible "a practically unlimited supply of stout, cheap, fast airplanes."[57] H. O. Basquin of Haskelite provided a similar but more sober assessment, pointing to the 170,000 workers in the furniture industry who could be shifted to wooden airplane production in wartime. Manufacturers of small airplanes appeared to be increasing their use of plywood, and a variety of small wooden airplanes were under development. Although wood still remained irrelevant to the vast majority of aviation engineers, the wooden airplane did appear poised for at least a small comeback.[58]

With the growing interest in wood construction, three more firms began working on plywood molding techniques. The second company to enter the field was the Aircraft Research Corporation, organized in 1937 by Eugene Vidal. Vidal had been director of civil aeronautics at the Commerce Department in the mid-1930s, where he tried to develop a $700 all-metal personal airplane. The project proved a failure, but when Vidal left government service he formed Aircraft Research to continue work on low-cost airplanes.[59] Vidal soon discovered molded plywood, and he began developing a new process. At first the Vidal process relied on thermoplastic rather than the thermosetting resins. Thermoplastic resins made manufacturing easier, but were weaker and less durable than the thermosetting adhesives used in the Duramold process. A significant innovation in the Vidal process was the molding of stiffeners and the skin in a single step. Vidal built a small seventy-five-horsepower airplane that was flying by early 1940, and in 1941 the Langley Aircraft Company produced a twin-engine passenger airplane using the Vidal process. A third process, dubbed "Aeromold," was developed by the Timm Aircraft Company of Van Nuys, California. The Timm company began work on molded plywood in 1938, but by mid-1940 the company had yet to fly its first airplane. Finally, the Hughes Aircraft Company began working on molded plywood after Howard Hughes bought partial rights to the Duramold process in mid-1939. By the spring of 1940, Hughes Aircraft had a small research program under way, with V. E. Clark assisting as a consultant.[60]

By early 1940, the promise of molded plywood airplanes had enticed four small companies to begin serious development work. But these companies still had a long way to go to translate promise into practice. As Donald MacKenzie has pointed out, the inherent potential of a technology, which he terms the "intrinsic" properties, are ultimately irrelevant in choices between competing technologies. When choosing capital goods, most engineers and managers base their decisions on extrinsic properties, that is, what the technology achieves in practice. But what a technology achieves in practice depends heavily on the resources devoted to its development. Beliefs about intrinsic properties can influence the allocation of resources to competing technologies, becoming in effect self-fulfilling prophecies, promoting the success of the technology that people believe has the most potential to succeed.[61]

Proponents of Duramold understood this process, which explains why they went public after Clark failed to obtain a development contract from the army. Their rhetorical strategy in many ways mirrored that followed by advocates of metal in the 1920s. Proponents of molded plywood had little time for arguments about indeterminacy but instead focused on the particular characteristics that offered the most promise for their material, such as buckling strength and ease of manufacture. They minimized the practical problems involved in achieving these results, just as advocates of metal had minimized the problems they needed to overcome.[62] Through their interventions in the technical press, proponents of molded plywood hoped to convince the aeronautical community to devote its resources to solving the considerable development problems that stood between promises and reality.

And the problems were indeed daunting. After more than a decade of neglect of wood airplanes, metal had a vast advantage in available design data, accumulated experience in manufacturing, and lessons learned from commercial and military service. As with metal construction in the 1920s, only the military had the resources to compensate for this disadvantage, but the U.S. military had little interest in changing the status quo. This attitude persisted until 1941, when a major shortage of aluminum threatened the viability of the aircraft mobilization program. Only then did the U.S. government give substantial support to wood construction. By then, however, it was already too late to save the wooden airplane.

10

World War II and the Revival of the Wooden Airplane

RARELY DOES AN ABANDONED TECHNOLOGY get a second chance. But wooden airplanes did get a second chance, one provided by the production demands of World War II. During the war, aluminum shortages and overtaxed metal-working industries constrained ambitious aircraft programs among all major belligerents. In the United States, the army responded to the aluminum shortage by launching a major program to substitute wood for aluminum in noncombat airplanes. While the aluminum shortage lasted, wood seemed to cast off its traditional symbolic associations, at least in public, and became "modern" enough for use in airplanes. But the military and the aviation industry could not reverse two decades of neglect overnight, and the American wooden airplane program made only a minor contribution to the war effort. Other combatants, in contrast, had much more success with wood, using it to build some of the best combat airplanes of the war.

The Aluminum Shortage in the United States

From the end of 1940 until the summer of 1943, the American airplane industry faced a severe shortage of aluminum, the single most important material for military aircraft. This shortage resulted directly from the expansion of U.S. military aircraft production that began soon after the Czech crisis of September 1938. Hitler's bellicose Nuremberg speech, along with the British and French capitulation at Munich, convinced President Roosevelt that he needed to expand U.S. air power. On November 14, 1938, FDR startled his senior advisers by calling for an air force of twenty thousand planes and the capacity to produce twenty-four thousand more each year. At this time the Air Corps had only twenty-one hundred serviceable aircraft. FDR eventually reduced his request to three thousand aircraft, in part to fund necessary expansion of ground facilities such as airfields and service depots. Congress acted quickly, allocating $178 million for the purchase of over thirty-two hundred airplanes to begin July 1939.[1] The Czech crisis also sparked a rapid growth in foreign demand for American military airplanes. Foreign orders, led by the increasingly desperate French and British, soon dwarfed the Air Corps' own expansion program. By the end of 1939, the

U.S. aircraft industry had amassed a backlog of $400 million in export orders alone.[2]

These orders were just a prelude to what was in store for the U.S. aircraft industry. On May 10, 1940, the German *Blitzkreig* turned west with the invasion of the Low Countries. Six days later, FDR asked Congress for an air force of fifty thousand airplanes and an annual production capacity of fifty thousand, roughly a tenfold increase over current production. According to I. B. Holley, "the President's call for 50,000 aircraft marked the real beginning of 'wartime' mobilization for the Air Corps." By the summer of 1940, the mobilization program began to pick up speed, and huge increases in defense spending "sent disturbing shock waves through the national economy." After Pearl Harbor, FDR raised production goals dramatically, demanding 60,000 airplanes for 1942 and 125,000 for 1943. The new goals placed incredible demands on the aircraft industry and its suppliers.[3]

Before FDR's fifty-thousand-airplane program, Air Corps planners and the aluminum industry had done almost nothing to insure adequate aluminum supplies for wartime airplane production. Since the 1920s the Air Corps had worried more about supplies of airplane woods than metals (see chapter seven). Military planners repeatedly insisted that aluminum supplies were ample to meet any "emergency," the standard euphemism for war.[4] Although Air Corps planners had given some attention to increasing the capacity of airplane plants, they had "virtually ignored" possible shortages of aircraft materials and accessories. Conditioned by interwar parsimony, the planners had little inkling of the numbers of airplanes that the president and armed forces would demand, especially when the United States got involved in a shooting war.[5] Yet even a glance at World War I would have given a sense of the possible magnitude of production in a shooting war; during just nineteen months of belligerency, the U.S. aircraft industry produced almost fourteen thousand airplanes and achieved an annual production rate of twenty-one thousand airplanes by the Armistice.[6] Given the almost universal agreement in the late 1930s that airplanes would play a vastly greater role in the coming war, annual production rates of two to four times the number achieved at the end of World War I should not have been shocking.

The production levels demanded by FDR exceeded the wildest dreams of American military planners. Nevertheless, they remained sanguine about aluminum supplies until a serious shortage developed in early 1941. Spot shortages appeared even at the beginning of the expansion program in 1939, providing hints of future problems. At first, Alcoa produced more than enough bulk aluminum to meet demand, but fabricators had difficulty supplying the specific forgings, castings, and extrusions needed by aircraft builders.[7] The situation became more serious as FDR's fifty-thousand-airplane program gathered momentum. In September 1940, the Glenn L.

Martin Company began reporting serious disruptions due to late deliveries of aluminum castings, forgings, and sheet. By December similar reports were flooding the Air Corps. Two days before Christmas, Northrop Aircraft Corporation announced that it was curtailing output due to late deliveries from Alcoa. Alcoa responded by denying that any shortage existed. Similar denials were issued by Edward R. Stettinius, head of the Materials Division at the National Defense Advisory Commission (NDAC), the organization established by FDR in May 1940 to coordinate defense production. NDAC planners had calculated that no shortage existed, so Stettinius continued to insist, as he had since the fall, that adequate aluminum supplies would be available to meet both military and civilian needs.[8]

In early 1941, however, the Office of Production Management (OPM), successor to the NDAC, finally acknowledged that it was facing a serious aluminum shortage. New estimates predicted a major shortfall by early 1942, and every revision of the production plans seemed to increase the predicted shortfall. Aluminum ingot was only half the problem. Aircraft required not ingot but sheets, tubing, extrusions, castings, and forgings, all fabricated from high-strength aluminum alloy with specialized equipment. By June 1941, for example, airplane manufacturers were experiencing a major shortage of high-strength extrusions. The OPM responded to the crisis by restricting civilian use of aluminum. Alcoa began curtailing civilian shipments in February, and by August the OPM had eliminated civilian use of primary aluminum for all but the most essential purposes. Despite the civilian cutbacks, only the most pressing defense orders received their full allotment of aluminum in 1941.[9]

The shortages of early 1941 prompted the government to take decisive action to increase aluminum production. Shortly after FDR announced his fifty-thousand-airplane program, the NDAC estimated that annual production of fifty thousand airplanes would require roughly 500 million pounds of aluminum per year, an amount equal to Alcoa's entire planned ingot capacity in 1942. These estimates provoked little concern at the NDAC, where planners relied on the military's current production program rather than likely wartime requirements. In the private sector, the Alcoa monopoly had little incentive to expand capacity for a war that the United States might never enter, leaving Alcoa with surplus capacity.[10] Alcoa did agree to a small expansion in the summer of 1940, adding plans to increase capacity to 690 million pounds by July 1942. The shortages of early 1941 made it clear that Alcoa's plans were woefully inadequate, and the federal government stepped in to finance a massive 600-million-pound increase in aluminum capacity. Increased production goals after Pearl Harbor prompted another massive program to expand aluminum capacity, this time by 640 million pounds annually.[11]

Despite the huge expansion program, airplane production goals continued to outpace the growth of aluminum supplies into 1943. In a March 1942 report for the War Production Board, successor to the OPM, consultant Mordecai Ezekiel argued that the president's 1943 goal of 125,000 airplanes "seems far outside the realm of possible attainment." According to Ezekiel, the most serious constraint was production capacity for airframes and propellers, but aluminum shortages also threatened to limit aircraft production. He predicted a significant shortfall in total aluminum through August 1942 and a continuing shortage of high-strength sheet, the most basic material for airframe construction, until mid-1943. Forgings were particularly short, with deliveries running only 75 percent of requirements.[12] To make matters worse, bauxite supplies also became critical. Until Pearl Harbor, the U.S. imported over half its bauxite needs, mostly from Guiana. In early 1942, German submarines began attacking ore boats, and imports began to plummet, reaching 30 percent of their February amount by June. Despite a massive expansion of domestic bauxite mining and an improved shipping situation in the fall, imports remained below requirements until the first quarter of 1943.[13]

The aluminum shortage finally eased in the summer of 1943, as expanding aluminum production finally caught up with the needs of the aircraft industry. By the end of 1943, U.S. refining capacity reached well over 2 billion pounds of primary aluminum, and output totaled 1.8 billion pounds, more than a fourfold increase since 1940.[14] With ample supplies of aluminum, the U.S. aircraft industry was able to produce almost one hundred thousand airplanes in 1944. This increase was even more impressive in terms of airframe weight, since heavy bombers constituted an increasing proportion of the aircraft produced.[15]

The expansion of aluminum production was indeed a heroic achievement, but one made necessary by a serious lack of foresight among military planners. Nevertheless, the fact remains that aluminum shortages constrained the expansion of airplane production during the early war years of 1941 and 1942.[16] Proponents of wood airplanes had predicted such shortages in 1939 and 1940, but the military ignored these warnings. Only when the aluminum situation became critical did the army and navy begin a serious effort to substitute wood for metal in military airplanes.

Wooden Airplanes: Procurement with Prejudice

In response to the aluminum shortage of World War II, the U.S. military launched a major program to use wood in airplanes. In total, the army and navy purchased some twenty-seven thousand airplanes that used wood for a significant part of the structure, along with nearly sixteen thousand gliders built largely of wood. These figures imply that wood airplanes made a significant contribution to the U.S. war effort, amounting to some 9 percent of the three hundred thousand airplanes produced for the military from July 1, 1940, to August 30, 1945.[17] But a closer look reveals this contribution to be less than it seems. With one exception, none of these wooden types were for combat, and the one combat airplane never entered production. The vast majority were relatively light-weight, low-performance training airplanes, mostly based on designs from the 1930s that did not take advantage of synthetic adhesives or molding techniques. In terms of airframe weight, a more reliable index of manufacturing effort, wooden airplanes accounted for only about 2.5 percent of the total.[18] Furthermore, most of the models produced in quantity used wood for just a small part of the total structure, such as the wing spars. In the final analysis, wood structures did not make a major contribution to U.S. air power during World War II.[19]

This minimal role for wood constituted a clear failure for the U.S. aircraft program. With the onset of the aluminum shortage in early 1941, the army and navy laid plans for a major expansion of wooden aircraft production, plans that grew even larger after Pearl Harbor. The cumulative effect of the progress ideology of metal, however, prevented the success of the program. The aircraft industry and the military had neglected wood for years and found themselves with neither the basic information nor the practical experience necessary for the design, production, and maintenance of wooden airplanes. In addition, wood construction continued to face considerable prejudice within the military, especially at Wright Field. By 1941 these prejudices had become self-fulfilling prophecies.

The aircraft industry and the military had not been entirely oblivious to the potential need for wooden airplanes, but effort remained minimal before 1941. In the spring of 1940, an NACA survey found a large number of manufacturers conducting design studies or small-scale experiments related to wood construction. Only a few companies, however, were actively developing new wooden airplanes. Neither the army nor navy had active programs to promote the use of wood in aircraft structures. Among the four companies working on molded airplanes, only Vidal had military support, in the form of a small contract from Wright Field for a static test model of a basic trainer, designated the BT-11. The navy had requested bids on "plastic" versions of two basic trainers, but had not signed any contracts.[20]

With the onset of the aluminum shortage in early 1941, military support for wooden airplane projects grew rapidly, although without any acknowledgment of a change in policy. An NACA survey that summer reported a "tremendous increase" in the use of plywood and plastics in the aviation industry. Every one of the forty-six airplane manufacturers surveyed reported doing at least some work in plywood parts or structures, while only two expressed decidedly negative opinions. Early in the year, Wright Field began asking some of the army's largest suppliers to establish programs for converting aluminum airplane parts to plywood or plastics, and by mid-1941 these programs were well under way. North American Aviation had an especially active substitution program for the AT-6, the most widely used advanced trainer in the war. Five small companies had contracts with Wright Field to develop additional plywood parts for the AT-6 and Vultee BT-13, the Air Corps' mainstay basic trainer. Three major manufacturers were developing all-wood bombing trainers for the army; two of them, Beech and Fairchild, received production contracts before the end of the year. The Air Corps also accelerated orders for its wood primary trainers already in production; by August 1941 Fairchild was building four PT-19 trainers a day. Cessna began building a twin-engine trainer for the army based on its commercial light transport. Wooden airplanes appeared poised to play a major role in American mobilization.[21]

Plans for wooden airplanes grew even more ambitious after Pearl Harbor. By March 1942, Wright Field had plans to order some sixteen thousand wooden airplanes, twenty-eight thousand wooden propellers, and three thousand wooden gliders. Wright Field staff estimated that the substitution program would save some 45 million pounds of aluminum in the production of existing airplanes, largely by using plywood for nonstructural parts. One example was the North American AT-6C, which used more than twelve hundred pounds less aluminum than the original AT-6 airframe. Although North American engineers achieved most of the reduction with a steel wing, the new version also had a plywood monocoque rear fuselage. North American built nearly three thousand AT-6Cs before switching back to aluminum when the shortage eased. In March the army ordered four hundred more Fairchild AT-13s, the new all-wood crew trainer, a fivefold increase over the original order. In an even more ambitious project, the army launched plans for large-scale production of a wooden transport to be developed by Curtiss-Wright. Curtiss-Wright received an order for two hundred airplanes in March; in December, Wright Field placed orders for an additional twenty-four hundred planes at a total estimated cost of over $400 million, including the cost of constructing two huge new factories.[22]

The military's apparent embrace of wooden airplanes was accompanied by a torrent of articles in the trade and technical press extolling the virtues of wood construction. The incessant criticism of wood during the previous two decades seemed simply to evaporate; plywood became "the hottest subject . . . in aviation." The aviation press commended wood structures for their simplicity of construction and low production costs. Wood was no "mere temporary substitute," ventured one author, but was likely to be "a serious competitor of metal" in postwar commercial airplanes. The trade journal *Aviation Week* ran a series of articles by Eugene Vidal's chief engineer on the principles of plywood airplane design, while also publishing articles on new synthetic adhesives. Although one or two authors expressed some ambivalence, questioning the more extravagant claims of wood's supporters, there was none of the wholesale condemnation of wood so common in prewar discussions. Wooden airplanes also caught the attention of the popular press, with the *Saturday Evening Post* featuring Eugene Vidal in an article titled "Airplanes and Bathtubs: Cooked to Order."[23]

Yet prejudice against wood had not disappeared from the aviation community. Alfred A. Gassner, chief engineer of the Duramold Aircraft Company, commented publicly about this prejudice in early 1942. As chief engineer of Fokker Aircraft in the early 1930s, Gassner had direct experience with the effects of progress ideology on wood construction. Gassner later moved to Fairchild, where he designed a successful all-metal seaplane before moving to the Duramold company when it was repurchased by Fairchild. In a technical paper on Duramold in early 1942, Gassner complained about the "antagonism or disinterest the average engineer has against wood," and he condemned the refusal of most engineers to accept wood as a legitimate material for engineering structures. According to Gassner, "the average engineer . . . will not readily admit that wood can be improved." Nevertheless, he argued, the advantages of thin veneers and synthetic resins should dispel the tendency "to see only metals as full-fledged engineering material," so that "wood in its modern technical conception should find again a good place in the minds and hearts of engineers."[24] Gassner was clearly trying to cast off the traditional symbolism of wood by insisting that it too could be a progressive, scientific material.

Gassner's arguments had little influence on the engineers and officers at Wright Field, where antipathy to wood remained strong, despite its rehabilitation in the aircraft press. J. B. Johnson, the army's chief expert on aircraft materials, continued to oppose wooden airplanes using all the familiar arguments, including poor durability, moisture absorption, and lack of uniformity. "Wherever possible," insisted Johnson in June 1942, airplane manufacturers "would continue to use metal structures." In a similar vein, a senior engineering officer advised a prospective manufacturer against building a wooden transport airplane, noting that "the Army Air Forces prefers [*sic*] all-metal airplanes to those constructed of plywood."[25] Although Wright Field personnel had responsibility for airplane development and production, they did not embrace the army's wooden airplane program.

Within the army, support for wooden airplanes came not from Wright Field but from Washington, where the Air Corps was under intense pressure to make at least a show of meeting the president's massive production goals.[26] General Arnold repeatedly pushed Wright Field personnel to buy more wooden airplanes despite their strong objections. These tensions were clearly revealed in a July 1941 telephone conversation between Maj. Orval

Cook, a senior technical officer in the Production Division at Wright Field, and Lt. Col. Bennett E. Meyers, General Arnold's assistant in Washington for aircraft procurement. During the conversation, Cook questioned the need for the wooden crew trainers being developed by Fairchild and Beech in the summer of 1941. Cook noted the massive expansion under way in aluminum refining, arguing that "by the time these trainers get into production there won't be any necessity, we hope, for conserving aluminum." Meyers sympathized with Cook, but noted that Arnold thought otherwise. According to Meyers, "General Arnold insists that we immediately embark on a program of substituting wood airplanes for all trainers."[27]

Wright Field personnel remained unhappy enough about wood trainers and transports, but above all they feared requirements to purchase wooden combat aircraft. After a conference in Washington in March 1942, Brig. Gen. K. B. Wolfe, chief of the Production Division at Wright Field, remarked upon the "great amount of pressure" being applied to the Air Corps to buy wooden combat airplanes. So far, noted Wolfe, Wright Field had "countered" this pressure by using wood in noncombat aircraft. General Arnold did not remain unaware of these attitudes, and he became increasingly annoyed at Wright Field's "apparent procrastination" in promoting the use of wood and plastics in airplanes. Arnold threatened personnel changes unless the situation improved.[28]

Maj. Gen. Oliver P. Echols, head of Wright Field, defended his organization against Arnold's criticism, insisting that the problem "has been prosecuted most vigorously." But further remarks by General Wolfe show continued prejudice against wood. In December 1942, H. H. Kindelberger of North American Aviation telephoned Wolfe to complain about the wooden fuselages that the Air Corps was requiring for the North American AT-6. Wolfe responded by condemning the entire wooden airplane program, arguing that it would be better to have fewer planes than to buy wood trainers. "We fought, bled and died over this wooden program," continued Wolfe, "and we were finally sold down the river on it. . . . So far as I am concerned, I would like to just push a few of these [wooden] jobs out into the training crowd and let them see what they are up against." Wolfe also complained about the "wooden cargo thing on our neck," a reference to the Curtiss-Wright C-76, and concluded that "we are just making a lot of trouble for ourselves on this wooden program."[29]

The Wooden Airplane Falters

Harsh as Wolfe's comments might seem, they were based on more than just prejudice. Despite the confident claims of wood's proponents, the army found it very difficult to procure wooden airplanes comparable to those designed in metal. Serious problems appeared in all areas, including design, production and maintenance.

Nowhere were the problems more serious than in the design process, where the industry lacked both basic engineering data and personnel with experience in wooden aircraft design. Designers of wood airplanes frequently lamented the paucity of available data. In a mid-1941 meeting of the NACA Subcommittee on Miscellaneous Materials, manufacturers complained bitterly. Airplane companies were under intense pressure to develop new wooden airplanes quickly to help alleviate the aluminum shortage. But without adequate data, designers were forced to rely on "cut and try methods," that is, educated guesses and static tests of full-scale components. Engineers at the Martin company, for example, had developed weight-saving plywood bomb-bay doors for a twin-engine bomber, but they "did not know why [the design] worked." Alfred Gassner of the Duramold company complained that he lacked even the most basic strength data for wood and plywood.[30] Designers particularly needed information on the strength of reinforced plywood panels, the basic component of stressed-skin construction. For metal airplanes, years of research with aluminum structures allowed designers to calculate optimal values for such variables as skin thickness and spacing between the reinforcing "stringers." The lack of comparable research on wood forced manufacturers to conduct expensive and time-consuming tests of their own.[31] Most design data was based solely on experiments with metals, rendering it almost useless for wood structures.[32]

To rectify this acute lack of design data, the Forest Products Laboratory launched a major research project in July 1941 to develop design criteria crucial to the successful use of wood in aircraft. This project resulted largely from the efforts of George Trayer, former airplane expert at the FPL, now head of the Forest Products Division of the U.S. Forest Service in Washington. In the summer of 1940, Trayer "began to wear out shoe leather around Washington" to generate support for a research program in wooden airplanes as insurance against possible shortages of aluminum. Although at first Trayer "did not get much of a reception," he eventually received support from the heads of the Army Air Corps and the Navy Bureau of Aeronautics. The Agriculture Department requested $300,000 for wooden airplane research at the FPL, but the request was cut in half during the budget process. Funds did not become available until July 1941, when the aluminum shortage had already become a major crisis.[33]

The FPL could not make up for almost two decades of neglect with just a few months of research. No organization in the United States had a better scientific understanding of wood, but application of this knowledge to airplane structures required time, especially time to learn the industry's problems and to try out solutions in practice. Pressured by the aluminum shortage, the military and the industry could not wait for research results. In February 1942, the War Production Board asked the FPL to produce two handbooks on the design and fabrication of wooden airplanes. One handbook would be supervised by the Army-Navy-Civil (ANC) Committee, the government entity that set design standards for U.S. airplanes. The standard ANC handbook for aircraft structures, ANC-5, contained only a "very incomplete section on wood." Participants at a planning conference in Washington agreed that the design manual was "urgently needed," especially the section on design details.[34] Back in Madison the FPL researchers put their full effort into producing the manuals, completing them in July. Only then were the FPL researchers able to devote their attention to pressing new research problems, such as understanding the complex behavior of plywood stressed-skin structures.[35]

The manuals vastly improved the availability of information on wooden aircraft structures, but FPL staff cringed at the uncertain data they were forced to include in the report. As Trayer put it, the ANC handbook "brought sharply into focus various points about which knowledge was deficient or altogether lacking." One FPL engineer, C. B. Norris, wrote a report to the ANC Committee detailing his reservations about the handbook. In this report, Norris listed the parts of the handbook that relied on preliminary or incomplete data. Some formulas were based on unpublished studies with such confidence-generating titles as "Approximate Tentative Method of Calculating the Strength of Plywood." Other formulas were derived mathematically and needed empirical confirmation. Norris showed where further research was needed to produce a reliable and authoritative handbook.[36]

Despite these shortcomings, the new handbooks provided much of the design data that the airplane industry needed—eighteen months too late. The time had passed for designing new wooden airplanes that could reach production before the end of the aluminum shortage. By August 1942, when the manuals were released to manufacturers, the army was already procuring wooden airplanes designed without the benefit of reliable data.

Even with the new handbooks, manufacturers faced a critical shortage of experienced designers. Wooden aircraft design had nearly become a lost art that no handbook could replace. According to a 1945 report, in early 1942 there were only ten aeronautical engineers in the United States with enough experience to design high-performance wooden airplanes.[37] General Echols referred to this shortage when defending Wright Field against Arnold's criticisms, noting that the army had "to comb the industry to find engineers to work in the [area] of wooden airplanes." Aeronautical engineers, complained wood expert George Allward, "are trained exclusively in the technique of all-metal design." Indeed, aircraft textbooks of the time often completely ignored wood structures.[38]

The Curtiss-Wright C-76 demonstrated the difficulties that metal airplane companies encountered when trying to design in wood. The C-76 was one of the most poorly designed airplanes to make it into production during the war. The airplane had its origins in the army's need for a transport plane that could land on short, unimproved airstrips near the front lines. Wright Field began discussing the project with Curtiss-Wright in February 1942; in March the army asked Curtiss-Wright to produce two hundred C-76 airplanes at a cost of almost $30 million. The contract called for a twin-engine airplane built almost entirely of wood, capable of carrying twenty troops or forty-five hundred pounds of cargo for six hundred miles (figure 10.1). Curtiss-Wright allowed itself a ridiculously short time to design and build the prototype, agreeing to deliver the first airplane by September, a mere six months after the initial contract letter. With a gross weight of twenty-eight thousand pounds, the C-76 was larger than any previous all-wood airplane built in the United States, and it presented numerous design difficulties. The army chose Curtiss-Wright largely for its success with the all-metal C-46 transport, which was based on the company's twin-engine commercial airliner. The company had absolutely no recent experience with wooden construction. Soon after the start of the project, a Wright Field officer agreed that the C-76 would represent a "premature birth" if completed in nine months, let alone six. Despite such doubts, in December the army ordered another twenty-four hundred of the still unfinished C-76 at a projected cost of $400 million.[39]

Curtiss-Wright took eleven months to deliver the first C-76, but its birth was still premature. The first airplane was seriously overweight, which reduced the maximum payload from forty-five hundred to thirty-one hundred pounds. The airplane also had poor flight characteristics and was particularly dangerous during landing.[40] The C-76 repeatedly failed its static tests, raising doubts about its safety at full load. Its tare weight only increased with subsequent modifications, and poor flight characteristics persisted despite major changes in the design. To make matters worse, the sixth airplane suffered a fatal crash on May 10, 1943, apparently due to a structural failure. In June repeated failures in static tests led Wright Field to reduce the permissible gross weight to 26,500 pounds pending successful strengthening of the structure, leaving the airplane with a pitiful payload of 549 pounds.[41]

As early as March 1943, Wright Field staff had called for canceling the project. Pressure against the airplane increased into the summer, and the project became the subject of a congressional investigation. At the end of July, General Arnold decided to cancel all but twenty-five of the 2,600 airplanes in the contract, which resulted in a $40 million loss for the army.[42]

The C-76 fiasco confirmed all the prejudices of opponents to wood construction.[43] But the army officers closest to the project traced the failure to Curtiss-Wright's unfamiliarity with wooden aircraft design not to funda-

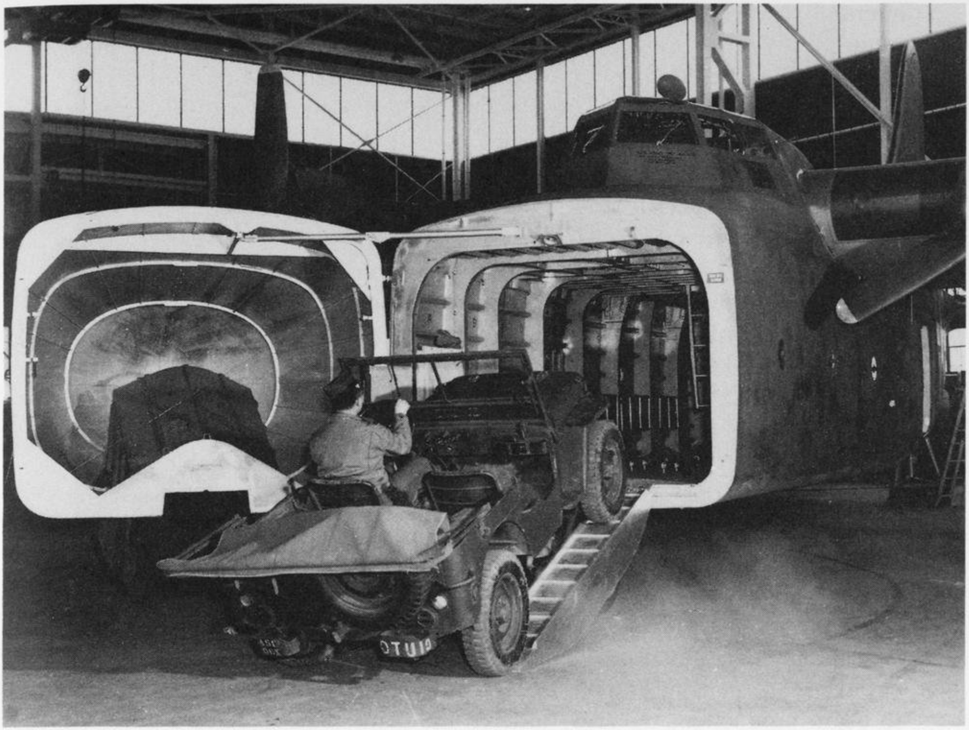

Figure 10.1. The unsuccessful Curtiss-Wright C-76 all-wood transport. National Air and Space Museum, Smithsonian Institution (SI neg. no. 73-1667).

mental flaws with wood as such. One report on the project complained that "the structural design was improper for wood construction," especially with respect to details. The C-76 engineers clearly thought in terms of metal and had little understanding of how to use wood effectively. For example, the Curtiss-Wright engineers designed the airplane with two-thirds of its plywood limited by shear stresses, for which plywood was only half as efficient as aluminum. An inspector working on the project condemned Curtiss-Wright for dealing "a damaging blow to the integrity of wood aircraft," while he expressed confidence that a successful airplane could be built given sufficient time for research and development.[44]

The aircraft industry had little recent experience in wooden aircraft design, but it had even less experience in wooden airplane production, especially in quantity. Neither management nor workers were familiar with modern wood production methods. By the early 1940s, few woodworkers remained in the aircraft industry, and most aircraft workers received no training in wood techniques.[45] Although proponents of wood confidently pointed to the woodworking industries as vast reservoirs of skilled labor, aircraft woodwork demanded exacting standards and specialized techniques not found elsewhere. Some furniture makers successfully adapted their expertise to high-volume wooden airplane production, such as the Grand Rapids plant that by late 1942 was building thirty-four glider floors daily, each made from four thousand parts. Others, however, proved less capable, suffering from deficiencies in production engineering, supervision, and inspection, especially in the trouble-plagued C-76 program.[46]

Companies that switched from casein glues to synthetic adhesives experienced another set of difficulties. Although resin-bonded plywood had become the norm in the aircraft industry, most assembly operations continued to use cold-setting casein glue. By the late 1930s, cold-setting synthetic adhesives had become available, but their use required a whole new set of skills and procedures, including careful control of temperature and humidity in the assembly areas. Encouraged by the military, many companies switched to the new cold-setting adhesives but lost valuable production time developing the new gluing procedures necessary to insure reliable joints.[47]

The Fairchild all-wood trainer provides a good example of the difficulties caused by rushing a wooden airplane into production. In March 1942 Fairchild received the second of two orders for the AT-13. Together these orders totaled 475 planes, which were to be manufactured in a new factory at Burlington, North Carolina. In early 1943, just when Fairchild was ready to begin production, the army ordered the plane redesigned as a gunnery trainer and redesignated it the AT-21. This and other major changes made production planning extremely difficult. Inexperienced workers at the new factory created more problems, requiring Fairchild to establish extensive training programs. Manufacturing methods at the plant remained relatively primitive, despite the use of some bag-molding equipment and a high-frequency electromagnetic gluing machine. Assembly required an "enormous amount" of hand labor, as illustrated by the process of attaching the Duramold skin to the wing framework with temporary hand-nailed wooden strips (figure 10.2). Obtaining reliable glue joints in the wing spars proved difficult, further delaying production.

By early December 1943, the Burlington plant had managed to deliver to the army only two airplanes out of an order that had grown to 725 planes, prompting a congressional investigation. Just as production finally began flowing smoothly in April 1944, the army slashed the order to 168. It finally canceled the project in August. The congressional report on the project criticized the army for setting completely unrealistic production schedules, especially in light of the continuing design changes and inexperienced personnel. Roughly two and a half years elapsed between the first quantity order and smooth production, a perfectly reasonable period for a new airplane built with novel methods in a new factory with untrained employ-

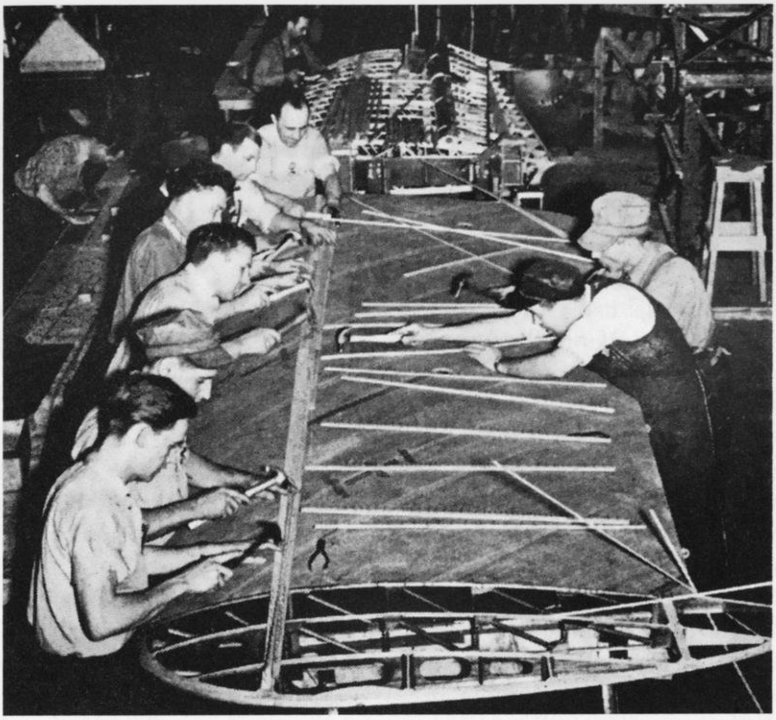

Figure 10.2. Manufacture of the Fairchild AT-21 wooden wing. Note the large amount of hand work involved. From *Modern Plastics* 20 (March 1943): 68, courtesy McGraw-Hill, Inc., New York.

ees—not to mention with a major redesign of the airplane halfway through the project. But by the time Fairchild was able to produce the AT-21 in quantity, the army no longer needed it.[48]

Troubles with wooden airplanes did not end when they left the factory; unfamiliarity with wood construction also caused problems with maintenance and repair. Routine procedures sufficed for older models like the Stearman PT-17, which used fabric-covered wooden wings. New types of wood construction, however, required new maintenance and repair procedures, which the army was slow to develop. One new design was the Fairchild PT-19, which used Duramold skins on some surfaces. When one airfield in 1943 needed to patch a small hole in the Duramold stabilizer of a PT-19, local personnel wrote Wright Field for instructions on "standard repair procedures" for Duramold structures. Wright Field had no such procedures; Fairchild had not yet completed the repair manual for Duramold airplanes, even though the PT-19 had been in service since 1940.[49] The PT-19 also suffered from deterioration due to moisture accumulation in the plywood-covered wing, which weakened the casein glue used in assembly. A troubleshooter from Wright Field traced the problem to the regular use of high-pressure water hoses to wash the airplanes, a common practice for metal planes but totally inappropriate for wood. Another difficulty with the PT-19 occurred when rough landings damaged the wood around bolt holes, damage that sometimes progressed to complete failure. This sort of failure resulted not from fundamental flaws in wood structures but rather from problems with design details, problems that could only be uncovered through operating experience.[50]

Army personnel had little patience for the specific maintenance requirements of wood airplanes. In September 1943, the Air Service Command went on record with a memorandum strongly opposing wooden training airplanes, citing their high maintenance costs and a tendency "to disintegrate from time to time." This memo was apparently solicited by the Production Division at Wright Field, which had consistently opposed wood construction. The Air Service Command pledged its support to the Production Division in "energizing action to eliminate procurement of any type of aircraft except that made of metal."[51]

With aluminum plentiful by the summer of 1943, Wright Field was ready to abandon wooden airplanes. At the end of September, J. B. Johnson reported to the NACA that the army was "discouraging the use of wood construction" due to "disappointing results" with wood airplanes.[52] Wright Field began canceling production of wood designs in favor of proven metal models. Promising prototypes, such as the Ryan PT-25, had no opportunity to prove themselves in production. The army and navy cut off all support for the FPL's wooden airplane program for fiscal year 1944, preventing the FPL from pursuing numerous research projects of critical importance to wooden airplane design. The momentum of projects like the AT-21 carried them on for almost another year, but in time they too were canceled. The army continued developing one wooden airplane, the Bell P-77, a lightweight, all-wood fighter. When completed in 1944, the P-77 failed to meet performance expectations. This tiny wood fighter seemed totally out of place in the emerging postwar world of jets and missiles, and it too was canceled.[53]

A Wooden Giant: Howard Hughes and His Flying Boat

There was one wooden airplane project that Wright Field could not kill—the most famous (or infamous) American wooden airplane of the war, Howard Hughes's giant flying boat, derisively termed the "Spruce Goose." The project emerged in the summer of 1942, at the height of the submarine menace and aluminum shortage, when Henry J. Kaiser proposed building a fleet of huge flying boats to ferry troops and supplies across the oceans. Kaiser's "Liberty Ships" had already made him a hero of war production, but mounting shipping losses still outpaced new construction. In mid-1942, however, aluminum supplies were inadequate for Kaiser's scheme, and most experienced airplane designers were committed to more pressing projects. Kaiser solved these problems through a partnership with Howard Hughes, who had a small airplane design staff in Culver City, California. Hughes also had acquired the rights to use the Duramold process on large airplanes (see chapter nine) and had been conducting research on Duramold since late 1939. The partnership with Kaiser provided Hughes with an opportunity to demonstrate the capabilities of this new material on a grand scale.[54]

The military had no time for Hughes or the flying-boat proposal, but Donald Nelson at the War Production Board proved more sympathetic. At Nelson's recommendation, Jesse Jones of the Defense Plant Corporation gave Kaiser and Hughes an $18 million contract to build three immense flying boats, designated the HK-1, each with eight 3,000-horsepower engines. The contract specified that these airplanes use no strategic materials, in effect requiring wood construction, and prohibited Hughes from recruiting experienced aircraft engineers from other manufacturers. Delivery of the first airplane was scheduled for December 1943, a mere thirteen months after the contract was signed.[55]

The HK-1 was an exercise of incredible technological hubris. Hughes proposed to build an airplane with a gross weight of 400,000 pounds, far larger than any previously constructed. At the time, the navy's largest flying boat, the Martin Mars, had a gross weight of 145,000 pounds while the army's largest bomber, the B-29, had a gross weight of 124,000 pounds. Major problems have always accompanied great leaps in airplane size, regardless of material. Yet Hughes not only proposed to build an airplane of unprecedented size but also to use new and relatively untested materials and construction techniques. In addition, Hughes had to convince the government that he could complete the airplanes in time for use in the war. Hughes hoped to design and build the prototype in less time than it took to develop a conventional metal airplane.[56] The requirement for rapid production led Hughes to misrepresent the amount of development work required, despite the frank admissions of Hughes's own wood expert, George Allward. In a November 1942 paper for the annual meeting of the American Society of Mechanical Engineers, Allward complained that the meager data available for wood airplanes made their development a "formidable . . . and in many cases, very discouraging" task.[57]

Predictably, the Hughes project soon ran into trouble. By mid 1943, it became apparent that the airplane would be late, overweight, and over budget.[58] In September, Donald Nelson sent his chief airplane consultant, aviation pioneer Grover Loening, to investigate the project. Loening had built one of the first metal airplanes in the United States in 1915, although he had not been directly involved in airplane design since the 1920s. Loening's twenty-three-page report contained an interesting mix of perceptive criticisms combined with deep-seated prejudice against wood construction. Loening praised the engineering skills of the Hughes team, along with the layout and aerodynamic design of the flying boat, but he questioned the wisdom of continuing the project in wood. Loening pointed out that the prototype was already almost ten thousand pounds over the contract weight and still far from complete. Using pessimistic assumptions, Loening estimated the final weight empty at 261,500 pounds, some 36,500 pounds more than the specified weight. As a result of this weight increase, concluded Loening, "the value of this craft as a cargo carrier does not justify proceeding with this wooden construction."[59]

Loening also commented on the progress of the development work, which made late delivery of the prototype inevitable. Loening found the progress to be reasonable, compared with other airplane projects. The slippage in the schedule resulted from the typical "overoptimism" of airplane manufacturers. More problematic, though, was the Duramold process itself, which was still under development: "the method of construction has not yet been wholly devised and *actually, the Government is financing an experimental development of a new wooden construction method*—at a time when it thought it was financing the development of a giant aircraft built on known structural fabricating methods." Loening blamed Hughes for creating many of his own problems by failing to be clear about the experimental nature of the project.[60]

Loening's criticisms of the project were quite valid, but his thorough prejudice against wood clouded his diagnosis of the cause of the problem and his final recommendations. In July, Loening had produced a scathing analysis of the Curtiss-Wright C-76 that contained a tirade against wood reminiscent of the early 1920s.[61] Loening included a similar denunciation of wood in his report on the Hughes flying boat. He rejected the claim that resin adhesives altered the fundamentals of wood construction, and he ridiculed the supposed link between wood and plastics, insisting that the new methods amounted to no more than "old-time wooden construction with a slightly improved glue." But just a few paragraphs later, Loening attacked Hughes for being too innovative, noting the problems that Hughes had encountered in developing molding techniques for large structural elements. Loening also demonstrated an extremely unsophisticated understanding of the relationship between material properties and structural weight. Loening noted that the birch veneer components were more dense than spruce, and therefore concluded that the molded plywood structure would weigh more than traditional wood construction. Loening was obviously completely ignorant of the research in improved woods, which had demonstrated that

Duramold-type materials could achieve compressive strength-to-weight ratios comparable to aluminum alloys.[62] For Loening, the fundamental problem with the project was its wood construction; he therefore recommended continuing the project but switching to metal.

Loening's attitude was widespread among the government agencies offering advice on the project, all of which supported cancellation, sometimes citing as justification the army's recent abandonment of wooden construction.[63] Nelson faced a variety of options, including completing the contract for the three airplanes, completing one airplane, switching to metal, or canceling outright. In February 1944 he asked the Defense Plant Corporation to cancel the project outright and solicit a proposal from Hughes to switch the design to metal. FDR, however, overruled Nelson and ordered that funds be provided to complete a single flying boat. In 1947 Hughes finally finished the huge airplane, which was renamed the H-4 *Hercules* after Kaiser pulled out of the project (figure 10.3). The *Hercules* completed only one brief test flight at the height of a few feet, after which it became a major tourist attraction in southern California.[64]

The HK-1 was undoubtedly an ill-conceived project that never had any likelihood of contributing to the war effort. After the Republican party took control of the Senate in the 1946 elections, a congressional committee investigated the HK-1, suggesting that Hughes had used improper influence to have the contract reinstated in 1944. Republican senators drew heavily on the symbolism of wood to make the project appear scandalously ill-advised. They elicited much testimony on the unsuitability of wood for airplane structures, drawing on all the standard prejudices. Hughes made little attempt to defend Duramold, but he did point out that the HK-1 was hardly the only multimillion-dollar failure of the aircraft program. Hughes noted that the HK-1 had apparently crossed a threshold in increasing aircraft size, where the aerodynamic efficiency gained in the fuselage was canceled out by the structural inefficiency of the wing.[65] In fact, only by substantially increasing wing loading, that is, the weight supported per unit area of wing surface, could large aircraft maintain structural efficiency. The wing loading of the HK-1 was reasonable for its time but far too low to produce an efficient structure in such a large airplane.[66] In all likelihood, the seaplane as designed would have been equally problematic in metal.

Even as a failure, the HK-1 was still an impressive achievement. Its wingspan remains the largest of any airplane ever built, 320 feet.[67] Although definitive weight figures were never released, Hughes claimed a final weight empty of 250,000 pounds. Increased engine power allowed him to raise the gross weight to 449,000 pounds, giving the final airplane a respectable though not outstanding ratio of weight empty to gross weight of about 56 percent.[68] Considering all the factors that handicapped the project, such as insufficient design data, lack of military support, mismanagement, and

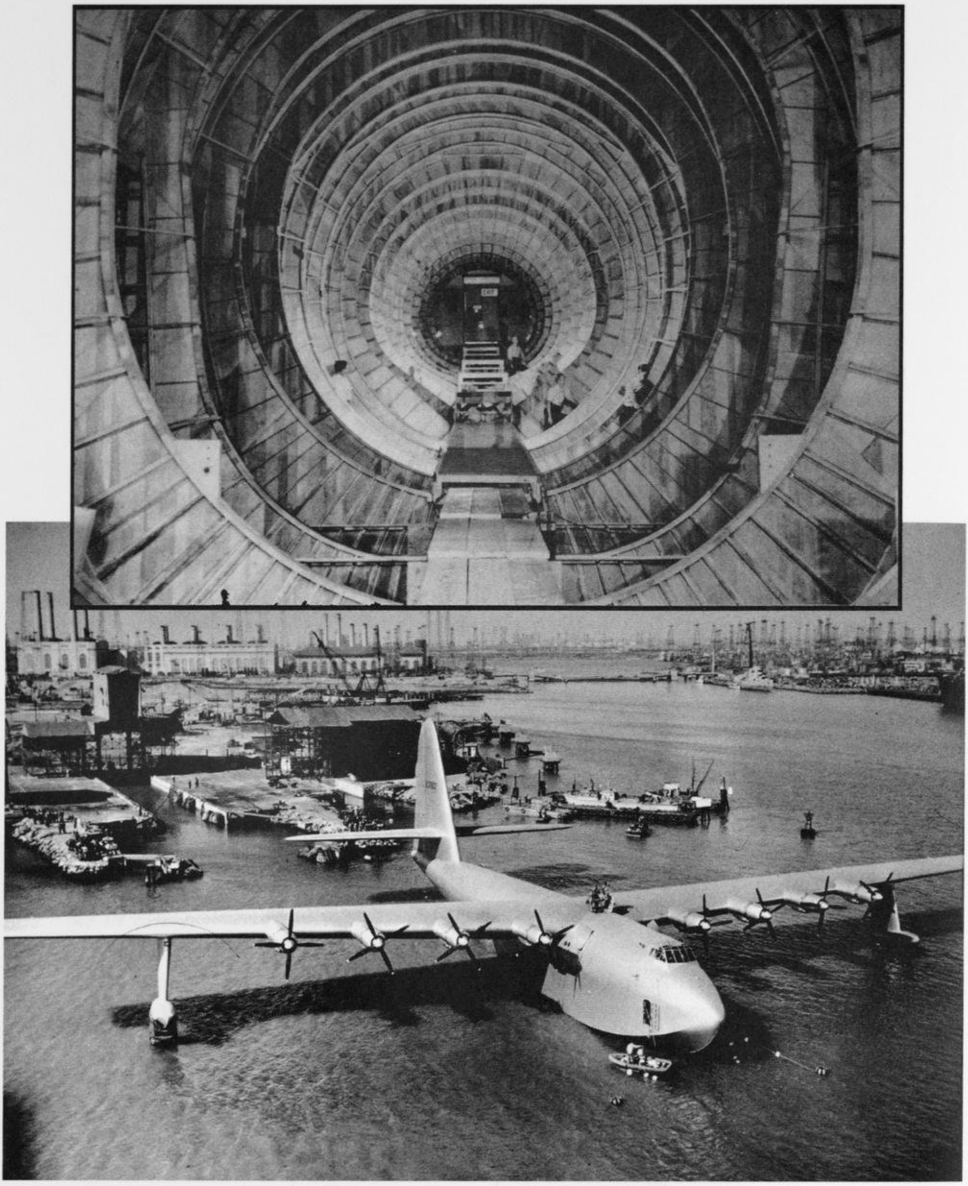

Figure 10.3. Hughes H-4 *Hercules* giant flying boat, with detail of fuselage interior under construction. National Air and Space Museum, Smithsonian Institution (SI neg. nos. 79-5026 and 71-142-12).

wartime shortages of personnel and materials, the mere fact that the HK-1 came even remotely close to its objectives suggests that the potential of wood construction had not been fully exploited. Nevertheless, the aviation community had no time for wood in the postwar era, and it made no effort to profit from the knowledge of wood construction that the project had generated.

By the end of the war, the failure of the wooden airplane projects had confirmed the antipathy to wood that remained widespread in the industry and the military. Relatively successful wooden airplanes were forgotten, among them the Beech AT-10, the Fairchild PT-19, and the Cessna UC-78, each produced in the thousands. In any case, the overall U.S. program clearly failed to fulfill the hopes of wooden airplane advocates.

In retrospect, failure was almost preordained, even disregarding the prejudices against wood. By waiting for an actual shortage of aluminum before launching the wooden airplane program, the U.S. military insured that the program would not achieve its main purpose, relieving the aluminum shortage. It took less time for the U.S. government to expand the existing aluminum industry fourfold than to create an entirely new wooden aircraft industry, especially given the availability of large reserves of hydropower for aluminum production. At the same time, the accumulated knowledge linked to the design and production of metal airplanes created a powerful momentum that put wood at a clear disadvantage. In the midst of the attempt to create a wooden airplane industry, Lockheed's chief structures engineer clearly described how this momentum worked against the wooden airplane:

> Under present conditions it would be disastrous for a large company to attempt a large scale change-over in the basic materials of construction. Every material has its peculiarities, extending down to such small matters as bend radii and the sharpening of drills! Countless hours of research and experimentation with details have been spent to "lick" the little everyday problems that can ruin the production line. It is not hard to realize why large aircraft manufacturers are reluctant to make any major changes in materials.[69]

With just a little more foresight or slightly better planning, however, wood could have played a much larger role in U.S. wartime aviation. It would not have taken a great deal of imagination for the Air Corps to have begun developing a few wood models in 1939, models that could have been ready for production before Pearl Harbor. By the summer of 1940 there was sufficient evidence to justify launching an aggressive wooden airplane program; such a program could have made a significant contribution to relieving the aluminum shortage. The transfer of relatively modest sums to the FPL at the beginning of the European war, say $50,000 a year, would have made the FPL tremendously more prepared to provide timely data for airplane designers. Even after the aluminum shortage had become acute, the military could have achieved better results by concentrating its efforts on just a few promising designs, rather than scattering the industry's limited expertise over dozens of major projects.[70] The attitudes associated with the progress ideology of metal, however, blinded military planners to the possibilities of wood, preventing them from anticipating its potential contribution to the war effort.

History is ultimately about what did happen, not what might have happened. In light of actual results, the American experience with wooden airplanes suggests that the critics of wood were right. Wooden wings weighed more than metal wings, mass production proved difficult, and maintenance problems limited effectiveness. Proponents of a rejected technology can always argue that they needed just a little more research or practical experience to make their alternative competitive. To make such an argument convincing, one needs to show that, at least in some cases, the rejected alternative proved itself viable. Indeed, such cases do exist but not in the United States.

Success Stories: Wooden Airplanes Abroad

Every major power in World War II made some attempt to use wooden airplanes, many with considerably more success than the United States. In fact, some of the most advanced *combat* airplanes of the war relied heavily on wooden structures. Britain, the Soviet Union, Germany, and Canada all made more and better use of wood for aircraft than did the United States. These countries succeeded where the United States failed not because they were immune to the progress ideology of metal: engineering prejudice against wood transcended national boundaries. But in each country, some specific conjunction of circumstances managed to overcome the bias against wood. Two factors proved particularly important: a strong government commitment to the use of wood, especially early in the war, and the presence of at least some manufacturers who had continued to design advanced airplanes in wood.

The British used wood quite successfully during the war. This success resulted largely from the presence of several companies that continued to develop advanced wooden airplanes for the civilian market despite the RAF's strong preference for metal. One of these firms, the de Havilland Aircraft Company, produced the most famous wooden airplane of the war, the de Havilland Mosquito, a twin-engine bomber, fighter-bomber, night fighter, and reconnaissance airplane.

The Mosquito was conceived by the de Havilland firm shortly after the Munich crisis in 1938. Geoffrey de Havilland, the company's founder, proposed building a fast unarmed bomber, protected only by its speed and maneuverability. The de Havilland design dispensed with the anti-aircraft guns standard for bombers at the time. Not only did the drag of the protruding guns significantly reduce a bomber's speed, but the extra weight of the guns, ammunition, and crew substantially reduced its bomb load and range. Without defensive armament, claimed de Havilland, his design would fly faster than the opposing fighters. He also noted the advantages of wood airplanes for production in wartime, when they would not compete for resources with the metal-using industries. The de Havilland proposal was presented to the Air Ministry in October 1938, but the unconventional design generated little interest. After the declaration of war the following September, the de Havilland firm pressed its case for the design before the Air Ministry, and in December de Havilland received an order for the Mosquito prototype. The Mosquito first flew in November 1940, a mere eleven months after serious design work began. Performance exceeded expectations, and the Air Ministry placed large production orders for the airplane.[71]

Production deliveries began in July 1941, only nineteen months after the project began. The airplane soon proved itself in combat, becoming "one of the most outstandingly successful products of the British aircraft industry in the Second World War." The Mosquito excelled in speed, range, ceiling, and maneuverability, making it useful in a variety of roles. Even before the prototype flew, de Havilland began developing reconnaissance and night-fighter variants.[72] With a range of more than two thousand miles, the original reconnaissance version could photograph most of Europe from bases in Britain at a height and speed that made it practically immune to enemy attack. Later modifications extended the range of the reconnaissance version to more than thirty-five hundred miles. From mid-1942 to mid-1943, Mosquito bombers made a series of spectacular daylight strikes against heavily defended targets on the Continent. The attacks proved effective, but high losses convinced the Bomber Command to abandon daylight raids.[73] The Mosquito then joined the night bombing campaign. Studies of the Allied air offensive against Germany showed the Mosquito to be far more efficient at placing bombs on target than the large all-metal bombers that formed the backbone of the bombing campaigns. Compared to the heavy bombers, the Mosquito was cheaper to build, required a much smaller crew, and suffered a much lower loss rate, only 2 percent for the Mosquito compared to 5 percent for the heavy bombers. One British study calculated that the Mosquito required less than a quarter of the investment to deliver the same weight of bombs as the Lancaster, the main British four-engine bomber.[74]

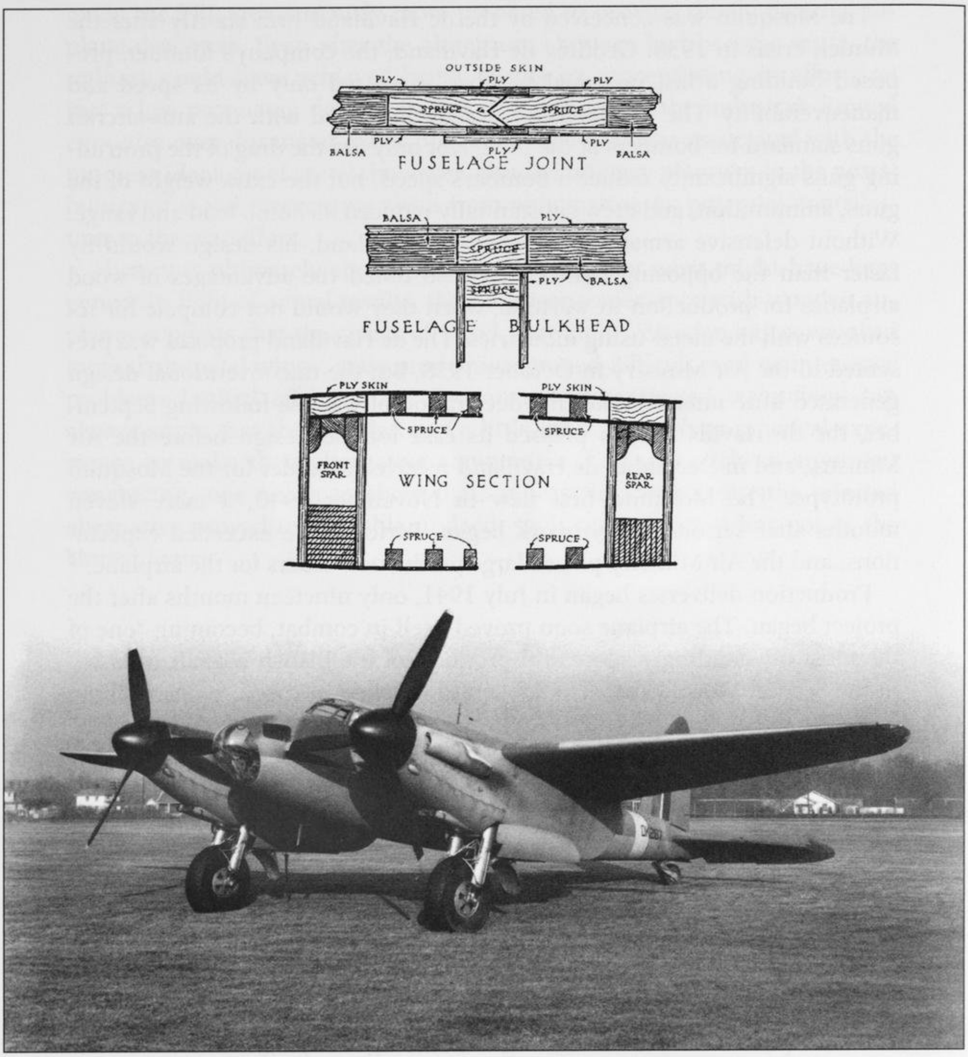

Figure 10.4. De Havilland Mosquito, all-wood fighter, bomber, and reconnaissance airplane. National Archives at College Park, Record Group 18-WP, photo no. 108803; detail from *Automotive and Aviation Industries* 88 (June 15, 1943): 30.

The Mosquito owed no small part of its success to its airframe, which was an exemplar of structural design in wood, both in technical characteristics and ease of manufacture (figure 10.4). The fuselage consisted of two layers of thin birch plywood over a balsa-wood core, forming a stiff, thick sandwich. The thickness of the shell gave it sufficient buckling strength to dispense with the numerous longitudinal stiffeners required on the skin of metal fuselages. De Havilland had first used this sandwich construction on its four-engine airliner, the DH-91 Albatross. The fuselage was assembled in two halves on male molds, with workers using casein glue to attach each layer. By the end of 1943, most Mosquito factories were using synthetic urea-formaldehyde adhesives. Workers installed much of the interior equipment in the fuselage halves before joining them together, simplifying production considerably. The wing was a complex structure of spruce and plywood, built as a single unit, fifty-four feet from tip to tip. The two spars used laminated spruce for the flanges (the top and bottom) and birch plywood for the webs (sides). The top of the wing was double-skinned like the fuselage but separated by strips of spruce or Douglas fir instead of balsa. By using laminated wood and plywood, the Mosquito had no need for large pieces of high-quality aircraft lumber.[75]

With its structure designed for ease of manufacture, the Mosquito helped refute arguments that wooden airplanes were unsuited to quantity production. Total production amounted to 7,619 Mosquitos, with 6,710 completed during the war. In addition to factories in Britain, production lines were established in Canada and Australia. The main factory at Hatfield completed an average of two Mosquitos daily for four years. The Mosquito's design permitted a large percentage of the work to be subcontracted, easing expansion while reducing vulnerability to bombing. In Britain, production accelerated at a rate comparable to that of metal aircraft, reaching eighty per month in February 1943, nineteen months after deliveries began. The de Havilland subsidiary in Canada built a large plant with a mechanized assembly line; monthly production there peaked at eighty-five airplanes in mid-1945.[76] The Mosquito cost about the same to build as the all-metal Bristol Beaufighter, a comparable airplane in size and weight.[77]

The structure also proved remarkably resistant to gunfire and was easy to repair when damaged. Opponents of wood construction had frequently voiced their doubts about the ability of wooden airplanes to withstand gunfire.[78] Combat experience demonstrated that the Mosquito could absorb as much if not more punishment than a comparable metal airplane. Popular accounts abound with descriptions of damaged Mosquitos limping home despite huge holes in the fuselage or wing. Light damage to the airplane was easily repaired with simple woodworking tools. In Malta, the local coffin maker helped keep Mosquitos flying when spare parts and materials failed to arrive.[79]

Outside of combat, the Mosquito airframe performed well in terms of reliability and maintenance, though it did suffer from some problems related to its wooden structure. Early experience with the airplane showed it to have "very few bad maintenance vices." In the airframe, the only "source of recurring maintenance troubles" was the engine cowling, which happened to be the only major part made of metal.[80] Concerns about the structure did arise as a result of the relatively high rate of fatal accidents. The great majority of these accidents resulted from pilot error, typically pulling out of a dive too quickly, which literally snapped the wings off. The great agility of the Mosquito made it easy for even an experienced pilot to stress the structure beyond its design limits. Escape from the tight cockpit was difficult, contributing to a high fatality rate in such accidents.[81]

Critics of wood construction often insisted that the uncertain strength properties of wood and the unreliability of glued joints made wooden airplanes unsafe. Experience with the Mosquito proved these fears to be exaggerated. Accident investigators carefully probed any hint of manufacturing defects or poor-quality wood. Only one accident was clearly attributed to such problems, an Australian-built Mosquito with improperly glued wings.[82] A few airplanes were discovered with defective gluing, largely due to teething problems at new production facilities. Considering that Mosquito factories shifted from casein to urea-formaldehyde glues during the war, the gluing problems were relatively minor. Improved procedures and strict quality control kept defective gluing to a minimum.[83]

The Mosquito also suffered weather-related maintenance problems, some of them serious but none insoluble. The Mosquitos were generally kept dispersed on airfields and given no special protection from the elements. The waterproof covering did a pretty good job of keeping moisture out, but in service some aircraft developed problems with water soakage, especially in the tropics. De Havilland devised various minor modifications to eliminate the trouble spots.[84] More serious problems occurred in India, where the long dry season caused major changes in the moisture content of the wooden structure. These changes produced large internal stresses in glued joints due to the differential shrinkage of solid wood and plywood. In October 1944 a Mosquito in India broke up in flight due to deterioration in the wing structure. A subsequent investigation found major problems in all Mosquitos assembled with casein glue, but not in those using the new urea-formaldehyde adhesives. Resin-glued Mosquitos soon returned to service in India, where they performed well in operations over the Burmese jungles despite the harsh climate. Mosquitos continued to operate in southeast Asia after the war, flying extensive photo-reconnaissance missions over the Malayan jungles from 1949 to 1955 in support of the British counterinsurgency campaign against communist guerrillas.[85]

Overall, the wooden structure accounted for a small fraction of the total maintenance required for the Mosquito. Most maintenance work was related to mechanical systems not the airframe structure. Furthermore, metal parts were hardly immune to maintenance difficulties, as illustrated by the continuing failures of the metal engine cowling and the serious corrosion of a magnesium casting in the control system.[86] When the wood structure did suffer from deterioration or manufacturing defects, users of the Mosquito treated these in the same manner as similar difficulties with metal airplanes, as solvable problems rather than inherent flaws.

For critics of wood construction in the United States, the success of the Mosquito was an anomaly in need of explanation. In April 1941 General Arnold witnessed a demonstration of the Mosquito in England and returned to the United States thoroughly impressed. After Arnold's visit there was some discussion about building the Mosquito in the United States, which ended when the British decided to build the airplane in Canada. Wright Field then asked a number of companies to comment on the Mosquito's design, and received responses almost uniformly hostile. These criticisms revealed that American engineers could not recognize a brilliantly designed wooden airplane when they saw one. Beech Aircraft had the strongest objections, concluding that the Mosquito "has sacrificed serviceability, structural strength, ease of construction, and flying characteristics in an attempt to use a construction material which is not suitable for the manufacture of efficient airplanes." Attitudes like these made it quite difficult for American manufacturers to design and build successful wooden airplanes.[87] The Mosquito also came up in September 1943 at a meeting of the NACA Materials Committee, when J. B. Johnson announced the army's decision to stop buying wooden airplanes. When questioned about the Mosquito's success, Johnson attributed it to Britain's uniform humidity. An army officer suggested that the Mosquito might have been a better airplane if built of aluminum.[88]

Perhaps. But in fact the Mosquito was built of wood, and no nation produced a comparable airplane in metal, let alone a better one. The success of the Mosquito contradicted those who argued that wood was inherently an inferior material for airplanes. There was nothing magic about the Mosquito. It owed its success largely to the uninterrupted experience of the de Havilland firm in the design and manufacture of high-performance wooden airplanes, beginning with the Comet racer that won the 1934 England-Australia air race. This race is more often remembered as a triumph for the American all-metal airliner, since second and third places were taken by a Douglas DC-2 and a Boeing 247, standard commercial airplanes that any airline could buy.[89] But de Havilland, rather than turning to metal like the rest of the industry, used the experience gained with the Comet to develop other wooden airplanes, most notably the four-engine Albatross airliner. The Albatross was not a great success, but it gave de Havilland the experience needed to succeed with the Mosquito, experience that American firms lacked.[90]

The Mosquito was not Britain's only successful wooden airplane of the war. The rearmament program of the late 1930s awakened the British military to its dangerous dependence on imported aluminum. Britain did not have a large aluminum industry of its own; in 1938 British production amounted to only 15 percent of Germany's. In the late 1930s, the RAF stepped up purchases of wooden training aircraft, and by 1943 all British training aircraft in production used all-wood or wooden-winged construction. In strong contrast to the United States, the British encountered "no major difficulties or problems" in the production or use of wooden airplanes. British training authorities found that wooden airplanes required somewhat more maintenance than metal types but were much easier to repair, especially after the frequent accidents that occurred with novice pilots. Except for the Mosquito, however, the British continued to build their combat planes of metal, assisted by huge imports of aluminum from Canada and the United States.[91]

Britain was not the only country to make better use of wood than the United States. Of all the major powers in World War II, the Soviet Union built the largest number of wooden combat airplanes. Forced industrialization had not included the development of a large aluminum industry, and Soviet production lagged far behind that of Germany. Although the Soviet aircraft industry had developed some aluminum airplanes, the Soviet military had not completed the transition to all-metal construction when the war started in 1939. As Soviet design bureaus raced to develop modern aircraft on par with those of Germany, they relied heavily on wood and steel, especially for fighters. When the Germans attacked in June 1941, the most advanced Soviet fighters had wooden-winged or all-wood structures, specifically the LAGG-3, the Mig-3, and the Yak-1. Early versions of these aircraft were somewhat inferior to their all-metal German counterparts, but by the end of 1942 Soviet fighters were comparable in performance to German designs. Soviet factories turned out these airplanes in huge numbers, despite the shortage of skilled labor and the hasty relocation of the factories away from the German advance. When more aluminum became available later in the war, the Soviets followed the Western lead and gradually converted their designs to metal construction. Nevertheless, from the battle of Moscow to Stalingrad, wooden aircraft played a central role in turning back the German onslaught.[92]

Germany also made use of wood in its combat airplanes but only under the pressure of severe aluminum shortages that developed well into the war. It began the war with the world's largest aluminum industry and little fear of a shortage. Despite early research in resin-bonded veneers by the Deutsche Versuchsanstalt für Luftfahrt (DVL), the Luftwaffe remained almost entirely dependent on aluminum airplanes. By 1942 it became apparent that aluminum supplies would not be adequate, but Germany had insufficient electric power to increase production. In August 1942 the Luftwaffe ordered a major program to replace aluminum in airplanes with wood and steel.[93] In September the Focke-Wulf company began developing the Ta 154, a German version of the Mosquito. The prototype performed well, but the project was abandoned when Allied bombing destroyed the Goldschmidt Tego glue-film factory. The Germans did succeed in developing some advanced airplanes that relied heavily on wood structures, such as the Me 163 rocket fighter and the Heinkel He 162 and Henschel Hs 132 turbojets, all of which had wood wings. The Allied victory ended plans for large-scale production of these airplanes.[94]

Although these German aircraft apparently performed well with their wood structures, a postwar American survey found many flaws in the Luftwaffe's wooden airplane program. The authors of the study especially criticized the Germans for their excessive enthusiasm for metal, quoting at length Junkers's 1923 paper for the Royal Aeronautical Society (see chapter three). The authors concluded that "the Germans made the familiar mistake of neglecting the study of wood and consequently did a lot of scurrying when the need to use the material became urgent."[95] The mistake seemed familiar, of course, because exactly the same mistake had been made in the United States.

In contrast to Germany and the United States, Canada made effective use of wood in its wartime aircraft program. The Canadian case is particularly instructive because of Canada's similarity with the United States in technology and availability of materials. World War II provided an important stimulus to Canadian nationalism. After the fall of France, anglophone Canada gave whole-hearted support to Britain, but the Canadians insisted on giving this support as an ally, not a colony. In the bleak summer of 1940, a British defeat seemed a very real possibility. For Canada's military aviators, the threat to Britain was particularly worrisome. In the interwar years, Canada had developed a significant airplane industry, but the country still depended heavily on Britain and the United States for engines, parts, and designs. After the fall of France, Britain cut off shipments of aircraft and parts to Canada, and no replacements seemed likely from the United States for quite some time. It appeared that Canada might be forced to depend on its own resources for defense.[96]

One key Canadian resource was timber. In a report dated May 1940, J. H. Parkin proposed a program for developing wooden military airplanes in Canada. Parkin, director of the Aeronautical Laboratories at the National Research Council (NRC), presented strong technical arguments in favor of wood structures. Parkin also stressed Canada's large timber resources, which included large reserves of virgin Sitka spruce. Parkin's report was soon followed by an even more remarkable memo from L. W. Brockington, a top adviser to Prime Minister King. The report echoed Parkin's arguments, but added a new twist—the need for Canadian self-reliance.

> Thus far, we have based our policy with respect to the production of war equipment upon the optimistic delusion that we can depend upon Great Britain and the

> United States. The point has been reached where we can rely upon neither. Aerial bombardment may render Britain an uncertain source of supply. . . . The United States may limit or cut off our supplies from the necessities of its own policy, or because of the political animosities of certain interests. Canada has now got to stand on her own feet, and utilize the resources she has for her own defence.

At the end of July, Brockington forwarded another report outlining a detailed plan for a design institute to develop wooden airplanes at an annual cost of $450,000.[97]

These proposals helped launch a major Canadian program for producing wooden airplanes. The Royal Canadian Air Force (RCAF) shared the sentiments expressed by Brockington and Parkin, although Brockington's specific proposal for a design institute received little support. Air Vice-Marshall E. W. Stedman, the chief technical officer in the RCAF, strongly advocated the construction of wooden airplanes, in sharp contrast to his counterparts at Wright Field. The RCAF actively sought to build a wooden airplane of British design in Canada, efforts that eventually led to Canadian production of the Mosquito.[98]

In coordination with the RCAF, the NRC launched a substantial research program to develop molded plywood construction. In July 1940 RCAF and NRC staff traveled to the United States to investigate the latest techniques in wooden aircraft construction. They were especially impressed with Eugene Vidal's process. By the fall of 1940, Vidal had become the leading American developer of plywood molding techniques. The Canadian government asked Vidal's company to build an experimental fuselage for the Anson twin-engine training plane, a British design then being built in Canada. The fuselage was a success, and in 1943 a Canadian company began manufacturing the fuselages under license to Vidal. From 1943 to 1945, more than a thousand of the Vidal Ansons were built in Canada (figure 10.5). A rugged, reliable airplane, the Vidal Anson found wide use as civil aircraft after the war. The Vidal Anson provided one of the largest and most successful applications of molded plywood to airplane structures during the war.[99]

Canada's success with wooden airplanes presents a striking contrast to the United States, especially with regard to the Anson. After all, the Vidal Anson relied on technology developed in the United States. Canada succeeded in applying this technology while the U.S. Army and Navy failed, despite Canada's far smaller resources in research and engineering. Canada's achievement was not the result of a greater availability of timber or a more severe shortage of aluminum. Per capita, Canada produced far more aluminum than any other country in World War II. Although Canada was indeed rich in timber, it was also rich in the most important raw material for aluminum, cheap electricity. Canada did experience some aluminum shortages early in the war, but it quickly expanded production, surpassing Germany

Figure 10.5. Avro Anson V, with Vidal-designed molded plywood fuselage. National Air and Space Museum, Smithsonian Institution (SI neg. no. 96-15633).

in 1942 to become the second largest producer of aluminum in the world.[100] Canada exported huge amounts of aluminum to both Britain and the United States. In hindsight, Canadian aluminum was much more important than Canadian timber for Allied aircraft production.

Canada's success with wooden airplanes did not represent the triumph of rationality over ideology. Rather, Canada's achievement resulted from a conflict between ideologies, in which Canadian nationalism proved stronger than the ideology of progress. The idea of Canada as a forest nation has deep roots in Canadian national consciousness.[101] Canadians shared the faith in technological progress that was behind American antipathy to wooden aircraft. But within the context of Canadian nationalism, wooden aircraft became a symbol of national autonomy rather than a slap in the face of progress.

The extensive use of wood structures in wartime airplanes was an impressive achievement in all these countries, given the massive neglect of wood research and the limited experience with stressed-skin plywood airplanes. The most successful airplanes of the period, like the Mosquito and the Vidal Anson, proved that wooden airplanes could compete on equal terms with all-metal designs. These airplanes succeeded because government agencies gave wholehearted support to innovative designers. Wooden structures certainly had their problems, but manufacturers could handle these difficulties when they treated them as engineering problems capable of solution. Given sufficient support and time to learn, manufacturers and users found the problems of wooden airplanes no more intractable than those of metal.

Wood construction might not have suited all airplanes of the war, such as large four-engine bombers. Perhaps the Mosquito represents the limit of wooden aircraft design, which would imply that metal structures were preferable for airplanes with gross weights over twenty-five thousand pounds and wing loadings exceeding fifty-five pounds per square foot. Such a limit seems unlikely, however, in light of the unexplored potential of veneer-resin combinations like Duramold. The Hughes flying boat was a failure at a design gross weight of four hundred thousand pounds, but the methods used to build the airplane might well have succeeded on an airplane of one-quarter the size, still larger than most four-engine bombers used in the war. Whatever the technical limits of wooden airplanes, they clearly could have made a much larger contribution to wartime aviation than they actually did.

The real issue is not whether wood or metal would have permitted air forces to inflict more death and destruction on their enemies. Although choices between specific technologies at a given time are beset with uncertainty, the real indeterminacy is not between static technologies but between alternative paths of development.[102] Choosing a particular path also means adopting a vision of the future, a set of R&D problems that, if solved, will shape the technology in a particular direction. Proponents of metal were committing themselves to one path, the use of the high-density, high-strength materials particularly suited to the emerging postwar era of high-speed flight and very large airplanes, applications that needed structures able to support large stresses in small areas. The metallic path also led directly into the brave new world of supersonic planes and missiles, where high temperatures displaced aluminum in favor of exotic new alloys. Yet there was still an alternative path, but it was not a wooden one.[103] Innovators like de Havilland and Vidal were not so much committed to wood as to low density materials, materials that we would now call fiber-reinforced composites. Just as the metallic path led away from aluminum in many high-speed applications, so the nonmetallic path led away from wood veneers to more completely synthetic materials.

11

Epilogue: Culture and Composite Materials

On December 23, 1987, an odd-looking experimental airplane named *Voyager* landed at Edwards Air Force Base in California after an incredible nine-day flight (figure 11.1). The *Voyager* and its pilots, Dick Rutan and Jeana Yeager, had achieved one of the last remaining aviation milestones, a nonstop flight around the world without refueling. The *Voyager* traversed 25,012 miles, more than doubling the previous record for a nonstop, unrefueled flight, a record set in 1962 by a huge B-52 jet bomber. Yet the *Voyager* was no massive metal behemoth. Its designer, Burt Rutan, had used practically no metal in the entire structure. Instead, the *Voyager*'s airframe consisted of "advanced composites," space-age combinations of exotic fibers and epoxy resins. Metal's ultimate triumph, so confidently predicted in the 1920s, now appeared threatened by a new set of high-performance materials.[1]

Or perhaps not so new. The *Voyager*'s structure was a variant of two ideas that aviation engineers had investigated since the 1930s—fiber-reinforced plastics and sandwich construction. German researchers first studied aviation uses for fiber-reinforced plastics in the early 1930s (see chapter nine). This research continued in England and the United States during and after World War II, eventually leading to the commercially available fibrous composites that Rutan used in the *Voyager*. Sandwich construction had first appeared in the de Havilland Albatross in the mid-1930s, and was then used with great success on the fuselage of the Mosquito (see chapter ten). Research on sandwich materials continued after the war, though plywood and balsa were replaced by synthetic materials. In a design reminiscent of the Mosquito fuselage, the *Voyager* used a thick, load-bearing skin, formed from a honeycombed core of synthetic Nomex paper bonded on both sides to thin sheets of resin-impregnated carbon fibers.[2] In a very real sense, the origins of the *Voyager* lie in the innovative wooden airplanes of the 1930s and related research on nonmetallic structural materials.[3]

The full history of composite materials in aviation lies beyond the scope of this book.[4] Yet a brief outline of this history reveals many parallels with the shift from wood to metal. First, composites faced, and continue to face, many of the same technical problems that metal had to overcome in the 1920s, problems that make the choice between composites and light alloys

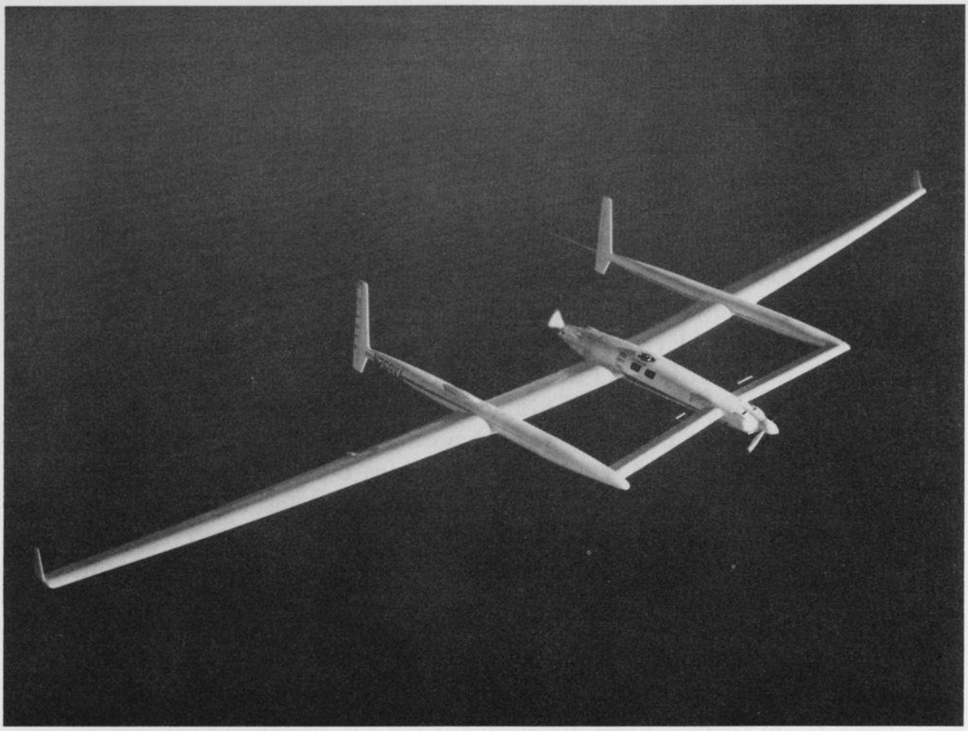

Figure 11.1. Record-setting *Voyager* airplane. The structure is completely nonmetallic. Courtesy Dick Rutan, *Voyager* pilot.

indeterminate. Second, the military, which played such a key role between the world wars, has been ubiquitous in the development of composites. Finally, proponents of composites have also worked hard to define composites as symbols of progress, most notably by de-emphasizing the link between composites and plastics.

From Reinforced Plastics to Advanced Composites

In the 1930s, a small group of scientists, engineers, and innovative airplane designers began research to develop fiber-reinforced plastics suitable for airframe structures. The technical promise of these plastics arose from the high strength-to-weight ratios of commercially available fibers like cotton and flax, ratios up to four times higher than those of typical aircraft metals. One cannot make airplanes out of yarn, however. To take advantage of the strength of these fibers, they were combined with thermosetting resins of high compressive strength, especially Bakelite. Because the resins contributed little tensile strength, the resulting materials typically had strength-to-weight ratios about one-quarter that of the fibers alone.[5]

These researchers were in fact developing *composite materials* some thirty years before the term came into widespread use. Conceptually, the term *composites* refers to any mechanical combination of two or more materials, a combination that creates physical properties superior to those of each material taken separately. Typically, composites combine a brittle material that has strength in compression with a fibrous material that is strong in tension. Such combinations go back to the ancient practice of adding straw to brick. Aircraft researchers in the 1930s were thus venturing into new territory along an old path. By combining synthetic resin plastics and natural fibers, researchers quickly found that they could produce laminated sheet materials with specific strength properties close to those of aluminum alloy, at least in one direction. These plastics were half the density of aluminum, however, allowing thicker cross-sections that provided a major advantage in buckling strength, an advantage that plastics shared with wood.

Despite promising results in strength, reinforced plastics lagged behind existing aircraft materials in one key property, stiffness, measured as the ratio of elastic modulus to density. According to a 1937 NACA study of aircraft plastics, researchers "realized very early" that low stiffness posed "a major problem in the utilization of reinforced plastics for structural purposes." As airplane speeds increased during the 1930s, stiffness became increasingly important, especially for wings and tail surfaces. The German researchers Kraemer and Brenner encountered low stiffness with reinforced plastics in the early 1930s; their search for a stiffer material led them back to wood veneers. The de Havilland Aircraft Company developed an improved structural plastic in the mid-1930s, but this material also suffered from a low elastic modulus, roughly one-third that of aluminum or steel when divided by density. Similar problems stymied Cambridge physicist Norman de Bruyne, who developed one of the most promising reinforced plastics before World War II. De Bruyne made some progress in improving stiffness, but his material still lagged significantly behind metal and wood.[6] The search for greater stiffness, especially stiffer fibers, thus became the key to the development of successful composite materials.

During World War II, research in reinforced plastics intensified in Britain and the United States. This research was not, however, directed to solving the fundamental problems of reinforced plastics; rather, engineers sought to find substitute materials to solve specific problems of aircraft production. In Britain, this research focused on developing a cellulose-fiber composite suitable for use as a wing covering. Much of this work was performed by J. E. Gordon at the Royal Aircraft Establishment (RAE). Field tests of the material revealed a serious problem—dimensional instability due to water absorption by the cellulose fibers. In addition, cellulose-reinforced plastics required very high molding pressures, which necessitated huge presses and expensive metal molds. These molding techniques proved very costly for the short production runs of most airplane parts. Problems with moisture absorption and cost led researchers to turn their attention to dimensionally stable inorganic fibers and to materials suitable for low-pressure molding. In England, Gordon's group at the RAE launched a project to develop airplane wings made from an asbestos-reinforced phenolic plastic, while in the United States efforts focused on glass-fiber reinforced plastics.[7]

This American research was stimulated by commercial production of glass fibers in the 1930s, later known as *fiberglass* after a popular trade name. Glass fibers are tremendously strong, with strength-to-weight ratios comparable to the strongest cellulose. In contrast to cellulose, glass fibers are impervious to moisture but share the low specific stiffness of organic fibers. Researchers also discovered that glass fibers do not combine well with phenolic resins, unlike cellulose fibers. By 1943, a new class of resins had become available, the polyesters, which bonded well with glass fibers and required very low molding pressures. These new resins made it possible to develop airplane structures using fiberglass plastics.[8]

Military aviation played a major role in developing fiberglass plastics during World War II. A key application was for lightweight, electromagnetically transparent coverings for airborne radars. But fiberglass also offered promise as a structural material, easily surpassing aluminum alloy in specific tensile strength, though far inferior to metals in stiffness. In addition, the new low-pressure resins eliminated many of the military's reservations about plastics, which stemmed largely from the production difficulties associated with high molding pressures. In 1943 the Aircraft Laboratory at Wright Field designed and built a glass-fiber monocoque fuselage for the Vultee BT-15 training airplane. This fuselage used sandwich construction, with a 7/16-inch balsa-wood core bonded on both sides to a thin sheet of glass-fiber-reinforced plastic. The resulting fuselage weighed seventy-eight pounds, only eight pounds more than the standard aluminum fuselage, an impressive achievement for a first design. Even more impressive was the strength of the fiberglass fuselage, some 67 percent greater than that of the metal fuselage, indicating that significant weight reductions were possible. Even with the low elastic modulus of the fiberglass plastic, the sandwich structure proved stiffer than the metal fuselage.[9] Despite these promising results, Wright Field engineers "had one outstanding objection"—the balsa-wood core. To avoid the detested wood, Wright Field initiated research to find a synthetic substitute for balsa, experimenting with various honeycomb structures and plastic foams.[10]

In the postwar era of jet engines, rockets, and supersonic flight, high-performance military applications set the agenda for research in aerospace materials. The most pressing problem was the high air temperatures produced by supersonic flight, which quickly reduced the strength of aluminum alloys. Fiberglass plastics performed well at moderately elevated temperatures, but they suffered from a fundamental flaw—low stiffness. The elastic modulus of these plastics was about one-third that of steel or aluminum, when adjusted for density. Although clever design could compensate somewhat for low stiffness, fiberglass structures remained unsuitable for high-performance aircraft.[11]

Even in the 1930s, it had been clear that low stiffness posed the main barrier to widespread use of fiber-reinforced plastics in aircraft structures. Not until the 1950s, however, did researchers turn their attention to developing new, high-stiffness fibers. Theoretical studies and laboratory experiments showed that a small range of materials promised tremendous increases in fiber stiffness. With support from military contracts, researchers worked with a variety of exotic materials, some highly toxic, like beryllium, others tremendously expensive, like boron. One of the most promising materials, however, was also among the most mundane—carbon. In Britain, research on carbon fibers began in the early 1950s under the direction of William Watt at the Royal Aircraft Establishment (RAE). In the United States, Roger Bacon at Union Carbide took the lead on carbon-fiber research in the late 1950s, with key sponsorship from the Non-Metallic Materials Division of the Air Force Materials Laboratory at Wright Field.[12] Through laboratory experiments, these researchers were able to produce very stiff fibers by stretching carbon at tremendously high temperatures, a difficult process unsuited to commercial production. By 1964, however, researchers at the RAE had developed a commercially viable technique for producing high-stiffness carbon fibers. By the mid-1960s, carbon fibers were available with almost nine times the specific elastic modulus of steel.[13]

In 1965 an Air Force study named "Project Forecast" predicted that airplane structures made from the new plastics (now called "composites") would weigh 35 percent less than equivalent metal structures. In an attempt to make these predictions come true, the Air Force Materials Laboratory launched research projects to move composite materials from the laboratory to military airplanes.[14] In the early 1970s, American manufacturers began incorporating components made of the new materials into combat airplanes. Civilian airliners began using carbon-fiber control surfaces in the late 1970s, aided by NASA contracts placed with Boeing, Lockheed, and McDonnel Douglas. In the 1980s, a number of companies developed all-composite business airplanes, though none has yet proved entirely successful. Also in the 1980s, the Air Force acknowledged the existence of two top-secret "stealth" aircraft, the B-2 and F-117, both of which are reported to rely heavily on nonmetallic composite materials.[15]

By the mid-1980s, enthusiasts were proclaiming a new materials revolution, the shift from metal to composites.[16] But composites still have a long way to go before dethroning light alloys as the principal material for aircraft structures. Perhaps the current situation will replay the history of the struggle between metal and wood, with composites cast in the victorious role of metal. Some proponents of composites have indeed made this comparison. A 1968 editorial in *Aviation Week* proclaimed a "new revolution in aerospace industry materials," one whose "eventual effects may wreak as many fundamental changes in aerospace . . . as the switch from spruce and fabric to aluminum." Dick Rutan, pilot of the *Voyager*, predicted that composites would produce a "renaissance" in airplane design during the 1980s, just as aluminum had in the 1930s. Aluminum had served aviation well, continued Rutan, but now "the age of aluminum is nearly over."[17]

Uneasy Comparisons, or the Lessons of History

The history of aircraft materials does not provide clear predictions for the future course of fiber-reinforced composites. But history does shed some light on the current situation, which involves many of the same issues as the earlier shift from wood to metal. Composites have both advantages and disadvantages compared to metal; the technical case remains indeterminate. The military continues to play a central role. And although the symbolism of composites is far less charged than that of wood or metal, proponents of composites have also struggled to shape cultural meanings, most notably by disassociating composites from plastics.

Composites face many of the same challenges as did the early metal airplanes, which had to demonstrate practical advantages over established materials in the face of inadequate design knowledge and daunting technical problems. In theory, the main advantage of composites lies in reducing structural weight, yet theoretical weight savings have often been difficult to achieve in practice, in part because of government safety criteria designed for metal aircraft. For example, the designers of the Beechcraft Starship, an all-composite business airplane, were forced to increase the airplane's weight substantially before receiving the necessary safety certifications from the Federal Aviation Administration.[18] Despite predictions of eventual advantages in production, the costs of composite airplanes remain high, tremendously so for the more exotic composites. Although technical details of the B-2 "Stealth" bomber remain secret, the airplane's composite structure has clearly contributed to its immense costs, $2.2 billion each for the first twenty airplanes.[19] Maintenance remains problematic because composites require entirely new repair procedures. The durability of composites has also proved disappointing; some structures have suffered from moisture absorption while others have delaminated like poorly glued plywood.[20]

As with the shift from wood to metal, the military has played the central role in making composites competitive with established airplane materials. This is not surprising since the military has contributed to practically every major new technology introduced since the end of World War II. Without heavy military support, composite materials could never have become competitive with metals, which are more deeply entrenched in aviation today than wood was in the 1920s. The USAF Materials Laboratory funded almost every major research project in aerospace composites in the United States during the 1960s. Even mavericks like Burt Rutan, the brilliant designer of the *Voyager* and other composite aircraft, have depended on military contracts for crucial support.[21]

But military support has not merely allowed engineers to realize the inherent technical potential of composite materials. Military influence has also steered materials research toward the needs of the military, which differ markedly from those of the civilian market. The military's emphasis on high-temperature materials in the 1950s made sense for missiles and supersonic aircraft but not for commercial airliners. The military's concern with radar-evading materials undoubtedly shaped composites research in the postwar era. The secret projects for the B-2 and F-117 airplanes began in the 1970s; research on radar-absorbing materials goes back much earlier than that. The paucity of reporting on radar-evading materials in the technical press before the 1980s is clearly due more to military secrecy than absence of research.[22] Obviously, radar-evading materials do not have a large commercial market. Finally, the military's focus on exotic, costly, small-batch materials has resulted in production methods ill-suited to the demands of commercial products.[23]

Composites researchers did not restrict themselves to shaping the technical characteristics of the new materials; they also labored to construct favorable cultural meanings. Just as with metal airplanes in the 1920s, proponents of composites sought to link these new materials with technological progress. This attempt to shape meaning appears in the very category of composite materials itself, which emerged in the mid-1960s to replace the previous category of fiber-reinforced plastics.

The category of composite materials emerged quite suddenly in the mid-1960s. Before the mid-1960s, the term *composites* was rarely applied to plastic resins combined with fibers. Instead, *fiber-reinforced plastics* was the standard term. But beginning in 1963, articles appeared in the technical press to map out a general field of research on combinations of materials with different physical properties. As articulated in the mid-1960s, composite materials encompassed all such combinations, including metals, ceramics, and even wood, in addition to fiber-reinforced plastics. Nevertheless, fiber-reinforced plastics remained at the center of most composites research, although by the late 1960s the aviation press almost never referred to these materials as plastics.[24]

The shift from plastics to composites did not mark a fundamental change in research strategy for airframe materials. Instead, the new terminology represented an attempt to control the cultural meanings of the new materials, to create a symbolic link between these materials and technological progress. Since the 1930s, manufacturers of plastics have self-consciously tried to link their new materials with technological utopianism and aesthetic modernism. Despite prophesies of an emerging "plastics age," though, plastics never resonated with progress in the same way as metals. Even before World War II, plastics carried contradictory meanings, simultaneously signifying "high-tech miracle materials and . . . cheap substitutes." The negative associations became attached to the very idea of the plastic airplane, which Disney parodied in a 1944 cartoon. It featured Donald Duck making a plastic airplane that melted when wet. The public perception of plastics as cheap substitutes deepened during World War II and after, particularly as the less durable thermoplastics replaced the thermosetting resins of the prewar era.[25] Throughout the postwar era, many manufacturers completely avoided the word *plastic*, preferring terms like *synthetic* or a *space-age polymer*.[26]

Of course, Disney cartoons do not accurately represent the beliefs of materials scientists and aeronautical engineers. But scientists and engineers do not live in isolation. For reinforced plastics to supplant metal in airplanes, a large number of people in industry, the military, and even Congress had to be convinced that these materials represented the wave of the future. Given the ambivalent symbolic meanings of plastics in postwar American culture, the term *plastics* was simply unsuited to this task. The science behind high-strength fibers was clear by the early 1960s, but there was no concerted campaign to generate enthusiasm for the new materials under the moniker of plastics. In the mid-1960s, with the appearance of technical articles praising the virtues of materials reinforced with the new carbon and boron fibers, *composites* had almost completely supplanted *plastics*.[27]

Under the new name *composites*, reinforced plastic structures generated tremendous enthusiasm, especially in the 1980s.[28] Yet no rapid shift to composites ensued. More than thirty years after the Air Force's "Project Forecast," which predicted weight savings of 35 percent from fiber-reinforced composites, metal remains the material of choice for the vast majority of civil and military aircraft.[29] In contrast, it took roughly fifteen years, from 1920 to 1935, for metal to achieve its dominance over wood. Advocates of composite materials in the 1960s had stronger technical arguments than proponents of metal in the 1920s, yet the change has been much slower. In a century that has supposedly experienced an accelerating rate of technical change, this apparent conservatism seems anomalous.

The apparent reluctance to adopt composite materials has not gone unnoticed. In the early 1980s, Nicholas Hoff, an emeritus professor of aeronautical engineering at Stanford, remarked upon the apparent reluctance to adopt composites. Hoff, whose aviation career began at the end of the wooden airplane era, suggested that new interpretations of product liability laws were inhibiting airplane manufacturers from using composites materials. Hoff has indeed identified a historical problem, but his explanation seems unconvincing. Since the 1920s, the aviation industry has recognized that airplanes must conform to the strictest safety standards to ensure public confidence in flight; product liability laws have not imposed more stringent requirements.[30]

Differences in symbolic meanings may provide a better explanation for the comparatively slow adoption of composites. In the 1920s, proponents of metal could invoke powerful, preexisting associations that linked metal with the industrial age and wood with traditional technologies. These symbolic meanings provided the basis for the progress ideology of metal, which convinced most of the aviation community that metal's success was certain. Advocates of composites cannot draw on comparable symbolic resources. As an emblem of modernity, metal has dulled somewhat during this century, but aircraft alloys have not lost their symbolic connections to high technology. In the early 1930s, Lewis Mumford placed aluminum and synthetic polymers together as technologies of the emerging "neotechnic age." Mumford's terminology did not catch on, but his schema did show that these two materials were of equal status symbolically. Over the next thirty years, however, the cultural status of plastics declined relative to that of aluminum and more exotic alloys like titanium. The new category of composites helped raise the symbolic status of reinforced plastics, but this change in terminology could not give composites the same cultural advantage that metals enjoyed in the interwar years.[31]

Although advocates of composites have succeeded in connecting the new materials with high technology, they have failed to generate the sense of inevitability conveyed by the progress ideology of metal in the 1920s. Widespread faith in the future of composite airplanes is essential to their success. As Lockheed's chief engineer F. R. Shanley pointed out in 1942, any shift to a new material is extremely disruptive, especially in production. In a mature industry like aviation, the adoption of a new material demands support from every sector involved in the creation and use of airplanes. The anisotropic properties of composite materials require entirely new design theories, in the same way that metal airplanes stimulated the theory of thin shells to handle the problem of compressive buckling. Even with better theories and powerful computers, designing an airplane with new materials still requires thousands of tests on structural components, just as it did for early metal airplanes. In manufacturing, very little of the industry's vast experience building metal airplanes can be transferred to composite structures, so manufacturing methods have become a major focus of composites research. And even with the best laboratory testing, durability and maintenance problems can only be solved through actual experience with composite airplanes in service.[32] Because the success of composites depends on coordinated action in all these sectors, their rapid adoption will only become possible when a large part of the aviation community becomes convinced that composites are the wave of the future.

New technologies do not arise through a process of natural selection, an objective process that insures the survival of only the fittest variations. Technologies are, rather, cultural expressions, reifications of human purposes. For new technologies to succeed, people must believe that they will succeed. Such beliefs depend in part on empirical evidence and reasoned arguments. But in the face of inevitable uncertainties about the future, reason alone rarely suffices, even for the most scientific of technologies. The symbolic meanings of technical things do more than shape modern culture; they also influence the course of technical change itself.

Notes

Archival Abbreviations

AAF	All abbreviations beginning with "AAF" refer to specific file series in the Records of the Army Air Forces, Record Group 18; National Archives, Washington, D.C.
AAF/E91	Reports, Questionnaires, and Other Records Relating to the Investigation of the Air Service by the Lampert Committee (U.S. House of Representatives), 1921–25; Inventory NM53, Entry 91.
AAF/E166	General Correspondence, 1917–38; Office of the Chief of the Air Corps, 1917–44, Administrative Division, Office Services Section; Inventory NM53, Entry 166.
AAF/E206	Document Collection of the Air Corps Library, 1917–38; Office of the Chief of the Air Corps, 1917–44, Administrative Division, Library Section; Inventory NM53, Entry 206.
AAF/E293	Security-Classified General Correspondence, January 1939–September 1942; Headquarters Army Air Forces, 1918–55, Office of the Commanding General; Inventory NM53, Entry 293.
AAF/NM6/E36	Correspondence, Reports, and other Papers Relating to the Planning of Army Air Forces Aircraft Procurement Programs and the Production and Procurement of Aircraft and Aircraft Parts, 1940–45; Headquarters Army Air Forces, Office of the Assistant Chief of Staff–Plans; Inventory NM6, Entry 36.
AFM-L	Vertical Files; United States Air Force Museum Library, Wright-Patterson Air Force Base, Dayton, Ohio.
BuAer	All abbreviations beginning with "BuAer" refer to specific file series in the Records of the Bureau of Aeronautics, Record Group 72; National Archives, Washington, D.C.
BuAer/E50	General Correspondence Relating to Aviation, 1917–25; Unpublished Inventory, Entry 50.
BuAer/E51	General Correspondence Relating to Aircraft Types, 1917–25; Unpublished Inventory, Entry 51.
BuAer/E56	Correspondence Relating to Contracts, 1915–26; Unpublished Inventory, Entry 56.
BuAer/E62	General Correspondence, 1925–47; Unpublished Inventory, Entry 62.
BuAer/E63	Classified Correspondence Relating to Aviation, 1922–25; Unpublished Inventory, Entry 63.
BuAer/E82	Contract Records, 1926–42; Unpublished Inventory, Entry 82.
CIT-A	Institute Archives, California Institute of Technology, Pasadena, Calif.
FPL-L	Library; U.S. Forest Products Laboratory, Madison, Wisc.
HFM/FMC	Ford Motor Company records; Research Center, Henry Ford Museum and Greenfield Village, Dearborn, Mich.

IA/AB	Subject-Numeric Correspondence File, 1916–45; Aeronautical Board; Inventory NM16, Entry 5; Records of the Interservice Agencies, Record Group 334; National Archives, Washington, D.C.
LCMD/AIAA	American Institute of Aeronautics and Astronautics Collection, Archives of the Institute of Aerospace Sciences, 1783–1962; Library of Congress, Manuscript Division, Washington, D.C.
NAC/DND	Records of the Department of National Defence, Record Group 24; National Archives of Canada, Ottowa, Ontario.
NACA	All abbreviations beginning with "NACA" refer to file series in the National Advisory Committee for Aeronautics Central Files; Records of the National Aeronautics and Space Administration, Record Group 255; National Archives, Washington, D.C.
NACA/Com/DF	Records Relating to NACA Committees and Subcommittees (Decimal File), 1918–51.
NACA/GC/DF	General Correspondence (Decimal File), 1929–52.
NACA/NF	General Correspondence (Numeric File), 1915–42.
NASA/LMAL	Library; Langley Research Center; National Aeronautical and Space Administration, Hampton, Va.
NASM/APB	Wright/McCook Field Aircraft Project Books (1920–25), Accession XXXX-0058; National Air and Space Museum Archives, Smithsonian Institution, Washington, D.C.
NASM/CMK	Clement M. Keys papers (1918–51), Accession XXXX-0091; National Air and Space Museum Archives, Smithsonian Institution, Washington, D.C.
NASM/TF	Technical Files; National Air and Space Museum Archives, Smithsonian Institution, Washington, D.C.
PRO/AVIA	Records of the Ministry of Aircraft Production; Public Record Office, Kew, Surrey, England.
PRO/DSIR	Records of the Department of Scientific and Industrial Research; Public Record Office, Kew, Surrey, England.
UCLA/AK	Alexander Klemin collection, Record Group 843; Department of Special Collections, University Library, University of California, Los Angeles.
UCLA/GHP	George H. Prudden collection, Record Group 907; Department of Special Collections, University Library, University of California, Los Angeles.
USAF/SCC	Research and Development Project Files (Sarah Clark Collection); Engineering Division, Materiel Command, Wright-Patterson Air Force Base; Records of United States Air Force Commands, Activities, and Organizations, Record Group 342; National Archives, Washington, D.C.
UTA/Corp	Corporate Records; Archives of the United Technologies Corporation, Hartford, Conn.
WPB/E1	Policy Documentation File, 1939–47; Inventory PI-15, Entry 1; Records of the War Production Board, Record Group 179; National Archives, Washington, D.C.

WPB/M187	Numbered Document File of the Advisory Commission to the Council of National Defense, 1940–41 (National Archives Microfilm Publication M187); Records of the War Production Board, Record Group 179; National Archives, Washington, D.C.

Other Abbreviations

A/C	Air Commodore
AAF	Army Air Forces
AAG	Air Adjutant General
Actg	Acting
AOC	Air Officer Commanding
ASME	American Society of Mechanical Engineers
AVM	Air Vice Marshall
BuAer	Navy Bureau of Aeronautics
BuC&R	Navy Bureau of Construction and Repair
CAS	Chief of Air Staff
C/AC	Chief, Army Air Corps
C/Airplane Sect	Chief, Airplane Section [Engineering Division]
C/AS	Chief, Army Air Service
C/BuAer	Chief, Bureau of Aeronautics
C/EngrDiv	Chief, Engineering Division
C/MatDiv	Chief, Materiel Division
Dir/AS	Director, Army Air Service
DND	Department of National Defence
EngrDiv	Engineering Division, Army Air Service
Exec	Executive
G/C	Group Captain
Ind	Indorsement
LMAL	Langley Memorial Aeronautical Laboratory
MatDiv	Materiel Division
MM&D	Materiel, Maintenance and Distribution
NAF	Naval Aircraft Factory
OCAC	Office of the Chief of the Air Corps
OCAS	Office of the Chief of the Air Service
RCAF	Royal Canadian Air Force
S/L	Squadron Leader
USN	United States Navy
W/C	Wing Commander
WPB	War Production Board

Chapter One

1. *Washington Post*, 21 May 1989. Thanks to Paul Schatzberg for this reference.

2. For a detailed account of Mosquito operations during World War II, see C. Martin Sharp and Michael J. F. Bowyer, *Mosquito* (London: Faber, 1967), 117–371.

3. For historiographic background, see chapter four, n. 1.

4. My use of the concepts of culture and power have been influenced by David J. Hess, *Science and Technology in a Multicultural World: The Cultural Politics of Facts and Artifacts* (New York: Columbia University Press, 1995), 8–14.

5. For these examples, see chapter three.

6. In the Anglo-American literature, the dominant view originated with Peter Brooks in the late 1950s. Brooks describes the origins of the fully cantilevered all-metal stressed-skin airliner, culminating in the first "modern airliners," the Boeing 247 and the Douglas DC-1, which first flew in 1933. Peter W. Brooks, *The Modern Airliner: Its Origins and Development* (London: Putnam, 1961; repr. Manhattan, Kan.: Sunflower University Press, 1982), esp. chap. 3. Other commonly cited technical histories follow and elaborate upon Brooks's interpretation. Charles Gibbs-Smith, *Aviation: An Historical Survey from Its Origins to the End of World War II* (London: HMSO, 1970), 200–201; John B. Rae, "The Airframe Revolution," chap. 4 in *Climb to Greatness* (Cambridge: MIT Press, 1968); Ronald Miller and David Sawers, *Technical Development of Modern Aviation* (London: Routledge & K. Paul, 1968), 53–71.

In a fascinating dissertation on the industrial use of wood, Charles Haines echoes this standard account, insisting that the shift to metal was an "inevitable" product of engineers' search for order. Haines reaches this conclusion without any detailed comparisons between wood and metal; he simply accepts that metal was the superior airplane material. At times Haines is sensitive to the symbolic meanings of wood, but in the end he uncritically adopts the standard view of wood as a traditional craft material inherently unsuited to the world of engineering. Haines ends his study just before the adoption of synthetic adhesives, a development that in some ways undermines his entire thesis. Charles M. Haines, "The Industrialization of Wood: The Transformation of a Material" (Ph.D. diss., University of Delaware, 1990), esp. chap. 6 (quote on 288).

7. John M. Staudenmaier, *Technology's Storytellers: Reweaving the Human Fabric* (Cambridge: Society for the History of Technology and MIT Press, 1985), 175; David F. Noble, *Forces of Production: A Social History of Industrial Automation* (New York: Knopf, 1984), 144–46; Ruth Schwarz Cowan, *More Work for Mother: The Ironies of Household Technology from the Open Hearth to the Microwave* (New York: Basic Books, 1983), 127–28; Hans-Joachim Braun, "Symposium on 'Failed Innovations,'" *Social Studies of Science* 22 (1992): 213–30.

8. On technical communities, see Edward W. Constant, "The Social Locus on Technological Practice: Community, System, or Organization," in *The Social Construction of Technological Systems*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge: MIT Press, 1987), 224–28.

9. John H. Morrow, Jr., *German Air Power in World War I* (Lincoln: University of Nebraska Press, 1982), 190–91.

10. Alfred Goldberg, "Equipment and Services," in *Men and Planes*, vol. 6 of *The Army Air Forces in World War II*, ed. Wesley F. Craven and James L. Cate (Chicago: University of Chicago Press, 1955; repr., Washington, D.C: Office of Air Force History, 1983), 350; James L. Stokesbury, *A Short History of Air Power* (New York: William Morrow, 1986), 210–11.

11. A. J. Sutton Pippard and J. Laurence Pritchard, *Aeroplane Structures* (London:

Longmans, Green, 1919), 16–32; John Cutler, *Understanding Aircraft Structures* (London: Granada, 1981), 3–6.

12. "Metal Construction of Airplanes," *SAE Journal* 25 (Nov. 1929): 451; Tom Crouch, *A Dream of Wings: Americans and the Airplane, 1875–1905* (New York: Norton, 1980), 70; Brooks (n. 6 above), 70; Gibbs-Smith (n. 6 above), 159, 164.

13. Robert Friedel, "Some Matter of Substance," in *History From Things: Essays on Material Culture*, ed. Steven Lubar and W. David Kingery (Washington, D.C.: Smithsonian Institution Press, 1993), 41–47; David Pye, *The Nature and Aesthetics of Design* (London: Herbert Press, 1978), 11–16.

14. Frederick L. Nussbaum, *A History of the Economic Institutions of Modern Europe: An Introduction to* Der Moderne Kapitalismus *of Werner Sombart* (New York, 1933), 285 (quote); Werner Sombart, *Das Wirtschaftsleben im Zeitalter des Hochkapitalismus*, vol. 3 of *Der moderne Kapitalismus* (Von Duncker & Humbolt, 1928), part 1, pp. 97–100; Lewis Mumford, *Technics and Civilization* (New York: Harcourt, Brace, Jovanovich, 1934), 109–11; Friedel (n. 13 above), 47–49. Lewis Mumford, although heavily influenced by Sombart, objected to Sombart's emphasis on the shift from the organic to the inorganic; the emerging Neotechnic age, claimed Mumford, was witnessing a "returning to the organic." *Technics and Civilization*, 371–72.

15. Julie Wosk, *Breaking Frame: Technology and the Visual Arts in the Nineteenth Century* (New Brunswick: Rutgers University Press, 1992), 111, 136. Cecilia Tichi emphasizes the cultural significance of "gear and girder technology" without, however, emphasizing the materials of construction. Cecilia Tichi, *Shifting Gears: Technology, Literature, Culture in Modernist America* (Chapel Hill: University of North Carolina Press, 1987), esp. 3–16. Figure 1.3 is discussed in Marianne Doezema, "The Clean Machine: Technology in American Magazine Illustration," *Journal of American Culture* 11 (winter 1988): 82, 87.

16. Emerson quoted in Charles Beard, introduction to J. B. Bury, *The Idea of Progress: An Inquiry Into Its Origin and Growth* (New York: Macmillan, 1932), xxxix.

17. Kenneth M. Roemer, *The Obsolete Necessity: American Utopian Writings, 1888–1900* (Kent, Ohio: Kent State University Press, 1976), 111; Helmut Maier, "'New Age Metal' or 'Ersatz': Technological Uncertainties and Ideological Implications of Aluminium up to the 1930s," *ICON* (1997): 181–201; David E. Nye, *Electrifying America: Social Meanings of a New Technology* (Cambridge: MIT Press, 1990), esp. chap. 4.

18. Le Corbusier-Saugnier, "L'esthétique de l'ingénieur: Maisons en série," *Nouvelle Esprit* 13 (December 1921): 1530. I was alerted to this article by Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm* (New York: Viking Penguin, 1989), 322–23.

19. Mumford (n. 14 above), 230.

20. F. T. Evans, "Wood Since the Industrial Revolution: A Strategic Retreat?" *History of Technology* 7 (1982): 37–55; Brook Hindle, ed., *America's Wooden Age: Aspects of Its Early Technology* (Tarrytown, N.Y.: Sleepy Hollow Press, 1976); Gregory K. Dreicer, "The Long Span: Intercultural Exchange in Building Technology: Development and Industrialization of the Framed Beam in Western Europe" (Ph.D. Diss., Cornell University, 1993), esp. 25–40.

21. Frank Lloyd Wright, "The Meaning of Materials—Wood," part 4 in "In the Cause of Architecture," *Architectural Record* 63 (May 1928): 481–88 (quote on 486).

22. For a brief discussion see Jürgen Habermas, *The Philosophical Discourse of Modernity: Twelve Lectures* (Cambridge: MIT Press, 1987), 5–8. For the influence of science and technology on the idea of progress in the seventeenth century, see Robert K. Merton, *Science, Technology and Society in Seventeenth Century England* (1938; New York: Howard Fertig, 1970), 232–38.

23. Hans-Georg Gadamer, *Truth and Method*, 2d rev. ed. (New York: Crossroad, 1990), 277–83 (quote on 270); on progress in general, see Bury (n. 16 above).

24. Leo Marx, *The Pilot and the Passenger: Essays on Literature, Technology, and Culture in the United States* (New York: Oxford University Press, 1988), 185 (quote); Merritt Roe Smith, "Technology, Industrialization, and the Idea of Progress in America," in *Responsible Science: The Impact of Technology on Society*, ed. Kevin B. Byrne (San Francisco: Harper & Row, 1986), 9–10; John Staudenmaier, "Perils of Progress Talk: Some Historical Considerations," in *Science, Technology, and Social Progress*, ed. Steven L. Goldman (Bethlehem, Pa.: Lehigh University Press, 1989), 270–74.

25. Beard (n. 16 above), xx.

26. Charles A. Beard, introduction to *Toward Civilization*, ed. Charles A. Beard (New York: Longmans, Green, 1930), 1–20.

27. Edwin T. Layton, *The Revolt of the Engineers: Social Responsibility and the American Engineering Profession*, 2d ed. (Baltimore: Johns Hopkins University Press, 1986), 54–60 (quote on 58). For an example of rhetoric by a leading engineer linking science and progress, see R. H. Thurston, "The Border-Land of Science," *North American Review* 150 (1890): 67–79, reprinted in *Changing Attitudes toward American Technology*, ed. Thomas P. Hughes (New York: Harper & Row, 1975), 178–90. For a study of the power of scientific symbols in American culture, see Christopher P. Toumey, *Conjuring Science: Scientific Symbols and Cultural Meanings in American Life* (New Brunswick: Rutgers University Press, 1996). Thanks to Ron Numbers for this reference.

28. Evans (n. 20 above), 51. On the symbolic impact of civil engineering structures, see Tichi (n. 15 above).

29. Robert S. Woodbury, *Studies in the History of Machine Tools* (Cambridge: MIT Press, 1972). Noteworthy examples of the new hardware history include Hugh G. J. Aitken, *Syntony and Spark: The Origins of Radio* (New York: Wiley, 1976; repr. Princeton: Princeton University Press, 1985); Robert Friedel and Paul Israel, with Bernard S. Finn, *Edison's Electric Light: Biography of Invention* (New Brunswick: Rutgers University Press, 1985); Walter G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies for Aeronautical History* (Baltimore: Johns Hopkins University Press, 1990). The high point of the sociological approach is Donald MacKenzie's *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge: MIT Press, 1990).

30. Mark Shields, "Reinventing Technology in Social Theory," *Current Perspectives in Social Theory* 17 (1997): 187–216 (quote on 190); Shields, "Thinking beyond Artifacts in the History of Technology" (paper presented at the annual meeting of the Society for the History of Technology, Charlottesville, Va., 20 Oct. 1995. For a broader critique of utilitarian and functionalist assumptions in social theory, see Marshall Sahlins, *Culture and Practical Reason* (Chicago: University of Chicago Press, 1976).

31. Schön describes this doctrine as "technical rationality," the idea that "professional activity consists in instrumental problem solving made rigorous by the application of scientific theory and technique." Donald A. Schön, *The Reflective Practitioner: How Professionals Think in Action* (New York: Basic Books, 1983), 21.

32. This separation between goal-directed and meaningful action is clear in Max Weber's concept of *Zweckrationalität*. For a discussion of Weber's instrumentalist view of technology, see Shields, "Reinventing Technology" (n. 30 above), 193–94.

33. See Kenneth Burke, *On Symbols and Society*, ed. Joseph R. Gusfield (Chicago: University of Chicago Press, 1989), 67–70; Ernst Cassirer, "Form und Technik," in *Symbol, Technik, Sprache*, ed. Ernst W. Orth and John M. Krois (Hamburg: Felix Meiner Verlag, 1985), 51–52; Sahlins (n. 30 above).

34. There are actually three distinct approaches, social construction, actor-network theory, and ethnomethodology. For a mature statement of social construction, see Wiebe E. Bijker, *Of Bicycles, Bakelite and Bulbs: Towards a Theory of Sociotechnical Change* (Cambridge: MIT Press, 1985); on actor-network theory see Bruno Latour, *Science in Action: How to Follow Scientists and Engineers through Society* (Cambridge: Harvard University Press, 1987); for ethnomethodology see Steve Woolgar, "The Turn to Technology in Social Studies of Science," *Science, Technology and Human Values* 16 (1991): 20–50.

35. Trevor J. Pinch and Wiebe E. Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," *Social Studies of Science* 14 (1984): 421; Donald MacKenzie, "Marx and the Machine," *Technology and Culture* 25 (1984): 500 (emphasis deleted). For an explicit discussion of indeterminacy in the history of technology, see Edward Constant, "Cause or Consequence: Science, Technology, and Regulatory Change in the Oil Business in Texas, 1930–1975," *Technology and Culture* 30 (1989): 427–30. The concept of technical indeterminacy is closely linked to the idea of alternative paths. See David Noble, *Forces of Production*, especially pp. xii–xiv, 42–45, 144–46. See also Eugene Ferguson, "Toward a Discipline of the History of Technology," *Technology and Culture* 15 (1974): 19.

36. For example, Hughes (n. 18 above); Brooke Hindle, *Emulation and Invention* (New York: Norton, 1981); Eugene Ferguson, *Engineering and the Mind's Eye* (Cambridge: MIT Press, 1992).

37. Donald A. Schön, *Technology and Choice: The New Heraclitus* (New York: Delacorte Press, 1967), 24–32. See also Michael Fores, "The History of Technology: An Alternative View," *Technology and Culture* 20 (October 1979): 859.

38. Pye (n. 13 above), 70. Several historians of technology have recognized the significance of Pye's work. For example, Eugene Ferguson, "Elegant Inventions: The Artistic Component of Technology," in *Technology and Choice: Readings from Technology and Culture*, ed. Marcel C. LaFollette and Jeffrey K. Stine (Chicago: University of Chicago Press, 1991), 327; Steven Lubar, "Culture and Technological Design in the 19th-Century Pin Industry: John Howe and the Howe Manufacturing Company," *Technology and Culture* 28 (1987): 252.

39. T. P. Wright, "Relation between Commercial Airplane Design and Commercial Uses of Airplanes," *ASME Transactions, Aeronautical Engineering* 51 (1929): 201–12 (quote on 201). See also Alfred A. Gassner, "Weight Saving by Structural Efficiency," *SAE Journal* 27 (October 1930): 466; Karl Thalau, "Aufgaben der Luft-

fahrzeug-Statik," *Deutsche Versuchsanstalt für Luftfahrt, Jahrbuch* (1931): 67. For a historical study that clearly illustrates indeterminacy in airplane design, see Walter Vincenti, "The Retractable Airplane Landing Gear and the Northrop 'Anomaly': Variation-selection and the Shaping of Technology," *Technology and Culture* 35 (1994): 20, 27–28.

40. Clifford Geertz defines culture as a "historically transmitted pattern of meanings embodied in symbols, a system of inherited conceptions expressed in symbolic forms by means of which men communicate, perpetuate, and develop their knowledge about and attitudes toward life." *The Interpretation of Cultures* (New York: Basic Books, 1973), 89. Although the definition of culture is very much contested, the concept of symbolic meanings has remained central to most definitions of culture after World War II. For an overview of recent developments in the anthropological concept of culture, see Sherry Ortner, "Theory in Anthropology since the Sixties," *Comparative Studies in Society and History* 26 (1984): 126–66. (Thanks to Henrika Kuklick for this reference.)

41. Hess (n. 4 above), 8–12; Joseph Rouse, "What Are Cultural Studies of Scientific Knowledge?" *Configurations* 1 (1992): 1–22. Rouse, in my opinion, draws too sharp a distinction between social construction and cultural studies. In technology studies at least, recent work in the social-constructivist tradition does grapple seriously with symbolic meanings. See Trevor Pinch and Ronald Kline, "Users as Agents of Technological Change: The Social Construction of the Automobile in the Rural United States," *Technology and Culture* 37 (October 1996): 763–95; Bijker (n. 34 above), 221–25, 262–66. Bijker's work is especially suggestive in the connections he draws between meanings and power.

42. John Staudenmaier, "Recent Trends in the History of Technology," *American Historical Review* 95 (1990): 717, 723.

43. The idea that technology has symbolic meanings as well as material effects is widely recognized. For example, see Pasquale Gagliardi, "Artifacts as Pathways and Remains of Organizational Life," in *Symbols and Artifacts: Views of the Corporate Landscape*, ed. P. Gagliardi (Berlin: Walter de Gruyter, 1990), 29–30; Pierre Lemonnier, introduction to *Technological Choices: Transformation in Material Cultures since the Neolithic*, ed. Pierre Lemonnier (London: Routledge, 1993), 22–24; Brian Pfaffenberger, "Fetishised Objects and Humanised Nature: Towards an Anthropology of Technology." *MAN*, n.s., 23 (1988): 244; Cynthia Cockburn and Susan Ormrod, *Gender and Technology in the Making* (London: Sage, 1993), 77; Svante Lindqvist, *Technology on Trial: The Introduction of Steam Power Technology into Sweden, 1715–1736* (Uppsala: Almqvist & Wiksell, 1984), 14.

44. Representative works include Nye (n. 17 above); Joseph J. Corn, *Winged Gospel: America's Romance with Aviation, 1900–1950* (New York: Oxford University Press, 1983); Alan Trachtenberg, *Brooklyn Bridge: Fact and Symbol*, 2d. ed. (Chicago: University of Chicago Press, 1979); Donald Reid, *Paris Sewers and Sewermen: Realities and Representations* (Cambridge: Harvard University Press, 1991); Leo Marx, *Machine in the Garden: Technology and the Pastoral Ideal in America* (New York: Oxford University Press, 1964); Wosk (n. 15 above). For an explicit study of symbolism and technological failure in aviation, see Guillaume de Syon, "The Socio-Politics of Technology: The Zeppelin in Official and Popular Culture 1900–1939" (Ph.D. diss., Boston University, 1994).

45. Other historians have made similar observation concerning the role of cultural meanings in shaping technical choice, most notably Joseph Corn in his study of popular enthusiasm for the airplane in America. Corn notes that "the airplane's impact on American culture . . . is only one side of the story; the other side is the way the culture influenced the technology and its adoption." Corn (n. 44 above), 136–38 (quote on 137). See also Lubar (n. 38 above), 253–55.

46. Many scholars have recognized the importance of such frameworks in technical change, although most have emphasized patterns of practice rather than systems of meanings. Edward Constant's application of the Kuhnian concept of the paradigm to technology is one example, along with the related idea of traditions of technological practice. Wiebe Bijker has developed a similar concept of "technological frame," while the evolutionary economists have used the terminology of "paradigm" and "technological trajectory." Edward W. Constant, *The Origins of the Turbojet Revolution* (Baltimore: Johns Hopkins University Press, 1980); Constant "The Social Locus of Technological Practice," in *The Social Construction of Technological Systems* (n. 8 above), 223–27; Wiebe Bijker, "The Social Construction of Bakelite: Toward a Theory of Invention," ibid., 168–77; Henk van den Belt and Arie Rip, "The Nelson-Winter-Dosi Model and Synthetic Dye Chemistry," ibid., 135–58.

47. The definition of ideology as the intersection of symbols and power is from John B. Thompson, *Ideology and Modern Culture: Critical Social Theory in the Era of Mass Communication* (Stanford: Stanford University Press, 1990), 56.

48. Noble (n. 7 above), esp. chaps. 3, 7; Harley Shaiken, *Work Transformed: Automation and Labor in the Computer Age* (New York: Holt, Rinehart and Winston, 1984). Noble ultimately sees the development of numerically controlled machine tools as the product of a will-to-power even stronger than the capitalist desire for profit.

49. There is a significant literature on the ideological *effects* of technology, which is a different issue altogether. For an explicit argument for considering the influence of ideology on technical change, see Hughie Mackay and Gareth Gillespie, "Extending the Social Shaping of Technology Approach: Ideology and Appropriation," *Social Studies of Science* 22 (1992): 690–93; see also Philip T. Shepard and Christopher Hamlin, "How Not to Presume: Toward a Descriptive Theory of Ideology in Science and Technology Controversy," *Science, Technology, and Human Values* 12 (March 1987): 19–28. Some scholars have examined the professional ideology of engineers, but without connecting this ideology to technical choice. Edwin T. Layton, "The Ideology of Engineering," chap. 3 in Layton (n. 27 above). For works that explicitly use the concept of ideology in accounts of technical change, see the references in Mackay and Gillespie, and also Bill Luckin, *Questions of Power: Electricity and Environment in Inter-War Britain* (Manchester: Manchester University Press, 1990); Frederick H. Buttel, "Ideology and Agricultural Technology in the Late Twentieth Century: Biotechnology as Symbol and Substance," *Agriculture and Human Values* 10 (March 1993): 5–15. For a work by a political scientist that examines the influence of the ideology of progress on technology policy, see Emanuel Adler, *The Power of Ideology: The Quest for Technological Autonomy in Argentina and Brazil* (Berkeley: University of California Press, 1987).

50. For a discussion of these criticisms, see Terry Eagleton, *Ideology: An Introduction* (London: Verso, 1991), chap. 1. For a historical overview of changing meanings

of the concept of ideology, see Thompson, *Ideology and Modern Culture*, chap. 1; also Jorge Larrain, *The Concept of Ideology* (Athens: University of Georgia Press, 1979).

51. My account of Ricoeur's argument is based on his book-length analysis in *Lectures on Ideology and Utopia* (New York: Columbia University Press, 1986). For a summary, see Ricoeur, "Ideology and Utopia," in *From Text to Action*, trans. Kathleen Blamey and John B. Thompson (Evanston: Northwestern University Press, 1991), 308–24.

52. For Geertz, see his essay, "Ideology as a Cultural System," in *The Interpretation of Cultures* (New York: Basic Books, 1973), 193–233. Geertz's concept of ideology has been popular among historians, but it has also been subject to recent criticism. For Geertz's influence in history, see John Higham, "Hanging Together: Divergent Unities in American History," *Journal of American History* (1974): 10; Robert Darnton, *The Great Cat Massacre and Other Episodes in French Cultural History* (New York: Vintage, 1984), xiii. For a critique of historians' use of Geertz, see Theda Skocpol, "Cultural Idioms and Political Ideologies in the Revolutionary Reconstruction of State Power: A Rejoinder to Sewell," *Journal of Modern History* 57 (1985): 86–96; also Dominick LaCapra, "Chartier, Darnton, and the Great Symbol Massacre," in *Soundings in Critical Theory* (Ithaca: Cornell University Press, 1989), 67–89.

53. There is no sharp boundary between ideological and nonideological symbolic systems, between systems that merely structure and those that distort. Nevertheless, the fuzzy boundary does not make the concept any less useful. Postmodernist criticism has blurred the boundaries of almost every major concept in social theory, and "ideology" is no different in this respect. The distinction between distorting and nondistorting systems is always relevant to a particular position, a position defined by a utopian framework of imagined possibilities that allows the critic to identify the systematic suppression of alternatives. See Ricoeur, *Lectures* (n. 51 above).

Chapter Two

1. These American airplanes include the Boeing B-9 and 247 and the Douglas DC-2. See chapters seven and eight.

2. Charles H. Gibbs-Smith, *Aviation: An Historical Survey from its Origins to the End of World War II* (London: HMSO, 1970), 159–63, 165, 172; John H. Morrow, Jr., *German Air Power in World War I* (Lincoln: University of Nebraska Press, 1982), 8, 11–12, 186–90, 198.

3. A. R. Weyl, *Fokker: The Creative Years* (London: Putnam, 1965), 31–32, 46, 64–70; N. J. Hoff, "A Short History of the Development of Airplane Structures," *American Scientist* 34 (1946): 221; Henri Hegener, *Fokker—The Man and the Aircraft* (Letchworth, Herts.: Harleyford, 1961), 198–202, 207; Anthony H. G. Fokker and Bruce Gould, *Flying Dutchman: The Life of Anthony Fokker* (New York: Henry Holt, 1931), 106–12. Information on Platz's role comes from Weyl, whose book is a personal diatribe against Fokker, apparently based on interviews with an embittered Platz. Weyl argues that most of Fokker's success could be attributed to Platz, who parted from Fokker in the early 1920s, apparently on bad terms. Fokker claimed in 1924 to have built his first steel fuselage in 1911, before his association with Platz. "Welded Steel Tubing in Fuselage Construction," *Aviation* 16 (16 June 1924): 642.

4. Weyl (n. 3 above), 67–69; "Welded Steel Tubing in Fuselage Construction" (n. 3 above), 642–43.

5. A third designer of all-metal airplanes during the war was Gotthold Baatz of the Luft-Fahrzeug-Gesellschaft. LFG's all-metal designs received little notice after the war, and the company continued to use wood in most of its wartime and postwar airplanes. C. W. Erich Meyer, *Entwicklung und gegenwärtiger Stand des Metallflugzeugbaues*, revised and expanded offprint from the *Deutsche Motor-Zeitschrift*, January 1924 (Dresden: Verlag Hellmut Droscha, 1925), 21–22, NASM/TF Y4000320.

6. Richard Blunck, *Hugo Junkers: Ein Leben für Technik und Luftfahrt* (Düsseldorf: Econ-Verlag, 1951), 79–84, 86, 90; Erik Hildesheim, "The German All-Metal Aeroplanes," *Aeroplane* 18 (19 May 1920): 996; Hugo Junkers, "Metal Aeroplane Construction," *Journal of the Royal Aeronautical Society* 28 (1923): 407, 415–16; Hoff (n. 3 above), 218; Günter Schmitt, *Hugo Junkers and his Aircraft* (Berlin: VEB Verlag für Verkehrswesen, 1988). Schmitt insists that Junkers' 1910 patent was not for a flying wing, but this seems a mere quibble over terminology. Also, Schmitt states that the wings of the *Ente* were covered in corrugated iron, not aluminum, as claimed by Hoff. Hoff is clearly the more reliable source, having no doubt verified his information with Hans Reissner himself, who in the 1940s was Hoff's colleague at Brooklyn Polytechnic Institute. Thanks to Mark Levinson for alerting me to this connection.

7. Blunck (n. 6 above), 93, 94, 99–101; Morrow (n. 2 above), 40; Junkers (n. 6 above), 428–29 (quote). The above-cited paper by Junkers states that the sheet iron was 0.1 mm. thick. Ibid., p. 429. This contradicts the 0.5 to 1 mm. figure given by Blunck (n. 6 above), 101. The 0.1 mm figure is almost certainly incorrect, because it is literally the thickness of a sheet of paper and thinner than any standard sheet-metal gage. Junkers' paper was translated from the German by W. J. Stern of the British Air Ministry, and Junkers apparently did not review the translation before publication. "Metal Aeroplane: Resume of Professor Junkers' Paper Read before R.Ae.Soc.," *Flight* 15 (11 Jan. 1923): 24. To further add to the confusion, a summary of a lecture given by Junkers in 1919 gives the metal thickness as 0.3 mm. "'Eigene Arbeiten auf dem Gebiete des Metall-Flugzeugbaues,'" *Zeitschrift für Flugtechnik und Motorluftschiffahrt* 11 (14 Feb. 1920): 36.

8. Hugo Junkers, quoted in Blunck (n. 6 above), 93, 96–98 (quote on 95).

9. H. Y. Hunsicker and H. C. Stumpf, "History of Precipitation Hardening," in *The Sorby Centennial Symposium on the History of Metallurgy*, ed. Cyril Stanley Smith (New York: Gordon and Breach, 1965), 275–80; Louis W. Kempf, "Wilm's Pioneer Investigations on Duralumin," *Metal Progress* 36 (September 1939): 256–58; see also "Wie das Duralumin erfunden wurde," *Aluminium* (Berlin) 18 (August 1936): 366–67. The latter two references courtesy Howard Wolko, National Air and Space Museum.

10. Corrugated materials are strongest in the direction of the corrugations. They support much smaller loads perpendicular to the corrugations. The main bending load in a wing creates compressive forces on top of the wing along its longest dimension (spanwise). Given the chordwise orientation (in the direction of flight) of the corrugations on the Junkers wing, the covering could support little of the bending load.

11. Blunck (n. 6 above), 98, 102–4, 107–9; Junkers (n. 6 above), 432–37; Morrow (n. 2 above), 106. The German army designated the J4 the J1, because it was the first Junkers type accepted for military service.

12. Howard S. Wolko, *In the Cause of Flight: Technologists of Aeronautics and Astronautics*, Smithsonian Studies in Air and Space, no. 4 (Washington, D.C.: Smithsonian Institution Press, 1981), 82; Douglas H. Robinson, *Giants in the Sky: A History of the Rigid Airship* (Seattle: University of Washington Press, 1973), 41. On Count Zeppelin, see Henry Cord Meyer, *Airshipmen, Businessmen and Politics, 1890–1940* (Washington, D.C.: Smithsonian Institution Press, 1991), 21–52.

13. G. W. Haddow and Peter M. Grosz, *The German Giants: The Story of the R-Planes, 1914–1919* (London: Putnam, 1962), 94, 195–96.

14. Haddow and Grosz (n. 13 above), 95–122 (quote on 101); B. E. Schröter, "Aus den Anfängen des Ganzmetallflugzeugbaues," *Illustrierte Flugwoche* 8 (1928): 212; Eric [sic] Hildesheim, "The Dornier Giant Flying Boats," *Aviation and Aeronautical Engineering* 8 (1 July 1920): 432.

15. Claude Dornier, *Vorträge und Abhandlungen aus dem Gebiete des Flugzeugbaues und Luftschiffbaues, 1914–1930* (Berlin-Lichterfelde: Verlag für Deutsches Flugwesen, 1930), 58, 60–61, 67, 83–84 (quote on 60); Morrow (n. 2 above), 129.

16. Morrow (n. 2 above), 105–106, 122, 129; Fokker and Gould (n. 3 above), 147–48.

17. Henry Ladd Smith, *Airways: A History of Commercial Aviation in the United States* (New York: Alfred A. Knopf, 1942), 38–41; John B. Rae, *Climb to Greatness: The American Aircraft Industry, 1920–1960* (Cambridge: MIT Press, 1968), 1–2.

18. Loening built a seaplane with a steel fuselage and steel tail structures around 1916. Alexander Klemin, "Metal Airplane Construction," *Aero Digest* 27 (July 1935): 45.

19. Ellis W. Hawley, *The Great War and the Search for a Modern Order* (New York: St. Martin's Press, 1979), 25; Smith (n. 17 above), 39.

20. W. F. Durand (chairman, NACA) to The president, 18 Sept. 1917, NACA/NF, box 289, 64–8.

21. Arthur Sweetser, *The American Air Service* (New York: D. Appleton, 1919), 49–58. Also see the correspondence for 1917 and 1918 in AAF/E166, box 863, 411.1A-Spruce.

22. Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915–1958*, NASA SP-4103 (Washington, D.C.: National Aeronautics and Space Administration, 1985), 1:32–43; Klemin (n. 18 above), 45; Rexmond C. Cochrane, *Measures for Progress: A History of the National Bureau of Standards* (Washington, D.C.: National Bureau of Standards, 1966), 185; "Report on Metal Airplane Construction for the Sub-Committee on Steel Construction of Aircraft, Advisory Committee for Aeronautics," 28 Feb. 1919, pp. 2–3, NACA/NF, box 290, 65-1.

23. "Report on Metal Airplane Construction" (n. 22 above), 3–4. Quote from Empire letterhead; see H. L. Whittemore to W. F. Durand, 24 Dec. 1917, NACA/NF, box 290, 65-1.

24. "Report on Metal Airplane Construction" (n. 22 above), 4; U.S. Bureau of Standards, *War Work of the Bureau of Standards*, Miscellaneous Publications of the Bureau of Standards, no. 46 (Washington, D.C.: GPO, 1921), 33.

25. "Report on Metal Airplane Construction" (n. 22 above), 6–9; "Development

of Metal Wings and Control Surfaces," *Bulletin of Experimental Department, Airplane Engineering Division* 2 (January 1919): 74. On the history of steel metallurgy, see Thomas J. Misa, *A Nation of Steel: The Making of Modern America, 1865–1925* (Baltimore: Johns Hopkins University Press, 1995).

26. "Development of Metal Wings and Control Surfaces" (n. 25 above), 73; Bettye H. Pruitt and George David Smith, "The Corporate Management of Innovation: Alcoa Research, Aircraft Alloys, and the Problem of Stress-Corrosion Cracking," in *Research on Technological Innovation, Management and Policy*, ed. Richard S. Rosenbloom (Greenwich, Conn.: JAI Press, 1986), 3:40–41; Margaret B. W. Graham, "R&D and Competition in England and the United States: The Case of the Aluminum Dirigible," *Business History Review* 62 (1988): 272–75; David W. Taylor (chief constructor, U.S.N.) to president, Aluminum Company of America, 26 July 1916, "Metal for Framework of Proposed Experimental Airship," BuAer/E50, box 431, 160-Z-12 vol. 1. The file containing the Taylor memo includes substantial correspondence documenting the Navy's efforts to promote American production of duralumin-type alloys.

27. "Report on Metal Airplane Construction" (n. 22 above), 9–12, 15.

28. "Development of Metal Wings and Control Surfaces" (n. 25 above), 74–78.

29. Ibid., 81–86; Alexander Klemin, *Airplane Stress Analysis: An Introductory Treatise* (New York: Ronald Press, 1929), 42–43.

30. "Development of Metal Wings and Control Surfaces" (n. 25 above), 81, 86 (quote); *U.S. Air Service Technical Orders* no. 3 (December 1918), 36.

31. "Development of Metal Wings and Control Surfaces" (n. 25 above), 72, 90, 96.

32. Morrow (n. 2 above), 145, 147, 151–53, 162–65.

33. Ibid., 152; Blunck (n. 6 above), 115–17, 122. The figure of seventy-three F13s in 1920 comes from Blunck and may well be an exaggeration. American military intelligence reported the construction of only twenty F13s through September 1920, based on information from the Inter-Allied Control Commission, which viewed this work as "decidedly illegal" under the Versailles treaty. Telegram, Milstaff Berlin to War Department, OCofS, MID, 30 Sept. 1920, AAF/E166, box 985, 452.1-All-Metal Planes.

34. Erik Hildesheim, "Dornier All-Metal Cantilever Monoplanes," *Aviation* 10 (6 June 1921): 721–22; Dornier (n. 15 above), 72–75; Morrow (n. 2 above), 163; Blunck (n. 6 above), 129–30.

35. Haddow and Grosz (n. 13 above), 267–72; Wolko (n. 12 above), 82; "The Zeppelin-Staaken 1000 Hp. Monoplane," *Aviation* 11 (3 Oct. 1921): 398–401; Dornier (n. 15 above), 83; G. Krupp, "Zerstörung des größten und schnellsten Verkehrflugzeuges," *Zeitschrift für Flugtechnik und Motorluftschiffahrt* 14 (26 Jan. 1923): 6; "A New Zeppelin-Staaken Monoplane," *Aviation* 11 (31 Oct. 1921): 505.

36. See in particular Peter W. Brooks, *The Modern Airliner: Its Origins and Development* (Manhattan, Kans.: Sunflower Press, 1982), 39; Gibbs-Smith (n. 2 above), 171, 182.

37. For the Control Commission's reasoning, see Commission Interalliée de Controle Aéronautique en Allemagne, *Rapport Technique* (Chalais Meudon: Atelier de Reproductions, 1922), 1:211.

38. Meyer (n. 5 above), 7–9.

39. In the United States, for example, the government had canceled $469 million in airplane contracts by February 1919. Thomas N. Walterman, "Airpower and Private Enterprise: Federal-Industrial Relations in the Aeronautics Field, 1918–1926" (Ph.D. diss., Washington University, 1970), 50.

40. For the United States see Roger E. Bilstein, *Flight in America 1900–1983: From the Wrights to the Astronauts* (Baltimore: John Hopkins University Press, 1984), 41–76; for Britain see David Edgerton, *England and the Aeroplane: An Essay on a Militant and Technological Nation* (Basingstoke, Eng.: Macmillan, 1991), 18–37.

41. George E. Quisenberry, "The Commercial Airplane in Its Present Day Development," *Automotive Industries* 42 (29 May 1920): 999; "Trends of German Airplane Design," *Automotive Industries* 40 (20 Jan. 1919): 262–65; Morrow (n. 2 above), 146, 159, 163.

42. Maj. J. C. Riley, "Junkers All-Metal Monoplane, Type R.E.-5," 28 Jan. 1919, p. 5, AAF/E206, box 477, D52.1-Junkers/5. See also *U.S. Air Service Technical Orders* no. 8 (September 1919), 86–90, and no. 9 (October 1919), 123–25.

43. Air Ministry, Directorate of Research, "Junker [sic] All-Metal Single-Seater Monoplane, Type D.1," July 1919, pp. 3–4, AAF/E206, D52.1-Junkers/10.

44. Morrow (n. 2 above), 164 (first quote); "Glimpses of the French Aircraft Industry," *Aviation* 14 (18 June 1923): 664 (second quote); Commission Interalliée de Controle Aéronautique (n. 37 above), 1:177–81 ; "The Paris Aeronautical Exposition," *Aviation* 8 (1 Feb. 1920): 10–13; W. H. Sayers, "Metal Construction at the Paris Show," *Aeroplane, Aeronautical Engineering Supplement* 21 (30 Nov. 1921): 543–46; "New Aircraft at the Paris Aero Exposition: Review of the Constructional Features and Specifications of the Aircraft Exhibited," *Aviation* 14 (5 Feb. 1923): 156–60. See also "Technical Bulletin No. 31," *Air Service Information Circular* no. 31 (December 1922–January 1923), 16.

45. "The Paris Aero Salon, *Aviation* 18 (19 Jan. 1925): 69; Gibbs-Smith (n. 2 above), 182; Hoff (n. 3 above), 223; John D. North, "The Case for Metal Construction," *Journal of the Royal Aeronautical Society* 28 (1923): 3; Albert P. Thurston, "Metal Construction of Aircraft," *Aeronautical Journal* 23 (Sep. 1919): 479–89, 516. The British, who were familiar with duralumin in airship construction, also experimented with duralumin airplanes in this period. "The Short All Metal 'Silver Streak,'" *Aviation* 9 (1 Nov. 1920): 217–19.

46. The American technical press paid little attention to German metal airplanes before 1920, except for a brief article and an editorial in *Scientific American*. "Airplane with Wings of Metal," *Scientific American* 120 (1 Feb. 1919): 95; "Metal Airplanes," *Scientific American* 121 (20 Sep. 1919): 276.

47. "The Junkers Metal Airplanes," *Automotive Industries* 42 (1 Apr. 1920): 823; "Design and Structure of the German Metal Airplane," *Automotive Industries* 42 (10 June 1920): 1360–62; "Junkers Armored Two-Seater Biplane, Type J.1," *Aviation* 8 (1 May 1920): 285–89.

48. Lester D. Gardner, comp., *Who's Who in American Aeronautics*, 2nd. ed., 1925 (New York: Gardner, 1928; repr. ed., Los Angeles: Floyd Clymer, 1960), s.v. "John Miller Larsen."

49. "All-Metal Plane Stirs Flyers Here," *New York Times*, 20 June 1920, sec. II, p. 9; Blunck (n. 6 above), 122–24; William M. Leary, *Aerial Pioneers: The U.S. Air Mail Service, 1918–1927* (Washington, D.C.: Smithsonian Institution Press, 1985), 118; Schmitt (n. 6 above), 57.

50. William C. Ocker (Mitchell Field) to Dir/AS, "Junkers Airplane," May 27, 1920, box 985, 452.1, All Metal Planes (first quote); Menoher to Larsen, 4 June 1920, AAF/E166, 452.1, quoted in Leary (n. 49 above), 119 (second quote); *New York Times*, 13 June 1920, 18; 15 June 1920, 14 (third quote).

51. "All-Metal Plane Stirs Flyers Here" (n. 49 above), 9. For a more sober assessment of aluminum-alloy airplanes, see "The Use of Duralumin," *Aviation* 8 (1 May 1920): 277.

52. Leary (n. 49 above), 119.

53. Roland (n. 22 above), 1:48–49, 73–74, 79–87, 102–103, 2:463; James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958*, NASA SP-4305 (Washington, D.C.: National Aeronautics and Space Administration, 1987), 5–9.

54. "Minutes of Meeting of Committee on Materials for Aircraft," 22 Mar. 1920, p. 4, NACA/NF, box 217, 42-6B.

55. Leigh M. Griffith to NACA (attn.: executive officer [George W. Lewis]), 12 July 1920, NACA/NF, box 217, 42-6B.

56. G. W. Lewis to LMAL (attn.: senior staff engineer [L. M. Griffith]), 16 July 1920; G. W. Lewis to Charles F. Marvin, 16 July 1920; G. W. Lewis to Dr. Ames, 28 July 1920; J. S. Ames to Charles F. Marvin, [29 July 1920], NACA/NF, box 218, 42-6C; "Minutes of Meeting of Committee on Materials for Aircraft," 14 Sept. 1920, NACA/NF, box 217, 42-6B.

57. G. W. Lewis to Dr. Ames, 28 July 1920; "A Program of Research Necessary for the Development of All-Metal Aircraft," 12 Aug. 1920, NACA/NF, box 218, 42-6C.

58. National Advisory Committee for Aeronautics, *Annual Report* 6th (1920), 52–53.

59. Adm. William A. Moffett, "The Navy's Record in Aeronautics," *Aviation* 12 (19 June 1922): 720–22; William F. Trimble, *Wings for the Navy: A History of the Naval Aircraft Factory, 1917–1956* (Annapolis, Md., 1990), 55–59, 85–89; "Development of Metal Aircraft," *Aviation* 12 (29 May 1922): 636; "The Stout Air Pullman: America's First All-Metal Commercial Plane, Built in Detroit, Passes Successful Flying Tests," *Aviation* 16 (19 May 1924): 533–34; Roy G. Miller and F. E. Seiler, Jr., "The Design of Metal Airplanes: Outstanding Features of Metal Construction as Illustrated by its Principal Exponents," *Aviation* 14 (19 Feb. 1923): 210 (quote).

60. John T. Nevill, "Ford Motor Company and American Aeronautic Development," *Aviation* 27 (1929): 229; Smith (n. 17 above), 336–37.

61. "Specifications of American Commercial Airplanes," *Aviation* 28 (22 Mar. 1930): 608–9. (Eight types provide no data on spar construction.) On federal certification of commercial aircraft, see Nick A. Komons, *Bonfires to Beacons: Federal Civil Aviation Policy under the Air Commerce Act, 1926–1938* (Washington, D.C., 1978), 98–99. The preponderance of wood was even greater in terms of the number of aircraft produced, since smaller airplanes, which invariably used wood wings, were produced in much greater quantities than larger airplanes.

Chapter Three

1. These articles were typically written by engineers involved in designing metal airplanes. Many of the French and German articles were translated into English; Junkers's 1923 paper for the Royal Aeronautical Society was widely cited (and often

practically plagiarized, as in Weyerbacher's paper of 1927). Among the more important articles are: Wellwood E. Beall, "All-Metal Airplane Construction," *ASME Transactions, Aeronautics* 52 (1930): 95–98; M. E. DeWoitine, "The Metal Construction of Airplanes: Its Advantages—Its Present State—Its Future," *U.S. NACA Technical Memorandum* no. 349 (February 1926); Alexander Klemin, "Metal Airplane Construction," *Aero Digest* 27 (July 1935): 43–45, 112–13; Hugo Junkers, "Metal Aeroplane Construction," *Journal of the Royal Aeronautical Society* 28 (September 1923): 406–49; Corley McDarment, "Will the Future Airplane Be of Metal?" *Iron Age* 115 (1 Jan. 1925): 19–23; Louis Merlin, "La Construction des Avions: Bois ou Métal?" *La Métallurgie* 60 (25 Oct. 1928): 5, 7, 9, 11, 13; Roy G. Miller and F. E. Seiler, "The Design of Metal Airplanes," *Aviation* 14 (19 Feb. 1923): 210–14; John D. North, "The Case for Metal Construction," *Journal of the Royal Aeronautical Society* 28 (1923): 3–25; Adolf Rohrbach, "Materials and Methods of Construction in Light Structures," *U.S. NACA Technical Memorandum* no. 515 (1929) [trans. of "Entwurf und Aufgaben des Leichtbaues," *Wissenschaftliche Gesellschaft für Luftfahrt, Jahrbuch* (1926): 64–78]; William B. Stout, "Veneer or Metal Construction," *Aviation* 10 (21 Feb. 1921): 232; idem, "The Modern Airplane and All-Metal Construction," *SAE Journal* 11 (December 1922): 495–504; idem, "Wood versus Metal for Airplanes," *U.S. Air Service* 8 (May 1923): 16–17; H. V. Thaden, "Metallizing the Airplane," *ASME Transactions, Aeronautics* 52 (1930): 167–72; A. P. Thurston, "Metal Construction of Aircraft," *Aeronautical Journal* 23 (November 1919): 473–518; R. D. Weyerbacher, "Metal Construction of Aircraft," *SAE Journal* 21 (November 1927): 489–93.

2. "Says Metal 'Plane Opens New Era," *New York Times*, 15 June 1920, 14 (second quote); Larsen to Menoher, 3 June 1920, quoted in William M. Leary, *Aerial Pioneers: The U.S. Air Mail Service, 1918–1927* (Washington, D.C.: Smithsonian Institution Press, 1985), 118 (third quote); "Minutes of Meeting of Committee on Materials for Aircraft," 22 Mar. 1920, p. 4, NACA/NF, box 217, 42-6B (first quote). Prometal articles frequently listed fire safety as an advantage; see Junkers (n. 1 above), 417; Beall (n. 1 above), 95; McDarment (n. 1 above), 22; Miller and Seiler (n. 1 above), 210.

3. Leary (n. 2 above), 121–26, 138–40.

4. Joseph S. Newell, comment to H. V. Thaden, "Metallizing the Airplane," *ASME Transactions, Aeronautics* 52 (1930): 171; "Tests of Fireproof Airplane Dope and Equipment," *Aviation* 9 (1 Aug. 1920): 21–22.

5. T. P. Wright, "Aircraft Engineering," *Annals of the American Academy of Political and Social Science* 131 (May 1927): 30. Richard K. Smith has done more than any other aviation historian to emphasize the centrality of weight; see "The Weight Envelope: An Airplane's Fourth Dimension . . . Aviation's Bottom Line," *Aerospace Historian* 33 (March 1986): 30–33; idem, "The Intercontinental Airliner and the Essence of Airplane Performance, 1929–1939," *Technology and Culture* 24 (1983): 428–31. On terminology see *Airworthiness Requirements of Air Commerce Regulations*, Aeronautics Bulletin no. 7-A (Washington, D.C., 1929), 11. The modern term for gross weight is "maximum takeoff weight" (MTOW). MTOW is a conventional figure, not an inherent physical limit; it represents the maximum weight at which government regulators believe the airplane can safely take off, fly, and land.

6. John E. Younger, *Structural Design of Metal Airplanes* (New York: McGraw-Hill, 1935), 3; Smith, "The Weight Envelope" (n. 5 above), 30–31; Wright (n. 5 above), 30; Grover Loening, "Flying from an Engineering Standpoint," *Aviation* 17 (27 Oct. 1924): 1225; Jerome C. Hunsaker, "Naval Architecture in Aeronautics," *Aviation* 9 (1 Aug. 1920): 10 (quote).

7. Thurston (n. 1 above), 473; "Metal Airplanes," *Scientific American* 121 (20 Sept. 1919): 276; North (n. 1 above), 5. Some engineers doubted that metal offered any weight advantages; see Hunsaker (n. 6 above), 11. On Hall's designs, see "Successful Design of Light Weight Metal Wings," *Aviation* 14 (8 Jan. 1923): 38, 41; Charles J. McCarthy, "Notes on Metal Wing Construction," *U.S. Air Services* 10 (March 1925): 10–11, 13–16. McCarthy's article compared wood and metal airplanes, but McCarthy could not demonstrate weight savings for metal wings, with the exception of two designs by Hall. The airplanes compared were mainly American but included some German all-metal types. McCarthy's position as a lieutenant in the Navy Construction Corps gave him access to reliable weight data for many models, data that manufacturers rarely released. See chapter four for further discussion of Hall's designs.

8. E. W. Dichman, "Resume of the Development of the Gallaudet DB-1B with Recommendations for the Future," *Air Corps Technical Report* no. 2369 (13 May 1924), 2–3; D. B. Weaver, "Static Test of the Gallaudet DB-1 Day Bombardment Airplane," *Air Corps Technical Report* no. 1957 (19 June 1922), 4. For more on the army's unsuccessful metal airplane projects, see chapter four.

9. McDarment (n. 1 above), 21 (first quote); Alexander Klemin, *Airplane Stress Analysis: An Introductory Treatise* (New York: Ronald Press, 1929), 116 (second quote). See also Stout, "The Modern Airplane" (n. 1 above), 499. French designers reached similar conclusions. M. E. DeWoitine, a leading French builder of metal airplanes, noted that designers "have met with quite considerable difficulties in the realization of an all-metal wing within compatible [*sic*] limits of weight and performance." DeWoitine (n. 1 above), 25–26. Klemin played an important role in interwar American aeronautics, both as an educator and technical journalist. See Maurice Holland with Thomas M. Smith, *Architects of Aviation* (New York: Duel, Sloan and Pearce, 1951), 79–93.

10. For a general introduction to the properties of materials, see J. E. Gordon, *The New Science of Strong Materials, or Why You Don't Fall through the Floor*, 2d ed. (Princeton: Princeton University Press, 1976), 129–53; on the strength properties of wood, see George W. Trayer, *Wood in Aircraft Construction* (Washington, D.C.: National Lumber Manufacturers Association, 1930), 49–50, 175–79. Torsion stresses are technically reducible to shear, and bending stresses to compression and tension, but in anisotropic materials torsion and bending *strength* are difficult to predict from strength properties in shear, compression, and tension. Thanks to Brett Steele for stimulating my thinking on this point.

11. J. A. Roché, "Selection of Materials for Aircraft Structures," *SAE Journal* 21 (November 1927): 494–95. As some engineers pointed out in the late 1930s, the proper basis for the comparison should be the strength of parts of equal weight, not the weight of parts of equal strength. When the weight/strength relationship is nonlinear, these measures are not equivalent. F. R. Shanley, "Pounds or Pounds per Square Inch," *Aviation* 35 (November 1936): 26–29.

12. The paper analogy was not uncommon. See Brian L. Martin, "Steel Spars," U.S. NACA *Technical Memorandum* no. 458 (April 1928) [from *Gloster*, September–December 1927], 4; Alfred S. Niles and Joseph S. Newell, *Airplane Structures*, 1t ed. (New York: John Wiley & Sons, 1929), 153–54; N. J. Hoff, "A Short History of the Development of Airplane Structures," *American Scientist* 34 (1946): 223.

13. Paul Brenner, "Problems Involved in the Choice and Use of Materials in Airplane Construction," U.S. NACA *Technical Memorandum* no. 658, February 1932 [trans. of "Baustoffragen bei der Konstruktion von Flugzeugen," *Zeitschrift für Flugtechnik und Motorluftschiffahrt* 22 (1931)], 9. Density data from Trayer (n. 10. above), 63, and John E. Younger, *Mechanics of Aircraft Structures* (New York: McGraw-Hill, 1942), 64, 66.

14. Stephen P. Timoshenko, *History of Strength of Materials* (New York: McGraw-Hill, 1953; repr. ed., New York: Dover, 1983), 33–34; John Cutler, *Understanding Aircraft Structures* (London: Granada, 1981), 81. Euler struts were a standard topic in books on airplane structures, starting with the influential textbook of Pippard and Pritchard; see A. J. Sutton Pippard and J. Laurence Pritchard, *Aeroplane Structures* (London: Longmans, Green, 1919), 209–10.

15. Nathan Rosenberg and Walter G. Vincenti, *The Britannia Bridge: The Generation and Diffusion of Technological Knowledge* (Cambridge: MIT Press, 1978), 19–22, 29; J. E. Gordon, *Structures: Or Why Things Don't Fall Down* (New York: Plenum Press, 1978), 285–95; Timoshenko (n. 14 above), 299, 413–15. Buckling stress in a flat plate is proportional to the modulus of elasticity divided by the density squared. Buckling load is therefore inversely proportional to the cube of the density. The problem is more complicated when comparing curved sheets, but low density materials still have a considerable advantage. See Hoff (n. 12 above), 224.

16. F. C. Marschner, "Structural Considerations Favoring Plastics in Aircraft Structures," *Modern Plastics* 17 (September 1939): 41–42+.

17. Younger, *Mechanics* (n. 13 above), 62–73. Younger discusses the influence on wing weight of a whole list of design criteria, some of which favored aluminum, some steel, and some wood. Aluminum and steel were, for example, somewhat stiffer than wood per unit weight. Wings and control surfaces had to be sufficiently stiff to retain their shape in high-speed flight and also to avoid the destructive oscillations known as flutter. I have found no evidence, however, that stiffness was a major factor in the choice of metal over wood.

18. A. S. Niles and E. C. Friel, "Progress Reports on Experimental Spars," *Air Corps Information Circular* no. 590 (26 Aug. 1927), 1.

19. "The Battleship of the Air," *Aviation* 3 (15 Aug. 1917): 93; F. H. Norton, "The Possibility of the Large Airplane," *Aviation* 10 (10 Jan. 1921): 48; Junkers (n. 1 above), 416–17; DeWoitine (n. 1 above), 7, 26. On the relationship between buckling strength and size, see Gordon, (n. 15 above), 310–11. The statement about the weight efficiency of American airplanes in 1930 is based on my calculation of the ratio of useful load to gross weight for the eight passenger landplanes in 1930 with gross weights greater than ten thousand pounds. See "Specifications of American Commercial Airplanes," *Aviation* 28 (22 Mar. 1930): 606–9.

20. The disadvantage of metal in buckling strength also decreases with increasing speeds, insofar as higher speeds are achieved through higher wing loadings. Ronald Miller and David Sawers, *Technical Development of Modern Aviation* (New York:

Praeger, 1970), 55–56. Miller and Sawers quote a 1944 source that shows clear awareness of this relationship; however, I have found no evidence that aviation engineers in the 1920s and early 1930s were aware of the connection between wing loading, buckling strength, and relative weight efficiencies. In any case, wood structures remained competitive with metal in weight efficiency even at wing loadings typical of World War II, as demonstrated by the de Havilland Mosquito Mk. 35 with its wing loading of forty-nine pounds per square foot. These wing loadings are several times higher than loadings typical of the early 1930s, when metal established its dominance. Mosquito data from C. Martin Sharp and Michael J. F. Bowyer, *Mosquito* (London: Faber and Faber, 1967), 409.

21. Gordon, (n. 15 above), 293, 311–13. Aviation engineers in the late 1920s and early 1930s seemed almost completely oblivious to the advantages of wood in stressed skin construction; see chapter six.

22. Michael Watter, "Metal Airplane Construction: Part 1—The Wings," *Aero Digest* 20 (April 1932): 32; Edward P. Warner, discussion comment to "Symposium on Metal Aircraft Construction," *SAE Journal* 22 (April 1928): 433. On Warner 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: University of Iowa Press, 1989), 113–26.

23. The most important firms were Ford, Sikorsky, Curtiss (for the B-2 and Condor models), and Boeing (for its model 80).

24. Hoff (n. 12 above), 225, 374, 378–81.

25. Junkers (n. 1 above), 417–18 (first quote); Stout, "The Modern Airplane" (n. 1 above), 503; *Aircraft Year Book 1930* (New York: D. Van Nostrand, 1930), 311. See also McDarment (n. 1 above), 21; DeWoitine (n. 1 above), 8, 12–14; Glenn L. Martin, "The Development of Aircraft Manufacture," *Aviation Engineering* 5 (December 1931): 28 (second quote).

26. "The United States Naval Air Service, 1922–23," *Aviation* 16 (14 Jan. 1924): 36 (quote); U.S. Congress, House, Select Committee of Inquiry into Operations of the United States Air Services (hereafter Lampert Committee), *Hearings*, 68th Cong., 1st sess., pt. 2, p. 1603. See also "The Paris Aero Exhibition," *Aviation* 14 (5 Feb. 1923): 151.

27. R. H. Fleet to Col. Bane, 12 Dec. 1921, RD3103, file 452.1-Gallaudet Type I Airplane/1921, USAF/SCC; Dichman (n. 8 above), 3, 8–9, 11–12, 27; "Technical Bulletin No. 29: Status of Aviation Material under Development for United States Air Service," *Air Service Information Circular* no. 379 (October 1922), 8. Total contract cost for the DB-1 and other airplane projects is from *Congressional Record*, 68th Cong., 2d sess., 66, pt. 2 (1925): 1399–1404. See chapter four for more details on the army's early metal airplane projects.

28. H. Herrmann, "Relative Economy of Different Methods of Airplane Construction," U.S. NACA *Technical Memorandums* no. 618, (1931) [trans. from *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, 14 and 28 Nov. 1930], 1 (quote); Gardner W. Carr, "Evolution of Metal Construction," preprint of paper for ASME aeronautic meeting, 6–8 June 1932, UCLA/AK, box 158, "Metal Construction: General; Beall: All Metal Airplane Const"; Charles D. Bright, "Machine Tools and the Aircraft Industry: The Boeing Case," *Journal of the West* 30 (1991): 50–57. On the Mosquito, see chapter ten. In a 1936 analysis of airplane costs, engineer T. P. Wright estimated

that structures of fabric-covered airplanes cost from $3.50 to $4.50 per pound, compared to $5.25 to $6.25 per pound for all-metal airplanes, assuming a production run of twenty-five. Wright insisted that the cost of metal types would decrease more rapidly than the cost of composite structures as production quantities increased, although he presented no evidence to support this claim. Wright's article became important after World War II, when it helped stimulate Kenneth Arrow's concept of the learning curve. T. P. Wright, "Factors Affecting the Cost of Airplanes," *Journal of the Aeronautical Sciences* 3 (February 1936): 126–27; Kenneth J. Arrow, "The Economic Implications of Learning by Doing," *Review of Economic Studies* 29 (1962): 155–73.

29. Carolyn C. Cooper, "The Portsmouth System of Manufacture," *Technology and Culture* 25 (1984): 182–225; Christopher Wilk, *Thonet: 150 Years of Furniture* (Woodbury, N.Y.: Barrons, 1980), 22–29; David A. Hounshell, *From the American System to Mass Production, 1800–1932* (Baltimore: Johns Hopkins University Press, 1984), 132–51; "Modern Methods in Railway Carriage Building," *Engineering* 116 (12 Oct. 1923): 467–69; "The Mass Production of Railway Wagons," *Engineering* 116 (28 Dec. 1923): 797–801. See also Carroll Pursell, "Variations on Mass Production: The Case of Furniture Manufacture in the United States to 1940," *History of Technology* 17 (1995): 127–41. For another example, the quantity production of wooden clock mechanisms, see Donald R. Hoke, *Ingenious Yankees: The Rise of the American System of Manufactures in the Private Sector* (New York: Columbia University Press, 1990), 65–82. Thanks to Tom F. Peters for calling my attention to Thonet, and to Jonathan Zeitlin for providing me the articles on British railroad cars.

30. Hounshell (n. 29 above), 274; U.S. Bureau of the Census, *Historical Statistics of the United States: Colonial Times to 1956* (Washington, D.C.: U.S. Department of Commerce, 1960), 466; Irving Brinton Holley, *Buying Aircraft: Materiel Procurement for the Army Air Forces*, United States Army in World War II, Special Studies (Washington, D.C.: Department of the Army, 1964), 579–79; I. B. Holley, "A Detroit Dream of Mass-produced Fighter Aircraft: The XP-75 Fiasco," *Technology and Culture* 28 (1987): 578–93; Jonathan Zeitlin, "Flexibility and Mass Production at War: Aircraft Manufacture in Britain, the United States, and Germany, 1939–1945," *Technology and Culture* 36 (1995): 46–79; "Wanted: A Cheap Airplane," *Aviation* 16 (12 May 1924): 501 (quote); E. P. Warner, "The Future Market for Airplanes," *Aviation* 17 (8 Sept. 1924): 958–60. See also "False Analogies to the Automobile Industry," in *The Aviation Industry: A Study of Underlying Trends* (Philadelphia: Curtis, 1930), 15–18. On continuing use of wood in small airplanes, see "Specifications of American Airplanes," *Aviation* 35 (March 1936): 82–85.

31. Junkers (n. 1 above), 417. See also DeWoitine (n. 1 above), 9–10; McDarment (n. 1 above), 24; Miller and Seiler (n. 1 above), 210.

32. Comment by Cmdr. Jerome Hunsaker, "Minutes of Meeting of Committee on Materials for Aircraft," 22 Mar. 1920, p. 4, NACA/NF, box 217, 42–6B (first quote); "Air Transport in the Tropics," *Aviation* 12 (5 June 1922): 655 (second quote); Ladislas d'Orcy, "Foreign Air Transport by Seaplane: Belgian Congo, Republic of Colombia and French Guiana Afford the Principal Fields of Activity," *Aviation* 14 (29 Jan. 1923): 122–25.

33. Thurston (n. 1 above), 478; Stout, "The Modern Airplane" (n. 1 above), 503;

F. O. Carroll, "Metals Used in Airplane Construction," *Iron Age* 113 (24 Apr. 1924): 1206.

34. Henry S. Rawdon, "Corrosion Embrittlement of Duralumin, I: Practical Aspects of the Problem," U.S. NACA *Technical Note* no. 282 (April 1928), 6–8; William Nelson, "Duralumin and Its Corrosion," *Aviation* 21 (1 Nov. 1926): 738.

35. Von DeWitz, discussion comment to C. Dornier, "Neuere Erfahrungen im Bau und Betrieb von Metallflugzeugen," *Wissenschaftliche Gesellschaft für Luftfahrt, Jahrbuch* (1925), 55; S. W. Stratton, "Report on the Investigation of the Causes of Failure of a Duralumin J. L. Elevator submitted by the U.S. Post Office, Postal Aviation Field, College Park, Md.," 19 Feb. 1921, BuAer/E50, box 19, 0-Z-64; R. Barnaby to Files, 12 Sept. 1924, "Condition of Duralumin and Protective Coatings on JL-6 Monoplane at Hampton Roads," BuAer/E50, box 400, 0-G-3; Rawdon (n. 34 above), 6.

36. George K. Burgess, "Report on Examination of a Sample of Duralumin Channel Exposed to Corrosive Atmosphere," 1 Dec. 1924; George K. Burgess to BuAer, Attn: H. C. Richardson, 2 Feb. 1925, "Report on Duralumin Samples," BuAer/E50, box 432, 160-Z-12 vol. 9; Rexmond C. Cochrane, *Measures for Progress: A History of the National Bureau of Standards* (Washington, D.C., 1966), 284; [C. P. Burgess], "Report of the Chairman, Committee on Materials for Aircraft," 16 Apr. 1925, NACA/NF, box 219, 42-6E; U.S. NACA, *Annual Report* 11th (Washington, D.C., 1925), 34.

37. "Discussion on Aircraft Materials," *American Society for Testing Materials, Proceedings* 30, pt. 2 (1930): 183, 188 (Harrison quote); Newell (n. 4 above), 171.

38. William F. Trimble, *Wings for the Navy: A History of the Naval Aircraft Factory, 1917–1956* (Annapolis: Naval Institute Press, 1990), 85. In any case, improved waterproof coatings were a potential solution to this problem, one that certainly might have seemed attractive considering the corrosive effect of salt water on duralumin. See George W. Trayer, "The Future of Wood in Aircraft Construction," *Southern Lumberman* 130 (15 Dec. 1930): 151–54.

39. Thomas P. Hughes, "The Evolution of Large Technological Systems," in *The Social Construction of Technological Systems*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch (Cambridge: MIT Press, 1987), 73–74. On the growth of civil aviation, see United States, Bureau of the Census, *Historical Statistics of the United States: Colonial Times to 1970* (Washington, D.C.: U.S. Dept. of Commerce, 1975), pt. 2, pp. 770, 772.

40. Edward W. Constant developed the concept of "presumptive anomaly" to explain the development of turbojet engines by engineers who anticipated future limitations on the speed of propeller airplanes. Constant, *The Origins of the Turbojet Revolution* (Baltimore: Johns Hopkins University Press, 1980), 15. Almost no one before the mid-1930s expected the increases in wing loading and engine power that made possible the large, high-speed metal airliners of the postwar era. Even if some aeronautical engineers did anticipate extremely large aircraft or supersonic flight, they did not connect these beliefs with support for metal. A good example is Igor Sikorsky, who advocated and built large passenger aircraft even before World War I and was one of the earliest American manufacturers to switch to metal. I know of no instance in which Sikorsky linked his use of metal with his advocacy of large

airplanes. See Igor I. Sikorsky, *The Story of the Winged-S* (New York: Dodd, Mead, 1948); Frank Delear, *Igor Sikorsky: His Three Careers in Aviation* (New York: Dodd, Mead, 1976).

41. The seminal paper on the social shaping approach is Trevor J. Pinch and Wiebe E. Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," *Social Studies of Science* 14 (1984): 399–441; a masterful empirical example is Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge: MIT Press, 1990). Recent work in social construction pays more attention to symbolic meanings: see Trevor Pinch and Ronald Kline, "Users as Agents of Technological Change: The Social Construction of the Automobile in the Rural United States," *Technology and Culture* 37 (October 1996): 763–95. See chapter one for a more detailed discussion.

42. For a nuanced discussion of strategy and structure in business history, see Charles F. Sabel and Jonathan Zeitlin, "Stories, Strategies, Structures: Rethinking Historical Alternatives to Mass Production," in *Worlds of Possibility: Flexibility and Mass Production in Western Industrialization*, ed. Charles F. Sabel and Jonathan Zeitlin (Cambridge: Cambridge University Press, 1997). For more on Alcoa see my chapter four. I have found only one observer from within the aviation community who blamed lumber suppliers for much of metal's popularity. John F. Hardecker, "Specializing in the Production of Wooden Parts," *Aviation* 28 (4 Jan. 1930): 20–21. Thanks to John Kenley Smith for pointing out to me the argument about the relative ability of wood and metals suppliers to innovate.

43. For a critique of perspectives that deny the significance of symbolic meanings, see Marshall Sahlins, *Culture and Practical Reason* (Chicago: University of Chicago Press, 1976). I address this issue at length in "Symbols in the Shaping of Technology" (paper presented to the annual meeting of the Society for the History of Technology, Charlottesville, Virginia, 20 Oct. 1995).

44. See chapter one for a discussion of the historical roots of the progress ideology of metal.

45. Paul Ricoeur, *Lectures on Ideology and Utopia*, ed. George H. Taylor (New York: Columbia University Press, 1986); Clifford Geertz, "Ideology as a Cultural System," in *The Interpretation of Cultures* (New York: Basic Books, 1973), 193–233. For a more thorough discussion of the concept of ideology, see chapter one.

46. North (n. 1 above), 3; McDarment (n. 1 above), 19; J. B. Johnson, "Metals Used in World Cruiser Airplanes," *Iron Age* 114 (1924): 994.

47. DeWoitine (n. 1 above), 5–6, 26; Stout, "The Modern Airplane" (n. 1 above), 500. J. B. Johnson also invoked the analogy to ships; see Johnson (n. 46 above), 994.

48. Miller and Seiler (n. 1 above), 210. On wood versus metal in railroad freight cars, see John H. White, "More Than an Idea Whose Time Has Come: The Beginnings of Steel Freight Cars," *History of Technology* 11 (1986): 181–207.

49. Miller and Seiler (n. 1 above), 210; DeWoitine (n. 1 above), 11–12; Stout, "Wood Versus Metal" (n. 1 above), 16.

50. According to Younger, the criterion of ultimate strength "imposes a heavy burden on the stress analyst because no theoretical process of analysis has been devised for calculating stresses above the proportional limit of the material." Younger

(n. 13 above), 5. See also "Exaggerated Refinement in Stress Analysis," *Aviation* 10 (21 Feb. 1921): 227.

51. McDarment (n. 1 above), 20–21, 23. See also Temple N. Joyce, "Successful Commercial Aviation Analyzed," *Aviation* 14 (16 Apr. 1923): 420.

52. On the benefits to wood of scientific research, see P. J. Champion, "Wood's Technological Coming of Age," Forest Products Laboratory mimeo. no. R1442, Madison, Wisc., December 1943 (typescript of article for *Scientific Monthly*), FPL-L. On technological style, see Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore: Johns Hopkins University Press, 1983), 404–5.

53. For the utility of systematic research, see "Airplane Research Work through Flight Tests," *Aviation* 15 (6 Aug. 1923): 154–55. For a sophisticated discussion of the limited role of scientific theory in airplane design, see North (n. 1 above), 11, 20; Stanley H. Evans, comment to A. J. Sutton Pippard, "The Training of an Aeronautical Engineer," *Journal of the Royal Aeronautical Society* 39 (1935): 85. The best analysis of science-technology historiography remains Otto Mayr, "The Science-Technology Relationship as a Historiographic Problem," *Technology and Culture* 17 (1976): 663–73. On science as an ideology in early-twentieth-century engineering, see Edwin T. Layton, *The Revolt of the Engineers: Social Responsibility and the American Engineering Profession* (Baltimore: Johns Hopkins University Press, 1986), 58.

54. A. P. Thurston, comment to North (n. 1 above), 22; Warner (n. 22 above), 433; [Heinrich] Focke, comment to Adolph Rohrbach, "Entwurf und Aufgaben des Leichtbaues," *Wissenschaftliche Gesellschaft für Luftfahrt, Jahrbuch* (1926), 78. My translation is a modification of that given in Rohrbach (n. 1 above), 44.

55. Robert Friedel, "The Coming of the All-Metal Airplane: A Study in Ideas," NASA Historical Office Summer Seminar 1974 (typescript, 13 Sept. 1974), 7–8 (copy courtesy of the author). On the aluminum-steel debate, see for example, Rohrbach (n. 1 above), 6a–9. See chapter one for further discussion of the identification of modern technology with inorganic materials.

56. Based on articles listed in U.S. NACA, *Bibliography of Aeronautics*, annual volumes for 1922–29.

57. McDarment (n. 1 above), 20; Walter M. Moore, "Some Recent Developments in the Use of Wood in Airplane Construction," *Journal of Forestry* 22 (1924): 366–71; Trayer (n. 38 above), 151–54. See also Trayer (n. 10 above), 142, 149, 153, 157–58. Even representatives of companies that continued to use wood rarely challenged prometal claims in public. One exception was Clement M. Keys, the president of the Curtiss Airplane & Motor Company, who in testimony before the Lampert Committee in 1925 expressed some mild skepticism about the immediate advantages of metal. Lampert Committee (n. 26 above), pt. 2, p. 1166.

58. Hoff (n. 12 above), 221; Peter W. Brooks, *The Modern Airliner: Its Origins and Development* (Manhattan, Kans.: Sunflower Press, 1982), 57.

59. "Why Are There No Fokker 'All Metal' Airplanes?" *Fokker Bulletin* no. 13 (September 1926), p. 2, NASM/CMK, box 15. Emphasis added. See also Anthony H. G. Fokker, "Air Transportation," *Annals of the American Academy of Political and Social Science* 131 (May 1927): 185–86; and Anthony Fokker, "An Answer to Mr. Mayo," *Western Flying* 10 (October 1931): 31.

Chapter Four

1. William H. McNeill, *The Pursuit of Power: Technology, Armed Force, and Society since A.D. 1000* (Chicago: University of Chicago Press, 1982), 9–13; Lewis Mumford, *Technics and Civilization* (New York: Harcourt Brace Jovanovich, 1934), 85–96; Carlo M. Cipolla, *Guns, Sails and Empires: Technological Innovation and the Early Phases of European Expansion, 1400–1700* (New York: Pantheon, 1965); Merritt Roe Smith, *Harpers Ferry Armory and the New Technology: The Challenge of Change* (Ithaca: Cornell University Press, 1977); Colleen A. Dunlavy, *Politics and Industrialization: Early Railroads in the United States and Prussia* (Princeton: Princeton University Press, 1994), 56–63, 110–14; Thomas J. Misa, *A Nation of Steel: The Making of Modern America, 1865–1925* (Baltimore: Johns Hopkins University Press, 1995). For a bibliographic overview of the literature on technology and the military, see Alex Roland, "Technology and War: A Bibliographic Essay," in *Military Enterprise and Technological Change*, ed. Merritt Roe Smith (Cambridge: MIT Press, 1985), 348–79.

2. A rare popular history that makes this point is Wayne Biddle, *Barons of the Sky* (New York: Simon and Schuster, 1991).

3. David Edgerton, *England and the Aeroplane: An Essay on a Militant and Technological Nation* (Basingstoke: Macmillan Academic, 1991), 19–20; John B. Rae, *Climb to Greatness: The American Aircraft Industry, 1920–1960* (Cambridge: MIT Press, 1968), 59–61; Ronald Miller and David Sawers, *Technical Development of Modern Aviation* (New York: Praeger, 1970).

4. "Civilian Contributions," *Aviation* 17 (6 Oct. 1924): 1081; "The Legacy from War Aviation," *Aviation* 10 (24 Jan. 1921): 99; W. B. Stout, "Requirements for Commercial Aircraft," *Aviation* 12 (16 Jan. 1922): 72–73; G. M. Bellanca, "Development of the Commercial Airplane," *ASME Transactions, Aeronautical Engineering* 51 (1929): 197–98; "The Aeronautical Chamber of Commerce in 1923," *Aviation* 16 (11 Feb. 1924): 148 (quote).

5. George S. Armstrong & Co., Inc., *An Engineering Interpretation of the Economic and Financial Aspects of American Industry*, vol. 1 of *The Aviation Industry* (New York: G. S. Armstrong, 1940), 7, UCLA/AK, box 139, "Industry: Investment."

6. "Expenditures of Government with Aircraft Industry," *Aviation* 18 (26 Jan. 1925): 98, 103; U.S. Bureau of the Census, *Historical Statistics of the United States: Colonial Times to 1956* (Washington, D.C.: U.S. Department of Commerce, 1960), 466; E. W. Axe and Co., *The Aviation Industry in the United States*, Axe-Houghton Economic Studies, series B, no. 6 (New York, 1938), 70, 71; Irving B. Holley, *Buying Aircraft: Matériel Procurement for the Army Air Forces*, United States Army in World War II, Special Studies (Washington, D.C.: Department of the Army, 1964), 10–11, 20–22; Edgerton (n. 3 above), 20. My estimate that civilian sales from 1920 to 1923 represented less that $1 million is based on the 1926 average price of a commercial airplane: $4,496. Axe, 71.

7. Armstrong & Co. (n. 5 above), 7.

8. Holley (n. 6 above), 10, 12, 20–21; Bellanca (n. 4 above), 197–98; "Where the Money Goes," *Aviation* 16 (5, 12 May 1924): 474, 509; *Comparative History of Research and Development Policies Affecting Air Materiel, 1915–1944*, USAF Historical Studies no. 20 (Washington, D.C.: Historical Division, Assistant Chief of Air Staff, Intelligence, 1945; repr. Manhattan, Kans.: Military Affairs/Aerospace Historian,

[1978?]), 46. For an example of the adaptation of a military design to commercial use, see "The Fokker C4 Commercial Airplane," *Aviation* 16 (24 Mar. 1924): 310. On federal aviation research, see below.

9. For example, the work of the Stout and Gallaudet companies discussed below.

10. For a study that stresses congressional interference, see Jacob A. Vander Meulen, *The Politics of Aircraft: Building an American Military Industry* (Lawrence: University Press of Kansas, 1991). Congressional policy had little influence on experimental contracts, where Congress gave the military air services wide latitude to negotiate contracts. For a more balanced discussion of these issue, see Edwin Rutkowski, *Politics of Military Aviation Procurement, 1926–1934: A Study of Political Assertion of Consensual Values* (Columbus: Ohio State University Press, 1966), esp. 139–214.

11. Irving B. Holley, *Ideas and Weapons: Exploitation of the Aerial Weapon by the United States during World War I* (New Haven: Yale University Press, 1953), 67–70; James Lea Cate and Wesley Frank Craven, "The Army Air Arm between Two Wars, 1919–1939," in *The Army Air Forces in World War II*, ed. Craven and Crate, 1:24; Maurer Maurer, *Aviation in the U.S. Army, 1919–1939*, Office of Air Force History, General Histories (Washington, D.C.: GPO, 1987), 44, 191.

12. Capt. G. E. Brower (C/Airplane Sect), "Engineering a New Type of Airplane," 8 Aug. 1928, AAF/E206, box 508, D52.16–73.

13. Ibid. For a more detailed description of the procurement process, see A. S. Niles, "General Considerations in Military Airplane Design Procedure," in U.S. Congress, House, Select Committee of Inquiry into Operations of the United States Air Services [Lampert Committee], *Hearings*, 68th Cong., 1st sess., 1925, pp. 3342–51.

14. The Air Service had continued its involvement with the Empire company, ordering a metal observation plane in September 1919; it had also acquired a war-surplus Dornier single-seat metal fighter from the navy, which the navy had acquired in Holland. U.S. Air Service, *Technical Orders* no. 8 (September 1919): 18; "War Department Tries Metal Planes," *Automotive Industries* 42 (22 Apr. 1920): 986; J. C. Hunsaker to C/EngrDiv, "Dornier D-1 Airplane," 9 Dec. 1919, USAF/SCC, RD3103, 452.1-Dornier Single Seater Land Planes/1921.

15. "Joint Army and Navy Board on Aeronautics," *Aviation* 8 (1 Feb. 1920): 27; President's Aircraft [Morrow] Board, *Hearings* (Washington, D.C.: GPO, 1925), 1:39–40; Lampert Committee, *Hearings* (n. 13 above), pt. 3, 1650.

16. "Minutes of Meeting of Technical Committee of the Aeronautical Board Held at Headquarters McCook Field, Dayton, Ohio," 18 June 1920, USAF/SCC, RD3103, 452.1-Airplane Junkers/1921 (quote); Commander A. K. Atkins to president of the Aeronautical Board, 18 June 1920, "Resolution re All-metal Airplanes"; Brig. Gen. Chas. T. Menoher to the Technical Committee, 12 July 1920, "All-Metal Planes," IA/AB, box 3, 502–3; William M. Leary, *Aerial Pioneers: The U.S. Air Mail Service, 1918–1927* (Washington, D.C.: Smithsonian Institution Press, 1985), 119. Enthusiasm for metal construction was also strong among the army's flyers. See Maurer (n. 11 above), 81.

17. Leigh M. Griffith to NACA (Attn: Executive Officer), "Some Features of McCook Field Development," 12 July 1920, NACA/NF, box 218, 42–6C.

18. Maj. Thurman H. Bane (C/EngrDiv) to C/AS, "Estimate Fiscal Year 1922," 19 Aug. 1920 (also dated 14 Dec. 1920), with enclosure, "Summary of Estimate for

Experimental Research Work, Engineering Division, . . . for Fiscal Year 1921–1922," USAF/SCC, RD3110, 121.4-Funds (Estimate of Funds)/1922.

19. *Historical Statistics of the United States* (n. 6 above), 718; Maurer (n. 11 above), 44–46; "Chapter—Experimental and Research Engineering Development," [June 1923], USAF/SCC, RD3119, 319.1-Annual Report/1923.

20. "Technical Orders No. 19," *Air Service Information Circular* no. 161 (October. 1920); "Technical Orders No. 20," *Air Service Information Circular* no. 162 (November 1920), 50 (quote); D. B. Weaver, "Report of Static Test on the Empire Metal Airplane, Type X," *Air Corps Technical Report* no. 1795 (31 Aug. 1921).

21. "Experimental Types Ordered by Army," *Aviation* 9 (27 Dec. 1920): 491–92.

22. "Technical Orders No. 18," *Air Service Information Circular* no. 160 (September 1920), p. 13; "Technical Orders No. 21, Dec.–May, 1921," *Air Service Information Circular* no. 163 (May 1921); "Technical Orders No. 22," *Air Service Information Circular* no. 347 (February 1922), p. 14; "Technical Orders No. 27," *Air Service Information Circular* no. 377 (July 1922), pp. 9–12; J. A. MacReady to chief engineer, "Initial Flight of CO-1," 26 Mar. 1922 (quote), USAF/SCC, RD3113, 452.1-CO-1 Airplane/1922.

23. Lester D. Gardner, comp., *Who's Who in American Aeronautics*, 2d. ed., 1925 (New York: Gardner, 1928; repr. ed., Los Angeles: Floyd Clymer, 1960), s.v. "Edson Fessenden Gallaudet"; "Technical Orders No. 26," *Air Service Information Circular* no. 351 (June 1922), 5; "Expenditures of Government with Aircraft Industry," (n. 6 above), 102. On Stout's refusal to build the CO-1, see correspondence in USAF/SCC, RD3113, 452.1-CO-1 Airplane/1922.

24. [Undated flight test report, 1922], USAF/SCC, RD3113, 452.1-CO-1 Airplane/1922 (first quote); Leigh Wade, "Performance Test of Engineering Division CO-1 Equipped with Liberty 12 Engine," *Air Corps Technical Report* no. 2023 (31 Aug. 1922), 5 (second quote); D. B. Weaver, "Static Test of the CO-1 Airplane," *Air Corps Technical Report* no. 1975 (12 July 1922).

25. "Technical Bulletin No. 29: Status of Aviation Material under Development for United States Air Service," *Air Service Information Circular* no. 379 (October 1922), 7; "Technical Bulletin No. 32," *Air Service Information Circular* no. 425 (February 1923), 6; D. C. Emmons, "Contract No. 559-T," 16 June 1923, NASM/APB, box 2659; "Expenditures of Government with Aircraft Industry" (n. 6 above), 102–3.

26. "Experimental Types Ordered by Army" (n. 21 above), 491; "Technical Orders No. 22" (n. 22 above), 15; E. W. Dichman, "Resume of the Development of the Gallaudet DB-1B with Recommendations for the Future," *Air Corps Technical Report* no. 2369 (13 May 1924), 2.

27. Dichman (n. 26 above), 2–3, 11; D. B. Weaver, "Static Test of the Gallaudet DB-1 Day Bombardment Airplane," *Air Corps Technical Report* no. 1957 (19 June 1922), 4.

28. Weaver, "Static Test of the Gallaudet DB-1" (n. 27 above), 4; Dichman (n. 26 above), 3.

29. R. H. Fleet to Col. Bane, 12 Dec. 1921, USAF/SCC, RD3103, 452.1-Gallaudet Type I Airplane/1921; "Engineering Conference," 4 Jan. 1922 (quote), USAF/SCC, RD3110, 337-Engineering Conference/1922.

30. Dichman (n. 26 above), 3, 8–9, 11–12, 27 (quote on 27); "Technical Bulletin

No. 29" (n. 25 above), 8; "Expenditures of Government with Aircraft Industry" (n. 6 above), 101.

31. "Technical Orders No. 22" (n. 22 above), 7; "Technical Orders No. 24," *Air Service Information Circular* no. 349 (April 1922), 5; "Technical Bulletin No. 29" (n. 25 above), 5; H. S. Martin to Procurement Section, 14 Sept. 1922, USAF/SCC, RD3113, 452.1-Gallaudet Aircraft Co., DB-1B, PW-4/1922; "Engineering Conference," [day illeg.] June 1922, USAF/SCC, RD3110, 337-Engineering Conference/1922. On the Dornier D1, see David S. Taylor and R. S. Griffin to secretary of the navy, 16 May 1921, "Purchase of Dornier Single Seater Land Plane," BuAer/E50, box 400, 0-ZF-24. In addition to the PW-4, the Air Service gave the Curtiss Aeroplane and Motor Company a contract to design a thick, internally braced metal wing for use on large airplanes. This wing also failed its static tests in early 1922. "Technical Orders No. 22" (n. 22 above), 21; "Technical Orders No. 23," *Air Service Information Circular* no. 348 (March 1922), 13.

32. "Technical Orders No. 18" (n. 22 above), 7; "Technical Orders No. 25," *Air Service Information Circular* no. 350 (May 1922), 5; Henri Hegener, *Fokker—the Man and the Aircraft* (Letchworth, Herts.: Harleyford, 1961), 188–89; "Expenditures of Government with Aircraft Industry" (n. 6 above), 99; Peter M. Bowers, *Curtiss Aircraft: 1907–1947* (London: Putnam, 1979), 182; idem, *Boeing Aircraft since 1916* (London: Putnam, 1968), 56–58; "Annual Report, Engineering Division, Air Service, Fiscal Year 1923–1924," *Air Corps Technical Report* no. 2368 (30 June 1924), 12.

33. H. S. Martin for C/EngrDiv to Gallaudet Aircraft Corp., "Stress Analysis of Gallaudet DB-1," 29 July 1921, USAF/SCC, RD3103, 452.1-Gallaudet Type I Airplane/1921.

34. L. W. McIntosh to C/AS, "Proposal for Bombardment Airplane," 22 Sept. 1922, AAF/E166, box 985, 452.1-All Metal Planes.

35. "The Wright All-Metal Pursuit Airplane," *Aviation* 14 (2 Apr. 1923): 364–66; "Wright All Metal Pursuit Plane—WP-1," [1923]; "Report on Dornier Wright Airplane," 7 Apr. 1923, AAF/E166, box 985, 452.1-All Metal Planes.

36. F. B. Rentschler to Maj. Gen. Mason M. Patrick, 30 Mar. 1923, AAF/E166, ibid.

37. 2d Ind., A. H. Hobley (for C/EngrDiv) to C/AS, 30 Apr. 1923 (first quote); "Report on Dornier Wright Airplane," 17 Apr. 1923, AAF/E166, ibid. (second and third quotes). McCook Field's maintenance concerns about the metal monocoque stemmed in part from its experience operating the prototype CO-1's, which proved especially troublesome to maintain. Airplane Section, Engineering Division, "Tentative Report Published for Criticism on the Overall Efficiencies of the Following Corps Observation Airplanes," 21 Mar. 1924, AFM-L, A1 (C)O/his.

38. 2d Ind., A. H. Hobley (for C/EngrDiv) to C/AS, 30 Apr. 1923; A. H. Hobley to C/AS, "Wright Pursuit Plane," 14 May 1923; L. W. McIntosh to Mason M. Patrick, 11 July 1923, AAF/E166, box 985, 452.1-All Metal Planes. On the fatal crash of the Fokker and the PW-5 flutter problems, see AAF/E166, box 980, 452.1-Fokker Airplanes.

39. 2d Ind., A. H. Hobley (for C/EngrDiv) to C/AS, 30 Apr. 1923, AAF/E166, box 985, 452.1-All Metal Planes (first quote); Charles N. Monteith, *Simple Aerodynamics and the Airplane*, prepared by direction of the Chief of the Air Corps—U.S. Army,

Reprint of 3d ed., November 1925 (Washington, D.C.: GPO, 1927), 263 (second quote). See also Muir S. Fairchild and O. H. Snyder, *Report on Structural and Design Characteristics of Present Type Airplanes Considered from a Maintenance Standpoint* ([McCook Field, Ohio?]: Air Service, Engineering Division, Airplane and Engine Maintenance Liaison Section, 26 Apr. 1924), 1–3, 23–26 (copy in FPL-L).

40. A. S. Niles, J. B. Johnson and R. L. Hankinson, "Airplane Design, Chapter III, Materials of Airplane Construction," *Air Corps Technical Report* no. 2233 (12 Sept. 1923), 2. A revised version of this chapter was included in a book by Niles titled *Airplane Design*, which the Air Service published in 1926. The book became, in effect, the first edition of the series of authoritative texts on airplane structural design that Niles coauthored with his former Engineering Division colleague Joseph S. Newell. Newell went on to become a professor of aeronautical engineering at MIT while Niles took a comparable position at Stanford. Alfred S. Niles, *Airplane Design* (Dayton, Ohio: Engineering Division, U.S. Army Air Service, 1926); Alfred S. Niles and Joseph S. Newell, *Airplane Structures* (New York: John Wiley & Sons, 1929), vi.

41. A. S. N[iles], "Design Contest, Type XII, . . . General Comparison of Designs," March 1923 (quote); L. W. McIntosh to C/AS, "Circular 2338—Type XII Airplane," 2 Apr. 1923, USAF/SCC, RD3122; 452.1-Bombardment—XII and XIII/1923.

42. "Expenditures of Government with Aircraft Industry" (n. 6 above), 101–2; "Annual Report, Engineering Division, Air Service, Fiscal Year 1923–1924," 4; L. W. McIntosh (Actg C/EngrDiv) to Section Chiefs, 20 Nov. 1922, USAF/SCC, RD3110, 337-Engineering Conference/1922; [L. W. McIntosh], "Chapter—Experimental and Research Engineering Development," [June 1923] (quote), USAF/SCC, RD3119, 319.1-Annual Report/1923.

43. H. S. Martin to Aeromarine Plane & Motor Corp., "Experimental Metal Construction," 20 Mar. 1923; Paul Zimmermann to EngrDiv (Attn: H. S. Martin), "Type XII Wing Ribs, Beams and Fuselage," 27 Apr. 1923; H. S. Martin to Aeromarine Plane & Motor Corp., "Experimental Construction," 11 May 1923, USAF/SCC, RD3121, 452.023-Wing Ribs—P.O. 46545 Aeromarine & Motor Co./1923; H. H. Wetzel (Douglas) to EngrDiv, "Quotation—Experimental Spars and Ribs," 19 Apr. 1923, USAF/SCC, RD3121, 452.023-Wing Ribs—P.O. 46378—The Douglas Co./1923; Telegram, Boeing Airplane Co. to C/EngrDiv, Apr. 17, 1923, USAF/SCC, RD3121, 452.023-Wing Ribs—P.O. 46378—Boeing Airplane Co./1923.

44. A. S. Niles to Chief Engineer, "Boulton and Paul System of Metal Construction," 15 Feb. 1924, USAF/SCC, RD3134, 452.1-All Metal Planes (Boulton & Paul)/1924.

45. J. S. Newell, "Comparison of Tests on Experimental 15-Inch Metal Spars and 11-Foot Chord Metal Wing Ribs, Parts 1 and 2," *Air Service Information Circular* no. 556 (1 Mar. 1926), 2 (first quote); A. S. Niles and E. C. Friel, "Progress Reports on Experimental Spars," *Air Corps Information Circular* no. 590 (26 Aug. 1927), 18 (second quote).

46. Niles to Chief Engineer, "Boulton and Paul System of Metal Construction," 15 Feb. 1924, USAF/SCC, RD3134, 452.1-All Metal Planes (Boulton & Paul)/1924.

47. Niles and Friel, "Progress Reports on Experimental Spars" (n. 45 above), 1, 21; E. W. Dichman/ASN, "Experimental Metal Spars," 14 Feb. 1927; W. F. Volandt to Buhl Aircraft Company, "Experimental Metal Spars," 8 Feb. 1927; W. F. Vo-

landt to Huff Daland Airplanes, Inc., "Experimental Metal Spars," 4 Feb. 1927, USAF/SCC, RD3163, 452.023-Experimental Metal Spars/1927.

48. Niles and Friel, "Progress Reports on Experimental Spars" (n. 45 above), 2.

49. Ibid.

50. Design methods for wood spars were developed at length in a series of NACA reports based on research at the Forest Products Laboratory. See J. A. Newlin and G. W. Trayer, "Deflection of Beams with Special Reference to Shear Deformations," U.S. NACA *Technical Report* no. 180 (1923); idem, "Form Factors of Beams Subjected to Transverse Loading Only," U.S. NACA *Technical Report* no. 181 (1923); idem, "Stresses in Wood Members Subjected to Combined Column and Beam Action," U.S. NACA *Technical Report* no. 188 (1924).

51. Niles and Friel, "Progress Reports on Experimental Spars" (n. 45 above), 17; "Development of Metal Wings and Control Surfaces," *Bulletin of Experimental Department, Airplane Engineering Division* 2 (January 1919): 72. Niles and Friel did not use the term "stressed-skin," which only became widely used after 1930 (see chapter seven).

52. Niles and Friel, "Progress Reports on Experimental Spars" (n. 45 above), 21–22; E. W. Dichman/ASN, "Experimental Metal Spars," 14 Feb. 1927; "First Annual Report of the Chief, Materiel Division, Air Corps, Fiscal Year 1927," *Air Corps Technical Report* no. 2805 (June 1927), 53–54. The memo of 14 Feb. 1927, signed by Dichman and written by Niles, was the draft of Appendix II in the Niles and Friel report. It contains the manufacturers' names, which were removed in the published version.

53. Margaret B. W. Graham and Bettye H. Pruitt, *R&D for Industry: A Century of Technical Innovation at Alcoa* (Cambridge: Cambridge University Press, 1990), 158–61; David W. Taylor to president, Aluminum Company of America, 26 July 1916, "Metal for Framework of Proposed Experimental Airship," (Confidential); George K. Burgess, "Memorandum to the Director on Light Alloys and Steel Substitutes," 1 Aug. 1916, BuAer/E50, box 431, 160-Z-12 vol. 1.

54. Graham and Pruitt (n. 53 above), 162–69; William F. Trimble, *Wings for the Navy: A History of the Naval Aircraft Factory, 1917–1956* (Annapolis: Naval Institute Press, 1990), 57–58.

55. Graham and Pruitt (n. 53 above), 169–172; Trimble (n. 54 above), 58–59; H. Y. Hunsicker and H. C. Stumpf, "History of Precipitation Hardening," in *The Sorby Centennial Symposium on the History of Metallurgy*, ed. Cyril Stanley Smith (New York: Gordon and Breach Science Publishers, 1965), 283; J. C. Hunsaker to Rear Adm. D. W. Taylor, 25 Aug. 1920, "Aeronautical Intelligence in England," BuAer/E50, box 432, 160-Z-12 vol. 5. For a clear summary of the navy's contribution to duralumin production in the United States, see J. C. Hunsaker, "The Development of Naval Aircraft: Rigid Airships," 19 Nov. 1923, pp. 1–5, BuAer/E63, box 5, file 602-0 vol. 1. Thanks to William F. Trimble for providing me with a copy of this document.

56. On independent inventors in America, see Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm* (New York: Viking Penguin, 1989), 13–95.

57. *Who's Who in America*, (Chicago: A. N. Marquis Co., 1952), vol. 27, s.v. "Stout, William Bushnell"; *New York Times*, 21 Mar. 1956, 37; William B. Stout, *So*

Away I Went (Indianapolis: Bobbs-Merrill, 1951), 126–32, 134–39; *U.S. Air Service Technical Orders* no. 3 (December 1918), 16; *U.S. Air Service Technical Orders* no. 4 (January 1919); "The Stout Batwing Monoplane," *Aviation* 8 (15 July 1920): 479.

58. [No signature], "Memorandum for Lieut. Harper," 22 Apr. 1920; Congdon [?] (Scientific Section, BuC&R) to Comdr. Hunsaker, 5 May 1920, "Stout Torpedo Plane," BuAer/E62, box 4452, QM(781); Wm. B. Stout to Col. Thurman Bane, 26 May 1920; Wm. B. Stout to Col. Thurman Bane, 7 June 1920 (quote), USAF/SCC, box 56, RD3097, 452.1-Junkers Airplanes/1920. On Stout see also William M. Leary, "Henry Ford and Aeronautics during the 1920s," in *Aviation's Golden Age: Portraits from the 1920s and 1930s*, ed. by William M. Leary (Iowa City: University of Iowa Press, 1989), 2.

59. William F. Trimble, *Admiral William A. Moffett: Architect of Naval Aviation* (Washington, D.C.: Smithsonian Institution Press, 1994), 71; Shatswell Ober, *The Story of Aeronautics at MIT* (Cambridge: MIT Department of Aerospace Engineering, 1965), 6–7. Hunsaker returned to MIT in the early 1930s, becoming chairman of the Departments of Mechanical Engineering and Aeronautical Engineering. Professor Trimble is currently writing a biography of Hunsaker.

60. Fulton (by direction) to Lt. Col. A. R. Chistie, Navy Bldg., 22 July 1920, "Award of Aeroplane Contract by Navy Department"; "Supplementary Agreement with Stout Engineering Laboratories," 27 Nov. 1920; Taylor to Bureau of Supplies and Accounts, 17 Dec. 1920, "Contract 51248—Extension of Delivery Date," BuAer/E56, box 106A, #51248, vol. 1; William B. Stout to Bureau of Aeronautics, 19 Oct. 1921 (quote); [S. F.?] (BuAer) to Scientific Section, 21 Oct. 1921, BuAer/E82, box 971, C-51248.

61. [Untitled memo for files], Nov. 1921; Harper to Files, 22 Oct. 1921, "ST and SV drawings," BuAer/E82, box 971, C-51248, vol. 3; Taylor and R. S. Griffin to sect. of the navy, 16 May 1921, "Purchase of All-Veneer Monoplane from Stout Engineering Laboratories" (first quote); Lt. Comdr. G. Fulton to Files, 9 Nov. 1921, "Visit to Plant of Stout Engineering Laboratories" (second quote), BuAer/E62, box 4452, QM(781).

62. Lt. F. M. Smith to BuAer, 1 Dec. 1921, "Contract 51248—ST Seaplane—Weights of," BuAer/E82, box 971, C-51248, vol. 3; W. A. Moffett (BuAer) to Wm. B. Stout, Stout Engineering Laboratories, 22 June 1922 (quote), BuAer/E62, box 4452, QM(781); Stout (n. 57 above), 153, 156–57. Stout's biographical account gives a very different impression from that conveyed by the navy's files.

63. Edwin Denby to Cmdr. George C. Westervelt, Construction Corps., USN, 1 Nov. 1922, "Board to Inquire into and Report on the Advance Made in Construction of Metal Aeroplanes by Engineering Development Work Carried on by the Stout Engineering Company"; George C. Westervelt, Kenneth Whiting, and Jerome C. Hunsaker, "Record of Proceeding of a Board to Inquire into and Report on the Advance Made in Construction of Metal Aeroplanes by Engineering Development Work Carried on by the Stout Engineering Company," 10 Nov. 1922, BuAer/E62, box 4452, QM(781); J. C. Hunsaker to Files, 16 Nov. 1922, "Contributions to the Art Made by Stout Engineering Laboratories" (quote), BuAer/E82, box 971, file C-51248, vol. 3.

64. Gordon Swanborough and Peter M. Bowers, *United States Navy Aircraft since 1911* (Annapolis: Naval Institute Press, 1990), 125–27; W. A. Moffett to C/BuAer,

21 Nov. 1922, BuAer/E62, box 4373, QM(57), vol. 1; Capt. E. S. Land to Files, 28 Mar. 1924, "Metal Wings for Airplanes—Status" (quote), BuAer/E62, box 5544, VV(1); "Contract #57525—History of F4C [and] Contract 50642—History of HS-3 Metal Wings," filed 21 Sept. 1925, BuAer/E56, box 213, C-57525, vol. 2; Charles J. McCarthy, "Notes on Metal Wing Construction," *U.S. Air Services* 10 (March 1925): 10–11.

65. JCH [Hunsaker] to Scientific Section, 27 May 1922; H. C. Mustin to C. W. Hall, "Proposal to build TS airplane in metal," 28 Nov. 1922; F. H. Russell to BuAer, 24 Jan. 1923, "Confirmation of Understanding and Delivery of Contracts for Shipboard Fighter Airplanes," BuAer/E62, box 4373, QM(57), vol. 1; "Contract #57525—History of F4C," filed 21 Sept. 1925, BuAer/E56, box 213, C-57525, vol. 2; S. H. R. Doyle to C/BuAer, 3 June 1927, Re: "Model F4C-1 Airplane No. A-6690—Information Concerning," BuAer/E62, box 4922, VF4C1/L9; McCarthy (n. 64 above), 11 (quote); "Expenditures of Government with Aircraft Industry" (n. 6 above), 103.

66. C. W. Erich Meyer, *Entwicklung und gegenwärtiger Stand des Metallflugzeugbaues*, revised and expanded offprint from the *Deutsche Motor-Zeitschrift*, January 1924 (Dresden: Verlag Hellmut Droscha, 1925), 31 (copy in NASM/TF Y4000320); Günter Schmitt, *Hugo Junkers and His Aircraft* (Berlin: VEB Verlag für Verkehrswesen, 1988), 30; Swanborough and Bowers (n. 64 above) 480, 511; J. C. Hunsaker to Files, 21 Jan. 1922, "Glenn L. Martin's Proposition for Metal Spotting Airplane," BuAer/E62, box 5544, VV(1); "Contract 56083," 12 June 1922, BuAer/E56, box 167, C56083; "The Martin Observation Plane," *Aviation* 13 (11 Dec. 1922): 772; "A Shipboard Scout Seaplane: the Martin-Navy," *Aviation* 14 (30 Apr. 1923): 474.; McCarthy (n. 64 above), 10.

67. Karl F. Smith to BuAer, 25 Apr. 1923, "Accident to MS-1 Airplane No. A-6521," BuAer/E56, box 167, C56083; A. E. Montgomery to Chief/BuAer, 29 Dec. 1923, "Preliminary Test Flights of MO-1 Airplane," BuAer/E51, box 406, O-G-23, vol. 1; Lt. Cmdr. G. B. Strickland, "Survey Report," 8 Feb. 1924, BuAer/E51, box 408, 0-G-31 (first quote); T. T. Craven to Chief/BuAer, 6 Sept. 1924, "MO-1 Airplanes—Condition of"; Stanford E. Moses to Lt. Cmdr. M. B. McComb, USN, 22 Oct. 1924, "Board of Investigation (MO-1 Planes)" (second quote), BuAer/E51, box 406, O-G-23, vol. 2.

68. This figure is an estimate based on data from various sources for the JL-6, CO-1, DB-1, PW-4, ST, TS-1, MS-1, and MO-1; it excludes spending on smaller projects like the Hall HS-3 wings or the army spar study. Figures for the CO-1, DB-1, PW-5, ST, and TS-1 are given in the text above. The army and navy each spent $100,000 on the JL-6; the navy MS-1 contract was for $60,000, and the navy spent at least $995,000 on the thirty-six MO-1's, according to figures supplied to Congress that do not include separate development costs. Josephus Daniels to Rep. Julius Kahn, 31 Jan. 1921, BuAer/E62, box 5544, VV(1); "Contract 56083," 12 June 1922, BuAer/E56, box 167, C56083; "Expenditures of Government with Aircraft Industry" (n. 6 above), 103.

69. See, for example McCarthy (n. 64 above), 9. McCarthy, an engineering officer in the Bureau of Aeronautics, had considerable knowledge of the navy's unsuccessful metal airplane projects. Nevertheless, he argued that "gradual but steady progress is being made in" metal construction, although he admitted to some problems

with metal wings, especially high cost. Despite "these limitations," insisted McCarthy, "a considerable amount of experimenting" has yielded "creditable results." In other words, the navy's metal airplane projects were not failures but rather learning experiences.

70. John M. Staudenmaier, *Technology's Storytellers: Reweaving the Human Fabric* (Cambridge: MIT Press and the Society for the History of Technology, 1985), 45–50; on the influence of science on postwar engineering education, see Bruce Seely, "Research, Engineering, and Science in American Engineering Colleges: 1900–1960," *Technology and Culture* 34 (1993): 344–86. See also the special issue of *Technology and Culture* devoted to the development process, esp. Thomas P. Hughes, "Introduction: The Development Process of Technological Change," *Technology and Culture* 17 (1976): 423–31.

71. For example, "Experimentation and Research on Airplanes and Accessories," 20 Aug. 1920, enclosure to Thurman H. Bane to C/AS, "Estimate Fiscal Year 1922," 14 Dec. 1920, USAF/SCC, RD3110, 121.4-Funds (Estimate of Funds)/1922. The term *research and development* begins to appear in army documents from the early 1930s. "Progress Report, Research and Development Work, Materiel Division," December 1931, AAF/E166, box 2766, 400.112C-Wright Field, Tests and Experiments, January 1928–December 1933. See also Holley (n. 6 above), 22–26.

72. In addition to these four organizations, the Forest Products Laboratory performed most of the research related to wood in aircraft. See chapter six.

73. John F. Curry to R. L. Walsh, 27 Jan. 1926, transmitting "A Consideration of the Feasibility of Transferring of Research and Technical Work from the Engineering Division to the Bureau of Standards," AAF/E166, box 2766, 400.112B; Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915–1958*, NASA SP-4103 (Washington, D.C.: National Aeronautics and Space Administration, 1985), 1:74, 101–11; James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958*, NASA SP-4305 (Washington, D.C.: National Aeronautics and Space Administration, 1987), 158–61.

74. Roland (n. 73 above), 1:103, 2:475, 487; Lampert Committee, *Hearings* (n. 13 above), 1506, 1538–42; U.S. NACA, *Annual Report* 8th (1922), 32. For the period 1917–1925, NACA appropriations amounted to just over $1.98 million, while bureau appropriations and fund transfers for aviation projects totaled just over $1.62 million. However, the NACA figures include headquarters expenses, overhead, and the costs of building the Langley laboratory, while the bureau's figures do not include the entire 1925 fiscal year, probably neglect overhead, and also neglect smaller projects that had no specific allotments. In addition, the NACA total includes $162,000 transferred to the bureau.

75. J. E. Gordon, *Structures, or Why Things Don't Fall Down* (New York: Plenum Press, 1978), 333–36.

76. Russell R. Voorhees, "Fatigue of Metals in Airplane Parts," *Iron Age* 115 (21 May 1925): 1498 (first quote); U.S. NACA, *Annual Report* 9th (1923), 34; "For Annual Meeting," 7 Oct. 1920 (second quote), NACA/NF, box 219, 42-6E; "Minutes of Meeting, Committee on Materials for Aircraft," 14 Sept. 1920 (third quote), NACA/NF, box 217, 42–6B.

77. U.S. NACA, *Eighth Annual Report* (1922), 32; *Ninth Annual Report* (1923), 34;

Tenth Annual Report (1924), 33; F. O. Carroll, "Metals Used in Airplane Construction," *Iron Age* 113 (24 Apr. 1924): 1206; Gordon (note 75 above), 334–37.

78. Henry S. Rawdon, "Corrosion Embrittlement of Duralumin, I: Practical Aspects of the Problem," U.S. NACA *Technical Note* no. 282 (April 1928), 6–8; William Nelson, "Duralumin and Its Corrosion," *Aviation* 21 (1 Nov. 1926): 738.

79. D. W. Taylor (chairman, Joint Army and Navy Airship Board) to J. H. Finney, 26 Apr. 1917, BuAer/E50, box 431, 160-Z-12, vol. 1; G. Fulton (BuC&R) to Bureau of Standards, Attn.: Dr. Finn, 9 Apr. 1919, "Metal Plates—Test of"; S. Truscott to Cmdr. Hunsaker, 18 Apr. 1919, "Aluminum Alloys—Specification Regarding Corrosion of," ibid., vol. 2; Acting Testing Engineer [name illeg.] (NAF), "Test 9T20-7 on Corroded Duralumin," 5 Nov. 1920, ibid., vol. 5.

80. Carroll (n. 77 above), 1206.

81. S. W. Stratton, "Report on the Investigation of the Causes of Failure of a Duralumin J. L. Elevator Submitted by the U. S. Post Office, Postal Aviation Field, College Park, Md.," 19 Feb. 1921 BuAer/E50, box 19, 0-Z-64. For references to powder on duralumin samples, see Watt to BuC&R, 30 Oct. 1917, "Airship Metal—Report on Condition of Specimen of," BuAer/E50, box 431, 160-Z-12, vol. 2; J. J. Raby (Naval Air Station, Pensacola) to BuAer, 22 Mar. 1924, "N-9 Metal Floats," BuAer/E50, box 369, RNAF-47.

82. W. A. Moffett, "JL-6 Airplane No. A-5869—Investigation of Corrosion of," 27 Dec. 1922, BuAer/E50, box 19, 0-Z-64; H. C. Cocke (Naval Air Station, Hampton Roads) to Chief/BuAer, 1 July 1924, "JL-6 No. 5869- Report of Investigation of Corrosion" (first quote); R. Barnaby to Files, 12 Sept. 1924, "Condition of Duralumin and Protective Coatings on JL-6 Monoplane at Hampton Roads" (second quote), BuAer/E50, box 400, 0-G-3.

83. George K. Burgess, "Report on Examination of a Sample of Duralumin Channel Exposed to Corrosive Atmosphere," 1 Dec. 1924; George K. Burgess to BuAer, Attn: H. C. Richardson, 2 Feb. 1925, "Report on Duralumin Samples," BuAer/E50, box 432, 160-Z-12, vol. 9.

84. H. C. Richardson, "Duralumin Corrosion—Conference on, at Bureau of Standards on Wednesday 6 May 1925," May 12, 1925 (first quote); H. C. Richardson (by direction of chief of bureau) to director, Bureau of Standards, 15 Jan. 1925, "Duralumin—Corrosion of," BuAer/E62, box 2730, JJ46–6(1), vol. 1; George K. Burgess to G. W. Lewis, 5 Feb. 1925; G. W. Lewis to George K. Burgess, 10 Feb. 1925, NACA/NF, box 218, 42–6C; George K. Burgess (by F. C. Brown, actg. dir.) to C/AC (attn.: Capt. R. L. Walsh), "Embrittlement of Duralumin," 13 July 1925; Leslie MacDill to OCAS, "Embrittlement of Duralumin Project," 18 July 1925 (second quote); [Bureau of Standards], "Outline Study of Intercrystalline Embrittlement of Duralumin," 5 June 1925, AAF/E166, box 1132, 470.1A-Aluminum, Duralumin.

85. "Minutes of Meeting of Committee on Materials for Aircraft," 26 Feb. 1926, NACA/NF, box 217, 42-6B (quotes on 4, 19).

86. For the NACA's public optimism, see U.S. NACA, *Eleventh Annual Report* 11th (1925), 35; *Twelfth Annual Report* (1926), 39; *Thirteenth Annual Report* (1927), 45.

87. "Minutes of Meeting of Committee on Materials for Aircraft," 3 May 1926, p. 8, NACA/NF, box 217, 42-6B; H. W. Gillett to BuAer, Attn.: Starr Truscott, 19 July

1926; George K. Burgess to BuAer, Attn.: W. A. Moffett, 14 Oct. 1926, "Patent on Method of Protection of Duralumin from Intercrystalline Attack," with enclosure, BuAer/E62, box 2730, JJ46–6(1) vol. 2.

88. Roland (n. 73 above), 2:645; H. W. Gillett and H. L. Whittemore to members of the Subcommittee on Metals, 27 May 1927 (quote), NACA/NF, box 219, 42-6E; E. H. Dix, Jr., "'Alclad': A New Corrosion Resistant Aluminum Product," U.S. NACA *Technical Note* no. 259 (August 1927), 3, 6, 9–11. On the annual Langley conferences, see Hansen (n. 73 above), 148–58.

89. Graham and Pruitt (n. 53 above), 143, 144–45; "Minutes of Meeting of Committee on Materials for Aircraft," 3 May 1926, p. 8, NACA/NF, box 217, 42-6B. See also Robert H. Brown, "Aluminum Alloy Laminates: Alclad and Clad Aluminum Alloy Products," in *Composite Engineering Laminates*, ed. Albert G. H. Dietz (Cambridge: MIT Press, 1969), 227.

Chapter Five

1. Other early builders of commercial metal airplanes include Remington-Burnelli, Aeromarine, and Sikorsky. In 1924 the Remington-Burnelli company built a large, all-duralumin, twin-engine freight airplane using stressed-skin construction, but the plane failed to meet weight and performance expectations. "Freight Airplane Tested," *Aviation* 17 (25 Aug. 1924): 918; "The New Remington-Burnelli Transport," *Aviation* 17 (22 Dec. 1924): 1435. In 1923, the Aeromarine Plane and Motor Company developed a dural monocoque hull for its passenger flying boats, and in 1925 Aeromarine built a mail plane for the Post Office with a dural monocoque fuselage. "The New Aeromarine Flying Boat," *Aviation* 14 (14 May 1923): 527; "Aeromarine Mail Plane Delivered," *Aviation* 16 (2 June 1924): 596. Igor Sikorsky built a metal-framework twin-engine transport in 1924, the S-29A. Alexander Klemin, "The Sikorsky S29A Twin-Engined Transport Plane," *Aviation* 18 (16 Feb. 1925): 182–84; Igor I. Sikorsky, *The Story of the Winged-S* (New York: Dodd, Mead, 1948), 156–58.

2. Thomas W. Walterman, "Airpower and Private Enterprise: Federal-Industrial Relations in the Aeronautics Field, 1918–1926" (Ph.D. diss., Washington University, 1970), 172–76; Peter M. Bowers, *Curtiss Aircraft, 1907–1947* (London: Putnam, 1979), 145–47.

3. William M. Leary, *Aerial Pioneers: The U.S. Air Mail Service, 1918–1927* (Washington, D.C.: Smithsonian Institution Press, 1985), 172ff, 197, 203–4.

4. Walterman (n. 2 above), 415–25; Edward P. Warner, *The Early History of Air Transportation* (Northfield, Vt.: Norwich University, 1938), 49; Paul T. David, *The Economics of Air Mail Transportation* (Washington, D.C.: Brookings Institution, 1934), 69–70.

5. R. E. G. Davies, *Airlines of the United States since 1914* (Washington, D.C.: Smithsonian Institution Press, 1982), 35, 39, 56–57; David (n. 4 above), 75, 176. On the Air Commerce Act, see Walterman (n. 2 above), 506–26; and David D. Lee, "Herbert Hoover and the Development of Commercial Aviation, 1921–1926," *Business History Review* 58 (1984): 78–102.

6. In the language of neoclassical economics, the argument that markets insure

the selection of the best technology applies both to shifts in the production function and to movement along a stable production function. An exogenous technological change (i.e., a new innovation) will be adopted only if it causes an overall shift in the production function toward the more efficient utilization of factor inputs. Likewise, choices among existing technical alternatives (movement along the production function) depend only on relative factor prices. Firms will select the production techniques that minimize the total factor costs per unit of output. C. Freeman, "Economics of Research and Development," in *Science, Technology and Society: A Cross-Disciplinary Perspective*, ed. Ina Spiegel-Rösing and Derek de Solla Price (London: Sage, 1977), 227.

7. David F. Noble, *Forces of Production: A Social History of Industrial Automation* (New York: Knopf, 1984), 144–46. There is a substantial body of literature critical of this "natural selection" model, both as it applies to the behavior of firms and technical change. For an excellent synthesis and overview, see Steven Tolliday and Jonathan Zeitlin, introduction to *The Power to Manage: Employers and Industrial Relations in Comparative-Historical Perspective*, ed. Tolliday and Zeitlin (London: Routledge, 1991), 12–18. .

8. On the neoclassical approach, see Jon Elster, *Explaining Technical Change* (Cambridge: Cambridge University Press, 1983), 96–111; for a trenchant critique from within economics, see Paul A. David, *Technical Choice, Innovation and Economic Growth* (Cambridge: Cambridge University Press, 1975), 4–16.

9. The leading contributor to the economic theory of increasing returns is W. Brian Arthur. See his "Competing Technologies, Increasing Returns, and Lock-in by Historical Events," *The Economic Journal* 99 (1989): 116–31; and "Competing Technologies: An Overview," in *Technical Change and Economic Theory*, ed. Giovani Dosi et al. (London: Pinter, 1988), 590–607. See also Robin Cowan, "Tortoises and Hares: Choice among Technologies of Unknown Merit," *Economic Journal* 101 (1991): 801–14; Karl F. Habermeier, "Competing Technologies, the Learning Curve, and Rational Expectations," *European Economic Review* 33 (1989): 1293–1311.

10. In addition to the citations above, see Paul A. David, "Understanding the Economics of QWERTY: the Necessity of History," in *Economic History and the Modern Economist*, ed. William N. Parker (New York: Basil Blackwell, 1986), 30–49. On the electric power industry, see Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880–1930* (Baltimore: Johns Hopkins University Press, 1983), esp. 218–22. The classic article on the learning curve is Kenneth J. Arrow, "The Economic Implications of Learning by Doing," *Review of Economic Studies* 29 (1926): 155–73. Arrow cited T. P. Wright as the discoverer of the learning curve in Wright's article analyzing decreases in production costs over time; Wright, however, claimed that this phenomenon was "well-known" from time studies of worker efficiency. T. P. Wright, "Factors Affecting the Cost of Airplanes," *Journal of the Aeronautical Sciences* 3 (February 1936): 124.

11. This result holds true in every case, but only under the assumption that the increasing returns continue indefinitely. Arthur, "Competing Technologies, Increasing Returns" (n. 9 above), 126.

12. Cowan (n. 9 above), 801.

13. Arthur, "Competing Technologies: An Overview" (n. 9 above), 594–95.

14. David (n. 10 above), 43. See also Nathan Rosenberg, "On Technological Expectation," in *Inside the Black Box* (Cambridge: Cambridge University Press, 1982), 104. Donald MacKenzie reaches the same conclusion about the self-fulfilling character of technological expectations. MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge: MIT Press, 1990), 168; idem, "From the Luminiferous Ether to the Boeing 757: A History of the Laser Gyroscope," *Technology and Culture* 34 (1993): 515.

15. Donald A. Schön, *Technology and Change: The New Heraclitus* (New York: Delacorte Press, 1967), 21–37; Tolliday and Zeitlin (n. 7 above), 14.

16. "Commercial Aircraft," *Aviation* 14 (7 May 1923): 493 (second quote); "Our Gordon Bennett Challengers," *Aviation* 9 (1 Sept. 1920): 70 (first quote); "Economical Airplanes," *Aviation* 14 (30 Apr. 1923): 465.

17. Technical Advisory Committee, "Report of Third Meeting, Held at Hartford, Connecticut, May 19th to 23rd, 1930," 18–19, UTA/Corp, box U-27. On operating costs, see Archibald Black, *Transport Aviation*, 2d ed. (New York: Simmons-Boardman, 1929), 228–91. Members of the committee were F. W. Caldwell (Hamilton Standard Propeller Corp.), C. H. Chatfield (UATC), D. B. Colyer (Boeing Air Transport), C. L. Egtvedt (Boeing Airplane Co.), T. F. Hamilton (Hamilton Standard), L. S. Hobbs (Pratt & Whitney Aircraft Co.), A. K. Humphries (Boeing Air Transport), S. F. Knauss (Stout Air Services), E. P. Lott (National Air Transport), C. J. McCarthy (Chance Vought Corp.), C. J. Mead (Pratt & Whitney), C. N. Monteith (Boeing Airplane Co.), J. K. Northrop (Northrop Aircraft), Mac Short (Stearman Aircraft), and I. I. Sikorsky (Sikorsky Aviation).

18. Earl D. Osborn, "Cost Accounting in Aerial Transportation," *Aviation* 15 (19 Nov. 1923): 628 (quote); see also W. Wronsky, "Commercial Aviation in Germany," *Aviation* 10 (28 Mar. 1921): 402; Ivo Edwards and F. Tymms, *Commercial Air Transport* (London: Sir Isaac Pitman & Sons, 1926), 41. On the connections between accounting techniques and technological change, see Judith A. McGaw, "Accounting for Innovation: Technological Change and Business Practice in the Berkshire County Paper Industry," *Technology and Culture* 26 (1985): 703–25.

19. On Fokker, see chapter three.

20. See chapter four for Stout's work with the navy.

21. John T. Nevill, "Ford Motor Company and American Aeronautic Development," *Aviation* 26 (1929): 2075–76; David Ansel Weiss, *The Saga of the Tin Goose: The Plane that Revolutionized American Civil Aviation* (New York: Crown, 1971), 51–55; William B. Stout, *So Away I Went* (Indianapolis: Bobbs-Merrill, 1951), 158–63; W. B. Stout, "Requirements for Commercial Aircraft," *Aviation* 12 (16 Jan. 1922): 72–74; William M. Leary, "Henry Ford and Aeronautics during the 1920s," in *Aviation's Golden Age: Portraits from the 1920s and 1930s*, ed. William M. Leary (Iowa City: University of Iowa Press, 1989), 4–5. The number of stockholders is from Nevill, p. 2076. Stout gives a figure of 128 in *So Away I Went*, 187. My account of Stout and Ford draws heavily on Leary's article, which also alerted me to relevant archival material at the Henry Ford Museum.

22. Stout, "Requirements" (n. 21 above), 73; William B. Stout, "The Modern Airplane and All-Metal Construction," *SAE Journal* 11 (1922): 503.

23. Allan Nevins and Frank E. Hill, *Ford: Expansion and Challenge, 1915–1933* (New York: Charles Scribner's Sons, 1957), 64–66, 239.

24. Leary (n. 21 above), 3; Weiss (n. 21 above), 55–56.

25. Hunsaker to Commanding Officer, Naval Air Station, Anacostia, 5 Jan. 1921, "Visit of Mr. W. B. Stout and Mr. G. H. Prudden," BuAer/E62, box 4452, QM(781); John T. Nevill, "Ford Motor Company and American Aeronautic Development," *Aviation* 27 (1929): 41.

26. Nevill (n. 25 above), 41–42; Nevins and Hill (n. 23 above), 239; L. W. McIntosh to C/AS, "Stout All-Metal Transport," 20 May 1924, AAF/E166, box 985, 452.1-All Metal Planes. On Prudden as the designer of the Air Pullman, see Harold Hicks, "Reminiscences," July 1952, 60, HFM/FMC; Tom Towle, "Who Designed the Ford Trimotor?" *AAHS Journal* 15 (September 1970): 183. A few years after leaving Ford, Prudden began producing metal airplanes similar to the Air Pullman; advertisements for the airplane identified Prudden as "designer of the original Ford Air Transport." Advertisement, Prudden-San Diego Airplane Company, *Aviation* 24 (12 Mar. 1928): 649. A few of Prudden's clippings and photos are preserved in UCLA/GHP.

27. L. W. McIntosh to C/AS, "Stout All-Metal Transport," May 20, 1924 (quote), AAF/E166, box 985, 452.1-All Metal Planes; Nevill (n. 25 above), 42; Nevins and Hill (n. 23 above), 239; "The Stout Air Pullman," *Aviation* 16 (May 19, 1924): 533–34.

28. On the reception of the Air Pullman, see Edward P. Warner, "An Engineer's View of the Races," *Aviation* 17 (13 Oct. 1924): 1125. On the difficulty of comparing airplanes, see David Edgerton, *England and the Aeroplane: An Essay on a Militant and Technological Nation* (Basingstoke: Macmillan Academic, 1991), 33.

29. A. V. Verville to Lt. C. W. Pyle, "Stout All-metal Transport," 29 Apr. 1924, USAF/SCC, RD3135, 452.1-Stout Metal Air Transport/1924. For the other weight figures on the Air Pullman, see "The Stout Air Pullman" (n. 27 above), 533–34; L. W. McIntosh to C/AS, "Stout All-Metal Transport," 20 May 1924, AAF/E166, box 985, 452.1-All Metal Planes.

30. C. W. Howard (for C/EngrDiv) to Stout Metal Airplane Co., "Procurement of Transport Airplane," 23 June 1924 (first quote); Wm. B. Stout to Maj. C. W. Howard, 27 June 1924 (third quote), USAF/SCC, RD3135; 452.1-Stout Metal Air Transport/1924; John G. Lee, "Who Designed the Ford Trimotor?" *AAHS Journal* 15 (September 1970): 188 (second quote).

31. Nevill (n. 25 above), 42–43; Nevins and Hill (n. 23 above), 239–40; "Henry Ford and the Airplane," *Aviation* 17 (4 Aug. 1924): 829 (quote).

32. Leary (n. 21 above), 4; Nevill (n. 25 above), 43–44; Nevins and Hill (n. 23 above), 240.

33. Leary (n. 21 above), 4–5; Nevill (n. 25 above), 43–44; Nevins and Hill (n. 23 above), 240–42.

34. Davies (n. 5 above), 50–51; Clement M. Keys to C. Roy Keys, 2 Apr. 1925 (first quote); Clement M. Keys to C. Roy Keys, 5 Sept. 1925 (second quote), NASM/CMK, box 2, C. M. Keys/C. R. Keys.

35. "New Junkers Transport Plane," *Aviation* 18 (6 Apr. 1925): 382; Leary (n. 21 above), 6–7; Towle (n. 26 above), 186; Hicks (n. 26 above), 61; Lee (n. 30 above),

189. In the late 1920s, the NACA developed a cowling for radial air-cooled engines; this cowling permitted the engines to be placed in the leading edge without disrupting the airflow around the wings. James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917–1958*, NASA SP-4305 (Washington, D.C.: National Aeronautics and Space Administration, 1987), 123–39.

36. Hicks (n. 26 above), 61–62 (quote); Leary (n. 21 above), 7; Nevins and Hill (n. 23 above), 243; Weiss (n. 21 above), 113–16.

37. On Stout's incompetence, see Hicks (n. 26 above), 62, 68, 74–75; Towle (n. 26 above), 183; Lee (n. 30 above), 189, 192. For criticism of Martin and Fokker see Wayne Biddle, *Barons of the Sky* (New York: Simon and Schuster, 1991); A. R. Weyl, *Fokker: The Creative Years* (London: Putnam, 1965).

38. Nevins and Hill (n. 23 above), 243–44; Weiss (n. 21 above), 116–18, 121–22, 168–69. Production figures are from Myron J. Smith, *Airliners and Foreign Air Transport*, vol. 2 of *The Airline Bibliography* (West Cornwall, Conn.: Locust Hill Press, 1988), 126–27. Towle later claimed that he provided the 4-AT designation, and that Stout then began calling his earlier designs the 2-AT and 3-AT to make it appear as if the 4-AT had evolved from Stout's earlier work. Towle (n. 26 above), 186.

39. Nevill (n. 25 above), 754–55; Nevins and Hill (n. 23 above), 246–47, 595; Weiss (n. 21 above), 214–15.

40. Nevins and Hill (n. 23 above), 241, 247; "Aircraft Statistics," *Automotive Industries* 64 (28 Feb. 1931): 372–73; Kenneth Munson, *Airliners between the Wars, 1919–1939* (New York: Macmillan, 1972), 139, 142 (trimotor production figures); Anthony H. G. Fokker, "Air Transportation," *Annals of the American Academy of Political and Social Science* 131 (May 1927): 186; W. E. Carnegie, "Data Relating to Airplane Division," 27 July 1932, HFM/FMC, Acc. 479, box 1, folder 5, pp. 70–74; W. E. Carnegie, "Comparative Statement of Profit and Loss, Airplane Manufacturing, Sales and Promotion," 4 Apr. 1932, ibid., p. 30. I have used the figures from Carnegie's July report where these differ from the April report.

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Chapter Six

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25. Maj. Ira A. Rader to C/SupplyDiv, 24 July 1926; Maj. Joseph E. Fickel to C/SupplyDiv, 26 July 1926; Maj. L. W. McIntosh to C/SupplyDiv, 7 Aug. 1926, AAF/E166, box 863, 411.1B-Spruce.

26. W. E. Gillmore to C/AC, "Specific Procurement Plan—Emergency Production of Spruce Aircraft Lumber," 27 Jan. 1928, AAF/E166, box 863, 411.1B-Spruce.

27. Ibid.

28. J. E. Fechet to Asst. Sect. of War, 4 Feb. 1928; Maj. Jacob E. Fickel (for C/MatDiv) to Materiel Liaison Sect., OCAC, "Replacement of Spruce Requirements by Metal Construction," 2 Mar. 1928, AAF/E166, box 863, 411.1B-Spruce.

29. Col. W. P. Wooten [by direction of Asst. Sect. of War] to C/AC, "Plan for Procurement of Aircraft Spruce," 19 Mar. 1928 (first quote); 2d Ind., J. E. Fechet to Asst. Sect. of War, 16 Apr. 1928, AAF/E166, box 863, 411.1B-Spruce; C. B. Robbins to NACA, 13 Feb. 1928; Joseph S. Ames to C. B. Robbins, Mar. 1, 1928 (second quote), NACA/NF, box 218, 42–6C.

30. Trayer (n. 16 above), 34–36, 38–40; E. W. Axe and Co., *The Aviation Industry in the United States*, Axe-Houghton Economic Studies, Series B, no. 6 (New York, 1938), appendix table 4. See also Edward M. Miller, "Airplane Spruce," *Aviation* 24 (7 May 1928): 1323. The assumption that 4 percent of the Sitka spruce would be suitable for aircraft use is based on the rate achieved by commercial mills in the late 1920s (Trayer, p. 36). Specialized sawmills during wartime could have increased this percentage, as they had during World War I, but any improvement would probably have been offset by the need to cut trees of lower quality. The 7 percent cost increase was estimated using the requirement of five hundred board feet of aircraft lumber for a small plane at $500 per thousand board feet (Trayer, p. 39). A single-engine open-cockpit commercial airplane in 1929 cost an average of $3,329, which was taken as the price of a typical small plane in the late 1920s (Axe, appendix table 4). Military airplanes were more expensive than commercial models, so the relative cost of wood was lower. See Irving B. Holley, *Buying Aircraft: Matériel Procurement for the Army Air Forces*, United States Army in World War II, Special Studies (Washington, D.C.: Department of the Army, 1964), 20.

31. U.S. Bureau of Standards, *War Work of the Bureau of Standards*, Miscellaneous Publications of the Bureau of Standards, no. 46 (Washington, D.C.: GPO, 1921), 35; "Veneer Fuselage Construction and Tests, Part I," *Bulletin of the Experimental Department Airplane Engineering Division U.S.A.* 2 (October 1918): 5.

32. Lt. A. J. Lyon to Capt. Robert L. Walsh (OCAS), 12 Feb. 1924, USAF/SCC, RD3134, 452.1-All Metal Planes [1924]; U.S. Bureau of the Census, *Historical Statistics of the United States: Colonial Times to 1956* (Washington, D.C.: U.S. Department of Commerce, 1960), 371.

33. U.S. Army Air Corps, Materiel Division, *Second Annual Report* (1928), 32–33.

34. Ibid., 55–56. The term *stressed-skin* did not come into general use until about 1930; the 1928 annual report referred to the "stressed covering." See chapters six and eight for more discussion of stressed-skin construction.

35. U.S. Army Air Corps, Materiel Division, *Third Annual Report* (1929), 15–16, 28, 33, 38, 42; Peter M. Bowers, *Curtiss Aircraft, 1907–1947* (London: Putnam, 1979), 213; Peter M. Bowers, *Boeing Aircraft since 1916* (London: Putnam, 1968), 143–45, 157, 173–74.

36. "Draft of a Letter to Chief of Air Corps on Estimates for Experimental Development for 1930," 26 Nov. 1927; Mason M. Patrick to General Fechet, 7 Dec. 1927, AAF/E166, box 2766, 400.112B and 400.112C-Wright Field, Tests and Experiments.

37. U.S. Army Air Corps, Materiel Division, *Fourth Annual Report* (1930), 27, 29, 30–32; Swanborough and Bowers (n. 12 above), 231–32, 556.

38. "Long-distance Telephone Conversation between Col. Arnold and Lt. Haddon," 5 May 1931, with report, USAF/SCC, RD3202, 400.112-Experimental Projects.

39. Bowers, *Boeing Aircraft* (n. 35 above), 159, 163. The P-12E was apparently not included in the report in note 38 above, because it did not receive a new numerical model designation.

40. Maj. Gen. J. E. Fechet (C/AC) to Chief of Staff, trans. "Summary of Experimental and Development Projects Now in Progress," 6 May 1931, pp. 13–14, AAF/E166, box 2766, 400–112C-Wright Field, Tests and Experiments.

41. Swanborough and Bowers (n. 12 above), 101–2; F. Robert van der Linden, *The Boeing 247: The First Modern Airliner* (Seattle: University of Washington Press for the National Air and Space Museum, 1991), 28.

42. Bowers, *Boeing Aircraft* (n. 35 above), 171, 173–78, 180–81; G. W. Carr, "Evolution of Metal Construction," *U.S. Air Services* 17 (August 1932): 36; Harold Mansfield, *Vision: A Saga of the Sky* (New York: Duell, Sloan and Pearce, 1956), 84–85, 88; "Long-distance Telephone Conversation between Col. Arnold and Lt. Haddon," 5 May 1931, with report, USAF/SCC, RD3202, 400.112-Experimental Projects; Jean H. Dubuque and Robert F. Gleckner, *The Development of the Heavy Bomber, 1918 to 1944*, Army Air Force Historical Study no. 6 (Maxwell Air Force Base, Ala.: Historical Division, Air University, U.S. Air Force, 1951), 70; C. G. Brown and Capt. Carl F. Greene, "Static-Test and Stress-Distribution Studies of the Materiel Division 55-Foot Cantilever All-Metal Wing," *Air Corps Information Circular* no. 663 (15 Feb. 1932), 1–2. Although Mansfield's reconstructed conversation between Claire Egtvedt and Eddie Hubbard about the decision to build the Monomail seems quite fanciful (pp. 84–85), his overall account appears well informed, with most of his information from documentary sources and detailed interviews with participants.

43. Bowers, *Boeing Aircraft* (n. 35 above), 187–89; U.S Congress, House, Committee on Military Affairs, *Investigation of Profiteering in Military Aircraft, under House Resolution 275*, H. Rep. No. 2060, 73d Cong., 2d sess. (1934), repr. *Congressional Record*, 73d Cong., 2d sess., 78, pt. 11 (1934): 12480.

44. Bowers, *Boeing Aircraft* (n. 35 above), 160, 193; *Historical Statistics of the United States* (n. 32 above), 92, 118; H. Herrmann, "Relative Economy of Different Methods of Airplane Construction," U.S. NACA *Technical Memorandums* no. 618

(1931) [trans. from *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, 14 and 28 Nov. 1930], 1, 11–12, 13. The drop in the price of the P-26 appears rather curious in light of the Boeing plant manager's comment in June 1932 that Boeing's construction costs for all-metal fuselages were twice that for steel-tube fuselages. Gardner W. Carr, "Evolution of Metal Construction," preprint of paper for ASME Aeronautic Meeting, 6–8 June 1932, pp. 5–6, UCLA/AK, box 158, "Metal Construction: General; Beall: All Metal Airplane Const."

45. Swanborough and Bowers (n. 12 above), 86, 375–76, 378; "Long-distance Telephone Conversation between Col. Arnold and Lt. Haddon," 5 May 1931, with report, USAF/SCC, RD3202, 400.112-Experimental Projects.

Chapter Eight

1. "Hamilton All-Metal Airplane," *Aviation* 22 (2 May 1927): 902, 904; "The Hamilton Metalplane Co. Starts Production of Planes," *Aviation* 24 (13 Feb. 1928): 383; "Hamilton Joins United Aircraft," *Aviation* 26 (2 Feb. 1929): 325; Allan Nevins and Frank E. Hill, *Ford: Expansion and Challenge, 1915–1933* (New York: Charles Scribner's Sons, 1957), 242–43; "George H. Prudden Dies at Newport," *Evening Tribune* (San Diego), 28 Jan. 1964, clipping in UCLA/GHP; "New Prudden Plane Tested," *Aviation* 23 (28 Nov. 1927): 1294–96; Richard M. Mock, "1927 Commercial Production," *Aviation* 24 (2 Jan. 1928): 36; "Announcement Made of First Sale of Prudden All-Metal Monoplane," *Aviation* 24 (20 Feb. 1928): 454; "The Thaden 'Argonaut,'" *Aviation* 24 (13 Feb. 1928): 386–87; William F. Trimble, *High Frontier: A History of Aeronautics in Pennsylvania* (Pittsburgh: University of Pittsburgh Press, 1982), 154, 156.

2. Igor I. Sikorsky, *The Story of the Winged-S* (New York: Dodd, Mead, 1948), 145, 155–62; "Sikorsky Airliner," *Aviation* 20 (5 Apr. 1926): 508B–508C; Frank Delear, *Igor Sikorsky: His Three Careers in Aviation* (New York: Dodd, Mead, 1976), 135–36; Technical Advisory Committee, "Report of Second Meeting, Held at Seattle, Washington, December 2nd to 6th, 1929," pt. 2, p. 24, UTA/Corp, box U-27.

3. Peter M. Bowers, *Boeing Aircraft since 1916*, 2d ed. (London: Putnam, 1968), 117–19. 122–24; "Boeing 80A," captioned photograph, UCLA/AK, box 180, "Photographs: Airplane Construction."

4. Peter M. Bowers, *Curtiss Aircraft, 1907–1947* (London: Putnam, 1979), 213–17.

5. "Specifications of American Commercial Airplanes," *Aviation* 28 (22 Mar. 1930): 608–9. I excluded the eight types that provided no data when calculating the percentages.

6. N. J. Hoff, "A Short History of the Development of Airplane Structures," *American Scientist* 34 (1946): 218, 371.

7. "Veneer Fuselage Construction, Part III," *Bulletin of the Experimental Department, Airplane Engineering Division U.S.A.* 2 (January 1919): 63; Wellwood E. Beall, "All-Metal Airplane Construction," *ASME Transactions, Aeronautics* 52 (1930): 96; William Nelson, "The Monocoque Fuselage," *Aviation Engineering* 6 (April 1932): 13. Beall and Nelson considered a shell fuselage reinforced with transverse "frames" (i.e., bulkheads) to be a "full" or "true" monocoque. Nelson distinguished the "reinforced frame" from the semimonocoque. The reinforced frame was a normal

framework with a rigid covering, as in the Junkers fuselage. The covering might help prevent buckling of the framework, but otherwise did not directly bear bending and shear loads. The reinforcements of the semimonocoque, on the other hand, contained no diagonal elements, and thus the skin had to support a large part of the shear loads and perhaps some of the bending loads.

8. The term *stressed-skin* appears to have first been used in a paper by Adolph Rohrbach, "Economical Production of All-Metal Airplanes and Seaplanes," *SAE Journal* 20 (January 1927): 60. Army reports began to use the term starting in 1929. John E. Younger, "Torsional Rigidity of a Stressed Skin Monoplane Wing," *Air Corps Technical Report* no. 3071 (14 May 1929). An earlier army report used the term "skin stressed" to describe the same type of wing construction. "Materiel Division Activities, January 1928," *Air Corps Technical Report* no. 2891 (January 1928): 12.

9. Roy G. Miller, "Metal Monocoque Construction," *Aviation Engineering* 8 (January 1933): 10.

10. John Mathar, "Metal Covering of Airplanes," *U.S. NACA Technical Memorandum* no. 592 (November 1930), 1 (quote) [trans. from "Beitrag zur Frage der Beplankung von Flugzeugen," *Wissenschaftliche Gesellschaft für Luftfahrt, Jahrbuch* (1929), 205–10]; H. V. Thaden, "Metallizing the Airplane," *ASME Transactions, Aeronautics* 52 (1930): 168–69; L. B. Tuckerman, "Memorandum to Subcommittee on Research Program on Monocoque Design," 10 June 1936, NACA/NF, box 227, 42-11C. See also J. E. Gordon, *Structures: Or Why Things Don't Fall Down* (New York: Plenum Press, 1978), 291–92. On the connection between stressed-skin design in naval and aeronautical engineering, see L.-L. Kahn, "Les Bordés Travaillants en Construction Navale et Aéronautique," *Bulletin Technique du Bureau Veritas* (June 1927): 119–26, translated as "Stressed Coverings in Naval and Aeronautic Construction," *U.S. NACA Technical Memorandum* no. 447 (1928).

11. Hugo Junkers, "Metal Aeroplane Construction," *Journal of the Royal Aeronautical Society* 28 (1923): 432. On Gallaudet and Stout, see chapter four. Current engineering opinion holds that monocoques are generally less efficient than frameworks for compressive or bending loads, though more efficient in torsion, but these generalizations were not recognized by airplane designers in the interwar period. Gordon (n. 10 above), 312–13.

12. On the Army's opposition to monocoque construction, see chapter four.

13. Charles J. McCarthy, "Notes on Metal Wing Construction," *U.S. Air Services* 10 (March 1925): 15; L.-L. Kahn (n. 10 above), 119.

14. On gunfire resistance, see Paul G. Zimmermann to Mason M. Patrick, "Data on Type 12 Airplane," 10 Mar. 1923, AAF/E166, box 985, 452.1-All Metal Planes; Thaden (n. 10 above), 169; Nelson (n. 7 above), 12. On the navy-sponsored research, see Bureau of Standards, "Progress Report Number 1 on Compressive Strength of Flat Plates for Bureau of Aeronautics Navy Department," 15 Feb. 1927, NACA/NF, 42-6E, box 219; Louis Schuman and Goldie Black, "Strength of Rectangular Flat Plates under Edge Compression," *U.S. NACA Technical Report* no. 356 (1930); Nicholas J. Hoff, "Thin Shells in Aerospace Structures," *Astronautics & Aeronautics* 5 (February 1967): 29.

15. U.S. Army Air Corps, Materiel Division, *Second Annual Report* (1928), 55–56; "The Rohrbach Ro II Twin-Engined Flying Boat," *Aviation* 17 (6 Oct. 1924): 1084–85.

16. Peter Brooks, *The Modern Airliner* (1961; Manhattan, Kans.: Sunflower University Press, 1982), 72–74 (quote); John B. Rae, *Climb to Greatness: The American Aircraft Industry, 1920–1960* (Cambridge: MIT Press, 1968), 54; Charles Gibbs-Smith, *Aviation: An Historical Survey* (London: HMSO, 1970), 200–201; Rohrbach (n. 8 above), 60–61; "The Zeppelin-Staaken 1000 Hp. Monoplane," *Aviation* 11 (3 Oct. 1921): 401; McCarthy (n. 13 above), 10; F. C. Vernon, "Study of Metal Wing Construction," *Air Corps Technical Report* no. 2749 (29 Oct. 1926), 115. Another reflection of American interest in Rohrbach was the NACA translation of a German paper by Rohrbach that covered much of the same ground as his SAE paper. Adolf Rohrbach, "Materials and Methods of Construction in Light Structures," *U.S. NACA Technical Memorandum* no. 515 (1929) [trans. of Adolf Rohrbach, "Entwurf und Aufgaben des Leichtbaues," *Wissenschaftliche Gesellschaft für Luftfahrt, Jahrbuch* (1926): 64–78].

17. [G. K. Burgess], untitled, 25 Feb. 1930, NACA/NF, box 220, 42-6E; U.S. Army Air Corps, Materiel Division, *Third Annual Report* (1929), 40.

18. Miller (note 9 above), 10.

19. "When it comes to carrying loads which are primarily compressive, the space-frame is *always* lighter and usually cheaper than the monocoque. The weight penalty for using a monocoque, however, is less severe when the loads are high in relation to the dimensions." Gordon (n. 10 above), 312. See also chapter three, note 20.

20. Gordon (n. 10 above), 262–70, 313; Thaden (n. 11 above), 169; Edward P. Warner, "The Needs and Problems of the Airplane Designer," paper no. 721, World Engineering Congress, Tokyo, 1929, p. 5, LCMD/AIAA, box 123, Warner, Edward P.-Printed Matter.

21. Younger (n. 8 above); C. G. Brown, "Torsional Characteristics of Cantilever Monoplane Wings," *Air Corps Technical Report* no. 3412 (20 Feb. 1931), 3. On other stressed-skin research at Wright Field, see C. G. Brown and Capt. Carl F. Greene, "Static-Test and Stress-Distribution Studies of the Materiel Division 55-Foot Cantilever All-Metal Wing," *Air Corps Information Circular* no. 663 (15 Feb. 1932); Maj. Gen. J. E. Fechet to Chief of Staff, transmitting "Summary of Experimental and Development Projects Now in Progress," 6 May 1931, pp. 13–14, AAF/E166, box 2766, 400-112C-Wright Field, Tests and Experiments.

22. On the importance of the Monomail and Alpha in the development of all-metal airliners, see Brooks (n. 16 above), 73–81, and below.

23. Bowers (n. 3 above), 112, 176; Harold Mansfield, *Vision: A Saga of the Sky* (New York: Duell, Sloan and Pearce, 1956), 95. On the Army's influence on the Monomail, see chapter seven.

24. Bowers (n. 4 above), 195–96.

25. Mansfield (n. 23 above), 91–92; Bowers (n. 3 above), 179.

26. Richard Sanders Allen, *Revolution in the Sky: The Lockheeds of Aviation's Golden Age*, rev. ed. (New York: Orion Books, 1988), 199, 238–39; John K. Northrop, "The All-Wing Type Airplane," *Aviation* 28 (29 Mar. 1930): 648; "Douglas and Northrop," *Aero Digest* 24 (June 1934): 27–28; Mansfield (n. 24 above), 83–87.

27. "The Northrop 'Alpha,'" *Aviation* 29 (December 1930): 361; Joseph P. Juptner, *U.S. Civil Aircraft*, vol. 4 (Fallbrook, Calif.: Aero, 1967), 252–55.

28. On cost and structural efficiency, see chapter three.

29. Edward P. Warner, *Technical Development and Its Effect on Air Transportation* (Northfield, Vt.: Norwich University, 1938), 40–41.

30. Archibald Black, *Transport Aviation*, 2d ed. (New York: Simmons-Boardman, 1929), 238–39; Adolf Rohrbach (n. 16 above), 11–12; "UATC Technical Advisory Committee, Report of Third Meeting . . . May 19th to 23rd, 1930," UTA/Corp, box U-27, pp. 19, 21; Luther Harris, "Air-Transport Maintenance Problems from the Service Standpoint," *SAE Journal* 31 (August 1932): 327.

31. Warner (n. 29 above), 38–39.

32. See chapter six, and Kenn C. Rust, "Early Airlines, Chapter 7—In the Great Depression," *American Aviation Historical Society Journal* 31 (Fall 1986): 165.

33. "Fleet Birds of a Feather," *Fortune* 7 (May 1933): 23–25; Civil Aeronautics Board, *Transport Aircraft Production*, S. Doc. 206, 77th Cong., 2d sess., 1942, pp. 23–24; U.S. Bureau of the Census, *Historical Statistics of the United States: Colonial Times to 1956* (Washington, D.C.: U.S. Department of Commerce, 1960), 467.

34. The principal account is Brooks (n. 16 above), chap. 3. Other standard histories that follow Brooks are Gibbs-Smith, *Aviation: An Historical Survey*, 200–201; Rae (n. 16 above), chap. 4; Ronald Miller and David Sawers, *The Technical Development of Modern Aviation* (London: Routledge & K. Paul, 1968), chap. 3; Roger E. Bilstein, *Flight in America, 1900–1983: From the Wrights to the Astronauts* (Baltimore: Johns Hopkins University Press, 1984), 85–92. For a well-researched account of the Boeing 247, see F. Robert van der Linden, *The Boeing 247: The First Modern Airliner* (Seattle: University of Washington Press for the National Air and Space Museum, 1991).

35. Mansfield (n. 23 above), 98–103; van der Linden (n. 34 above), 35–36, 48, 53, 64–69; Bowers (n. 3 above), 176–78; R. E. G. Davies, *Airlines of the United States since 1914* (Washington, D.C.: Smithsonian Institution Press, 1982), 180–81.

36. Van der Linden (n. 34 above), 62–63, quoting Brig. Gen. H. Conger Pratt to Boeing Airplane Co., 2 Dec. 1932.

37. Mansfield (n. 23 above), 106; Davies (n. 36 above), 185. The TWA letter is reproduced in Frederick Allen, "The Letter that Changed the Way We Fly," *American Heritage of Invention & Technology* 4 (fall 1988): 6.

38. Davies (n. 35 above), 184–86, 190; "Douglas Airliner for Transcontinental Service," *Aviation* 32 (October 1933): 331.

39. "Success in Santa Monica," *Fortune* (May 1935): 182; Davies (n. 35 above), 658; J. M. G. Gradidge, *The Douglas DC-3 and its Predecessors* (Tonbridge, Kent: Air-Britain, 1984), 16; Civil Aeronautics Board (n. 33 above), 23.

40. Robert Serling, *Howard Hughes' Airline: An Informal History of TWA* (New York: St. Martin's/Marek, 1983), 31 (quote). A recent retelling of the myth is Allen (n. 37 above). One of the few recent books to remark upon the military contribution to the DC-1 is Wayne Biddle, *Barons of the Sky* (New York: Simon & Schuster, 1991), 183.

41. "Douglas Airliner for Transcontinental Service" (n. 38 above), 331; "Douglas and Northrop" (n. 26 above), 27; "Success in Santa Monica" (n. 39 above), 178; E. W. Axe and Co., *The Aviation Industry in the United States*, Axe-Houghton Economic Studies, series B, no. 6 (New York, 1938), 172, 175; U.S. Department of Commerce, *Statistical Handbook of Civil Aviation* (Washington, D.C.: Dept. of Commerce, December 1945), 119.

42. "Success in Santa Monica" (n. 39 above), 181–82, 190; Douglas Aircraft Co., "Development of the Douglas Transport," Engineering Department Technical Data SW-157A, [1934], UCLA/AK, box 81, "Airplane Descriptions: Transport Douglas DC-2."

43. A. S. N[iles], "Design Contest, Type XII, . . . General Comparison of Designs," March 1923, USAF/SCC, RD3122; 452.1-Bombardment—XII and XIII/1923; H. H. Wetzel (Douglas) to EngrDiv, "Quotation—Experimental Spars and Ribs," 19 Apr. 1923, USAF/SCC, RD3121, 452.023-Wing Ribs—P.O. 46378—The Douglas Co./1923; E. W. Dichman/ASN, "Experimental Metal Spars," 14 Feb. 1927; USAF/SCC, RD3163, 452.023-Experimental Metal Spars/1927; Gordon Swanborough and Peter M. Bowers, *United States Military Aircraft since 1909* (Washington, D.C.: Smithsonian Institution Press, 1989), 257–29; René J. Francillon, *McDonnel Douglas Aircraft since 1920* (Annapolis: Naval Institute Press, 1988), 1:99–101.

44. Swanborough and Bowers (n. 44 above), 259, 635; Ralph W. Mossman and Russell G. Robinson, "Bending Tests of Metal Monocoque Fuselage Construction," U.S. NACA *Technical Note* no. 357 (November 1930), 3; interview with Arthur E. Raymond by Ruth Powell, C.I.T. Oral History Project, 2 Apr. 1982, CIT-A.

45. "Douglas and Northrop" (n. 26 above), 27; "Success in Santa Monica" (n. 39 above), 175; Douglas Aircraft Co. (n. 42 above); A. E. Raymond, "Who? Me? Autobiography of Arthur E. Raymond," November 1974, pp. II-3–1, CIT-A.

46. Compare structural drawings of Douglas DC-3 with British Aerospace HS 748 in John Cutler, *Understanding Aircraft Structures* (London: Granada, 1981), 10, 13.

Chapter Nine

1. Gregory Dreicer refers to this lack of fixed characteristics as the "naturelessness" of materials. Personal communication with the author, 20 Dec. 1995.

2. Robert D. Friedel, *Pioneer Plastic* (Madison: University of Wisconsin Press, 1983), 103–8; Wiebe Bijker, "The Social Construction of Bakelite: Toward a Theory of Invention," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch (Cambridge: MIT Press, 1987), pp. 170–71, 174–79. Bakelite was hardly the first plastic, having been preceded most significantly by celluloid. But Bakelite was the first *synthetic* polymer plastic, that is, a material synthesized using the techniques of organic chemistry. Celluloid, on the other hand, was based on cellulose, a naturally occurring polymer found in trees and vegetable fibers.

3. For a detailed technical discussion, see de N. A. de Bruyne, "Plastic Materials for Aircraft Construction," *Journal of the Royal Aeronautical Society* 41 (1937): 523–90.

4. Friedel (n. 2 above), 105–6.

5. U.S. Patent 1,299,747, 8 Apr. 1919; L. A. Sontag and A. J. Norton, "Phenolic Resin Adhesives in the Plywood Industry," *Industrial and Engineering Chemistry* 27 (October 1935): 1115; Andrew Dick Wood and Thomas Grey Linn, *Plywoods: Their Development, Manufacture and Application* (Edinburgh: W. & A. K. Johnston, 1942), 83.

6. "Plywood," *Fortune* 21 (January 1940): 55; Otto Gerngross, "Über Sperrholzleime," *Deutsche Versuchsanstalt für Luftfahrt, Jahrbuch* (1930): 432. An American firm, Resinous Products and Chemical Company, acquired rights for American production of Tego film in 1934. Sheldon Hockheiser, *Rohm and Haas: History of a Chemical Company* (Philadelphia: University of Pennsylvania Press, 1986), 49–50.

7. "New Products: Wood, Textiles, Paper," *Architectural Record* 73 (April 1933), 296–97; F. E. Brill, "Wood-Veneering—A New Use For Phenolic Plastics as an Adhesive," *Modern Plastics* 7 (December 1931): 689–90.

8. F. E. Brill, "Phenol Resin Gives New Tool to Marine Engineers," *Plastics* 9 (July 1933): 189.

9. *Architectural Record* 73 (April 1933): 295.

10. Ray Sorensen, "Dry Film Gluing in Plywood Manufacture," *ASME Transactions, Wood Industries* 56 (1934): 43–45. Long-term exposure tests conducted by the FPL confirmed the superiority of resin-bonded plywood. Don Brouse, "Exposure Tests on Plywood," *Mechanical Engineering* 60 (November 1938): 853–56.

11. James R. Fitzpatrick, "T.S.S. Washington Features New Fire-Resistant Paneling," *Marine Engineering* 78 (June 1933): 208–9; Brill (n. 8 above), 189–90. For detailed discussion of plywood manufacturing with the General Plastics colloidal resin, see Sontag and Norton (n. 5 above), 1115–18.

12. Charles A. Nelson, "A History of the Forest Products Laboratory" (Ph.D. diss., University of Wisconsin, 1964), 264, 266–67 (quote at 266); Andrew McNall, "The Navy's Blimp Hangars: A Choice Between Recent Developments in Wood Technology," seminar paper, History of Science 921, University of Wisconsin–Madison, fall 1993, 15–16; C. Pantke, "Modern Timber Construction: Timber as a Structural Material and Devices for Joining Timbers," *Mechanical Engineering* 61 (November 1939): 795–96; "Revival of Wood as a Building Material," *Architectural Record* 86 (December 1939): 69; "Modern Connectors for Timber Construction," *Architectural Record* 73 (April 1933): 302–3.

13. Ira D. S. Kelly, "Timber Research and Timber Structures." *Civil Engineering* 9 (December 1939): 727 (first quote); Bryan Westwood, "Timber as a Natural Material," *Architectural Review* (London) 79 (February 1936): 60 (second quote); "New Uses for Wood," *Popular Mechanics* 67 (April 1937): 538 (third quote); Richard Guy Wilson, Dianne H. Pilgrim, and Dickran Tashjian, *The Machine Age in America, 1918–1941* (New York: Brooklyn Museum in association with Harry N. Abrahms, 1986), 333 (fourth quote).

14. I have found only one mention of resin plywoods in the American aviation press before 1935, an article that noted the use of "bakelite plywood" in the interiors of KLM Fokkers. "Maintenance on the Royal Dutch Air Lines," *Aviation* 32 (April 1933): 111.

15. Alexander Klemin, "Metal Airplane Construction," *Aero Digest* 27 (July 1935): 43, 113. Klemin, who almost certainly read German (his personal papers contain a number of German articles), apparently overlooked the work of Kraemer and Brenner (see below), even though the annual *DVL Jahrbuch* was a standard source for German aviation research, comparable to the *NACA Technical Reports*.

16. T. C. Bennett, "Wood in Modern Aircraft Construction," *Aero Digest* 27 (July 1935): 52–53. I have assumed that the author is Theodore Claire Bennett. See *Who's*

Who in Government, 1st ed., 1972–1973 (Chicago: Marquis Who's Who, 1972), s.v. "Bennett, Theodore Claire."

17. "Minutes of Meeting of Committee on Materials for Aircraft," 2 June 1933; "Minutes of Meeting of Committee on Materials for Aircraft," 23 Mar. 1934, NACA/NF, Box 218, 42-6B.

18. U.S. NACA, *Twenty-first Annual Report* (1935), 35. See also "Minutes of Meeting of Subcommittee on Miscellaneous Materials and Accessories, Committee on Aircraft Structures and Materials," 2 Aug. 1935, p. 6, NACA/NF, Box 229, 42-13B.

19. Jeffrey Meikle, "Plastic, Material of a Thousand Uses," in *Imagining Tomorrow: History, Technology and the American Future*, ed. Joseph J. Corn, (Cambridge: MIT Press, 1986), esp. 80–89. See also Meikle, "Into the Fourth Kingdom: Representations of Plastic Materials, 1920–1950," *Journal of Design History* 5 (1993): 173–82; idem, *American Plastic: A Cultural History* (New Brunswick, N.J.: Rutgers University Press, 1995).

20. Otto Kraemer, "Kunstharzstoffe und ihre Entwicklung zum Flugzeugbaustoff," *Deutsche Versuchsanstalt für Luftfahrt, Jahrbuch* (1933): Part VI: 69–77.

21. Kraemer (n. 20 above), 77–80. British engineers at the de Havilland Aircraft Company came to similar conclusions about the advantages of resin-impregnated wood. See discussion comments of E. P. King and C. C. Walker to de Bruyne (n. 3 above), 583–84, 588–89.

22. P. Brenner, "Wood as a Homogeneous Material: Part I—A Method of Improving Wood for Structural Purposes," *Aircraft Engineering* 10 (May 1938): 130–34.

23. Ibid., 133. Brenner did not compare laminated beech to aluminum alloy in this article. There are no precise compressive strength values for ductile metals like aluminum; at the time designers typically used yield strength. Following later design procedures, I used the more favorable figure of 52,000 psi for "column yield stress" calculated for 24ST rolled bar using the formula in table 3.21 of the ANC-5 Bulletin. United States, ANC-5 Panel on Strength of Metal Aircraft Elements, *Strength of Metal Aircraft Elements*, ANC-5 Bulletin, rev. ed. (Washington, D.C.: Dept. of the Air Force, Air Research and Development Command, 1955), 14, 71, 115.

24. For example, J. M. Dinwoodie, *Wood: Nature's Cellular, Polymeric Fibre-composite* (London: Institute of Metals, 1989).

25. Quote from O. Kraemer, "Wood as a Homogeneous Material: Part II—The Glueing of Wood with Synthetic Resin," *Aircraft Engineering* 10 (June 1938): 183.

26. The British began serious consideration of aircraft plastics quite early, led by N. A. de Bruyne and the Aero Research company. Marcus Langley, "Plastic Materials for Aircraft Construction," *The Aeroplane* 49 (9 Oct. 1935): 443.

27. Gordon Kline, "Plastics as Structural Materials for Aircraft," NACA *Technical Note* no. 628 (1937); U.S. NACA, *Twenty-second Annual Report* (1936), 35; *Twenty-third Annual Report* (1937), 34; *Twenty-fourth Annual Report* (1938), 32 (quote); "Minutes of Meeting of Subcommittee on Miscellaneous Materials and Accessories, Committee on Aircraft Materials," 3 June 1938, NACA/NF, Box 229, 42-13B.

28. Lewis quote from "Minutes of Meeting of Subcommittee on Miscellaneous Materials and Accessories, Committee on Aircraft Materials," 3 June 1938, ibid.

29. See text and citations below.

30. George E. Poling, "An F-46 by Any Other Name . . . ," *AAHS Journal* 19

(March 1974): 46; Sherman M. Fairchild, "Details of Duramold Fabrication," *Aero Digest* (February 1943): 232, 235–36. Half a million refers to the Fairchild 91 amphibian (Poling, 46); fifty thousand rivets at five cents each refers to the North American AT-6 ("News release, North American Aviation," 31 Mar. 1942, UCLA/AK, box 74, "Airplane Descriptions: North American Aviation."

31. V. E. Clark, "Low-Density Structural Material," *Aero Digest* 35 (July 1939): 101.

32. Walter Vincenti, "Design and Production: The Innovation of Flush Riveting in American Airplanes, 1930–1950," in *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore: Johns Hopkins University Press, 1990), 170–99. Dissatisfaction with riveting led at least some manufacturers to experiment with spot-welded stainless-steel airplanes.

33. Lester D. Gardner, comp., *Who's Who in American Aeronautics*, 2d. ed., 1925 (New York: Gardner, 1928; repr. Los Angeles: Floyd Clymer, 1960), s.v. "Virginius Evans Clark"; *Who's Who in America, 1944–45*, s.v. "Virginius E. Clark"; Forest Davis, "Airplanes, Unlimited! Molded Fuselages and Wings Make Possible Mass Production," *Scientific American* 161 (July 1939): 17 (quote).

34. This wing was to be molded in a single piece using a special rubber compound or bakelite. U.S. Patent 1,552,112, 1 Sept. 1925.

35. "Molded Airplanes for Defense," *Modern Plastics* 17 (July 1940): 27, 29; Charles Barton, *Howard Hughes and his Flying Boat* (Fallbrook, Calif.: Aero, 1982), 83; Thomas D. Perry, *Modern Plywood*, 1st ed. (New York: Pitman, 1942), 230 (quote); James R. Fitzpatrick, "Plywood in Aircraft Construction," *Aviation* 26 (January 1929): 166–67; Poling (n. 30 above), 46–47.

36. It is not clear why the F-46 failed to sell. Poling points to the airplane's high cost; according to Barton, Sherman Fairchild blamed distrust of the airplane's unconventional wooden structure. Poling (n. 30 above), 47; Barton (n. 35 above), 83.

37. Clark always remained secretive about the Duramold process, which changed significantly after its first use on the F-46. The best account I have found of the original method is in Carlile P. Winslow, *Airplanes: Current Interest and Progress in the Use of Forest Products in Aircraft Construction*, 15 May 1940, p. 10, FPL-L. See also Alfred A. Gassner, "Resin-Bonded Wood Laminates for Shell Type Aircraft Structures," *Journal of the Aeronautical Sciences* 9 (March 1942): 162; Office of the Coordinator of Research, *Use of Plastics in Aircraft*, OCR Report (Washington, D.C.: National Advisory Committee for Aeronautics, May 1940), 3–4; "Molded Airplanes for Defense" (n. 35 above), 29; Fairchild (n. 30 above), 236.

38. G. R. Meyercord to Maj. J. H. Bogman (Signal Corps, Chicago), 16 Dec. 1937; V. E. Clark to Materiel Division, Air Corps, "A New Combination of Materials and Processes for Aircraft Construction," 12 Jan. 1938, USAF/SCC, box 3976, RD2610, 452.1-Duramold; Davis (n. 33 above), 17. The claim of one hour for molding the first half-shell seems rather low, given the time required to arrange the thin veneers and Tego film on the die.

39. My rough estimate of six person months is based on the 1939 production planning figure of eighty pounds of airframe weight per worker per month, and the assumption that the F-46 fuselage weighed 15 percent of the weight empty of 3,173 pounds. The 15 percent figure comes from Alfred S. Niles and Joseph S. Newell,

Airplane Structures (New York: John Wiley & Sons, 1929), 356; the production planning figure is from Irving B. Holley, *Buying Aircraft: Matériel Procurement for the Army Air Forces*, United States Army in World War II, Special Studies (Washington, D.C.: Department of the Army, 1964), 191.

40. H. H. Arnold (acting chief of AC) to Duramold Aircraft Corporation (Attn.: V. E. Clark), 12 Jan. 1938; V. E. Clark (VP, Duramold Aircraft Corporation) to Materiel Division, Air Corps, 12 Jan. 1938, "A New Combination of Materials and Processes for Aircraft Construction," USAF/SCC, box 3976, RD2610, 452.1-Duramold.

41. G. R. Meyercord (V.P., Haskelite Manufacturing Corp.) to Maj. J. H. Bogman (Signal Corps, Chicago), 16 Dec. 1937; J. B. Johnson (chief, Material Branch) to chief, Engineering Section, 5 Jan. 1938, "Letter 12–16–1937 from Haskelite Corporation, Reference Plywood," USAF/SCC, box 3976, RD2610, 452.1-Duramold; *Who's Who in Engineering*, 1954, s.v. "Johnson, John Burlin."

42. Lt. C. K. Moore, Maj. H. Z. Bogert, and Lt. Col. O. P. Echols, "Conference on "Duramold" Process of Aircraft Construction," 27 Jan. 1938 (E.S.M.R. Serial No. Str-51–170), USAF/SCC, box 3976, RD2610, 452.1-Duramold.

43. O. P. Echols (acting chief, Materiel Division) to C/AC, 11 Feb. 1938, Duramold, USAF/SCC, box 3976, RD2610, 452.1-Duramold.

44. V. E. Clark to C/AC, 7 Feb. 1938 (quote), AAF/E166, box 985, 452.1-All Metal Planes.

45. O. Westover (C/AC) to Adjutant General, "Plastic Materials," 15 Feb. 1938; Brig. Gen. George R. Spalding (asst. chief of staff) to Chief of Staff, "Plastic Materials," 17 Feb. 1938 (quote), AAF/E166, box 939, 423A-Plastic Materials. Another reason given for rejecting Westover's request was that it appeared to favor a particular firm, the Duramold Aircraft Corporation.

46. The president's 28 Jan. 1938 message to Congress reprinted in U.S. House of Representatives, *Military Establishment Appropriation Bill, Fiscal Year 1939*, H. Rep. 1990, 75th Cong., 3d sess., 23 Mar. 1938, pp. 3–4.

47. For financial information on the company, see "Exhibit A," attached to V. E. Clark (VP, Duramold Aircraft Corp.) to Materiel Division, 4 Feb. 1938, USAF/SCC, box 3976, RD2610, 452.1-Duramold.

48. Brig. Gen. A. W. Robins to Maj. Gen. Oscar Westover, 8 July 1938. On negotiations with Clark, see John H. Jouett to Brig. Gen. H. H. Arnold, 9 May 1938; Cross-reference record, AJL:EKG to Maj. Gen. Oscar Westover, C/AC, 27 July 1938, USAF/SCC, box 3976, RD2610, 452.1-Duramold; W. W. Cumberland to Gen. Oscar Westover, "Duramold Aircraft Construction," 15 Aug. 1938, AAF/E166, box 939, 423A, Plastic Materials.

49. "Minutes of Meeting of Subcommittee on Miscellaneous Materials and Accessories, Committee on Aircraft Materials," 3 June 1938, NACA/NF, Box 229, 42-13B. On Vidal see below and "Molded Airplanes for Defense" (n. 35 above), 32.

50. Air Corps, Materiel Division, Wright Field, "Engineering Section Memorandum Report on Comparison of Wood Reinforced Plastics (Plywood) Submitted on R-39-D," serial no. M-56-3191 Add. 3, 17 Mar. 1939, appended to "Proceedings of the Seventh Meeting of the Subcommittee on Wooden Aircraft, [National Research Council, Canada]," 27 May 1941, copy courtesy Tim Dubé.

51. Poling (n. 30 above), 47, 49 (quote); Barton (n. 35 above), 84.

52. Arnold's testimony of 30 Jan. 1939 in U.S. House of Representatives, Committee on Appropriations, Subcommittee on War Department, *Military Establishment Appropriation Bill for 1940, Hearings*, 76th Cong., 1st sess., 1939, pp. 320–21.

53. *Public Papers and Addresses of Franklin D. Roosevelt* (New York: Macmillan, 1941), 8: 70–74. On the influence of the Munich crisis, see Michael S. Sherry, *The Rise of American Air Power: The Creation of Armageddon* (New Haven: Yale University Press, 1987), 76–80. France and Britain had significantly overestimated the strength of the Luftwaffe in 1938; see R. J. Overy, *The Air War, 1939–1945* (London: Europa, 1980), 22–23.

54. F. G. Miles, "Timber in the Construction of Aeroplanes," *Aeroplane* 55 (9 Nov. 1938): 565–67 (quote on 565); see also Edgar Percival, "The Structure of Wooden Aeroplanes," *Aeroplane* 55 (9 Nov. 1938): 568–70. The Fokker company also renewed its case for mixed wood and metal construction. See Fokker [Vliegteugfabrik], *Wood or Metal? Holz oder Metall? Bois ou Metal?* (Amsterdam: May 1938), FPL-L. This pamphlet was also published in Dutch as "Houtbouw en Metalbouw," *Het Vliegveld* 23 (March 1939): 67–74. For France see Maurice Victor, "La construction en bois et la Défense Nationale," *Les ailes* 19 (16 Mar. 1939): 7.

55. U.S. Congress, Temporary National Economic Committee, *Hearings, . . . Part 3, Patents: Proposals for Changes in Law and Procedure*, 76th Cong., 1st sess. (Washington, D.C.: GPO, 1939), 1092–94 (quote); "'Plastic' Airplanes May Speed Output," *New York Times*, 21 Jan. 1939, 1; John H. Crider, "Scan Worth of Plastics," *New York Times*, 29 Jan. 1939, sec. 10, 5; R. DeWitt Miller, "Plastic Airplanes Revolutionize Aircraft Design," *Popular Science* 137 (August 1940): 66–69+; for a technical account, see "The Plastic Airplane," *Modern Plastics* 16 (March 1939): 41, 66–70.

56. V. E. Clark, "Low-Density Structural Material," *Aero Digest* 35 (July 1939): 101–2, 105. For a similar but technically more sophisticated version of the weight argument, see F. C. Marschner, "Structural Considerations Favoring Plastics in Aircraft Structures," *Modern Plastics* 17 (September 1939): 41–42+. See chapter three for a further discussion of compressive buckling.

57. Davis (n. 33 above), 15. See also "Plastic Airplanes," *New York Times*, 4 Aug. 1940, sec. 4, p. 8.

58. O. H. Basquin, "Plywood Structures," *Aero Digest* 35 (July 1939): 47; Gordon Sear Williams, "The Wooden Airplane Returns," *Air Trails* 12 (September 1939): 23, 77–78; Leslie Long, "Is the Wooden Airplane Doomed?" *Popular Aviation* 25 (October 1939): 38–39, 80; "New Methods in Airplane Building." *Science Digest* 5 (April 1939): 66–69.

59. Joseph J. Corn, *The Winged Gospel: America's Romance with Aviation, 1900–1950* (New York: Oxford University Press, 1983), 98–102.

60. "Molded Airplanes for Defense" (n. 35 above). 31–32, 78, 80; "Molding Plastic-Plywood," *Modern Plastics* 19 (July 1942): 46–47, 114; *Use of Plastics in Aircraft* (n. 37 above), 4–7; Langley Aviation Corporation, "'Langley Process' for the Manufacture of Molded Plastic Plywood," [ca. 1942], UCLA/AK, box 107, "Design: Plywood."

61. Donald MacKenzie, "From the Luminiferous Ether to the Boeing 757: A History of the Laser Gyroscope," *Technology and Culture* 34 (1993): 514–15. Of course,

there is no guarantee that the material world will cooperate to fulfill a particular prophecy, whatever the resources devoted to the problem. Consider the billions spent on fusion energy research without producing a single erg of usable energy.

62. More balanced assessments of the choice among airplane materials did indeed appear, but only later in the debate. See for example John E. Younger, *Mechanics of Aircraft Structures* (New York: McGraw-Hill, 1942), 80–82; Fletcher Platt, "Relative Merits of Materials Used for Light-Weight Structures," *Product Engineering* 14 (February 1943): 67–72.

Chapter Ten

1. Jeffrey S. Underwood, *The Wings of Democracy: The Influence of Air Power on the Roosevelt Administration, 1933–1941* (College Station: Texas A&M University Press, 1991), 126–37; Michael S. Sherry, *The Rise of American Air Power: The Creation of Armageddon* (New Haven: Yale University Press, 1987), 76–80; Irving Brinton Holley, *Buying Aircraft: Materiel Procurement for the Army Air Forces*, United States Army in World War II, Special Studies (Washington, D.C.: Department of the Army, 1964), 169–75; Mark Skinner Watson, *Chief of Staff: Prewar Plans and Preparations*, United States Army in World War II, War Department (Washington, D.C.: Historical Division, United States Army, 1950), 136–43; U.S. Congress, House, *Military Establishment Appropriation Bill for 1941, Hearings*, 76th Cong., 3d sess., 1940, 473–75. Sherry (377, n. 9) notes that accounts of the November 14 meeting vary; I used the figures in Holley, which are in turn taken from Watson.

2. Holley (n. 1 above), 202.

3. Ibid., 238–39, 249, 254. See also Robert Dallek, *Franklin D. Roosevelt and American Foreign Policy, 1932–1945* (New York: Oxford University Press, 1979), 247–51.

4. Charles M. Wiltse, *Aluminum Policies of the War Production Board and Predecessor Agencies, May 1940 to November 1945*, Historical Reports on War Administration: War Production Board Special Study, no. 22 (Washington, D.C.: Civilian Production Administration, 1946), 4–5; Testimony of H. H. Arnold, U.S. Congress, House (n. 1 above), 495. For further evidence of the government's complacency about aluminum supplies, see Paul M. Tyler, "Minerals and War," in *Industry Goes to War: Readings on American Industrial Rearmament*, ed. Cecil E. Fraser and Stanley F. Teele (New York: McGraw-Hill, 1941), 48.

5. Holley (n. 1 above), 180. In Congressional testimony in early 1939, General Arnold expressed confidence in the adequacy of the airplane industry's annual production capacity of twelve thousand planes. "It is hard for me to appreciate any emergency, unless it was a major emergency, which would require a continuous production of 12,000 airplanes a year." U.S. Congress, House, *Military Establishment Appropriation Bill for 1940, Hearings*, 76th Cong., 1st sess., 1939, 298.

6. John B. Rae, *Climb to Greatness: The American Aircraft Industry, 1920–1960* (Cambridge: MIT Press, 1968), 2.

7. Holley (n. 1 above), 180.

8. J. Carlyle Sitterson, *Aircraft Production Policies under the National Defense Advisory Commission and Office of Production Management, May 1940 to December 1941*, Historical Reports on War Administration: War Production Board Special Study,

no. 21 (Washington, D.C.: Civilian Production Administration, 30 May 1946), 126–27; Wiltse (n. 4 above), 20; Holley (n. 1 above), 250–51; Louis Stark, "Lack of Aluminum Cuts Plane Output," *New York Times*, 25 Dec. 1940, 1, 12; "Aluminum Ample, Stettinius Finds," *New York Times*, 29 Dec. 1940, 18.

9. Wiltse (n. 4 above), 40–54, 64, 76, 88, 98–103.

10. Ibid., 6, 10. Alcoa's reluctance to expand capacity was revealed in congressional hearings held by the Truman Committee in 1941; Alcoa received intense criticism from journalists, especially I. F. Stone. See his *Business as Usual: The First Year of Defense* (New York: Modern Age Books, 1941), 49–113.

11. Wiltse (n. 4 above), 45–49, 166–70; Gerald Taylor White, *Billions for Defense: Government Financing by the Defense Plant Corporation during World War II* (Alabama: University of Alabama Press, 1990), 42–43.

12. Mordecai Ezekiel to Robert Nathan, 28 Mar. 1942, transmitting Report on Airplane Program, 28 Mar. 1942, AAF/NM6/E36, box 1, [unlabeled file]; Wiltse (n. 4 above), 141–42. As an example of the problems caused by the shortage of forgings, in February Curtiss-Wright officials predicted a one-month loss of output of P-40 fighters due to unavailability of an engine-mount forging. P. N. Jansen to Burdette S. Wright, 26 Feb. 1942, Aluminum Alloy Forging Situation, AAF/E293, Series II, box 227, 410.2-Aluminum 1942.

13. Wiltse (n. 4 above), 194–205.

14. Ibid., 261, 340, 347.

15. Holley (n. 1 above), 548.

16. Some historians, among them Wiltse, tend to minimize the impact of the aluminum shortage on airplane production, claiming that production was limited as much if not more by shortages in other areas, such as machine tools. These historians tend to blame the shortage on airplane manufacturers, claiming that they exaggerated their requirements and used aluminum inefficiently. This view reflects the position taken by the WPB during the war. See esp. Wiltse (n. 4 above), 139–40, 164. For the army, however, the aluminum shortage was very real, although in retrospect other shortages would have prevented increased production even if aluminum supplies had been adequate. For a defense of the army's position, see Alfred Goldberg, "Equipment and Services," in *The Army Air Forces in World War II*, ed. Wesley F. Craven and James L. Cate (Washington, D.C.: Office of Air Force History, 1983), 6:342–44.

17. Total production and glider figures from Goldberg (n. 16 above), 352. I have found no complete list of wood airplanes for World War II, and standard reference works are often vague about construction materials. The precise figure for my estimate of wood airplane production is 27,268, based on the following army and navy models: Beech AT-10, Bell P-77, Boeing-Stearman AT-15, Boeing-Stearman PT-13 (B and D variants), PT-17, PT-18, PT-27, N2S (variants 1 through 5), Cessna C-78, C-106, AT-8, AT-17, Curtiss C-76, Fairchild AT-13, AT-14, AT-21, Fairchild PT-19, PT-23, PT-26, North American AT-6C, Ryan PT-20, PT-21, PT-22, PT-25, Timm N2T, and Vidal BT-16. This list is probably incomplete, and may also include designs that eliminated wood structures in later variants. At least three other wooden airplane projects received army model designations but produced no finished airplanes: the Tucker P-57, Vidal BT-11, and Waco C-62. For individual production figures, see Gordon Swanborough and Peter M. Bowers, *United States Military Air-*

craft since 1909 (Washington, D.C.: Smithsonian Institution Press, 1989); idem, *United States Navy Aircraft since 1911* (Annapolis: Naval Institute Press, 1990).

18. I estimated the percentage of wooden airframe weight using the average weight for all training airplanes. Goldberg (n. 16 above), 352–53.

19. I have excluded the contribution of wooden gliders from this assessment. The American glider program experienced many of the same technical problems as the wooden airplane program, but in the end it proved a success. See John A. McQuillen, "American Military Gliders in World War II in Europe" (Ph.D. diss., Saint Louis University, 1975).

20. These conclusions are based on two government surveys of the use of wood and plastics in aircraft conducted shortly before FDR announced the fifty-thousand-airplane program. See Office of the Coordinator of Research, *Use of Plastics in Aircraft*. OCR Report (Washington, D.C.: National Advisory Committee for Aeronautics, May 1940), 3–7, 11–12, copy in NASA/LMAL; C. P. Winslow, "Airplanes: Current Interest and Progress in the Use of Forest Products in Aircraft Construction," typescript, 15 May 1940, 11, 18–20, FPL-L. For further evidence of Wright Field's minimal interest in wood, see Col. O. P. Echols, "Annual Report, Assistant Chief, Materiel Division, Air Corps, U.S. Army, Fiscal Year 1940," 1 Oct. 1940; J. B. Johnson to chief, Experimental Engineering Section, 15 Aug. 1940, Annual Report, Fiscal Year 1940; Major F. O. Carroll to chief, Technical Data Branch, 24 Aug. 1940, Annual Report, F.Y. 1940, USAF/SCC, box 6486, RD3377, 319.1-Annual Report—Chief of the Materiel Division/1940.

21. H. C. Chandler, E. P. Hartman, and W. J. McCann, *The Application of Plastics and Plywood in the Aircraft Industry*. OCR Report (Washington, D.C.: National Advisory Committee for Aeronautics, 15 Aug. 1941), 10, 17, 20, 28, 50, 62–63, 77–78 (quote on 2); W. I. Beach, *The North American Program for Wooden Aircraft Structures*, NA-5157 (North American Aviation, Inc., Inglewood, Calif., 1941), FPL-L; see also the entries on specific airplanes in Swanborough and Bowers, *United States Military Aircraft* (n. 17 above).

22. Col. F. O. Carroll to chief, MatDiv, OCAC, 21 Mar. 1942, Conservation of Aluminum; OPE [Oliver P. Echols] to chief of air staff, 30 Mar. 1942, Detail of Col. Jack Jouett and Lt. Col. Harold Evans Hartney, AAF/E293, Series II, box 227, 410.2-Aluminum 1942; Swanborough and Bowers, *United States Military Aircraft* (n. 17 above) , 455; news release, North American Aviation, 31 Mar. 1942, UCLA/AK, box 74, "Airplane Descriptions: North American Aviation"; U.S. Congress, House, Committee on Military Affairs, *Investigation of the National War Effort: Second General Report*, House Rep. no. 1903, 78th Cong., 2d sess. (Washington, D.C.: GPO, 19 Sept. 1944), 19, 77.

23. Stratford Enright, "Plywood . . . Takes Off!" *Western Flying* 22 (July 1942): 28 (first quote); James E. Thompson, "Engineering in Wood," *Western Flying* 22 (July 1942): 50 (second quote); L. J. Marhoefer, "Design Considerations for Plywood Structures," *Aviation* 41 (November 1942): 114–17; 42 (December 1942): 146–49; (January 1943): 150–51, (April 1943): 164–65+; H. N. Haut "Synthetic Resins in Construction," *Aviation* 41 (March 1942): 84–85, (April 1942): 103+; Paul Christian and David G. Wittels, "Airplanes and Bathtubs: Cooked to Order," *Saturday Evening Post* 215 (18 July 1942): 12–13+. I have examined about forty articles on wooden airplanes in the trade and technical press from 1941 to 1943 and found only

one that I would characterize as slightly negative. Robert W. Hess, "Problems Affecting the Use of Wood in Aircraft," *Mechanical Engineering* 65 (September 1942): 653–56, 660.

24. Alfred A. Gassner, "Resin-Bonded Wood Laminates for Shell Type Aircraft Structures," *Journal of the Aeronautical Sciences* 9 (March 1942): 161–62. On Gassner's career, see also Matthew E. Rodina, Jr., "The Fairchild Model 91 Amphibian," *AAHS Journal* 32 (summer 1987): 82–83.

25. "Minutes of Meeting of Committee on Aircraft Materials," 11 June 1942, NACA/Com/DF, box 135, 119 Minutes (Former Materials) (first quote); F. O. Carroll to J. Neil Patterson, 26 Oct. 1942, USAF/SCC, RD2995, 452.1-Airplanes-Wood (Wooden Transport)/1942–43–45 (second quote); Lt. Col. Paul H. Kemmer to chief, Experimental Engineering Section, Wright Field (attn.: Maj. P. E. Shanahan), 3 Oct. 1941, Comments on Hughes Proposed Plywood Pursuit Airplane, USAF/SCC, RD2425, box 3345, 452.1-Airplanes, Pursuit-Plywood/1941–42.

26. For an analysis of this "numbers racket," see Holley (n. 1 above), 239–43.

27. "Telephone Conversation between Lt. Col. B. E. Meyers, OCAC, Materiel Division, Washington, D.C., and Maj. O. R. Cook, Materiel Division, Wright Field, Dayton, Ohio," 9 July 1941, USAF/SCC, RD2995, 452.1-Training Airplanes/1940–45.

28. K. B. Wolfe to Gen. Vanaman, 18 Mar. 1942, Conference with General Echols, USAF/SCC, box 3342, RD2424, 452.1-Airplanes, Aluminum, Maximum Elimination of, In New Designed/1942; L. S. Kuter (by command of Lt. Gen. Arnold) to asst. chief of air staff, A-4, 27 Mar. 1942, Wood and Plastic Airplanes or Parts, AAF/E293, Series II, box 227, 410.2-Aluminum 1942. See also J. B. Johnson to chief, Experimental Engineering Section, Wright Field, 17 Mar. 1942, USAF/SCC, RD2995, 452.1-Airplanes-Wood (Wooden Transport)/1942–43–45.

29. OPE [Oliver P. Echols] to CAS, 30 Mar. 1942, AAF/E293, Series II, Box 227, file 410.2-Aluminum 1942; "Telephone conversation between Mr. H. H. Kindelberger, North American, Inglewood, talking from Dallas, and Brig. Gen. K. B. Wolfe, Materiel Center, Wright Field, Dayton," 14 Dec. 1942, USAF/SCC, RD2995, 452.1-Airplanes-Wood (Wooden Transport)/1942–43–45.

30. "Minutes of Meeting of Subcommittee on Miscellaneous Materials and Accessories, Committee on Aircraft Materials," 30 June 1941, 5–6, NACA/Com/DF, box 135, 119 Minutes (Former Materials); Gassner (n. 24 above), 161.

31. For example, in mid-1942 the NACA informed a glider manufacturer that the NACA had no information on the shear strength of reinforced plywood panels, and instead provided the company with advice on testing methods. G. W. Lewis to Innes Bouton, June 1, 1942, NACA/GC/DF, box 154, 453.4-Plywood, 1941–1950.

32. Thomas D. Perry, "Aircraft Plywood and Adhesives," *Journal of the Aeronautical Sciences* 8 (March 1941): 212; Alexander Klemin, "Problems in the Use of Plywood in Airplane Construction," *Mechanical Engineering* 65 (February 1943): 105–9. See also G. A. Allward, "Plywood in Aircraft Construction," *Mechanical Engineering* 65 (January 1943): 14–16.

33. Testimony of George Trayer in U.S. Congress, Senate, Joint Committee on Military Affairs, "Hearing . . . on S. 888," March 17, 1942, 41–42 [Unpublished hearing, CIS microfiche #(77) SMia-Ti42] (quote); Civilian Production Administration, *Minutes of the Advisory Commission to the Council of National Defense, June 12,*

1940, to October 22, 1941, Historical Reports on War Administration: War Production Board (Washington, D.C.: GPO, 1946), 115 (minutes for 27 Nov. 1940). Other correspondence, undoubtedly generated by Trayer, supported funding for an FPL program an wooden airplanes. See Grover B. Hill (acting sect., Dept. of Agriculture) to Vannevar Bush, 17 Aug. 1940, NACA/NF, box 222, 42–8A; William K. Ebel, (chief engineer, Glenn L. Martin Company) to George W. Lewis, 18 Oct. 1940, NACA/Com/DF, box 135, 119-Former Materials; E. R. Stettinius to Mr. McReynolds, 22 Nov. 1940, "Suggested Research by the Forest Products Laboratory for the Development of Impregnated Wood and Plywood for Combat Airplanes," WPB/M187, doc. #144.

34. "Minutes of Special Conference to Consider the Preparation of a Manual on Wood Aircraft Design Technique," 2 Mar. 1942, NACA/Com/DF, box 135, 119-Former Materials.

35. Army-Navy-Civil Committee, *ANC Handbook on the Design of Wood Aircraft Structures*, July 1942; U.S. Forest Products Laboratory for the Aeronautical Board, *Wood Aircraft Fabrication Manual*, July 1942, FPL-L; "Report of Progress on Aircraft Program at the Forest Products Laboratory," Appendix E to "Minutes of Meeting of Subcommittee on Miscellaneous Materials and Accessories, Committee on Aircraft Materials," 4 Nov. 1942, NACA/Com/DF, box 135, 119 Minutes (Former Materials).

36. "Minutes of Meeting of Subcommittee on Miscellaneous Materials and Accessories, Committee on Aircraft Materials," 4 Nov. 1942, 5, NACA/Com/DF, box 135, 119 Minutes (Former Materials) (Trayer quote); C. B. Norris, *Notes Regarding the Background of the Data Presented in Chapter 2 of the ANC Handbook on the Design of Wood Aircraft Structures* (Madison: Forest Products Laboratory, 16 Mar. 1943), FPL-L.

37. "German Aircraft Industry," Project 2 in *Reports of the Technical Industrial Disarmament Committees* ([Washington, D.C.?]: Enemy Branch, Foreign Economic Administration, July 10, 1945), 1:21 (thanks to Jonathan Zeitlin for this reference). Despite its title, the aircraft section of this report focuses entirely on the United States.

38. OPE [Oliver P. Echols] to chief of air staff, 30 Mar. 1942, AAF/E293, Series II, box 227, 410.2-Aluminum 1942; Allward (note 32 above), 14; Frederick K. Teichmann, *Airplane Design Manual* (New York: Pitman, 1939), esp. 190–92.

39. U.S. Congress, House, Committee on Military Affairs (n. 22 above), 76–77, 283–84 (Sept. delivery date from p. 284); Col. Orval R. Cook to Col. George A. Brownell (Office Asst. Secretary of War for Air, Pentagon Building), 26 July 1943, C-76 Airplane; "Telephone conversation between Mr. Meigs, of the War Production Board, Washington, D.C., and Colonel O. R. Cook, Materiel Division, Wright Field. Subject: Glider Program–the Wooden Transport," 25 Mar. 1942, USAF/SCC, RD2995, 452.1-Airplanes-Wood (Wooden Transport)/1942–43–45. The "premature birth" comment itself was made by Meigs.

40. Vanaman (Materiel Center) to General Echols, 24 Feb. 1943; "Telephone Conversation between Major Bradbury, Washington, D.C., and Col. S. R. Brentnall, Wright Field, Re Flight at St. Louis on C-76 Airplanes," 4 Mar. 1943, USAF/SCC, box 5117, RD2999, 452.1-Curtiss-Wright C-76/1942–45.

41. Lt. Col. G. A. Hatcher to chief, Production Division, 13 May 1943, Summary of Unsatisfactory Characteristics in Model C-76 Airplane; Col. Orval R. Cook to Commanding General, Materiel Command, Wright Field, 22 June 1943, USAF/SCC, box 5117, RD2999, 452.1-Curtiss-Wright C-76/1942–45.

42. Lt. Col. G. A. Hatcher to chief, Production Division, 13 May 1943; chief, Materiel Div. [Washington, D.C.] to CG Materiel Command, attn.: General Branshaw, 24 July 1943; Brig. General B. W. Chidlaw to Commanding General, Materiel Command, Wright Field, 24 July 1943, Cancellation of C-76 Project, USAF/SCC, box 5117, RD2999, 452.1-Curtiss-Wright C-76/1942–45.

43. For example, Grover Loening to C. E. Wilson, Executive Vice Chairman, WPB, 10 July 1943, Discussion of C-76 Aircraft Production, WPB/E1, box 1117A, 314.4413.

44. "Brief Summary of Engineering and Difficulties (Past, Present and Anticipated) in Connection with the C-76 Airplane," 15 July 1943 (first quote); Phimister B. Proctor, "Investigation of Inspection Policies and Procedures, C-76 Airplane, Curtiss-Wright Corp., Louisville, Ky., and Subcontractors," INSP-M-3A-(255), 16 July 1943 (second quote), USAF/SCC, box 5117, RD2999, 452.1-Curtiss-Wright C-76/1942–45; Curtiss-Wright Corporation, "Report on Wood Construction Problems Arising on the Model C-76 Wood Airplane Program," enclosure to A. J. McCulloch to Sect., DND-Air, Ottawa, attn.: AVM E. W. Stedman, Director General Air Research, 23 May 1944, NAC/DND, vol. 5054, HQ-938-3-4, vol. 3.

45. Allward (note 32 above), 14. Handbooks for aircraft workers demonstrate the lack of training in wood construction. See William H. Alderman, *Audel's Aircraft Worker* (New York: Theo. Audel, 1942); T. A. Wells, *Wells' Manual of Aircraft Materials and Manufacturing Processes* (New York: Harper & Brothers, 1942).

46. "Minutes of Meeting of Committee on Aircraft Materials," 19 Nov. 1942, 14, NACA/Com/DF, box 135, 119 Minutes (Former Materials); "Report of the Committee on Aircraft Materials Submitted at Annual Meeting," 21 Oct. 1943, NACA/Com/DF, box 135, 119-Former "Materials"; Phimister B. Proctor, "Investigation of Inspection Policies and Procedures, C-76 Airplane, Curtiss-Wright Corp., Louisville, Ky., and Subcontractors," INSP-M-3A-(255), 16 July 1943, USAF/SCC, box 5117, RD2999, 452.1-Curtiss-Wright C-76/1942–45.

47. Albert G. H. Dietz, "Observations of Wood Fabrication Practices at Aircraft Plants: Field Trip Report, Apr. 30-May 27, 1942," Project 302–4, (Madison: FPL, 28 July 1942), 9–10; O. Kraemer, "Wood as a Homogeneous Material: Part II—The Glueing of Wood with Synthetic Resin," *Aircraft Engineering* 10 (June 1938): 183–84; Perry (n. 32 above), 207; Thomas D. Perry, *Modern Plywood*, 1st ed. (New York: Pitman, 1942), 150.

48. Kent A. Mitchell, "The Saga of the Fairchild AT-21," *AAHS Journal* 23 (September 1987): 163–71 (quotes on 164, 165); U.S. Congress, House, Committee on Military Affairs (n. 22 above), 18–20, 89–97; J. L. Giles, "Investigations into U.S. Wood Aircraft Fabrication, Notes on Visit to Fairchild Aviation Corporation, Burlington, N.C.—9th February, 1944, Fairchild AT-21," C.T.I. Technical Note No. 91, February 1944, NAC/DND, vol. 5054, HQ-938-3-4, vol. 3.

49. Col. Jack E. Shuck, Patterson Field, Fairfield, OH to commanding general, AAF Materiel Center, Wright Field, attn.: Aircraft Laboratory, Structures Branch,

4 Sept. 1943; Brig. Gen. F. O. Carroll to commanding general, Patterson Field, attn.: Maintenance Div., 27 Sept. 1943, Repair—Duramold Stabilizer—PT-19 Series Airplanes, USAF/SCC, box 3767, RD2566, 319.1-Unsatisfactory Report, Fairchild PT-19/1942.

50. L. J. Gregory, "Memorandum Report on Center Section for PT-19 Airplanes, Robert W. Irwin Company, Grand Rapids, Mich.," 6 Aug. 1943, USAF/SCC, RD2610, box 3977, 452.1-Fairchild PT-28-ASHA Committee; G. E. Heck, "Report on Examination and Tests of Broken Sections from Four PT-19 Airplane Vertical Stabilizer Spars" (Madison, Wisc.: Forest Products Laboratory, 12 June 1944), FPL-L.

51. Chief, Production Division (Wright Field) to asst. chief of air staff MM&D, Personal Attention Brig. Gen. B. W. Chidlaw, 1 Sept. 1943, USAF/SCC, RD2995, 452.1-Airplanes-Wood (Wooden Transport)/1942–43–45.

52. "Minutes of Meeting of Committee on Aircraft Materials," 28 Sept. 1943, 10, NACA/Com/DF, box 135, 119 Minutes (Former Materials).

53. "Ryan Develops Plywood Primary Trainer for Army," *Automotive and Aviation Industries* 88 (1 Jan. 1943): 24–25, 54; L. J. Markwardt, "Suggested Projects for Research Relating to the Use of Wood in Aircraft, July 1943, Not Included in 1943 or 1944 Program," 30 July 1943, FPL-L; "Case History of the XP-77 Airplane Project," December 1944, reprinted in *AAHS Journal* 26 (December 1981): 311–13; George D. Colchagoff, "AAG Technical Report 5359: Final Report of the XP-77 Airplane," [15 Nov. 1945], reprinted in *AAHS Journal* 26 (December 1981): 314–27.

54. Charles Barton, *Howard Hughes and His Flying Boat* (Fallbrook, Calif.: Aero, 1982), 13–17; Stephen B. Adams, *Mr. Kaiser Goes to Washington: The Rise of a Government Entrepreneur* (Chapel Hill: University of North Carolina Press, 1997), 131–33. For Kaiser's account of these events, see his testimony in U.S. Congress, Senate, Special Committee Investigating the National Defense Program [Truman Committee], *Hearings*, Part 40, *Aircraft Contracts (Hughes Aircraft Co. and Kaiser-Hughes Corp.)*, 80th Cong., 1st sess., July–August 1947, pp. 23582–604. Hughes was already thinking in terms of large Duramold airplanes by May 1940, though he remained very secretive about specifics. Winslow (note 20 above), 16; Office of the Coordinator of Research (n. 20 above), 6–7; Howard R. Hughes to V. Bush, 7 Apr. 1941, NACA/Com/DF, box 135, 119-Former "Materials."

55. Barton (n. 54 above), 53–60; Donald M. Nelson to Harry S. Truman, 11 Feb. 1944; Defense Plant Corporation and Kaiser-Hughes, "Contract for the Construction of Three Cargo Planes," 16 Nov. 1942, both reprinted in Truman Committee (n. 54 above), pt. 40, pp. 24415–17, 24443–47. Hughes later disputed the December 1943 delivery date, which was taken from Nelson's letter to Truman, and in fact the contract did not specify a delivery date. A November 1942 telegram from the Defense Plant Corporation's representative, presented by Senator Ferguson during Hughes's testimony, mentioned December 1943 as the delivery date for the static-test model, with the first flight article to be delivered May 1944. As Hughes pointed out, this telegram was not contractually binding, but it does clearly indicate the government's expectations. Hughes testimony, Truman Committee (n. 54 above), pt. 40, pp. 24340–42.

56. By comparison, the Martin Mars took four years from initial contract to first

flight, while the B-29 took more than two years. Swanborough and Bowers, *United States Military Aircraft* (n. 17 above), 113–14, 119; idem, *United States Navy Aircraft* (n. 17 above), 511.

57. Barton (n. 54 above), 84–86; Allward (note 32 above), 14.

58. Truman Committee (n. 54 above), pt. 40, pp. 23728–31, 23762–64, 23796–98, and accompanying exhibits; Donald M. Nelson to C. E. Wilson, 18 Sept. 1943, WPB/E1, box 1117A, 314.44413.

59. Grover Loening, "Report on Kaiser-Hughes Aircraft Inspection and Recommendations on HK-1 Project," 29 Sept. 1943, WPB/E1, box 1117B, 314.4442, quote on 10. This report was reprinted in Truman Committee (n. 54 above), pt. 40, pp. 24396–405, quote on 24400.

60. Loening, "Report on Kaiser-Hughes Aircraft Inspection," in Truman Committee (n. 54 above), pt. 40, pp. 24401–2. Emphasis in original.

61. Grover Loening to C. E. Wilson, 10 July 1943, Discussion of C-76 Aircraft Production, WPB/E1, box 1117A, 314.4413.

62. Loening, "Report on Kaiser-Hughes Aircraft Inspection," in Truman Committee (note 54 above), pt. 40, 24397–98, quote on 24397.

63. Truman Committee (n. 54 above), pt. 40, pp. 23568–70, and accompanying exhibits; R. L. Horne to Files, 25 Oct. 1943, WPB/E1, box 1117B, 314.4442. The Horne memo is a wonderful document summarizing a meeting on the fate of the HK-1. This meeting included Loening, Hughes, Kaiser, and high-level representatives from the navy, the NACA, and the Commerce Department. The memo concluded, "since the government representatives present were opposed to wood, it appears that if the plane is built at all, it will be constructed of metal."

64. For a detailed discussion of the events leading up to the decision to continue the contract, see Barton (n. 54 above), 94–101. See also Edward Warner et al., "Report on the Design and Prospective Performance of the Kaiser-Hughes Flying Boat," 15 Jan. 1944, WPB/E1, box 1117B, 314.4442.

65. For a standard critique of wood, including completely unsubstantiated claims about gunfire resistance, see the testimony of Gen. Franklin O. Carroll, Truman Committee (n. 54 above), pt. 40, pp. 23840–43. For Hughes's defense of the flying-boat project, see his testimony, ibid., 24357–65.

66. Total wing weight varies approximately inversely with the square root of wing loading. John E. Younger, *Mechanics of Aircraft Structures* (New York: McGraw-Hill, 1942), 68, eq. 4.44. (I derived the square-root relationship from Younger's equation by keeping total lift constant while maintaining geometric similarity in aspect and thickness ratios.) Loening pointed out the problem of low wing loading in his report of 29 Sept. 1943, arguing for a metal wing with a higher loading, like that of the Martin Mars, which was 39.3 lb./sq. ft. (for the JRM-1) as compared to 35 lb./sq. ft. for the HK-1 (at 400,000 lbs. gross weight). Such an increase would not have made a very large difference due to wing loading alone, reducing wing weight by less than 6 percent, about five thousand pounds. Truman Committee (n. 54 above), pt. 40, pp. 24440–41, 24418.

67. Barton (n. 54 above), 145–50; Laurence K. Loftin, *Quest for Performance: The Evolution of Modern Aircraft*, NASA SP-468 (Washington, D.C.: National Aeronautics and Space Administration, 1985), 208–9.

68. Truman Committee (n. 54 above), pt. 40, p. 23799. This weight-empty figure did not include some elements that were in the original specification, for example provisions for carrying a sixty-ton tank. This figure most likely did not account for water absorption, which was a matter of dispute between Hughes and his critics. Furthermore, the airplane had never been static tested, so its safety at the higher gross weight was not assured. Static tests would have required production of an additional airframe.

69. F. R. Shanley, "Problems in Aircraft Structural Research," preprint for ASME Annual Mtg., Nov. 30–Dec. 4, 1942, p. 20, UCLA/AK, box 207, "Stress Analysis: Research."

70. These hypotheticals are justified by a number of facts, in particular the history of British, Russian, and Canadian wooden airplanes discussed below. This experience suggests that wooden airplanes could have been designed and put into production in about two years, so projects begun in mid 1940 could have helped offset the aluminum shortage by mid 1942. Similarly, if the FPL had begun working on wooden airplanes in late 1939 instead of mid 1941, the airplane industry would have received desperately needed design data well before the August 1942 release of the ANC-18 manual.

71. C. Martin Sharp and Michael J. F. Bowyer, *Mosquito* (London: Faber and Faber, 1967), 29–39; M. M. Postan, D. Hay, and J. D. Scott, *Design and Development of Weapons: Studies in Government and Industrial Organisation* (London: HMSO, 1964), 84–86. There is additional archival material on the Mosquito's design, production, and durability in the Public Record Office, London, which I consulted after completing this section of the book. These records are consistent with the information in secondary sources and the Canadian archives. See esp. PRO/AVIA 10/364, 15/4, 15/224, 15/2605; 15/2606; 44/596, and 46/116.

72. Sharp and Bowyer (n. 71 above), 43–45; Postan (n. 71 above), 149; Owen Thetford, *Aircraft of the Royal Air Force since 1918*, 6th ed. (London: Putnam, 1976), 192 (quote).

73. Sharp and Bowyer (n. 71 above), 186–208.

74. Robin Higham, *Air Power: A Concise History* (London: Macdonald, 1972), 130; Edward Bishop, *The Wooden Wonder: The Story of the de Havilland Mosquito* (London: Max Parrish, 1959), 119; Charles Webster and Noble Frankland, *The Strategic Air Offensive against Germany, 1939–1945* (London: HMSO, 1961), 2:199–202, 3:307–8.

75. M. W. Bourdon, "The de Havilland Mosquito," *Automotive and Aviation Industries* 88 (15 June 1943): 27–31, 89; William Winter, "Building the Mosquito," *Air Trails Pictorial* 20 (August 1943): 96–97; Philip Birtles, *Mosquito: A Pictorial History of the DH98* (London: Jane's, 1980), 56–65. On the shift to synthetic resins, see J. L. Giles, "Visits to Aircraft Constructors and Research Establishments in Canada, 15th to 20th November, 1943," C.T.I. Technical Note No. 75, December 1943, NAC/DND, vol. 5054, HQ-938-3-4, pt. 3.

76. Sharp and Bowyer (n. 71 above), 81–82; Birtles (n. 75 above), 45; Postan et al. (n. 71 above), 149; Fred W. Hotson, *The de Havilland Canada Story* (Toronto: CANAV Books, 1983), 81–82, 236.

77. U.S. Forest Products Laboratory, *Use of Wood for Aircraft in the United King-*

dom: Report of the Forest Products Mission, mimeo no. 1540, June 1944, 2, FPL-L. Most of this report was published as "Wood Aircraft Design and Production," *Aero Digest* 49 (1 May 1945): 126+, and 50 (1 Aug. 1945): 111–12+.

78. Such opinions were expressed about the Mosquito before it proved itself in combat. See Lt. Col. John S. Gullet, USAAC, "Military Attaché Report, Great Britain, Subject de Havilland Aircraft Limited," 1942, NASM/TF, A0176900, de Havilland DH-98 Mosquito, General.

79. Sharp and Bowyer (n. 71 above), 222; Bishop (n. 74 above), 84–86. For a description of Mosquito repair procedures, see U.S. Forest Products Laboratory (n. 77 above), 66–67.

80. S/L R. J. Brearley, for Air Officer Commanding in Chief, RCAF Overseas, to Sect., DND-Air, 19 Jan. 1943, Mosquito Aircraft, NAC/DND, vol. 5400, HQS-60-3-36, vol. 2.

81. See reports in file HQS-60-11-36, "Mosquito Aircraft, Reports on Structural Failures," NAC/DND, vol. 5406, in particular Vernon Brown, "Mosquito Structural Failures," Service Accident Report no. Misc. 231, 11 Aug. 1945. In addition, see Aircraft and Armament Experimental Establishment, Boscombe Down, "Flight Tests of Some Operational Mosquito Aircraft in Air Defence of Great Britain," Report No. A. & A.E.E./767,n, part 2, 6 Aug. 1944, NASM/TF, A0176900, de Havilland DH-98 Mosquito, General.

82. Brown, "Mosquito Structural Failures," 11 Aug. 1945; S/L F. C. Cook, "Report on Mosquito Wing—Flexural Stiffness," RAAF HQ, Directorate of Technical Service, Detail No. 622/52/26, April 1945, NASM/TF, A0176900.

83. W/C R. J. Brearley (for AOC-in-C, RCAF O/S) to Officer Commanding, no. 51 A.I. Detachment, de Havilland Aircraft, Ltd., Toronto, 22 Sept. 1944, Report on Liaison Visit to de Havilland Aircraft Ltd. Hatfield, Mosquito Aircraft, enclosing H. Povey, (chief inspector, Aircraft Division, DH-Hatfield), Circular Letter, nd, NAC/DND, vol. 5008, HQ-938BY-2-5, pt. 10; S/L J. E. Macdonald (O.C., No. 51 A.I. Detachment, DH-Canada, Toronto) to Sect, DND-Air, 21 Feb. 1945, Mosquito Aircraft—Construction and Gluing of Wings, ibid., pt. 13.

84. For ex., W/C R. J. Brearley (for AOC-in-C, RCAF, Overseas HQ, London) to officer commanding, No. 51 A.I. Detachment, RCAF, DH-Canada, Toronto, 18 Jan. 1945, Report on Liaison Visit to de Havillands, Hatfield, Mosquito Aircraft, NAC/DND, vol. 5009, HQ-938BY-2-5, vol. 13; Birtles (n. 75 above), 119; Sharp and Bowyer (n. 71 above), 156.

85. Sharp and Bowyer (n. 71 above), 263–69; Bishop (n. 74 above), 130–31. For a description of the technical problem that the Mosquito faced in India, see J. E. Gordon, *New Science of Strong Materials: Or Why You Don't Fall through the Floor*, 2d ed. (Princeton: Princeton University Press, 1976), 168–69. The Malay-based Mosquitos continued to suffer from maintenance problems related to the tropical climate. See David Lee, *Eastward: A History of the Royal Air Force in the Far East, 1945–1972* (London: HMSO, 1984), 58–59; 76–77, 255–56. Lee concludes that the Mosquito's wooden construction was not suitable for the climate of the Far East, but he notes that metal aircraft also suffered from the tropical climate.

86. For evidence of the small proportion of maintenance problems due to the wooden structures, see the thousands of memos in file HQ-938BY-2-5, "Aircraft—

D.H. 98—Technical Aspects of," parts 1–16, in NAC/DND, vols. 5006–8. On problems with the cowling and casting, see W/C S. A. Greene (for C.A.S.) to Air Officer Commanding, Eastern Air Command, RCAF, Halifax, 16 Apr. 1943, Throttle Control Support—Mosquito Aircraft, ibid., pt. 1; G/C T. C. Dickens (for A.O.C. in Chief, E.A.C., Halifax) to Sect., DND-Air, 24 Apr. 1943, Mosquito Aircraft, ibid.

87. Hotson (n. 76 above) , 67; Robert S. Brown (Army Air Forces, Materiel Center), "Memorandum Report on Comments by U.S. Manufacturers on de Havilland 'Mosquito' Airplane," Serial No. ENG-M-48-4, 26 Apr. 1943, AFM-L, A1/de Havilland Mosquito/his. Beech produced the AT-10 wooden-winged trainer during the war, which appears to have been relatively successful. Near the end of the war, a senior engineer at Beech presented a paper attacking the claims of wooden airplane proponents, arguing that wood would almost always be more costly to build and heavier than metal. Herb Rawdon, "Wood vs. Metal Construction in Aircraft," *SAE Journal (Transactions)* 53 (December 1945): 691–712, 718.

88. "Minutes of Meeting of Committee on Aircraft Materials," 28 Sept. 1943, NACA/Com/DF, box 135, 119 Minutes (Former Materials).

89. F. Robert van der Linden, *The Boeing 247: The First Modern Airliner* (University of Washington Press, 1991), 102–13; "MacRobertson Score Sheet," *Aviation* 33 (November 1934): 365–66.

90. The FPL's report on wooden airplanes in Britain stressed the importance of de Havilland's experience in wood construction. U.S. Forest Products Laboratory (n. 77 above), 15. On the Albatross, see Peter W. Moss, "The de Havilland D.H. 91 Albatross," *Air Pictorial* 26 (1964): 228–31, 292–94.

91. U.S. Forest Products Laboratory (n. 77 above), 1, 16 (quote), 65–66; "Large Scale Production in Wood (Airspeed Oxford)," *Aircraft Engineering* 11 (June 1939): 243–53, 257; Thetford (n. 72 above), 18–19, 53–58, 183, 407–12 (descriptions of training airplanes). For aluminum production and consumption figures, see Sterling Brubaker, *Trends in the World Aluminum Industry* (Baltimore: Johns Hopkins Press, 1967), 20–22, 38–39.

92. Alexander Boyd, *The Soviet Air Force since 1918* (New York: Stein and Day, 1977), 101–2, 118–19, 195–96; Von Hardesty, *Red Phoenix: The Rise of Soviet Air Power, 1941–1945* (Washington, D.C.: Smithsonian Institution Press, 1982), 72, 80, 97–100; Jean Alexander, *Russian Aircraft since 1940* (London: Putnam, 1975), 5–6, 163–73, 193–98, 421–24, 430–33; Walter Schwabedissen, *The Russian Air Force in the Eyes of German Commanders*, USAF Historical Studies, no. 175 (Maxwell Air Force Base, Ala.: USAF, 1960; repr. New York: Arno Press, 1968), 103, 210. Boyd suggests that Soviet aircraft often suffered in performance because of their reliance on wood. This may be true for some airplanes. Nevertheless, Soviet aircraft did demonstrate that combat airplanes built largely of wood could compete successfully with all-metal airplanes, in production as well as combat.

93. Helmut Maier, "'Austauschmetall' und 'Stromfresser': Aluminium im Dritten Reich," *Praxis Geschichte* 5 (1993): 33, 36. Thanks to Dr. Maier for this and other useful references.

94. J. R. Smith and Antony L. Kay, *German Aircraft of the Second World War* (London: Putnam, 1972), 211–14, 307–16, 339–41, 508–20.

95. "Minutes of the Meeting of the Subcommittee on Wood and Plastics for Aircraft, Committee on Aircraft Construction," 16 Oct. 1945, including Appendix A,

"Air Technical Intelligence Report, Plastics and Wood in the German Aircraft Industry," NACA/Com/DF, box 99, 114.22-Minutes.

96. J. L. Granatstein, *Canada's War: The Politics of the Mackenzie King Government, 1939–1945* (Toronto: Oxford University Press, 1975), 42–66, 93–96. See also F. J. Hatch, *Aerodrome of Democracy: Canada and the British Commonwealth Air Training Plan, 1939–1945* (Ottowa, Ont.: Directorate of History, Department of National Defence, 1983).

97. J. H. Parkin, "Memorandum Regarding the Design and Construction of Wooden Military Aircraft in Canada," May 1940; L. W. Brockington to Hon. C. G. Power, M.P., minister for air, DND, Ottawa, 12 July 1940 (quote); L. W. Brockington to J. S. Duncan, deputy minister for air, DND, Ottawa, 30 July 1940, NAC/DND, vol. 5054, HQ-938-3-4, "Construction of Wooden Aircraft in Canada, R.C.A.F."

98. [J. S. Duncan?] to L. W. Brockington, Office of the Prime Minister, Ottawa, 20 July 1940; J. S. Duncan (acting deputy minister for air) to L. W. Brockington, K. C., Office of the Prime Minister, Ottawa, 6 Aug. 1940; J. Easton (for A/C G. V. Walsh, Air Officer Commanding, RCAF in Gt. Britain) to C.A. Banks, Canada House, London, 9 Aug. 1940; W/C A. Ferrier, "Project for Quantity Production of Wooden Aircraft in Canada," 24 Sept. 1940, NAC/DND, vol. 5054, HQ-938-3-4.

99. S/L H. S. Rees to D.A.E., 19 July 1940, Report on Journey to Bendix Airport, N.J., to Inspect Wooden Aircraft Construction; E. L. Vidal to Ralph P. Bell, Director General of Aircraft Production, Ottawa, 23 Sept. 1940, NAC/DND, vol. 5054, HQ-938-3-4. On the Vidal Anson, officially designated the Anson 5, see K. M. Molson and H. A. Taylor, *Canadian Aircraft since 1909* (Stittsville, Ont.: Canada's Wings, 1982), 60–64. On the NRC's wooden airplane research, see W. E. Knowles Middleton, *Mechanical Engineering at the National Research Council of Canada, 1929–1951* (Waterloo, Ont.: Wilfrid Laurier University Press, 1984), 113–17.

100. Brubaker (n. 91 above), 38–39.

101. Arthur Lower, "The Forest: Heart of a Nation," in *History and Myth: Arthur Lower and the Making of Canadian Nationalism*, ed. Welf H. Heick (Vancouver: University of British Columbia, 1975), 193–99.

102. On the concept of alternative paths, see David F. Noble, *Forces of Production: A Social History of Industrial Automation* (New York: Knopf, 1984), esp. xii–xiv, 42–45, 144–46. See also Eugene Ferguson, "Toward a Discipline of the History of Technology," *Technology and Culture* 15 (1974): 19.

103. Wood in fact never disappeared completely from airplane structures. At the end of the war, there were still quite a few American sport airplanes in production with wooden wing structures. Since World War II, wood has remained popular for homebuilt airplanes, although wood is now increasingly being displaced by plastic composites. Even in the 1990s, a French firm, Avions Mudry, was still selling its popular wooden-winged training airplane, the CAP 10B, which first flew in 1968. A total of 275 CAP 10/10Bs were built by 1995, and a number were bought by the French Air Force for use as trainers. "Aviation's American Aircraft Specifications," *Aviation* 46 (March 1947 suppl.); Bud Evans, "Aircraft Wood Structures," in *The Advancing Technology of Homebuilt Aircraft: A Joint A.I.A.A.-EAA Conference, March 13–14, 1976, San Diego, California* (North Hollywood: Western Periodicals, 1976), 25–28; Elaine de Man, "Homebuilt Airplanes: The Sky's the Limit," *Technology Review* 86 (April 1983): 26–34; *Jane's All the World's Aircraft, 1996–97* (Coulsdon:

Jane's Information Group, 1996), 109. Thanks to Frederick Suppe for alerting me to the CAP 10B, which Suppe describes as "a fabulous plane to fly." Frederick Suppe, personal communication, 7 Feb. 1998.

Chapter Eleven

1. For the pilots' account of the flight, see U.S. Congress, House, Committee on Science, Space, and Technology, *Flight of the Voyager: Hearing before the Committee on Science, Space, and Technology*, 100th Cong., 1st sess., 3 Feb. 1987.

2. Burton Bernstein, "The Last Plum," *New Yorker* 62 (4 Aug. 1986): 40. For a technical overview of early postwar sandwich construction, see Subcommittee on Air Force-Navy-Civil Aircraft Design Criteria of the Munitions Board Aircraft Committee, *Sandwich Construction for Aircraft*, ANC-23 Bulletin, 2 parts (Washington, D.C.: GPO, 1951). This manual was prepared by the Forest Products Laboratory.

3. This claim strictly applies only to fiber-reinforced polymer composites, not to ceramic or metallic matrix composites.

4. So far, materials scientists and aeronautical engineers have published a few brief historical accounts of composite materials; the subject is ripe for a fuller treatment. See N. J. Hoff, "Innovation in Aircraft Structures—Fifty Years Ago and Today," in *A Collection of Technical Papers—Twenty-fifth AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference* (14–16 May 1984), paper AIAA-48-0840 (copy courtesy of the author); N. J. Hoff, "Composite Materials in Aircraft Structures," *Progress in Science and Engineering of Composites*, ed. Tsuyoshi Hayashi, Kozo Kawata, and Sokichi Umekawa (Tokyo: Japan Society for Composite Materials, 1982), 49–61; P. McMullen, "Fibre/Resin Composites for Aircraft Primary Structures: A Short History, 1936–1984," *Composites* 15 (1984): 222–30; J. E. Bailey, "Origins of Composite Materials," in *Composite Materials in Aircraft Structures*, ed. Donald H. Middleton (Burnt Mill, Harlow, Essex, England: Longman Scientific and Technical, 1990), 1–8.

5. G. de Havilland, "'Filled' Resins and Aircraft Construction," *Journal of the Aeronautical Sciences* 3 (1936): 356; N. A. de Bruyne, "Plastic Materials for Aircraft Construction," *Journal of the Royal Aeronautical Society* 41 (1937): 541–42; Gordon M. Kline, "Plastics as Structural Materials for Aircraft," *Journal of Aeronautical Sciences* 5 (August 1938): 392.

6. Kline (n. 5 above), 392 (quote); Otto Kraemer, "Kunstharzstoffe und ihre Entwicklung zum Flugzeugbaustoff," *Deutsche Versuchsanstalt für Luftfahrt, Jahrbuch* (1933), VI-77; de Havilland (n. 5 above), 356; de Bruyne (n. 5 above), 571. On de Bruyne see Elizabeth Garnsey, "An Early Academic Enterprise: A Study of Technology Transfer," *Business History* 34 (1992): 79–98.

7. McMullen (n. 4 above), 225–27; J. E. Gordon, *The New Science of Strong Materials, or Why You Don't Fall through the Floor* (Princeton: Princeton University Press, 1976), 181–83. Considerable archival information on Gordon's work is available in "Composite Veneer Plastic Materials—Investigation of," PRO/AVIA, 15/3222.

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28. For example, "Fabricating the Future with Composite Materials," *Materials Engineering* 106 (October 1989): 53–57; Carl Zweben, "The Limitless World of Composites," *Chemtech* 18 (December 1988): 733–37.

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Italicized page numbers indicate illustrations. Bold-faced page numbers indicate pages on which the term is defined. The term *passim* (here and there) is used to indicate that the topic is mentioned repeatedly in a passage and contributes to the discussion while not being central to the discussion Wherever possible, individual models of aircraft are listed under the manufacturer's name.

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