Military Airframe Costs

The Effects of Advanced Materials and Manufacturing Processes

Obaid Younossi • Michael Kennedy • John C. Graser

Project AIR FORCE
RAND

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PREFACE

This is one of a series of reports from the RAND Project AIR FORCE project entitled “The Cost of Future Military Aircraft: Historical Cost Estimating Relationships and Cost Reduction Initiatives.” The purpose of the project is to improve cost-estimating tools available for projecting the cost of future weapon systems. It focuses on how recent technical, management, and government policy changes affect cost. This report discusses the effects of airframe material mix and manufacturing techniques on airframe costs, emphasizing the effect of new manufacturing techniques. It also presents statistical analyses of a new airframe historical cost data set, MACDAR, which is owned by the Air Force Cost Analysis Agency (AFCAA).

This project was requested by Lieutenant General George K. Muellner, SAF/AQ, now retired. The current sponsor is Lieutenant General Stephen B. Plummer, SAF/AQ. The project technical points of contact have been John Dorsett, former Technical Director of AFCAA, and Jay Jordan, current Technical Director of AFCAA.

The information collection cutoff date was 2000.

The report should be of interest to the cost analysis community, the military aircraft acquisition community, and acquisition policy professionals generally.

PROJECT AIR FORCE

Project AIR FORCE, a division of RAND, is the Air Force federally funded research and development center (FFRDC) for studies and analysis. It provides the Air Force with independent analyses of policy alternatives affecting the development, employment, combat readiness, and support of current and future aerospace forces. Research is performed in four programs: Aerospace Force Development; Manpower, Personnel, and Training; Resource Management; and Strategy and Doctrine.

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SUMMARY

Good cost estimates can make important contributions to effective acquisition policy. RAND has a long history of producing cost-estimating methodologies. Two of its more recent studies are Hess and Romanoff (1987) and Resetar, Rogers, and Hess (1991).

This report both updates and extends these earlier studies, focusing on the effects of material mix, manufacturing technique, and part geometric complexity on cost. We collected two types of information on these effects. First, we surveyed the military airframe industry for estimates of how aircraft production costs vary with airframe structure material mix. Second, we analyzed a large set of actual part data from recent aircraft manufacturing efforts that we collected from industry. We also estimated a set of airframe cost-estimating relationships (CERs) for labor hours based on MACDAR, a historical airframe database.[1] We then integrated the effects of material mix into these estimates.

AIRFRAME MATERIALS

The first part of this report reviews material properties that are important in airframe applications. Chief among these properties are strength and stiffness, especially in relation to weight.[2] Many air-

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[1] MACDAR stands for Military Aircraft Cost Data Archive and Retrieval, a database owned by the Air Force Cost Analysis Agency.

[2] As outlined in the body of the report, when a material is referred to as low weight, technically it is the material's density (pounds per cubic inch) that is being discussed.

frame parts require high strength and stiffness to withstand the loads (forces) placed on airframes during flight; low weight increases performance in such areas as range, payload, acceleration, and turn rate. Other important material properties, such as corrosion resistance, toughness, and service temperature, are also briefly discussed. We then discuss the properties of composite materials that are important in airframe applications: carbon fiber with epoxy, bismaleimide (BMI), and thermoplastic resins. In most cases, these composites have better strength and stiffness in relation to weight than do metals. In addition, composite parts can be designed and built with more strength and stiffness in some directions than in others and can thus be tailored to the directional loads the part is expected to bear. This leads to the more efficient design and use of material. Another advantage of composite materials is that they lend themselves to unitization—that is, to the substitution of one integrated part for several smaller ones that must be fastened into a subassembly.

However, composite materials have some drawbacks, the most significant of which is higher design and fabrication cost. Composites fail in ways that metals do not—e.g., through delamination—posing inspection and maintenance challenges. We discuss the pros and cons of individual composites and also review the properties—and pros and cons—of the metals aluminum, steel, and titanium.

This report also discusses part fabrication techniques. Toward this goal, it reviews the traditional composite hand layup process, in which workers manually stack individual plies on a tool to form the part. Two newer techniques are then discussed: automated fiber placement,[3] in which a machine lays down the plies, and resin transfer molding (RTM), in which the part is formed in a complex die. These techniques make it possible to fabricate highly complex parts less expensively and with significantly better tolerances than would be possible by hand layup. We then discuss two advanced techniques for producing metal parts. The first such technique is high-speed machining (HSM), which both lowers the cost and increases the complexity of parts that can be machined. The second is hot iso-

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[3] We use the term *automated fiber placement* in its generic sense to refer to automated tape placement, automated tow placement, and contour tape placement.

static press (HIP) investment casting of titanium, which greatly improves the properties of titanium-cast parts compared to more traditional processes.

AIRFRAME COST INFORMATION

The second part of the report presents our results on how costs—primarily labor hours—vary by material mix, manufacturing technique, and part geometric complexity. Results from both an industry survey and data analysis are shown, and the reasons behind the results are discussed. We also present estimates of learning rates, weight-sizing factors, and raw material prices in the year 2000. In Chapter Five we estimate recurring labor hour CERs from the MACDAR data set, which has production data on five recent fighter-class aircraft: AV-8B, F-14, F-15, F-16, and F/A-18. Material effects on cost are part of these CERs.

Finally, the report describes how all the cost estimates presented herein can be integrated to generate airframe cost projections, illustrating this by estimating the cost of a notional future fighter aircraft.

ACKNOWLEDGMENTS

The authors of this study had extensive discussions with knowledgeable aerospace professionals in many government and industry organizations. Many of these generously provided us with data for the study and shared their insights into the issues. They are too numerous to thank individually; we explicitly acknowledge here the organizations we visited and our principal points of contact in them. We offer an overall "thank you" to all those who shared information with us.

The government organizations we met with and our principal contacts were:

- Office of the Assistant Secretary of the Air Force for Acquisition (SAF/AQ): Lieutenant General George K. Muellner (retired), General Gregory S. Martin, and Lieutenant General Stephen B. Plummer.
- Air Force Cost Analysis Agency: Joseph Kammerer, Director; John Dorsett, former Technical Director; and Jay Jordan, Technical Director.
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- NETMA (NATO EF2000 and Tornado Development, Production, and Logistics Management Agency), Unterhaching, Germany: Christian Biener, Deputy General Manager.

The industry organizations we visited and our principal contacts were:

- Alliant Techsystems, Salt Lake City, Utah: Albert Vaccario.
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- The Boeing Company, St. Louis, Missouri: Donna Chapman.
- The Boeing Company, Seattle, Washington: Dave Brower and Jim Hayes.
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- DaimlerChrysler Aerospace, Munich, Germany: Hanas Ross.
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- Kurt Manufacturing Company, Minneapolis, Minnesota: Lars Ossmo.
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Finally, we acknowledge our RAND colleagues who worked either on this or on related projects and who made significant contributions to this research: Cynthia Cook, Mark Lorell, Michael McMahon, Daniel Raymer, Susan Resetar, Bob Roll, Jerry Sollinger, Don Stevens, and

Stephanie Williamson. We would also like to thank Andi Fellows for her editorial help.

ACRONYMS

A/C	Aircraft
AFCAA	Air Force Cost Analysis Agency
Al-Li	Aluminum-lithium
ARCO	Aircraft Resources Control Office
AUW	Airframe unit weight
AV	Air vehicle
BMI	Bismaleimide
BTF	Buy to fly
CAC	Cumulative average cost
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CER	Cost-estimating relationship
CNC	Computerized numerical control
CSCI	Computer software configuration item
CTE	Coefficient of thermal expansion
DoD	Department of Defense
DOE	Design of experiments

ECO	Engineering Change Order
EMD	Engineering and manufacturing development
FSD	Full-scale development
HIP	Hot isostatic press
HM	High modulus
HPM	High-performance machining
HSM	High-speed machining
IFF	Identification friend or foe
IM	Intermediate modulus
IPT	Integrated product team
IR	Infrared
JDAM	Joint Direct Attack Munition
JSF	Joint Strike Fighter
KSI	Thousand pounds per square inch
LCP	Liquid crystal polymer
LO	Low observable
MACDAR	Military Aircraft Cost Data Archive and Retrieval
MRB	Material review board
MSI	Million pounds per square inch
NAVAIR	Naval Air Systems Command
NC	Numerically controlled
NDI/T	Nondestructive inspection and test
OLPA	Optical laser ply alignment
PAN	Polyacrylonitrile

PEEK	Polyetheretherketone
PEI	Polyetherimide
PEKK	Polyetherketoneketone
PPI	Producer price index
QA	Quality assurance
R^2	Coefficient of determination
RFI	Resin film infusion
RPM	Revolutions per minute
RRH	Resetar, Rogers, and Hess
RTM	Resin transfer molding
SEE	Standard error of estimate
SM	Standard modulus
SPC	Statistical process control
SPF/DB	Superplastic forming and diffusion bonding
S/RFI	Stitched resin film infusion
TTU	Through-transmission ultrasonic
UHM	Ultrahigh modulus
UV	Ultraviolet
VARTM	Vacuum-assisted resin transfer molding
WBS	Work breakdown structure
WMCF	Weighted material cost factor

Chapter One

INTRODUCTION

BACKGROUND AND PURPOSE

Good cost estimates for military aircraft can play an important role in developing sound budgets and in contributing to effective acquisition policy. RAND has a long tradition of developing cost estimation techniques and has published a number of widely used reports on the topic. As the methods and materials used in aircraft production change and as new information becomes available, however, these techniques should be updated. This report presents the results of a research project on the determinants of military airframe costs and offers a methodology for projecting future costs.

This work is part of a larger research project on military aircraft costs. Two other publications from this project are relevant to the work described here. One is on the impact of lean manufacturing and other advanced manufacturing techniques on airframe costs,[1] and the other is on the effect of acquisition reform on these costs.[2] This report also discusses how the results described in those reports can be integrated into an overall methodology for projecting future airframe costs. Appendix E presents a complete list of subjects addressed in all three reports.

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[1] Cook and Graser (2001).

[2] Lorell and Graser (2001).

RELATION TO PREVIOUS WORK

This report updates two RAND reports that dealt with different aspects of estimating the cost of aircraft production: Hess and Romanoff (1987) and Resetar, Rogers, and Hess (1991).[3] The Hess and Romanoff work is itself an update of traditional airframe cost-estimating methodologies that were based on historical cost data of various aircraft, usually annual data on cost and quantity produced by aircraft type. In traditional cost estimation methodology, costs are sometimes expressed in dollars and sometimes in labor hours and are disaggregated in various ways. These costs are then used as the dependent variables in statistical regression analysis. Explanatory variables typically include factors such as cumulative production quantity, annual production rate, aircraft characteristics (e.g., weight and speed), and the like. The resulting estimated equations are referred to as cost-estimating relationships, or CERs. The Hess and Romanoff study estimated CERs for a wide range of military aircraft. This study updates that work by using a new aircraft cost data set called MACDAR.[4] This data set includes information on the AV-8B, F-14, F-15, F-16, and F/A-18 aircraft for the years 1971 to 1991.

Resetar, Rogers, and Hess (1991) factor the new materials used in aircraft construction into cost estimates. An important technical development in military airframe manufacturing over the past 50 years has been the increasing use of materials other than aluminum. The most important of these are the metals titanium, steel, and aluminum-lithium and the composite materials carbon-epoxy, carbon-bismaleimide (BMI), and carbon-thermoplastic. Resetar, Rogers, and Hess (1991) pioneered the analysis and measurement of the cost implications associated with the use of these materials. That report, hereafter called RRH, estimates the ratio of the cost (per pound) of airframe structure made of any given material to the cost of structure

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[3] Hess and Romanoff (1987) and Resetar, Rogers, and Hess (1991) included total recurring and nonrecurring cost estimates for airframes. This report addresses only recurring labor and raw material cost in the main body and nonrecurring engineering and tooling labor in Appendix D.

[4] MACDAR stands for Military Aircraft Cost Data Archive and Retrieval, a database owned by the Air Force Cost Analysis Agency.

made of aluminum.[5] Separate ratio estimates were made for the following cost categories:

- Nonrecurring engineering labor
- Nonrecurring tooling labor
- Recurring engineering labor
- Recurring tooling labor
- Recurring manufacturing labor
- Recurring manufacturing material
- Recurring quality assurance labor.

For the six labor categories, the measure of cost was labor hours per pound. Thus, the ratio in question was hours per pound required to manufacture airframe structure from the given material divided by hours per pound required to manufacture airframe structure from aluminum. For manufacturing material, the measure of cost was dollars per pound.

All the estimates were based on a survey of companies in the military aircraft industry. The cost ratio estimates thus derived were then integrated with the Hess and Romanoff CERs. The Hess and Romanoff CERs did not include material composition as an explanatory variable. In the integrated structure proposed in RRH, for each aircraft–cost category combination a weighted-average overall material cost ratio is calculated, with weights proportional to the share of each material in the aircraft structure. This weighted-average cost ratio is then used as a multiplicative adjustment factor for the appropriate CER. RRH also included some “primer” material on the properties and manufacturing techniques for composite materials as well as metals.

We are updating these earlier studies for several reasons. First, the RRH report gives only one cost ratio for each material–cost category

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[5] In that report, the cost ratios were referred to as “complexity factors” with the connotation that the increased costs were due to the increased complexity of the production process. Since this research introduces part geometric complexity as a cost determinant, we simply use the term *cost ratios*.

combination, representing typical part geometry and manufacturing technique at that time. This was appropriate in that composite materials at the time of the RRH study were generally used for simple parts such as surfaces and panels rather than for more complex applications.[6] In addition, one manufacturing technique then dominated composite material fabrication: hand layup.[7] Since then, a wider variety of part types have been made from composite materials, and new manufacturing techniques have become much more common, especially automated fiber placement and resin transfer molding (RTM). In addition, new manufacturing techniques for metals are becoming more common, especially high-speed machining (HSM) for aluminum and hot isostatic press (HIP) investment casting for titanium. Thus, the cost-estimating community has called for a more detailed set of cost ratio estimates in which cost ratios are a function of part geometry and manufacturing technique as well as of material type and cost category. This approach would allow cost estimators, for example, to make their projections sensitive to what manufacturing technique was planned for each part—an approach that was not possible with earlier estimates.

Second, the RRH results were based on estimates provided by a group of military aircraft companies with no detailed backup data. This occurred because at the time of that work, relatively little systematic data were available on the cost of individual parts as a function of material type. As a result, the RRH estimates were based on engineering judgment informed by the experience to date. Since then, some systematic data have become available, and this study has been able to take advantage of those data. We present cost ratio results based both on a new survey of industry estimates and on statistical analysis of data that we obtained.

Third, as mentioned above, the MACDAR database has become available, offering some additional data that were not available to the earlier studies.

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[6] We say "generally" because there were in fact limited applications to relatively complex parts—for example, sine wave spars in the AV-8B.

[7] Again, there were some exceptions, such as pultrusion and early tape-laying machines for the B-2.

Fourth, as was discussed in RRH, their two-step integration procedure did not account for the fact that the airframe CERs estimated in the Hess and Romanoff study—and incorporated into the RRH study—did not factor in material composition. Thus, as RRH clearly pointed out, there was a possibility that material composition effects were biasing the coefficient estimates in the CERs, as a result of which the integration process proposed therein might have misestimated the net effect of material composition. RRH noted that with the limited data available at the time, these effects could not be reliably disentangled. With the new data, however, they now can, and our CER estimation thus includes an explicit material composition variable that should improve the quality of the estimates.

HOW THIS REPORT IS ORGANIZED

This report is divided into two parts. The first part, made up of Chapters Two and Three, presents a primer on aircraft materials and manufacturing techniques that is intended to provide background information for cost analysts who may not be familiar with some of the technical aspects of aircraft construction that influence aircraft cost. Discussed herein are the properties of various materials and considerations that are important in choosing material for different applications. Also described are alternate manufacturing techniques. Those familiar with these areas can skip over the primer material and move to the second part of the document, which consists of Chapters Four, Five, and Six. Chapter Four presents estimates of how costs vary by material mix, manufacturing technique, and part geometric complexity, with estimates based both on our industry survey and on data analysis. Chapter Five presents a statistical analysis of historical production cost data on five recent fighter-attack aircraft. Chapter Six integrates all the estimates to develop an overall methodology for projecting future airframe costs.

Chapter Two

MATERIAL CHARACTERISTICS

This chapter discusses some characteristics of the materials whose costs are assessed in this report toward the goal of providing useful background information to the reader in interpreting the cost results presented herein. The chapter begins by providing some background and historical perspective on aircraft material mix, and it then presents an overview of some key material properties that are important for airframe structural use. We then present a characterization of composite material; a discussion of the advantages and disadvantages of composite use in airframe structure; and an overview of metals used in airframe structures.

Many material characteristics not discussed in this chapter are also important to airframe structure design but lie beyond the scope of this report. These include thermal and electrical conductive properties and radar transparencies relevant to stealth airframes. The reader should thus be aware that this is not a comprehensive account of important material properties for airframe application.

BACKGROUND AND HISTORICAL PERSPECTIVE

What Are Composite Materials, and Why Are They Used in Producing Aircraft?

A composite material is simply one composed of distinct kinds of material components. The composites we consider are typically made up of two components: a reinforcing material and a matrix material into which the reinforcing material is embedded. The reinforcing material is usually made up of discrete fibers that are distributed within the matrix, a contiguous material that envelops and supports the reinforcing fibers. Carbon fiber is the most common airframe structure reinforcing material; the most common matrices used in airframe structures are thermosets such as epoxy and BMI resins as well as some thermoplastic resins. We will say much more about manufacturing techniques in Chapter Three, but for introductory purposes we will give a brief description of a typical way in which one kind of carbon-epoxy is made.

Continuous carbon fibers are collimated (i.e., lined up in parallel) and pressed into a resin film. This material is called "preimpregnated," or "prepreg." The tape is cut into shapes appropriate to the aircraft part, and several layers of the tape are laid upon each other to form the part. This assembly is then cured in an autoclave, a device that heats the material under pressure. The resulting part is a black solid that is surprisingly light in comparison to an aluminum part of the same size and shape.

Although composites are used in airframe structures for several purposes, their primary advantage lies in their light weight. As we discuss in further detail below, composites have mechanical properties that are comparable to metals, such as strength and stiffness, but are lighter than metals. Composites also lend themselves to more efficient structural designs by combining several distinct parts into one (a design practice called "unitization"). Hence, when composite structures replace metal designs in an aircraft, the airframe is lighter and has higher range and payload capabilities. In addition, composites offer advantages over metal in the way they resist fatigue and corrosion and tolerate damage. Composites have other properties, such as electric and thermal conductivity and radar transparency, that make them an ideal material for stealth applications and radome construction.

Why Aren't All Metal Parts Replaced by Composites?

There are four major reasons composites have not completely supplanted metal parts. First, some metals, such as titanium and steel, have mechanical and temperature properties that are crucial in some applications and cannot be matched by today's composites. Second, composites are still evolving, and new fibers and matrices are being introduced whose properties are not as well known as those of metals. Therefore, a conservative approach has generally been taken toward introducing new composites, at least until their properties—particularly how they fail—are more completely understood. Third, some complex shapes cannot be made from composites in a cost-effective fashion. Finally, a primary focus of this study lies in the fact that composites generally cost more to produce per pound than do metals, especially aluminum. Chapter Four directly addresses this cost issue.

With this background, we introduce Figure 2.1, which shows historical trends in the use of composites in airframes. This figure shows the gradual increase in the percentage of composites used in aircraft. An interesting aspect of the history of composite use in military aircraft is that the percentage of composites in any given design typically decreases as the design matures in the course of the development process (see Figure 2.2). This phenomenon is generally

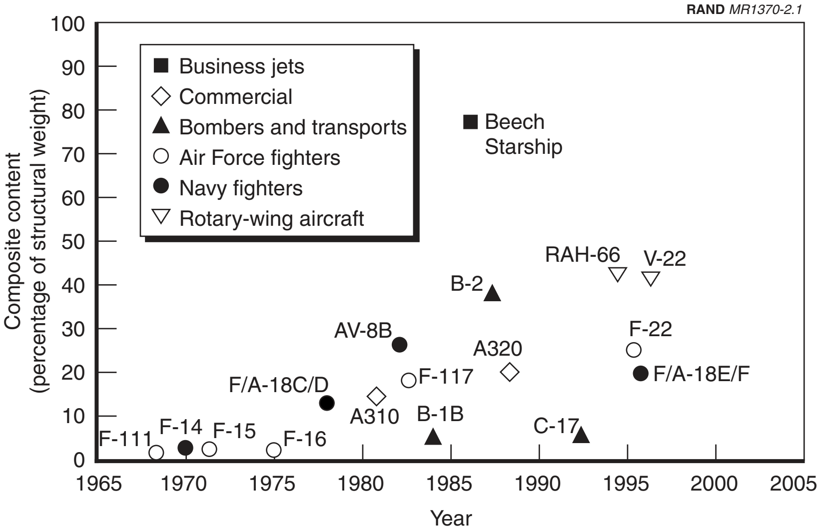

Figure 2.1—History of Aircraft Composite Use

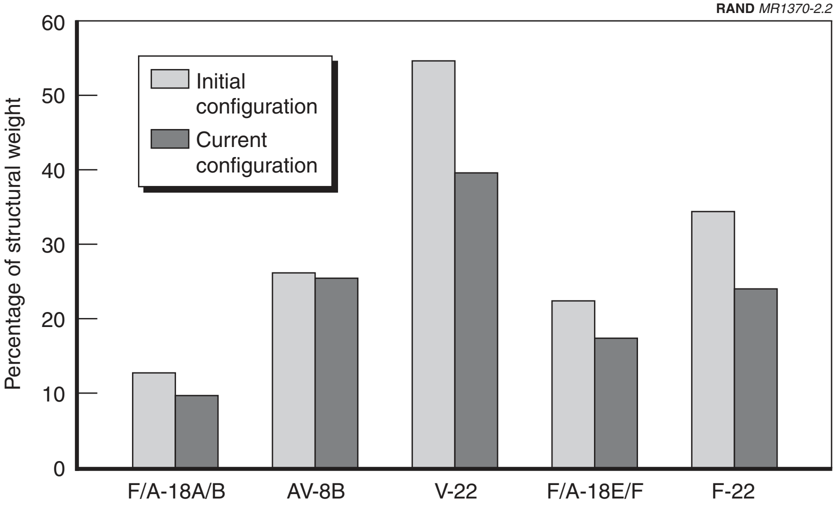

Figure 2.2—A Comparison of the Percentage of Composites Used in the Initial Configuration with the Current Configuration of Some Military Airframes[1]

believed to occur because at the beginning of the design process, designers are thought to be overly optimistic about both the properties and the ease of fabrication of composites. As testing and early production continue, however, some of this optimism proves unfounded, at which point the initial design no longer meets cost, schedule, and weight constraints. As a result, the percentage of composites falls. (To be sure, there can be other explanations for this phenomenon, such as an increase in metal weight of an airframe with no change in composite weight and changes to the original requirements; however, the major reason is believed to be overoptimism early in the design process.)

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[1] For all aircraft but the V-22, this figure compares the percentage of composites in the initial proposal to the percentage of composites in the current configuration. The V-22 comparison is between the airframe built during the early full-scale development (FSD) program and the current configuration.

Figure 2.3 shows the history of titanium use on military aircraft. As this figure illustrates, titanium use shows no consistent trend over time. However, it does tend to be higher in dedicated air superiority fighters, which are characterized by stringent temperature and other performance requirements.

The following figures show five recent aircraft that identify where various materials are used. Figure 2.4 illustrates three views of the F/A-18E/F. Figure 2.4a shows material use in the substructure; Figure 2.4b shows carbon-epoxy use on the surfaces, highlighting differences between the F/A-18C/D and the E/F; and Figure 2.4c shows overall material use. Figures 2.5, 2.6, 2.7, and 2.8 show material distribution on the B-2, F-117, F-22, and V-22, respectively.[2] Finally, Table 2.1 outlines the types of applications for which composites have been used in a variety of aircraft.

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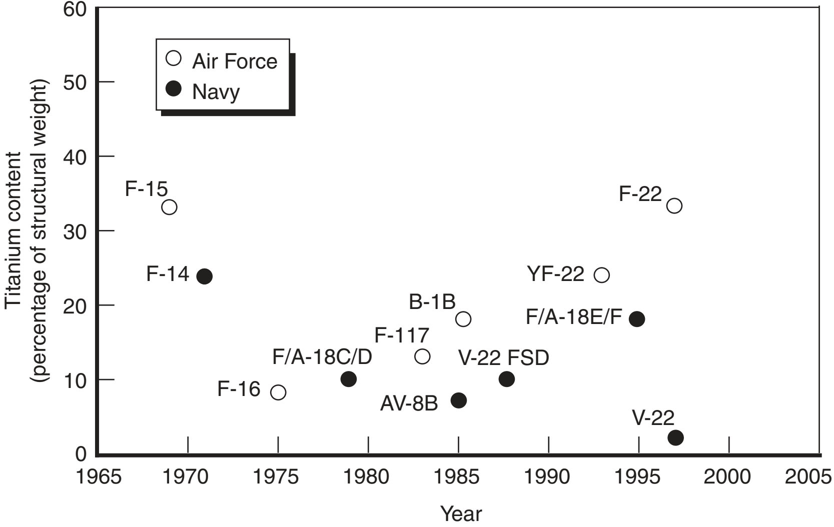

Figure 2.3—History of Titanium Use

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[2] In Figure 2.5, the extensive use of composite skins in the B-2 might give the impression of a higher percentage of composite use than the actual figure—which, as Figure 2.1 shows, is roughly 40 percent.

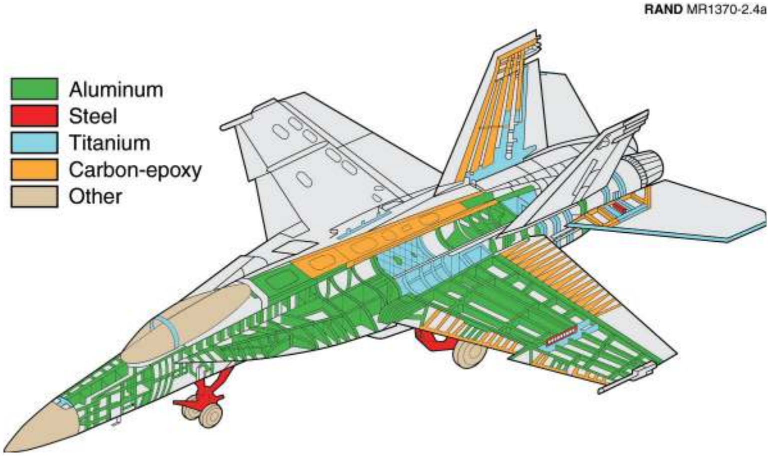
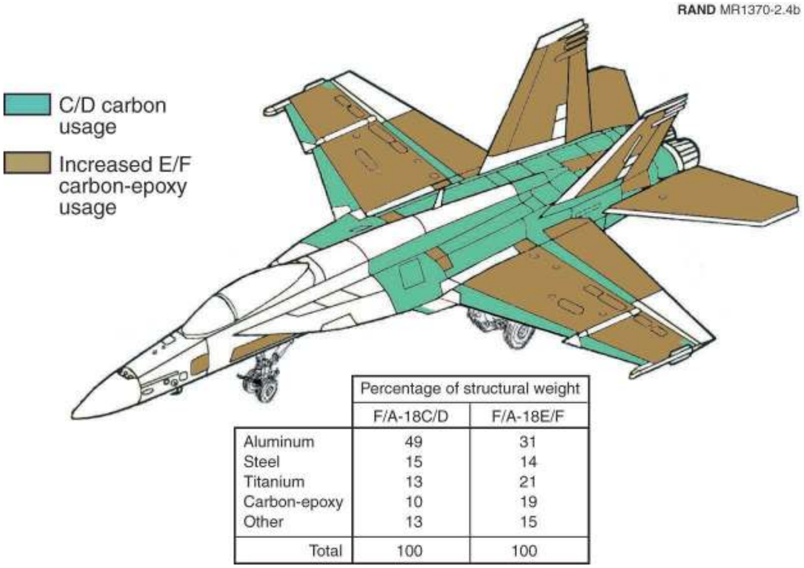


Figure 2.4a—F/A-18E/F Substructure Material Use



	Percentage of structural weight	
	F/A-18C/D	F/A-18E/F
Aluminum	49	31
Steel	15	14
Titanium	13	21
Carbon-epoxy	10	19
Other	13	15
Total	100	100

Figure 2.4b—F/A-18E/F Composite Use As Compared to the F/A-18C/D

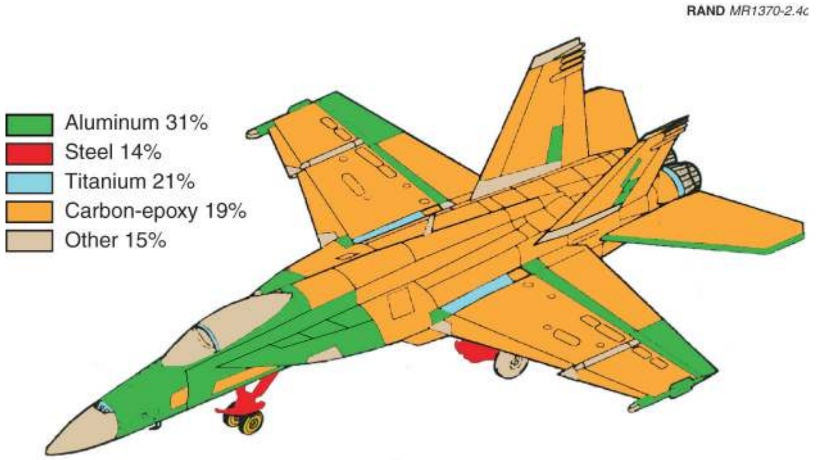


Figure 2.4c—F/A-18E/F Overall Material Use

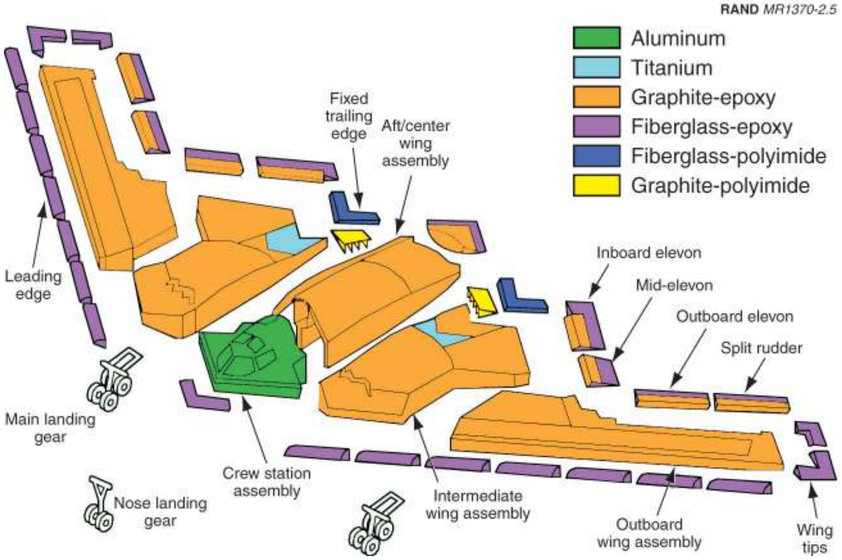
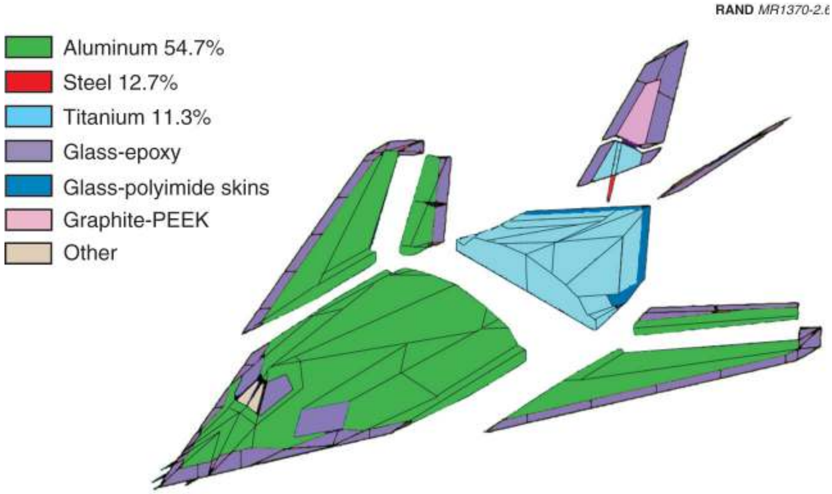


Figure 2.5—B-2 Overall Material Use



NOTE: Glass-epoxy, glass-polyimide, graphite-PEEK, and the category "other" constitute 21.3%.

Figure 2.6—F-117 Overall Material Use

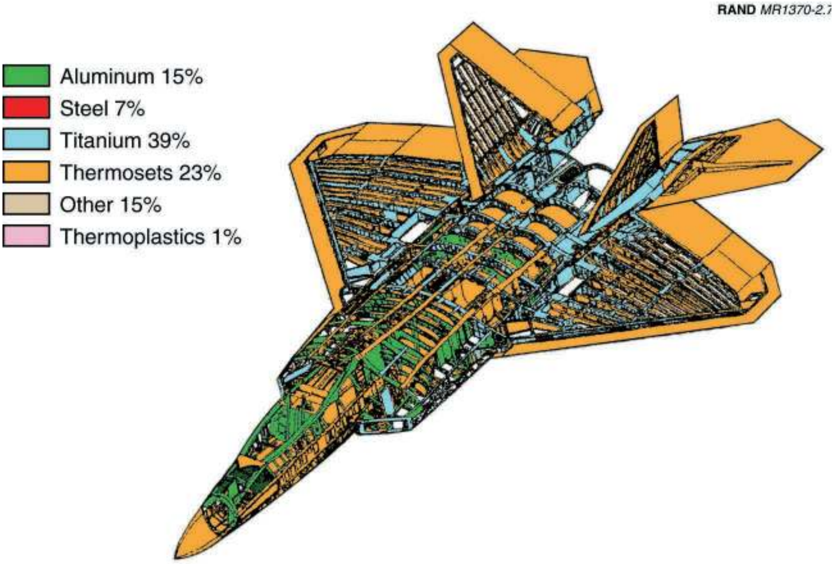


Figure 2.7—F-22 Overall Material Use

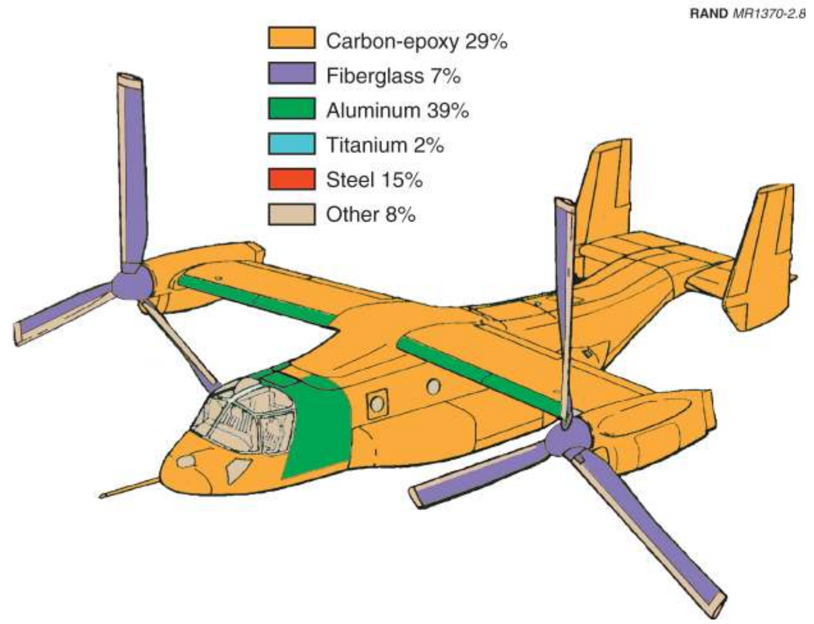


Figure 2.8—V-22 Overall Material Use

MATERIAL PROPERTIES DEFINED

This section is a catalog of material properties that defines only those properties to which we refer later in the report.[3] We begin with **density.** Density is simply the weight of a material per unit volume, which is measured in pounds per cubic inch. When a material is referred to as lightweight, low density is what is technically meant.

Next, we discuss mechanical properties such as strength, modulus of elasticity, and toughness. Aircraft structural parts are subjected to forces during flight called loads. The **stress** experienced by a part is defined as the force to which it is subject divided by the area of the

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[3] This section simply presents definitions with only minimal discussion of the materials science behind them. Readers interested in more background information are referred to Gordon (1978), which is a good nontechnical primer on these issues, or to any of the many excellent materials engineering textbooks, such as Flinn and Trojan (1975), Juvinall (1967), Van Vlack (1985), and Shigley and Mischke (1989).

Table 2.1

Composite Components in Aircraft Applications

Composite Component	F-14	F-15	F-16	F-18A	B-1	AV-8B	F-18E	F-22	V-22	DC-10 Demo	L-1011 Demo	737 Demo	727	757	767	Lear Fan
Doors	✓			✓	✓	✓	✓	✓	✓					✓	✓	✓
Rudder		✓				✓	✓	✓		✓				✓	✓	✓
Elevator									✓				✓	✓	✓	✓
Vertical tail		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓
Horizontal tail	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓				✓
Aileron						✓					✓			✓	✓	
Spoiler												✓		✓	✓	
Flap						✓	✓	✓	✓					✓		✓
Wing box						✓	✓	✓	✓							✓
Body						✓	✓	✓	✓							✓
Miscella-neous	Fairings	Speed brake		Speed brake, fairings	Slats inlet	Fairings	Speed brake, fairings	Fairings	Rotor blades		Fairings			Fairings	Fairings	Propeller blades

SOURCES: J. M. Anglin (1987) and Boeing and Lockheed Martin nonproprietary information.

part facing (i.e., perpendicular to) the force. The **strength** of a material is simply the maximum stress that material can experience without failure.[4] It is measured in units of force per area (we will use thousand pounds per square inch, abbreviated KSI).

Tensile strength is the maximum pulling stress a piece of material can withstand without failing. In this report, when we refer to the numerical value of the strength of a material (as in Table 2.2), tensile strength is what is meant. **Compressive strength** is the maximum pushing stress that a material can withstand without failing. Tensile and compressive strength are not necessarily equal. Airframe materials subject to bending loads are subject to both tensile and compressive stress.

Materials lengthen (that is, stretch) when pulled, and the percentage a material changes in length when subjected to a pulling load is referred to as **strain.** At levels of stress below those at which materials begin to fail, the strain of a material is proportional to the stress put upon it.[5] Put another way, the amount a part of a given material stretches when subjected to a force is proportional to the level of the force.[6]

Modulus of elasticity is defined as stress divided by strain at levels of stress below the beginning of failure. Since strain is proportional to stress in that region, this quantity is well defined.[7] Modulus of elasticity is the measure of the **stiffness** or rigidity of a material; the higher the modulus, the less a material lengthens when subjected to a given stress. It is measured in units of force per area (we will use million pounds per square inch, abbreviated MSI). Stiffness is an

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[4] The definition of failure depends on the material. Some materials fail by suddenly breaking apart, while others elongate or yield so that they can bear little or no load. Strength is an inherent property of a material; therefore, the strength of a part is the same whether the part is operating in an airframe or waiting to be assembled.

[5] This relation is known as Hooke's law.

[6] The relation of tensile stress and strain is empirically determined through a tensile test, in which a test specimen is mounted in a test machine and pulled by applying increasing loads (stresses) while the percentage change in the length of the specimen is recorded. The observed stresses and strains are then plotted in a **stress-strain diagram.** The stress-strain diagram is discussed in detail in Appendix A.

[7] This region is referred to as the Hookean region.

important property of airframe structural materials because if airframe parts changed length substantially under loads, aerodynamic performance, which is dependent on many relative dimensions of the airframe, would suffer dramatically. Structural integrity would also be hard to maintain.

The relation of the strength of a material to its weight is very important in airframe applications, and **specific strength**—or strength divided by density—is a measure of that concept. The weight of a part that can withstand a given load pattern will be approximately proportional to its specific strength, and achieving low weight is critical to improving the performance characteristics of aircraft. It should be noted that since strength is measured in weight per area and density in weight per volume, specific strength is measured in length (thousands of inches in this report).

Specific stiffness is stiffness divided by density. As with specific strength, this variable is important because the weight of a part that will change dimension only a given percentage under a given load pattern will be approximately proportional to specific stiffness. Since stiffness is measured in MSI, specific stiffness is measured in millions of inches.

A part failure that results from repeated (constant or fluctuating) tensile and compressive stress is called a **fatigue failure.** A fatigue failure begins as a small crack in metals and as a delamination[8] in composite parts. This is important in that airframe parts undergo repeated loads during operation. As the airframe ages, structural fatigue is carefully monitored by the airframe maintainer. Failure can also be caused by **corrosion.** Corrosion in structural parts results from contact with external agents. These agents can be natural, such as the environmental agents of the atmosphere and ocean (e.g., salt), or artificial, such as solvents. Both cause chemical degradation and changes in material properties.

Toughness is the ability of a material to absorb energy without damage. It is defined as the energy that a material can absorb without fracturing, measured in units of energy per volume. For aircraft, this property is important because tools and the like may be dropped on

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[8] Delamination of composites is discussed later in this chapter.

surfaces; the tougher the material, the greater the impact that can be absorbed without causing damage. The opposite of toughness is called brittleness. A “damage-tolerant” material or part is defined as one that can withstand a reasonable level of damage or defect during the manufacturing process or while in service without jeopardizing aircraft safety. In contrast to metals, composites are relatively brittle; therefore, toughening agents are added to the matrix to create a more damage-tolerant composite part.

The **service temperature** of a material is the highest temperature that a material can withstand in operation without suffering significant loss of its structural integrity or essential mechanical properties. Although service temperature is an inherent property of metals, it is, of course, affected by alloy composition. The property is quite important in military aircraft, since skin temperature is related to speed and exhaust temperature to engine power.

SPECIFIC MATERIAL PROPERTIES

We now turn to a discussion of the specific properties of materials considered in this report. We introduce it with Table 2.2, which shows the properties of some common airframe structural materials. It should be noted that material properties change with the specific designation and form of the material; these are representative values for aircraft application. Material designations generally begin as specific to a given company but often are subsequently licensed to other manufacturers. The first three columns in Table 2.2 present data for metals commonly used in aircraft construction; the next three columns present data for composites.

The implications of this table are discussed extensively below. Here we simply point out that composites show significantly higher specific strength and stiffness than do metals.

COMPOSITE MATERIALS

This section presents a brief overview of composite materials that is intended to complement the overview given in Resetar, Rogers, and Hess (1991). This overview highlights changes that have occurred since that earlier report.

Table 2.2

Material Properties

Property	Aluminum (7050-T7451)[a]	Titanium (6Al-4V)[a]	Steel (PH13-8Mo)[a]	Carbon/ Epoxy (IM7/ 977-3)[a]	Carbon/ BMI (IM7/ 5250-4)[a]	Carbon/ Thermoplastic (IM7/PEEK)[a]
Density (lb./sq in.)	0.102	0.160	0.279	0.057	0.056	0.058
Strength (KSI)	70	134	201	332	349	323
Stiffness (MSI)	10.3	16.0	28.3	22.2	22.2	22.7
Specific strength (K in.)	685	840	720	5825	6230	5570
Specific stiffness (M in.)	100	100	100	390	395	390
Service temperature (degrees F)	250	450	1000	275	325	275

[a] The designations in parentheses refer to the specific alloy or fiber/matrix.

As described above, composite materials are simply those composed of two or more constituent parts. This report focuses on composites made up of a reinforcing material embedded in a binding matrix. The primary reinforcing material that we consider is carbon fiber in long-strand form.[9] In this context, we focus on three matrices: epoxy, BMI, and thermoplastics.

Reinforcing Material

We concentrate herein on continuous carbon fiber strands as a reinforcing material. To put this in context, we note that reinforcing ma-

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[9] The terms *carbon fiber* and *graphite fiber* are often used interchangeably, although technically carbon and graphite fibers differ in the temperature at which they are produced and in their carbon content. In this report, we use the term *carbon fiber* to refer to both.

terial can come in forms other than continuous fiber—for example, short or long whiskers or particulates. By continuous fiber strands we mean fibers of approximately the same length as the dimensions of the part itself or longer; whiskers and particulates tend to be short in comparison to part dimensions. The advantage of continuous fiber is that the strands can be oriented within the part so that it has different mechanical properties, such as strength and stiffness, in different directions. This is called having *anisotropic properties*. This property is advantageous in airframe applications because loads on parts tend to be highly concentrated in specific directions. In general, metals are equally strong and stiff in all directions and are thus described as having *isotropic properties*. Carbon-whisker- and particulate-reinforced composites tend to have lower strength than continuous fibers and thus have only limited airframe applications. Continuous fiber reinforcement currently dominates airframe applications.

Several other continuous-fiber-reinforcing materials are commonly used. These include glass (as in fiberglass), aramid (known commercially as Kevlar), and boron. All of these materials have had some aerospace applications, but since carbon fibers predominate, we will concentrate on them in the remainder of this report. Carbon fibers dominate because in general, glass is relatively heavy, boron is relatively expensive, and aramid has a lower tensile modulus of elasticity. Glass is transparent to radio waves and is therefore an ideal material for radome construction and low-observable (LO) applications. Aramid fibers are used primarily in products such as bulletproof vests. Boron has been used in very flat applications but currently is not used in airframe structures.

Carbon fibers are made from a precursor such as polyacrylonitrile (PAN), petroleum pitch, or rayon in a continuous, precisely controlled process. During this process, the fiber is exposed to heat and tension in a series of ovens. This heating process chemically changes the precursor, yielding high strength-to-weight and high stiffness-to-weight properties. PAN-based fibers are the most common carbon fibers used in military airframe structures.[10] Figure 2.9 illustrates this

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[10] Pitch-based fibers have higher stiffness and thermal conductivity, which make them ideal for space applications. Rayon-based carbon fibers have extremely low thermal

process. The resulting product consists of very fine carbon fiber filaments—each approximately 5 microns, or 0.0002 inch, in diameter—that feel like fine silk thread to the touch. These filaments are then arranged into various forms, described below. One example is "tow," 0.125-inch-wide by 0.005-inch-thick tape in which all the fibers are aligned along the tape. In aerospace applications, each strip of tow contains 3000, 6000, or 12,000 filaments.

Carbon fibers are classified primarily according to their stiffness or modulus of elasticity. Most carbon fiber used in aerospace structural applications today is intermediate modulus (IM), which is characterized by a stiffness of 40–50 MSI. IM-7, the type of reinforcement used in the materials shown in Table 2.2, is such a fiber. Note that the stiffness of the composite materials listed in this table is only about 22 MSI. This is because the stiffness (as well as the strength) of a composite is typically lower than that of the reinforcing material.[11]

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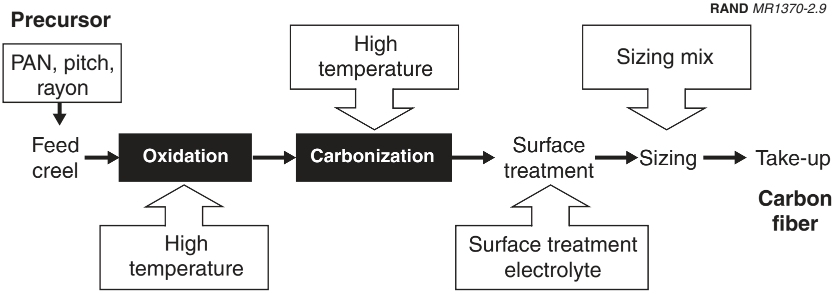

Figure 2.9—Carbon Fiber Fabrication Process

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conductivity, which makes them ideal for use in extremely high temperature applications (Traceski, 1999).

[11] Carbon fiber also comes in standard modulus (SM) (33–35 MSI), high modulus (HM) (50–70 MSI), and ultrahigh modulus (UHM) (70–140 MSI). SM fiber is used in aerospace applications in which lower mechanical properties can be accepted. A part made of SM fiber and untoughened epoxy has about 20 percent less strength and 10 percent less stiffness than a part made of IM fiber and toughened epoxy. HM and UHM do not have widespread use in airframes owing to their poor compression properties, although there is limited HM use now.

Matrix Materials

In this report we concentrate on polymer matrices, which are by far the most commonly used matrices in aerospace applications. However, three other kinds of matrix materials are used in advanced composites: metal, ceramic, and carbon. Metal matrices are currently too expensive and difficult to work with for widespread application, and ceramic matrices have insufficient toughness (i.e., they are brittle). Both have limited use in aircraft applications but are used in some applications involving high-temperature operating conditions (e.g., engines). Carbon matrix composites are costly and difficult to produce, and their primary airframe application is in aircraft brakes (they are also used in racing-car brakes). Carbon matrix composites are also used in space launch and reentry vehicles.

Thermoset Matrices

Polymer matrices, which are also called resins, are characterized as either thermosets or thermoplastics. Thermosets are the most widely used polymer matrices in airframe structures. In this study, we consider two kinds of thermosets: epoxy, which is most commonly used, and BMI, the next most common thermoset. No other thermoset currently has widespread aircraft structural application.[12]

After a composite part with a thermoset matrix has been formed at room temperature (a process described in Chapter Three), it must be cured under temperature and pressure, typically in an autoclave. During this process, chemical reactions occur in the resin in which molecules are cross-linked, forming a three-dimensional network of strong covalent bonds. (A cured thermoset composite piece is hard to the touch, much like shellacked wood.) Once cured, a part cannot be reprocessed. Most thermoset materials must be stored frozen; after a limited time out of the freezer at room temperature, they start curing, thereby losing properties, becoming difficult to form, and

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[12] Other thermosets include phenolics, cyanate esters, and polyimides. Phenolics are used in aircraft interior features for their flame resistance. Cyanate esters are used in rocket motor cases for their low moisture absorption and electrical properties. Polyimides have limited high-temperature applications.

eventually becoming useless. These out-of-freezer times are between one and four weeks. Thermosets also have a shelf life in the freezer of only 6 to 18 months.

Epoxies are the most commonly used thermoset resins in aircraft structures, with toughened epoxies used for high-performance applications. For example, the epoxy 977-3, shown in Table 2.2, is toughened. Toughening agents such as thermoplastics and rubber are added to counteract brittleness.

BMIs are used in higher-temperature and toughness applications; the resin 5250-4 in Table 2.2 is a toughened BMI. BMIs available in the 1980s were harder to work with than were epoxies and were thus associated with manufacturing labor penalties. As illustrated in Chapter Four, today's BMIs have improved handling qualities, and their cost differential has thus diminished.

Thermoplastic Materials

Thermoplastics are the other type of polymer matrix used in aircraft composites. One important potential advantage of thermoplastics is that after a thermoplastic part is formed, it can be reformed through the application of heat and pressure. Thus, if parts are defective on first try or are later damaged, they can be repaired rather than scrapped. This is because thermoplastics do not undergo any permanent chemical transformation akin to the molecular cross-linking that occurs in thermosets during autoclave processing. PEEK (polyetheretherketone) in Table 2.2 is a thermoplastic, as are PEKK (polyetherketoneketone), PEI (polyetherimide), and LCPs (liquid crystal polymers).

Another advantage of thermoplastics is that they are solid at room temperature and can be stored without refrigeration, thus offering a virtually indefinite shelf life. Moreover, thermoplastics offer high toughness and impact resistance. However, this advantage was greatly eroded with the advent of increased-toughness thermosets such as 977-3 epoxy and 5250-4 BMI, whose toughness is similar to that of thermoplastics.

The primary drawback of thermoplastics lies in their high cost, which is due primarily to difficulties in manufacture. Thermoplastics have poor handling qualities at room temperature, which makes laying them up difficult and therefore time-consuming.[13] In addition, some thermoplastics require solvents to allow the material to be worked into the desired shape. During the autoclave process, these solvents must be removed from the part. Sometimes, however, solvents are not completely removed, causing porosity that greatly compromises the mechanical properties and reliability of the part. Porosity is currently a major problem in thermoplastic part manufacturing and inspection.

Autoclave processing temperatures for most thermoplastics are between 500°F and 700°F.[14] Such temperatures require that production tooling be made from materials with a low coefficient of thermal expansion (CTE) that can withstand the wear from repeated high-temperature autoclave cycles. Tools with these qualities—such as Invar, a high-quality nickel alloy with a desirable CTE—are very expensive. Finally, thermoplastic raw material costs are relatively high compared with those of thermosets.[15]

Both because these manufacturing difficulties have not been overcome since the early 1980s and because some thermoplastic advantages have eroded, thermoplastic applications in airframe structures remain limited. (The relatively low rate of new-aircraft development and production since the end of the Cold War no doubt made the introduction of new materials even less attractive to industry.) Boeing,

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[13] These poor qualities include low drapability and low tack. Drapability is ease of conforming to a complex surface; thus, a ply made of low-drapability material can be laid up on a complex tool only with difficulty, which means that more labor hours are required for manufacturing. Tack is stickiness, so laid-up plies made of a low-tack material tend to separate more easily, leading to voids that later lead in turn to higher susceptibility to delamination. To compensate for these factors, more time must be taken in manufacturing to ensure that plies appropriately adjoin. This extra time includes additional debulking and compaction steps.

[14] Technically, thermoplastics do not "cure" during autoclave processing; they "form." We will use the term *autoclave processing* when referring specifically to thermoplastics. We will use the term *cure* generically when referring to composites in general.

[15] There may well be a "vicious circle" effect relating high thermoplastic raw material prices to low levels of use. For many industrial products, an expansion of demand leads to incentives for manufacturers to invest in more efficient large-scale processes, which ultimately leads to lower prices. Industry experts often project that such an effect would occur for thermoplastics, although this cannot be known with certainty before the fact.

for example, originally intended its Joint Strike Fighter (JSF) candidate to involve substantial thermoplastic use (e.g., in its wing skins), but as the development program continued, it was decided not to use thermoplastics. This illustrates not only the limited penetration thermoplastics have made but also the tendency to use proven materials in an aircraft as development proceeds (see Figure 2.2). Examples of aircraft that use thermoplastics are the F-117 and F-22 doors and panels (see Figures 2.6 and 2.7), which are susceptible to runway debris (Harper-Tervet et al., 1997).

Combining Reinforcement and the Matrix: The Composite Material

Composite material for aircraft use comes in two basic forms; unidirectional tape and fabric. In unidirectional tape (hereafter simply called tape), all the fibers (i.e., filaments) are aligned lengthwise in the same direction along the tape. A roll of tape is typically 0.005 inch thick, between 0.125 inch and 60 inches wide, and on the order of 1000 feet long. Narrow tape is often referred to as “slit tape.”

A composite part made of tape is typically fabricated by cutting a series of plies from the tape, stacking (“laying up”) the plies on a tool to form the shape of the part, and then curing the part with heat and pressure in an autoclave. For narrower tape, the plies are typically just lengths of tape; for wider tape, they are often cut out with complex shapes. (More detail on the fabrication process is provided in Chapter Three.) If the plies are laid so that all the fibers in the part are aligned in the same direction, the part will have maximum strength and stiffness in that direction and substantially less in others owing to the anisotropic nature of composite material properties discussed earlier. A quasi-isotropic part can also be made with tape by stacking the plies such that one-quarter of the fibers are aligned in one direction—say, 0°—and the other three-quarters are aligned in directions 45°, 90°, and –45°, respectively. Figure 2.10 illustrates both a quasi-isotropic and a unidirectional laminate. Since a part is typically made by laying up between 4 and 80 plies, a wide variety of strength/stiffness differentials can be achieved. As will be discussed further, this property is one of the critical advantages of composites. Fiber can be aligned so that the directional strength/stiffness properties of a part can best meet the loads the part is expected to experience in flight. Additional layers can be added to specific areas of a part to increase strength locally as well in a process commonly referred to as "planking." The three composite examples given in Table 2.2 are all unidirectional tape, and the strength and stiffness numbers are maximum values—that is, they are the values that apply if force is applied in the same direction as that in which the fibers are aligned.

The strength and stiffness of a quasi-isotropic part made with tape for given constituent materials (see Figure 2.10) is on the order of one-third to one-half the values unidirectional tape has in the maximum direction. (Of course, for quasi-isotropic fabric, the strength and stiffness values apply for loads coming from all directions, not just two.) Actual relative values vary by material type.

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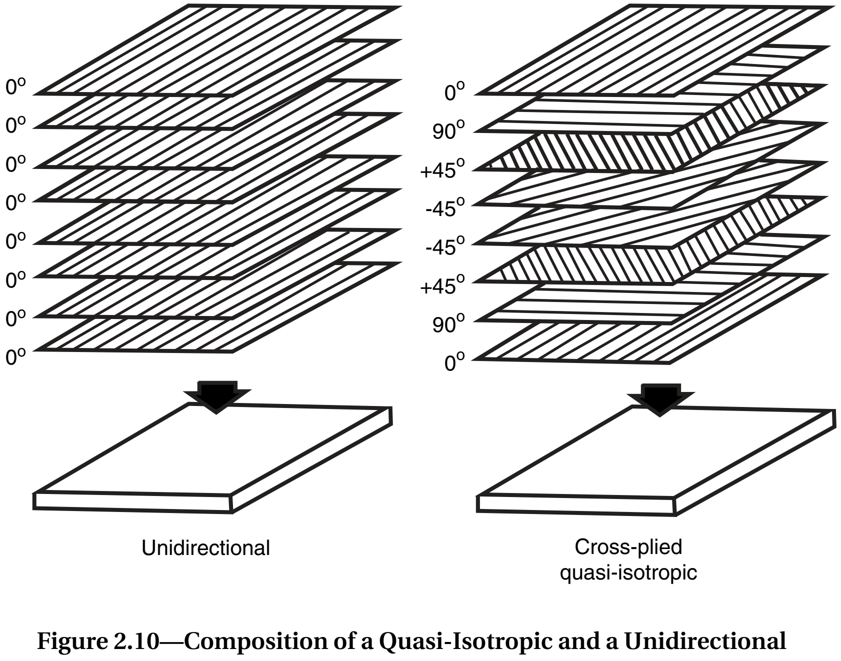

Figure 2.10—Composition of a Quasi-Isotropic and a Unidirectional Laminate

In fabric composite materials, fibers are woven together into a pattern. Fabric can be made in a wide variety of patterns and forms, and there can also be complex three-dimensional braids of fiber in the fabric. Various weave designs can be chosen to achieve different patterns of directional properties, and these designs affect other properties of the part, such as toughness. Typical weave patterns are shown in Figure 2.11.

The decision to use tape or fabric rests on several factors. As discussed above, unidirectional tape leads to structurally efficient part design, which can provide the lowest possible weight for a given part geometry and directional load pattern. It is most often used for parts with mild contours and for larger parts. Fabric has excellent contour capability and is most often used in lightly loaded parts that are small and complex. Three-dimensional carbon fiber braids are often used as preforms for the RTM process described below. Fibers such as glass or aramid can be combined and woven with different types of carbon fibers to improve damage tolerance and to optimize electrical

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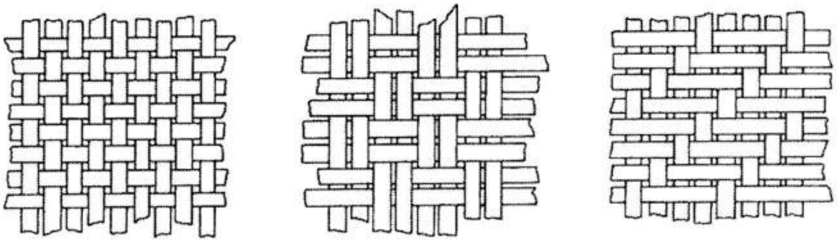
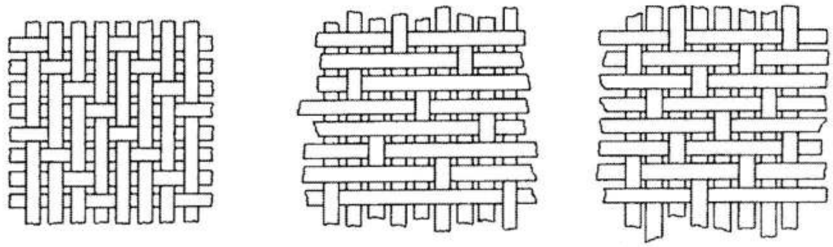


a. Plain weave b. Basket weave c. Twill



d. Crowfeet satin e. Eight-harness satin f. Five-harness satin

Figure 2.11—Typical Composite Fabric Weave Patterns

conductivity. In both tape and fabric form, fiber is usually about 60 to 65 percent of the volume of the composite material and the matrix about 35 to 40 percent.

The fiber and resin of a composite material can be put together in two ways. In the first, dry carbon fiber is “wetted” (i.e., enveloped in resin) just as the part is being fabricated, shortly before cure. More commonly, prepreg is produced. This is done by applying resin to the fiber, resulting in a combined resin/fiber tape or fabric product (prepreg) that is uncured and must be stored frozen until it is fabricated into parts (with the exception of thermoplastics, which can be stored at room temperature). This tape or fabric is called prepreg because it is impregnated with resin well before it is used to make parts. When prepreg is made, the resin can be applied to the fiber through either a solution or a hot-melt process. In the solution process, the fibers are pulled through a resin bath. In the hot-melt process, a thin resin film is applied to the fiber form and melted onto it.

ADVANTAGES OF COMPOSITE MATERIALS IN AIRFRAME APPLICATIONS

One of the primary purposes of this research project is to estimate the cost of using composite materials in airframe production. As further background for analysts who may use the cost-estimating factors and methods presented in later chapters, we present this account of the considerations that go into deciding whether to use composite materials in an airframe. We begin with the disclaimer that this is nowhere near a complete account of such a complex decision process but is simply an overview of the primary issues.

Weight Versus Strength and Stiffness

As already discussed, the great advantage of composites lies in the fact that their weight is relatively low compared to their strength and stiffness. Table 2.2 clearly shows this advantage. The specific strengths of composites are on the order of eight times higher than those of metals; specific stiffnesses are on the order of four times larger.

To be sure, these composite numbers are for unidirectional tape and thus represent strength and stiffness in the direction for which they are highest. As we have seen, however, quasi-isotropic composites have strength and stiffness in all directions of about one-third to one-half that of the maximum for unidirectional tape, which would still represent an advantage of roughly 3 for specific strength and 1.5 for specific stiffness over metals. All this implies that composite airframe structures can match the performance of metal structures with less weight, which will in turn increase the range, payload, and maneuverability of the airframe.

Directionality of Strength and Stiffness

Another significant advantage of composites is that they can be designed with properties that differ by direction. Many parts are subject to much greater loads in some directions than in others. Thus, to balance the performance of the part, one would want a part that had the differential ability to withstand loads by direction. That is, a reasonable way to characterize a well-designed part would be one for which the ratio of part strength to maximum load encountered would be the same in all directions.

A part made of isotropic material will by its very nature have equal strength in all directions.[16] Most metals are isotropic.[17] A composite part, however, can readily be made to have different strengths in different directions simply by changing the pattern of orientation of the fibers. Thus, a designer who knows the pattern of loads likely to be encountered can design a part so that its directional strength is roughly proportional to the directional stresses expected. If the part is made of unidirectional tape, for example, differential directional strength can be achieved by adjusting the orientation of the fibers that are laid down to form the part. This is often characterized as “aligning the fibers with the load paths.” The more concentrated the

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[16] This does not mean that the part can withstand equal loads in all directions. The maximum load that can be borne is strength times the cross-sectional area perpendicular to the load, and in any part geometry that is not spherical, this cross-sectional area will differ by direction.

[17] Some alloys are not isotropic. Some aluminum-lithium alloys, for example, are not isotropic, posing a disadvantage because the directional properties are not controllable.

directionality of load patterns on the part, the larger the relative advantage of composites because of the ability to directionally tailor their strength. (Everything just said for strength applies to stiffness as well.)

Composite Part Design Issues

The aforementioned design flexibility advantage of composites, however, has an associated disadvantage. Composite parts are inherently more difficult to design because each "part" is really a layered amalgam of several plies cured together into one part. The designer must therefore analyze how different ply alignment patterns will perform under different load patterns and must then choose the number, shape, and alignment of the plies to achieve a best outcome. Not surprisingly, the increase in degrees of freedom in design afforded by composites has led to a complicated and time-consuming design task. (This is true at least if one wants to take advantage of the increased capabilities that composites offer; designing composite parts in exactly the same way one would design metal parts has been disparagingly characterized as treating composites as "black aluminum." This practice generally results in parts with additional weight and no significant increase in performance.) Instructions must also be prepared for the manufacturing department on how to cut and assemble plies. Creating such instructions is a complex process that lies well beyond the basic specification of part geometry.

Finally, additional airframe design complications arise when metal and composite parts are in proximity, since there are some incompatibility problems between materials. For example, galvanic corrosion problems can arise if aluminum and carbon fiber composite parts touch in the presence of an electrolyte. In such cases, the designer must either ensure that a protective coat of some material is between these parts or employ some other design practice to resolve the problem. These issues also add to the time required to develop airframe designs with composites.

Part Complexity and Design Automation

Over the past 20 years, the process of aircraft design has undergone a process revolution in which automated design tools have almost completely replaced older manual techniques. Parts and whole aircraft are now represented three-dimensionally in aircraft design computer tools such as Unigraphics and CATIA. Among other things, these design tools reduce the need for physical mock-ups to ensure that individual subsystems fit together. Such tools can be used to send digital instructions to many kinds of machines on the factory floor, including numerically controlled milling machines, composite ply cutters, and optical laser ply alignment systems (see Chapter Three). The whole set of such computer systems is referred to as computer-aided design and computer-aided manufacturing (CAD/CAM). It has been argued that this increase in automated design capability should decrease the *relative* effort required to design composite parts—that is, the effort that must be expended in relation to that required to design metal parts.

We will specifically address this issue when we discuss our cost results in Chapter Four. Here, however, we make one simple observation. One would also have expected these new technologies to have decreased all absolute costs of aircraft design and development. However, there is virtually no evidence that aircraft development costs are falling; in fact, there is substantial evidence to the contrary. Yet credible reports indicate that the CAD/CAM revolution has reduced the cost of certain specific tasks.[18]

How can these two observations be reconciled? Our discussions with industry indicate that rather than being used to design aircraft more cheaply, CAD/CAM tools are being used to design aircraft better. In effect, far more analyses are being done for new aircraft than was the case in the past, including more analyses of loads encountered under varying flight conditions (“load cases”) and more detailed and accurate modeling of underlying structural phenomena in aircraft, such as load paths. In addition, these tools allow for the integration of manufacturability and supportability in the design process, thereby adding more steps and time to the design phase. In short, the same number of engineers or more are being used to design an aircraft,

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[18] For example, the elimination of hardware mock-ups was estimated to have saved the V-22 program 150,000 man-hours in engineering and manufacturing development (EMD) (Dougherty and Liiva, 1997). Some industry estimates indicate that up to 60 percent savings in design-to-build information release time has been attained as a result of CAD/CAM systems.

and each is more productive owing to CAD/CAM. Thus, as a result of CAD/CAM, we are getting safer, more efficient, and higher-performance aircraft today than was the case 20 years ago. In addition, aircraft should in theory be more producible and supportable at the end of development, thus lowering the need for design changes during production. The military aircraft industry has therefore derived gains from CAD/CAM in the form of better aircraft rather than cheaper aircraft of unchanged quality.

Composite Unitization

Another advantage of composites in design is that they lend themselves to unitization—that is, to the substitution of a larger, more complex integrated part for several smaller ones that must be fastened together into a subassembly. Unitization saves on the weight of fasteners and on the time required to assemble the subassembly, including the time needed to shim, attach fasteners, and inspect connections. In addition, the holes associated with fastening parts together are inherently weaker than integral structure and more susceptible to cracks and other damage.

Unitization can be achieved with composites in four ways. First, composite layup techniques can form relatively complex shaped parts that in standard metal design practice would have been made of several subparts. Inlet ducts are a good example of this. Second, unitized parts can be made by “cocuring”—a process in which two or more newly formed parts are cured together at the same time and are held together under pressure during the cure such that they physically join to become one part. Third, composites can be cobonded. When a newly formed part is about to be cured, it can be held with pressure against an already fully or partially cured part while in the autoclave, causing the parts to be chemically bonded together while the first one cures. Finally, composite parts can be adhesively bonded to each other more readily than can metal parts. (Whether this is really unitization is debatable, but it does do away with fasteners and holes.) An example is adhesively bonded honeycomb sandwich parts.

The unitization advantages of composites have been eroded somewhat, however, by the advent of high-speed machining of metals (described in Chapter Three). This technique lowers the cost of unitization of metal parts and makes possible more extensive unitized metal structures than can be made with conventional machining techniques.

OTHER CONSIDERATIONS IN USING COMPOSITES

Knowledge Base for Composite Materials

One factor to be considered in using composite materials in airframes is their relative newness. (And newer materials are continuously being introduced.) Knowledge about the properties of composites is not as complete as is knowledge about metals. Thus, a more conservative approach is taken in generating "design allowables."

A part is designed as though its strength is only some percentage of its actual estimated strength to provide a margin of safety against uncertainties in both material properties and loads encountered by the part. For example, if a part is designed as though its strength is only 50 percent of its actual estimated strength, it is said to be designed with an "allowable" of 50 percent. In aerospace applications, these allowables are between 40 and 90 percent of the strength of the part, depending on the nature of the loads expected to be encountered. The newer a material, the less confidence one has in its properties, and hence the lower (more conservative) the allowable. The same principles apply to other mechanical properties, such as stiffness: The more conservative (i.e., the lower) the allowable, the heavier and thus more expensive the part must be for any given load pattern expected.

Initial estimates of the mechanical properties of a material are made through a series of tests conducted on many samples of material. As many as 10,000 test samples are required to develop an initial database to support the design of airframe structural parts. These samples are called "coupons," and the tests are called "coupon tests." These tests are also used to determine accept/reject criteria for part inspection after manufacture. For composites, this is done through "effects of defects" analyses in which defects—for example, voids or delaminations—are deliberately introduced into coupons. The resulting changes in material properties are then assessed.

Introducing new materials thus increases costs for two reasons, regardless of the cost of manufacturing or using the material itself. The first is the cost of the testing process, and the second is the weight penalties that must be accepted in the early stages of material use, when allowables are very conservative (i.e., low). As time goes on, these costs fall as the initial large testing effort is completed and data are compiled that can be used for later designs. In addition, allowables become less conservative as test data and production and flight experience increase confidence both in the average properties of the material and in the limits on variability of that material from part to part.

An extreme case of adverse cost impacts early in a material's development occurs when, as sometimes is the case, a dual-aircraft design path is chosen—that is, when aircraft sections are designed both with and without the new material in the event that the expected (or hoped-for) performance of the material is not attained. This obviously increases certain design costs.

These knowledge base problems are not of major importance with carbon-epoxy because the industry has accumulated a great deal of experience with that composite. Carbon-thermoplastic composites, on the other hand, have had little flight experience, especially in safety-of-flight-related applications, and are still relatively new in this respect. Carbon-BMI falls in between and is just now becoming widely used on aircraft.

Failure Modes

One part of generating information about materials lies in the analysis and understanding of how and why parts fail. In airframe structures, corrosion, fatigue, and in-service damage cause failures. The analysis of these causes of failure in metals has been occurring for decades and, while certainly not completely understood, is ahead of similar analysis for composites.

Properly designed composite parts resist fatigue and corrosion better than do aluminum and steel, but composites fail in one way that metals do not: delamination. Since composites are laminates—that is, are produced by the curing together of a stack of plies (laminae)—they can fail through the separation, or peeling apart, of the plies.

Even small amounts of such delamination can substantially reduce mechanical properties. More will be said below about techniques for testing for minute delaminations and other kinds of voids in a part, which can eventually lead to larger and more serious delamination. One basic issue, however, is that these small initial delaminations or voids can be difficult to detect, and unless inspection techniques are very good, the first sign of a problem could thus be complete failure of the part. Both battle damage and peacetime accidents (such as dropped tools) can also induce delamination. Analysis of the causes of, indicators for, and propagation processes of delamination thus continues.

Tooling

Composite parts are typically laid up on a tool that helps form the part and hold its shape while curing. This tool must therefore withstand repeated heat and pressure cycles of the autoclave cure and must not lose its often stringent dimensional tolerances as a result of these cycles.[19] It must also have thermal expansion properties that do not lead to distortion of part shapes.[20] These two qualities often require very expensive tools for two reasons. First, the raw materials for the tools are sometimes very expensive, especially Invar. Second, they are often quite difficult to work with, leading to high tool fabrication and maintenance costs. Depending on the specific application, production tools used to make composite parts can be made of metals, ceramics, carbon, or high-quality composites. Chapter Four presents our estimates of relative tooling costs for various materials.

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[19] This criterion is relevant for “production,” or “hard,” tooling, which is typically designed for aircraft production runs of 100 or more. “Soft” tooling, which is associated with much less durability, is sometimes used in low-production-run programs such as experimental, concept demonstrator, or prototype aircraft. It is much less expensive and often uses less durable material, such as aluminum or composites.

[20] This means that the CTE of the tool and the CTE of the part must be close enough that differential expansion during autoclave heating and cooling does not distort the part.

Nondestructive Inspection and Test (NDI/T)

One of the critical steps in composite part fabrication is nondestructive inspection for defects. Composite part defects include porosity, ply delamination, cracks, and foreign object inclusion. NDI/T methods are also used to verify composite subassembly joint and bond integrity. The two main techniques of inspection are noninstrumented and instrumented.

Noninstrumented techniques include visual inspection and the coin-tap method. The coin-tap method literally involves tapping a coin or a special hammer on a laminate and listening for variations in sound, which indicate a void or other material nonuniformity. These two methods are effective and inexpensive but are limited in terms of the types of defects they can detect.

A number of sophisticated instrumented means of inspecting composites have also been developed. These methods include ultrasonics, X-ray, infrared (IR) thermography, laser shearography, and laser ultrasonics. The primary method used today is ultrasonics with either the through-transmission ultrasonic (TTU) or pulse-echo technique. In TTU, sound pulses are passed through the part, and the signal received is compared to that received when the same test is performed on a part known to be defect free. This technique requires access to both sides of the part. The pulse-echo method uses the same principles but requires access to only one side of the part, since the reflected echo of the transmitted sound is the signal received. The X-ray inspection method has limited application in detecting foreign objects in a part. It can be performed relatively quickly but requires expensive equipment, including lead shielding.

The other three methods, which have been developed more recently, are still being refined and are thus not yet in widespread use. In IR thermography, the part is briefly heated, and the resulting temperature differences across the part are interpreted to indicate defect areas (McDonnell Douglas, 1997). In laser shearography, stress is applied to the part, and illumination by a laser produces an image that reveals flaws (McDonnell Douglas, 1997). In laser ultrasound, a laser is used to introduce a sound pulse into the part, which is then analyzed using the ultrasound methods described above. If successful, this method will reduce NDI time, especially for complex and large skins (Drake, 1998).

METALS

This section offers a brief overview of metal properties as a complement to that on composites. The three primary metals used in aircraft are aluminum, titanium, and steel. Chapter Four discusses their cost implications.

Aluminum

Conventional aircraft-grade aluminum is used where strength requirements are moderate. Historically, aluminum has found extensive use in the airframe industry owing to its comparatively low weight, low raw material cost, good thermal properties, extensive manufacturing experience, and extensive database, which lead to high-confidence design allowables.

Although aluminum-lithium alloys have not yet made any significant penetration in airframe structural applications, newly developed alloys are much more promising. Current aluminum-lithium alloys can provide improvements in specific stiffness and strength as well as in fatigue and corrosion resistance over conventional aluminum alloys. Moreover, the mechanical and processing properties of current aluminum-lithium alloys are considerably superior to those of previous versions. (Older aluminum-lithium alloys often had such high directional property variation that the average weight and strength advantages were negated. Another problem with older aluminum-lithium alloys was raw material batch-to-batch inconsistency.) However, aluminum-lithium machining chips must be segregated from normal aluminum chips and more carefully disposed of. Aluminum is normally recycled into products such as beverage cans, but aluminum-lithium cannot be used for such purposes owing to environmental and health concerns about lithium. This raises the costs of using aluminum-lithium.

Titanium

Titanium has excellent heat and corrosion resistance and is stronger than aluminum. Its primary drawback is cost; the raw metal itself is five to seven times as expensive as aluminum, and more labor hours are required per pound to fabricate it (see Chapter Four). Titanium is used extensively in military airframe aft fuselages by virtue of the need to withstand engine exhaust temperatures, and it is also used where strength is a key property. Titanium's mechanical properties, such as strength and stiffness, are more compatible with those of composites than are aluminum's, so titanium is used for applications in airframe substructures that are part metal and part composite. Titanium prices have risen in recent years owing to commercial uses in sporting goods such as golf clubs, bicycle frames, and the like. The producer price index (PPI) for titanium rose 56 percent between 1987 and 1999, while the PPI for all metals rose only 16 percent over that time period.

Titanium alloys with small percentages of aluminum, vanadium, and other metals are commonly used in place of pure titanium in airframe structures. Titanium 6-4 (Ti-6Al-4V) is a common alloy used in airframe structures.

Steel

Steel application in military aircraft structure is limited. It is the material of choice where very high strength is required—for example, in fasteners,[21] landing gear, arresting hooks, and spindles for horizontal stabilizers. It has superior strength but very high density, so steel parts are very heavy.

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[21] Sixty percent of the steel used in the F-16 airframe structure is in fasteners.

Chapter Three

MANUFACTURING TECHNIQUES

This chapter discusses the primary manufacturing techniques that are currently used to make aircraft structural components. This discussion is intended as background for the cost results outlined in the next chapter, which vary by manufacturing technique. First we discuss the composite manufacturing techniques currently in use. These techniques are hand layup, automated fiber placement (tape layup or tow/slit tape placement), and RTM. We then discuss some promising new techniques that may mature and become important in the future as well as some minor techniques in use today. Subsequently we discuss metal manufacturing techniques, including both conventional and promising newer techniques.

COMPOSITE MANUFACTURING TECHNIQUES

We begin with some general observations about which composite manufacturing techniques are best for what kind of part. Almost any part can be fabricated by hand layup, although the process may be time-consuming and expensive for large or complex parts.[1] Flat parts with simple contours are suitable for either hand layup or automated tape layup, while more complicated contours are more suitable for automated tow/slit tape placement. Most internal primary structural parts are suitable for either hand layup or RTM. Parts that

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[1] For example, costly special platforms and tooling might be necessary. Stories are told of workers being suspended by harnesses in midair and being moved about to hand-lay material on large wing skin parts. This was done so that the workers would not damage other areas of the skin by walking on them.

require extreme dimensional accuracy, small tolerances, and unitization are especially suitable for RTM.

Hand Layup

Hand layup is the oldest and most frequently used composite fabrication process. In it, fabrication workers place successive layers (plies) of prepreg broadgoods, such as tape or fabric, on tools to form the part. Figure 3.1 illustrates this process. First, the plies are cut out of rolls of prepreg either by hand or, more commonly, with automated cutting equipment using reciprocating knives or lasers.[2] At the same time, the tool on which the part will be laid up must be inspected; tools must be cleaned with chemical solvents after each autoclave cycle. Fabrication workers are guided in ply placement either by Mylar templates or by automated optical projection systems such as the optical laser ply alignment (OLPA) system. It is critical that plies be laid in the correct order and in the correct direction, as it is this directional alignment that gives composite parts strength and stiffness in the right directions. Parts can have as many as 80 plies that must be laid down and stacked in the proper sequence, with the fibers of each ply of tape or fabric oriented in the proper direction.

After several plies have been laid on the tool, the plies are debulked. In this process, pressure is applied to the laminate pile to remove voids and to ensure that the stacked plies are sufficiently compacted. The process of laying up and debulking plies uses more than 40 percent of part fabrication labor (Boeing, 1999).

After all the plies have been laid up, the part is bagged and sealed before being cured in an autoclave. The bagging process involves placing materials such as peel ply, release fabric, bleeder ply, breather ply, a caul plate, and a plastic, heat-resistant bag over the tool and part. The matrix bleeder materials are important because some excess resin must be bled out of the laminate during the cure. If this does not occur, the excess resin degrades final part properties and adds weight. Proper bagging and sealing are also critical. If vac-

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[2] This technology is similar to that used in the garment industry to cut fabric.

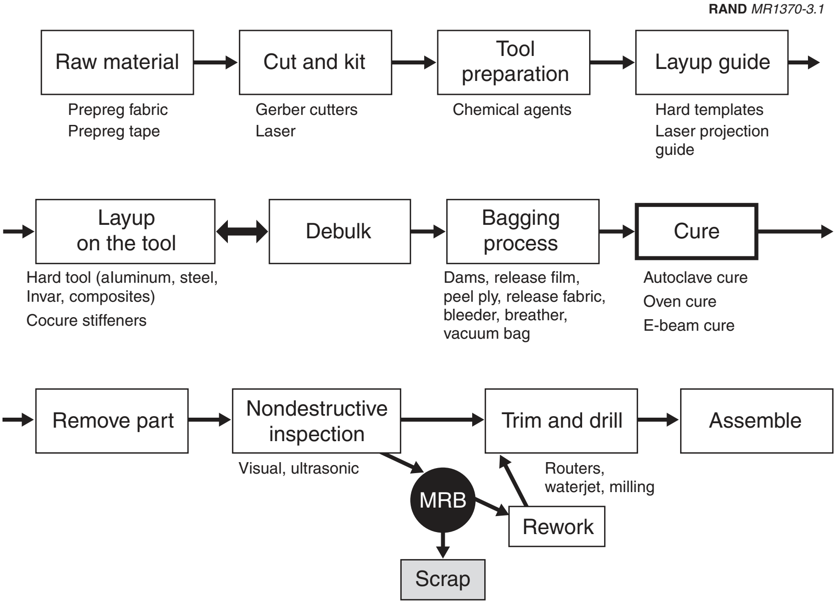

Figure 3.1—Hand Layup Process Steps

uum seal is lost during the cure cycle, it is likely that the part either will not meet dimensional tolerances or will have unacceptable voids or delaminations.

The part is then cured under heat and pressure in an autoclave. A typical carbon-epoxy cure takes 5 to 10 hours, with temperatures reaching 350°F and pressures reaching 100 psi. Carbon-BMI autoclave cures require about 11 hours at comparable temperatures and pressures. Carbon-BMI parts also require a postcure cycle of roughly 18 hours at around 450°F in an oven or autoclave. (Some companies also put some toughened carbon-epoxy parts through a postcure cycle.) Thermoplastics have autoclave processing times of around 4 hours and require temperatures between 500°F and 700°F. After cure, the part is nondestructively inspected. If it passes NDI, the part is then trimmed. The bagging, curing, NDI, and trimming steps use another 40 percent of part fabrication labor (Boeing, 1999). After the part is trimmed, holes are drilled if fasteners are used in subassembly or final assembly. This completes the fabrication step for the part.

If the part fails NDI, it is sent to a material review board (MRB). The MRB decides on the disposition of the part, which can be "use as is," "rework and repair," or "scrap" depending on the type, location, and severity of the defect.

Automation in Hand Layup

The hand layup process has become more automated over the past ten years. Plies are now almost always cut by machine rather than by hand, which, in addition to being a faster process, is also more accurate, leading to less scrap and less required inspection. Moreover, the sets of plies that will make up a part are increasingly being labeled and arranged into kits using automated pick-and-place techniques. This process is also faster and more accurate than manual procedures.

A more important automation development that has only recently gained widespread use is the OLPA system. In this system, workers are shown where to place each ply by means of an optical boundary projected onto the tool or laminate surface. This system has three main advantages. First, it lowers the labor time required to lay up parts, since workers no longer have to select and position Mylar templates (see Chapter Four for estimates). Second, it improves part quality by increasing the accuracy of part layup—especially directional fiber alignment, which is critical. Finally, it eliminates the need to design, fabricate, maintain, and replace Mylar templates.

Of course, engineering costs are associated with all of these automated techniques. Computerized instructions must be developed for the cutting, kitting, and laser projection machines, with one set of instructions for each part. However, the digital output of the CAD/CAM systems that are used to design parts can be processed by translation programs to generate such instructions. This greatly lowers the costs of developing the instructions (which is equivalent to programming the cutting, kitting, and projection machines).

Automated Fiber Placement

Automated fiber placement is the process by which plies of composite material are placed on a tool surface in their proper position by a machine rather than by hand. Today, industry primarily uses two types of fiber placement techniques. The first is done with a tape layup machine. This machine is fed by a roll of prepreg tape that is usually six inches wide. A dispensing roller head is moved, based on computerized numerical control (CNC) instructions, to the proper place and orientation over the tool. It then rolls a piece of tape across the tool surface in the appropriate length and direction and automatically cuts the tape when it is done laying that piece. Subsequently it moves to a different position and repeats the process until the part has been laid up. This technique is considered first-generation fiber placement technology and is most suitable for minimally contoured large skins.

The other fiber placement technique is called tow/slit tape placement. This is similar to tape layup except that the machine is fed by 8 to 32 individual narrow strips of tape between 0.125 and 0.25 inch wide. The feed can be tow (individual narrow tapes) or slit tape (a wide tape cut lengthwise into narrow strips). The dispensing roller head then lays these narrow strips of tape down simultaneously with the capability to stop and start individual strips in any pattern. With this capability, part thickness and thus strength can be varied nearly continuously along the part to best meet expected loads at minimum weight. In addition, the ability to vary the effective width of the ply being laid down just by varying the number of contiguous strips being dispensed at any time allows the roller head to follow complex part contours, thus permitting geometrically complex parts to be laid up (see Figure 3.2). This technique can therefore lay up complex contoured parts such as inlet ducts and fuselage skins.

Some hand layup work is still involved in automated fiber placement techniques. In such cases, the machines are occasionally stopped for manual placement of cutouts, inserts, or stiffeners onto the fiber layers, after which automated placement continues.

Automated fiber placement techniques offer several advantages over hand layup. First, the time and labor hours required to lay up a part decrease (estimates of such savings are in Chapter Four). This is partly because, as shown in Figure 3.3, several steps in the hand layup process are reduced or eliminated. Cutting and kitting are eliminated because the fiber placement process effectively does this

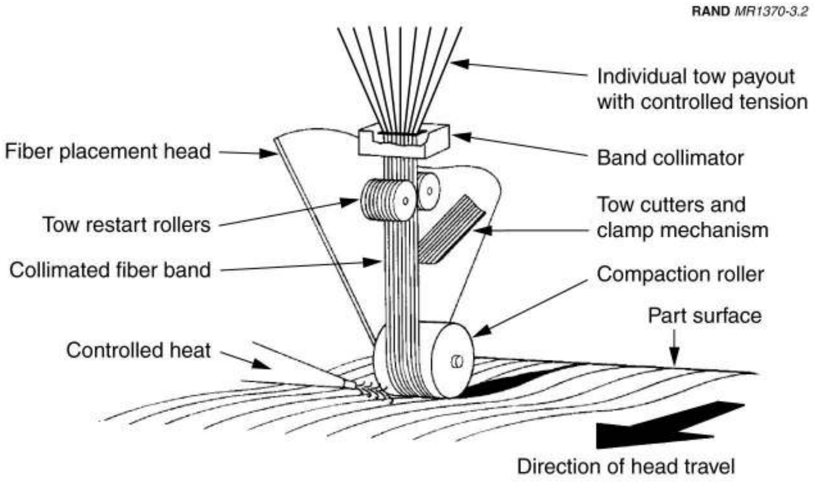

Figure 3.2—Fiber Placement Machine Fiber Placement Head

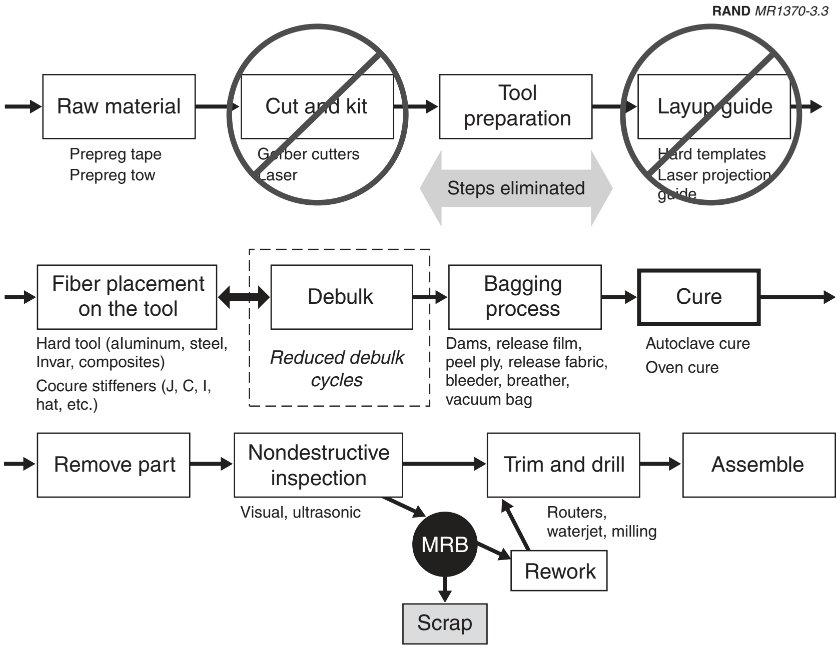

Figure 3.3—Automated Fiber Placement Steps Compared to Hand Layup

as it proceeds, dispensing and cutting the tape. Layup time is reduced in that the machine can lay tape faster than people can. Debulking is reduced by virtue of the fact that the fiber placement dispensing head compacts and heats the tape, and lays it down with pressure. Thus, manual debulking has to occur less frequently.

The second advantage, as noted above, is that tow/contoured tape placement allows fine part-thickness control to optimally balance weight and strength, since the tape pattern can be tailored to strength requirements. Third, the machine can orient the plies more accurately than people can, so part quality improves. Fourth, losses due to cutting the raw material out of wide rolls are eliminated, so the material buy-to-fly (BTF) ratio is improved. Finally, equipment needed to guide hand placement of the plies, such as Mylar templates or OLPA systems, is not required. One cost offset is that CNC instructions for fiber placement must be created for the machines. With CAD/CAM improvements, however, this penalty is not overwhelming. Another cost offset is the cost of the fiber placement machine itself. A tow/contoured tape machine can be in the $6 million to $7 million range (installed). The savings it allows in other ways, however, generally make this a good investment for substantial production runs.

Resin Transfer Molding

In RTM, catalyzed resin matrix material is injected into a closed tool or mold containing a fiber part preform, and heat and pressure are then applied to the tool/fiber/matrix package to cure the part. Figure 3.4 is a schematic of the process.

The preform can be created in two ways. One is by weaving or braiding dry carbon fiber into a three-dimensional form. The second is by laying up layers of carbon tape or fabric by hand with 5 to 6 percent resin applied. The preform is then placed into the RTM mold.

The RTM mold is a set of matched metal dies. Once the preform is in the mold, additional resin is injected under heat and pressure to bring the resin content to about 40 percent of the final part weight. Extremely low viscosity resin must be used to permeate the preforms quickly and evenly. The mold is then placed into a heated press in

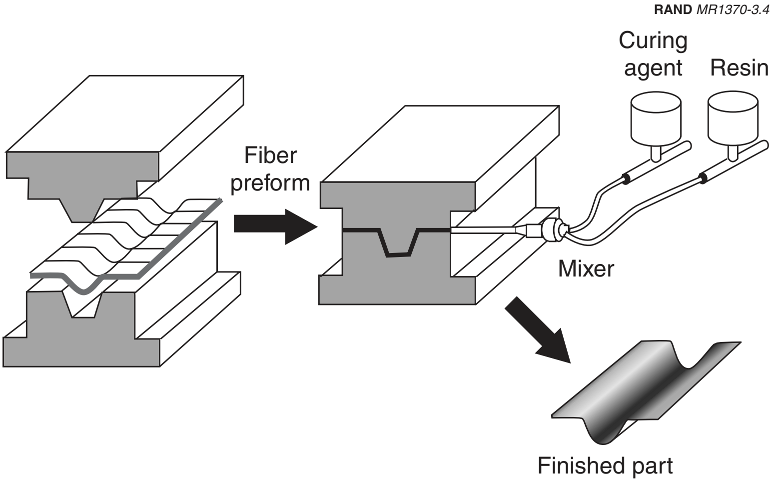

Figure 3.4—RTM Process

which the two halves of the mold are compressed and the part is cured under the heat and pressure applied by the press. After the part is removed from the mold, the process is much the same as with hand layup or automated fiber placement. Figure 3.5 illustrates the steps of the overall RTM fabrication process.

The primary advantage of RTM is that it can produce geometrically complex parts with precise dimensional tolerance, which also implies little variation from part to part. This complexity capability means that compared with metal assemblies, substantial part unitization can occur, yielding the associated weight and assembly time savings described in Chapter Two. One disadvantage is that the initial tooling cost is high owing to the need to make matched tools that will not warp under the pressure and heat required for cure. To meet this requirement, production tools are made of highly durable (and hence expensive) material, usually Invar. Therefore, RTM is most attractive for longer production runs.

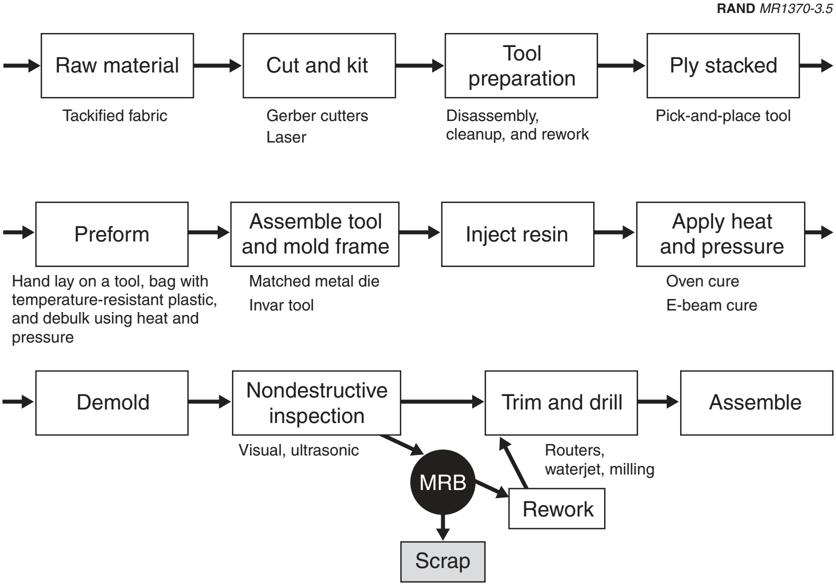

Figure 3.5—RTM Fabrication Process Steps

Other Current Composite Manufacturing Techniques

This section briefly discusses two manufacturing techniques used in composite manufacture today that are not widely applied to airframe parts: filament winding and pultrusion.

Filament Winding. Filament winding is the automated process of pulling dry fiber bundles, or narrow tapes or tows, through a resin bath and then immediately winding them onto a rotating mandrel (tool). This method was one of the first composite fabrication techniques. A prepreg tow can also be used in the filament-winding process, which eliminates the need for the resin bath (also called a wetting station). The applications of this process are limited to cylindrical parts such as rocket motor cases, pressure vessels, and tubes.

Pultrusion. In the pultrusion process, a continuous bundle of dry fiber is pulled through a heated resin-wetting station and then into heated dies. The cross-sectional shape of the pulled fiber is formed by these dies, and the resin is cured in them. Parts are then made by slicing the long cured piece that emerges. The pulling through the dies, which is done by automated equipment, occurs continuously. This process is limited to straight parts with a constant cross section, such as structural members (e.g., I beams, T beams, or frame sections) and ladder rails.

Possible Future Manufacturing Techniques

This section briefly discusses a variety of composite manufacturing techniques currently being developed. None of these are widely used in manned airframe applications today, but all have the potential to improve manufacturing efficiency. Only the outcome of the development process will tell us whether they will reach their potential for airframe applications.

Vacuum-Assisted Resin Transfer Molding (VARTM). VARTM is very similar to the RTM process except that the resin is drawn into the preform and mold with vacuum pressure rather than being pumped in. Generally, fiber preform is put on a one-sided mold and is covered with a rigid or flexible top and vacuum sealed. The resin is then introduced. This technology eliminates the need for expensive matched metal tooling and allows for the fabrication of large, unitized composite assemblies. It is often used with resins that cure at relatively low temperature.

Resin Film Infusion (RFI). In RFI, a dry preform is placed in a mold on top of a solid resin plaque or film. Heat and pressure are then applied so that the resin infuses throughout the preform, and the cure occurs under this heat and pressure as well.

A variation of this process is called stitched resin film infusion, (S/RFI). In this process, the preform consists not only of layers of horizontally woven patterns but also of vertical stitching through the weave layers and sometimes dry preform stiffeners attached with stitches as well. Parts made with this technique should have improved survivability from ballistic impact and increased tolerance to low-velocity skin impacts. Additional development and testing are required before the process will be accepted for military aircraft parts.[3]

Out-of-Autoclave Curing. Since autoclaves are expensive to maintain and operate as well as a process bottleneck, industry is exploring other means of curing composite parts. A variety of radiation curing methods, such as electron beam (E-beam), microwave, X-ray, and ultraviolet (UV), are being evaluated. Currently, E-beam appears to be the most promising technique. This is a rapid curing process that uses electron beam radiation rather than heat to cure the part. The E-beam process may also have an application in assembling composites without fasteners by cocuring of parts. E-beam equipment is generally not expensive, but facilities and equipment to house and control the radiation are a major investment. Again, more development work is needed before this technique will be accepted for aircraft parts.

METAL MANUFACTURING TECHNIQUES

This section begins with a review of metal manufacturing processes that have long been in use. We then describe in more detail two relatively new processes for which we have specific cost estimates in the next chapter: HSM and HIP investment casting of titanium. We then briefly discuss one promising new technique that is still in development for airframe uses: laser forming of titanium.

Conventional Processes

In the airframe industry, most metals are processed using conventional techniques such as CNC machining, forging, casting, and superplastic forming and diffusion bonding. The most widely used fabrication method is machining a plate or sheet of metal. In this process, a CNC milling machine is used to remove excess material from a raw metal billet, thus forming a part.

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[3] In a pilot project in which a stitched composite wing was made, a computer-controlled, multineedle-stitching gantry sewed together up to 20 stacks of precut, knitted carbon tow plies at a combined rate of 3200 stitches per minute. Braided and stitched stiffeners were folded into T shapes and sewn on. They perform the same function as spanwise stringers in a conventional aircraft (Proctor, 1998).

In the forging process, fully consolidated billet material is heated and plastically deformed by compressing the metal between an upper and lower die to shape the part. Typical parts made by forging are airframe structural components such as frames, bulkheads, ribs, and spars. After the forging process, parts usually require some machining.

In the conventional casting process, molten metal is introduced into a mold cavity, and after cooling and solidification, the metal takes the shape of the mold cavity. Today casting has limited applications because it has highly conservative design allowables.[4] This is because of the potential for microporosity in a cast part, which can seriously weaken the part. Thus, parts made from castings are required to be heavier than parts made with other processes. To date, there is not enough confidence that testing will detect such porosity; hence the conservative allowables. Like forgings, castings result in near-net shapes, which then still require some machining to finish.

Superplastic forming and diffusion bonding (SPF/DB) require similar processing environments and are often done together. Superplastic forming consists of placing flat sheet stock over a die of the desired part shape. The titanium stock is heated to 1625°F to 1650°F, and a burst of inert gas forces the flowing material into the die. The metal stock assumes the required part shape and is held under temperature and pressure for a short time before cooling. In diffusion bonding, the surfaces to be bonded are held together under near-melting temperatures and high pressure. Bonds are formed as a result of the diffusion of atoms across the mating surfaces, and these bonds have a strength approaching that of the parent metal.

SPF/DB processes are primarily used to make titanium parts (aluminum can be SPF but not DB). SPF/DB can produce unitized complex shapes (saving weight and assembly time) with close tolerances.

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[4] This is accomplished by applying a casting knockdown factor to the strength the designer would otherwise be allowed to assume for the part.

High-Speed Machining of Aluminum

HSM is, as its name implies, a fast metal machining procedure. Conventional machining of aluminum is done with cutter rotations of roughly 3000 revolutions per minute (RPM); high-speed machines have rotations of 10,000 to 40,000 RPM with considerably higher metal removal rates than conventional machining. One advantage of this technique is simply faster part fabrication and hence a reduction of machine operator hours per pound of part. A more fundamental advantage is that with multiaxis cutters running at high speeds, HSM can produce more complex unitized parts than can conventional machining. Unitized parts, as noted previously, save weight and assembly time.

HSM is also characterized by a significant reduction in machining forces and heat absorption by the part. It dramatically shifts the heat energy distribution from the cutter/workpiece to the chips. Because of the reduced heat buildup and force required of the cutter, the webs and flanges of the part can be thinner, thus saving weight.

High-Performance Machining of Titanium

High-performance machining (HPM) of titanium is essentially the same concept as HSM of aluminum but with significantly reduced feed rates and cutter speeds. The normal CNC machining rate for titanium is roughly 250 RPM. It is hoped that as a result of the improvements associated with HPM, rates of some 700 RPM can be achieved. This is still an immature technology with substantial development work required before it will be ready for factory use.

Hot Isostatic Press Investment Casting of Titanium

Another process experiencing more widespread use in making airframe parts is HIP investment casting of titanium. The first step in this investment casting process is preparing a wax model of the part. This can be done by stereolithography[5] or by using a hard mold. A

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[5] Stereolithography is a process that produces a three-dimensional object from a 3D CAD file by using a computer-controlled laser to cure a photosensitive resin layer by layer.

ceramic mold is then prepared by dipping the wax model in a ceramic slurry. The mold is then dried, baked, and fired, during which the wax is melted out of the mold. (The term "lost wax" is sometimes used to describe this process.) Molten metal is subsequently poured into the ceramic mold. The part in the mold is then subjected to very high temperature (1700°F to 1750°F) and high pressure (around 15,000 psi) in a cycle lasting as long as eight hours. This is the "hipping" process, which is meant to force micropores out of the part, thereby increasing strength (and preventing the porosity problem we discussed in regard to conventional casting). Some machining or chemical milling is still required. HIP investment casting costs more per pound than the traditional investment casting process (see the estimates in Chapter Four). However, significant weight savings should occur in each part as allowables are adjusted to reflect the higher confidence in part integrity (i.e., reduced porosity). Finally, as with conventional castings, HIP-cast parts can be highly unitized, with the associated savings.

Laser Forming of Titanium

Laser forming of titanium is a technology now in development; it has not yet been used in airframe part production. In this process, a computer-controlled laser system fuses titanium powder into part preforms in an inert atmosphere.[6] The preform is then heat treated and machined into final net shape. This new technology has the potential for excellent mechanical properties and a very low BTF ratio.

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[6] This information is based on AeroMet Corporation's presentation at the Defense Manufacturing Conference, December 1999, in Miami Beach, FL.

Chapter Four

AIRFRAME COST INFORMATION

This chapter presents our results on the cost implications of using different materials to produce airframes. It is based on industry data that we collected of two primary types. The first was an industry survey on the relative costs of producing airframe structures from various materials. This survey followed the same format as that in Resetar, Rogers, and Hess (1991). It collected estimates on the relative costs of seven materials by six labor categories, as described below. The second type of data we collected consisted of actual recurring manufacturing labor hours for a large sample of parts. These data allowed us to estimate the cost implications of part geometric complexity and manufacturing technique as well as material type. The data consisted primarily of actual manufacturing cost data from production runs. For some newer manufacturing techniques that are not yet in widespread use, however, the data were from experiments or demonstrations specifically designed to measure the costs of using different techniques. The implications of these two kinds of data are discussed below. Finally, we collected data on raw material costs and BTF ratios, discussed at the end of the chapter.

REVISITING THE RESETAR, ROGERS, AND HESS STUDY

We begin the chapter with the results of the industry survey. We first review the results of Resetar, Rogers, and Hess, who performed a similar survey in the late 1980s. This survey first asked industry to estimate, for each of several material and labor categories, the hours per pound needed to produce airframe structure from the given material at the time of the survey (i.e., the late 1980s). The ground rules for these estimates were as follows:

- Labor hours included all structural fabrication and assembly up through the airframe group level (wing, fuselage, and empennage). They did not include final assembly and checkout or any subsystem installation.
- Labor hours represented cumulative average values for a quantity of 100 aircraft and a finished material weight of 1000 pounds.
- Responses assumed whatever mix of material forms (e.g., tape versus fabric, sheet versus plate) and fabrication techniques that were in use for each company at the time of the survey.

Results from this part of the survey are given in Table 4.1. Labor categories included the following:

- Nonrecurring engineering labor
- Nonrecurring tooling labor
- Recurring engineering labor
- Recurring tooling labor
- Recurring manufacturing labor
- Recurring quality assurance labor.

Results are given as the *ratio* of aggregate airframe hours per pound for the given labor category/material combination to hours per pound for aluminum for that labor category. Thus, all entries in the first row of Table 4.1 are unity.

The recurring manufacturing column, for example, has the following interpretation. Recurring manufacturing hours per pound of titanium structure were estimated to be 60 percent higher than hours per pound of aluminum and 80 percent higher for carbon-epoxy. Similarly, recurring tooling hours per pound of titanium structure were estimated to be 90 percent higher than hours per pound of aluminum and 120 percent higher for carbon-epoxy.

Table 4.1

Late 1980s Cost Ratios from Resetar, Rogers, and Hess (1991)[a]

Material	Non-recurring Engineering	Non-recurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.0	1.0	1.0	1.0	1.0	1.0
Aluminum-lithium	1.1	1.2	1.1	1.1	1.1	1.1
Titanium	1.1	1.4	1.4	1.9	1.6	1.6
Steel	1.1	1.1	1.1	1.4	1.2	1.4
Carbon-epoxy	1.4	1.6	1.9	2.2	1.8	2.4
Carbon-BMI	1.5	1.7	2.1	2.3	2.1	2.5
Carbon-thermoplastic	1.7	2.0	2.9	2.4	1.8	2.6

[a] Late 1980s aluminum = 1.0.

The survey then went on to ask industry to forecast what the hours-per-pound numbers would be in the mid-1990s time frame. The first two ground rules were the same; for the third, industry was asked to assume whatever mix of material form and fabrication techniques they expected in the mid-1990s. Table 4.2 shows these results, given as the ratio of hours per pound to *late 1980s* aluminum hours per pound. Thus, the aluminum numbers are no longer necessarily unity. Indeed, as Table 4.2 shows, industry respondents expected a 10 percent improvement in hours per pound of aluminum structure in all recurring labor categories. Because the denominator of the ratio—1980s aluminum hours per pound—was held constant, all other figures in Tables 4.1 and 4.2 can be compared to reveal expected productivity changes in any category. A comparison of the two tables shows that no productivity decreases were expected (all numbers in Table 4.2 are less than or equal to corresponding numbers in Table 4.1), and in most categories productivity was expected to rise. For example, recurring manufacturing hours per pound of titanium structure were expected to fall by 12.5 percent (1.4 versus 1.6), and hours per pound of carbon-epoxy were expected to decrease by 16.7 percent (1.5 versus 1.8).

Table 4.2

Expected Mid-1990s Cost Ratios from Resetar, Rogers, and Hess (1991)[a]

Material	Non-recurring Engineering	Non-recurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.0	1.0	0.9	0.9	0.9	0.9
Aluminum-lithium	1.0	1.1	1.0	1.1	1.0	1.0
Titanium	1.0	1.4	1.2	1.6	1.4	1.4
Steel	1.1	1.1	1.1	1.4	1.2	1.4
Carbon-epoxy	1.2	1.4	1.5	2.0	1.5	1.8
Carbon-BMI	1.3	1.5	1.6	2.1	1.8	2.1
Carbon-thermoplastic	1.4	1.6	1.4	2.4	1.6	2.0

[a] Late 1980s aluminum = 1.0.

CURRENT STUDY RESULTS: AGGREGATE AIRFRAME DATA BY FUNCTIONAL LABOR CATEGORY

In the survey we conducted, we asked industry respondents to estimate what their actual mid-1990s experience had been using the same ground rules as Resetar, Rogers, and Hess. The next sections show the results of the survey, with results again expressed as a ratio of hours per pound to late 1980s aluminum hours per pound. Thus, comparisons with the expected mid-1990s values from the earlier survey are direct. The companies that responded to the survey are as follows:

- Boeing
- Hexcel (composites information only)
- Lockheed Martin
- Northrop Grumman
- Sikorsky (composites information only)

For some companies, we received more than one set of estimates from different divisions at different locations.

A section follows below for each of the six labor categories included in the survey. For each category, we present a table with the average value of the cost ratio for each material as well as the range of responses.

Nonrecurring Engineering

Nonrecurring engineering includes the engineering hours spent developing the airframe. We note that such hours are incurred throughout an aircraft program's life, since design change effort, which often continues until program termination, is included in nonrecurring engineering. Specifically, nonrecurring engineering includes hours expended for (1) design, consisting of trade studies, stress analysis, aerodynamic performance analysis, weight and balance analyses, and airframe integration; (2) wind-tunnel models and mockups; (3) laboratory testing of components and subsystems and static and fatigue articles; (4) preparation and release of drawings; and (5) process and material qualification. Excluded are engineering hours not directly attributable to the airframe: flight testing, ground-handling equipment, spares, and training equipment.

Table 4.3 shows that on average, nonrecurring engineering hours were estimated to be 30 to 40 percent higher for composites than for metals. Some of the reasons for this difference were discussed in Chapter Two. Composite part designers must consider the direction-

Table 4.3

Late 1990s Nonrecurring Engineering Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	1.00	1.00/1.00
Aluminum-lithium	1.00	1.00/1.00
Titanium	1.00	1.00/1.00
Steel	1.05	1.00/1.10
Carbon-epoxy	1.33	1.00/2.00
Carbon-BMI	1.38	1.10/2.00
Carbon-thermoplastic	1.33	1.20/1.40

[a] Late 1980s aluminum = 1.00.

tionality of fiber alignment and how that property should be adjusted to load patterns; designers must choose the number of plies in a part and their individual shape and alignment and must prepare instructions for ply cutting and layup. There are also increased material qualification costs if there is no extensive industry experience with the specific material. Additional design time is required to analyze and specify bonding and assembly techniques and to choose the degree of unitization—i.e., to determine how large and complex to make integral structures.

Nonrecurring Tooling

Tooling refers to the tools designed solely for use on a particular airframe program and includes layup tools, autoclave tools, assembly tools, dies, jigs, fixtures, work platforms, and test and checkout equipment. Not included are general-purpose tools or machinery such as automated cutting machines, automated fiber placement machines, autoclaves, NDI/T equipment, milling machines, presses, routers, drilling equipment, and the like, whose cost would be captured in factory overhead rates. Nonrecurring tooling hours are those required to plan fabrication and assembly operations and to design, fabricate, assemble, and install the initial set of tools as well as all duplicate tools required for the planned rate of production. Nonrecurring tooling costs occur not only during development but also during the production program if rate or airframe changes require new tools. Survey results appear in Table 4.4.

Table 4.4

Late 1990s Nonrecurring Tooling Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.96	0.90/1.00
Aluminum-lithium	1.10	1.10/1.10
Titanium	1.44	1.30/1.80
Steel	1.08	1.00/1.10
Carbon-epoxy	1.38	1.00/1.80
Carbon-BMI	1.48	1.08/1.80
Carbon-thermoplastic	1.68	1.30/2.40

[a] Late 1980s aluminum = 1.00.

On average, nonrecurring tooling hours were estimated to be 40 to 70 percent higher for composites than for aluminum. This difference is attributable to tool exposure to high temperatures and pressures in the autoclave; requirements to build tools with appropriate CTEs that will not lead to unacceptable part spring-back during cure; tool complexity resulting from the complex shapes of unitized structures; and the difficulty of working with composite tooling material. Thermoplastic tooling hours are the highest owing to the high autoclave processing temperatures involved. Tools used to machine titanium are often made of very strong and very hard material such as carbide, which is difficult to work and thus requires increased hours for fabrication.

Recurring Engineering

Table 4.5 shows recurring engineering hours, which represent the effort required to initiate, analyze, and implement minor engineering changes and product improvements that do not specifically change product form, fit, or function. Some of these improvements may enhance performance, but most are done for producibility reasons. This category also includes any modifications to CAD/CAM software. (Major changes that do affect product form, fit, or function are documented in formal Engineering Change Orders [ECOs], and the hours spent on these changes would be counted as nonrecurring regardless of when in the program they were incurred.)

Table 4.5

Late 1990s Recurring Engineering Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.92	0.77/1.00
Aluminum-lithium	1.00	1.00/1.00
Titanium	1.09	0.91/1.47
Steel	1.08	0.91/1.23
Carbon-epoxy	1.68	1.00/2.40
Carbon-BMI	1.75	1.00/2.40
Carbon-thermoplastic	1.60	1.00/1.93

[a] Late 1980s aluminum = 1.00.

Recurring engineering labor associated with composites was estimated to be 60 to 75 percent more than that for metals. We do not believe that the minor difference in the averages for epoxy and BMI is significant because during our interviews, industry engineers said that the recurring engineering efforts associated with the two materials were equal.

Recurring Tooling

Recurring or sustaining tooling (Table 4.6) refers to all labor associated with tool cleaning, repair, maintenance, rework, modification, and replacement.

Recurring tooling labor for composites is higher than that for aluminum because the tools used to form composite parts go into the autoclave. They must therefore be cleaned after every cure, which is a time-consuming process. These tools also sustain extensive temperature and pressure cycling in the autoclave, resulting in flaws that can require extensive repair. Tools for composites are complex and must be replaced more often than those required for metal manufacturing, also as a result of the rigors of the autoclave.

Tools used to machine titanium require replacement more often than do those used to machine aluminum. Carbide cutters require more frequent maintenance and replacement than do their counterparts used on aluminum. Moreover, titanium requires complicated tools, since titanium parts are on average more complex than aluminum parts.

Table 4.6

Late 1990s Recurring Tooling Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.93	0.82/1.00
Aluminum-lithium	1.07	1.00/1.11
Titanium	1.44	0.91/2.03
Steel	1.25	0.91/1.46
Carbon-epoxy	1.62	0.82/2.38
Carbon-BMI	1.77	0.82/2.49
Carbon-thermoplastic	1.86	0.82/2.61

[a] Late 1980s aluminum = 1.00.

Since the nonrecurring tooling hours used to *make* the original tools for use with both composites and titanium are relatively high, the recurring hours used to *replace* them are also high.

Recurring Manufacturing

Recurring manufacturing (Table 4.7) includes all hours expended on production scheduling, fabrication, processing, reworking, modification, minor assembly, and major assembly of the airframe structure.

As Table 4.7 shows, the manufacturing hours required to make aluminum-lithium parts are slightly higher than those required for aluminum, largely because the chips resulting from machining must be segregated from regular aluminum chips and carefully disposed of for health and environmental reasons. Titanium machining is considerably more time-consuming than aluminum machining because it requires much lower spindle feed and speed rates. This is primarily due to the heat generated at the tool as a result of the low thermal conductivity of titanium alloys. Finally, composites use much more manufacturing labor than does aluminum because they require a significant amount of handling during the fabrication process, as described in Chapter Three. During our discussions with industry, most technical personnel said that the manufacturing hours required for toughened epoxies and BMI should be the same, but the survey results showed roughly a 7.5 percent penalty for BMI. This difference

Table 4.7

Late 1990s Recurring Manufacturing Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.90	0.82/1.00
Aluminum-lithium	1.00	1.00/1.00
Titanium	1.61	1.18/2.36
Steel	1.27	1.09/1.61
Carbon-epoxy	1.58	1.00/2.36
Carbon-BMI	1.71	1.00/2.52
Carbon-thermoplastic	1.77	1.09/2.82

[a] Late 1980s aluminum = 1.00.

might be due to the fact that not all respondents had significant experience with the new BMI materials and may have based their response on older BMI matrices that were more difficult to handle.

In the 1980s, some industry analysts predicted that thermoplastics would be the composite material of the future. Indeed, early F-22 designs and one early JSF design included large amounts of thermoplastic, but these were significantly reduced in later configurations. Thermoplastics are currently used in military aircraft only in areas that require significant toughness, such as in underbody doors and access panels (Harper-Tervet et al., 1997). As discussed in Chapter Two, thermoplastics are hard to work with in that they lack drapability and tack. In addition, some thermoplastics require solvents to soften them for forming. These solvents must be recaptured during the curing process and, owing to their toxic nature, disposed of carefully. This adds to the complexity and hours required for the layup, bagging, and autoclave curing processes.

Recurring Quality Assurance

Recurring quality assurance (QA) includes hours expended in the in-process and final inspection of tools, parts, subassemblies, and final assembly. It also includes the hours used for nondestructive testing, MRBs, and quality monitoring processes such as statistical process control (SPC), design of experiments (DOE), and the like. Industry practices for estimating QA hours vary from direct time recording to estimation by multiplying recurring manufacturing hours by a QA "factor."

Metal parts are inspected for dimensional tolerances and surface finish. Using a fluorescent dye penetrant technique, they are inspected for cracks and other physical imperfections.

The estimates for composite QA hours per pound (Table 4.8) were significantly higher than those for aluminum for the following reasons:

- Increased inspection hours are required because of composite failure modes not present in metals, such as ply delamination, foreign object inclusion, and resin and fiber ratio imbalance.

Table 4.8

Late 1990s Recurring Quality Assurance Cost Ratios[a]

Material	Average	Minimum/Maximum
Aluminum	0.91	0.83/1.00
Aluminum-lithium	1.06	1.00/1.18
Titanium	1.30	1.00/1.83
Steel	1.20	1.00/1.50
Carbon-epoxy	2.04	1.09/3.17
Carbon-BMI	2.08	1.09/3.33
Carbon-thermoplastic	2.18	1.09/3.50

[a] Late 1980s aluminum = 1.00.

Other failure modes, such as porosity and loss of bond integrity, require more testing in composites than in metals.

- Ultrasonic inspection techniques used on composites are more labor intensive than X-ray, liquid penetrant, and other techniques used for aluminum.
- There are inspection requirements for composite surface finish problems, which result from the less durable tools used to form composites.
- There are higher inspection failure rates for composites than for metals, leading to increased material disposition activities, including additional hours for MRB- and scrap-related activities.

Some parts of industry and government are still wary of composites and impose more stringent QA procedures on them than on metals.

COMPARISON TO 1980s SURVEY RESULTS

Table 4.9 summarizes the results from the above sections in the same format as Tables 4.1 and 4.2. It is of interest to compare these results with those projected for the mid-1990s in Resetar, Rogers, and Hess. Table 4.10 displays such a comparison.

Table 4.9

Late 1990s Cost Ratios[a]

Material	Nonrecurring Engineering	Nonrecurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.00	0.96	0.92	0.93	0.90	0.91
Aluminum-lithium	1.00	1.10	1.00	1.07	1.00	1.06
Titanium	1.00	1.44	1.09	1.44	1.61	1.30
Steel	1.05	1.08	1.08	1.25	1.27	1.20
Carbon-epoxy	1.33	1.38	1.68	1.62	1.58	2.04
Carbon-BMI	1.38	1.48	1.75	1.77	1.71	2.08
Carbon-thermoplastic	1.33	1.68	1.60	1.86	1.77	2.18

[a] Late 1980s aluminum = 1.0.

Table 4.10

Comparison of Late 1990s Cost Ratios to Projected Mid-1990s Cost Ratios from Resetar, Rogers, and Hess (1991)[a]

Material	Nonrecurring Engineering	Nonrecurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.00/*1.0*	0.96/*1.0*	0.92/*0.9*	0.93/*0.9*	0.90/*0.9*	0.91/*0.9*
Aluminum-lithium	1.00/*1.0*	1.10/*1.1*	1.00/*1.0*	1.07/*1.1*	1.00/*1.0*	1.06/*1.0*
Titanium	1.00/*1.0*	1.44/*1.4*	1.09/*1.2*	1.44/*1.6*	1.61/*1.4*	1.30/*1.4*
Steel	1.05/*1.1*	1.08/*1.1*	1.08/*1.1*	1.25/*1.4*	1.27/*1.2*	1.20/*1.4*
Carbon-epoxy	1.33/*1.2*	1.38/*1.4*	1.68/*1.5*	1.62/*2.0*	1.58/*1.5*	2.04/*1.8*
Carbon-BMI	1.38/*1.3*	1.48/*1.5*	1.75/*1.6*	1.77/*2.1*	1.71/*1.8*	2.08/*2.1*
Carbon-thermoplastic	1.33/*1.4*	1.68/*1.6*	1.60/*1.4*	1.86/*2.4*	1.77/*1.6*	2.18/*2.0*

[a] Late 1980s aluminum = 1.0. Late 1990s cost ratios are the top entry; mid-1990s cost ratios expected in the late 1980s are the bottom entry (in italics).

The results of the current survey show no significant differences from the 1980s projections for nonrecurring engineering and nonrecurring tooling.

The recurring engineering results of the current survey for aluminum, aluminum-lithium, and steel are also roughly the same as the 1980s projections, and the results for titanium indicate lower recurring engineering than had been forecast. Recurring engineering estimates for composites are consistently higher than had been forecast in the 1980s; however, they are lower than the survey level *for* the 1980s. Thus, the productivity improvements that are estimated to have occurred are not as large as had been projected. (About a 35 percent productivity improvement had been projected, a roughly 25 percent improvement is evidenced in the survey.)

The recurring tooling estimates from the survey are almost uniformly lower than had been projected earlier, by about 20 percent.

The recurring manufacturing category makes up some 60 percent of all recurring labor hours, so it is the most important cost driver. The survey results for aluminum and aluminum-lithium do not differ from 1980s projections for them. Estimates for titanium and steel are higher than had been projected and are in fact slightly above the survey estimates of cost for those materials in the 1980s. Thus, manufacturing productivity for making airframes from these materials is estimated to have stagnated at best. A reasonable explanation for this finding lies in the dramatic reduction in military aircraft production that occurred in the 1990s, which lowered opportunities for economies of scale. This might have been expected to have hit manufacturing the hardest, since development activity did not decrease as much and since development has higher engineering and tooling content. (See Chapter Five for more detail on how labor hours by category change as a program proceeds.)

Manufacturing productivity in composites is assessed to have changed its pattern. Carbon-epoxy is assessed to have improved since the 1980s by 12 percent rather than by the 17 percent that had been forecast.[1] Carbon-epoxy and carbon-BMI are now assessed to

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[1] Of course, it may well be that this difference merely reflects variations in individual judgment rather than a true consensus that realized productivity is less than had been

be closer in cost than had been projected, with BMI productivity improvement somewhat higher than projected (20 versus 15 percent). Thermoplastics are estimated to have had no productivity improvement, which is no doubt associated with the fact that their anticipated penetration into the market has not occurred. More analysis would be needed to disentangle the "chicken-and-egg" issues here; lack of productivity growth would discourage use, but some of the productivity growth was expected to occur as experience and hence learning accumulated with thermoplastics. In any case, the current survey's picture of relative composite costs is different from the earlier one. This survey shows both epoxy and BMI improving in productivity and thermoplastics stagnating, thus increasing in cost relative to epoxy and BMI. By contrast, the earlier survey showed epoxy and thermoplastics to be roughly equal in cost, with BMI being the relatively more expensive material.

As discussed earlier, during our industry visits many industry analysts and engineers said that manufacturing costs for toughened carbon-epoxy composites and carbon-BMI composites were the same. Why did the formal survey fail to yield the same result? This discrepancy may be due to a lack of BMI experience on the part of some of the respondents or to the use of data reflecting older BMIs, which were more difficult to use in fabrication. BMI is still not as widely used as epoxies.

QA results show an increase for carbon-epoxy and carbon-thermoplastics from what had been projected, although again, these estimates are still better than those *for* the 1980s. Thus, productivity growth is assessed to have occurred, but not as rapidly as had been projected. BMI figures approximate the projected levels, again reflecting *relative* improvement in this material from what had been projected. Metals are in general seen to have improved more in QA productivity than had been projected. This is an interesting reversal

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expected. We do not think any meaningful statistical significance levels can be assigned to this survey process, since the estimates were derived in a series of meetings between RAND researchers and industry with much discussion on clarifying ground rules and definitions. This was also the case for the Resetar, Rogers, and Hess survey. We discuss differences between the surveys only when it is our judgment that these differences are meaningful, but these judgments are inherently subjective, are based on the full content of our interactions with industry, and cannot be formally justified.

from the manufacturing results, which showed relatively little improvement, since manufacturing and QA hours are often thought to move together. (Indeed, as mentioned above, many companies estimate QA hours simply as a fraction of manufacturing hours.)

CURRENT STUDY RESULTS: PART-LEVEL DATA BY MATERIALS, MANUFACTURING PROCESS, AND PART GEOMETRIC COMPLEXITY

We now turn to the statistical analysis of part cost data we received from various companies. We believed that while the survey results were useful, it would also be useful to analyze real data on parts made of varying materials and to make inferences about the cost implications of material composition based on that analysis. The companies we visited agreed and generously supplied us with the data required to make such analysis. These data were provided to us on a proprietary basis, so we cannot identify any specific costs but instead report average results. These observations are all from the 1990s.

As discussed above, the data came in two forms. Most were actual manufacturing cost data from production experience. For some newer manufacturing techniques that are not now in widespread use, however, the data were derived from experiments or demonstrations specifically designed to measure the costs of using different techniques. How well the results of such studies represent what would actually happen if the techniques were used on the factory floor in a production environment is uncertain, and the results should be interpreted with that caveat in mind. All results will be identified as based on either "manufacturing data" or "experiment/demonstration data."

Table 4.11 shows the sources of the "manufacturing data" part data. We had the advantage of being able to disaggregate the data both by part geometric complexity and by manufacturing technique. Thus, we can identify separate cost ratios for these. Unfortunately, only recurring manufacturing labor data were sufficient to allow for analysis; the other labor categories could not be estimated using these data.

Table 4.11

1990s Part-Level Manufacturing Data

Program	Composite Manufacturing Labor Data	Metal Manufacturing Labor Data	Contractors
F-22	Yes	Yes	Alliant Techsystems, Boeing, GKN Westland, Lockheed Martin
F/A-18 E/F	Yes	Yes	Alliant Techsystems, Boeing, Northrop Grumman
Comanche	Yes	No	Sikorsky
V-22	Yes	No	Alliant Techsystems, Bell Textron, Boeing
F-16	Yes	Yes	Lockheed Martin

Part Geometric Complexity

It is intuitive that the cost of parts made of either metal or composites should be a function of the complexity of the shape of the part. To empirically estimate such an effect, we divided airframe parts into four geometric complexity categories: simple, medium, complex, and very complex.

Simple parts are defined here as monolithic, minimally contoured, or flat parts. Examples include covers, doors, fittings, flat skins, and panels.

Medium parts are defined as surfaces with moderate curvature and thickness, with stiffeners and cutouts, or parts with a moderate amount of unitization. Examples include chines, contoured skins, equipment trays, floor panels, fuel decks, fuel tank sidewalls, and stiffened skins.

Complex parts are defined as surfaces with complex curvatures or primary internal structures, or parts with an extensive amount of unitization or varying thickness. Examples include beams, bulkheads, frames, inlet ducts, keels, longerons, multicurvature skins, pylons, ribs, spars, and webs.

Very complex parts are defined as those with complex geometry or extensive dimensional control and tolerance requirements. Examples include intake diverter lips, edges, hubs, inlet lips, and spindles.

This taxonomy is meant to be exhaustive. Some technical and engineering judgment is obviously required to assign any given part to one of these four bins. We thus categorized all the parts for which we received cost data. We reviewed the categorization with some outside experts, but it remains true that the validity of our statistical results depends on the quality of our categorization judgments.

Table 4.12 illustrates the part categories.

Methodology

We also categorized the part data we received by material and by fabrication process (categories shown in tables that follow). For each part geometric complexity/material/fabrication process combination, we calculated average recurring manufacturing hours per pound. To account for learning effects, we normalized the data to cumulative average cost (CAC) for quantity 100, and we also normalized to a part weight of 15 pounds. The part/labor hour data we received included part weight and cumulative production level, so this normalization was possible. Estimates of learning rates and weight-sizing factors also come out of these normalization calculations and are reported below.

The raw data we used consisted of part fabrication hours per pound only. To facilitate use of the cost ratios for overall airframe cost estimates (described in Chapter Six), we converted these data to an “all-airframe labor basis” by adding an estimate of assembly hours per pound—3.05 hours per pound (CAC 100) in this case—to all estimates of part hours per pound.[2] Thus, the cost ratios in Tables 4.13,

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[2] This assembly-hours-per-pound estimate (CAC 100), along with an estimate that assembly hours would be 40 percent of total recurring manufacturing hours for an all-aluminum aircraft (also CAC 100), was based on averages of some industry data that had such a categorization. These data, like the part cost data, were proprietary and were provided to us under an agreement that we would use only averages.

Table 4.12

Part and Geometric Complexity Cross-Reference Matrix

Part	Simple	Medium	Complex	Very Complex
Beams			X	
Bulkheads			X	
Chines		X		
Contoured skins		X		
Covers	X			
Diverter lips				X
Doors	X			
Edges				X
Equipment trays		X		
Fittings	X			
Flat skins	X			
Floor panels		X		
Frames			X	
Fuel decks		X		
Fuel tank sidewalls		X		
Hubs				X
Inlet ducts			X	
Inlet lips				X
Keels			X	
Longerons			X	
Multicurvature skins			X	
Panels	X			
Pylons			X	
Ribs			X	
Spars			X	
Spindles				X
Stiffened skins		X		
Webs			X	

4.14, and 4.15 are precisely defined as follows: Let x be the estimated recurring manufacturing fabrication hours per pound required for a part of a given geometric complexity/material/fabrication process combination. The quantity 4.60 hours per pound (CAC 100) is our estimate, based on our data, of the recurring manufacturing fabrication hours per pound required for a medium-complexity aluminum part made by conventional machining. The *cost ratio* for the given geometric complexity/material/fabrication process combination is then $(x + 3.05)/7.65$. The quantity 7.65 is the sum of 4.60 and 3.05. Thus, cost ratios are defined as the ratio of "all-airframe labor basis" hours, where these hours include both fabrication and a fixed estimate of assembly hours. Ratios are relative to medium-complexity aluminum parts made with conventional machining.[3]

The companies that provided us with part cost data were as follows:

- Alliant Techsystems
- Bell Textron
- Boeing
- GKN Westland
- Lockheed Martin
- Northrop Grumman
- Sikorsky.

Results

Table 4.13 shows recurring manufacturing labor hour cost ratios for conventionally machined metals. These data show the expected pattern. Part costs increase with geometric complexity, since more complex parts require more machining than simple parts, and aluminum is the least costly material. The cost penalties due to complexity are larger than those due to material differences.

Table 4.14 shows cost ratios for metals produced using advanced methods. As one would expect, part labor hour costs are lower for the advanced techniques than for the conventional methods. This relative advantage tends to increase for more complex parts, partly because unitization opportunities are greater. The advantage is greater for aluminum and aluminum-lithium HSM than for titanium HPM.

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[3] Conventional machining is currently the dominant aluminum fabrication process. For example, 46 percent of the aluminum used in the F-16 structure is conventionally machined.

Table 4.13

1990s Cost Ratios Based on Part Data Analysis: All-Airframe Labor Basis, Conventionally Machined Metal[a,b]

Material/Fabrication Process	Simple	Medium	Complex	Very Complex
Aluminum/conventional machining	0.7	1.0	1.5	2.3
Aluminum-lithium/conventional machining	0.7	1.0	1.6	2.5
Titanium/conventional machining	0.7	1.2	1.7	2.9
Steel/conventional machining	0.7	1.1	1.8	2.9

[a] 1990s medium-complexity, conventionally machined aluminum = 1.0.

[b] Based on manufacturing data except for aluminum-lithium, which is based on experiment/demonstration data.

Table 4.14

1990s Cost Ratios Based on Part Data Analysis: All-Airframe Labor Basis, Advanced Manufacturing Metal[a,b]

Material/Fabrication Process	Simple	Medium	Complex	Very Complex
Aluminum/HSM	0.6	0.8	1.0	1.5
Aluminum-lithium/HSM	0.6	0.8	1.1	1.6
Titanium/HPM	0.7	1.1	1.5	2.5
Titanium/HIP investment casting	Not available	Not available	1.0	Not available

[a] 1990s medium-complexity, conventionally machined aluminum = 1.0.

[b] Based on manufacturing data except for aluminum-lithium/HSM and titanium/HPM, which are based on experiment/demonstration data.

Table 4.15

1990s Cost Ratios Based on Part Data Analysis: All-Airframe Labor Basis, Composites[a,b]

Fabrication Process	Simple	Medium	Complex	Very Complex
Hand layup	1.3	1.8	2.2	3.0
Hand layup with OLPA	1.1	1.6	1.9	2.6
Automated fiber placement	0.7	1.3	1.7	Not available
Resin transfer molding	Not available	Not available	1.4	2.3

[a] 1990s medium-complexity, conventionally machined aluminum = 1.0.

[b] Based on manufacturing data except for OLPA, which is based on experiment/ demonstration data.

Table 4.15 shows cost ratios for composites. The data we received showed no systematic differences between carbon-epoxy and carbon-BMI, so we have combined the two in Table 4.15. (This is consistent with what many in industry told us if not with the survey results, as noted above.) We received no data for thermoplastics, so they are not included. Table 4.15 shows the expected results: hours per pound increase with complexity and fall with automation. The fiber placement factor for the simple category represents a tape layup machine; the medium and complex factors represent a tow/contoured tape placement machine. We stated above that the RTM process is most suitable for internal primary structure and for parts with strict dimensional tolerances and complex geometry. The data reflected this, as we received RTM data only for complex and very complex parts. One implication of Tables 4.13 through 4.15 is that, overall, part geometric complexity is a more important cost driver than material or process.

We asked industry for part-level cost data for the other labor categories: tooling, engineering, and quality assurance. However, we obtained little such data because most companies did not keep part-level data for those categories. Many companies did not collect any data by part for the nonmanufacturing labor categories but instead used standard factors based on manufacturing hours to estimate these categories.

The information we did obtain indicated that nonmanufacturing labor requirements increase with part complexity in roughly the same way as do manufacturing requirements. However, the data are so sparse that we did not feel average numbers would be reliable, so we do not show any. Our judgment would be that modifying nonmanufacturing ratios for part complexity proportional to manufacturing ratios would be a reasonable procedure, but this should be viewed as a hypothesis rather than as a finding of the study. On the basis of the little data we have and our conversations with industry, we would not modify nonmanufacturing ratios based on manufacturing technique, but this too is merely a hypothesis. We do not have sufficient data to justify more definitive statements about how nonmanufacturing hours vary with part complexity or manufacturing technique.

COST IMPROVEMENT SLOPES

One of the most well-known properties of aircraft production lies in the reduction of labor hours per pound that occurs as cumulative production increases—a phenomenon also called "learning by doing."[4] This is a result not only of workers "learning" the fabrication and assembly processes better but also of manufacturing and engineering planning improvements and producibility innovations. The part data we received allowed us to calculate cost improvement slopes by material and manufacturing process. However, there were not enough data to yield confident estimates of differences in learning rates by part geometric complexity; this is an important area for further research.

Table 4.16 shows estimated cost improvement slopes for four fabrication categories.[5] We estimate that all metal fabrication and composite hand layup fabrication have slopes of 86 percent, while the two primary composite automation techniques have a lower rate of

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[4] Among the early references to this are Asher (1956) and Wright (1936). A good introduction to learning theory can be found in Lee (1997). A recent study that estimates both learning and "forgetting" effects in commercial aircraft manufacturing is Benkard (2000).

[5] We use "unit learning" theory in this report. (See Lee, 1997, for a discussion of various approaches to modeling learning.) A "cost improvement slope" of x% indicates that each time cumulative production doubles, unit cost falls $(100 - x)$%.

learning of 90 percent. This can be paraphrased in the statement "machines don't learn as fast as people." It reflects the fact that because automated processes must initially be carefully designed in order to program the machines, such processes have less potential room for learning than do manual processes, which are generally described only verbally during airframe development. As production occurs, workers learn the most efficient routines through trial and error.

The figure in the table for "all-manufacturing" labor for metals and hand-laid-up composites—80 percent—is based on the airframe CERs described in Chapter Five. The 71 percent slope for assembly is derived from the assumption that, using the estimate discussed above, 60 percent of hours are fabrication and 40 percent assembly. As discussed below, we assume in this study that assembly labor required is independent of manufacturing technique for parts, so we apply the 71 percent across Table 4.16. The all-manufacturing slope of 81 percent for automated composites is then derived from these figures. We took into account the 51 percent reduction in fabrication hours that occurs when automated techniques are used, based on Table 4.15.

WEIGHT-SIZING SLOPES

Another well-known property of aircraft production is the reduction of part fabrication labor hours per pound that occurs as part weight increases. The magnitude of this effect is represented by a "weight-sizing factor," also known as an ARCO factor.[6] Table 4.17 shows by fabrication technique the ARCO factors we estimated from the part data.

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[6] ARCO is an acronym for Aircraft Resources Control Office, which was the agency that controlled aircraft production during World War II. ARCO factors are similar to cost improvement slopes. An ARCO factor of x% indicates that each time part weight doubles, labor hours per pound fall $(100 - x)$%.

Table 4.16

Cost Improvement Slopes (in percentages)

Process	Fabrication Slope	Assembly Slope	All-Manufacturing Slope
Composite—hand layup	86	71	80
Composite—fiber placement	90	71	81
Composite—RTM	90	71	81
Metal—all machining	86	71	80

Table 4.17

Weight-Sizing (ARCO) Factors

Process	Labor Weight-Sizing Factor (%)
Composite—hand layup	75
Composite—fiber placement	80
Composite—RTM	75
Metal—machining	75

MATERIAL COSTS

Two main elements determine the total cost of material: raw material cost and BTF ratios. We collected data on these elements in our discussions with industry and present average results here. All prices are in dollars of FY2000 purchasing power. We note that raw material prices fluctuate frequently; thus, anyone doing cost-estimating work involving such prices must check current market conditions, as the prices quoted here may well have changed.

Raw Material Costs

Composite raw material costs depend on fiber type, fiber form, resin type, and the size of the buy. Table 4.18 shows our estimates of FY2000 prepreg prices as a function of these four factors. As discussed in Chapter Two, composites can be purchased in the form of unidirectional tape or fabrics. Table 4.18 shows that fabrics are more expensive per pound, primarily as a result of the additional labor

Table 4.18

Composite Prepreg Costs[a]

Material	Unidirectional Tape—Small Buy	Unidirectional Tape—Large Buy	Fabric—Small Buy	Fabric—Large Buy
SM/epoxy	85	50	115	60
IM/epoxy	120	90	185	125
SM/BMI	95	60	135	70
IM/BMI	145	100	185	135
SM/thermoplastic	195	155	255	195
IM/thermoplastic	250	190	295	230

[a] FY2000 dollars per pound.

required for weaving. Fiber quality is represented by the IM/SM distinction. IM is stiffer and is thus required for airframe parts that endure high stress. SM is acceptable for airframe parts that endure lower loads. Table 4.18 shows the price premium required for the higher-quality product. It also shows that BMI is currently more expensive than epoxy and that thermoplastic is more costly than both.

Composite costs can vary greatly with the size of the buy. Table 4.18 shows costs both for a relatively small buy (e.g., during the aircraft development phase—approximately 50,000 pounds in total) and for a large buy (e.g., during the production phase—approximately 250,000 pounds or more per year). For even larger buys, additional price reductions were said to be possible, but we have no data on this.

One of the factors affecting market prices for composites is the level of commercial (i.e., nongovernment) demand for the material. In the short run, increases in commercial demand tend to increase price, as more buyers bid for existing production capacity. In the long run, however, an increased market may lead to lower prices, as producers can often move to lower unit-cost production techniques if volume is sufficiently large. Industry-wide learning occurs with commercial market growth as well. It is not possible to predict with precision either the future level of commercial demand or the ultimate effect of such demand on price. This underscores the fact that cost analysts must watch the market or monitor current bill-of-material data to ensure that their raw material cost estimates reflect changing market conditions. In recent years, increased commercial use of composites has tended to lower price.

The state of industry competition also influences raw material cost. Through normal competitive processes, industries with a relatively large number of producers tend to be characterized by lower prices. Some of the composites of most interest to aircraft manufacturing are produced by a limited number of domestic companies, and currently there are legal restrictions on using foreign sources of composite material in military aircraft programs. Changes in competitive structure are hard to predict (depending partly on government policy) and can lead to changed prices, representing still another reason cost analysts must watch industry developments.

Metal raw materials are purchased in sheet and plate form.[7] Table 4.19 shows our estimates of FY2000 metal prices as a function of metal form and size of buy (using the same definition of "size of buy" as for composites). The differences in price between a small and a large buy tend to be less than those for composites because aerospace-grade metal is more similar to commercial-grade metal than is the case with composites. Thus, more sources are available to produce these metals, and a single large military aircraft buy may not be large in comparison to the overall market. Titanium cost has increased in recent years owing to its extensive use in sporting goods and to the geologic limitations on expanding titanium ore mining capacity. As mentioned above, the PPI for titanium rose 56 percent between 1987 and 1999, while that for all metals rose only 16 percent over the same time period.

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[7] Aircraft manufacturers are increasingly purchasing metal parts or near-net forms such as castings, extrusions, and forgings from other suppliers and thus are not purchasing the raw materials themselves.

Table 4.19

Metal Costs[a]

Metal Type	Metal Form	Small Buy	Large Buy
Aluminum	Plate	4	3
	Sheet	3	2.50
Titanium	Plate	22	21
	Sheet	28	23
Steel	Plate	3	2
	Sheet	2	2
Aluminum-lithium	Plate	16	12
	Sheet	16	12

[a] FY2000 dollars per pound.

BUY-TO-FLY

The BTF ratio (Table 4.20) is the ratio of total purchased material weight to the weight of the finished parts that are installed on the aircraft. Aggregate BTF ratios include material lost as a result of handling problems, machining and cutting processes, parts that are eventually scrapped, and other steps in the manufacturing process that cause material loss. Some companies calculate separate BTF ratios for each of these loss modes.

BTF ratios vary by manufacturing process. Composite automated processes result in a lower BTF than does hand layup. Material losses in hand layup include cutting table scrap, lost or misplaced plies, operator errors, and loss of prepreg by virtue of excessive time out of the freezer.[8] The estimated BTF for RTM is the same as that for hand layup, since the fabrication of a preform is comparable to a hand layup process in this respect. If a company buys RTM preforms from a supplier, then the BTF for that company would be much lower (roughly 1.2), since the only material loss would be from excess resin, trimming, or defective parts. (Of course, the supplier would incur the material losses associated with making the preform, which would presumably be reflected in the preform price.)

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[8] See Boeing (1999) for more details.

The BTF ratios of metals vary by manufacturing process and are independent of the type of metal. There is a great deal of variation in these ratios because different part types generate different levels of material loss. More geometrically complex parts and unitization, for example, lead to higher BTF ratios for metals.

Table 4.20

BTF Ratios

Fabrication Process	BTF Ratio	Remark
Composite—hand layup	2.5–1.9	Fabric and wide tape
Composite—fiber placement	1.5–1.3	Tape and tow
Composite—RTM	2.5–1.2	Fabric and preform
Metal—machining	20–16	NC[a] and HSM—independent of metal type
Metal—forming	3–2	Sheet forming, SPF/DB
Metal—casting	2–1	Results in near-net shape casting
Metal—forging	6–5	Independent of metal type
Metal—extrusion	3–2	Independent of metal type

[a] NC = numerically controlled.

Chapter Five

AIRFRAME COST-ESTIMATING METHODOLOGY

In this chapter, we discuss how the survey results presented in Chapter Four should be applied to CER estimation.[1] We then estimate CERs for recurring labor hours in fighter production. These estimates are based on the MACDAR database that was developed in a series of research projects by RAND, Tecolote Research, Incorporated, and Science Applications International Corporation (SAIC) and sponsored by the Air Force Cost Analysis Agency (AFCAA). We have also included a short discussion on nonrecurring CERs in Appendix D.

APPLICATION OF SURVEY COST RATIOS TO CERs

A primary objective of estimating cost ratios of the sort shown in Table 4.9 is to facilitate accurate estimation of CERs for labor hours required to build new aircraft. Many CERs, including those we estimate in this report, are for labor hours used to produce the whole airframe. In this case, *the cost ratios of Table 4.9 must be adjusted before they are valid for use with the CERs.* This is because, as the ground rules given in Chapter Four state, these cost ratios apply only to labor used for all structural fabrication and assembly up through the airframe group level (wing, fuselage, and empennage) and do not

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[1] CERs are equations in which cost is the left-hand-side (dependent) variable. On the right-hand side of the equation are explanatory (independent) variables such as cumulative and annual production and aircraft weight. With a data set of such variables, regression or some other statistical method can be used to estimate the parameters of the right side. Cost is usually measured as either dollars or labor hours; all CERs estimated in this report use labor hours.

apply to final assembly and checkout or to any subsystem installation. In a modern fighter aircraft, the latter two categories account for roughly 35 percent of recurring manufacturing labor, 13 percent of recurring and nonrecurring tooling, 40 percent of recurring quality assurance, and 57 percent of nonrecurring and recurring engineering.[2] These values must be accounted for in applying the cost ratios to CERs for all airframe labor.

Resetar, Rogers, and Hess (1991) proposed the following method for applying the cost ratios. Suppose there are M material types and L labor categories. Let C_l^m be the cost ratio associated with material m ($m = 1, \ldots, M$) and labor category l ($l = 1, \ldots, L$) (e.g., from Table 4.9, $C_{\mathit{rec.\ manu.}}^{\mathit{aluminum}}$ is 0.9). Let S_m be the share of material m in the airframe, with $\sum_{m=1}^{M} S_m = 1$.[3] Let σ_l be the share of category l labor hours associated with structural fabrication and assembly through the airframe group level. RRH then defined a weighted material cost factor for each labor category l, $(WMCF)_l$, as

$$(WMCF)_l = \sigma_l \sum_{m=1}^{M} S_m C_l^m + (1 - \sigma_l) \tag{5.1}$$

RRH proposed that $(WMCF)_l$ be used as a multiplicative factor on CERs.

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[2] See Resetar, Rogers, and Hess (1991), p. 71 and below.

[3] Since the list of materials in Table 4.9 is obviously not exhaustive, an "other" category is needed. In recent practice, the cost ratios for carbon-epoxy have been used for "other," since it encompasses many nonmetallic composites, including fiberglass. However, one should look at the specific material composition of any aircraft to be analyzed before making such a decision.

We use a modified cost ratio, γ_l^m, which is the ratio appropriate to apply to all airframe hours, not just group-level (fuselage, wing, empennage) hours. We define

$$\gamma_l^m = \sigma_l C_l^m + (1 - \sigma_l) \tag{5.2}$$

Then we note

$$\begin{aligned} (WMCF)_l &= \sigma_l \sum_{m=1}^{M} S_m C_l^m + (1 - \sigma_l) \\ &= \sum_{m=1}^{M} S_m \gamma_l^m \end{aligned} \tag{5.3}$$

The γ_l^m can thus be applied directly to calculate the multiplicative factors for all-airframe CERs. They are a good intuitive measure of the total airframe-hour penalty associated with using nonaluminum material rather than the penalty associated with just one part of hours.

Table 5.1 shows our estimates of the γ_l^m, the cost ratios appropriate for applying at the all-airframe labor level for the late 1990s based on our survey. They are related to the C_l^m of Table 4.9 by Equation 5.2. Values of σ assumed were 65 percent for recurring manufacturing labor, 87 percent for recurring and nonrecurring tooling, 60 percent for recurring quality assurance, and 43 percent for nonrecurring and recurring engineering.

The reader will note that this section has assumed that material type does not affect hours required for final assembly, checkout, and subsystem installation. We in fact make this assumption throughout the study. We have seen no data or report indicating that this assumption is wrong. In our discussions with industry and other experts, we raised this issue, and no one argued that the assumption was misleading. However, future research in this area should certainly be done with an open mind, and new information and data sets that emerge should be analyzed to test the continuing appropriateness of the assumption.

Table 5.1

Late 1990s Cost Ratios, All-Airframe Labor Basis[a]

Material	Non-recurring Engineering	Non-recurring Tooling	Recurring Engi-neering	Recurring Tooling	Recurring Manufac-turing	Recurring Quality Assurance
Aluminum	1.00	0.97	0.97	0.94	0.94	0.95
Aluminum-lithium	1.00	1.09	1.00	1.06	1.00	1.04
Titanium	1.00	1.38	1.04	1.38	1.40	1.18
Steel	1.02	1.07	1.03	1.22	1.18	1.12
Carbon-epoxy	1.14	1.33	1.29	1.54	1.38	1.62
Carbon-BMI	1.16	1.42	1.32	1.67	1.46	1.65
Carbon-thermo-plastic	1.14	1.59	1.26	1.75	1.50	1.71

[a] Late 1980s aluminum = 1.0.

STATISTICAL ANALYSIS OF THE RECURRING COSTS OF RECENT FIGHTERS

The MACDAR Database

MACDAR contains annual recurring labor hour data for the aircraft and years shown in Table 5.2. It should be noted that the "number of aircraft" figure is somewhat misleading with regard to the size of the database; the cost data are accumulated by lot (on a yearly basis), showing, for each year, total production, total recurring labor hours associated with that production, and other annual data. In addition to the data on production years shown in Table 5.2, for each aircraft type there are data on the engineering and manufacturing development (EMD) lot,[4] which is generally produced over a period of more

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[4] This activity was called full-scale development when the aircraft in Table 5.2 were developed.

than a year. The number of observations for this analysis in a statistical sense is the total number of lots, which is 64.

Table 5.3 shows the material distribution of each of the MACDAR aircraft.

"Stylized Facts"

Before proceeding to the statistical analysis, we present some interesting summary statistics derived from the MACDAR database. We begin with the share of the different types of recurring labor. Following standard DoD reporting practice, MACDAR identifies the same four types of recurring labor discussed in the last chapter: engineering, tooling, manufacturing, and quality assurance. Table 5.4 shows average shares of each in total recurring labor at four stages of production: EMD, first production lot, all lots, and last two lots. *It is critical to note that because of differences in production patterns among these programs, these figures have no formal statistical validity. They are literally descriptors of the data that are meant for general context only.*

Table 5.2

Aircraft in the MACDAR Database

Aircraft	Production Years (number of lots)	Number of Aircraft
AV-8B	82–86 (5)	195
F-14	71–78 (8)	439
F-15	73–91 (19)	1241
F-16	77–90 (14)	2357
F/A-18	79–91 (13)	1196

Table 5.3

MACDAR Aircraft Material Distribution (percentage of airframe structure weight)

Material	F/A-18	AV-8B	F-16	F-15	F-14
Aluminum	51	41	75	50	39
Steel	12	10	11	2	21
Titanium	14	6	1	34	30
Composites	11	25	2	2	2
Other	12	17	11	12	8

Table 5.4

Percentage of Recurring Labor at Different Stages of Production

Stage of Production	Engineering	Tooling	Manufacturing	Quality Assurance
EMD	24	22	45	9
First production lot	21	16	55	8
All production lots	15	13	62	10
Last two production lots	12	11	66	11

Our later regression estimates should be used to make formal statistical assessments. These results are literally intended to communicate to the reader "what the data look like"; hence the summary characterization "stylized facts." These are the arithmetic averages of each aircraft's proportions.

With that caveat in mind, we see interesting patterns in the data, none of which is surprising. Manufacturing labor dominates, constituting almost two-thirds of the program total. The shares of engineering and tooling fall as production proceeds; the share of manufacturing rises; and that of quality assurance is stable.

Another interesting set of stylized facts is the distribution of manufacturing labor across subcategories. MACDAR includes five such categories: fuselage, wing, empennage, subsystem installation, and integration. We categorize the first three into "structural" labor and the last two into "nonstructural" labor. ("Structural" is equivalent to "airframe group level" as defined in Chapter Four; "integration" is equivalent to "final assembly and checkout" in Chapter Four.) On average across aircraft types in MACDAR, structural labor is 65 percent of manufacturing labor and nonstructural 35 percent. Of total manufacturing labor, 45 percent is fuselage, 15 percent wing, 5 percent tail, 17 percent subsystem installation, and 18 percent integration. Another interesting set of average figures from the data set pertains to the relations of the various kinds of weight of the aircraft. (Weight definitions are given in Appendix B.) On average, structural weight is roughly three-quarters of airframe unit weight (AUW), and AUW is about two-thirds of empty weight. Thus, structural weight is approximately one-half of empty weight. Once again, these figures are just interesting descriptors of the data set and should not be construed as having formal statistical validity.

Statistical Results

We begin with regression equations in which labor hours are a function of several explanatory variables. There are four equations, one for each recurring labor category. The equations combine all the MACDAR aircraft observations referred to in Table 5.2, so they are of the "time-series cross-section" or "panel" form, with 64 total observations, one for each aircraft-lot combination (each year's production is defined as a lot, and the EMD data observation for each aircraft is another lot). The dependent variable is hours per aircraft divided by AUW. The independent variables include cumulative production to reflect learning effects and lot size (annual production except for EMD lots) to reflect rate effects. Weight is included to reflect the well-known effect in which hours per pound fall with pounds. There is a dummy variable for the EMD lot, both to reflect actual differences in the manufacturing of EMD aircraft[5] versus the aircraft built during production and to reflect the fact that the EMD aircraft were produced in a period of over a year, so the EMD coefficient also includes some rate effects.

Another dummy variable (called *MODEL*) represents significant model change. What constitutes a significant model change is obviously a judgment call. In these estimates, we assume that there were no such changes in the AV-8B or F-14 and that the following were significant model changes: F-15A/B to C/D and then to E; F-16A/B to C/D and then Block 30/32 to 40/42; and F/A-18A/B to C/D. If an aircraft was on its first model, the value of *MODEL* is zero; if on its second model (resulting from the first significant model change) the

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[5] Not all EMD aircraft are production configuration, and the tooling used during development is different from that used in production.

value is one; and if on its third model (e.g., F-15E or F-16 Block 40/42 or higher) the value is two.[6]

We also include the variable $(WMCF)_l$ as defined above to represent the effect of material mix on labor hours. For this estimation, $(WMCF)_l$ values based on the MACDAR database were used. MACDAR's data were based on the cost ratios of Table 4.1—i.e., those reported in Resetar, Rogers, and Hess for the mid-1980s based on their industry survey.

The specific functional form we use is

$$\frac{H_{l,j}/Q_j}{W_j} = \alpha_l \left(WMCF\right)_l \left(Q_j\right)^{\rho_l} \left(W_j\right)^{\eta_l} \left(C_j\right)^{\beta_l} \exp\left[\omega_l \left(EMD\right)_j + \theta_l \left(MODEL\right)_j\right] \tag{5.4}$$

This represents four regression equations, one for each of the four recurring labor categories (indexed by l). The index j represents production lots and goes from 1 to 64. The variables are defined as follows:

$H_{l,j}$ = recurring hours of type l used in the production of lot j

Q_j = number of aircraft produced in lot j in units

W_j = average AUW for aircraft produced in lot j in pounds

$(WMCF)_l$ = weighted material cost factor associated with labor category l as defined above

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[6] This definition of model change was proposed by SAIC analysts working on the MACDAR database and should be credited to them. We also did regressions in which two separate dummy variables were included, one for first-model change and one for second. The difference between the coefficients was not statistically significant, and the values were very close to each other. Thus, the specification of equal cost impact of each model change is supported by the data. Readers should be cautious in applying the model change variable to future programs in that future model changes would have to be comparable to the ones in this data set for the results to be applicable.

C_j = cumulative aircraft production for lot j, defined as the level of cumulative production, in units[7]

$(EMD)_j$ = a dummy variable whose value is unity if this is an EMD lot and zero otherwise

$(MODEL)_j$ = a dummy variable representing significant model changes, defined above

Estimated values of the coefficients are given in Table 5.5. The implied learning slopes, weight-sizing slopes, and rate slopes are given in Table 5.6. All the learning and weight coefficients are statistically significant at the 95 percent confidence level; only tooling shows a statistically significant rate effect at that confidence level. However, the rate coefficients for engineering, manufacturing, and quality assurance are marginally significant between the 73 and 87 percent confidence levels. (Owing to the proprietary nature of individual observations in MACDAR, we cannot show the residuals from the regressions.)

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[7] Since a lot has more than one unit, lot cumulative production is ambiguous. Given that we are using unit learning theory, the correct cumulative production figure for each lot is

$$C = \left(\sum_{i=F}^{L} \frac{i^{\beta}}{\left(L - F + 1\right)} \right)^{1/\beta},$$

where L and F are the first and last units of the lot and β is the natural logarithm of the learning slope divided by the natural logarithm of two. Since calculation of this depends on β but β is estimated from the data, an iterative procedure is used. First β is estimated using an estimated lot midpoint as the measure of cumulative production; then C is calculated and β is reestimated. In all results reported here, the second estimate of β was very close to the first and was in fact equal to two significant digits.

Table 5.5

Coefficient Estimates for Equation 5.4[a]

Coefficient	Coefficient Symbol	Engineering	Tooling	Manufacturing	Quality Assurance
Constant term	α	4113	1502	295	3235
C	β	–0.49 (–5.1)	–0.37 (–4.9)	–0.33 (–11.7)	–0.23 (–4.1)
W	η	–0.53 (–3.1)	–0.41 (–3.2)	–0.24 (–5.3)	–0.72 (–7.3)
Q	ρ	–0.19 (–1.5)	–0.41 (–4.0)	–0.04 (–1.1)	–0.08 (–1.1)
EMD	ω	–0.51 (–1.6)	–0.36 (–1.6)	0.02 (0.2)	0.35 (1.7)
MODEL	θ	0.30 (2.2)	0.09 (0.9)	0.23 (5.7)	0.21 (2.6)
Standard error of estimate	SEE	0.43	0.34	0.12	0.30
Coefficient of determination	R^2	0.78	0.88	0.96	0.78

[a] The t-statistics are in parentheses.

Table 5.6

MACDAR Learning, Weight-Sizing, and Rate Slopes (in percentages)

Category	Learning	Weight Sizing	Rate
Engineering	71[a]	69[a]	88
Tooling	77[a]	75[a]	75[a]
Manufacturing	80[a]	85[a]	97
Quality assurance	85[a]	61[a]	95

[a] Statistically significant at the 95 percent confidence level.

EMD effects, while only marginally significant at best, are large in three categories. First, there is a large negative effect in engineering and tooling. This is probably because recurring engineering hours are used largely to *improve* production activity and to make minor system *changes*. Neither of these will occur much in EMD, when the system and its production mode are *initially* being developed using nonrecurring engineering hours. Similarly, much of recurring tooling during production is to refurbish tools, which are just being built during EMD. The large positive effect on QA hours probably reflects the working out of QA procedures on the shop floor during EMD and really represents a high learning rate between EMD and regular production.

The coefficients on the variable *MODEL* imply that each new model introduction causes a 30 percent increase in engineering, a 9 percent increase in tooling, a 23 percent increase in manufacturing, and a 21 percent increase in quality assurance. All but the tooling coefficient are significant at the 95 percent confidence level; the tooling coefficient is significant at the 63 percent level. In this model's functional form, after the one-time jump in labor associated with each model change, hours continue to follow a learning pattern with the same slope as before.

The $(WMCF)_l$ factors used in these estimates are shown in Table 5.7. As noted above, these were taken from the MACDAR database, which was itself based on the cost ratios of Table 4.1 from the earlier RRH study—i.e., on estimates for the late 1980s. The MACDAR database actually includes estimated values not of $(WMCF)_l$ but instead of

$$\sum_{m=1}^{M} S_m C_l^m \tag{5.5}$$

We used Equation 5.1 to convert these numbers to $(WMCF)_l$.

The reader will note that in Equation 5.4, the variable $(WMCF)_l$ does not have an exponent—or, put more precisely, an exponent of unity is imposed. We did this because the $(WMCF)_l$ factors were meant to modify CERs multiplicatively and were in fact constructed *specifically* for this use. Put another way, the $(WMCF)_l$ factors answer the question "What is the ratio of the cost of using material *X* to the cost of using aluminum," which implies an exponent of unity when modifying a CER equation. Therefore, our use of them here corresponds to the manner in which they were constructed and intended to be used.

Table 5.7

$(WMCF)_l$ Factors and σ Values Used for the Regression Results Shown in Table 5.5

$(WMCF)_l$ Factors

Aircraft	Engineering	Tooling	Manufacturing	Quality Assurance
AV-8B	1.14	1.41	1.24	1.30
F-14	1.07	1.34	1.15	1.17
F-15	1.08	1.35	1.20	1.18
F-16	1.02	1.08	1.04	1.07
F-18	1.09	1.31	1.16	1.20

σ Values

Aircraft	Engineering	Tooling	Manufacturing	Quality Assurance
AV-8B	0.43	0.87	0.66	0.60
F-14	0.50	0.94	0.66	0.60
F-15	0.43	0.87	0.74	0.60
F-16	0.19	0.69	0.45	0.60
F-18	0.43	0.87	0.66	0.60

Some cost analysts have argued that rather than impose an exponent of unity on the $(WMCF)_l$ factor in Equation 5.4, one should estimate a value for that exponent from the data, as is the case with other exponents in the equation. If such a procedure finds an exponent different from one, two explanations are possible. One is that the construction of the $(WMCF)_l$ factors was *systematically* flawed so that they are in fact related to cost nonproportionately. This would imply that estimating an exponent gives the best results. (Note that simple random errors in estimating the $(WMCF)_l$ factors would not lead to a nonunity estimate of the exponent; the flaws would have to follow a highly specific pattern to lead to a true nonunity coefficient.) The second explanation is that the true exponent on $(WMCF)_l$ is in fact unity, but some other variables that affect cost and are correlated with $(WMCF)_l$ are left out of Equation 5.4. If this is the case, imposing an exponent of unity provides better results.

We did estimate values for coefficients on the $(WMCF)_l$ factors to explore this issue. Table 5.8 shows the results, giving the point estimate of the exponent and the lower and upper bounds of the 95 percent confidence interval.

Table 5.8

Point Estimates and 95 Percent Confidence Interval Bounds for the Exponent on $(WMCF)_l$

Equation	Lower Bound	Point Estimate	Upper Bound
Engineering	–13.32	–9.70	–6.40
Tooling	–0.47	0.80	2.06
Manufacturing	0.29	0.94	1.59
Quality Assurance	0.27	1.97	3.67

We see that the exponent in the manufacturing equation is estimated to be very close to one. The exponents in the tooling and quality assurance equations are estimated imprecisely (i.e., they have wide confidence intervals) but do include unity in the confidence interval. Since these equations do not imply that a value of unity is statistically rejected, we accept unity as the value. The exponent in the engineering equation not only has the wrong sign but also has a highly implausible absolute value (a change of $[WMCF]_l$ from 1 to 1.5 changes hours by a factor of 50). We infer that this must be due to other variables that are left out of the equation and thus also accept the value of unity for this equation. In summary, we do not find evidence of systematic misestimation of the $(WMCF)_l$ that would lead us to reject functional form 5.4, in which the $(WMCF)_l$ values are entered multiplicatively as they were designed to be.

Some cost analysts have pointed out that in the manufacturing equation, if only observations for the *first* model of each aircraft are included, then an estimated exponent on $(WMCF)_{manu}$ is significantly different from one (i.e., these would be observations for which the variable $[MODEL]_j$ has a value of zero). We also explored this issue, and the results are given in Table 5.9, which shows the point estimate of the exponent on $(WMCF)_{manu}$ as well as the associated confidence interval for four samples. The first two, in the first column, are for the full sample and for just the original models. Full sample results are, of course, the same as those in Table 5.8. The bottom left box confirms the first sentence in this paragraph. If the manufacturing equation is estimated on observations only for the original models, the estimated coefficient on $(WMCF)_{manu}$ is significantly greater than one.

Table 5.9

Point Estimates and 95 Percent Confidence Interval Bounds for the Exponent on $(WMCF)_{manu}$ in Four Samples[a]

Sample	All Aircraft	Excluding F-16
All models	0.94 (0.3, 1.6)	0.65 (–0.6, 1.9)
Original aircraft model only (observations for which $[\text{MODEL}]_j = 0$)	2.03 (1.5, 2.6)	0.22 (–1.8, 2.3)

[a] The first entry in each cell is the point estimate; confidence interval bounds are in parentheses below.

However, the second column of Table 5.9 puts this in a different perspective. This column shows results for the same two samples but *excludes the F-16.* For these samples, although the coefficient on $(WMCF)_{manu}$ is estimated imprecisely, the value of unity is not rejected. We interpret these results as in fact a "missing variable" phenomenon. The F-16A/B was deliberately developed as a *low-cost* fighter, with extreme attention paid to affordability (see Lorell and Levaux, 1998, Chapter Five). It also happens to have the lowest $(WMCF)_{manu}$ value in the sample. Thus, "extreme attention to affordability" is a programmatic variable that is left out of Equation 5.4, and it happens to be correlated with low $(WMCF)_{manu}$. In the "original model only" equation, the coefficient on $(WMCF)_{manu}$ is therefore estimated at a high value owing to the correlation between it and the left-out variable. We base this interpretation on the results that are derived when the F-16 is not included in the sample at all.

Based on all this, we conclude that the best statistical procedure is indeed to use Equation 5.4 as is, applying the $(WMCF)_l$ factors as they were designed and intended to be. We conclude that there is insufficient evidence to infer that the $(WMCF)_l$ values were systematically misestimated, which would justify estimating a nonunity coefficient on the $(WMCF)_l$ variables.

The next chapter discusses the application of Equation 5.4 to estimating the cost of new aircraft.

Chapter Six

APPLYING THE RESULTS

We now discuss how the results of this study can be applied to future aircraft programs. First, we discuss how the aggregate airframe data survey results in Table 5.1 can be used to estimate the effect of material mix on airframe labor hours. For recurring manufacturing hours, we show how using the part-level cost ratio information in Tables 4.13, 4.14, and 4.15 can be used to estimate the effects on cost of part geometric complexity and manufacturing technique as well as material mix.

APPLYING THE SURVEY COST RATIOS

First, the results in Table 5.1 can be used to estimate the effect of material mix on airframe labor hours. For any given composition of structural weight by material (i.e., the S_m of Chapter Five), a weighted material cost factor $(WMCF)_l$ for each labor category can be computed using Equation 5.3.[1] The γ_l^m from Table 5.1 can be used if the program is expected to employ technology comparable to that of the late 1990s. The effect of material mix on each labor category can be explored by calculating $(WMCF)_l$ for various material mixes (i.e., sets of S_m). The effect of material mix on total recurring hours can be

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[1] To refresh the reader's memory, we repeat the definitions of the symbols used from Chapter Five. The index m runs over material types, and the index l runs over labor categories. S_m is the share of material m in the airframe; $(WMCF)_l$ is the weighted material cost factor for each labor category l; and γ_l^m is the cost ratio associated with material m and labor category l at the all-airframe hour level. (Table 5.1 shows one such set of γ_l^m.)

calculated by taking a weighted sum of the $(WMCF)_l$'s . If the appropriate weights for the labor categories for the future aircraft under consideration are known, they should be used. Otherwise, one can use the weights shown in Table 5.4 for "all production lots" as representative of recent fighter aircraft. The implications of any projections of future γ_l^m, such as the "optimistic" projections we give below, can be compared with the 1990s experience as represented in Table 5.1 by comparing the $(WMCF)_l$'s calculated with the two sets of γ_l^m.

The procedures discussed so far allow for relative comparisons only across material mix alternatives—i.e., they can estimate the percentage changes in hours associated with different mixes but do not address absolute numbers of hours. For recurring labor needed to produce fighter aircraft, the hours can be projected based on Equation 5.4 in Chapter Five. A projection of the AUW of the aircraft is needed along with a projected production profile, since the CERs are rate dependent. Given the material mix assumed, the associated $(WMCF)_l$'s can be plugged directly into Equation 5.4. (We note that for this procedure to be valid, the $(WMCF)_l$'s must be based on γ_l^m calculated on the assumption that mid-1980s aluminum hours equal 1.0. This is true of the γ_l^m from Table 5.1 and of our future "optimistic" projections, given in Table 6.6.)

We note that these equations are relevant only to fighter/attack-class aircraft. Previous statistical work on CERs (e.g., Hess and Romanoff, 1987) that included non–fighter/attack-class aircraft such as cargo and aerial refueling aircraft found that maximum speed was an important determinant of hours required. Each doubling of speed was found to lead to a 40 to 115 percent increase in hours, depending on the labor category. Speed is highly correlated with the fighter/nonfighter split, of course.[2] Therefore, we recommend that Equation 5.4 *not* be used for non–fighter/attack-class aircraft, since we believe it would overpredict hours. (We do note that the AV-8B is subsonic, so this argument is not pure. However, we still believe that

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[2] This previous work did not include material effects. It is possible that the higher advanced-material content in some high-speed aircraft, especially titanium, led to the statistical association between speed and cost. This issue needs further investigation to be resolved.

the recommendation is correct.) We *do* recommend these equations for future fighter/attack-class aircraft.

APPLYING THE PART-LEVEL DATA

For recurring manufacturing hours, the information in Tables 4.13, 4.14, and 4.15 can be used to estimate the effects of part geometric complexity and manufacturing technique on cost as well as the effect of material mix. For this, estimates of the percentage of structural weight accounted for by each material/manufacturing-technique/geometric complexity category would be needed. An index of the material/manufacturing-technique combination—say, τ—can be defined as shown in Table 6.1. (For clarity, we also show the associated cost ratio for "complex" parts from Tables 4.13, 4.14, and 4.15.) We require a set of S_τ^c, the shares of airframe structural weight accounted for by each (c, τ) category: $\sum_{\tau=1}^{12} \sum_{c=1}^{4} S_\tau^c = 1$. We define $(\phi_\tau^c, \tau = 1, \ldots, 12; c = 1, \ldots, 4)$ as the cost ratios from Tables 4.13, 4.14, and 4.15. (For example, $\phi_1^1 = 0.7$.) We use them to compute a new weighted material cost factor for recurring manufacturing, which we will designate $(WMCF)^*$.

$$(WMCF)^* = \sum_{\tau=1}^{12} \sum_{c=1}^{4} S_\tau^c \phi_\tau^c \tag{6.1}$$

This can be used to compare the recurring manufacturing cost implications of different sets of S_τ^c, regardless of whether they vary by material, manufacturing technique, or part geometric complexity distribution. (Note that this is possible only because the cost ratios were defined on an "all-airframe basis," as discussed in Chapter Four.) We then define an index of part geometric complexity (c) as shown in Table 6.2.

Table 6.1

Definition of Material/Manufacturing (M/M) Technique Index (τ)

M/M Index(τ)	M/M Technique	Cost Ratio Value for "Complex" Parts
1	Aluminum/conventional machining	1.5
2	Aluminum-lithium/conventional machining	1.6
3	Titanium/conventional machining	1.7
4	Steel/conventional machining	1.8
5	Aluminum/HSM	1.0
6	Aluminum-lithium/HSM	1.1
7	Titanium/HPM	1.5
8	Titanium/HIP investment casting	1.0
9	Composites/hand layup	2.2
10	Composites/hand layup with OLPA	1.9
11	Composites/automated fiber placement	1.7
12	Composites/resin transfer molding	1.4

Table 6.2

Definition of Part Geometric Complexity Index (*c*)

Complexity Index (*c*)	Geometric Complexity Category
1	Simple
2	Medium
3	Complex
4	Very complex

COMPARISON OF AIRFRAMES MANUFACTURED USING TRADITIONAL TECHNIQUES WITH THOSE USING ADVANCED TECHNIQUES

We illustrate such a comparison using two structural weight breakdowns for a notional future fighter. Each is assumed to have the same material mix and part geometric complexity, but different manufacturing techniques are assumed. Tables 6.3 and 6.4 show the two assumed sets of S_{τ}^{c}.

Table 6.3

S_{τ}^{c} for a Notional Future Fighter: Traditional Manufacturing Techniques[a]

	Part Complexity Index Value (c)	1	2	3	4
M/M Index (τ)	M/M Technique	Simple	Medium	Complex	Very Complex
1	Aluminum/ conventional machining	6.2	13.1	9.2	
2	Aluminum-lithium/conventional machining		2.7		
3	Titanium/conventional machining	0.3	10.9	8.5	
4	Steel/conventional machining		0.9	6.6	
5	Aluminum/HSM				
6	Aluminum-lithium/HSM				
7	Titanium/HPM				
8	Titanium/HIP investment casting				
9	Composites/hand layup	1.8	17.8	17.0	5.0
10	Composites/hand layup with OLPA				
11	Composites/automated fiber placement				
12	Composites/resin transfer molding				

[a] Table values are 100 $*$ S_{τ}^{c}.

Table 6.4

S_τ^c for a Notional Future Fighter: Advanced Manufacturing Techniques

	Part Complexity Index Value (c)	1	2	3	4
M/M Index (τ)	M/M Technique	Simple	Medium	Complex	Very Complex
1	Aluminum/ conventional machining				
2	Aluminum-lithium/conventional machining				
3	Titanium/conventional machining				
4	Steel/conventional machining		0.9	6.6	
5	Aluminum/HSM	6.2	13.1	9.2	
6	Aluminum-lithium/HSM		2.7		
7	Titanium/HPM	0.3	10.9	8.5	
8	Titanium/HIP investment casting				
9	Composites/hand layup				
10	Composites/hand layup with OLPA	1.8	13.8	5.0	2.5
11	Composites/automated fiber placement		4.0	10.4	
12	Composites/resin transfer molding			1.6	2.5

The value of *(WMCF)** is 1.61 using Table 6.3 shares and 1.34 using Table 6.4. In this example, changing from a largely 1980s-type manufacturing mix to a more advanced one decreases recurring manufacturing labor hours by 17 percent.

That example was done on a CAC100 basis assuming an average part weight of 15 pounds, as was used in normalizing the ϕ_τ^c estimates. The factors in Tables 4.16 and 4.17 could be used to calculate relative costs under different cumulative production and average part weight assumptions.

These comparisons are still for *relative* costs across material/manufacturing-technique/complexity mixes—i.e., the percentage by which the recurring manufacturing hours of one mix will differ from those of another. We now turn to absolute calculations.

We use the recurring manufacturing equation shown in Equation 5.4. However, $(WMCF)^*$ is not exactly comparable to $(WMCF)_{manu}$. $(WMCF)^*$ is calculated from ratios of labor hours divided by 1990s aluminum conventionally machined medium-complexity part labor hours. $(WMCF)_{manu}$ is calculated from ratios of labor hours divided by 1980s average aluminum labor hours. To make these comparable, we need an estimate of average aluminum hours per pound for the MACDAR aircraft at CAC100. Based on Equation 5.4 for manufacturing labor and an average production profile across the five aircraft (shown in Table 6.5), this is 7.86 hours per pound. Thus, recurring manufacturing hours for future fighter aircraft can be estimated by plugging in $[(7.65/7.86)\ (WMCF)^*]$ instead of $(WMCF)_{manu}$ in Equation 5.4 for manufacturing.[3]

Table 6.5

Average Lot Size for MACDAR Aircraft[a]

Lot	Number Produced
EMD	11
1	21
2	50
3	80
4 and beyond	110

[a] The pattern of production decrease at the end of the production run is very irregular across aircraft.

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[3] The figure 7.65 is 1990s aluminum conventionally machined medium-complexity part labor hours per pound (corresponding to the cost ratio “1.0” in Table 4.13) (“all-aircraft basis”) as discussed in Chapter Four.

We illustrate this with the two notional fighter aircraft characterized in Tables 6.3 and 6.4. We assume a pattern of production timing shown in Table 6.5, the MACDAR averages across airframes. We assume an AUW of 15,355 pounds in EMD and 15,800 pounds in all other lots; these are also the MACDAR averages (illustrating the weight growth that typically occurs between the EMD aircraft and the regular production aircraft). Using traditional manufacturing techniques (the Table 6.3 S_τ^c), CAC100 recurring manufacturing hours per pound total 12.3. Using advanced techniques (the Table 6.4 S_τ^c), the figure is 10.2.

This example indicates that airframe manufacturing hours should decrease as modern manufacturing techniques are introduced, but the increased complexity of the next-generation airframes to meet future military requirements must also be taken into account.

COST RATIOS IN THE 2000s: OPTIMISTIC AND PESSIMISTIC PROJECTIONS

Can we expect production improvement in airframe labor hours in the coming decade? We asked industry to project future cost ratios, but most did not, citing the high uncertainty associated with the future environment. We did engage in many discussions with industry of how different future environments might change costs, and some companies ventured projections of cost ratios given specific futures. We also reviewed many studies done by industry on the cost implications of potential future technologies. Based on this information, we have prepared two projections for the 2000s, “optimistic” and “pessimistic.” (We note explicitly that this means optimistic or pessimistic with respect to airframe costs; we take no position on the overall desirability of futures leading to high or low costs.) Table 6.6 contains an “optimistic” set of cost ratio projections for the mid-2000s. Table 6.6 is based on an “all-airframe labor” basis and is thus comparable with Table 5.1.

Table 6.6

Optimistic Mid-2000s Cost Ratio Projections, All-Airframe Labor Basis[a]

Material	Nonrecurring Engineering	Nonrecurring Tooling	Recurring Engineering	Recurring Tooling	Recurring Manufacturing	Recurring Quality Assurance
Aluminum	1.00	0.88	0.91	0.86	0.82	0.95
Aluminum-lithium	1.00	0.99	0.94	0.97	0.87	1.04
Titanium	1.00	1.26	0.97	1.26	1.29	1.18
Steel	1.02	0.97	1.02	1.12	1.05	1.12
Carbon-epoxy	1.14	1.21	1.18	1.33	1.17	1.50
Carbon-BMI	1.16	1.29	1.21	1.44	1.24	1.52
Carbon-thermoplastic	1.14	1.44	1.15	1.50	1.27	1.58

[a] Late 1980s aluminum = 1.0.

Table 6.6 assumes the use of higher-productivity part fabrication processes such as HSM/HPM for metals and automated fiber placement and RTM for composites. It also assumes increased unitization and thus assembly labor savings. Some innovations in assembly are now being introduced whose labor savings in large-scale production and ultimate market penetration are not yet clear. (We had no access to data from production applications.) They include self-locating parts, reduced tooling, and single-pass drilling. In Table 6.6, we assume that they will lead to some labor savings as well.

These optimistic projections are the same as the figures in Table 5.1 for nonrecurring engineering and in recurring quality assurance for metals. We did not see any compelling evidence for significant advances in technology in these areas in the next few years.

This set of cost factors, assuming increased industry penetration of advanced technology, is optimistic basically because of the high level of uncertainty concerning future military aircraft production levels. Every program existing today is controversial in some government and policy circles, and each is seriously challenged on a regular basis.

Thus, the incentives for industry to introduce new techniques, with their capital and training costs and uncertainty about precise effectiveness, are low. The optimistic projections of Table 6.6 are ones that might hold if the military aircraft production climate were to become robust—with, say, annual production in the several hundred range and high confidence in program stability. For any given composition of structural weight by material (i.e., the S_m of Chapter Five), one can compute a weighted material cost factor $(WMCF)_l$ for each labor category using Equation 5.3. One can use the γ_l^m from Table 6.6 if our "optimistic" future scenario seems appropriate.

Our pessimistic projection would be no change from today—i.e., that the cost ratios of Table 5.1 will continue for the rest of the decade. This would be consistent with relatively low levels of production (say, less than 100 per year) and with high program instability and uncertainty. Industry would have little reason to make the investments required to reach the higher productivities shown in Table 6.6, since there would be little confidence in recouping the investments.

COST-ESTIMATING CONSIDERATIONS FOR AIRFRAME STEALTH REQUIREMENTS

One notable subject not explicitly addressed in this report is the impact of LO materials and structures on the cost of airframe production. Because of the classification of the entire subject of LO materials and structures, this issue could not be addressed in detail in this report. However, anecdotal discussions with some of the participating contractors indicate that the fabrication of these materials and their installation were not significantly greater in terms of production costs than those associated with non-LO materials. The major difference is an increase in the complexity of structural parts such as inlets and edges and in the nonrecurring design and testing of the LO materials and structure.

The cost analyst has two options on how to handle LO materials in a production estimate. The first is to obtain data by material type for the proposed airframe structure, including the LO materials and the geometric complexity of the associated parts, and proceed to calculate the $(WMCF)^*$ as described in this chapter. This assumes that the materials used for the LO purposes and the complexity of the parts are accurately reflected in the overall S_T^c. Also, if part of the LO requirement is met by internal carriage, for example, the added weight, advanced materials, and complexity of a "bomb bay" would be included in the weight and material distribution estimate for the structure. The other option is to obtain access to what is normally a highly classified body of data, establish discrete cost estimates for the fabrication and assembly tasks for the LO materials, and add that to the cost estimate for the rest of the structure.

LEAN MANUFACTURING AND ACQUISITION REFORM

As mentioned in Chapter One, two companion reports to this one—Cook and Graser (2001) and Lorell and Graser (2001)—present research on the effects of lean manufacturing and acquisition reform on military aircraft costs. This section summarizes their results and discusses how they can be integrated into the overall costing methodology presented in this chapter. A list of specific subjects addressed in the three reports can be found in Appendix E. This is a brief review of two rich and detailed reports, and interested readers are urged to read the reports themselves.

One kind of acquisition reform is regulatory and oversight relief, including relief from government-mandated accounting and record-keeping standards, cost-reporting requirements (including Truth in Negotiation Act provisions), and audit and oversight practices. Based on the data available, the best estimate of the effect on total program cost of *all* such proposed regulatory/oversight acquisition reform measures is a savings of 3 to 4 percent. This range is substantially less than had been projected earlier. Furthermore, all such acquisition reform measures must be implemented together if these effects are to be attained. In addition, industry must perceive acquisition reform measures as permanent, since a major part of the savings accrue from personnel reductions among those who administer the government regulations such reform would do away with. If a given case of relief from regulations is not viewed as permanent, industry will be wary of reducing the workforce that has been trained to deal with such regulations in the event that they are reimposed. In any case, acquisition reform of this sort will generally affect overhead personnel rather than those billing to specific programs. Thus, our best estimate is that the vast majority of such savings should be reflected in lower wage burden or other overhead rates rather than in labor hours associated with the program.[4] A reduction of these rates equivalent to a 3.5 percent decrease in total program costs would be a justifiable estimate assuming that *all* regulatory and oversight relief measures now being proposed are implemented and that industry *perceives these measures as permanent.* If either of these conditions is violated, no savings should be attributed to acquisition reform.

Some programs, such as Joint Direct Attack Munition (JDAM), have seen savings as a result of a commercial approach to many program elements, such as part selection and qualification, cost-benefit tradeoff analysis, requirements definition, contracting, and buyer-seller relations. However, there is no evidence to date that this approach can work on a more sophisticated system such as a combat aircraft.

Multiyear procurement programs have a proven record of decreasing costs by about 5 percent compared to year-to-year programs.

Lean manufacturing is a set of practices meant to reduce the labor, material, and interest costs of manufacturing. It includes practices such as just-in-time inventory control, reengineering of factory layout and process sequencing to minimize idle time by personnel and machinery, and closer integration of manufacturing experts with designers during product development. Impressive savings have been associated with lean practices at the level of individual processes or manufacturing cells. However, because of limited enterprise-wide implementation of lean practices by military aircraft manufacturers, there is no systematic industry-wide evidence to date that lean practices can significantly affect overall airframe costs (although there *is* evidence that such practices have significantly lowered automobile costs). We therefore recommend that overall CERs estimated from historical data *not* be modified to reflect lean manufacturing efficiencies unless and until there is more evidence to support this

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[4] One of the few acquisition reform measures that would be reflected in labor hours is the Single-Process Initiative, which combines multiple process and inspection standards such as those for welding into one. This should increase labor efficiency by lowering the number of specific tasks in which a worker must maintain expertise and increasing repetitions—and thus specific task learning—for each task.

practice. In cases in which specific savings can be demonstrated at the process level, appropriate marginal adjustments to CERs would be justified. If lean manufacturing becomes a general practice throughout the industry, future data-based updates of material cost factors and CERs will reflect these practices. In that case, no further adjustments for lean manufacturing should be made, to avoid double counting of improvements.

CONCLUSION

This report has presented estimates of the effect of material mix, manufacturing technique, and part geometric complexity on airframe recurring costs. We discussed the results of an industry survey of aggregate airframe cost factors and then presented a quantitative analysis of actual part data we collected from industry. These factors were integrated with a historical data set, MACDAR, to estimate airframe recurring hour CERs.

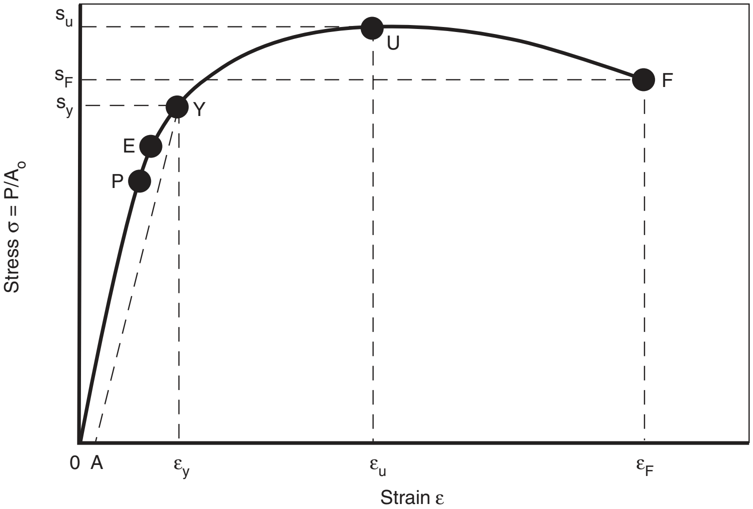
One finding of our part-level data analysis was that recurring manufacturing hours could decrease by roughly 17 percent as a result of advances in manufacturing technology, but the increased airframe complexity of future fighters may offset some of this potential savings. Future overall airframe cost factors, assuming increased industry penetration of advanced manufacturing technology, were presented as an "optimistic" forecast. We noted the high level of uncertainty surrounding any such forecast, primarily as a result of the high level of uncertainty about future military aircraft production levels. We illustrated the application of our overall cost-estimating methodology with a notional aircraft example using both conventional and advanced manufacturing techniques.

In view of the high level of uncertainty about the future military aircraft environment, cost analysts should continue working with industry to follow what changes in practice and technology are actually occurring. They should also continue to collect actual part- and airframe-level cost data. Both practices will serve to continually improve the quality of cost-estimating tools available.

STRESS-STRAIN DIAGRAM

A tensile test is used to determine a variety of mechanical characteristics of a material. A test specimen composed of a rod made of a material for which the properties are to be determined is mounted in a test machine and gradually loaded in tension in increasing increments. The total elongation over the original length is measured at each increment of load. The loads (*stress*) are observed and the changes in length (*strain*) are recorded and then plotted in a *stress-strain diagram* (Figure A.1).

RAND *MR1370-A.1*



SOURCE: J. E. Shigley and C. R. Mischke, *Mechanical Engineering Design*, 5th ed., New York: McGraw-Hill, 1989. Reprinted by permission of The McGraw-Hill Companies.

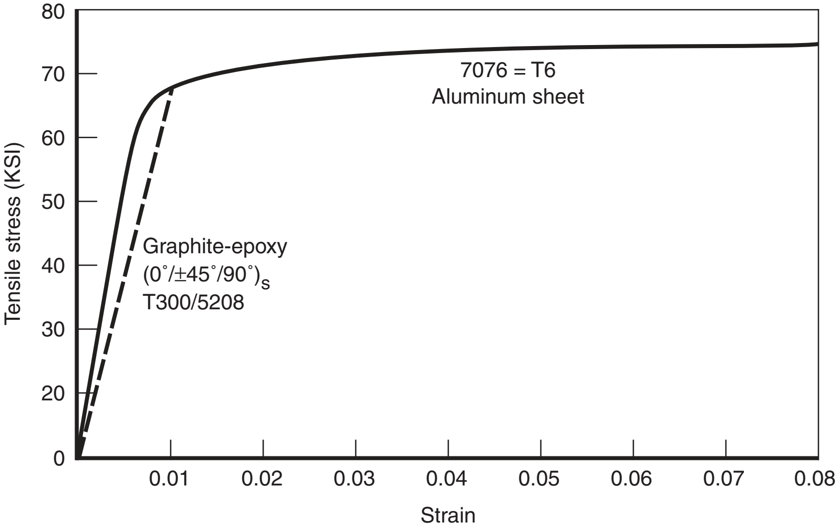
Figure A.1—Notional Stress-Strain Plot

Point *P* is called the proportional limit where stress is proportional to strain. The slope of the line 0P is the *modulus of elasticity*. Point *E* is the *elastic limit;* that is, if a part is loaded to a stress level below point *E,* no permanent deformation will be sustained.

During the tension test, many materials reach a point where the strain begins to increase rapidly without an appreciable increase in stress. This point is called the *yield point*. The *ultimate or tensile strength* is represented by point *U*. This is the *maximum stress* that can be withstood by a part. Point *F* is where the part ruptures.

Figure A.2 compares the stress-strain plot of sheet aluminum with carbon-epoxy laminate.

RANDMR1370-A.2



SOURCE: R. E. Horton and J. E. McCarty, “Damage Tolerance of Composites,” in T. J. Reinhart et al., eds., *Engineering Materials Handbook*, *Vol. 1: Composites,* Materials Park, OH: ASM International, 1987. Reprinted by permission of ASM International.

Figure A.2—Stress-Strain Plot of Sheet Aluminum with Carbon-Epoxy Laminate

Appendix B

AIRCRAFT WEIGHT DEFINITIONS

This set of definitions is consistent with Military Standard 374

Weight Empty

MINUS

- Wheels, brakes, tires, and tubes
- Engines
- Rubber or nylon fuel cells
- Starters
- Propellers
- Auxiliary power plant unit
- Instruments
- Batteries and electrical power supply and conversion
- Avionics
- A/C, anti-icing and pressurization units and fluids
- Cameras

= Airframe Unit Weight

PLUS

- Wheels, brakes, tires

MINUS

- Propulsion group
    - Accessory gear box and drives
    - Exhaust system
    - Engine cooling
    - Water injection
    - Engine control
    - Starting system
    - Smoke abatement
    - Lubricating system
    - Fuel system
    - Drive system (if helicopter)
- Flight controls
- Auxiliary power plant group installation
- Instrument installations
- Hydraulics and pneumatics
- Electrical group installations
- Avionics group installation
- Armament group
- Furnishing and equipment

= Structural Weight

Appendix C

AIRCRAFT WORK BREAKDOWN STRUCTURE (WBS) LEVELS (FROM MILITARY SPECIFICATION 881)

Level 1	Level 2	Level 3
Aircraft System		
	Air Vehicle (AV)	Airframe
		Propulsion
		AV Applications Software
		AV System Software
		Communications/Identification
		Navigation/Guidance
		Central Computer
		Fire Control
		Data Display and Controls
		Survivability
		Reconnaissance
		Automatic Flight Control
		Central Integrated Checkout
		Antisubmarine Warfare
		Armament
		Weapon Delivery
		Auxiliary Equipment
	System Engineering/ Program Management	

System Test and Evaluation	Development Test and Evaluation
	Operational Test and Evaluation
	Mock-ups
	Test and Evaluation Support
	Test Facilities
Training	Equipment
	Services
	Facilities
Data	Tech Publications
	Engineering Data
	Management Data
	Support Data
	Data Depository
Peculiar Support Equipment	Test and Measurement Equipment
	Support and Handling Equipment
Common Support Equipment	Test and Measurement Equipment
	Support and Handling Equipment
Operational/Site Activation	System Assembly, Installation, and Checkout on Site
	Contractor Technical Support
	Site Construction
	Site/Ship/Vehicle Conversion
Industrial Facilities Construction/Conversion/Expansion	Equipment Acquisition or Modernization
	Maintenance (Industrial Facilities)
Initial Spares and Repair Parts	

DEFINITIONS

Aircraft System

The complex of equipment (hardware/software), data, services, and facilities required to develop and produce air vehicles.

Includes:

- those employing fixed, movable, rotary, or compound wing
- those manned/unmanned air vehicles designed for powered or unpowered (glider) guided flight

Air Vehicle

The complete flying aircraft.

Includes:

- airframe, propulsion, and all other installed equipment
- design, development, and production of complete units—prototype and operationally configured units which satisfy the requirements of their applicable specifications, regardless of end use
- Subelements to the air vehicle

Airframe

The assembled structural and aerodynamic components of the air vehicle that support subsystems essential to designated mission requirements.

Includes, for example:

- basic structure—wing, empennage, fuselage, and associated manual flight control system
- rotary wing pylons, air induction system, thrust reversers, thrust vector devices, starters, exhausts, fuel management, inlet control system

- alighting gear—tires, tubes, wheels, brakes, hydraulics, etc.
- secondary power, furnishings—crew, cargo, passenger, troop, etc.
- instruments—flight, navigation, engine, etc.
- environmental control, life support and personal equipment, racks, mounts, intersystem cables and distribution boxes, etc., which are inherent to, and nonseparable from, the assembled structure
- dynamic systems—transmissions, gear boxes, propellers, if not furnished as an integral part of the propulsion unit
- rotor group and other equipment homogeneous to the airframe

In addition to the airframe structure and subsystems, this element includes:

1) Integration, assembly, test, and checkout:

Includes:

- common elements to provide the integration, assembly, test, and checkout of all elements into the airframe to form the air vehicle as a whole
- all administrative and technical engineering labor to perform integration of level 3 air vehicle and airframe elements; development of engineering layouts; determination of overall design characteristics, and determination of requirements of design review
    - — overall air vehicle design and producibility engineering
    - — detailed production design; acoustic and noise analysis
    - — loads analysis; stress analysis on interfacing airframe elements and all subsystems
    - — design maintenance effort and development of functional test procedures
    - — coordination of engineering master drawings and consultation with test and manufacturing groups

  - tooling planning, design, and fabrication of basic and rate tools and functional test equipment, as well as the maintenance of such equipment
  - production scheduling and expediting
  - joining or installation of structures such as racks, mounts, etc.
  - installation of seats, wiring, ducting, engines, and miscellaneous equipment and painting
  - setup, conduct, and review of testing assembled components or subsystems prior to installation
- all effort associated with the installation, integration, test, and checkout of the avionic systems into the air vehicle including:
  - design of installation plans
  - quality assurance planning and control including material inspection
  - installation
  - recurring verification tests
  - integration with nonavionics airframe subsystems
- ground checkout prior to flight test; production acceptance testing and service review; quality assurance activities and the cost of raw materials, purchased parts, and purchased equipment associated with integration and assembly

2) Nonrecurring avionics system integration which is associated with the individual avionics equipment boxes and avionics software in a functioning system.

Includes:

- the labor required to analyze, design, and develop avionics suite interfaces and establish interface compatibility with nonavionics support equipment systems, aircraft systems, and mission planning systems
- drawing preparation and establishment of avionics interface equipment requirements and specifications

- technical liaison and coordination with the military service, subcontractors, associated contractors, and test groups

Excludes:

- development, testing, and integration of software (which should be included in air vehicle applications and system software)
- avionics system testing (included in System Test and Evaluation) and aircraft systems engineering efforts (included in Systems Engineering/Program Management)
- all effort directly associated with the remaining level 3 WBS elements

Propulsion

That portion of the air vehicle that pertains to installed equipment (propulsion unit and other propulsion) to provide power/thrust to propel the aircraft through all phases of powered flight.

Includes, for example:

- the engine as a propulsion unit within itself (e.g., reciprocating, turbo with or without afterburner, or other type propulsion) suitable for integration with the airframe
- thrust reversers, thrust vector devices, transmissions, gear boxes, and engine control units, if furnished as integral to the propulsion unit
- other propulsion equipment required in addition to the engine but not furnished as an integral part of the engine, such as booster units
- the design, development, production, and assembly efforts to provide the propulsion unit as an entity

Excludes:

- all effort directly associated with the elements and the integration, assembly, test, and checkout of these elements into the air vehicle

- all ancillary equipments that are not an integral part of the engine required to provide an operational primary power source—air inlets, instruments, controls, etc.

Air Vehicle Applications Software

Includes, for example:

- all the software that is specifically produced for the functional use of a computer system or multiplex database in the air vehicle
- all effort required to design, develop, integrate, and check out the air vehicle applications computer software configuration items (CSCIs)

Excludes:

- the nonsoftware portion of air vehicle firmware development and production (ref. ANSI/IEEE Std. 610.12)
- software that is an integral part of any specific subsystem and software that is related to other WBS level 2 elements

Air Vehicle System Software

That software designed for a specific computer system or family of computer systems to facilitate the operation and maintenance of the computer system and associated programs for the air vehicle.

Includes, for example:

- operating systems—software that controls the execution of programs
- compilers—computer programs used to translate higher-order language programs into relocatable or absolute machine code equivalents
- utilities—computer programs or routines designed to perform the general support function required by other application software, by the operating system, or by system users (ref. ANSI/IEEE Std 610.12)

- all effort required to design, develop, integrate, and check out the air vehicle system software, including all software developed to support any air vehicle applications software development
- air vehicle system software required to facilitate development, integration, and maintenance of any air vehicle software build and CSCI

Excludes:

- all software that is an integral part of any specific subsystem specification or specifically designed and developed for system test and evaluation
- software that is an integral part of any specific subsystem, and software that is related to other WBS level 2 elements

Communications/Identification

That equipment (hardware/software) installed in the air vehicle for communications and identification purposes.

Includes, for example:

- intercoms, radio system(s), identification equipment (IFF), data links, and control boxes associated with the specific equipment
- integral communication, navigation, and identification package (if used)

Navigation/Guidance

That equipment (hardware/software) installed in the air vehicle to perform the navigational guidance function.

Includes:

- radar, radio, or other essential navigation equipment, radar altimeter, direction-finding set, doppler compass, computer, and other equipment homogeneous to the navigation/guidance function

Central Computer

The master data processing unit(s) responsible for coordinating and directing the major avionic mission systems.

Fire Control

That equipment (hardware/software) installed in the air vehicle which provides the intelligence necessary for weapon delivery such as bombing, launching, and firing.

Includes, for example:

- radars and other sensors, including radomes
- apertures/antennas, if integral to the fire control system, necessary for search, target identification, rendezvous, and/or tracking
- self-contained navigation and air data systems
- dedicated displays, scopes, or sights
- bombing computer and control and safety devices

Data Display and Controls

The equipment (hardware/software) which visually presents processed data by specially designed electronic devices through interconnection (on- or offline) with computer or component equipment and the associated equipment needed to control the presentation of the necessary flight and tactical information to the crew for efficient management of the aircraft during all segments of the mission profile under day and night all-weather conditions.

Includes, for example:

- multifunction displays, control display units, display processors, and on-board mission planning systems

Excludes:

- indicators and instruments not controlled by keyboard via the multiplex data bus and panels and consoles which are included under the airframe

Survivability

Those equipments (hardware/software) installed in, or attached to, the air vehicle which assist in penetration for mission accomplishment.

Includes, for example:

- ferret and search receivers, warning devices and other electronic devices, electronic countermeasures, jamming transmitters, chaff, infrared jammers, terrain-following radar, and other devices typical of this mission function

Reconnaissance

Those equipments (hardware/software) installed in, or attached to, the air vehicle necessary to the reconnaissance mission.

Includes, for example:

- photographic, electronic, infrared, and other sensors
- search receivers
- recorders
- warning devices
- magazines
- data link

Excludes:

- gun cameras

Automatic Flight Control

Those electronic devices and sensors which, in combination with the flight control subsystem (under airframe), enable the crew to control the flight path of the aircraft and provide lift, drag, trim, or conversion effects.

Includes, for example:

- flight control computers, software, signal processors, and data-transmitting elements that are devoted to processing data for either primary or automatic flight control functions
- electronic devices required for signal processing, data formatting, and interfacing between the flight control elements; the data buses, optical links, and other elements devoted to transmitting flight control data
- flight control sensors such as pressure transducers, rate gyros, accelerometers, and motion sensors

Excludes:

- devices—linkages, control surfaces, and actuating devices—covered under the airframe WBS element
- avionics devices and sensors—central computers, navigation computers, avionics data buses, and navigation sensors—which are included under other avionics WBS elements

Central Integrated Checkout

That equipment (hardware/software) installed in the air vehicle for malfunction detection and reporting.

Antisubmarine Warfare

That equipment (hardware/software) installed in the air vehicle peculiar to the antisubmarine warfare mission.

Includes, for example:

- sensors, computers, displays, etc.

Armament

That equipment (hardware/software) installed in the air vehicle to provide the firepower functions.

Includes, for example:

- guns, high-energy weapons, mounts, turrets, weapon direction equipment, ammunition feed and ejection mechanisms, and gun cameras

Weapon Delivery

That equipment (hardware/software) installed in the air vehicle to provide the weapon delivery capability.

Includes, for example:

- launchers, pods, bomb racks, pylons, integral release mechanisms, and other mechanical or electromechanical equipment specifically oriented to the weapons delivery function

Excludes:

- bombing/navigation system (included in the fire control element)

Auxiliary Equipment

Auxiliary airframe, electronics, and/or armament/weapon delivery equipment not allocable to individual element equipments, or which provides the ancillary functions to the applicable mission equipments.

Includes, for example:

- auxiliary airframe equipment such as external fuel tanks, pods, and rotodomes
- multiuse equipment like antennas, control boxes, power supplies, environmental control, racks, and mountings, not homogeneous to the prescribed WBS elements

Appendix D

AIRFRAME DEVELOPMENT COST-ESTIMATING RELATIONSHIPS

Airframe development includes four major cost elements: nonrecurring engineering, nonrecurring tooling, development support, and flight test. We independently estimated CERs for nonrecurring engineering (NRENGR) and tooling (NRTOOL) based on recent information obtained from AFCAA and the Naval Air Systems Command (NAVAIR).

NONRECURRING ENGINEERING AND TOOLING CERs

The CER for NRENGR hours was based on the most recent data from 13 military aircraft: A-4A, A-6A, AV-8B, B-2, B-52, F-4A, F-111A, F-14A, F-15, F-18 A/B, F-18 E/F, F-22, and S-3.

The NRENGR hours include the engineering hours spent developing the airframe. We note that such hours are incurred throughout an aircraft program's life, since design change effort, which occurs until program termination, is included in nonrecurring engineering.

The CER for NRTOOL hours was based on the most recent data from 10 military aircraft: A-6A, AV-8B, A-10, F-4, F-14, F-15, F-16, F-18A/B, F-18E/F, and F-22.

Nonrecurring tooling hours are those required to plan, design, fabricate, assemble, and install the initial set of tools, and all duplicate tools required for the planned rate of production.

The NRENGR and NRTOOL CERs are in hours and are listed in Table D.1.

Table D.1

Nonrecurring Engineering and Tooling Cost-Estimating Relationships (in hours)[a]

CERs	R^2	SEE	N
NRENGR = $7924.314\ WE^{0.561}\ ADVMAT^{0.671}\ (1.034)^{FF}\ (1.389)^{Stealth}$	0.97	0.26	13
(5.872) (0.488) (3.653) (1.156)			
NRTOOL = $2769.13\ AUW^{0.685}\ ADVMAT^{0.075}\ RATE^{0.570}\ (1.59)^{Stealth}$	0.86	0.24	11
(2.95) (0.95) (3.08) (1.29)			

[a] R^2 = coefficient of determination; SEE = standard error of estimate; N = sample size; numbers in parentheses are the t-statistics for each coefficient.

WE = Weight empty (lb.).

AUW = Airframe unit weight (lb.).

ADVMAT = composite and titanium weights as percentage of structural weight.[1]

RATE = maximum production rate that can be sustained by the development tooling (rate per month).

FF = year of first flight minus 1950.

Stealth = 0 for nonstealth aircraft and 1 for stealth aircraft.

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[1] We used the percentage of advanced materials instead of WMCF because we did not have a complete bill of material for all the aircraft used in the analysis.

Appendix E

SUBJECTS OF THE THREE RAND STUDIES ON INDUSTRY INITIATIVE DESIGNED TO REDUCE THE COST OF PRODUCING MILITARY AIRCRAFT

MR-1370-AF, *Military Airframe Costs: The Effects of Advanced Materials and Manufacturing Processes,* by Obaid Younossi, Michael Kennedy, and John C. Graser (2001)

Automated fiber placement

Computer-aided design/computer-aided manufacturing (CAD/CAM)

Electron beam (E-beam) curing

Filament winding

Infrared thermography

High-speed machining

High-performance machining

Hot isostatic press (HIP) investment casting

Laser forming of titanium

Laser ply alignment

Laser shearography

Laser ultrasonics

Optical laser ply alignment

Out-of-autoclave curing

Pultrusion

Resin film infusion

Resin transfer molding

Statistical process control

Stereolithography

Stitched resin film infusion

Superplastic forming/diffusion bonding

Unitization of aircraft structure

Ultrasonic inspection

Vacuum-assisted resin transfer molding

MR-1329-AF, *An Overview of Acquisition Reform Cost Savings Estimates,* by Mark A. Lorell and John C. Graser (2001)

Civil-military integration

Commercial-like programs

Commercial insertion

Commercial off-the-shelf (COTS) technology

Contractor configuration control

Cost as an independent variable (CAIV)

Defense acquisition pilot programs (DAPPs)

Federal Acquisition Reform Act (FARA)

Federal Acquisition Streamlining Act (FASA)

Integrated product teams

Military specification (mil spec) reform

"Must-cost" targets

Multiyear procurement

Other transaction authority (OTA)

Procurement price commitment curve

Regulatory and oversight burden reductions

Single-process initiative (SPI)

MR-1325-AF, *Military Airframe Acquisition Costs: The Effects of Lean Manufacturing,* by Cynthia R. Cook and John C. Graser (2001)

Cellular manufacturing

Computer-aided design/computer-aided manufacturing (CAD/CAM)

Continuous flow production

Design for manufacturing and assembly (DFMA)

Electronic data interchange (EDI)

Electronic work instructions (EWI)

Enterprise resource planning (ERP)

First-time quality

Flexible tooling

Integrated product teams

Just-in-time (JIT) delivery

Kaizen events

Kitting of parts or tools

Lean Aerospace Initiative (LAI)

Lean enablers

Lean human resource management (HRM)

Lean pilot projects

Operator self-inspection

Production cost reduction plans (PCRPs)

Purchasing and supplier management (PSM)

Pull production

Single-piece flow production

Six-sigma quality

Six “S’s” of housekeeping

Statistical process control (SPC)

Strategic sourcing agreements

Takt time

Target costing

Three-dimensional (3D) design systems

Total Productive Maintenance (TPM)

Unitization/part count reduction

Visual manufacturing controls *(Kanban)*

Value (cost) stream analysis

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With the reduction in post–Cold War defense budgets in the United States, affordability of weapon systems has become more important to Department of Defense decisionmakers and the Congress. Aerospace industry and some government officials have asserted that government cost estimates of defense programs use outdated methodologies that produce forecasts that are higher than they should be. This book updates cost estimating methodologies and focuses on military airframes by examining the costs of airframe materials and manufacturing processes.

After providing basic background on the various materials and manufacturing processes used to produce airframe structures, the authors analyze relative costs of the materials in terms of manufacturing labor hours and material costs. The data collected for the study consist of industry estimates of relative manufacturing costs of structural materials as well as analyses of part manufacturing data provided by industry. In general, the costs of manufacturing composite parts remain higher than comparable metal parts, even with new manufacturing processes and technologies. But composite parts are less costly than what historical data would suggest. The authors also find that technology in the metals area has advanced, so that manufacturing of metal structures requires fewer labor hours per pound than in the past. However, as aircraft designs evolve and performance requirements become more stringent, the question arises as to whether aircraft structures will require greater complexity, thereby offsetting some of the cost reductions achieved or forecast compared to historical manufacturing costs.

The book provides cost estimators and engineers with factors useful in adjusting or creating estimates of aircraft structure based on parametric estimating techniques. It recommends that cost analysts remain abreast of changes in industry practices so that they may accurately gauge the potential effects of continuing changes in processes and materials used in future airframe designs.

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