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PARAMETRIC COST ESTIMATION
APPLIED TO
COMPOSITE HELICOPTER AIRFRAMES

by

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March 1994

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Parametric Cost Estimation Applied to Composite Helicopter Airframes

by

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

Composite materials offer great promise to all future air vehicles by allowing engineers to design and build aircraft that weigh less, have better performance, and lower lifecycle cost. However, even though these materials have been used by the industry for over a decade, there still does not exist an accurate means to estimate their cost. The primary objective of this study is to develop cost estimating relationships for composite helicopter airframes. It also provides information about composite materials, cost estimation in the DoD acquisition process, and current composite material cost estimating models. An accurate cost estimate is a crucial element of any successful weapons acquisition program. The results of this study are the development of a predictive model that relates cost in direct labor hours to various performance parameters of a helicopter constructed of composite materials. This thesis should provide information to cost estimators and program managers that will assist them in formulating accurate cost estimates for composite helicopter airframes.

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I. INTRODUCTION

It is clear from a cursory examination of history that mankind's progress had been charted by his advances in materials technology. The Stone Age, the Iron Age, the Nuclear Age, the Electronic Revolution of today -- all have critically depended on, or resulted from, breakthroughs in material technology [Ref. 1]. Currently, we are witnessing the emergence of a new class of materials that will radically change the way we design and build rotorcraft forever.

Composite materials are a dynamic technology that promises to revolutionize our way of thinking about materials technology. They are the combination of two different substances which produces a material with highly desirable characteristics. Composites can be used to improve the strength and performance of anything from the space shuttle to helicopters to tennis rackets. Indeed, these extraordinary materials are an enabling technology for many future advances in the aerospace industry.

These remarkable materials offer great promise to all future air vehicles by allowing engineers to design and build aircraft that weigh less, have better performance, and result in lower lifecycle cost. However, even though they have been used by the industry for over a decade, there still does not exist an accurate means to estimate their cost.

A reliable cost estimate is a crucial element of any successful weapon system acquisition program, particularly in today's fiscally constrained environment. Information about the cost of a system is of paramount importance throughout the acquisition process, but it is most critical during the development of the cost and operational effectiveness analysis (COEA). The COEA is performed early in the acquisition cycle, prior to milestone I, when there does not exist a lot of detailed cost data about the new weapon system [Ref. 2:p. 10.A.1]. A parametric cost model would be a very useful tool at this early stage for assisting in predicting cost.

Composite materials have been used extensively in fixed wing aircraft and, therefore, there has been some research into fixed wing cost estimating relationships (CER) for composites. However, composite helicopter airframes have not received as much attention. Due to the lack of research in this subject area and the current vertical lift requirements of the Army, Navy, and Marine Corps, the focus of this thesis is on determining cost estimating relationships for composite helicopter airframes.

A. OBJECTIVE

The primary objective of this thesis is to determine cost estimating relationships for composite helicopter airframes. Paramount to this objective was the gathering of accurate cost data. This proved to be the most difficult and time consuming aspect of the entire thesis.

It is hoped that this study will provide information to assist cost estimators and program managers in formulating accurate cost estimates for composite materials.

B. RESEARCH QUESTION

The primary research question is what parametric model best forecasts the production cost of composite helicopter airframes. In an attempt to gain insight into this question, I must answer many subsidiary research questions. Some of the more significant ones are listed below:

1. What are composite materials and what are their uses?

2. What current models are available to assist the cost estimator?

3. What cost data are available and can it be used to develop an accurate cost estimating relationship?

4. What are the different approaches to cost estimation?

5. What is the role of cost estimation in the DoD weapons acquisition process?

C. SCOPE

The thrust of this thesis is the development of a parametric model that accurately predicts the cost of composite helicopter airframes. This model is focused on rotary wing aircraft consisting of composite materials because that is where the current need exists. The output from the model is direct labor hours for the first unit prototype composite airframe. This output is then manipulated to arrive at an average recurring direct labor hour estimate. Direct labor hours are the most difficult aspect of composite construction to estimate. The conversion of man labor hours to dollars, although not a trivial process, can be more accurately accomplished on a case-by-case basis.

D. METHODOLOGY

A comprehensive literature research was conducted to determine the existence and validity of available cost models. Research was also conducted to learn about advanced composite materials and the manufacturing processes associated with their applications. Personal interviews were conducted at Army Aviation and Troop Command (ATCOM), Naval Air Systems Command (NAVAIR), the Army Cost and Economic Analysis Center (CEAC), the Cost Analysis Improvement Group (CAIG), and private contractors. The data obtained were analyzed in accordance with the *Cost Estimators Reference Manual*, by

Rodney D. Stewert and Richard Wyskidia, as well as other current, acceptable statistical methods.

E. DEFINITIONS AND ACRONYMS

All acronyms are defined when first used, but as a convenience to the reader, a comprehensive list is presented in Appendix A. Definitions are listed in Appendix B. During the discussion of cost estimating relationships, critical definitions are further explained.

F. ORGANIZATION

The next chapter of this thesis is a discussion on the uses of composite materials in the current fleet of DoD helicopters as well as their use in developmental aircraft.

The third chapter is an investigation into the world of composites. It first defines composite materials and their uses in the aerospace industry. It then discusses the manufacturing considerations and nonrecurring costs associated with composites.

The fourth chapter is concerned with the cost estimation process. It discusses the role of cost estimation in the weapon systems acquisition process and three general cost estimation techniques. It then reviews the models currently available to estimate composite airframe cost and their advantages and disadvantages.

The fifth chapter is the development of cost models that may be useful in predicting the direct labor hours associated with the construction of a prototype composite helicopter airframe. The model is analyzed with respect to output and sensitivity analysis is performed to determine stability.

The sixth chapter applies the model developed in chapter five to a composite helicopter airframe. The prototype direct labor hours are then used to develop an average recurring direct labor hour for a production composite helicopter airframe.

The final chapter presents conclusions and recommendations to include areas of future research.

II. AIRCRAFT DATA

One of the initial steps in the development of a cost estimate is to understand the assigned system and its associated technology.

> An analyst should have a good knowledge of the kind of equipment with which he is dealing -- its characteristics, the state of its technology and the available sample. [Ref. 3:p. 12]

The purpose of this chapter is to provide that understanding. The first section of this chapter examines the current fleet of DoD helicopters. It presents information on the mission, flight parameters, and composite material usage. The second section presents rotorcraft that are currently under development by the Army and Navy. The last section discusses the Army Advanced Composite Aircraft Program (ACAP).

All information in this chapter was obtained from the *U.S. Military Aircraft Data Book*, *Jane's All the World's Aircraft*, and respective program offices. Each aircraft is presented in a table format with data on production, performance, mission and composite usage.

A. CURRENT FLEET

In the early 1980's, experts predicted an increase in the application of composite materials to all air vehicles.

> The future 1990+ helicopter airframes will be made almost entirely of fiberglass, graphite, kevlar, and other advanced composite materials in contrast to present helicopter airframes which are made principally of aluminum, steel, and titanium [Ref. 4:p. 1].

Although composite components are more commonplace today than they were in the past, their use has not grown as rapidly as previously predicted.

This section examines the selected characteristics and the application of composite materials to the current fleet of military helicopters. It presents only active duty component aircraft. It does not attempt to provide information on the various mission configurations and special operations variants that exist.

1. AH-1W Sea Cobra

The mission of the AH-1W Sea Cobra is armed helicopter escort. It can provide close in fire support and anti-armor capability during the ship-to-shore phase of an amphibious assault and ground operation. Various performance parameters are shown in Table 1.

The AH-1W Sea Cobra has a conventional all metal airframe. There are no significant amounts of composite materials utilized. An illustration of the aircraft is provided in Figure 1.

TABLE 1 AH-1W Sea Cobra				
U.S. Marine Corps		Bell Helicopter Textron		
Production Years	84-94	Weight:	Empty	10,140
Quantity	637		Take-off	14,750
Rotor Diameter	48		Pay Load	2,081
Length Fuselage	48.2	Maximum Speed		225
Height to Rotor Hub	14.2	Combat Range		395 Nmi
Overall Length	58.0	Service Ceiling		14,000

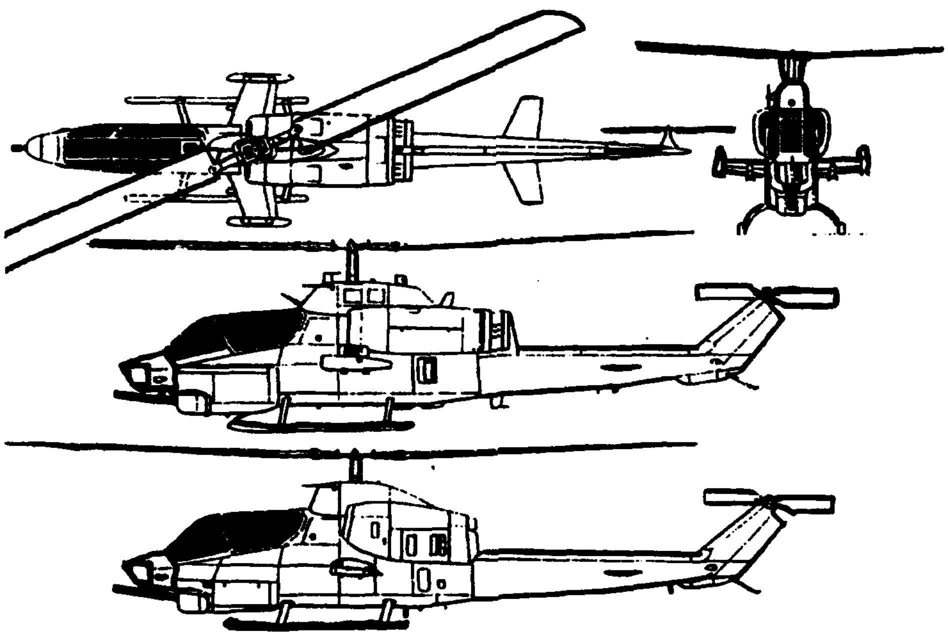

Figure 1 AH-1W Sea Cobra *(Source: Jane's All the World's Aircraft)*

2. OH-58D Kiowa Warrior

The mission of the OH-58D Kiowa Warrior is aerial observation and target acquisition. It is currently being retrofitted to an armed configuration with air-to-air stinger missile and air-to-ground weapons.

The OH-58D is comprised of 199 pounds of composite materials. Almost the entire rotor head is made from composite material. The main rotor blades and the tail rotor blade are constructed with a fiberglass epoxy. The main rotor blade yoke consists of a carbon composite material. The ball which houses the mast mounted sight is graphite composite. Performance parameters and an illustration of the aircraft are provided in Table 2 and Figure 2, respectively.

TABLE 2 OH-58D Kiowa Warrior			
U.S. Army		Bell Helicopter Textron	
Production Years	83-91	Weight: Empty	3,050
Quantity	250	Take-off	5,400
Rotor Diameter	35	Pay Load	1,000
Length Fuselage	33.1	Maximum Speed	118
Height to Rotor Hub	8.6	Combat Range	345 Nmi
Overall Length	42.2	Service Ceiling	12,000

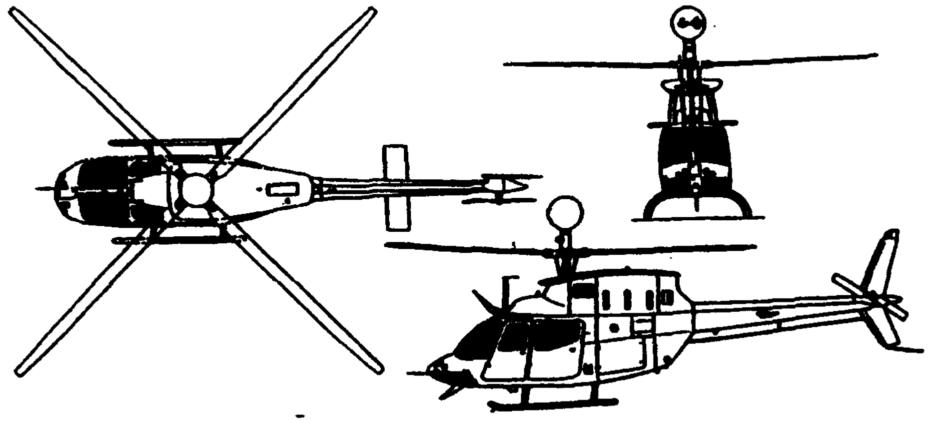

Figure 2 OH-58D Kiowa Warrior *(Source: Jane's All the World's Aircraft)*

3. AH-64 Apache

The AH-64 Apache provides anti-tank, anti-vehicle, anti-personnel capability in support of infantry and armored units. The helicopter is well suited to perform in both the attack and armed reconnaissance mode. It has all-night, all-weather capability and was extremely successful during Operation Desert Storm. Details are shown in Figure 3.

The AH-64 hosts 408 pounds of composite materials. This represents approximately 5 percent of the aircraft empty weight. The majority of the composite material is kevlar used on aerodynamic fairings and secondary structures which provides ballistic protection. The main rotor blades of the AH-64 are also constructed of composite material. Further data are provided in Table 3.

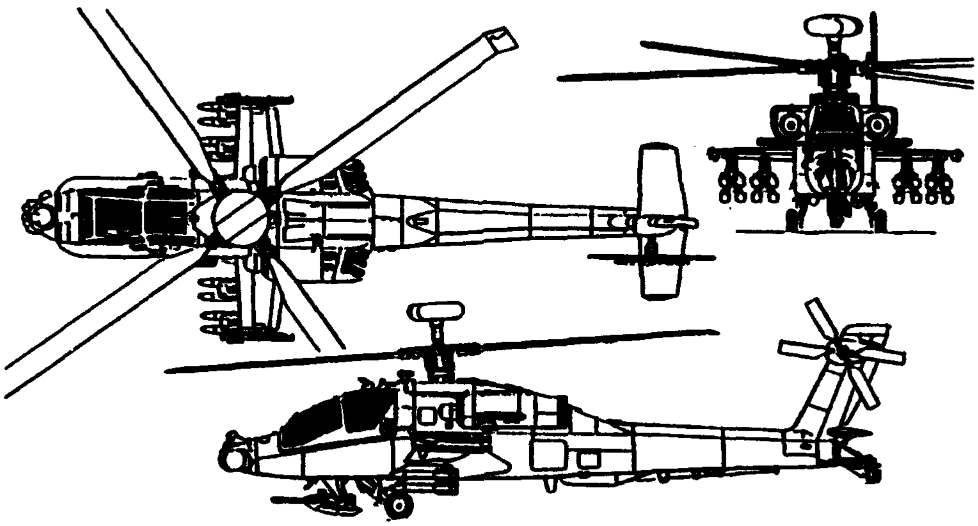

Figure 3 AH-64 Apache *(Source: Jane's All the World's Aircraft)*

TABLE 3 AH-64 Apache			
U.S. Army		McDonnell Douglas Helicopter	
Production Years	81-93	Weight: Empty	11,015
Quantity	811	Take-off	17,650
Rotor Diameter	48	Pay Load	2,527
Length Fuselage	49.5	Maximum Speed	236
Height to Rotor Hub	12.4	Combat Range	525 Nmi
Overall Length	57.6	Service Ceiling	20,500

4. CH-47D Chinook

The mission of the CH-47D Chinook is to provide combat service and combat service support. Because of its large cargo carrying capability, it is extremely useful in providing rapid aerial transportation of troops and equipment. It has both external and internal cargo carrying capability. The Chinook is shown in Figure 4.

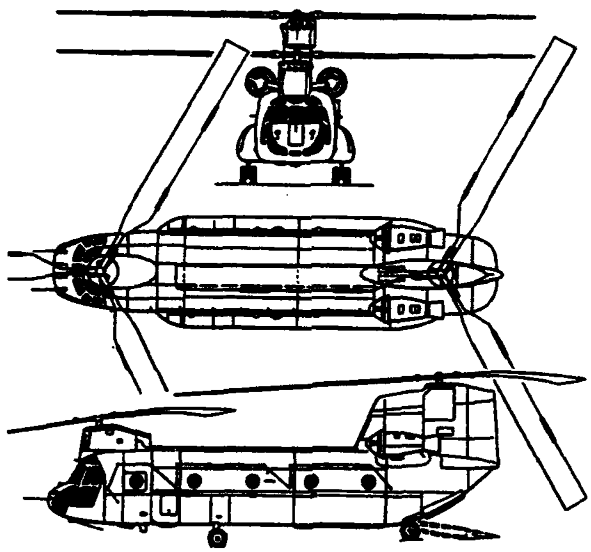

Figure 4 CH-47D Chinook *(Source: Jane's All the World's Aircraft)*

The CH-47D utilizes 2014 pounds of composite materials. The main rotor blades and the fuel pods structure are almost exclusively fiberglass. Approximately 8.7 percent of aircraft empty weight is composite materials. Additional parameters are provided in Table 4.

TABLE 4 CH-47D Chinook			
U.S. Army			Boeing Helicopters
Production Years	80-92	Weight: Empty	23,100
Quantity	472	Take-off	50,000
Rotor Diameter	60	Pay Load	22,000
Length Fuselage	51	Maximum Speed	178
Height to Rotor Hub	18.8	Combat Range	200 Nmi
Overall Length	99.0	Service Ceiling	12,800

5. SH-60B Sea Hawk

The mission of the SH-60B Sea Hawk is to provide anti-submarine warfare, plane guard, search and rescue, as well as medevac and logistic operations.

The SH-60B incorporates 612 pounds of composite materials. The majority of this consists of fiberglass and kevlar. The tail rotor blades and main rotor blades both have composite skins. The drive shaft cover, the engine and transmission cowlings, and many other secondary structures are composed of kevlar and graphite. Details are provided in Figure 5 and Table 5.

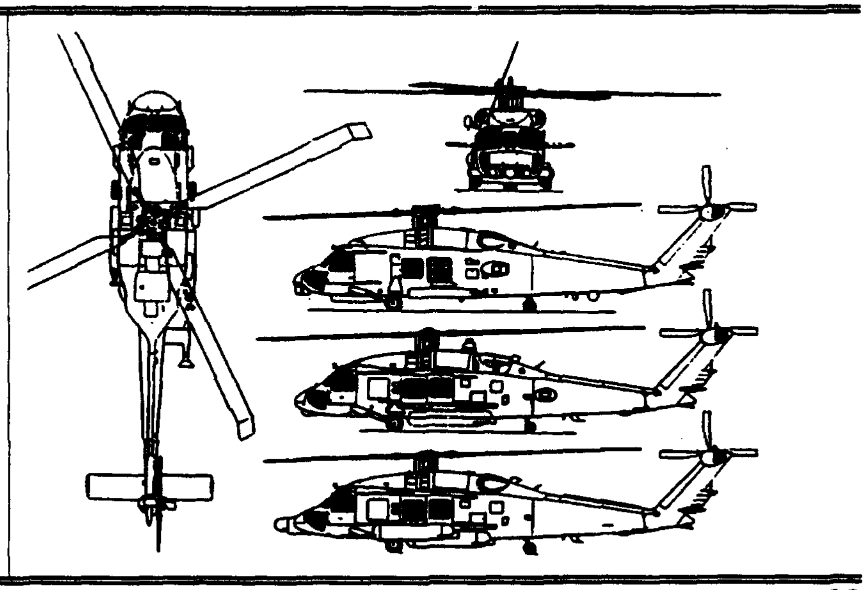

Figure 5 SH-60B Sea Hawk *(Source: Jane's All the World's Aircraft)*

TABLE 5 SH-60B/F Sea Hawk			
U.S. Navy			Sikorsky Aircraft
Production Years	81-99	Weight: Empty	13,648
Quantity	261/175	Take-off	21,884
Rotor Diameter	53.8	Pay Load	5,000
Length Fuselage	50	Maximum Speed	171
Height to Rotor Hub	17	Combat Range	680 Nmi
Overall Length	64.8	Service Ceiling	19,000

6. UH-60A/L Blackhawk

The mission of the UH-60A/L Blackhawk is to transport troops and equipment into combat, resupply them, and perform associated functions of aeromedical evacuation and other combat support missions. A depiction of the Blackhawk can be seen in Figure 6.

Like the Sea Hawk, the UH-60 incorporates 612 pounds of composite materials. The majority of this consists of fiberglass and kevlar. The tail rotor blades and main rotor blades both have composite skins. The drive shaft cover, the engine and transmission cowlings, and many other secondary structures are composed of kevlar and graphite. Additional details can be found in Table 6.

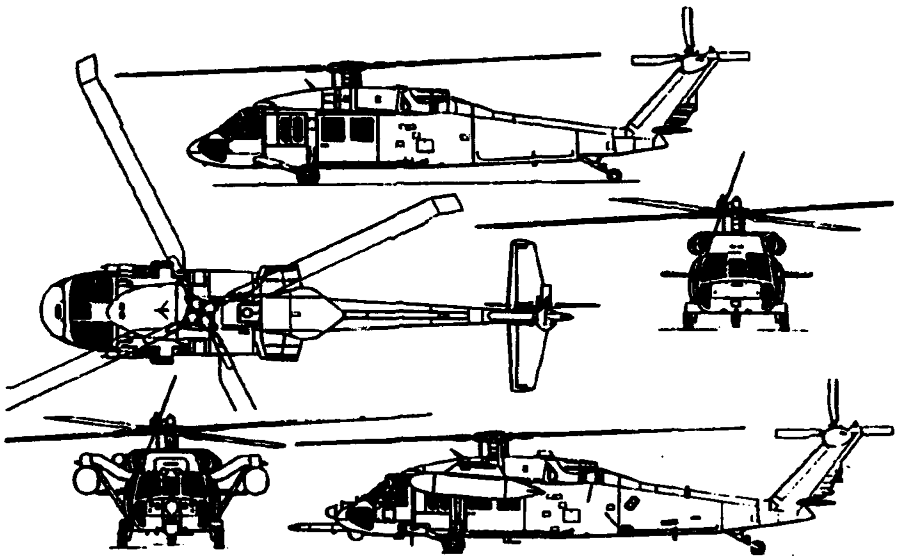

Figure 6 UH-60A/L Blackhawk *(Source: Jane's All the World's Aircraft)*

TABLE 6 UH-60A/L Blackhawk			
U.S. Army			Sikorsky Aircraft
Production Years	77-98	Weight: Empty	17,295
Quantity	1,437	Take-off	23,000
Rotor Diameter	58.7	Pay Load	12,050
Length Fuselage	50.1	Maximum Speed	184
Height to Rotor Hub	16.8	Combat Range	330 Nmi
Overall Length	64.8	Service Ceiling	19,100

7. C/MH-53E Super Stallion

The mission of the C/MH-53E Super Stallion is shipboard compatible heavy transport. It conducts fleet replenishment and mine countermeasure operations. The Super Stallion is the largest helicopter within the DoD fleet.

The C/MH-53E utilizes kevlar in transmission fairings and engine cowlings. The rotor blades consist of fiberglass composite skin over a nomex honeycomb core. Additional details are provided in Table 7 and Figure 7.

TABLE 7 C/MH-53E Super Stallion			
U.S. Navy/Marine Corp			Sikorsky Aircraft
Production Years	77-96	Weight: Empty	34,000
Quantity	197	Take-off	75,100
Rotor Diameter	79	Pay Load	32,000
Length Fuselage	73.8	Maximum Speed	196
Height to Rotor Hub	27.9	Combat Range	990 Nmi
Overall Length	99	Service Ceiling	27,900

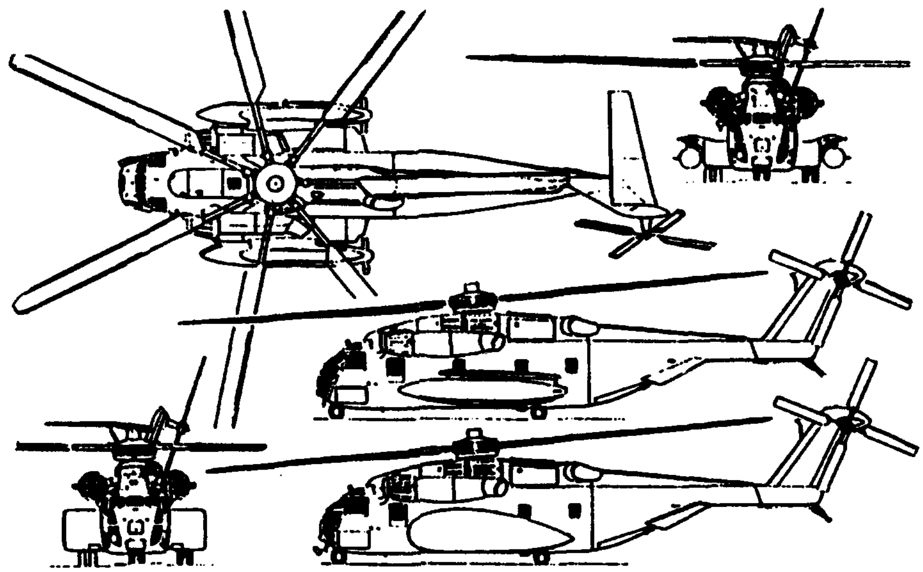

Figure 7 C/MH-53E Super Stallion *(Source: Jane's All the World's Aircraft)*

B. DEVELOPMENT AIRCRAFT

This section explores two military aircraft presently being developed by the Army and the Navy. These aircraft incorporate large amounts of composite materials in their respective airframes. It should be noted that some of the material presented on these development aircraft could possibly change as the result of program evolution.

1. V-22 Osprey

The V-22 Osprey is a multi-mission, tilt-rotor, vertical take-off and landing aircraft. It will provide the amphibious/vertical assault needs of the Marine Corps and Navy. The V-22 is a joint development between Bell Helicopter

Textron and Boeing Helicopter. It is currently in the advanced engineering manufacturing development (EMD) stage.

Approximately 31% of the airframe is composite material. Graphite epoxy is used extensively in the wing, fuselage and tail sections. In addition, the floor panels and cockpit enclosure utilize composite materials. Additional details are provided in Figure 8 and Table 8.

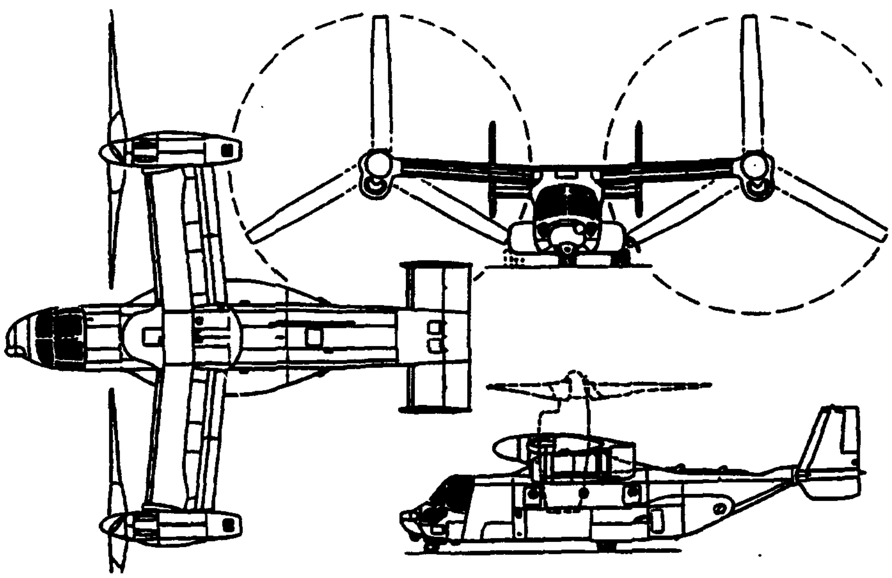

Figure 8 V-22 Osprey *(Source: Jane's All the World's Aircraft)*

TABLE 8 V-22 Osprey			
U.S. Navy/Marine Corp/Air Force		Bell Helicopter Textron/ Boeing Helicopter	
Production Years	92-98	Weight: Empty	31,786
Quantity (development)	10	Take-off	55,000
Wing Span	46.5	Pay Load	24,000
Length Fuselage	56.8	Maximum Speed	319
Height to Rotor Hub	17.4	Combat Range	450 Nmi
Overall Length	56.8	Service Ceiling	30,000

2. RAH-66 Comanche

The RAH-66 is the Army's next generation rotorcraft which will replace the aging unarmed scouts and AH-1 attack helicopters. It will be used for observation and attack missions. The Comanche is in the advanced stage of demonstration/validation. A depiction of the Comanche can be seen in Figure 9.

The Comanche airframe will consist of approximately 60% composite materials. The entire fuselage will be built around an all composite internal box beam. The rotor system, fuselage and secondary structures will all contain significant amounts of this advanced material. Additional parameters are shown in Table 9.

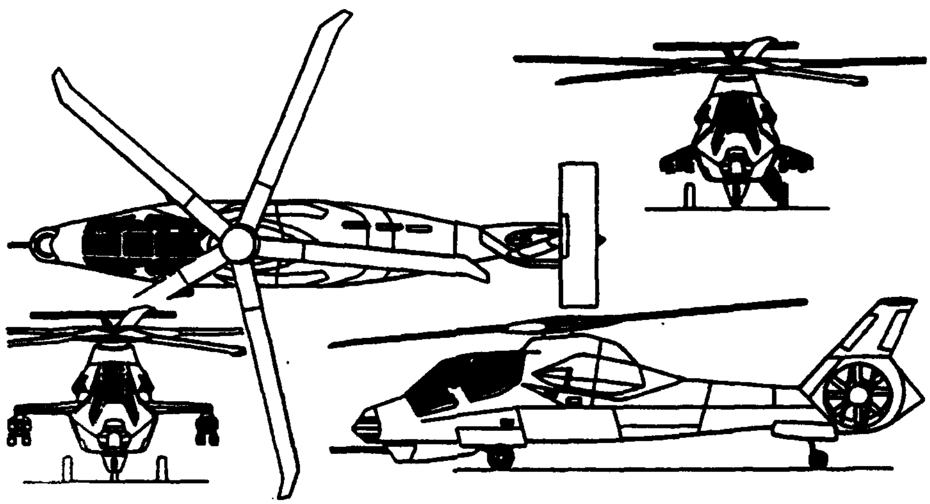

Figure 9 RAH-66 Comanche *(Source: Jane's All the World's Aircraft)*

TABLE 9 RAH-66 Comanche			
U.S. Army		Boeing Helicopter/Sikorsky Aircraft	
Production Years	94-98	Weight: Empty	7500
Quantity (projected)	1292	Take-off	12000
Rotor Diameter	39	Pay Load	2200
Length Fuselage	43.4	Maximum Speed	184
Height to Rotor Hub	11	Combat Range	1260 Nmi
Overall Length	47.5	Service Ceiling	Unknown

C. ADVANCED COMPOSITE AIRFRAME PROGRAM (ACAP)

This ambitious program was initiated by the Aviation Applied Technology Directorate of the U.S. Army Aviation

Systems Command. The purpose of the program was to demonstrate the advantages of the application of advanced composite materials to the airframe structure of a military helicopter [Ref. 5:p. 657]. The ACAP venture included a preliminary design phase, detailed design and design support testing, full-scale fabrication, laboratory testing, and a ground/flight test demonstration.

In 1979, the U.S. Army awarded contracts to five major U.S. helicopter manufacturers to conduct a preliminary design of an all-composite helicopter airframe. The aircraft was to be designed as a utility helicopter weighing less than 10,000 pounds with a 2.3 hour mission endurance. The results of these preliminary design studies indicated that a 22% reduction in aircraft weight and a 17% reduction in production cost could be achieved while improving the crashworthiness, reliability, maintainability, and survivability of the helicopter [Ref. 5:p.658].

The Army selected Bell Helicopter Textron and Sikorsky Aircraft to proceed with the detailed design phase of their respective helicopters in March of 1981. The basic approach to detailed design by each contractor was substantially different and was indicative of their background and experience with other composite designs. It is interesting to note that the ACAP detailed design was performed with the use of Computer Aided Design (CAD), a first for U.S. military helicopters [Ref. 5:p.659]. The Bell D292 and the Sikorsky S-75 helicopters are shown in Figures 10 and 11.

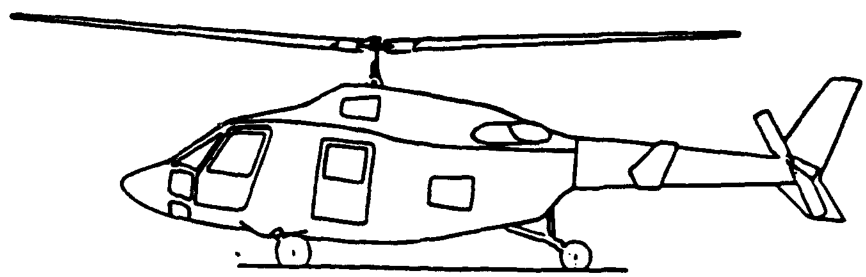

Figure 10 Bell ACAP D292

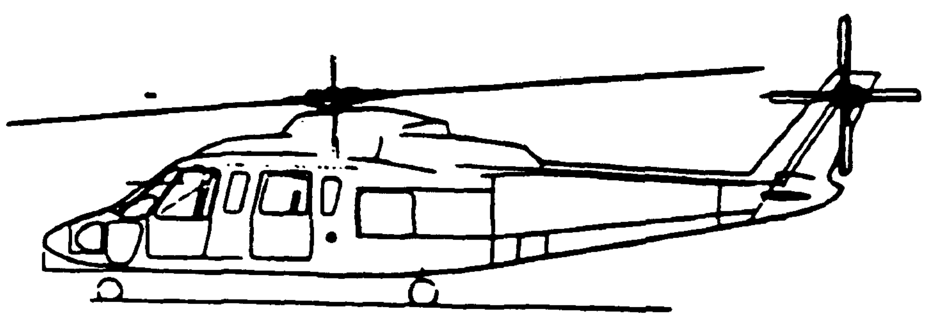

Figure 11 Sikorsky ACAP S-75

During full scale fabrication each manufacturer was required to maintain detailed cost and weight data on all components. Both contractors fabricated three composite airframes. The first was the tool proof article (TPA) and was used to verify the tooling concept. The TPA also underwent ballistic testing to determine the survivability of a composite airframe. The second vehicle was the static test article (STA) and was used for both static and shake testing. The final airframe was fabricated with all the dynamic systems, subsystems, and landing gear to produce an airworthy flight test vehicle (FTV) [Ref. 5:p. 663].

The Sikorsky S-75 conducted its first flight in July of 1984. Slightly over a year later, in September of 1985, the Bell D-292 made its maiden flight. Numerous flight tests were conducted for the next three years to evaluate various aspects of the composite helicopters airframes. These tests included analysis of vibrations, weapon system blasts, acoustic levels, radio reception, and electrical grounding. After providing significant amounts of valuable composite airframe information, the program was designated complete in early 1989.

III. COMPOSITE MATERIALS

The next step in the development of an accurate estimate is to become familiar with the materials utilized and any associated advanced technologies.

> In order to provide accurate cost estimates it is essential to have a thorough understanding of material behavior and processing capabilities [Ref. 6:p. 69].

This chapter explores the composite material manufacturing process and briefly addresses some pertinent manufacturing issues concerning this technology. It then defines and classifies composites and gives examples of their use in the aerospace industry.

A. MANUFACTURING CONSIDERATIONS

There are a wide variety of manufacturing processes available for providing composite helicopter airframes. The manufacturing process selected has a tremendous impact on the airframe cost. Particular fabrication methods are governed not only by the types of materials used as reinforcement and matrix, but by equipment requirements and desired composite properties [Ref. 7:p. 69].

This section provides a brief overview of the general process used to produce composite structures. It is beyond the scope of this thesis to detail all the different types of fabrication techniques utilized by the aerospace industry. However, it is important to understand the basic manufacturing process and some significant cost considerations.

1. Process

The manufacturing of composite components is accomplished by transforming raw composite material into a usable airframe component. Each step of the process is constantly changing and evolving in response to technology advances, design considerations, and cost implications. The selection of the fabrication process is determined by the characteristics of the composite material, part complexity, and the quantity of components to be produced. Table 10 details some current fabrication techniques [Ref. 6:p. 67].

TABLE 10
Current Production Techniques for PMC Components

Technique	Characteristics	Examples
Sheet molding	Fast, flexible, 1-2" fiber	SMC automotive body parts
Injection molding	Fast, high volume very short fibers, thermoplastics	Gears, fan blades
Resin transfer molding	Fast, complex parts, good control of fiber orientation	Automotive structural panels
Prepreg tape lay-up		
- hand	Slow laborious, reliable, expensive (speed improved by automation)	Aerospace structures

TABLE 10
Current Production Techniques for PMC Components

Technique	Characteristics	Examples
- Automated Tape Lay-up (ATL)	Fast for large area, uniform thickness	Skin structures
- ATL + drape forming	Fast, flexible requires further process development	I-, J-, hat-sections
Pultrusion	Continuous, constant cross-section parts	I-beams, columns
Filament winding	Moderate speed, complex geometries, hollow parts	Aircraft fuselage, pipes, drive shafts, rocket motor cases
Thermal forming *(future)*	Reinforced thermoplastic matrices; fast, easy repair, joining	All of above

Prior to fabrication, composite materials are acquired in a "preform" or "prepreg" condition. Prepregs are reinforcement materials (usually tape, fabric, or broad good) which have been pre-impregnated with liquid matrix material and precured to a viscous state [Ref. 14:p.38]. Preforms are different from prepregs in that the matrix material and reinforcement material are in separate states until combined for fabrication of the component.

The composite material is then cut into patterns for the lay-up process. At one time, pattern cutting was performed manually. However, automated pattern cutting, such as Gerber knife machines, waterjets, lasers, and chisel cutters, are now common among the major composite manufacturers. These automated machines are much faster, more accurate, and reduce the need for costly inspections [Ref. 14:p. 40].

Once the patterns are cut, each ply is laid-up and oriented in the tool as predetermined by design [Ref. 7:p. 13]. Fiber alignment is critical to ensure the composite component meets performance requirements. Therefore, lay-up is the most demanding and costly step in component fabrication. The lay-up process, by one estimate, represents 30 percent of all composite labor costs [Ref. 14:p. 40].

Although there have been advances in automation of lay-up procedures, much of the lay-up in the aerospace industry is accomplished manually. Even the recent Northrop Stealth Bomber aircraft and the Beech Starship general aviation airplane have the labor-intensive hand lay-up sequence in their production [Ref. 6:p. 69].

Depending on the lay-up procedure used, debulking may be necessary prior to proceeding to the curing phase. Debulking is the compacting of plies to eliminate any internal gaps or voids [Ref. 14:p. 41]. Curing is accomplished through the application of temperature and pressure. The most common technique requires the use of a vacuum bag and an autoclave. The vacuum bag encloses the component and maintains pressure between the composite laminate and the forming tool. The autoclave is a device that produces an environment of fluid pressure, with or without heat that facilitates the curing process. However, the exact process varies depending on the type of composite material being utilized. Essentially, curing transforms the composite material into its final hardened state.

The last step in the manufacturing process is assembly of the composite part. Mechanical assembly procedures include drilling holes, trimming, cutting, sanding, bonding, cocuring (practically speaking, this is part of the cure cycle), fitup, mechanically fastening, etc. [Ref. 14:p. 42]. Assembly incorporates the composite part with other components to construct the entire airframe. The actual assembly or joining of composites is not a trivial process. The "Achilles heel" of many structural designs is the joint configuration and method of joining. In aircraft structures, one objective is to reduce the number of metallic fasteners which add weight and increase cost in terms of assembly time [Ref. 6:p. 14].

2. Cost Considerations

The major cost drivers associated with the fabrication of composite helicopter airframes are the result of immature manufacturing technology. The development of new cost effective fabrication technologies for the end-use conversion of new materials has been, and remains, a major obstacle in the timely realization and implementation of advanced materials technologies [Ref. 6:p. 67]. Clearly, more advanced research must be accomplished in this extremely critical area.

This shortcoming that impedes application of composite materials also hinders progress in the development of accurate cost estimates. This section presents some cost issues that must be considered by the analyst when attempting to develop cost estimates.

a. Part Complexity

Perhaps it is intuitively obvious that the size and shape of a composite component influences its cost. However, the part complexity also impacts the ability of an airframe manufacturer to automate his process.

Generally speaking, the more complex the shape of a composite component, the more costly it is to manufacture. The complexity characteristics associated with the fabrication processes -- curvature, cutouts, and contour -- influence the difficulty of the fabrication process, specifically ply lay-up, vacuum bagging of the structure, and cutting and trimming procedures [Ref. 8:p. 11]. More complex components require more skillful composite technicians or expensive robotics equipment.

b. Automation

The amount of automation applied to the manufacturing process directly impacts costs. Automation equipment involves significant initial capital investment. However, there is significant potential savings in recurring labor costs in the long run. Many experts agree that automation will make composite materials more competitive with conventional monolithic metals.

While there have been improvements in the automation of composite manufacturing, many firms continue to use large amounts of touch labor. Implementing automation in this (airframe) industry has not been easy given the limited production of aircraft, the high cost of automation equipment, and the complexity of typical aircraft composite parts [Ref. 9:p. 88]. It is clear that companies will automate only when it is in their benefit to do so.

c. Tooling

The tooling required to manufacture composite helicopter airframes is difficult to design and fabricate. This, in turn, causes them to be very expensive. Non-recurring tooling for composite products is, and will be, substantially higher than non-recurring tooling for aluminum products [Ref. 14:p. 60].

The major reasons for these higher costs are: temperature and pressure requirements of the autoclave; mismatch of the coefficient of thermal expansion between the tool and the composite part; and the need for highly accurate tools. Also, because of the curing requirements of composite materials, multiple sets of tooling and molds are required in order to produce components at a reasonable rate.

d. Assembly

Assembly can be a considerable portion of the total part cost; estimates range as high as 40 percent [Ref. 14:p. 42]. Composite materials can be joined to each other through a technique called cocuring. This process both cures and joins multiple parts through application of temperature and pressure. The main limiting factor on cocuring is autoclave size.

Joining composite parts to metal parts is significantly more difficult and costly. This process requires standard mechanical fastening methods. Consideration must also be given to the Galvanic reaction that occurs when aluminum and graphite are in contact. Corrosion is the result of any such contact, and thus more expensive titanium fasteners are used instead of aluminum [Ref. 14:p. 42].

e. Scrap Rates

The fabrication of composite parts inherently produces large amounts of scrap material. Since composite materials are purchased in the form of rolls of fabric or tape, there will always be some scrap from the pattern cutting process [Ref. 10:p. 12.2]. In addition, substantial scrap material is generated in the finish trim operations.

Very high scrap rates were experienced in the Army's Advanced Composite Airframe Program (ACAP) by both contractors. During the prototype air vehicle fabrication, scrap rates as high as 115 percent were common [Ref. 10:p. 7.5]. However, the contractor asserts that the scrap rate was abnormally high because it was a prototype fabrication. The contractor's estimate for a production airframe was a 25 percent scrap rate [Ref. 10:p. 7.6].

It is important for the cost analyst to note that the scrap rates for composite airframe manufacturing will be high, especially for early production runs. However, as the production quantities increase and the manufacturing processes becomes more automated, scrap rates should come down to a more reasonable level.

B. TYPES OF COMPOSITES

Broadly defined, composites are the result of embedding a fibrous material in the surrounding matrix of another material. Figure 12 depicts some examples of composite materials [Ref. 15:p. 11]. The reinforcing fibers provide strength and stiffness while the

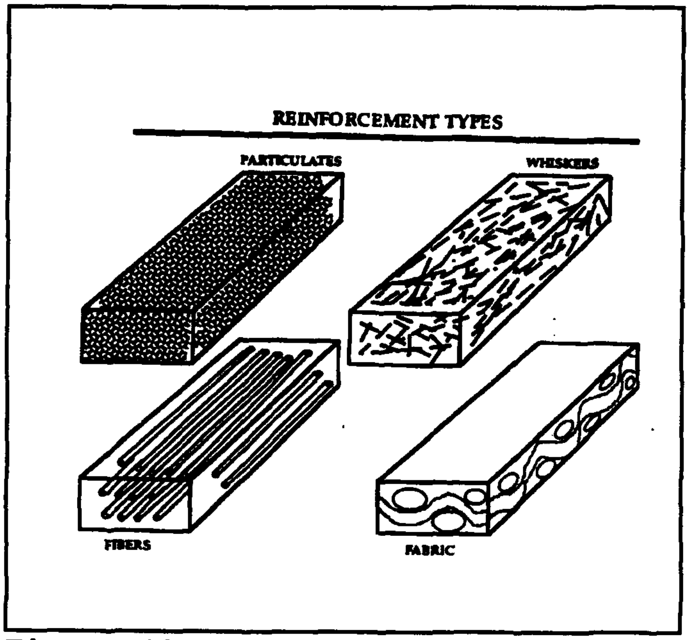

Figure 12

purpose of the matrix is to transfer loads between the fibers [Ref. 6:p.2]. The resulting substance has beneficial properties which far exceed the characteristics of the original materials. Composite materials range from relatively simple reinforced plastics to complex silicon carbide ceramics. The latter category is referred to as "advanced" composites and is distinguished from the former by its high performance characteristics. The focus of this thesis is on composites utilized by the aerospace industry with only a slight detour to gain historical perspective.

It is difficult to establish the origins of composites, but the first written record of them dates back before the birth of Christ. The Israelis discovered that placing straw in the mortar of bricks caused them to dry faster with less cracking and produced a stronger building material. The American Indian added the sinew from animals to willow branches to make strong, flexible bows for hunting [Ref. 11]. Although composite materials have existed in crude form for hundreds of years, experts credit the Cold War as the catalyst for the development of modern composites. The National Aeronautics and Space Administration (NASA) and DoD, with the need for high performance materials, funded the research and development of these remarkable materials. For twenty years, between 1969 and 1989, composites have experienced phenomenal growth, especially in the aerospace and defense-related industries. There is also some usage in sports equipment, as well as some limited usage in automotive and industrial applications [Ref. 12].

Advanced composites are high performance materials that are the result of detailed design and complex processing. They are classified in the following categories: polymer matrix composites, metal matrix composites, ceramic matrix composites, carbon-carbon composites and hybrid composites. Figure 13, shown below, illustrates the composite material family. I will now describe each type of composite material and its application within the aerospace industry.

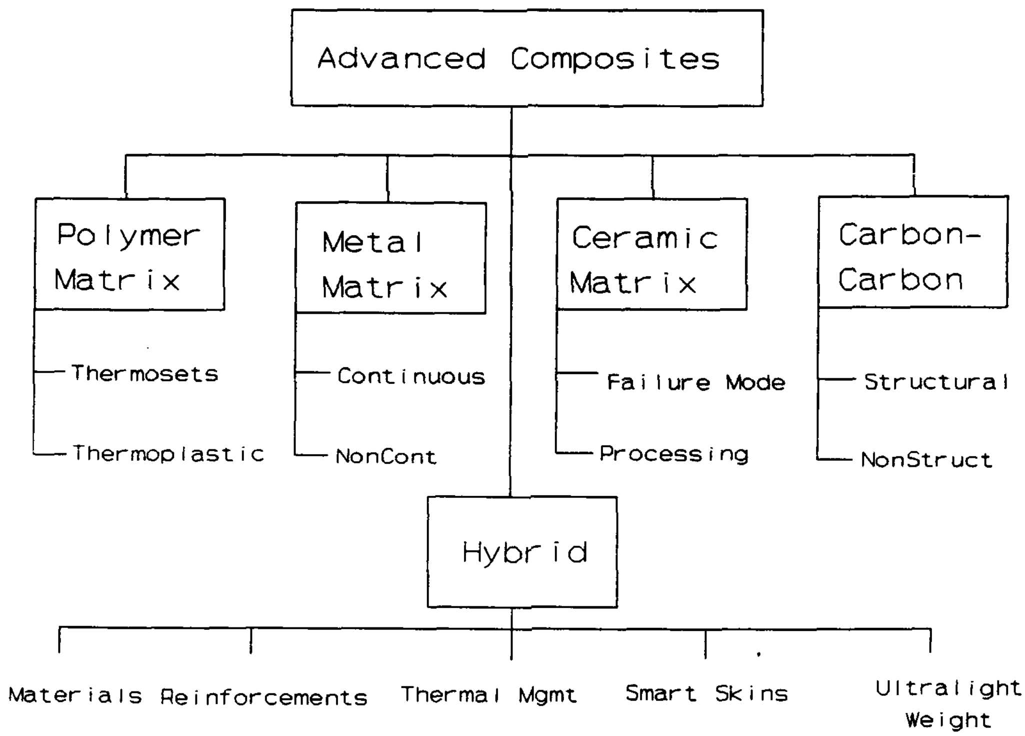

Figure 13 Composite Material Family

1. POLYMER MATRIX COMPOSITES (PMC)

a. Description

Polymer matrix composites (PMCs) are named for the organic polymer matrix which binds together the reinforcing fibers of carbon, kevlar, or boron. The combination of strong, stiff filaments within a matrix of epoxy or polyamide produces a material which is not only lightweight but has the desirable properties of high stiffness and strength. Polymer matrix composites also have greater corrosion and fatigue resistance as compared to most other metals. These advanced composite materials are categorized as thermosets or thermoplastics [Ref. 6:p.28].

(1) Thermosets

Thermosets use epoxy, polyamides or bismaleimides as their matrix material. Epoxy thermosets have existed for over two decades and are considered suitable for many applications, especially in the aerospace and sporting goods industry. Although they are considered strong, the desire for improved temperature tolerance and toughness led to the development of polyamides and bismaleimides.

Polyamides have excellent temperature tolerance (600 degrees fahrenheit) but they must be processed at temperatures that exceed the average autoclave. This requires a substantial modification to the manufacturing process and, therefore, a large investment by the manufacturer.

Bismaleimides have a lower processing temperature than polyamides, but retain much of the heat tolerance capabilities except at the very high-end range [Ref. 13]. Thermosets retain their strength up to temperatures of 450 degrees fahrenheit and can be processed in the standard autoclave. Production parts made from these advanced thermosets are prevalent in the secondary structures of aircraft, particularly in advanced high performance helicopters.

(2) Thermoplastics

This second general category of PMCs offers great promise in overcoming many of the deficiencies and shortcomings of thermosets. Thermoplastics have been the subject of intense research because of their potential for increased toughness, short processing times, and reformability of parts [Ref. 14:p. 23]. There are numerous thermoplastics in existence today, with the most common being polyetherether-ketone (PEEK), polyphenylene sulfide (PPS), and polyether-ketone (PEK).

Although thermoplastics have superior performance characteristics compared to most thermosets, more advanced manufacturing processes must be developed before their use increases significantly. The high temperature requirements (650 - 800 degrees fahrenheit) will undoubtedly force upgrades to the current manufacturing processes. When processing temperatures exceed 650 degrees fahrenheit, many conventional manufacturing procedures and equipment must be revised or replaced. For example, metal tools will degrade very quickly, rubber tools cannot be used at all, and autoclaves are subject to extreme wear [Ref. 14:p.24].

b. *Applications*

PMCs are the most commercially available and widely used of all advanced composites. The market is considered international, and there is a solid manufacturing and technological base both in the United States and overseas. PMCs have prevailed in the airframe industry for more than 25 years because they strike an effective balance among performance, versatility, and cost [Ref. 14:p.22].

PMCs are the most commonly used composite material on helicopter airframes. They are utilized in rotor blades, cowlings and support panels on many DoD helicopters. Discussions contained in this thesis pertaining to composite materials are, unless otherwise noted, exclusively referring to PMCs.

2. METAL MATRIX COMPOSITES (MMC)

a. *Description*

Metal matrix composites (MMCs) consist of a metal matrix (aluminum, titanium, magnesium copper) reinforced with fibers of another material (typically graphite, boron, silicon carbide, and aluminum oxide). Using fiber reinforcements with metal matrices yields superior temperature capabilities while maintaining strength-to-density properties greater than those achieved by superalloys. Metal matrix composites offer better compression strength than polymer or ceramic matrix composites [Ref. 12:p. 6]. These materials also have the distinct advantage over other advanced composites of being able to readily conduct heat and electricity.

The type of reinforcement virtually determines every aspect of the composite. The reinforcement determines mechanical properties, the composite cost, and the approach and cost of manufacturing [Ref. 12:p. 5]. In addition, MMCs are categorized according to the reinforcement fibers length-to-diameter ratio. Metal matrix composites with short fiber length (particulates, flakes, and whiskers) are labeled discontinuous, while those with long fiber length (filaments, woven, or continuous wires) are called continuous.

(1) Discontinuous

Discontinuous MMCs have reinforcements spread evenly throughout the matrix material. These short fibers strengthen the material while maintaining many of the fabrication and design properties of the metal matrix. In many instances, the same or slightly modified metallurgical processes and fabrication techniques can be used with discontinuous MMCs [Ref. 14:p. 25].

The major disadvantages of discontinuous MMCs becomes evident during the secondary fabrication of the material, when the composite is incorporated into an end product. Conventional machining tools cannot withstand the hardness of MMCs, particularly when silicon carbide, one of the hardest materials known to man, is used as a reinforcing fiber. It is also difficult to join these composite materials using existing methods such as welding. Currently, extensive research is being conducted to overcome these problems.

(2) Continuous

This type of MMC utilizes continuous fibers within a matrix of metal. Unlike discontinuous MMCs, the fibers do not strengthen the matrix but rather form a union with it, resulting in a strong composite material being created. The orientation of the continuous fibers is also an important consideration for determining the properties of the MMC. For strength and modulus, the highest values are obtained when the reinforcing fibers are straight and parallel [Ref. 12:p. 8].

The major advantage of continuous MMCs is their high strength coupled with low weight, high temperature tolerance, and directional tailorability. Because of these characteristics, this material was used for the antenna mast on the Hubble Space Telescope and the support struts in the space shuttle. However, the high cost of the fibers and the complexity of the manufacturing process continues to limit the use of continuous metal matrix composites in most helicopter airframe applications.

b. Applications

Although the DoD has funded much research in MMCs, there is currently little in the way of military applications. The most notable military application is the whisker reinforced aluminum repair patches and escapes hatches for C-131 aircraft produced by the Advanced Composite Materials Corporation [Ref. 15:p. 36].

The earliest commercial application occurred in 1983 when Toyota made pistons for their diesel engines out of a discontinuous MMC. Mitsubishi also incorporated the design in their pistons. The Honda Prelude Si engine boasts of reduced weight, better wear resistance, improved friction resistance and increased horsepower due to a metal matrix composite cylinder liner.

In 1989, aluminum graphite drive shafts entered the automotive market on GMC and Chevrolet pickup trucks. The drive shafts, developed jointly by Hercules Inc. and Dana Corporation, offer a 60% weight reduction versus a two piece steel assembly [Ref. 12:p. 16]. There is also some prototyping of brake systems and other automobile applications by Duralcan, Lanxide, Allied Signal, Rockwell, Ford and Mahle.

This material has great potential in the aerospace industry. Metal matrix composites could be used to replace steel push-pull tubes and drive shafting in helicopter airframes. These substitutions would not only provide added strength and stiffness but would increase damage tolerance as well [Ref. 15:p. 35].

3. CERAMIC MATRIX COMPOSITES (CMC)

a. *Description*

Ceramic matrix composites (CMCs) are a class of structural material with reinforcements such as silicon carbide fibers embedded in a ceramic matrix such as alumina, silicon carbide or silicon nitride [Ref. 12:p.22]. Although research into this advanced composite has made great strides, it is still considered an immature technology. The fiber reinforcements, matrix materials, and manufacturing processes are constantly being improved and developed.

It is anticipated that CMCs will offer exceptional wear resistance, high temperature strength (in excess of 3000 degrees fahrenheit), and greater chemical stability compared with metals. Two obstacles to widespread use of ceramic matrix composites are the development of high strength, high modulus, small diameter, continuous fibers whose mechanical properties are not drastically degraded by ceramic matrix processing, and fabrication processes that result in uniform nondegraded aligned fiber surrounded by low porosity matrices [Ref. 12:p.25].

b. Applications

My research indicates that there is very little in the way of an industrial base specifically for CMCs. However, there is a tremendous amount of Government interest in this technology, and it is considered **enabling** for many advanced programs. Key specific applications for ceramic matrix composites include the High-Speed Civil Transport (HSCT) and its Enabling Propulsion Materials Program (EPM) initiative, National Aerospace Plane (NASP), Boost-Glide Vehicle (BGV), Advanced Tactical Fighter (ATF), Integrated High Performance Turbine Engine Technology (IHPTET), and other programs either classified or in the research stage [Ref.12:p.51]. There is also great potential for this durable material in the machine tooling industry. Some experts think that ceramic matrix composites may be the solution to the cutting tool problems associated with other advanced composites.

4. CARBON-CARBON COMPOSITES

a. Description

This advanced composite has some very unique characteristics which should pay substantial dividends in the future. Carbon-carbon composites consist of carbon fiber reinforcements embedded in a carbonaceous matrix. Processing of this material is very similar to polymer composites.

Carbon fiber is filament wound, woven, or laid up as a laminate and cured to provide a rigid preform for subsequent processing [Ref. 14:p.26]. The part is then subjected to high temperature which causes the matrix material to turn to carbon. Additional carbon is then deposited in the porous material to provide the desired strength characteristics. An anti-oxidation coating is then applied to protect the material from the environment.

Typical carbon-carbon composites are about two-thirds as strong as superalloys, but they increase in strength at high temperatures where the alloys begin to lose strength [Ref. 12:p.27]. Carbon matrix composites often use graphite (a form of carbon) as reinforcement material which not only gives the composite a high degree of strength, but allows sliding against other components with no galling [Ref. 12:p.36].

b. Applications

There are several U.S. companies with the capability to produce carbon-carbon composites. However, at this time there is only a small demand for the product due to the high materials cost and a lengthy, expensive manufacturing process. The most significant use to date is on the wheel brakes of commercial and military aircraft. Also, carbon-carbon composites can be found on the nose cap and leading wing edges of the space shuttle.

Carbon-carbon composites have the potential for wide applications in turbine engines and aerospace vehicles, but a breakthrough in manufacturing process technology must be accomplished before there is widespread use. Most experts agree that the manufacturing base must be stimulated in order to achieve high payoffs in this advanced composite [Ref. 6:p. 297].

5. HYBRID COMPOSITES

a. Description

Hybrid composites are defined as a material system derived from the integration of dissimilar materials, at least one of which is a basic composite. This class of advanced composites blends the desirable properties of two or more types of materials into a single system which displays the beneficial characteristics of the separate constituents [Ref. 16]. This composite gives design engineers considerable flexibility in designing advanced systems. However, because this is a new material technology, it is not understood very well, and fabrication cost could be excessive.

b. Applications

A good example of a hybrid composite is aramid reinforced aluminum laminate (ARALL). This material consists of high strength aluminum alloy sheets interleaved with layers of aramid fiber. This composite is already being used on secondary structural components of subsonic fixed wing aircraft, such as the Airbus. Although ARALL has been in use for several years, the majority of the hybrid composite industry is considered to be in its infancy. It is expected that U.S. research will greatly propel this technology forward.

One particularly interesting hybrid composite, smart skins, offers great potential for the aerospace industry. Smart skins contain circuitry and electronic components that enable the skin of aircraft to serve as antennas, sensors and structural monitors. This material could revolutionize aircraft design by allowing new aerodynamic shapes simply by reducing the need for the volume to accommodate the many black boxes within the vehicle and by reducing the weight of the aircraft [Ref. 6:p. 313].

IV. APPROACHES TO COST ESTIMATION

Cost estimating is defined as the process of predicting or forecasting the cost of a work activity or work output [Ref. 17:p. 1]. This concept is not difficult for most people to understand. In fact, we perform cost estimation on a regular basis in our daily lives. Fortunately for the average person, there is much certainty in the process. However, when there is a lack of information or the proposed item differs substantially from ones procured in the past, then cost estimation becomes more difficult. The DoD must face this type of challenge on a recurring basis.

This chapter discusses cost estimation procedures within the DoD weapons system acquisition process. It also presents three basic cost estimation methods: industrial engineering, analogy, and parametric. Although there are other techniques available, most are a combination or a variant of these three methods. It also should be noted that most cost estimation methodologies combine various aspects of these techniques. Finally, the chapter concludes with a discussion of the cost estimation models currently available to estimate the cost of composite helicopter airframes.

A. COST ESTIMATION IN THE DOD ACQUISITION PROCESS

The Department of Defense is heavily reliant upon accurate cost estimates throughout the weapon systems acquisition process. The high dollar value associated with modern weaponry and support equipment dictates that the Pentagon should have reasonably good predictions of system cost. This, coupled with a shrinking defense budget, requires meticulous attention by the program manager to cost estimates, thus ensuring a successful program while safeguarding public funds and the public trust.

Although it is beyond the scope of this thesis to present a detailed description of the DoD acquisition process, it is important for the reader to have some familiarity with the various phases and milestones. Figure 14 portrays the basic acquisition cycle. A detailed description of the process can be found in DODI 5000.1, "Defense Acquisition" [Ref. 18:p. 2.1].

ACQUISITION MILESTONES & PHASES

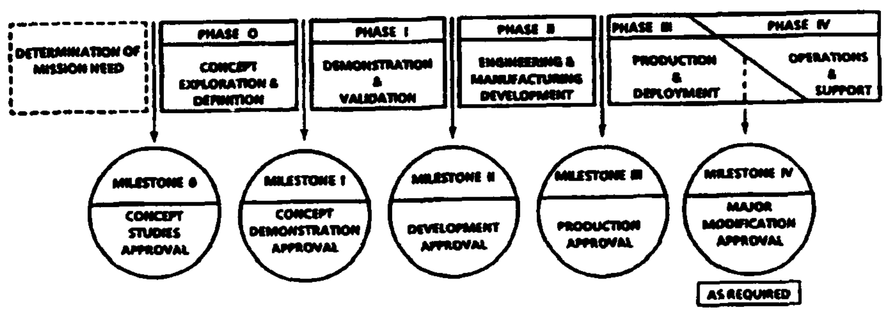

Figure 14

The legal requirements for cost estimation originate from Title 10, United States Code, Section 2434, "Independent cost estimates; operational manpower requirements." These requirements, as they pertain to DoD, are spelled out in DODI 5000.2, "Defense Acquisition Management Policies and Procedures," February 23, 1991:

a. Cost estimates shall be prepared in support of Milestone I and all subsequent milestone reviews.

b. Cost estimates prepared in support of milestone and other reviews shall be:

(1) Explicitly based on the program objectives, operational requirements and contract specifications for the system (see Section 11-A), including plans for such matters as peacetime utilization rates and the maintenance concept;

(2) Comprehensive in character, identifying all elements of additional cost that would be entailed by a decision to proceed with development, production, and operation of the system; and

(3) Neither optimistic nor pessimistic, but based on a careful assessment of risks and reflecting a realistic appraisal of the level of cost most likely to be realized [Ref. 2:p. 10.A.1].

Basically, this DoD instruction requires two separate cost estimates to be prepared in support of all milestones and any required reviews. One of the estimates is prepared by the program office and the other is prepared by an organization that does not report through the acquisition chain [Ref.2:p. 10.A.1]. These estimates are presented to the DoD Cost Analysis Improvement Group which will usually complete a third estimate. The format used for the reports is spelled out in DoDI 5000.2M, "Defense Acquisition Management Documentation and Reports" [Ref. 19:p. 15].

The cost estimate prepared by the program office is extremely detailed. It is first prepared early in the acquisition process, prior to milestone I, and after periodic updating serves as the baseline for all subsequent tracking and auditing purposes. Military Standard 881A, Summary Work Breakdown Structure (WBS), is the principal means for preparing this comprehensive cost estimate [Ref. 17:p. 521]. It should be noted that the primary source of cost information for preparation of the estimate is supplied by the contractor.

The next step in the process is the development of an independent cost estimate (ICE) or independent parametric cost estimate (IPCE). The purpose of the ICE is to verify the reasonableness of the program office's estimate. The document is prepared by an independent cost analysis group within the respective service at the headquarters level (e.g., Cost and Economic Analysis Center [CEAC] in the Department of the Army). The focus of the ICE is to consider cost at a higher level of the WBS and is predicated upon actual historical costs encountered in similar programs [Ref. 17:p. 523].

Both cost estimates are briefed to the CAIG at least 21 calendar days before the milestone review meeting of the cognizant Defense Acquisition Board Committee [Ref. 19:p. 10.A.3]. Coincident to this review, the CAIG will also prepare a cost estimate of the weapon system. DoD Instruction 5000.2, part 13, section C explicitly outlines the procedures and formats required for the CAIG review.

The cost estimate produced by this exacting procedure will continue to receive great scrutiny throughout the entire federal budgeting process. Executive level DoD officials, the Office of Management and Budget (OMB), and the various committees and subcommittees of Congress will all evaluate and critique the cost estimate. The existence and success of a weapons system acquisition program may very well depend on the accuracy and precision of the current cost estimate.

B. METHODS OF COST ESTIMATION

1. Industrial Engineering Cost Estimation

The industrial engineering method of cost estimation is a multi-stepped process. First the product is broken down into the smallest feasible portions of work output or work activity possible. The costs are estimated for each of these segments at an extremely high level of detail. For example, estimates would be made on the number of engineers by department, type and quantity of test material, specific tools required, parts list and raw materials required, and direct and indirect labor standards. The estimates are then systematically combined to produce a total. This method is sometimes referred to as "grass-roots" estimating [Ref. 3:p. 2].

The biggest advantage of this type of estimate is that it compels a comprehensive understanding of the output being produced. It dictates a detailed breakdown of the system and the costs associated with the production of each element. Thus, the requirements of this estimating process embellish the amount of information available to management about the program.

The industrial engineering cost estimation is very costly in terms of resources. This method requires a large number of estimates, which involve many people and consumes a great amount of time. One of the largest aerospace firms judges that the use of this approach in estimating the cost of an airframe requires about 4500 estimates; for this reason, the firm avoids making industrial engineering estimates whenever possible [Ref. 3:p. 5].

At first glance it would appear that this method would be extremely reliable. However, many experts believe that this type of cost estimation is less accurate for two significant reasons. First, the "whole" turns out to be greater than the sum of its "parts." This is typically the result of the aggregation of small errors from the detailed estimates of separate elements. Secondly, there is usually variability in the fabrication and assembly of successive production units. Numerous design changes in product and process, as well as fluctuations in production rates, all tend to abrogate the original cost estimate [Ref. 3:p. 6].

2. Analogous Cost Estimation

The analogy method utilizes an analogous system as a baseline to arrive at the cost estimate of a different system. To perform this method the cost analyst collects resource information on a similar or like task, component, subsystem, or system and compares it to the similar or analogous one [Ref. 17:p. 200]. He then adjusts the resource approximation for the baseline system by some judgmental factor to arrive at the estimate for the system of interest.

The analogy technique is particularly useful when making estimates on an item that utilizes unfamiliar materials or has design considerations that are radically different than previously experienced. For example, the Douglas Aircraft Company made a good estimate on the cost of the Thor intermediate range ballistic missile by using the DC-4 transport airplane as an analogous system [Ref. 3:p. 7]. As seen from this example, this method has the distinct advantage that it allows cost analysts to venture into new technology arenas while allowing them to use methodologies and models with which they are familiar.

The major disadvantage to the analogy method is that it is a judgment process and thus requires considerable experience. There is always the possibility that the estimator fails to identify subtle differences in the two work activities and therefore, estimates the cost of the system based on an activity that is really not similar or analogous [Ref. 17:p. 200]. Also, this method requires the analyst to apply an adjustment factor to the analogous system; this is not a trivial matter. Development of the adjustment component requires considerable domain knowledge and cost estimating skill.

3. Parametric Cost Estimation

The parametric method of cost estimating uses mathematical equations that relate cost to one or more physical or performance characteristics associated with the item being estimated [Ref. 17:p. 225]. In order to develop these correlations, the cost analyst acquires historical data, normalizes it, and determines what type of relationship exists using some statistical techniques, usually regression. Once a cost estimating relationship (CER) is established and verified, the analyst can then use it to estimate the costs associated with a new system.

Although more commonly used in the earlier phases of the acquisition process, parametric models are sometimes used throughout the detailed design, production, and operational phases of a program. As the system matures, parametrics may be utilized in conjunction with other estimating techniques, either as an independent verification or as an estimating method for a selected element of cost [Ref. 17:p. 226].

The most obvious advantage to this method is that it requires substantially fewer resources than the industrial engineering technique. Because the model focuses only on true cost drivers, less important details about the system are not required. Therefore, the analysis can be performed rapidly, with low labor requirements, and with computerization. Also, cost sensitivity studies, cost optimizations, and trade studies are a natural extension of the parametric technique [Ref. 17:p. 229].

Perhaps the most useful benefit of parametric cost estimation is that it inherently accounts for program fluctuations. Historical cost data intrinsically incorporate system development setbacks, such as engineering and design specification changes, and other project fluctuations. Industrial engineering estimates are usually optimistic in that they do not allow for these unforeseen problems [Ref. 20:p. 6].

The biggest disadvantage to this method is that it requires the collection of historical data. Although the Government has been collecting cost and program data on weapon and support systems for many years, it is typical that the right data are seldom available when an estimating job is required [Ref. 3:p. 11]. In some cases, especially with new technologies, data collection proves to be the most difficult and time consuming aspect of model development. Generally, historical cost and performance data on new systems are proprietary in nature and highly protected by the contractor.

C. APPLICABLE COMPOSITE AIRFRAME MODELS

There have been numerous cost estimating relationships developed for fixed wing aircraft, some of which may be applicable to helicopters. However, currently there are very few helicopter-airframe models available to assist the cost analyst in making estimates. This section presents several of the more recent reports with emphasis given to models that could be used to estimate the costs associated with the production of composite helicopter airframes.

1. Cost Estimating Relationships for Army Helicopter Composite Airframes, December 1983

This report, published by the Army Aviation Systems Command (AVSCOM), developed the first composite helicopter airframe cost estimating relationships [Ref. 4]. It presents a short history of composite material usage in the rotary wing manufacturing industry, it introduces the Army's ACAP program, and it identifies the need for a more adequate data base of composite airframe costs. However, the main thrust of the report is the development of a methodology for estimating composite airframe recurring cost.

The methodology is based on the Timed Phased Parametric Life Cycle Cost Model for Army Helicopters which is considered very accurate and widely accepted by most cost experts. Utilizing the Army metal airframe historical data CER as the baseline, it adjusts the cost per pound for the latest state-of-the-art technology learning curve. It then applies a multiplier called the composite technology cost factor. This cost factor can be estimated by industrial experts for different composite materials or can be derived based on the airframe weight and cost saving predictions applied to a formula.

The authors of the report utilize three data sets in the development of their model. First, the metal airframe helicopter historical data base is 1950's and 1960's vintage and includes the OH-6A, OH-58A, UH-1A, AH-1G, UH-2A, SH-3A, CH-46A, CH-47A, CH-54A, and the CH-53A. All are normalized to the 100th unit of production. The new technology airframe data set is based on historical data from the AH-64, UH-60, and the CH-47D programs. The final data set used to derive the technology cost factors are taken from the ACAP and JVX programs and analysis of three previous reports, the Rand V/STOL Airframe Materials study and two Grumman Corporation studies.

Although this study was prepared over a decade ago, it still has merit and continues to be used by cost estimators throughout the industry. The cost estimating methodology presented is logical and relatively simple to apply. The biggest disadvantage to the model is due to the limited data base available at the time of its inception. Therefore, it relies on CERs developed for metal airframes which are transformed via adjustment factors to composite materials.

2. Parametric Cost Analysis of Helicopters and Advanced Rotorcraft Designs, September 1987

This study, published in the *Journal of Parametrics*, provides a step-by-step approach to estimate the lifecycle cost of rotorcraft [Ref. 21]. It basically outlines the techniques used to estimate the costs of the light helicopter family (LHX) by the U.S. Army. This program eventually evolved into what is today the RAH-66 Comanche.

The report divides lifecycle cost into the following areas: research and development, production, and operating costs. It estimates costs by dividing the effort into manageable elements that may be parametrically addressed. The authors give considerable attention to the difficulties in estimating advanced technology, which does not usually follow trend data.

The study does not attempt to develop cost estimating relationships, rather it leads the reader through the methodology used to arrive at a comprehensive lifecycle cost estimate for the LHX. The report relies heavily on the analogy technique to estimate cost for the research and development phase. Production estimates are derived utilizing CERs from USAAVSCOM TM 75-74: A Time Phased Parametric Life Cycle Cost Model for Army Helicopters, January 1976. The estimates are then adjusted by a calibration factor for recent developments based on UH-60 and AH-64 production experience. Operation and support costs are captured by estimating the costs associated with the operation of the fielded rotorcraft fleet.

The data base used is not presented in the study. However, there are references made to various Government reports which developed CERs from UH-60 and AH-64 data. The authors also note that some portions of rotorcraft parametric lifecycle cost estimation are subjective and do not readily lend themselves to the development of CERs.

The methodology introduced is extremely logical and very easy to follow. It is comprehensive because it focuses on the lifecycle cost of the system. The study presents CERs that were generally accepted in the cost estimation field in the early 1980's. The major disadvantage to the report is that it employs CERs based on old technology airframes. Although the paper presents calibration factors to adjust for recent developments, the current state of aircraft technology may have surpassed the data base utilized.

3. Development of Cost Estimating Methodologies for Composite Aircraft Structure and Components, November 1987

This study was conducted under the auspices of the U.S. Army CEAC by LSA Incorporated [Ref. 22]. The focus of the report was the development of a composite material data base and supporting CERs that would be useful in estimating the development and production costs of composite structures. The authors of the study state that the methodology is suitable for application not only to aircraft but to any structure made of composite materials (e.g., missiles, wheeled vehicles and amphibious vehicles).

The model utilizes a manufacturing complexity factor (MCF) to normalize the weight of a structure with respect to the amount of difficulty in fabricating and assembling the component. The MCF is obtained from a matrix which is based on the individual rankings of six complexity rating characteristics for each part manufactured. The fabrication characteristics evaluated are degree of curvature, number and shape of cutouts, and number and degrees of contour. The assembly ranking criteria are type of construction employed, length and shape of edges, and type of curing process used. The model's output is direct labor hours for the fabrication of a composite component.

The data base used in this report was obtained from the U.S. Army Advanced Composite Airframe Program. As discussed previously, this program was conducted to judge the applicability of composite material for rotary wing aircraft. Each contractor was required to track cost information down to the part level on all components constructed. These data are the basis for the CERs developed by this study.

The technique of using complexity factors to normalize weight data when dealing with composite components is reasonable and valid. The CER developed provides a good fit over a wide range of data, but as the authors note, the CER generated should only be used for estimating structures built in a prototype environment. Another limitation of the model is that it is only applicable to individual components. Therefore, to determine the labor hour cost of an airframe, each individual composite part must be estimated and then summed. However, this is not a true total cost because it disregards the assembly time required to join the components.

4. Advanced Airframe Structural Materials: A Primer and Cost Estimating Methodology, July 1988

This document, produced by the Rand Corporation, is considered by many as the industry standard for estimating the cost of composite materials [Ref. 14]. It is truly comprehensive and includes a background of composite usage, material types and characteristics, manufacturing processes, and cost information. Although the study is primarily focused on fixed wing cost estimates, it has merit across the entire spectrum of composite usage.

The methodology utilizes weighted material indexes which are applied to baseline CERs assumed to be representative of all-aluminum aircraft. The study provides distinct CERs and material indexes for the nine cost elements listed on the following page.

Nonrecurring	Recurring
Engineering	Engineering
Tooling	Tooling
Development Support	Labor
Flight Test	Material
	Quality Assurance

The required inputs to utilize the model are: aircraft empty weight, maximum speed, number of flight test aircraft, type of aircraft (cargo or noncargo), total structure weight by material type, and the percentage of functional cost elements attributable to structure.

An industry survey was used to gather data to conduct this study. The survey requested that aerospace contractors respond to questions on corporate history, material usage within an aircraft, recurring and nonrecurring cost information, and general questions. Data were gathered for the time periods of 1987 and 1995. Data from 1987 were based on current experience, while 1995 data were a forecast of future use and technology.

This cost model has many distinct advantages. The CERs are based on the relatively current information and can be easily applied across the aerospace industry. Also the weighted material indices permit a great deal of flexibility in application [Ref. 7:p. 38].

The biggest disadvantage to the model is the accuracy of the mid 1990's projections. At the time of the survey, there was much optimism within the defense contractor industry. There were numerous defense related contracts available and there was confidence that cost of composite materials would decrease. However, this has not been the case. The current environment has not realized the expected gains in experience, the large outlays for automation and capital equipment, and the availability of inexpensive and abundant composite material.

5. ASD Advanced Materials Cost Research, Volume I, Final Report, May 1989

This study is the most recent of all composite airframe reports [Ref. 8]. It is organized into two separate volumes. The first volume contains CERs and cost factors, a description of composite materials, an explanation of the methodology applied, and presentation of the model. The second volume contains proprietary contractor cost data that are used in the study.

The model utilizes metal weight of the structure, the composite weight of the structure, and total structure weight as the independent variables. The output of the CER is normalized to the one hundredth production unit. Each CER and cost factor is expressed in terms of dollars for materials and in hours for each labor category. CER development is illustrated in great detail within the study. The methodology utilizes four distinct steps. First, the authors hypothesize the relationships to be developed. Then, regression analysis is performed on the data. The third step involves validating the CER through statistical analysis. Finally, the last step is the documentation of the developed CER.

The data base consisted of various fixed wing aircraft including the AV-8B, A-6E, A-7A, F-4B, F-5E, F-111A, F-101C, A-10A, B-1B, F-14A, F-15A, F-16A, and the F/A-18A. The composite percentage by weight varied between aircraft from 1 to 26 percent. The aircraft were analyzed according to pre-1970 versus post-1970, and according to mission configuration (i.e., fighter or bomber). All observations were actual, but in some cases outliers were discarded. The data base was also adjusted for unit quantities of one hundred.

The biggest advantage to this report is the data base accumulated by the authors. The data are presented in great detail and at a level of WBS that is extremely useful for parametric estimation by a cost analyst. Also, the CERs and cost factors presented by the report are sensible and should prove useful in estimating the cost of fixed wing aircraft.

The biggest disad ntage of this study is that it may not be applicable to ry wing aircraft. Fixed wing aircraft are designed to withstand greater forces than helicopters and therefore must be stronger and more rigid. However, certain analogies could be made between two similar elements of rotary and fixed wing aircraft with the assistance of engineering input.

V. CER DEVELOPMENT

There are many costs associated with the production of a composite helicopter airframe (e.g., labor, material, and engineering). However, the largest and most difficult cost to estimate is the recurring direct labor hours. Although the other categories of costs are not insignificant, they can generally be estimated with a fair amount of certainty utilizing engineering and design information. The focus of this chapter is on the development of cost estimating relationships that may be useful in predicting the direct labor hours needed to fabricate and assemble a prototype composite helicopter airframe.

The first part of this chapter explains the data collection process. This is followed by a presentation of the logic used for data normalization. The last section introduces the cost estimating relationships that were developed through both simple and multiple regression analysis.

The dependent variable selected for analysis was total direct labor hours. This variable represents the amount of time, in hours, that is required to fabricate and assemble a rotorcraft airframe which has significant amounts of composite material. Total direct labor hours include both composite labor and traditional metal labor. In addition, it includes any direct labor hours associated with scrapped work. Direct labor hours do not include overhead or quality assurance hours.

A. DATA COLLECTION

The most worrisome and time consuming process of this entire thesis was the accumulation of the cost and performance data for the topic of interest.

> The first and most difficult step the analyst must overcome in developing a useful CER is collecting the data. The quality of the CER can be no better than the data upon which it is based.[Ref. 23:p. 11]

Although this problem is frequently addressed in the open literature, data collection proved to be more of a difficult task than was originally envisioned.

The population for the collection effort was originally defined as any type of aircraft that utilized composite components. However, this broad category was narrowed to exclude fixed wing aircraft for the following reasons:

1) Fixed wing aircraft are generally subjected to greater aerodynamic stresses than helicopters.
2) The fuel for fixed wing aircraft is generally stored in the wing area of the aircraft.
3) Rotary wing aircraft experience substantially more vibration throughout the airframe than do fixed wing aircraft.

4) Fixed wing aircraft must withstand greater impacts for landing.

An examination of the current DoD helicopter fleet revealed that although composite materials were utilized, they represented a very small element of the total aircraft weight, usually between 2 and 9 percent. Also, it was exceedingly difficult to acquire historical cost data on these components because of the age of the aircraft, the type of production contract utilized, and the lack of a detailed breakdown of the composite fabrication costs.

The search for rotorcraft with substantial amounts of composite material soon led to the prototype environment. The Army's Advanced Composite Airframe Program provided excellent information on two composite airframes, the Bell D292 and the Sikorsky S75. The V-22 Osprey Program Office also assisted in this study by furnishing relevant composite cost information. In addition, data were acquired from a non-military source, the Boeing Model 360 Advanced Technology Demonstrator program.

B. DATA PRESENTATION

This section presents the methodology of data normalization by aircraft type. The data were assimilated from technical reports obtained from the various program offices. Each technical report was slightly different with respect to format and comprehensiveness. The information was interpreted and analyzed so that it would be comparable and therefore useful in CER development. The data are presented in Table 11 and defined below.

TABLE 11
AIRCRAFT DATA

ACFT TYPE	**YEAR (*Year*)**	**GROSS WEIGHT (*Gross*)**	**COMPOSITE WEIGHT (*Cwgt*)**	**MAX SPEED (*speed*)**	**TOTAL MANHOURS (*Hrs*)**
D-292	1984	7525	1076	120	32,455
S-75	1985	8470	784	141	52,121
B-360	1987	30,500	2900	214	78,373
V-22	1989	48,680	9632	319	397,274

1. General Considerations and Data Definitions

Independent variables were selected on the criteria that they could logically be related to total manhours. In addition, they had to be obtainable and comparable across the data base. The independent variables are identified and explained below:

(a) ***Year*** is defined as the year in which the aircraft made its first flight.

(b) ***Gross weight*** represents the maximum weight, in pounds, the aircraft can weigh for takeoff and not overstress the airframe structure, transmissions, or engines.

(c) ***Composite weight*** is defined as the amount of composite material, in pounds, embodied within the airframe.

(d) ***Maximum speed*** represents the fastest speed, in knots, attained by the aircraft in level flight. The speed parameters are measured at sea level on a standard day (15° C, 29.92" Hg).

The term ***airframe***, as utilized in this thesis, refers to the assembled structural and aerodynamic components of the rotorcraft that support subsystems essential to a particular mission. It specifically excludes propulsion, avionics, and armament. ***Composite airframe*** is defined as an airframe structure consisting of at least 30 percent composite materials.

The following sections explain the methodology used to assimilate the data from the various aircraft programs.

2. ACAP Bell D-292

The cost data utilized for this study are from the flight test vehicle. The information was obtained from the Final Technical Report Volume IV Cost, 20 June 1986 [Ref. 24:p. 11.2]. The labor hours presented in the report include both composite fabrication and assembly at level five of the work breakdown structure. The total labor hours include both scrap and rework hours.

The weight data for the D-292 were accumulated from the Actual Weight Report, Military Standard 1374, 1 August 1985 [Ref. 25:p. 6]. Gross weight includes the weight of the crew, payload, fuel and oil. Composite weight represents the actual amount of composite material in the airframe. Information on speed and year of first flight represent actual aircraft accomplishments.

3. ACAP Sikorsky S-76

The cost information for this aircraft was derived from the Manufacturing Cost Report Volume IV, 20 January 1984 [Ref. 26:p. 143]. This cost information pertains to the flight test vehicle. Although the format for this report was considerably different from the Bell report, the information is comparable. The biggest difference was the inclusion of quality assurance hours that were not represented in the D-292 cost data. In order to make the data compatible, quality assurance hours were subtracted from the dependent variable used for CER development.

Information about the weight of the Sikorsky S-76 was gathered from the Post Design Weight Analysis Report, 18 March 1985 [Ref. 27:p. 117]. Sikorsky Aircraft also used Military Standard 1374 for their weight report, thus facilitating comparability of data. Similar to the Bell D-292, speed and year represent actual aircraft performance.

4. Boeing Model 360

Cost data for this high performance civilian helicopter were obtained from the 1993 Alexander A.

Nikolosky Lecture presented to the American Helicopter Society by K.I. Grina [Ref. 28:p. 1]. The lecture furnished composite airframe fabrication and assembly cost experience for the Boeing Model 360 in manhours per pound. It also presented a graph of historical composite cost for various helicopters built by Boeing Helicopters. The total composite airframe weight was interpolated from the abscissa and applied to the manhour per pound figures to obtain an estimated total direct manhours. It should be noted that these cost figures were not verified by Boeing Helicopters and represent estimates by this author.

Weight data were obtained from the same source as the cost information. The gross weight was verified through telephonic conversations with the Model 360 program office [Ref. 29]. Although the weights are not certified to meet Military Standard 1374 information, they are consistent with those requirements. Performance information was obtained directly from the Nikolosky Lecture paper and represents aircraft actuals.

5. V-22 Osprey

The V-22 Program Office provided the labor hour cost data utilized in this thesis [Ref. 30]. The data supplied represent average cost experience for the six Engineering and Manufacturing Development (EMD) phase aircraft. Cost data were provided by Boeing Aircraft and Bell total. This was accomplished by combining the distributed average manufacturing hours for the airframe (WBS 1100) provided by both contractors. The cost data include all direct labor hours, both metal and composite, associated with the fabrication and assembly of the V-22 airframe.

The program office also supplied weight information for the aircraft [Ref. 31]. Although the data were not presented in Military Standard 1374 format, it could easily be developed from the information provided. Gross weight for the V-22 represents the maximum weight for the aircraft to perform a vertical takeoff (i.e., helicopter mission profile). The performance data represent aircraft actuals and were verified by the program office.

C. DATA MANIPULATION

All statistical manipulations were accomplished using the STATGRAPHICS statistical graphics system. STATGRAPHICS provided the capability to perform both simple and multiple regressions. The output facilitated analysis of the relationship between independent and dependent variables. The software package uses the least squares method to estimate the regression model. It also calculates a variety of relevant statistics, to include analysis of variance. Another helpful feature of STATGRAPHICS is that it provides numerous types of data plots which are useful for data evaluation.

D. CER DERIVATION

The objective of the CER is to relate total direct labor manhours to the potential explanatory variables of year of first flight, maximum speed, composite material weight, and aircraft gross weight.

Prior to attempting regression, correlation analysis was performed to determine if any of the independent variables were highly correlated. Table 12 shows a correlation matrix provided by STATGRAPHICS. The results in the table show that indeed all the independent variable are highly correlated.

TABLE 12
Correlation Matrix (N=4)

	Year	Gross Wgt	Composite Wgt	Max Speed
Year	1.0			
Gross Wgt	.9865	1.0		
Composite Wgt	.9195	.9410	1.0	
Max Speed	.9894	.9907	.9664	1.0

A high correlation between independent variables should restrict the analysis to simple regression models. This is because a multiple regression model assumes there is an exact linear relationship among two or more independent variables. Including two highly correlated variables in a regression will degrade the model's ability to support hypothesis testing, and it may result in dubious estimated regression coefficients that produce illogical results. [Ref. 32:p. 18] However, multiple regression is presented at the conclusion of this chapter for the reader's information.

Simple regression was performed for each independent variable. Three different models were fitted to the data: linear, multiplicative, and exponential. The results of the regression analysis are depicted in Table 13. The equations are presented with their respective coefficient values and t-ratios. In addition, the table displays the coefficient of determination (R^2), F-ratios with probability levels, and the standard error of the regression.

A cursory examination of Table 13 reveals that there exist definite relationships between total direct manhours and the various independent variables. The high R^2 values indicate that a large percentage of the variation in the total direct manhours can be explained by the model. However, R^2 values should not be considered in isolation because they can be misleading. In order to determine the most appropriate model, it is necessary to evaluate the equations, coefficients, and all pertinent statistics in unison. Also, it should be noted that the R^2 values and the standard error of the estimates are not directly comparable between the linear models and the multiplicative/exponential models. This is because the dependent variables in the multiplicative and exponential models are converted to logarithms, thus creating different measurement scales. [Ref. 3:p. 60]

TABLE 13
REGRESSION ANALYSIS OF VARIABLES
UTILIZING THREE MODELS

Equation	R^2	SEE	F-Ratio	Prob. Level
MODEL: Linear				
$Hrs = -1.3629E8 + 68685.3\,Year$ (-2.66) (2.66)	77.94	99223.9	7.0680	.11714
$Hrs = -8568.46 + 41.308\,Cwgt$ (-.39) (9.45)	97.81	31269	89.31	.01101
$Hrs = -216666 + 1797.09\,Speed$ (-2.13) (3.77)	87.65	74257.5	14.19	.06380
$Hrs = -45699.2 + 7.8069\,Gross$ (-.56) (2.78)	79.45	95777.3	7.732	.10865
MODEL: Multiplicative				
$Hrs = -7103.57\,Year^{936.913}$ (-4.93) (4.94)	92.41	.367037	24.35498	.03869
$Hrs = 4.4285\,Cwgt^{.8995}$ (2.36) (3.72)	87.35	.4739	13.80917	.06539
$Hrs = -1.0597\,Speed^{2.3793}$ (-.42) (4.91)	92.34	.368762	24.10894	.03906
$Hrs = 1.182\,Gross^{1.0408}$ (.32) (2.76)	79.15	.608453	7.590213	.11036
MODEL: Exponential				
$Hrs = e^{(-925.511 + .4717 Year)}$ (-4.88) (4.94)	92.43	.366676	24.40689	.03861
$Hrs = e^{(10.427 + 2.573E\text{-}4 Cwgt)}$ (51.42) (6.44)	95.39	.285928	41.42796	.02330
$Hrs = e^{(8.9911 + .0119 Speed)}$ (26.67) (7.53)	96.59	.246084	56.62923	.01720
$Hrs = e^{(10.106 + 5.240E\text{-}5 Gross)}$ (27.97) (4.25)	90.02	.420957	18.03582	.05122

E. CER ANALYSIS

The linear model utilizing composite weight as the independent variable reflects a "good fit." It is also interesting to note the high F-ratio associated with the equation. The t-statistic for the constant value indicates that the constant is not significantly different from zero. Although it seems logical that total manhours of labor increase as the composite weight increases, a negative constant or a constant of zero is non-intuitive and may provide illogical results.

Analysis of the multiplicative construct reveals equations with fairly high coefficients of determination for the independent variables of year, composite weight, and speed. However, the standard error of the estimate is higher in all cases than those for the exponential models. This could be significant because the standard error of the estimate represents the estimated standard deviation of the error and is a measure of the amount of variability in the dependent variable that is not explained by the model.

Overall, the exponential model provides the best explanation of the relationship between total direct labor hours and the independent variables. The reasonableness of the statistics, the high R^2 values, and the intuitive equations all indicate that these models are the best candidates for estimating total direct labor hours.

The equation utilizing maximum airspeed as the independent variable appears to be the best model to estimate total direct labor hours. The results associated with this regression present a high R^2 value and a low standard error of the estimate. The model has the following form:

$$Hrs=e^{(8.911+.0119Speed)} .$$

Figure 15 portrays the model graphically. The data points appear to be well represented by the fitted line. The dashed lines represent the 95 percent confidence limit for the mean response at a given value of speed for this model. All data points lie within this confidence limit, which adds credibility to the statistical analysis.

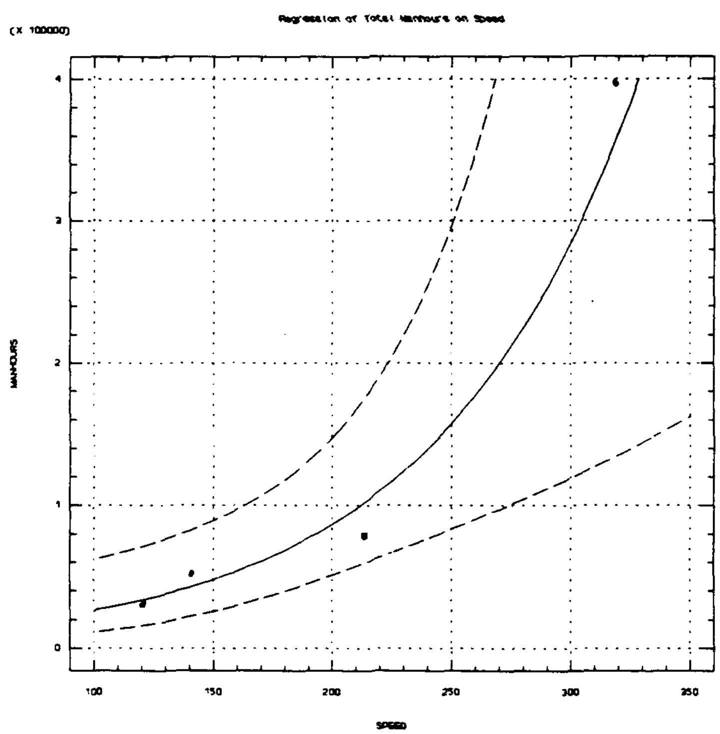

Figure 15 Regression of Total Manhours on Speed

The validity of any regression equation can also be verified by analyzing its residuals [Ref. 23:p. 23]. Figure 16 presents a residual plot for the regression of total manhours to speed. Residual analysis shows the difference between actual and predicted values as represented by the model. The residuals are dispersed in a random pattern indicating that the model is a good estimate of population data. In addition, the residual plot depicts relatively small deviations from expected values.

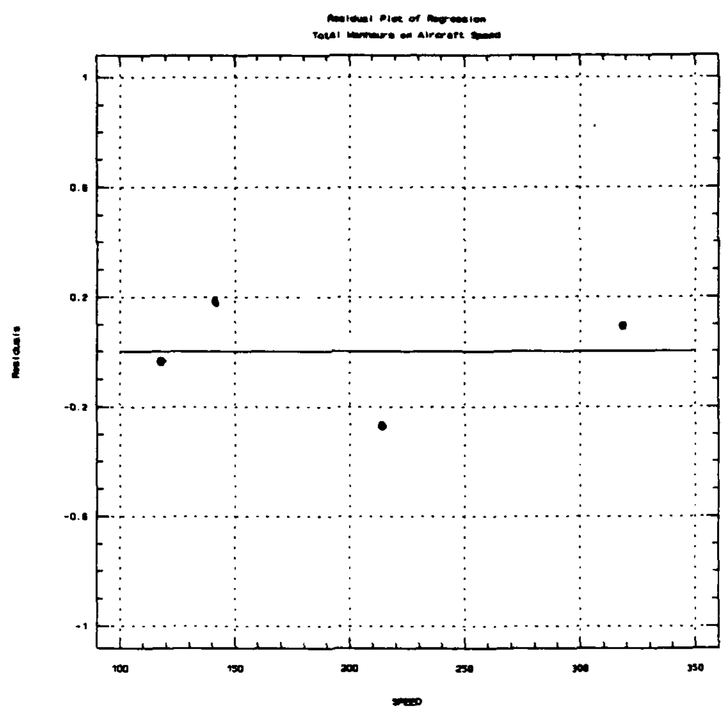

Figure 16 Residual Plot - Total Manhours on Speed

The biggest limitation to this model is the small number of data points used in its development. This is unfortunate, but there simply does not exist a large amount of composite helicopter airframe data. Perhaps, as more composite-intensive helicopter airframes are built, the data base will be enlarged and the model can be updated.

The relevant range of the model is restricted to the airspeed and manhour ranges of the historical data. This limited scope is an inherent restriction of parametric cost estimation. Although the range is finite, the model does encompass most values that are reasonably attainable by a rotorcraft.

Another limitation to this model is that it would only be useful in predicting total direct labor hours for a composite helicopter airframe in a prototype environment. This is due to the fact that the historical data were obtained from prototype rotorcraft. However, there are mathematical techniques that can transform prototype cost predictions into production forecasts. One such technique will be discussed in the next chapter.

F. MULTIPLE REGRESSIONS

To gain further insight about the relationships between independent and dependent variables, multiple regressions were performed. The results of the linear multiple regression and exponential multiple regression analyses are presented in Table 14 and Table 15, respectively. Due to the high multicollinearity among independent variables, the reader is cautioned against using these multiple regression models.

TABLE 14 MULTIPLE REGRESSION ANALYSIS LINEAR MODELS				
Equation	Adj. R^2	SE	F-Ratio	P-Value
Two Variable Regression with a Constant				
Hrs = 60,999+53.21*Cwgt*-566.3*Speed* (.51) (2.58) (-.597)	95.16	37,967	30.47	.1254
Hrs = 2.645E7+47.89*Cwgt*-13,335*Year* (.5112) (3.42) (-.51)	94.79	39,372	28.3	.1300
Hrs = -5.49+5529.95*Speed*-17.19*Gross* (-1.83) (1.70) (-1.16)	84.25	68,466	9.02	.2260
Hrs = 3.188E8+5727.19*Speed*-1.61E5*Year* (1.63) (2.36) (-1.64)	89.92	54,774	14.38	.1808
Hrs = -2.11E7+6.63*Gross*+10,614.98*Year* (-.0498) (.276) (.0497)	38.50	135,282	1.92	.4460
Two Variable Regression without a Constant				
Hrs = 43.74*Cwgt*-94.93*Speed* (6.14) (-.56)	98.38	30,138	91.33	.0108
Hrs = 41.31*Cwgt*-4.32*Year* (9.44) (-.387)	98.25	31,267	84.78	.0117
Hrs = -271.75*Speed*+8.45*Gross* (-.291) (1.24)	81.83	100,797	7.25	.1211
Hrs = 1799.96*Speed*-109.37*Year* (3.77) (-2.13)	90.15	74,220	14.22	.0657
Hrs = 7.81*Gross*-23.04*Year* (2.78) (-.56)	83.59	95,778	8.14	.1094

TABLE 15
MULTIPLE REGRESSION ANALYSIS
EXPONENTIAL MODELS

Equation	Adj. R^2	SE	F-Ratio	P-Value
Two Variable Regression with a Constant				
$Hrs = -0.415 Cwgt^{.123} Speed^{2.074}$ (-.07) (.13) (.82)	77.38	.517	6.13	.2708
$Hrs = -5689.18 Cwgt^{.193} Year^{750.466}$ (-.87) (.23) (.87)	78.34	.506	6.42	.265
$Hrs = -2.63 Speed^{5.491} Gross^{-1.5}$ (-1.81) (4.39) (-2.54)	96.92	.191	48.3	.099
$Hrs = -5801.81 Speed^{.437} Year^{765.194}$ (-.010) (.022) (.010)	77.24	.519	6.09	.2716
$Hrs = -14418 Gross^{-1.187} Year^{1901.626}$ (-2.61) (-1.36) (2.61)	91.97	.308	18.19	.1613
Two Variable Regression without a Constant				
$Hrs = Cwgt^{.177} Speed^{1.915}$ (.45) (3.26)	99.92	.367	1929.31	.0005
$Hrs = Cwgt^{.899} Year^{.584}$ (3.71) (2.36)	99.87	.474	1155.44	.0009
$Hrs = Speed^{4.138} Gross^{-1.046}$ (2.82) (-1.34)	99.95	.279	3326.12	.0003
$Hrs = Speed^{2.379} Year^{-.139}$ (4.90) (-0.41)	99.92	.369	1907.58	.0005
$Hrs = Gross^{1.040} Year^{.156}$ (2.75) (.32)	99.78	.608	700.15	.0014

The tables present the models with their respective coefficient values and t-ratios. In addition, the tables display the coefficient of determination adjusted for degrees of freedom (R^2 Adj), the standard error of the regression (SE), F-ratios, and P-values of the F-ratios. Multiple regression was only performed using two variables, with and without constants, whose combination was logical (e.g., gross weight and speed).

The two variable models developed may not be useful in predicting direct labor hours because of the high correlation between independent variables and the low number of degrees of freedom associated with the small number of data points. However, in the future, they may become relevant as more data are accumulated on composite helicopter airframes.

VI. CER APPLICATION

The cost estimating relationships developed in the previous chapter will now be applied to the RAH-66 Comanche Helicopter. The direct labor hours for the first unit prototype airframe will be estimated using maximum airspeed as the input variable to the model. This estimate will then be transformed through the use of a stepdown ratio to estimate the recurring direct labor hours for the first unit of production. Sensitivity analysis will be performed on the learning curves and airframe quantities throughout the process.

A. RELEVANT RANGE

The first step in generating any estimate is to determine if the proposed aircraft lies within the relevant range of the estimating sample. The RAH-66 maximum design airspeed of 184 knots is well below the 314 knot limitation of the hypothesized model. Also, the Comanche airframe will consist of over 30% composite materials, thus meeting the composite airframe requirement. Since the RAH-66 helicopter meets all pertinent criteria, it should be a good candidate for applying the model developed in the previous chapter.

B. DEVELOPMENT OF FIRST UNIT PROTOTYPE DIRECT LABOR HOUR ESTIMATE

The next step in the process is to apply the model to the helicopter of interest. This is accomplished by using the 184 knot maximum airspeed as the independent variable and substituting it into the exponential equation. This yields the following results:

$$Hrs = e^{(8.991 + .0119\ speed)}$$

$$Hrs = e^{(8.991 + .0119\ [184])}$$

$$Hrs = 71{,}733$$

The outcome of this model indicates that it will take approximately 71,733 total direct labor hours to fabricate and assemble the first unit prototype composite helicopter airframe. Table 16 portrays the upper and lower bounds of the prediction intervals associated with this estimate.

TABLE 16
Total Direct Labor Hours at Various Prediction Intervals

Prediction Interval	Upper	Mean	Lower
85%	124,038	71,733	41,484
90%	167,475	71,733	30,725
95%	234,261	71,733	21,965

It can be seen from Table 16 that as the prediction interval is increased, the range of the confidence region

$$CumHrs_{dev} = \sum_{X=1}^{n} T_1 X^B = T_1 (1^B + 2^B + \ldots + n^B)$$

where

T_1 = 1st Airframe Total Labor Hours

X = Airframe Unit

$$B = \frac{\log \text{(learning curve)}}{\log 2}$$

n = Total Number of Airframes .

This formula requires input of the quantity of prototype articles to be manufactured and the learning curve expected during the prototype phase. The acquisition strategy of the RAH-66 calls for the manufacture of four airframes during the demonstration validation and engineering manufacturing development phases. In addition, during the Advanced Composite Airframe Program, Sikorsky Helicopters (a contractor for the Comanche) projected a learning curve of 84% for composite airframes in a prototype environment [Ref. 26:p. 7]. Applying this information to the equation produces the following cumulative labor hours:

$$CumHrs_{dev} = \sum_{X=1}^{4} 71{,}733 X^{-.2515}$$

$$= 71{,}733 (1^{-.2515} + 2^{-.2515} + 3^{-.2515} + 4^{-.2515})$$

$$= 237{,}016 \ .$$

$$CumHrs_{dev} = \sum_{X=1}^{n} T_1 X^B = T_1 (1^B + 2^B + . . . + n^B)$$

where

T_1 = 1st Airframe Total Labor Hours

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$$CumHrs_{dev} = \sum_{X=1}^{4} 71,733 X^{-.2515}$$

$$= 71,733 (1^{-.2515} + 2^{-.2515} + 3^{-.2515} + 4^{-.2515})$$

$$= 237,016 .$$

To determine the average prototype direct labor hours, the cumulative labor hours are simp y divided by the prototype quantity. This yields the following:

$$AvgHrs_{dev} = \frac{CumHrs_{dev}}{Q_{dev}}$$

$$AvgHrs_{dev} = \frac{237,016}{4}$$

$$= 59,254 \ .$$

Sensitivity analysis was applied to the prototype aircraft quantity and the projected learning curve. This analysis yields the information shown in Table 17.

TABLE 17
Sensitivity Analysis
Average Direct Labor Hours for Prototype Aircraft

Learning Curve	**Total Prototype Aircraft**			
	3	**4**	[illegible]	**8**
82%	60,976	57,790	53,226	50,000
84%	62,134	59,254	55,096	52,133
86%	63,301	60,739	57,012	54,334
88%	64,478	62,246	58,974	56,604

Table 17 shows that as the learning curve increases, the average direct labor hours increase at a faster rate. Also, as the number of prototype aircraft are increased, substantial unit savings can be achieved, especially at the lower learning curves. The selection of the projected learning curve, as well as the aircraft quantity can have a significant impact on the prototype average direct labor hour estimate.

D. DEVELOPMENT OF PRODUCTION AVERAGE DIRECT LABOR HOUR ESTIMATE

The next step in the procedure is to develop the estimate for the first production unit airframe. To do this, it is assumed that automation and other manufacturing technologies are introduced into the production process. Thus, we can predict the first unit labor hours by reducing the average unit prototype airframe labor hours by a stepdown ratio. Figure 17 graphically depicts this concept.

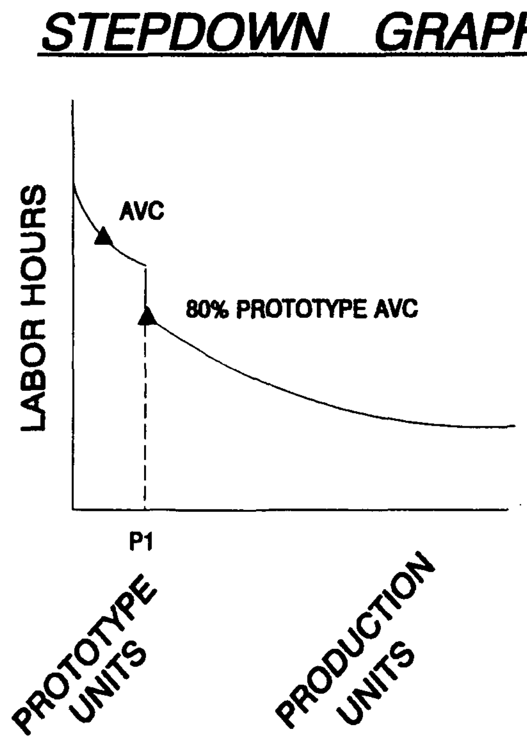

Figure 17 Stepdown Ratio

Various stepdown ratios can be applied depending on the equipment being estimated, the state of technology, and the maturity of design. According to the CEAC, a reduction of 80% would be reasonable in this case [Ref. 34]. Applying this stepdown ratio to the prototype average direct labor hour estimate yields the following:

$$P_1 = \text{StepDown Ratio} * AvgHrs_{dev}$$

$$P_1 = .80 * 59{,}254$$
$$= 47{,}403 \; .$$

Utilizing stepdown ratios of 85 percent and 90 percent provide first production airframe direct labor hours of 50,366 and 53,329, respectively. There is an obvious direct relationship between the stepdown ratio and the first production unit estimate. Higher stepdown ratios would be utilized in cases where the production techniques are not expected to be substantially different from those of the prototype.

To determine the average labor hour estimate for any production program, it is necessary to calculate the area under the learning curve for the quantity of items manufactured. This can be done by utilizing the following equation [Ref. 33:p. 7.15].

$$CumHrs_p = \int_{1-0.5}^{N+0.5} (P_1 X^B dx)$$

Integrating this formula yields:

$$CumHrs_p = \frac{P_1 X^{(B+1)}}{B+1}\Bigg|_{1-0.5}^{N+0.5} = P_1\frac{(N+0.5)^{(B+1)}}{B+1} - P_1\frac{(1-0.5)^{(B+1)}}{B+1}$$

where

P_1 = 1st Production Airframe Total Labor Hours

X = Airframe Unit

$B = \dfrac{\log\text{ (learning curve)}}{\log 2}$

N = Last Airframe Produced .

In order to apply this formula to the current example, a learning curve must be projected. The cost estimates developed by the Comanche Program Office utilized a 88 percent learning curve. [Ref. 35] Applying this learning curve to the following equation yields:

$$CumHrs_p = P_1\frac{(N+0.5)^{(B+1)}}{B+1} - P_1\frac{(1-0.5)^{(B+1)}}{B+1}$$

$$= 47{,}403\frac{(1292+0.5)^{(-0.184+1)}}{-0.184+1} - 47{,}403\frac{(1-0.5)^{(-0.184}}{-0.184+1}$$

$$= 20{,}042{,}469 - 33{,}024$$

$$= 20{,}009{,}445\ .$$

Average unit labor hours are determined by dividing cumulative direct labor hours by the production quantity.

$$AvgHrs_p = \frac{CumHrs_p}{Q_p}$$

$$= \frac{20,009,445}{1292}$$

$$= 15,487$$

The outcome of this equation indicates that on the average it will take 15,487 total direct labor hours to build one Comanche helicopter airframe.

Sensitivity analysis was performed to determine the stability of the estimate. This was accomplished by varying the quantity of production aircraft and the applied learning curves. The quantities utilized in the analysis reflect proposed RAH-66 program numbers. The learning curves are representative of the aerospace industry standard. The results are presented in Table 18.

TABLE 18
Sensitivity Analysis
Average Direct Labor Hours for Production Aircraft

Learning Curve	Total Production Aircraft		
	954	1292	1641
84%	11,241	10,422	9,817
86%	13,585	12,723	12,082
88%	16,372	15,487	14,822
90%	19,678	18,797	18,129

For a fixed quantity of aircraft, the direct labor hours increase by approximately 10 percent for every one percent increase in the learning curve. Although the average unit cost increases as production quantity is reduced, the impact is not as dramatic as changes to the learning curves. It is obvious from this sensitivity analysis that selection of the learning curve has a significant effect on the final cost estimate.

The final results of the stepdown ratio methodology are highly dependent on the input of the average prototype direct labor hours. Therefore, sensitivity analysis was performed on both the highest and lowest prototype average direct labor hour values (64,478 and 50,000), utilizing an 80 percent stepdown ratio. The results of this analysis are presented in Table 19 and Table 20. Both tables display characteristics congruent to those observed in Table 18. A comparison between the two tables of the high and low values with similar parameters reveals a range of differences between 22 percent and 29 percent.

TABLE 19
Sensitivity Analysis for Low Prototype Labor Hour Value
Average Direct Labor Hours for Production Aircraft

Learning Curve	Total Production Aircraft		
	954	1292	1641
84%	9,486	8,794	8,284
86%	11,463	10,736	10,195
88%	13,815	13,068	12,507
90%	16,605	15,861	15,297

TABLE 20 Sensitivity Analysis for High Prototype Labor Hour Value Average Direct Labor Hours for Production Aircraft			
Learning Curve	Total Production Aircraft		
	954	1292	1641
84%	12,232	11,341	10,683
86%	14,782	13,845	13,147
88%	17,816	16,853	16,129
90%	21,413	20,454	19,727

This chapter presented a methodology which may be useful in developing an average direct labor hour estimate. The prediction derived from the model in this chapter is consistent with the production airframe direct labor hour data obtained from the RAH-66 Comanche Program Office. The two estimates are within 3 percent of each other [Ref. 36]. However, as was seen from the sensitivity analysis performed, any significant variation in production quantity or projected learning curve can substantially impact the final estimate.

VII. CONCLUSION

The shattering of the Cold War paradigm has forced the Department of Defense to reevaluate how it justifies its budgets for the acquisition of weapon systems. Cost estimation is an integral element of any budget development effort. Therefore, any advances in cost estimation techniques should prove useful to program managers.

This thesis presented information about composite material usage in the current fleet of DoD helicopters, composite material technology, cost estimation techniques, and a review of composite airframe cost estimation models. However, the focus of this study was the development of cost estimating relationships that may be useful in predicting the direct labor hours required to fabricate and assemble a composite helicopter airframe. This was accomplished by utilizing prototype airframe data. The model was then applied to a composite helicopter airframe to demonstrate how it could be used to develop an estimate of the average recurring direct production labor hours.

A. RESULTS

The analysis performed in conjunction with this thesis provides a strong argument that parametric cost estimation could be applied to composite helicopter airframes with a reasonable amount of success. Although the developed CERs were based on limited data, there does appear to be meaningful correlation between direct labor hours and various performance parameters. Maximum airspeed was selected as the best overall explanatory independent variable for this data set, but other variables could prove useful as more data are gathered on composite helicopter airframes.

The transformation of the prototype estimate to a production estimate was performed through a stepdown ratio. This technique provided reasonable results with the information currently available. However, great care must be used when applying this procedure because it is highly dependent upon projections of learning curve rates that are sometimes difficult to determine.

Another principal finding of this thesis is that the application of composite materials to DoD helicopters is proceeding at a much slower, more methodical rate than was originally predicted. This is due to many factors; the most noteworthy are shrinking defense dollars, manufacturing automation problems, and uncertainty about costs. Future DoD helicopter airframes will undoubtably contain more composite materials. However, the extent of composite usage will be influenced by many factors, the least significant of which will be aircraft performance.

B. RECOMMENDATIONS

The cost estimating relationships developed in this thesis should be applied and utilized in the acquisition of Department of Defense composite helicopter airframes. These CERs, used in conjunction with other techniques, may prove useful in the development of accurate cost estimates. As more cost data becomes available, it should be incorporated into the model, thus improving and expanding its predictive capability.

Composite materials have the potential to greatly improve the performance while simultaneously reducing the weight of advanced rotorcraft. Their use could benefit both future and current DoD helicopters. However, the incorporation of composite materials into an airframe is very risky in terms of cost and schedule. More applied research must be performed on this advanced technology. In addition, contractors should be given incentives to apply composite material technology to all new aircraft as well as upgrades to the current fleet.

The current DoD downsizing environment dictates that program managers focus increasing amounts of attention toward the subject of cost control. This burden could be lightened by a heightened awareness and further education of the acquisition workforce on the benefits and shortcomings of cost estimation.

C. AREAS OF FUTURE RESEARCH

The research conducted for this thesis revealed many questions that deserve answering. In particular, further inquiry is warranted in the areas of composite material technology and cost estimation within the Department of Defense. It is hoped, that the following topics will be addressed in future research:

- cost estimation applied to composite material tooling.
- the implications of composite material scrap rates on manufacturing costs.
- the influence of computer aided design (CAD) and computer aided manufacturing (CAM) in composite component production.
- application of the prototype step down ratio process to an advanced technology program.
- analysis of the variance between program cost estimates and actual program cost.
- the implications of learning curves in a prototype environment.

APPENDIX A

ACRONYM LIST

ACAP	Advanced Composite Aircraft Program
ARALL	Aramid Reinforced Aluminum Laminate
ATCOM	Aviation and Troop Command
ATF	Advanced Tactical Fighter
ATL	Automated Tape Lay-up
AVSCOM	Army Aviation Systems Command
BGV	Boost-Glide Vehicle
CAD	Computer Aided Design
CAIG	Cost Analysis Improvement Group
CEAC	Cost and Economic Analysis Center
CER	Cost Estimating Relationships
CMC	Ceramic Matrix Composites
COEA	Cost and Operational Effectiveness Analysis
DoD	Department of Defense
DODI	Department of Defense Instruction
EPM	Enabling Propulsion Materials program
FTV	Flight Test Vehicle
HSCT	High Speed Civil Transport
ICE	Independent Cost Estimate
IHPTET	Integrated High Performance Turbine Engine Technology

IPCE	Independent Parametric Cost Estimate
JVX	Joint Services Advanced Vertical Lift Aircraft
LHX	Light Helicopter Family
MCF	Manufacturing Complexity Factor
MMC	Metal Matrix Composites
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plan
NAVAIR	Naval Air Systems Command
OMB	Office of Management and Budget
PEEK	Polyetheretherketone
PEK	Polyetherketone
PMC	Polymer Matrix Composites
PPS	Polyphenylene Sulfide
STA	Static Test Article
TPA	Tool Proof Article
V/STOL	Vertical/Short Take Off and Landing
WBS	Work Breakdown Schedule

APPENDIX B

GLOSSARY

The following definitions were taken from *Cost Estimator's Reference Manual* [Ref.17], *New Structural Materials Technologies: Opportunities for the Use of Advance Ceramics and Composites* [Ref. 37], and *DoD/NASA Advanced Composite Design Guide* [Ref. 38].

Acquisition Cost: Total expenditures estimated or incurred for the development, manufacture, construction, and installation of an item of physical or intangible property, or the total acquisition cost of a group of such items.

Actual Cost: A cost sustained in fact, on the basis of costs incurred, as opposed to a standard, predetermined, or estimated cost. Actual costs to date include cost of direct labor, direct material, and other direct charges, specifically identified to appropriate cost accounts as incurred, and overhead costs and general administrative expenses reasonably allocated to cost accounts.

Adhesive: A substance capable of holding two materials together by surface attachment. In the Guide, the term is used specifically to designate structural adhesives, which produce attachments capable of transmitting substantial structural loads.

Advanced Filaments: Continuous filaments made from high strength, high modulus materials for use as a constituent of advanced composites.

ANOVA: Analysis of Variance; used in the statistical evaluation of the appropriateness of estimating relationships.

Aramid: Lightweight polyaromatic amide fibers having excellent high temperature, flame resistance, and electrical properties. These fibers are used as high strength reinforcement in composites.

Autoclave: A closed vessel for producing an environment of fluid pressure, with or without heat, to an enclosed object while undergoing a chemical reaction or other operation.

Autoclave Molding: A process similar to the pressure bag technique. The layup is covered by a pressure bag, and the entire assembly is placed in an autoclave capable of providing heat and pressure for curing the part. The pressure bag is normally vented to the outside.

Baseline Cost Estimate: The first deliberate, detailed estimate of acquisition and ownership costs. This estimate is normally performed in support of costing required for high-level decisions and serves as the base point for all subsequent tracking, auditing, and traceability.

Best-Fit-Line: A line that passes through a group of data point values in a manner that best represents the trend of the data points. The "least squares method" is frequently used to compute this line-of-best-fit.

Bias: An effect that systematically distorts a statistical result. The distortion may be small enough to ignore or large enough to invalidate the results. It may be due to the sample design, the sampling process, or the estimating technique. Analysts try to use "unbiased" techniques.

Capital: (1) The excess of assets over liabilities of an accounting entity. (2) The expendable or revolving funds used to finance enterprise or activity. (3) The assets of an enterprise, especially fixed property.

Capital Assets: Assets of a permanent character having continuing value.

Carbon/Graphite: These fibers, which are the dominant reinforcement in "advanced" composites, are produced by pryrolysis of an organic precursor--e.g., polyacrylonitrile (PAN), or petroleum pitch--in an inert atmosphere. Depending on the process temperature, fibers having high strength or high elastic modulus may be produced.

Ceramic: An inorganic,nonmetallic solid.

Coefficient of Correlation: A measure of the relationship (correlation) between two variables. Ranges from +1 when a perfect positive correlation exists (as *x* increases, *y* increases linearly) to a -1 when there is a perfect negative correlation. A correlation coefficient of zero indicates no relationship between the variables.

Coefficient of Determination: A measure used in regression analysis. It ranges from zero to one and is developed by dividing the variation in *y* (dependent variable) explained by the regression equation by the total variation in *y*. A coefficient of determination of 0.89 means 89% of the total variation was explained by the regression equation.

Comparative Cost Estimating: Comparing the job (or portions of it) to be done to all or parts of a previously completed job for which valid and comparable cost and technical information is available. This method of cost estimating can be applied to any level of work, detailed or summary, for estimating the cost producing elements or the cost itself. Generally, a proficient cost estimator will use this method to some extent, consciously or unconsciously, because his experience and natural thought processes force this measurement or appraisal. In comparative cost estimating, complexity factors or ratios may be used and applied to the known costs or cost elements to create the estimates--if enough information is available on the completed program to make a valid comparison of the new with the old prog Other terms that apply to this kind of estimating are spec analogy, cost history, estimating by comparison, compara analysis, "key factor estimating," delta from a previous estimate.

Confidence Level: The degree of probability that actual cost will fall within an expressed interval of the estimated cost, for example, +/- 5% of the estimated cost.

Consolidation of Parts: Integration of formerly discrete parts into a single part that encompasses several functions, a key advantage of engineered materials such as ceramics and composites.

Continuous Fiber: A reinforcing fiber in a composite that has a length comparable to the dimensions of the structure.

Continuous Filament Yarn: Yarn formed by twisting two or more continuous filaments into a single, continuous strand.

Correlation: Statistical technique used to determine the degree to which variables are related or associated. It does not prove or disprove a causal relationship.

Cost: The amount paid or payable for the acquisition of materials, property, or services. In contract and proposal usage denotes dollars and amounts exclusive of fee or profit (i.e., cost does not include profit or fee). Also used with a descriptive adjective such as "acquisition cost," or "product cost." Although dollars or other monetary units are normally used as the unit of measure, the broad definition of cost equates to economic resources, that is, manpower, equipment, real facilities, supplies, and all other resources necessary to accomplish work activities or to produce work outputs.

Cost Analysis: The methodical organization and systematic study of actual costs, statistical data, and other information on current and completed work. Cost analysis also includes the extrapolation of these cost data to completion, comparisons and analyses of these data, and comparisons of cost extrapolations on a current contract with the cost in the contract value for reports to customers, program and functional managers, and price estimators. In the procurement organizations of the U.S. government, cost analysis is the review and evaluation of a contractor's cost or pricing data and of the judgmental factors applied in projecting from the data to the estimated costs to form an opinion on the degree to which the contractor's proposed costs represent what the performance of the contract should cost, assuming reasonable economy and efficiency.

Cost Data: The term given to cost statistics or records of a program and which usually have not been analyzed and organized into cost information.

Cost Estimating: The skill of accurately approximating the probable resources required to produce a work activity or a work output based on information available or that can be collected at the time. Price estimating is defined as the art or skill of predetermining the market value of an item or activity that assures an acceptable profit.

Cost Estimating Methods: The several methods of preparing cost estimates and a variety of combinations of these methods used by individual cost estimators. The combinations depend on the character and size of the effort to be estimated, the available usable historical costs and technical data, and the experience and developed skill of the estimators. Each of the methods requires an analysis of the total job and a definition of the work to be performed. Examples of cost estimating methods are as follows: (1) detailed cost estimating; (2) comparative cost estimating; (3) parametric/ statistical cost estimating; (4) standards cost estimating; (5) expert opinion/roundtable cost estimating; and (6) empirical (historical) cost estimating.

Cost Estimating Relationships (CER): Mathematical expressions relating cost as the dependent variable to one or more independent cost driving variables. The relationship may be cost-to-cost, such as using manufacturing costs to estimate quality assurance costs or using manufacturing costs to estimate costs for expendable material such as rivets, primer, or sealant. The relationship may also be cost-to-noncost, such as estimating manufacturing costs by the use of weight or using the number of engineering drawings to estimate engineering costs. (Both weight and number of engineering drawings ar noncost variables.)

Cost Model: An ordered arrangement of data, ground rules, assumptions, and equations that permits translation of physical resources or characteristics into costs. Consists of a set of equations, logic, programs, and input formats to specify the problem; program information, including both system description data and estimating relationships; and an output format.

Cure: To change the properties of a thermosetting resin irreversibly by chemical reaction--i.e., condensation, ring closure, or addition. Cure may be accomplished by addition of curing (cross-linking) agents, with or without catalyst, and with or without heat.

Debond: A deliberate separation of a bonded joint or interface, usually for repair or rework purposes.

Delamination: The separation of the layers of material in a laminate. This may be local or may cover a large area of the laminate. It may occur at any time in the cure or subsequent life of the laminate and may arise from a wide variety of causes.

Detailed Cost Estimating: A method of cost estimating characterized by a thorough, in-depth analysis of all tasks, components, processes, and assemblies. Requirements for labor, tooling, equipment, and material items are produced by this type of estimating. The application of labor rates, material prices, and overhead to the calculated requirements translates the estimate into dollars. This type of estimating is further characterized by the presence of complete calculations, records and quotations to support the estimate.

Direct Labor: Labor that can be specifically and consistently identified or assigned to a particular end or deliverable work activity or output and that bears full overhead.

Direct Material: The term "direct material" includes raw materials, standards, commercial items, purchased parts, purchased equipment, outside production, and subcontracted items required to manufacture and assemble completed end or deliverable products or services. Direct material often also includes the costs associated with materials or products received from other company divisions under an interdivisional support agreement.

Disbond: An area within a bonded interface between two adherents in which an adhesion failure or separation has occurred. It may occur at any time during the life of the structure and may arise from a wide variety of causes. Also, colloquially, an area of separation between two laminae in a finished laminate (where "delamination" is preferred).

Drapability: The ease in which a material may be formed into a complex contoured shape without undesirable features (i.e., folds, wrinkles, etc.).

Ductility: The ability of a material to be plastically deformed by elongation without fracture.

Elasticity: The property whereby a solid material deforms under stress but recovers its original configuration when the stress is removed.

Estimate: A term describing the resources (labor hours, material costs), travel, computer costs, and other costs required to accomplish a contract, task, or work item. It also includes the effect of rates and factors that are applied to the labor and materials to develop estimated costs.

Estimated Cost: The conversion of resource estimates (labor hours and material quantities) into dollars by the application of rates and factors. The amount stated in a contract as the estimated cost. In proposal usage includes costs with no profit or fee.

Estimating Methodology: A definition of the estimating system and how estimates are prepared.

Estimating Technique: Refers to the processes or procedures used to develop an estimate; that is, cost model, estimating relationship, improvement curve, and so on.

Extrusion: A process in which a hot or cold semisoft solid material, such as metal or plastic, is forced through the orifice of a die to produce a continuously formed piece in the shape of the desired product.

Fabric: A generic material construction consisting of interlaced yarns or fibers, usually a planar structure. Specifically, a cloth woven in an established weave pattern from advanced fiber yarns and used as the fibrous constituent in an advanced composite lamina. In a fabric lamina, the warp direction is considered the longitudinal (L) direction, analogous to the filament direction in a filamentary lamina.

Factor: A numerical expression of value, or ratio, expressed as a percentage. A factor is used as a multiplier and, when combined with or related to other factors, contributes to produce a resource or cost estimate.

Failure: Collapse, breakage, or bending of a structure or structural element such that it can no longer fulfill its purpose.

Fatigue: Failure of a material by cracking resulting from repeated or cyclic stress.

Fiber: A single homogeneous strand of material, essentially one-dimensional in the macro-behavior sense, used as a principal constituent in advanced composites because of its high axial strength and modulus.

Fiber Direction: The orientation or alignment of the longitudinal axis of the fiber with respect to a stated reference axis.

Filament: A variety of fibers characterized by extreme length, such that there are normally no filament ends within a part except at geometric discontinuities. Filaments are used in filamentary composites and are also used in filament winding processes, which require long continuous strands.

Filament Winding: An automated process in which continuous filament (or tape) is treated with resin and wound on a removable mandrel in a pattern.

Filler: A second material added to a material to alter its physical, mechanical, thermal, or electrical properties. Sometimes used specifically to mean particulate additives.

Glass: A state of matter that is amorphous or disordered like a liquid in structure, hence capable of continuous composition variation and lacking a true melting point, but softening gradually with increasing temperature.

Hardness: Resistance of a material to indentation, scratching, abrasion, or cutting.

Heat Treatment: Heating and cooling of a material to obtain desired properties or conditions.

Homogeneous: Descriptive term for a material of uniform composition throughout; a medium that has no internal physical boundaries; a material whose properties are constant at every point--with respect to spatial coordinates (but not necessarily with respect to directional coordinates).

Hot Pressing: Forming a metal powder compact or a ceramic shape by applying pressure and heat simultaneously at temperatures high enough for sintering to occur.

Hybrid: A composite laminate composed of laminae of two or more composite material systems.

Independent Cost Estimate: Any cost estimate developed in organizational channels separate and independent from program channels and having the express purpose of serving as an analytical tool to validate or cross-check program office or contractor-developed estimates.

Independent Government Cost Estimate (IGCE): In government procurement, a government-prepared estimate of the probable price of a proposed procurement.

Independent Parametric Cost Estimate (IPCE): A physical and/or performance parameter-related life cycle cost estimate accomplished outside of the functional control of program proponents. The IPCE is developed to test the reasonableness of the proponent's baseline cost estimate and to provide a second opinion as to the cost of a product or service for consideration at a key decision point in the acquisition cycle.

Industrial Engineering Estimate: (1) A cost estimate made by the summation and pricing of the labor hours and material quantities required to produce tasks, end items, and components. The estimates are usually made by the persons responsible for the task or who will be doing the task. (2) An estimate based on timed or estimated labor standards, labor efficiency measures, and labor rates.

Injection Molding: Forming metal, plastic, or ceramic shapes by injecting a measured quantity of the material into shaped molds.

Integral Composite Structure: Composite structure in which several structural elements that would conventionally be assembled by bonding or mechanical fasteners after separate fabrication are instead laid up and cured as a single, complex, continuous structure--e.g., spars, ribs, and one stiffened cover of a wing box fabricated as a single integral part. The term is sometimes applied more loosely to any composite structure not assembled by mechanical fasteners.

Labor: A generic term that covers the effort of hourly skilled or salaried personnel. Usually expressed in labor-hours, or labor-months.

Laminate: A product made by bonding together two or more layers or laminae of material or materials.

Laminate Orientation: The configuration of a crossplied composite laminate with regard to the angles of crossplying, the number of laminae at each angle, and the exact sequence of the lamina layup.

Layup: A process for fabricating composite structures involving placement of sequential layers of matrix-impregnated fibers on a mold surface.

Learning Curve: (1) The learning curve is based on the assumption that as the quantity of units produced is doubled, the hours or costs to produce the units declines by a constant percentage. The constant rate of decline is the slope of the learning curve. This curve is linear when plotted on log-log coordinates. (2) A tool of calculation used primarily to project resource requirements in terms of direct manufacturing labor-hours or the quantity of material (for this purpose, usually referred to as an improvement curve) required for a production run. Used interchangeably with the term "improvement curve." Also referred to as progress curve, progress function, or experience curve. (3) Two types of learning curves are used: *Unit curves* identify the value of resources required to produce each unit; and *Cumulative curves* show the value of resources required to produce a given amount of units. A *Cumulative average curve* is developed by dividing the cumulative value by the cumulative units.

Least Squares Method: A regression method used to develop an equation that best fits a grouping of cost data points.

Level-of-Effort: Normally refers to a constant number of personnel assigned to a given job for a specified period of time.

Life Cycle Cost: All costs incurred during the projected life of the system, subsystem, or component. It includes total cost of ownership over the system life cycle including all research, development, test, and evaluation; initial investment; production; operating and support maintenance costs; and disposal costs.

Linear Regression: A technique for fitting a straight line to a family of plotted points on Cartesian coordinates. Used in developing cost estimating relationships.

Load: The weight that is supported by a structure, or mechanical force that is applied to a body.

Man-Hour: A unit of work representing the productive effort of one person in one hour. Currently referred to as a "labor-hour," "work-hour," or "hour."

Manufacturing Labor: Generally that direct labor performed directly on the end item or processing of parts used in the finished product, and the functional testing of the product. It normally covers fabrication, assembly, and manufacturing support activities. Sometimes also includes tooling and quality control labor.

Matrix: The composite constituent that binds the reinforcement together and transmits loads between reinforcing fibers.

Metal: An opaque material with good electrical and thermal conductivities, ductility, and reflectivity; properties are related to the structure in which the positively charged nuclei are bonded through a field of mobile electrons that surrounds them, forming a close-packed structure.

Methodology: A term used in estimating to describe the methods used to develop an estimate (i.e., detailed, empirical, comparative, statistical, parametric, standards, etc.).

Milestone: A date or event that signifies either the start or completion of a task, work item, or activity.

Model: A model is a representation of the reality of a situation or condition being studied. Consists of a series of equations, ground rules, assumptions, relationships, constants, and variables that describe and define the situation or condition being studied.

Modulus Of Elasticity: A parameter characterizing the stiffness of a material, or its resistance to deformation under stress. For example, steel has a fairly high modulus, while Jello has a low modulus.

Monolithic: Constructed from a single type of material.

Nonrecurring Costs: Those elements of development and investment cost that generally occur only once in the life cycle of a work activity or work output. Examples are engineering, system test, tooling, and preproduction activities. Includes basic design and development through first release of engineering drawings and data, all system and subsystem test activities (except end item acceptance testing), configuration audits, qualification testing, technical publications through initial release, basic tool and production planning through initial release, all basic tooling, prototypes, engineering models, units built for test purposes only, units not built to production configuration, and specialized work force training.

Normalize: *Data Base*: To render constant or to adjust for known differences. *Dollars*: Previous year costs are escalated to a common year basis for comparison.

Parameter: A characteristic that is considered to be essential in accurately describing a problem, population, or system. The characteristic is used to calibrate, measure, or calculate a series of results or tests. It might be a design, system, equipment, or cost parameter. In cost estimating, a parameter is often hours per pounds, dollars per horsepower, hours per wire, and so on.

Parametric Cost Estimating: Parametric cost estimating is a technique that employs one or more cost estimating relationships for measurement of costs associated with the development, manufacture, and/or modification of a specified end item based on its technical, physical, or other characteristics.

Point Estimate: (1) An estimate that measures a single numerical value rather than a range of values. (2) An estimate that is made based on total resources required to do a job but that is not time scheduled. Expenditures are estimated as if they are to be used at a single point in time. A noncalendar-based estimate.

Polymer: Substance made of giant molecules formed by the union of simple molecules (monomers); for example, polymerization of ethylene forms a polyethylene chain.

Pore, Porosity: Flaw involving unfilled space inside a material that frequently limits the material strength.

Prepreg: Fiber reinforcement form (usually tape, fabric, or broadgoods) that has been preimpregnated with a liquid thermosetting resin and cured to a viscous second stage. Thermoplastic prepregs are also available.

Procurement: The act of obtaining raw material, purchased parts and equipment, subcontract, and outside production items. The obtaining of equipment, resources, property, or services by purchasing, renting, leasing, or other means. In the supply management sense it may include the functions of design, standards determination, specification writing, selection of suppliers, funding, contract administration, and other related functions.

Pultrusion: A fabrication process that uses guides, shape dies, and heat to produce long parts with constant cross sections, which are then automatically cut to desired lengths. The process consists of pulling dry fibers through a resin bath and then through steel dies that define the shape of the part and control the amount of resin in it. Heat must be supplied to cure the part.

Recurring Costs: Repetitive costs that vary with the quantity being produced.

Regression Analysis: The association of one or more independent variables with a dependent variable. The relationships are associative only; causative inferences are added subjectively by the analysts.

Relevant Range: A range over which a fixed cost applies. A cost element may have more than one relevant range, and, if so, the "fixed costs" may vary in a stepwise function.

Statistical Cost Estimating: Parametric or "top-down" estimating, statistical cost analysis, cost analysis, or formula estimating. This estimating method requires an analysis of the work to be performed, but generally can be based on a less detailed definition of work than is required for other methods. In this kind of estimating, cost is estimated for the entire job, or major portions of it, using certain major or technical or physical characteristics (weight, speed, horsepower, etc.) with their relationships to costs as developed by studies of past jobs, their technical characteristics, and their costs.

Strain: Change in length of an object in response to an applied stress, divided by undistorted length.

Stress: The force acting across a unit area in a solid material in resisting the separation, compacting, or sliding that tends to be induced by external forces.

Tack: Stickiness of a prepreg.

Thermal Conductivity: The rate of heat flow under steady conditions through unit area per unit temperature in the direction perpendicular to the area--the ability of a material to conduct heat.

Toughness: A parameter measuring the amount of energy required to fracture a material in the presence of flaws.

Unitized Design: A unitized design refers to the philosophy of designing and building a structure in one piece, thereby eliminating the need for fasteners. Traditionally these structures were manufactured in separate pieces and then mechanically aligned, shimmed, and fastened. The unitization of the piece then can save much of the alignment and assembly work and makes the piece less likely to contain undetected flaws associated with drilling holes, etc.

Wettability: The ability of any solid surface to be wetted when in contact with a liquid.

Work Breakdown Structure (WBS): A product- or service-oriented family tree or hierarchy, composed of hardware, software, services, and other work tasks, that completely displays the project/program. A management technique for subdividing a total job into its component elements, which then can be displayed in a manner to show the relationship of these elements to each other and to the whole. The work breakdown structure can equate to an outline of a statement of work. Also called Work Element Structure.

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