Design and Manufacture of Advanced Composite Aircraft Structures Using Automated Tow Placement

by

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Bachelor of Science in Mechanical Engineering
University of California at Los Angeles, 1991

Submitted to the Alfred P. Sloan School of Management and the Department of Mechanical Engineering in partial fulfillment of the requirements for the Degrees of

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Abstract

To meet the pressures of manufacturing defense aircraft in the 1990's, manufacturers have turned to automated tow placement to reduce costs and improve quality. There is a tight link between design and manufacture of aircraft fuselage structures with automated tow placement (ATP). Since ATP is a new technology, there is little historical production data. This thesis begins to fill that void by gathering information about the tow placement process through relevant literature, a physical model, historical data and a benchmark study of six different companies with tow-placement machines.

A linear model is introduced which predicts lay-up times from part shapes and sizes. This model is found to reasonably predict lay-up times in approximately one-eighth of the time necessary to build a CAD data file and import it for NC code generation. Additionally, it can be simply expanded to estimate recurring costs of a part. This model can be used to develop intuition about ATP by understanding the effects of complexity as well as orientation.

The average lay-up rate of the first production ATP machine is found to be 0.72 lb./hr. — a number well below previous expectations. Two options to inexpensively improve production are considered: purchasing used equipment and improving present operations. A process improvement team at a major defense aircraft manufacturer found downtime to be 44% of the total time to lay-up a part. Thus, reducing downtime was a major focus of improving operations and is discussed in detail in this thesis.

Thesis Advisors:

Thesis Supervisor: Karl Ulrich, Sc.D.
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The last group of people who should be thanked is the Boeing Company for their financial support of myself and the Leaders for Manufacturing Program. Tim Copes, Frank Hughes and Ruth Dabbs frequently worked very hard to make my internship a pleasant one. Thanks again to everyone.

Dedication

This thesis is dedicated to my Fiancée, Charlene Stroup. She has gone through four moves in two years, endless long nights and she will not even get a degree. Such dedication is hard to find and impossible to thank. May these pages at least be a token of appreciation.

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1. Introduction

This thesis discusses the fabrication of advanced composite structures using the Automated Tow Placement (ATP) lamination process. It is the result of a Leaders for Manufacturing Internship at Boeing Defense and Space Group (BD&SG), Helicopters Division (HD). This internship included a six-day benchmarking study of companies who use automated tow placement to fabricate defense industry aircraft structures. The companies participating in this study are shown in **Table 1.**

Company	Supplier of ATP Machine
McDonnell-Douglas (MDA)	Ingersoll
Cincinnati-Milacron (CMI)	CMI
Bell Helicopter	McLean Anderson/Automated Dynamics
Northrop-Grumman	CMI
BD&SG, Helicopters Division	CMI
BCAG, Fabrication Division	Ingersoll

Table 1: Benchmark Study Participants

In the first chapter the automated tow placement process is introduced. Then, the problem which is addressed in this document is described. That section is followed by a discussion about the Helicopter Industry. An introduction to advanced composites processing and design follows. With this background a reader with minimal knowledge of composites and the helicopter industry should be prepared for the following chapters.

The second chapter discusses design for the Automated Tow Placement Process. It begins with reasons to choose tow placement to manufacture a part. Then, a concurrent design process is suggested:

1. Select the process for the part
2. Tailor the equipment to the part
3. Design for the process

Concurrent design of equipment, part and process is not earth-shattering, but a detailed case study and execution strategy goes beyond previous efforts in this technology.

Chapter 3 and 4 introduce and apply a physically-based cost model for advanced composites. This model has been used extensively at MIT's Laboratory for Manufacturing Productivity. This thesis is the first attempt to apply this simplified model for production with automated tow placement. The theory behind the model is discussed first. Then, the model is verified and used. Chapter 4 outlines guidelines for using the model and describes how the reader can apply the model with a practical example.

Chapter 5 discusses manufacturing with tow placement technology. First, a benchmark summary of the technology is introduced. Then, production data is used to determine the present capacity of Helicopter's tow placement efforts as well as an innovative way to look at the efficiency of a tow placement machine. Sources of downtime are then identified because downtime was found to be 44 percent of the total time to lay a part.

With downtime identified, the author suggests a learning process to improve the operation of BD&SG's tow placement machine.

The final chapter summarizes the main points and introduces items for future research.

1.1 The Problem

Automated tow placement (ATP) was developed in the 1980's. Several companies have taken credit for its invention and initial development, including Boeing Commercial Air Group (BCAG), Northrop and Hercules. It is also known as fiber placement, automated fiber placement and advanced tow placement. BCAG succinctly defined automated fiber placement in internal documents [7]:

Automated Fiber Placement is the process by which composite prepreg materials are applied to lay-up tools in an automated way to form parts with significant curvature. It can be thought of a technology which combines the virtues of automated tape laying and filament winding while eliminating the disadvantages of each.

Automated fiber placement does not eliminate the disadvantages of the other lamination processes, but it is a technology that combines other processes to manufacture a wide variety of aerospace part shapes. ATP is not the ideal process for all part shapes, sizes and volume produced — there is no ideal process for every part. Boeing Defense and Space Group (BD&SG), HD installed the first machine to be used for production aircraft in April 1994. The machine is a Cincinnati-Milacron *Viper* as shown in **Figure 1**.

The internship which led to this thesis spanned from June to December 1995. Using Concept Engineering, the author identified the helicopter division's main concern in general terms:

Although ATP is a new technology with substantial development data, HD lacked the data required to make educated business decisions for design and production of fiber placed parts.

Thus, the purpose of this thesis is to use data from manufacturing to make design decisions. This problem statement exposes the linkage between business, design and production. Thus, it is important to understand the industry (external environment), the company (internal environment), composites design and composites processing. The following sections explain background information as well as the current status of ATP in industry.

1.2 The Industry

Helicopter manufacturers sell to civilian and military markets. **Figure 2** [1, p. ES-6 & ES-7] shows the world demand for helicopters. Numbers after 1995 are projections. The conclusion from the graph is that the cost of military aircraft is much higher than civilian aircraft. This is due to the additional requirements of flying low to the ground, firing weapons, surviving a projectile penetration and using "integrated systems to fly at night, acquire targets and reduce signatures" [1, p. ES-3]. Additionally, the charts also show a decline in production in the 1990's. This forecast is optimistic — the Teal group projected not only a decline in future military demand, but also civil. Additionally, their numbers were about two-thirds of the numbers shown in these figures.

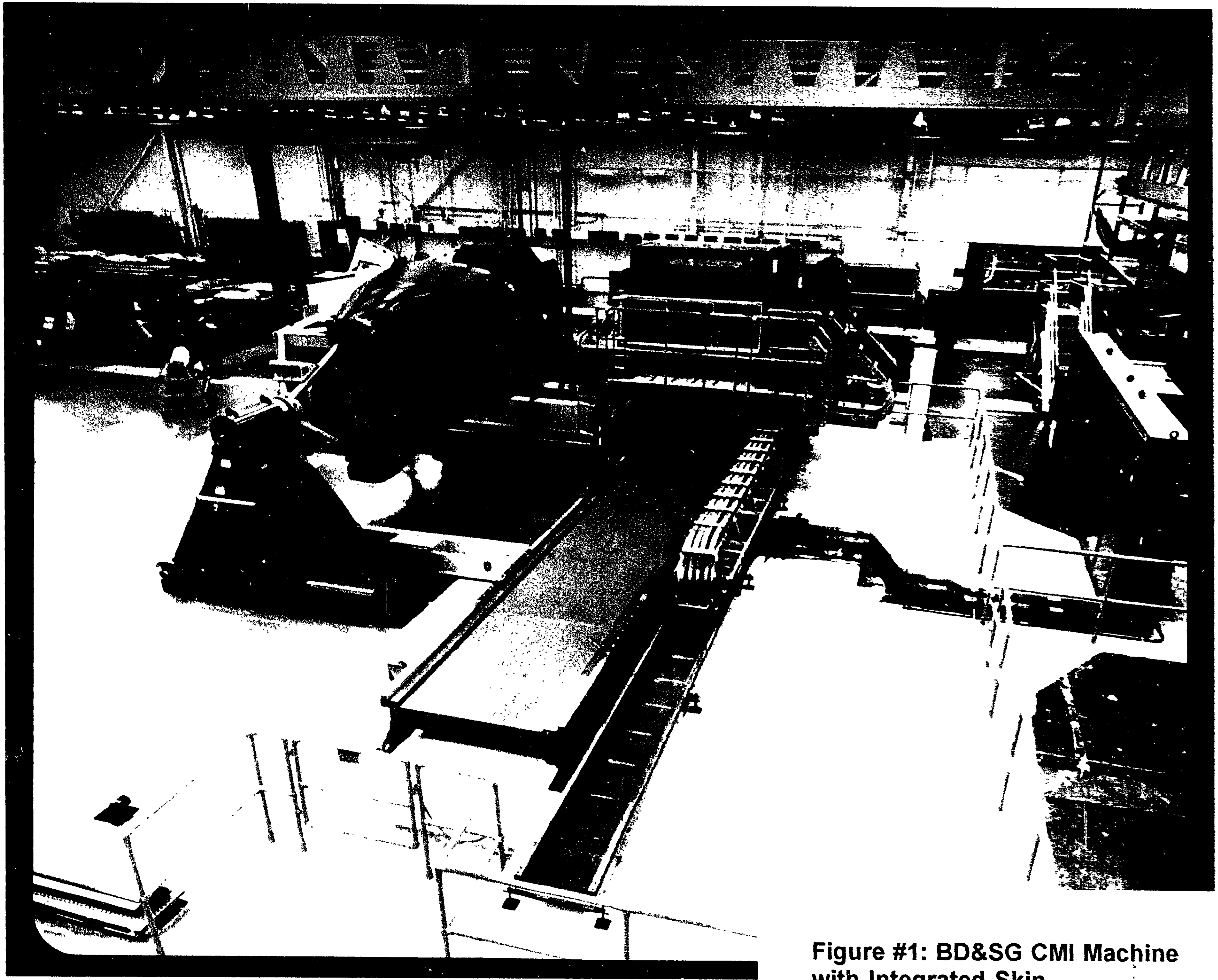


Figure #1: BD&SG CMI Machine with Integrated Skin

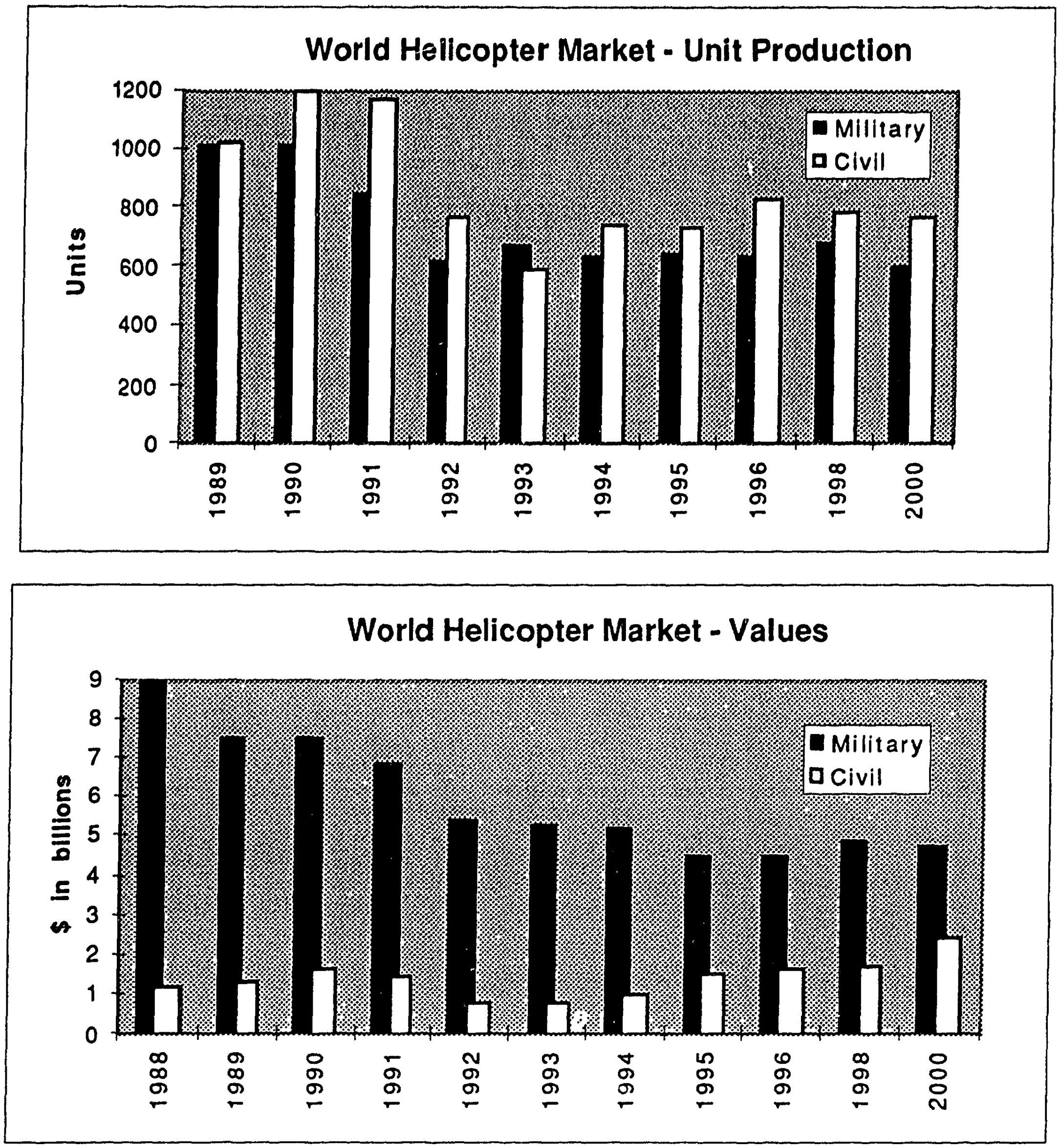


Figure 2: The World Helicopter Market

This section first takes a static look at the industry to understand the equilibrium forces present in the military aircraft industry. Next, a dynamic view of the industry is presented to introduce the effect that military downsizing is having on the prime helicopter contractors.

The reader who is interested in a more in-depth assessment of the helicopter industry can refer to a Department of Defense document titled *Industrial Assessment for Helicopters* [1].

1.2.1 A Static Analysis

Porter's five forces framework has been widely accepted since 1980 [26]. The five forces are:

1. Buyers
2. Existing Rivalry
3. Suppliers
4. Substitutes
5. Potential Entrants

In the U.S. military market there are four prime contractors supplying the Department of Defense: BD&SG, MDA, Bell/Textron and Sikorsky. There is little rivalry within this group. Additionally, some are teamed with each other to produce future helicopters for the Department of Defense. Since there is overcapacity in the helicopter industry, some consolidation is expected between these firms. Over the past year, there have been rumors about HD merging with MDA, Bell and Sikorsky. None have shown the test of time. All four contractors have the systems integration capabilities required of a military aircraft assembler.

Farther down the supply chain, the companies who supply components to primary defense contractors are consolidating. In 1996 Lockheed Martin agreed to acquire Loral's defense-electronics and systems integration businesses, Northrop-Grumman agreed to buy Westinghouse Electric's defense electronics business and Rockwell International is seeking a buyer for its aerospace and defense holdings [10].

There is little chance of substitutes or new entrants. Civilian helicopters cannot substitute the way a modified 747 freighter could for a C-5. There is little chance of success for a new entrant in the military helicopter market. This is due to industry overcapacity as well as the design and capital capabilities required to produce a military aircraft. Lockheed was the last to attempt to enter the market with the Cheyenne Attack Helicopter. They failed due to technical difficulties. Foreign competitors are not expected to enter this industry because of U.S. security reasons.

In summary the Department of Defense has more power than the four domestic suppliers, but prime contractors have a reasonable amount of power due to the low level of competition after a contract is awarded (a two-part tariff) and the lack of substitutes.

1.2.2 A Dynamic Analysis

As shown in **Figure 3** [27] a company's business strategy should respond to the social, political and economic environment in which it is immersed. This response will be in the form of internal changes to structure. processes, job roles and/or technology.

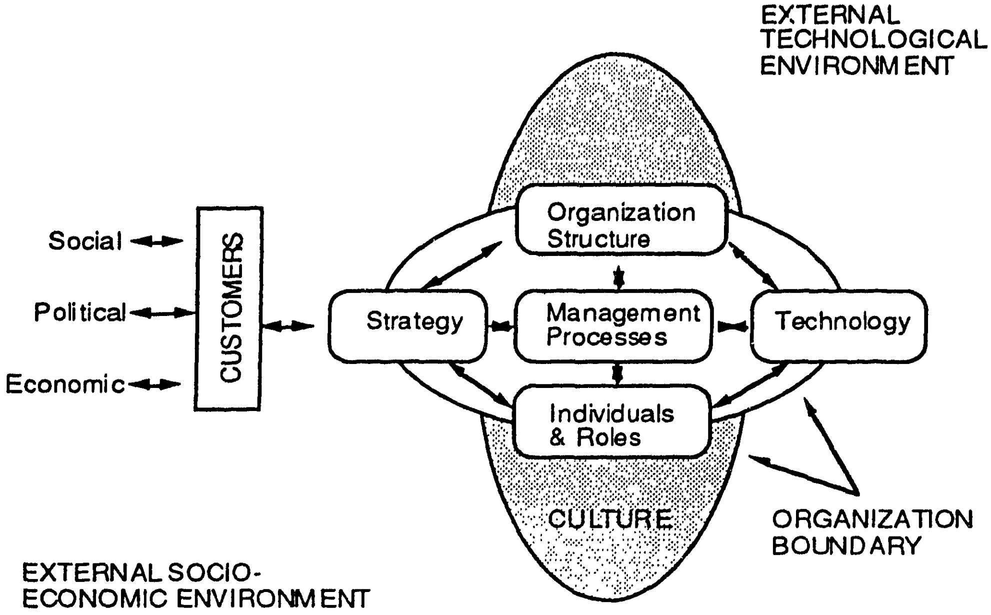


Figure 3: A framework for the Dynamic Analysis of the Industry

Significant political-economic changes have occurred following what Joshua Gotbaum, the Assistant Secretary of Defense of the United States, called "Victory in the Cold War era" [1, p. i]. Defense development budgets have dropped 50% in real terms over the last decade. Prime contractors are consolidating facilities, streamlining their organizational structure, reviewing management processes, laying off employees and investing in new technologies. The goal is to realize an adequate profit despite the increased pressures to reduce costs. Indeed, their goal is being met: "Despite declining military sales significant excess capacity and strong foreign competition, all four of these prime [helicopter] contractors are currently profitable [1, p. ES-2]."

One way the defense department is hoping to reduce costs is to use some standard commercial parts in military aircraft. This may be a primary reason for Boeing's involvement with both of the present development efforts: the V-22 Osprey (Bell/Boeing) and the RAH-66 Comanche (Boeing/Sikorsky).

The changes in the defense environment as well as the maturing of tow placement technology resulted in HD adopting fiber placement. HD expects a cost savings by manufacturing integrated, advanced composite aircraft structures with ATP.

Although it is difficult to separate a dynamic analysis from a static analysis, this section exposed the dynamics of the defense aircraft market which has been downsizing. Downsizing affected actions inside and between firms. Finally, this trend will probably continue unless a significant threat, such as an unpredictable China, causes America to rethink its defense posture.

1.3 Composites Processing

In this section the author first introduces advanced composite materials. Second, a typical composites process flow is described. Then, the motivation for automating the manufacture of advanced composites is discussed and lay-up processes are highlighted. Finally, automated tow placement is described in more detail.

1.3.1 Materials

Most people are familiar with common composite materials like wood, cement and adobe. Advanced composites are materials with specialty fibers embedded in a polymer matrix. They are becoming more common on race cars, aircraft and sports equipment due to their high strength to weight ratios. This section addresses several issues: (1) benefits and disadvantages of composites, (2) resin systems, (3) fibers and (4) material costs.

In her 1990 MIT master's thesis Christy Shipp describes a host of possible advantages which are outlined here: weight savings, corrosion resistance, fatigue resistance, reduced manufacturing costs [with integrated structures] and increased product sales due to a "high tech" marketing appeal [13, p. 26 & 27]. She also listed some disadvantages: increased manufacturing cost, limited understanding of product and process when compared with metals, high maintenance costs, difficulties with lightning strikes and part warpage during cure. Recently, increased material standardization has improved maintenance costs, a copper mesh layer reduces the effects of lightning strikes and improvements have been made to decrease warpage.

Thermoset and thermoplastic resins are differentiated by the amount of polymer cross-linking. Thermoplastics (very little cross-linking) are not included in this document. Thermoplastics are beneficial because they can be heated and reformed. An excellent discussion on thermoplastic and thermoset resins is given by Jenks [12, p. 54-59].

There are various thermosetting resins, including epoxies, polyester, polyamide and bismaleimide (BMI). Thermosets undergo a permanent cross-linking reaction induced by temperature and/or a chemical catalyst. At present, thermosets are more common than thermoplastics. Polyamide and BMI can operate at higher temperatures than epoxies, but they are more expensive and difficult to manufacture.

This thesis focuses on epoxies because they are the primary resin used in automated tow placement applications. **Table 2** identifies several common resin systems used with automated tow placement. Tows are untwisted bundles of fibers. There are two types: (1) towpreg and (2) slit-tape. Towpreg is tow material preimpregnated with epoxy resin. Slit tape is preimpregnated unidirectional tape which has been slit into tows of material and mounted to a polymer interleaf strip which is removed as the tow is dispensed.

Resin	Supplier	Tow Type	Users
3501-6	Hercules	(1) & (2)	Boeing
8552	Hercules	(1) & (2)	Boeing, Northrop Grumman
E7T1-2	Fiberite	(2)	Bell, Raytheon, CMI
977-3		(2)	MDA, Northrop Grumman

Table 2: Resin and Tow Forms used by various companies

3501-6 is a non-toughened epoxy resin which is extensively used with military aircraft. It is delivered in a semi-cured condition known as the "B-stage." The others are toughened resin systems. Toughened resins have reduced tack for improved handling. With ATP a toughened resin does not deposit along the fiber delivery system as quickly. This results in less downtime and more production for the equipment. The disadvantage is that toughened resins often perish earlier (a shorter shelf-life).

There are a variety of advanced composite fibers, including boron, graphite, aramid (Kevlar), S-Glass and E-Glass. The physical properties of two frequently-used graphite fibers along with bulk steel (for comparison) are shown in **Table 3**.

Material	**E_1** GPa	**failure stress,** MPa	**Maximum strain, %**	**Density,** g/cm^3
Stiff Graphite, IM7	300	5313	1.8	1.78
Strong Graphite, AS4	248	4071	1.65	1.8
410 Stainless	200	1000	20	7.8

Table 3: Physical Properties [20]

The table reveals the obvious benefits of using graphite fibers: the stiffness to weight ratio of IM7 is 6.6 times that of 410 stainless steel. Fibers are much stronger than bulk materials because their small diameter naturally excludes large scale voids and defects. The strength of these fibers can be exploited by aligning them with the direction of forces. Therefore, there are performance benefits to using fiber-reinforced composites.

It is useful to understand how carbon fibers are made. There are seven steps to make a graphite fiber:

1. Poly Acrylonitrile (PAN) is delivered
2. PAN is stretched in a steam atmosphere
3. PAN is oxidized in air at 230°C
4. Fibers are skeined
5. Material is oxidized in air at 230°C
6. Material is carburized at 1000°C in Nitrogen
7. Material is graphitized at 2500°C in Argon

The PAN raw material is stretched and oxidized in air. Then, this stretched material is wound onto a coil (pronounced sk ā ned) to ease feeding as it unwinds into the series of following oxidation steps. In each of the steps the molecular arrangement of the carbon fiber changes. After graphitization, the fiber is cooled and resin is introduced to form preimpregnated broad goods (fabric or tape) or tow.

Fiber/Resin	Prepreg Fabric ($/lb.)	Slit-Tape ($/lb.)	Towpreg ($/lb.)
AS4/3501-6	33	35	35
AS4/8552	41	42	43
AS4/977-3	58	60	96
IM7/977-3	80	84	120

Table 4: Approximate Costs of Materials [28]

Another issue with advanced composites is the cost as shown in **Table 4**. The costs are approximate because material suppliers charge a setup price as well as a price per pound. Thus, a larger batch will cost less to purchase on a per pound basis. In general, fabric costs are less expensive than tow, but increased material costs can be offset by a reduction in manual labor and scrap costs from automating layup.

For comparison purposes, a 777-200 will cost approximately $420/lb and a Ford Probe will cost about $8/lb. Thus, a commercial or military aircraft could cost effectively use graphite/epoxy composites and a car could not. Christina Shipp found that the present value of fuel savings per pound of weight over a 20-year aircraft life is approximately $300 per pound [13, p. 24]. Thus, there is a motivation to use composites in aircraft.

With an understanding of material forms and costs, the process steps required to fabricate advanced composite structures can be discussed.

1.3.2 Process Flow

A simple process flow diagram for advanced composites manufacturing is shown in **Figure 4**. Although the figure is quite understandable, some points are highlighted:

- The raw material is advanced composite fabric, tape or tow
- After ply cutting, some material is stored in "kits" in a freezer
- Dashed lines represent the flow of the tool without the part
- Some sub-assemblies require sealing from the environment
- Triangles represent inventory process steps

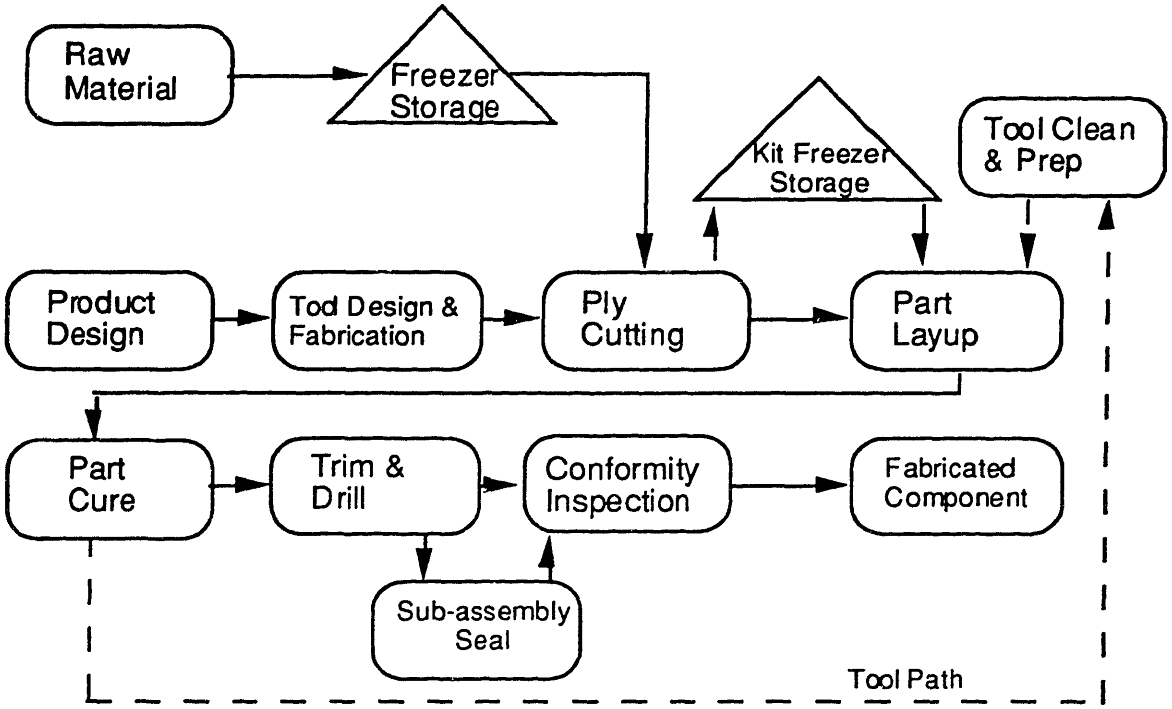


Figure 4: Typical Composite Fabrication Process Flow (courtesy Northrop-Grumman)

There are four basic process steps for fabrication of thermoset materials [20, spring 1995]. These are:

- Wetting (prior to layup)
- Placement of fibers (during layup)
- Flow & Consolidation (at layup and beginning of cure)
- Cure

These processes can occur separately or at the same time. "Wetting" will typically occur at the material supplier's plant. This is the step where resin is introduced to the fibers. It is beneficial to introduce resin at the latest stage possible because it hardens when exposed to the environment. The tradeoff is that handling of materials wet with resin is difficult and messy. Thus, most materials are wetted before the lay-up step. Resin kinetics and thermodynamics are critical at this stage because all fibers should be wetted with resin prior to an increase in resin viscosity which limits flow.

The placement of fibers (layup) is the act of orienting and layering fibers. This process can be done by hand, by machine, or by some hybrid of the two. Surface curvature and resin tack are the critical physical concerns at this stage. As shown in Chapter 2, in-plane and out-of-plane curvature (shown in **Figure 5**) will limit the processes as well as the speed at which the part is fabricated. Tam and Gutowski wrote an excellent discussion about the geometric difficulties of mapping fibers into complex shapes [21]. Tack is important because a low-tack resin may not be able to conform to, for example, a concave surface because the tack force cannot overcome the tension along the fibers.

"Flow and consolidation" is the flow of resin through the matrix and consolidation of fibers into a densely-packed volume. **Figure 6** shows a representation of fiber packing as well as the viscosity change of 3501-6 resin. This step is critical because part strength will increase with reduced voids and densely packed fibers. Flow is often encouraged through elevated temperatures, but the manufacturer must be careful to maintain the correct temperature or the resin will set prematurely. Resin pressure is critical because too much could cause voids as resin exits the capillaries between fibers.

Figure 5: Representation of In-Plane (geodesic) and Out-of-Plane Curvature (normal)

The final basic process step, "cure", is essential to part geometry. Reaction kinetics typically occur according to the Arrhenius equation:

$$k = Ae^{-(E_a/RT)}$$

This equation reveals that the reaction occurs faster with increased temperature and slower with increase activation energy (E_a). The critical concerns with cure are warp, burn and part degradation. With the anisotropy of the thermal expansion coefficients in composites, warping is a genuine concern. Additionally, the exothermic reaction could advance too quickly and cause a portion of the part to burn or degrade. Finally, cure time depends on part thickness and a part with extreme thickness changes could also see strength degradation at thin wall points.

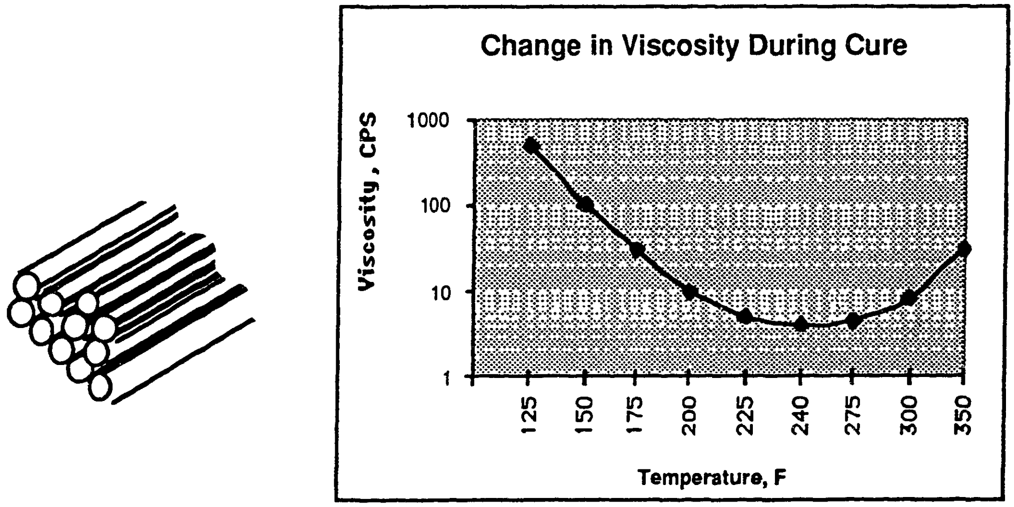


Figure 6: Fiber Packing and Viscosity change During Cure[20]

1.3.2.1 Large Fairing Process Plan

The major steps of the process plan for HD's large fairing are listed below. Since this fairing has a sandwiched honeycomb construction, there is little ply cutting and no kit making for stiffeners. There are 22 major process steps:

1. Prep the tool face
2. Stack and cut isolation plies
3. Load and align ATP mandrel / clean machine head / install material
4. **Apply inner copper shielding ply (needed because near fuel tank)**
5. **Apply E-Glass isolation ply**
6. Lay inner skin
7. **Lay-up adhesive film**
8. Bag and Debulk
9. **Fit Core**
10. Lay-up Outer 1st ply
11. Bag and Debulk
12. Lay-up other outer plies
13. **Apply outer copper shielding ply**
14. Transfer to curing tool
15. Install caul plate (for inner surface smoothness)
16. Vacuum bag and leak check
17. Transport to autoclave
18. Cure in autoclave
19. Transport to inspection
20. Non-destructive testing
21. Rework if necessary
22. Trim, package and ship to assembly

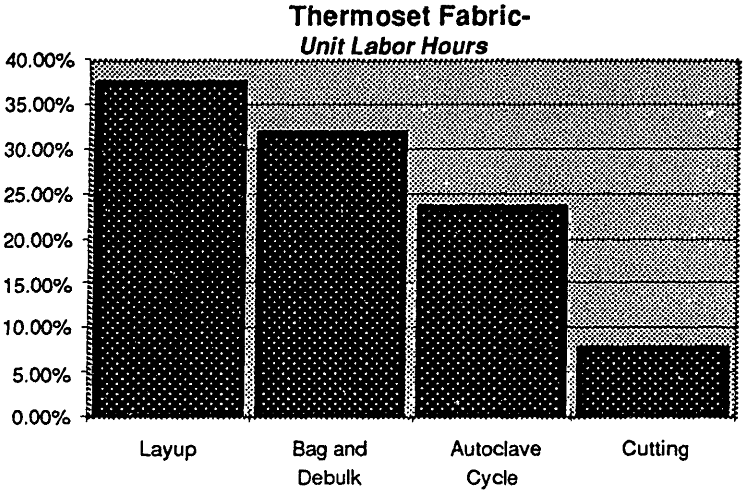
Only items 6, 10 and 12 involve the automated tow placement machine. Item numbers in bold typeface are hand operations during the lay up stage. These steps are representative of an ATP part with honeycomb construction. A skin/stiffener construction will have stringers installed before or after a single lay-up stage. Now that the reader has an understanding of the process steps, the next step is to develop an understanding of the motivation for automation as well as the processes available.

1.3.3 Automation

A change in the economic-political environment was one of the driving factors for Boeing to purchase their CMI tow placement machine. Is it reasonable to expect a cost savings through automating the layup of composites? Foley and Bernardon looked at this question with thermoset fabric and thermoplastic uni-directional tape, biaxial broad goods and the preconsolidated sheet [5., p.71.]. They found that among labor, material, equipment, and other factors, labor was the most significant driver for cost effective materials (thermoset fabric and thermoplastic unidirectional tape). Within the labor realm, the lay-up cycle was the most significant portion of labor hours in composite fabrication (**Figure 7**). They also determined that automation should be used in house to make low cost materials more cost effective because the manufacturer would:

1. Increase their control of final part quality
2. Gain flexibility in tailoring the final properties of the part
3. Add value in-house rather than paying a material supplier profit

The first two items are generally accepted to be true in modern business literature: automation will have (1) more consistent quality and (2) flexibility in tailoring the final properties. Taguchi and the Japanese proved there is a cost with lower quality [30]. Flexibility allows improved products because the aircraft performance is improved. Even with military production, better products should result in increased throughput and long-term profitability.



20.7 hour average, 700 parts

Figure 7: Layup is a primary source for labor costs [5, p. 71]

Foley and Bernardon may not have considered two aspects of the system: the cost of inventory and the supply chain. Inventory cost is especially important because holding cost is high and material can perish due to the shelf-life of a thermoset resin (a manufacturer either buys expensive freezers or wastes material). Additionally, the manufacturers are typically aerospace companies which pay high wages. Lower costs at a supplier firm may reduce the total cost of production. Indeed, outsourcing has been a significant cost savings for car and computer manufacturing. Although Bernardon and Foley's analysis is excellent for 1990, future studies should consider the system costs in more detail.

1.3.3.1 Automation Processes

Various steps in the fabrication of advanced composites were described previously in this chapter. To date there has been significant automation in cutting, layup, cure, trim and inspection. Since Jenks presents a concise overview of relevant manufacturing processes in his master's thesis, this thesis does not reiterate them [12, p. 49-53]. For ease of reading, Jenk's overview table has been included as **Table 5**.

There are a variety of other technologies which are used at various stages of composites processing: ultrasonic and reciprocating ("gerber") cutters; honeycomb machining;

autoclave and press-forming (flow, consolidation and cure steps); waterjet, router and laser trim; and automated ultrasound part inspection.

Process Category	Processes Included
Resin Transfer Molding (RTM)	Vacuum-assisted Resin Injection (VARI) Preform Molding Structural Reaction Injection Molding (SRIM)
Injection Molding	Reaction Injection Molding (RIM) Reinforced Reaction Injection Molding (RRIM)
Compression Molding	Sheet Molding Compound (SMC) Thermoplastic Molding (Stamping) Diaphragm Molding Hot Transfer Press Molding
Pultrusion	Axial Fibers Multi-directional Fibers
Lamination	Hand Lay-up Automated Tape Laying (ATLM) Contoured Tape Laying (CTLM) Tow (Fiber) Placement Filament Winding
Textile Processing	Braiding Complex 3-D Weaving Knitting

Table 5: Advanced Composite Manufacturing Processes

Table 6 summarizes the limits and capabilities of relevant lamination processes. Hand lay-up is a labor-intensive process which can be used to effectively manufacture a large variety of shapes of limited size by laying sheets of fabric. CTLM is a high volume process which dispenses preimpregnated tape directly to a tool surface. It is excellent for shapes with little curvature like wing-skins. Fiber placement is useful for a large variety of parts with non-constant cross sections, buildups and single and double curvature. Since filament winding is a continuous process which lays a band of tows, but it cannot add or drop tows. It is excellent for parts with circular, constant thickness cross-sections like rocket motors and liquid storage tanks for corrosive materials.

Hand Lay-up	Versatile making complex parts as large as 60 inches (due to human ergonomics). Simple parts can be made larger (the belly skin is 251 inches). Can lay buildups.
Contoured Tape Laying	Limited to contours less than 15 degrees. Large size capability. Can lay buildups.
Tow Placement	Capable of large parts & complex contours with non-constant cross-section, but not excessive tapers that require material placement across the tip (i.e. nose cones). Can lay buildups.
Filament Winding	Capable of surfaces of revolution only. Not capable of complex contours & non-constant cross-sections without excessive weight buildup. Limited fiber orientations. Cannot lay buildups.

Table 6: Comparison of Lamination Processes

Table 7 gives typical lay-up rates for a variety of composite processes. This table shows there is substantial overlap between the processes. To maximize the lay-up rate (and minimize recurring labor cost) filament winding and CTLM are excellent choices. Unfortunately, **table 6** showed that these processes are not capable of laying up as many part shapes as hand lay-up or tow placement. ATP can manufacture the widest range of aerospace part families, but this can sometimes be at a cost in lay-up rate as well as the equipment is more expensive than all other options. RTM and hand lay-up are viable for smaller parts.

Process	**Typical Lay-up Rate (lb/hr)**
RTM	.09 to .21
Filament Winding	up to 100
Fiber Placement	.1 to 2
Contoured Tape Layup	3 to 12
Manual Hand Layup	.002 to .30
Hand Lay-up with an automated debulk assist	2.0

Table 7: Process Lay-up Rate Comparison - typical values

At this point the reader should have an understanding of the industry, material, process flow and various types of automated fabrication techniques. The next step is to understand more about the automated tow placement process.

1.3.4 Automated Tow Placement

The definition of ATP was given in **section 1.1** and a description of shapes were listed in **Table 6**. Automated tow placement is the dispensing of preimpregnated tows (or slit-tape) through a collimator into a band onto a tool surface. The tows can be dispensed at different rates and cut individually. **Figure 8** is an artists rendering of the CMI tow placement head. The Ingersoll and the ADC heads have individual payout, controlled tension, a band collimator, tow cutters and clamps, restart rollers and a compaction roller. The Ingersoll has controlled heat for tack enhancement. These components can look very different, but the machines still dispense tows to build a part.

There are several important ATP concepts which the reader should consider:

- Axes
- Steering
- Dropping and Adding Tows
- Minimum Cut Length and Boundaries
- Downtime
- Software

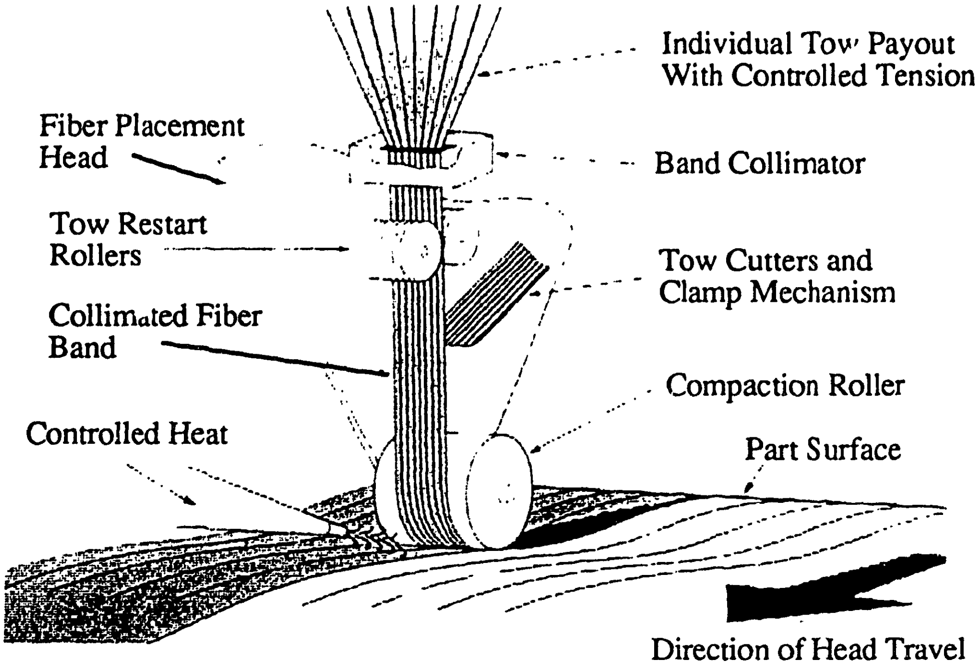


Figure 8: Artist's rendering of the fiber placement head (courtesy CMI)

Other important issues are tooling, programming and inspection. These issues are briefly discussed in **section 1.5.**

1.3.4.1 Axes

The CMI machine has seven axes (letters in parenthesis refer to the figure in **Appendix 1**): three head axes (i, j, k), a vertical arm movement (y), two horizontal arm movements (x, z) and a mandrel rotation axis (c). The Ingersoll machine has seven axes, but the head axes are roll-pitch-roll vs. CMI's yaw-pitch-roll. The ADC machine is a six-axis machine because it has only two head axes (pitch and roll). Axes are a benefit because they allow the machine to deposit tows onto a more complex part shape. They are a hindrance because the slowest machine axis limits the laydown speed. This is one of the reasons why the ADC machine can lay the V-22 Grip faster than either of the other brands.

1.3.4.2 Steering

Steering a fiber band allows the fiber placement machine to map a constant fiber angle on a surface with in-plane curvature (geodesic curvature). This separates the fiber placement machine from a CTLM machine which can only lay "natural" paths or the tape will wrinkle. Differential payout of tows as well as resin tack allow geodesic curvature. Differential payout allows the outer tow to dispense faster than the inner tow, similar to a tractor which slows the inner track to make a turn. Tack assists the inner fiber, under compression, and outer, under tension, to hold to the surface.

Flory and Bernardon calculated the effect of material steering and conformability requirements on machine design as well as the composite part itself [4, p. 4-8]. They found several items:

- Acceptable steering radius increased linearly with tow width
- Compaction roller gap decreases non-linearly as the part radius increases
- Increased roller compliance reduces tow placement control
- Cutting, turning and/or retracting took 44% of total time
- Overall deposition rates can be improved more easily by reducing time spent on non-productive operations than by increasing head speed (Flat 8' x4' part)
- Tilt-Crossfeed ATP has the broadest commercial aircraft part capability (97%)
- Lower-cost gantry tape layers cost substantially less with most of the part capability (at least 71%)

Most of these findings are in excellent agreement with the discussions on equipment tailoring and downtime in future sections. The paragraphs below explain and clarify the points outlined above.

The author can expand on Flory's and Bernardon's paper after viewing fiber placement in a production setting. They predict a substantial gap (>.05") between the roller and the part for any part radius less than ten inches with a machine that has greater than a one-inch bandwidth or a segmented three-inch bandwidth compaction roller with less than eight segments. Observation of BD&SG's machine suggests CMI's pneumatic compaction roller is robust to a minimum radius of about 2 inches.

Flory and Bernardon concluded that "increasing [deposition] roller compliance reduces tow placement control [4, p 6]." This is not always true. Tow placement accuracy decreases with increased roller segments, not roller compliance. Their mistake was that they assumed roller conformance was proportional to the number of roller segments. The CMI machine has a highly conformable pneumatic roller which had little or no loss of control due to compliance when compared with a hard roller. Segmented rollers on Boeing's machine had less control than their standard pneumatic roller. Flory and Bernardon's study used a Hercules ATP machine with a solid and a segmented roller.

Flory's and Bernardon's non-productive time includes cut time, turn/retract time and material load/thread time. This is not the same as the downtime as it is defined in this thesis. The use of a flat 8' x 4' part for a comparison of productive and non-productive time is questionable because an 8' long part will never reach the 1200 ipm steady-state lay-up rate. This concept is shown by the figure in **Appendix 3**. Additionally, a 1200 ipm rate is not very likely because material tack presently limits laydown rates in the field to below 800 ipm.

1.3.4.3 Dropping and Adding Tows

At the start and end of each course, tows need to be added and dropped, respectively. Tows need to be added when the surface area of the part increases along the surface path. They may need to be dropped if the head is traveling from a large area to a smaller area. An example of this area change is the 0-degree orientation on the large fairing (**Appendix 4**). Tow adds and drops add significantly to the lay-up time because the machine must slow to execute them. Then, it must accelerate back to speed. With subsequent tow cuts and adds, the machine often never reaches its full program speed. **Figure 9** explains adds/drops and the minimum cut length.

1.3.4.4 Minimum Cut Length and Boundaries

The minimum cut length is the distance from the tow cutters to the lay-down point between the compaction roller and the part surface. This distance limits the coverage of the area which is desired for the ply boundary. Smaller tows will have more coverage, but increase the complexity of the head (reduces reliability). **Figure 9** shows several overlap scenarios for tows at a ply boundary (0, 50, 100%). No overlap has less coverage but does not waste material. Complete overlap wastes a substantial amount of material, requires trim and/or increases part weight. If tows are added or dropped due to surface area changes within the ply boundary, there can be a spectrum from a triangular gap (no overlap) to a triangular overlap (complete overlap).

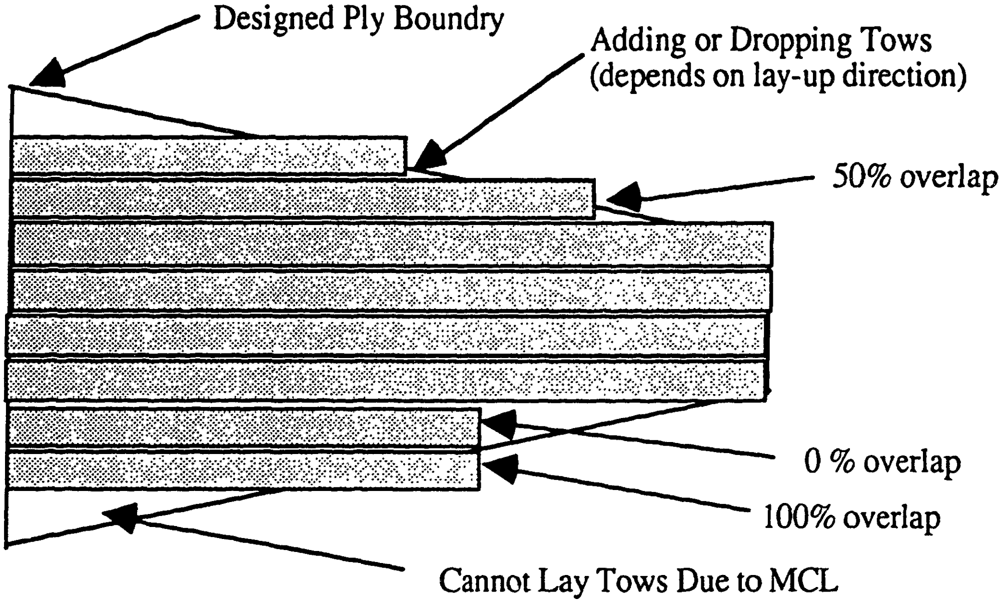


Figure 9: Tow Adds/Drops, MCL and Ply Boundary

1.3.4.5 Downtime

Downtime is a significant portion of the time on the fiber placement machine. The author and Boeing employees formed a continuous improvement team to reduce downtime. In this thesis downtime is considered to be any time when the machine is not laying tows that it could be, except for cuts, drops and the carriage return. The team found an average of 44% of the time to lay a part is downtime. Downtime is discussed in more detail in **Chapter 5**.

This section discussed many issues which were pertinent to manufacturing as well as design. It is now important to gain a deeper understanding of military aircraft design as it applies in HD.

1.3.4.6 Software

Machine software is critical for an automated tow placement machine. In the case of automated tow placement it has been the deciding factor in the development of a complete system: production was delayed for Ingersoll machines due to glitches in software development. ADC and CMI both have robust software systems that control the process.

In general an automated tow placement software system will import surfaces and ply boundaries from a computer aided design package. These surfaces may already have been run through a finite element package to test part stress. Paths are generated from the surfaces. Then, the NC code can be generated as well as a simulation of the ply laydown. When the completed NC codes are loaded into the control unit at the machine, the machine has the information necessary to move the head along the tool surface.

Many of the parameters which are set during NC programming significantly effect how the machine lays up the part as well as the rate at which it is laid. Thus, it is very important for the programmer to understand the effects of a parameter. For example, **Appendix 3** shows the effect on lay-up rates of lay-up speed settings.

Section 1.3 introduced composites processing and focused into a description of the tow placement process. The components of the system were introduced, but a holistic view of ATP has not yet been presented. Putting it all together, the fiber placement machine is supported by subprocesses: tooling, software and material. The material-machine interface presents many challenges — the primary one is downtime. There is significant pre or post lay-up processing to install longerons or other details (**Section 1.4.4** describes longerons) as well as adding caul plates, an isolation ply and/or copper mesh. Finally, the tool must be unloaded and the part prepared for cure.

1.4 Composites Design

This section introduces concepts in the design of advanced composite military aircraft structures. First, examples of the physical link between manufacturing and design are introduced. Second, a motivation for using data early in the decision-making process is discussed. Third, the military design process is outlined. Fourth, aircraft part families are identified. Then, the realm of the concurrent engineering team at Boeing precedes a final discussion of ATP parts.

1.4.1 The Manufacturing-Design Linkage

The design of advanced composites is integrally linked with manufacturing due to the anisotropic properties of the laminate (a lamina is one ply, a laminate is a stack of plies). **Table 8** shows Young's modulus along the fiber direction, E_1, across the fibers, E_2, Poisson's ratio, V_{12}, and the torsional modulus, G_{12} [20]. These values represent the strength and elastic stiffness of the material in each orientation.

Property	Glass/Epoxy	Boron/Epoxy	Graphite/Epoxy
E_1	7.8×10^6 psi	30×10^6 psi	30×10^6 psi
E_2	2.6×10^6 psi	3×10^6 psi	$.75 \times 10^6$ psi
V_{12}	.25	.3	.25
G_{12}	1.3×10^6 psi	1×10^6 psi	$.375 \times 10^6$ psi

Table 8: Bulk Moduli for Various Laminate Orientations

Clearly, the physical properties of the part depend on the fiber orientation. Physical properties that depend on orientation are known as anisotropic properties. The fiber orientation affects the manufacture of the part. For example, a tow placement machine will lay tows at a different speed along its mandrel axis than perpendicular to this axis. This is one example of how design is physically linked with manufacturing.

The link between design and manufacturing can be extended to all parts of the composite fabrication process: lay-up, cure, trim and inspection. Trim, the process of cutting the edges of the part, is an excellent case study to enhance the link between composite design and manufacturing.

Edge Clarity of Part	Material	Dissociation Temperature	Conduction of Fiber	HAZ size
Best	Kevlar/Epoxy	500°C	Low	small
Moderate	E-Glass/Epoxy	1250°C	Moderate	medium
Worst	Graphite/Epoxy	3500°C	High	large

Table 9: Material Choice affects Trim Process Effectiveness

Table 9 shows the effect of material choice on the laser trim process effectiveness [31]. The most clear edge will be smooth and ready for inspection directly after the cut. The least clear will often need hand-sanding as a finishing process after the automated cut.

A few of the items in the table require discussion. The dissociation temperature (DT) is the temperature differential between the resin melt and the fiber decomposition. For example, epoxy resin melts at about 500°C where graphite fibers vaporize at 4000°C. This makes the surface of the cut very rough because resin is melting while the heat is still being applied to cut the fiber. Additionally, the fiber conducts heat as it is being cut. Graphite's high thermal conductivity (it is 1000 times as high as epoxy resin) melts more resin along the fiber surface than a fiber with low conductivity. Finally, a high conductivity fiber requires additional heat input because more heat is conducted away from the cut area.

High conduction and high DT cause the heat affected zone (the zone where heat alters the properties or state of the material) to increase in size. Thus, graphite has a large HAZ. Since graphite is the most common advanced composite used for aircraft structures, applying laser cutting has been difficult. But, laser cutting is desirable because it accurately cuts at a rate six times as fast as waterjet or router cutting. Additionally, the laser takes less set-up time and less fixturing. With the benefits of laser cutting, it will continue to be adapted to cutting graphite/epoxy materials.

part thickness (inches)	**heat affected zone (inches)**	**feedrate (inches/second)**
.040	.012	10
.070	.035	2

Table 10: Laser Cutting's link to the Part Thickness

Once graphite/epoxy has been chosen, the link between design and manufacturing does not stop. **Table 10** shows that the heat affected zone and the feedrate of the laser trim machine are affected exponentially with part thickness: they are affected by a factor of three while the thickness does not even double. The designer should consider that an increase in thickness will increase the time to lay up a part, to cure a part and to trim a part. Additionally, it will add weight and material and could add a hand-finishing step.

With the above example, the reader can see how material property data provided information from which the design team can make decisions. Using manufacturing data to make design decisions about a fiber-placed part is the purpose of this thesis. The next section identifies the motivation for making educated decisions during design.

1.4.2 Motivation for good early decisions

Early decisions significantly effect the life-cycle cost of the product. As shown in **Figure 10**, researchers have found that companies typically spend 5% of program costs during the initial phases of a project while committing 90% of the total program cost [2]. Instead, managers should invest resources early in the development process to realize potential cost savings while they are available. It is equally important that design teams have adequate knowledge and data to make good economic decisions.

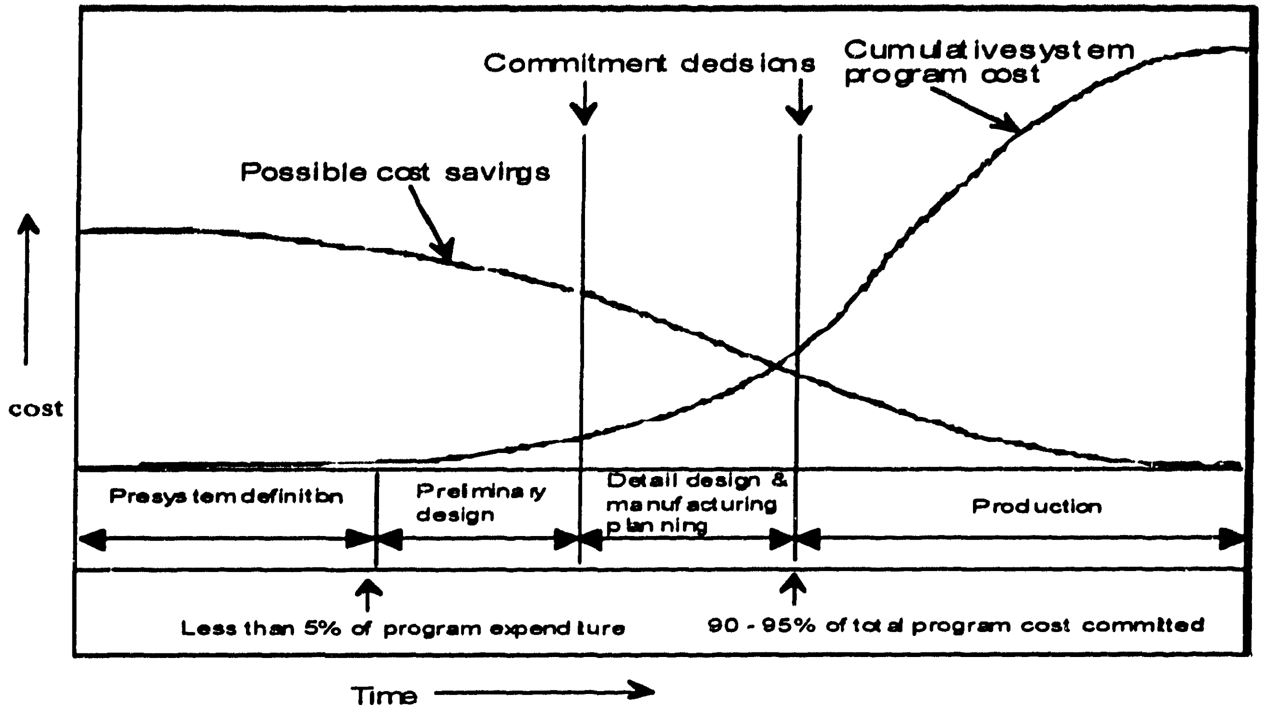


Figure 10: The product life cycle

1.4.3 The Military Design Process

The military design process is unlike any other in industry. The development of a military aircraft can span nearly twenty years. This process has five stages:

1. Preliminary Design (~3 years)
2. Full-Scale Development (~3 years)
3. Engineering Manufacturing Development (~3 years)
4. Low Rate Initial Production (~3 years)
5. Production (~15 - 20 years)

Between each of the first four stages is a one-year period during which prototype models are extensively tested and funds are lobbied for in congress.

Preliminary Design is the initial concept of the aircraft. It is where a significant portion of the outer fuselage and aerodynamics are defined. Additionally, the "mission" for the aircraft is determined during this stage. The DoD divides missions into three groups: combat, combat support and services. Combat support can be subdivided into aeromedical evacuation, observation, search and rescue, and assault utility vehicles. Services are primarily cargo, courier and training [1, p. I-4].

MDA's AH-64 is a multiple-engine turbine attack helicopter which fits into the combat category. Bell/Boeing's RAH-66 is an armed reconnaissance attack helicopter which also fits into the combat category. The V-22 Osprey is a tiltrotor aircraft which takes off vertically and flies like a propeller plane. Its missions are combat support and services.

Full-scale development is where several full-scale prototype products are manufactured for testing and air worthiness. The kinks in the designs of each of the four subsystems — airframe, avionics, propulsion and weapons — are worked out during this testing.

Engineering Manufacturing Development is the period where the manufacturing process for the aircraft is developed. At this stage the government commits a significant proportion of the product cost because aircraft manufacturers purchase tooling and equipment for the production process. For example, Boeing's Automated Tow Placement machine and its expensive Invar tooling were purchased for EMD.

Low Rate Initial Production is the phase of the project where production begins in earnest and the supplier works out the kinks in coordinating the flow of material as production increases. At this stage procedures which span for the length of the project will typically be put into place. In the case of Boeing's CH-47, many of the procedures set up during LRIP 30 years ago were still in place as production ended in 1995.

1.4.4 Part Families

The helicopter airframe subsystem can be divided into structure, landing gear, environmental control and flight control. Within the structure sub-subsystem metal airframes and skins are being replaced with advanced composites for enhanced performance with reduced aircraft weight, fatigue and corrosion.

The author identified several "families" of composite structure which were common to HD's products. All of these, except rotors, are also common to airplanes. Rotor blades are also not part of the airframe structure. The part families are shown in **Table 11**. The reader may refer to **Figure 11** to gain a better understanding of where these families fit onto an aircraft.

skins	frames
fairings	spars
floors	longerons
bulkhead	ribs
rotor blades	angles

Table 11: Part Families observed at BD&SG, HD

Skins and fairings are typically the outer surface of the aircraft which often must meet stringent aerodynamic shape and surface smoothness requirements. In **Figure 11** the belly skins and large fairings are representative of this family. They often have a significant amount of single and double curvature.

Floors and bulkheads are typically flat structures which must support the pressure of cargo or the internal pressure of a pressurized cabin, respectively. The floor of the V-22 rests on the keel framework shown in **Figure 11**. These parts are often thick because the flat shape must withstand the bending moments of the pressure forces.

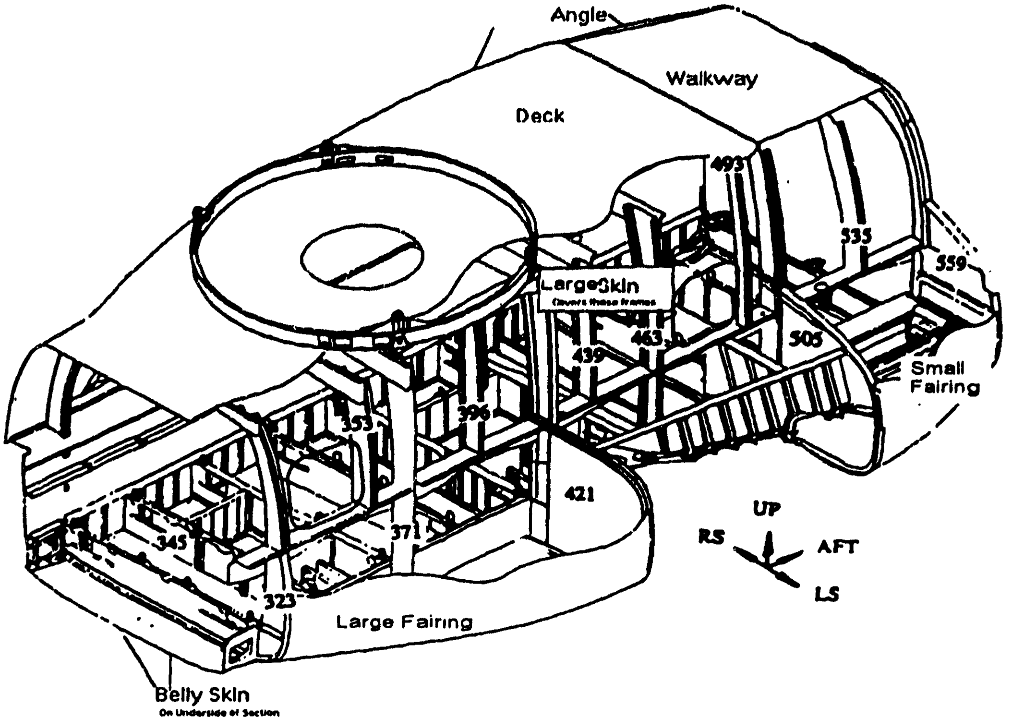


Figure 11: the V-22 Center Section

Frames are the primary load carrying structure in the fuselage. For example, the frames at stations 369 and 422 take the vertical and shear loads from the wings (The numbers shown are station numbers which are measured in inches along the length of the aircraft.). The fuselage is a torque box which must withstand forces caused by turning as well as the pull or push of the wings (tension if the wing is top-mounted). The frames are the primary load carrying structure for torque and compression or tension of the wing lift.

Spars are the load-carrying structure which run the length of a wing or stabilizer. They are typically under an extreme bending moment, especially with the V-22 which has its engines and rotors mounted at the ends of the wings. For this reason a composite frame will typically have a significant amount of fibers oriented length-wise along the spar.

Longerons, ribs and angles are all smaller load-bearing structure. Longerons, also known as stiffeners, are oriented with the length of the aircraft. They stiffen the skins by withstanding bending loads and buckling. Ribs are the load carrying structure which runs in the airflow direction of a stabilizer or wing. They transmit the forces and moments due to lift as well as when the aircraft turns. Angles are load bearing structures which connect parts.

The rotor blades are a critical load carrying member in a helicopter. They withstand the centrifugal forces from rotating, the bending forces of lift when in motion and their own weight when idle.

Frames, spars, longerons, angles, rotor blades and sometimes skins, ribs and bulkheads are primary load carrying structure. Primary structure sustains the critical loads of flight.

Secondary structure is the other type of structure in an aircraft; it is not essential to sustaining the loads of flight. This section summarized a large portion of the types of structural parts one will observe on an aircraft.

1.4.5 Design at BD&SG, HD

BD&SG, HD adopted Integrated Product Teams during the development of the 777, the V-22 EMD and the RAH-66 Comanche . IPT's are Boeing's name for a concurrent engineering team. Since IPT's changed the organization structure at HD, this section describes IPT's and their decision realm.

After Marketing and the customer have identified the function of the aircraft, the preliminary design team determines the preliminary outer shape and size of the aircraft. The aircraft is then separated into sections. The cockpit area is the 41 section, the center payload area is the 43 section and the aft portion of the aircraft is known as the 46 section. These numbers are standard across aircraft at Boeing.

There are several links between IPT's. IPT leads are members of an airframe integration team (AIT). The AIT was the primary communications link between the sections and the subsystems (avionics, controls, structures, etc.). Functional members between sections also discussed integration issues. CATIA, a computer aided design database, was the final link between sections. With CATIA, a designer can check for interferences on the drawing, build a solid, or execute a simulated "fly through" of the aircraft. Interference checking and part accuracy are the tasks CATIA does well. CATIA does not reduce development time. It also does not have a design for manufacturability database.

The IPT is typically given stringent requirements for the OML and the splice lines. Thus, the IPT has a limited amount of influence over this dimension. The OML, the outer mold line of the aircraft, is the airflow surface when flying. In **Figure 11** the fairings, large skins and belly skin lie along the OML (the deck and walkway are covered by another fairing). The splice line is the line where mechanical fasteners (rivets) are used to join component parts of the aircraft structure. In **Figure 11** there is a splice line between the canted deck and the aft walkway.

Typically, the IPT has a substantial amount of influence over the inner mold line. For example, the integrated skin section IPT designed stiffeners the length of the part and mouse-holed the frames to reduce the part count and cost [24]. This was not possible on the large skins because several of the frames on the IML are primary load-carrying members which could not be cut.

The realm of the IPT is now defined. The IPT will typically have the splice lines, weight limits and design loads fixed. Until the configuration freeze, they may change the OML and the IML. They must then determine material, part thicknesses, ply orientation, location of buildups and cutouts, stiffener type and the number of stiffeners and tolerances. Additionally, the team should consider design for manufacturability items similar to those described in **section 2.2.2**.

1.4.6 Applications of ATP

BD&SG, HD manufactures four sets of parts on their tow placement machine:

- Fairings
- Angles
- Integrated Skin
- Large Skins

Pictures of each of these parts, except the integrated skin, are included in **Appendix 4.** The integrated skin is shown in **Figure 1.** Some of the information written here can also be found in [6] and [24].

1.4.6.1 Fairings

Four fairings are manufactured using BD&SG's automated tow placement machine: two forward and two aft. These fairings house fuel and auxiliary equipment. Three of the four are sandwiched honeycomb construction. Material is IM7/8552 because low flow resin is needed so the honeycomb core does not get loaded with resin.

The tows are laid onto a male aluminum tool. When part lamination is complete, the part is dropped into a female Invar curing tool. The large fairings have substantial normal and geodesic curvature along the 0- and 45- degree orientations. The 90-degree orientation plies have substantial normal curvature and little geodesic. The 0-degree orientation has a substantial amount of adds as the surface area of the part increases along the tow path.

The honeycomb core is hand placed into a recess in the tool after the inner plies have been laid. The hand-placing of the core adds substantial variation to the lay-up time: core placement time is from one hour to 16 hours. Additionally, Boeing has had higher than normal rework rates on the parts with honeycomb construction.

1.4.6.2 Angles

The angles are load-carrying members which connect the large skins to the deck and the walkway. These parts do not have stringers or sandwiched construction. Material is IM7/3501-6. They are long parts with substantial double curvature and a very short width. They are laid up on an Invar lay-up/curing tool which has a 3/8th inch radius along the middle center. This radius is difficult for the three-inch wide compaction roller to traverse without substantial gaps between the roller and the part surface. For this reason, twelve tows are laid per strip instead of the normal 22.

1.4.6.3 Integrated Skin

This part is a large integrated structure which connects the center fuselage to the empennage. The cargo door is also mounted to this structure. The part has skin/stringer construction. Material is IM6/3501-6. Between FSD and EMD, the Air Force Materials Laboratory chose this part to integrate 10 modular pieces into one component part to demonstrate the cost savings from reduced assembly time[24]. For a clear discussion comparing modular and integral architecture, please refer to Ulrich [32].

Tows are laid onto a male tool after the stringers have been installed into this tool. The stringers run the length of this part which has little geodesic curvature along its course paths. The 45 degree ply has minimal complexity effects for a U-shaped part.

This integrated structure is one of the great success stories of the V-22 program. Through intelligent design changes from FSD, they were able to reduce part count by 70% and fastener count by 34% — 34% is 1887 pieces [24].

1.4.6.4 Large Skins

The large skins cover the frames of the cabin. The OML is exposed to the flowstream. This part also has an integrated longeron to handle some of the load transferred from the angle. This part has skin/stringer construction, but the stringers are not one piece like the aft section. Material is IM7/3501-6.

The stringers are added to this part after it has been tow placed onto its female Invar tool. The part has little geodesic and normal curvature except the upper aft portion near the deck to walkway spliceline. At this juncture the concavity of the tool is so large that a fiberglass splash was added between the tool and the deposition surface to smooth the contour. The splash is removed and the material is smoothed against the tool by hand after layup and prior to adding stiffeners. The part has a substantial amount of cutouts and buildups which add to the complexity.

1.5 Chapter Summary

The reader has now completed an introduction to the problem, the industry, composites processing and composites design. He should now be prepared to dive deeper into the design and manufacturing issues uncovered in this thesis.

2. Design for Automated Tow Placement

There is significant incentive to designing a part to be an efficient shape for tow placement: a new machine costs $1 to $6 million. Thus, increased production can reduce capital expenditures significantly. This section provides data so the engineering team can concurrently develop the equipment, part and process. First, six reasons to fiber place a part are discussed. Then, a design process which emphasizes concurrent development of the tow placement machine is introduced. Finally, a physically-based cost model is introduced and applied for HD.

2.1 Reasons to choose the Automated Tow Placement Process

Data suggests that automating lay-up is a good idea for quality, material cost, and labor cost. This data was gathered during the October benchmark trip. There are six primary considerations which effect the decision to fiber place a part:

1. Scrap
2. Lay-up Rate
3. Part Size and Complexity
4. Accuracy /Repeatability
5. Material Cost
6. Strategy

2.1.1 Scrap

Scrap is generated at various times during fabrication: (1) ply cutting, (2) lay-up, (3) material expiration, (4) damaged parts and (5) excess trim. Fiber placement reduces scrap because there is no ply cutting phase. Bell helicopter found that 50% of the material they purchase for hand lay-up is scrapped. They found that 7% to 10% of fiber placement tow is scrapped. Cincinnati-Milacron also found that 7% of tow placement raw material goes to waste. Boeing expected less than 25% of the aft fuselage material to be scrap [24]. The *hypothetical calculation* below compares the material cost of two 251 inch long hand-laid skins with fiber-placed ones. Here are the assumptions:

- 10% of fiber placed material is scrap
- 50% of hand laid material is scrap
- Four aircraft are produced per month
- Program starts in January of 1997
- The program continues for 20 years
- Fabric costs $55 per pound [28]
- Towpreg costs $57 per pound [28]
- Material Costs $50 per pound to discard as hazardous waste
- Material cost is constant over the 20 years
- The discount rate is 12%

Detailed calculations are in **Appendix 11**. The expected value of the savings over the life of the program is about $200,000. The appendix also has a sensitivity to the discount rate and the production of the aircraft. The same calculation performed for all HD tow placed parts would show an expected savings of $650,000 with a range from $360,000 to $1.3 million.

2.1.2 Lay-up Rate

The average lay-up rate of the in **Figure 12** is 0.72 lb./hr. This suggests that ATP is not significantly faster than hand lay-up, but when complexity is considered, it may actually be faster. Additionally, the parts which Boeing fiber places could not easily be produced by hand or with a tape layer. The weights and rates in the figure are normalized to the weight and rate of the integrated skin structure.

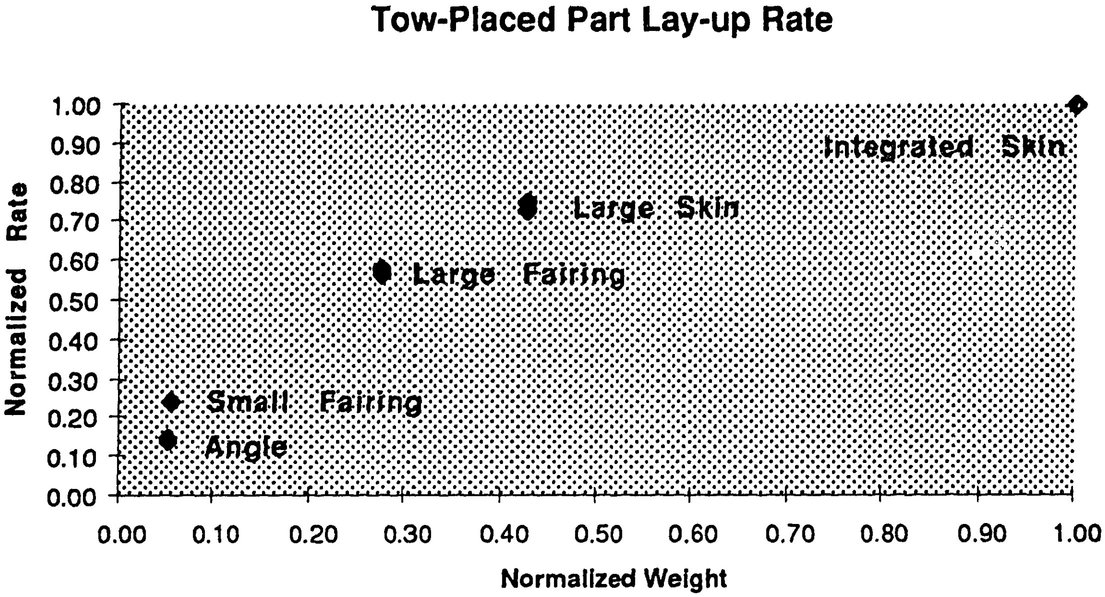


Figure 12: Normalized Lay-up Rates of V-22 EMD Parts
Normalized to the Integrated Fuselage Structure

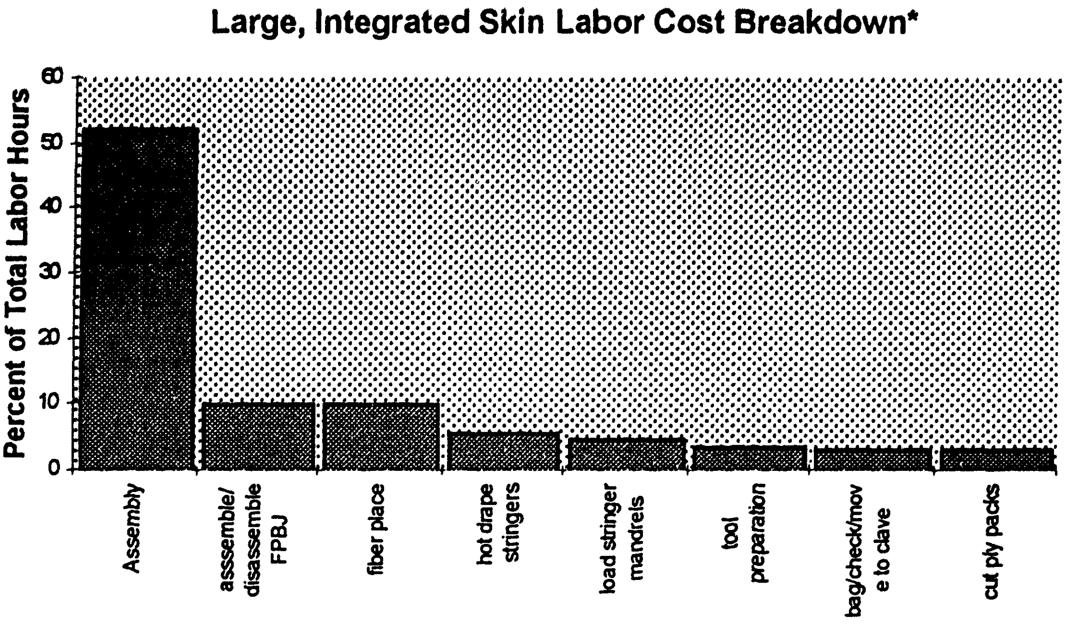
Tow placement is evolving rapidly. Equipment suppliers have improved the fiber delivery system design as well as the software. These improvements have already significantly reduced the downtime of the machine and increased lay-up rates. Calculations suggest that a 2-3 lb./hr. average rate could be achieved prior to the turn of the century.

2.1.3 Part Size Capability and Complexity

Automated tow placement enables the manufacture of parts larger than a person can make by hand without the loss of complexity dictated by using filament winding or tape laying. For example, Raytheon has considered manufacturing a civilian aircraft which would have a one-piece shell over 25 feet in length.

Large, co-cured aerospace structures can reduce total costs because large parts reduce the number of fasteners as well as the number of parts to locate, drill and fasten. Additionally, the component tools for lay-up, cure, inspection and transportation are reduced. Finally, reduced inspection, machine set-up, design drawings and finishing could reduce the cost of an aircraft.

Figure 13 shows that assembly is 52% of the recurring costs of four large, integrated fuselage skins for the V-22 EMD. Following assembly, fiber placement and a combined tooling assembly and disassembly have 10% of recurring costs each. This large, integrated, co-cured part still has over 50% of its recurring labor hours in assembly.



*Only the top 8 steps are included(93% of total time)

Figure 13: Labor Breakdown of V-22 Aft Fuselage

Figure 13 does not provide conclusive evidence that larger parts reduce assembly hours. Several <u>additional pieces of information</u> are needed to determine the "ideal" part size:

- The cost of a splice
- The increase in tooling assembly and disassembly (A&D) time
- An understanding of how complexity decreases fabrication rate
- An understanding of lay-up size vs. out time

All items should be subjects for future research. Qualitatively, this author suspects that there is still a gain from manufacturing larger parts: the cost of a splice will offset the additional component fabrication hours. A material with an out-time of 42 days (3501-6) must be laid-up, have stiffeners added, bagged and transported within 1008 hours from the time material is removed from the freezer. If adding stiffeners and bagging takes 2 days and transporting takes one-half a day 900 hours is left for lay-up. At .72 lb./hr. and 1.5 hours/day for lunch, the part can be a maximum of 608 lb. With variation the allowable part size is smaller.

2.1.4 Accuracy/Repeatability

Although there is not quantitative evidence, every company in the benchmark study listed improved quality as a *major* reason to fiber place a part. Fiber placement is a 7-axis, numerically-controlled lay-up machine. A computer-aided design file is translated into a set of points which is used to generate paths and NC code. Thus, the machine can follow this code repeatedly with accuracy and precision.

2.1.5 Material Cost

Although there is no cost savings using towpreg over fabric at present, Hercules expected the cost to drop to $35 per pound by 1995. Since this has not happened, reduced raw material cost is not a reason for fiber placement (outside of scrap reduction).

2.1.6 Strategy — Competition and Learning

There are two other reasons why a company may want to adopt fiber placement early: competition and learning effects. McDonnell-Douglas bought their machine primarily to keep up with competitors who were doing the same. Other companies (Boeing, Bell and Northrop) all indicated that they expect a greater amount of composites in aircraft structures in the 21st Century. As Bob Young at Northrop put it, "if you want to build aircraft in the next century, you better fiber place."

Fiber placement is becoming an effective way to fabricate fuselage structures. Many companies want to understand this technology while it is still in its early production/late development stages. This way, engineers, managers and operators will have begun to make the transition to the technology before it becomes a necessity.

People have been aware of these **learning effects** for decades. These effects come primarily from worker learning as well as from changes in tools and fixtures. T.P. Wright called these effects the Progress Function in 1936 [15, p. 52]. In 1977 Kivenko quantified the effects [15, p. 135]: direct labor was responsible for 25%; order-writing, blueprint issuing and other paperwork for 35%; and supervision, planning, engineering and tooling specification for the other 40%. Neoh summarized the factors which attribute to a reduction in unit cost for aircraft assembly [15, p. 136]:

- Repetition of tasks by workers
- Improvement in tool coordination, shop organization and engineering liaison
- Development of more efficiently produced subassemblies
- Development of more efficiently produced parts supply systems
- Development of more efficient tools and fixtures
- Improvements in the manufacturing equipment

The most interesting aspect of this discussion is that the major portion of learning comes from better management and changing tools, fixtures and equipment. According to the numbers above, at least 75% of learning effects happen because of management action.

A warning is in order. *Learning effects should be used for growth and improvement, not projected costs or reduction in employment.* Application of learning curves is difficult and projecting costs with them is rarely useful. Shipp saw no or negative learning with the 737 composite spoiler [13, p. 80]. She attributed their lack of learning to high turnover, frequent design and process changes, and a static information system. Dutton, Thomas and Hill found that fitting a facility's historical learning curves to predict future performance resulted in high margins of error in labor costs [15, p. 13].

In **Section 2.1** the reader has been shown that fiber placement is a technology which makes large, complex parts with less scrap and improved quality. That makes this budding process a worthwhile investment to consider because, with learning, it will be an efficient process for manufacturing structures in the 21st century.

2.2 An Innovative Process for Design

BD&SG, HD, speaks frequently about part selection and producibility. Producibility is what the author calls "design the part for the process." Boeing has done an excellent job selecting and producing parts which matched the fiber placement process. Bell took this concept one step farther with the V-22 Grip: they modified their retrofitted Maclean-Anderson filament winder to improve lay-up efficiency.

Pat Dolan of HD suggested that their efforts to "implement the process on the part" resulted in costs which were 76% of hand lay-up on FSD. "Design for the process" reduced the cost to 47% of FSD [24]. Bell reduced the costs of the EMD grip to 25% of the cost of the hand-laid FSD grip. These lessons can be generalized to suggest a design process for tow placement:

1. Select the process for the part (or the part for the process)
2. Tailor the equipment to the part
3. Design for the process

The last two tasks should be performed concurrently. These lessons are not new to general industry, but it is unique because it is applied specifically to tow placement. This section uses historical data, benchmark data and a case study to explain this design process.

2.2.1 Selecting the process for the part

This section answers the question "which shapes are efficient to tow place" using historical data and experience. In general there seem to be three efficient fiber placement part families or shapes:

- Skins
- Fairings
- Surface of Revolution

The Advanced Composites Technology Program suggests that aircraft fuselages, skins and fairings are efficient parts to fiber place[11, p.354]. HD's larger parts are efficient parts to fiber place. The small fairing and angle lay-up rates are lower due to core variation and many short courses.

Bell's V-22 Grip suggests that bodies of revolution with complex curvature and non-constant cross-sections are effective to fiber place, even with short courses. Equipment must be tailored for speed with short courses. Bell modified an ADC fiber placement machine to lay-up faster with short courses on bodies of revolution. Their machine is dedicated to the production of one part: the Grip. With Bell's equipment modifications it may be effective to fiber place spars and other dynamic components, but the design team should also consider RTM with automated preforms and hand lay-up to a tow-placed part.

Individual fabrication rates of ATP parts were looked at during the internship. The V-22 grip, a body of revolution, is a very efficient tow placed part shape, especially since 30% of total fabrication time is used to compact plies manually. Angles and stiffeners are much less efficient to lay up than a body of revolution. They do not seem to be efficient parts to tow place and may be fabricated more efficiently with hand lay-up or hot-drape forming.

Two other candidates for ATP are aircraft nose cones and engine cowlings. Boeing's tow placement machine lacked the stroke length (x-axis) and head movement range to lay the nose cone for the V-22. Different tooling or equipment would be required to remove this deficiency. HD manufactured a developmental engine cowling [6, p. 8]. This syncore-reinforced structure was approximately 9 feet in diameter and 10 feet long with a taper at each end. The gently curving geometry had multiple tow adds and drops on every course. This reduced the lay-up efficiency because the ATP machine never reached full rates before slowing for another cut or add. The second cowling which was manufactured at CMI was programmed to minimize tow drops. Despite the lay-up rate inefficiencies, the machine easily proved that it could lay this large part with gradual double curvature.

As previously stated, a tow placement machine can manufacture large, complex parts which are difficult or impossible for a person to hand-lay. The next section transitions from part selection to designing a part for the process by performing a case study about the integration of several modular parts for the V-22 into a large, integrated structure.

2.2.1.1 Part Integration

The following section documents a process for integrating parts as well as a case study which considers integrating the V-22 center section. The process steps are:

1. Discuss the function of the integrated part
2. Discuss the shape
3. Find the thinnest web area (assumes a skin)
4. Find the orientation of the thinnest area
5. Add in extra plies for buildup where you need strength
6. Consider Cure, Tooling, Trim, Assembly and Others

The challenge is to efficiently convert the lay-up to one orientation from several. Three engineers from the HD looked at a case study to integrate the center section of a military tilt-rotor aircraft.

In this study the deck, walkway, large skins, angles and the belly skin are laid at one time on the fiber placement machine. These parts are shown in **Figure 11**. The belly skin is separated after the autoclave cure through mechanical or laser cutting.

The <u>function</u> of the integrated structure can be determined from initial constraints:

- Frame 505 takes a landing gear loads
- Frame 559 takes a tie-down load
- Frames 422 and 369 take loads from the wing

These frames cannot have cutouts in them because they cannot afford stress concentrations in their structure. The frame at station 559 could have mouse holes in the web, but not on the outside surface which handles bending loads and the cab area.

The primary connections at STA 422 and 369 take loads from the wing which are transferred into the large skin, the belly skin and the deck. The large skins provide vertical shear strength. The belly skin and deck provide lateral shear from the wing. The deck has a difficult time carrying loads because there are many holes in it.

The shape of the center section does not need to be altered substantially, except possibly the angle. It's 3/8" radius is difficult for a fiber placement machine to navigate in the 0- and 45-degree orientations. The 3" diameter pneumatic roller must conform around the sharp radius. Operators replace the compaction roller cover once for each angle. Additionally, operators perform substantial amounts of hand lay-up because of roller non-compliance. Finally, the pneumatic bladder is replaced several times per angle. Thus, future shapes should avoid this tight radius. A two inch minimum radius is a practical alternative.

The V22 center has its thinnest web area on the skins. The deck thickness is approximately 1/8" thick because it takes lateral shear loads and has a substantial number of holes. It requires substantial build-up over the belly and the large skin. This will decrease the lay-up efficiency of the laminate.

The orientation of the thinnest area of the belly skin, large skins and the deck are different. The walkway orientation is similar to the large skin. The engineering team would have to perform a detailed analysis to standardize the lay-up and use buildups to make module (belly, large and deck skins) meet their functional requirements. Additionally, stiffeners must attach in a similar fashion.

Cure, tooling and trim must be considered. The 251-inch long [24] center section would fit into a 12 foot diameter autoclave. Some autoclave modifications may be necessary to allow for adequate heat flow. The minimum cure time will be determined by making sure the maximum thickness reaches cure temperature for the required time.

There are tradeoffs between an OML and/or IML tooling. A male tool is more realistic, but drop-offs will cause the OML to be less aerodynamic. Aerodynamically, stream-wise build-ups are better than across stream. An outer caul plate and/or a recessed tool to smooth the outer surface. A caul-plate is used on the EMD integrated skin; a recessed tool was used on FSD. The tradeoff is aerodynamics and part smoothness. A fighter aircraft will have substantially more surface smoothness requirements due to the increased velocity of the fluid flow along the boundary layer.

The center section would probably use a male tool. The large skins, belly skin, deck and walkway are presently female tools with stiffeners installed after lay-up. A caul plate or recessed tool must be used to obtain the surface smoothness needed for aerodynamics. Additionally, stiffeners would have to be installed in the tool prior to lay-up. Longerons can be integrated into the large skin to reduce part count. This was done well with the EMD large skin. Stiffener spacing may be increased by increasing skin thickness intelligently as was done on the belly skin.

The part does not fit into existing trim fixtures. Fixtures are needed to separate the belly skin and to cut holes in the large skins and the deck. The reader may want to check **section 2.3** for a discussion on the cost of a cutout.

Assembly and out-time are significant concerns. Assembling side and crown frames with a one-piece center section will be difficult, but hockey-stick style frames are easier than three-piece frames. The upper section must be adequately supported for transport and lifting. Integrated stiffeners could be used for support, but must be interrupted for frames carrying wing loads.

Some other concerns for assembly are related to the fixture. The part could be assembled vertically or on its side. A rotating fixture could be used. The constraint is that all fastener locations must be reasonably reached by a mechanic from the ground or a level above ground. The assembly sequence must also be considered when the fixture is designed.

Material out-time will be a concern. Out-time depends on the number of shifts worked:

lay-up rate (lb./hr)	total hours needed	min. 2-shift out-days	min. 3-shift out-days
1.0	500	31	22
1.2	416	28	18
1.5	333	22	15

Table 12: Material Out-time Estimates for the Integrated Center Section

Table 12 does not account for time needed to add stiffeners, to bag and transport, and for variation. The out-time for 3501-6 is 42 days, 8552 is 15. Thus, 3501-6 is a feasible resin system for this large part. The 8552 resin is not presently feasible, but Hercules has discussed introducing a newer version which has a longer out-time.

As a final note, inventory holding costs and floor space should be considered. For example, if a part is worth $78,000 after lay-up (labor and material) and the cost of capital is 12%, the inventory holding cost for one month is $780. If floor space is worth $100 per square foot per month (a reasonable rental cost), the floor space for a horizontally laid section is $15,625 per month. Of course, if the building is already paid for, the floor space consideration does not apply until additional space is needed at the facility.

2.2.2 Equipment Tailoring

This section highlights a case study of the V-22 Grip. Bell concurrently developed the equipment, part, material and process for the tow-placed V-22 grip during Engineering and Manufacturing Development. In this section the part is introduced, Bell's reasoning for using an ADC machine is discussed and their equipment changes are outlined.

The grip connects the yoke to the base of the rotor blade; it is subject to dynamic loads. The filament wound FSD grip subassembly had hundreds of part details. The fiber placed EMD grip is a single subassembly where labor hours are 25% of the hand-laid and filament wound

FSD part. The part has 238 plies, but only 20 are full coverage. Orientations are typically 5°, 15° and 45°. **Appendix 5** shows pictures of the V-22 Grip.

Bell decided not to purchase an Ingersoll or CMI machine for two reasons:

- CMI and Ingersoll machines are not as well suited for short courses
- They did not want to pay the $3.5 million purchase price

CMI and Ingersoll machines are larger than the ADC/Maclean Anderson machine. Thus, the ADC accelerates to speed faster. Additionally, the ADC machine was better suited to perform tow cuts and adds at speed more quickly. They realized that Milacron and Ingersoll machines would not lay down quickly with the grip because of the substantial number of cuts and restarts which would be needed. This head cut the full bandwidth, but still had individual tow steering to accept contour. It is ideal for parts with numerous short courses and substantial complexity. Bell retrofitted a Maclean-Anderson filament winder with an ADC fiber placement head for $400,000. A new ADC/M-A machine would cost approximately $1 million. There is one caveat the buyer should be aware of: ADC is a small company with limited resources. If they were to go out of business during the life of the equipment, it could become difficult to get spare parts. Maclean-Anderson 's future is more assured than ADC.

During a two-year development process, they incorporated several equipment features to improve the lay-up rate:

Feature	**Effect**
Full Bandwidth Cut	Faster than individual cut.
1" bandwidth	Improved Lay-up rate over smaller bandwidth, acceptable coverage.
Cut at Full Speed	Overshoot start of course, but significantly faster than slowing to cut.
Double tow thickness	Lay down at twice the rate of single tow (if you can stack plies).
Slit-Tape	Improved dimensional control and reduced stringers.
Toughened Resin	Low tack for reduced resin deposits in head.
6" ID spools	Despools easier. Less restart errors.

Table 13: Equipment Improvements for the V-22 Grip

To increase the fiber bandwidth and allow for a full bandwidth cut, designers allowed non-exact ply boundaries but maintained fiber weight & orientation. The coverage area was shifted, but analysis showed that it did not affect structural properties substantially. Weight did not change from FSD to EMD.

To cut at full speed, ADC tailored the off-the shelf, DOS-based programming software so the machine can cut at full speed and then back up to start the next course. This allowed an improved lay-up speed because there are no courses longer than 24 inches. Mid-course cuts are needed so the part fits tight against the bonding tool when the silicone rubber bag pushes the IML into the tool to form the OML surface. Other short courses are caused by the part's 48-inch length.

Toward the end of equipment development lay-up rate targets were still not being met. They had designed the part to be hand-laid two plies at a time or to be fiber placed due to the immaturity of fiber placement technology. Instead, they decided they could fiber place a double thickness tow (.015" thick). This also removed problems with random dry spots in the individual thickness tows. This is not as easy to do for thin-walled structures.

Slit tape was chosen primarily for tow width control. It also had the benefit of reduced stringers which are caused when towpreg overlaps or sticks together and catches when despooling. The polyethylene interleaf prevents tows from overlapping and sticking together. It does add to process complexity because the machine must have a system to remove the interleaf.

E7T1-2 toughened resin was chosen for its low-tack, low-flow and cure temperature above 250 °F. Low tack material causes less machine downtime because there is less resin buildup in the head. Low flow is desirable because it conforms to the tool surface well at temperatures above 100° and flow into open holes is limited.

Spools with a six-inch diameter were used as opposed to the standard three-inch spools used by Milacron and Ingersoll. A large diameter spool lever arm reduce the tension required to despool the tow (spool friction torque = radius x tension). This reduces the frequency of burn-through. Burn-through happens when tow tension exceeds the friction component of the restart force.

In summary, Bell persevered through many setbacks and developed the equipment to make small, thick parts efficiently. There are six lessons to learn from this case study for small parts like angles and spars:

1. Cut multiples of tows at once on parts with short courses
2. Maximize the lay-up band width without sacrificing roller conformance
3. Develop full-speed cuts for parts with short courses
4. Double tow thickness when possible
5. Use low-tack resin
6. Reduce restart errors by reducing tow tension and friction

This case study is very complementary to some work that Don Evans performed with CMI's Acraplace simulator.

2.2.2.1 Comparing Large vs. Small Equipment

The study in the previous section and the data below suggest that there is a tradeoff between large equipment which can lay a huge variety of parts and smaller equipment that may be dedicated to only a few parts. The key lesson in this section is that machine size is linked to speed. Engineering personnel should develop a mindset which takes this idea into consideration when purchasing new equipment. The typical mindset in the aerospace industry is to do everything, but a company does not need to do everything, it should <u>do a few things well</u>.

Don Evans of CMI performed a study which quantifies the discussion about large and small machines. **Table 14** shows the results of the simulation which compared four part shapes with two different Viper tow placement machines—one owned by Boeing in Philadelphia and one owned by General Electric at CMI's plant in Ohio. The important parameter in this study is the mandrel weight capacity: 20,000 pounds for the GE and 40,000 for Boeing's. This parameter is important because it will effect: (1) response servo times and (2) accelerations.

Part Geometry	GE (lb./hr)	Boeing (lb./hr)	Difference (%)	Part Complexity
Flat Plate	7.7	6.9	11.59	low
Cylinder	16	14.3	11.89	low
Cone	10.3	8.2	26.61	medium
Duct	10.6	6.2	70.97	high

Table 14: Comparison of two fiber placement machines [33]

The conclusion is that as part complexity increases (contour, cuts/adds, etc.) the smaller machine lays substantially faster than the larger machine. This data and Bell's experience with the grip suggest that smaller machines can lay-up light parts and tools with shorter courses faster. Smaller machines have less inertia, so they accelerate more quickly. The drawback to smaller machines is that they cannot lay integrated fuselage structures. Therefore, it makes sense to tailor the equipment to the part and match a part to your equipment. As will be seen in future sections, this concept can be applied to used equipment as well as new. The key challenge for industry personnel is to develop a balance of economies of scale (production rates) with economies of scope (laying many parts on one machine).

2.2.3 Design for the Process

This section first introduces the concept of complexity and the physics between the part and the process. Then, the primary factors affecting the lay-up rate are addressed. A list of ideas which all tow placement manufacturers seem to be using for design/process matching is outlined in the final portion of this section.

Tow placement lay-up speed depends on ply orientation, resin tack, part complexity and size. Fiber placement machines lay tow at different speeds for each ply orientation. This is because the lay-up rate depends on the speed of the limiting axis (the bottleneck). **Appendix 6** outlines axis speed capabilities of the CMI Viper.

The lay-up speed depends substantially on the resin in the towpreg. Dynamic analysis of the tow lay-up forces suggest that a tow with a tackier epoxy can be laid faster than a lower tack resin. In practice this is not true because tackier resins build up in the fiber delivery system. Thus, lay-up rate decreases with a tackier resin because operators must clean the head with increased frequency. The Ingersoll would probably have less downtime than the CMI with a tacky resin because it has an airy fiber path.

Complexity items include part contour, cutouts, and buildups. Part contour limits the machine speed because the head must "steer" around curvature. Since the servo motor pivot point travels a substantially longer distance than the compactor roller, the head motion is slow. This is demonstrated in **Figure 15**. The motor pivot point must move 17.8 in. to lay tow for 1.05 in. on the part surface. Thus, negotiating the surface curvature which requires pitch and yaw movements will reduce the machine's lay-up rate.

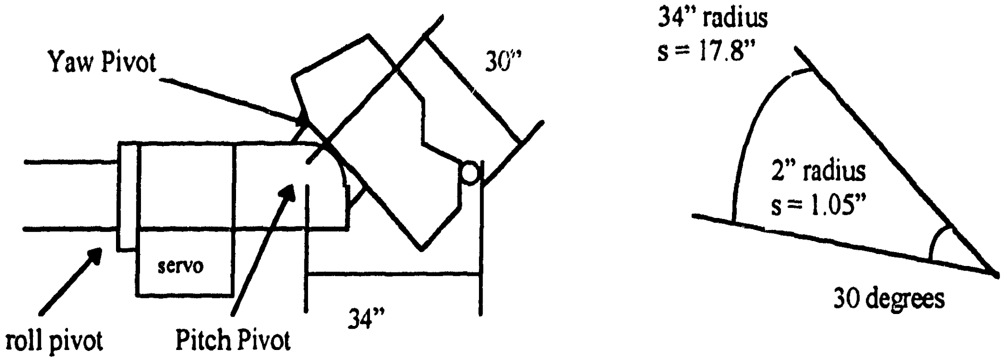
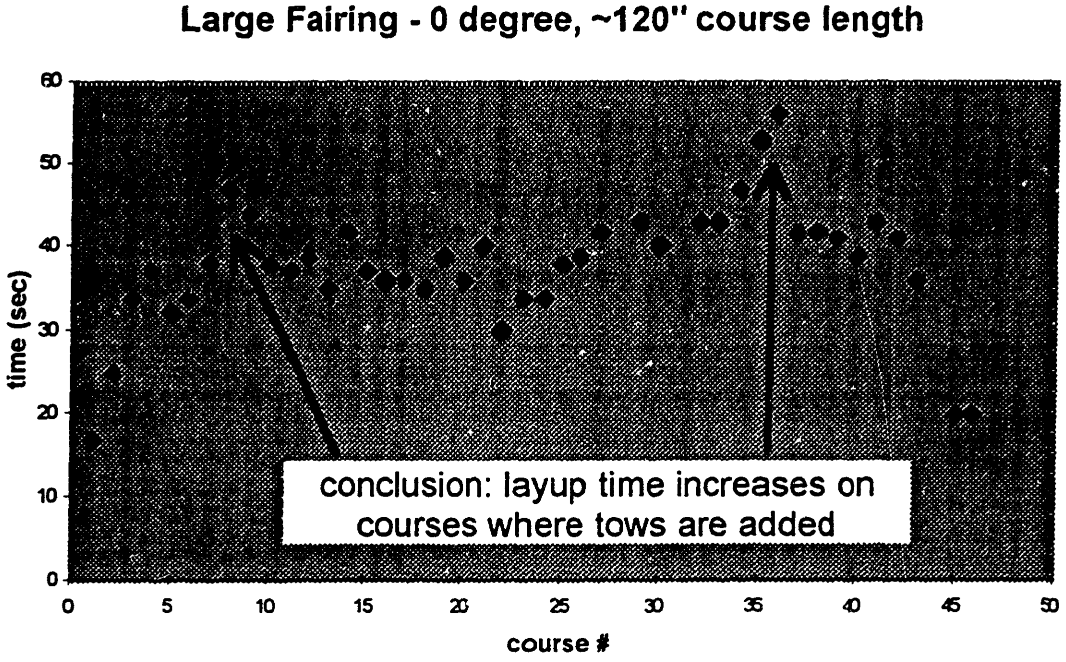


Figure 14: Head Steering Geometry for Boeing's Viper

Cutouts and buildups limit the speed because the machine slows down substantially to cut ("drop") and restart ("add") tows. If the ply boundary is not perpendicular to the orientation, the machine will cut each tow individually at the slower speed.

Contour can also cause the machine to add or drop tows. An example of this is BD&SG's large fairing. Since it has significantly more surface area at the back of the part, the machine adds individual tows on the zero degree ply as it lays each course. Actual measures of course lay-up time shown in **Figure 15** show that adding tows increases the lay-up time.


Large Fairing - 0 degree, ~120" course length

conclusion: layup time increases on courses where tows are added

Figure 15: Fairing course lay-up time is increased by adds

2.2.3.1 The primary factors affecting the lay-up rate

To determine the primary factors which affect lay-up rate, data was gathered in literature, in the plant and through simulation. Some generalizations can be made for the CMI machine:

- Low-tack resins are typically faster due to reduced resin deposits
- 0-degree orientation is faster than 90-degrees
- 90-degree orientation courses are faster than 45-degrees
- Longer courses have faster average rates
- Less curvature is faster (unless hoop plies)
- Less tow adds are faster
- Less tow cuts are faster
- Cuts are more reliable than adds

Thus, the primary factors are: (1) material, (2) orientation, (3) course length, (4) curvature and (5) tow cuts/adds. This data is specific to the CMI machine because the physics of the axes are different than the roll-pitch-roll head on the Ingersoll machine. Additionally, the Ingersoll machine may not be as effected by the resin tackiness. Longer courses and less curvature would still be desirable because the machine follows a first-order system and the head physics are similar to **Figure 14**. Tow cuts and adds definitely add to lay-up times on an Ingersoll machine, but this author cannot predict the reliability of cuts and adds. The section is divided into three areas for consideration: (1) material, (2) software and (3) the results of a designed simulation. The factors affecting lay-up rate are discussed in more detail in these sections.

Material

Experiments at Bell and Cincinnati-Milacron indicate that low-tack resins reduce the build-up of resin in the head. There are several toughened resins which have had considerable success:

Resin	Manufacturer	Material Type	Users
8552	Hercules	Towpreg	Boeing, Northrop
E7T1-2	Fiberite (was BP)	Slit-tape	Bell, Raytheon
977-3		Slit-tape	MDA

Table 15: Toughened Resin Systems in Use

Although the Hercules 3501-6 resin is commonly used, it is not ideal for fiber placement. 3501-6 has relatively high flow and tack. The high flow resin fills empty spaces like honeycomb core cells. The high tack resin sticks well to the surface, but causes the head to build up deposits which jam chutes, cutters and other parts of the fiber delivery system.

Since there is not a significant amount of data on material, an excellent future project would be to execute a designed experiment determining the lay-up rate for several materials with environmental and process noise parameters minimized.

Software

Software is a critical factor in the lay-up. This section addresses CMI's recent improvements to its NC code, then the results of a designed simulation are discussed. Cincinnati-Milacron has made excellent strides to improve lay-up efficiency in Version 2 of its NC code:

- Course reordering algorithm
- Smart retract
- Process Regions

The old course reordering algorithm chose the shortest path first and laid up subsequently longer paths. This caused strange course orders which were not efficient and distracted operators. Cincinnati-Milacron changed this so the closest course is the next one to be laid [conversation with Mark Trudan]. Smart retract causes the head to follow the contour of the part. This will save time on high complexity parts which require the machine to move the head to completely clear the tool every time the head is retracted. Process regions allow the programmer to specify a region which moves slower in process critical regions rather than slowing the whole course. This could increase overall lay-up speed on parts with recessed regions.

Two interesting ideas can improve the programming of fiber-placed parts. First, a part with surface area variation should have the lay-up orientation go from large area to small area. For example, the lay-up orientation on the 0-degree ply for the sponson should go from back to front. Then, the machine will cut tows instead of add tows. This is desirable because cutting is more reliable than restart. Second, the NC code output should not be changed to improve the lay-up. Change the input parameters instead so the output can be regenerated if the programmer is changed. For example, if the head crashes and a programmer changes the G-code without a new path or NC generation, the machine could crash again when the programmer leaves and the part is modified.

Results of the Designed Simulation

A designed simulation was performed with three surfaces: a cylinder, a cylinder with double curvature and a flat plate. It consistently showed the importance of lay-up speed and cut speed. **Appendix 7** has additional information about the results of the designed simulation.

The lay-up speed was varied from 100 to 1200 in. per minute. For a long ply, laying up at 1200 ipm was consistently more than 10 minutes faster (on a 30-minute nominal ply) than laying up at 100 ipm. Thus, the part should be programmed to lay up at the fastest speed acceptable to material tack. Operators can turn down the override if there is a problem. For a short ply, the lay speed could change lay-up times by 40%. A 700 to 800 ipm setting translates into 65-70% of the time savings quoted above.

The cut speed was varied from 25 to 150 ipm. It significantly effected the lay-up time on short plies: 54 seconds on a 2.11 minute ply to 2.28 minutes on a 5.0 minute ply. Thus, increasing the cut speed on a 45-degree angle ply could save 30 minutes. With the angle's excess material at the ply boundary, accuracy will not be affected. This is a similar to Bell's findings on the V-22 Grip. Time savings for cut speed on long plies was less significant. Programming should be for efficiency, not just for machine operation. Additionally,, data and experience should be used to make programming decisions.

The designed simulation consistently showed the importance of contour. The flat plate and the single curvature cylinder had very similar times for the same length. The double curvature cylinder's time was forty percent greater than either the flat plate or the cylinder (i.e.. 10 minutes for a 25 minute ply). The lesson to be learned is that you should avoid double curvature whenever possible or expect large lay-up times.

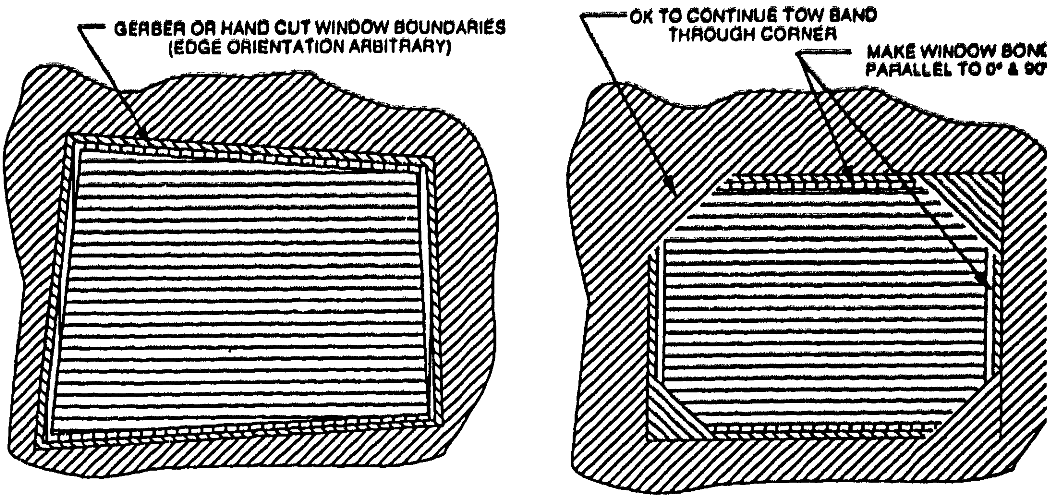
Cutouts did not affect lay-up time significantly. At worst a cutout added one minute to a 28 minute ply. This could be misleading because only one cutout was used on the simulation, but typical plies have more than one.

Design for Tow Placement Guidelines

A database of ideas which improve the part design for the process is summarized in this section. The data was gathered from the benchmark companies and relevant literature [35].

- *Make the longest courses possible.* The longer the course the less acceleration and return delays will affect the part lay-up time.
- *Distribute cutouts between plies to maintain minimum cut length.* The aggregate structure is the same even though the lay-up has been changed. Weight reduction cutouts should take precedence over features which are later cutout.
- *Overlap plies to create a buildup ply.* A schematic of the non-overlapped ply and the overlapped ply is shown below.

- *Special orientations are available for directional strength requirements* as seen on the 45-degree ply on the integrated skin and on the zero ply of the angle.
- *Maximize all radii.* Orientation angle and recess depth affect radius size. Thus, a 2-inch convex radius and a 6-inch concave radius should be guidelines for minimums on the HD machine.
- *Install a splash on a tight radius of curvature* so tows can be draped into the tool surface after the splash is removed. (This is only viable near the edge of the tool.)
- Make ply edge boundaries parallel to the orientation to minimize individual cuts. Run the part through the NC program to verify a parallel boundary.
- Ply widths should be at multiples of tow widths to eliminate unnecessary adds and drops
- Continue the tow band through the corner on 45-degree cutouts (see **Figure 16**).
- Make window boundaries parallel to the 0- and 90-degree plies (**Figure 16**).



CONVENTIONAL HAND-LAYUP "WINDOW"

EFFICIENT TOW PLACED "WINDOW"

Figure 16: A well-designed Cutout (courtesy of Northrop-Grumman)

2.3 Chapter Summary

In this section six reasons to fiber place were introduced. Making large, complex integrated parts with consistently good quality is one of the major benefits of tow placement. A three-step process for design was suggested and discussed with supporting data from a benchmark tour as well as a designed simulation. Then, the primary factors that determine lay-up rate were identified:

- Material
- Orientation
- Course Length
- Curvature
- Cuts and Restarts

It is a good idea to keep these factors in mind when designing a part for tow placement. The next chapter explains a tool which will help evaluate recurring costs to strengthen the link between design and manufacturing.

3. Applying a Physical Cost Model

In this chapter a physical cost model for advanced composites manufacturing is introduced and applied to automated tow placement. This model uses a physical theory to map the shape of a part into the time to manufacture this part. The first section introduces four types of cost models. Then, the theory behind the model is discussed. Following this theory, model parameters are determined for each ply orientation. These parameters are the tool that maps the part shape into a relationship with the process lay-up time. Finally, the model is compared to a NC-code simulation of a variety of shapes for verification.

This model is meant to be used as a simple tool for the concept engineering team prior to importing the CAD data into the off-line programming system. The model should take about one hour per ply to use. It can help the team evaluate design features like contour and cutouts without spending endless hours manipulating the data files. The people at HD realized the need for this several years ago. The NC programmer was nicknamed "Just-in-Time Jim" because just about the time he had completed generating the NC code for one design change, the designer had the next change to that same ply. The whole process to evaluate the change took Jim about 8 hours. Thus, this model helps reduce the iteration time and frees up the NC programmer.

3.1 Types of Cost Models

Four types of cost models provide a history leading to the present model:

1. Power-law
2. Detailed Process
3. Production
4. Physical

These four models provide a variety of information to different degrees of accuracy. The major benefit of the physical model is that it is a simple model which uses statistics and physically-based theory to predict the recurring lay-up cost. The others are either statistical only (the Power law model); physically based, but complicated (detailed process model); or too-broad to predict part cost at each process step accurately (process model). Neoh has an excellent discussion of the categories of time estimating methods [15, p. 22].

Power law models typically plot historical time data versus weight in the form of $t = AL^r$. Empirical data models cannot be generalized since they have no conceptual basis. In particular they cannot accommodate changes in the process.

The Advanced Composites Cost Estimating Manual developed by Northrop for the United States Air Force is the most famous detailed process model [25]. It lists 63 steps to make a J stringer. There is a detailed process model for many types of parts. The planner calculates the time to perform each step and sum the steps to estimate the labor cost. ACCEM has the capability to account for part size and complexity, but only for specific cases. It cannot account for process changes.

A production cost model accounts for production, but not the link between part shape and cost. Masi developed this type of model to the fabrication of thermoset and thermoplastic composites in 1988 [14]. It accounted for capital, labor, materials and energy. This type of model is more useful for comparing manufacturing technologies than for part shapes.

A physical cost model links the physical design of a part with the historical manufacturing cost. It characterizes and compares parts and processes with has three features:

- Dimensionally correct equations
- A physical interpretation of all coefficients
- Is derivable from a plausible physical argument.

These features allow three benefits for a physical model:

- The model structure is transparent
- The model is well-defined
- The model has a physical interpretation

The best way to describe a transparent structure is that it is the opposite of a black box: you can see its inner workings. A well-defined model has a basis in already accepted theory. In the case of the model in **section 3.2** control theory and information theory concepts are used. The physical interpretation allows for adjustments to be made to the model when the part or the process changes.

Jenks applied a physically-based manufacturing cost model to pre-developmental processes with little historical data in 1991 [12]. He looked at tow placement as one of several technologies in the process flow of a part. He used an average lay-up rate based on part volume and tow or tape thickness and width with adjustments for acceleration time and head turn time [12, p. 65].

This thesis uses historical data and theory to characterize and compare part shapes and sizes for lay-up with automated tow placement machines. It applies an analytical framework developed at the Laboratory for Manufacturing Productivity which applies to a variety of additive and subtractive processes. Neoh presents this framework in his 1995 Ph.D. thesis titled "Adaptive Framework for Estimating Fabrication Time [15]." This simple, physically-based model provides an accurate rank of part shapes and sizes when compared with ACCEM and proprietary estimates for tow placement.

3.2 The Model

Several steps are required to build a complete dynamic model which characterizes and compares airframe parts for the ATP process. First, a dynamic model with two parameters, τ and Vo, is introduced (**Section 3.2**). This model follows the framework outlined in [16]. Second, these two parameters are estimated from data gathered at HD. A limited amount of data was then used to relate time penalties to features of the course (**sections 3.3-3.5**). Third, the course time estimates would be related to the macroscopic part geometry. Due to limited time and data, the third step was not completed during this thesis. This thesis does characterize course times individually for the integrated skin and the large fairing at BD&SG, HD. Additionally, it is verified with some simple part shapes in **section 3.7**.

The model uses control theory equations to characterize the lay-up time. These equations characterize size effects with two parameters: a steady-state velocity and a time delay. Using control equations makes intuitive sense because automated lay-up machines are controlled by servomotors and positioners (feedback control loops). This approach estimates the time for human and machine activities in three steps [17]:

1. Build a Simple Dynamic Model
2. Simplify and Sum these Steps
3. Account for Complexity

The fiber placement manufacturing process can be viewed as laying a collection of primitive steps: courses of tows. One bandwidth of tows is called a "course". These primitive tasks are modeled as two types of physical systems: (1) the positioning of a dampened mass with a servomotor (machine operations) and (2) pure gain with a pure feedback delay (manual operations). Control theory calls these an over-damped second-order system and a first-order system, respectively. The response of a first order system to a step input is shown in **Figure 17**.

A first order system can be characterized by the following equations for spot velocity and length traveled:

$$V(t) = V_0(1-e^{-t/\tau}) \qquad (1)$$

$$L(t) = V_0[t - \tau(1-e^{-t/\tau})] \qquad (2)$$

V_0, the steady state velocity, and τ, the time constant, are physical characteristics of the machine. The steady state velocity is the maximum velocity achieved for the orientation. The time constant represents the delay involved with attaining full speed. These are shown in **Figure 17**. V_o and τ are extensive properties: they vary based on orientation, part geometry, etc. For comparison an intensive property, like pressure, is constant between subdivisions.

V_o and τ can be found for equations (1) and (2) by running a curve fit when L and t are known in large quantities by using a user-defined curve fit function in Deltagraph 3.5.2 software package.

Figure 18 is a graphical representation of equation (2). The square dots are actual data for a 45-degree ply which was laid on the large, integrated skin structure. The line is a best fit line of the data to the size scaling equation (2). The best fit (predictor line) was performed by minimizing a chi-squared function of the length-time equation using solver in Excel. The predictor line applies for shapes similar to the integrated skin with the same orientation and material. It shows that the 45-degree ply on the integrated skin has very few complexity effects and can be characterized by size equations alone.

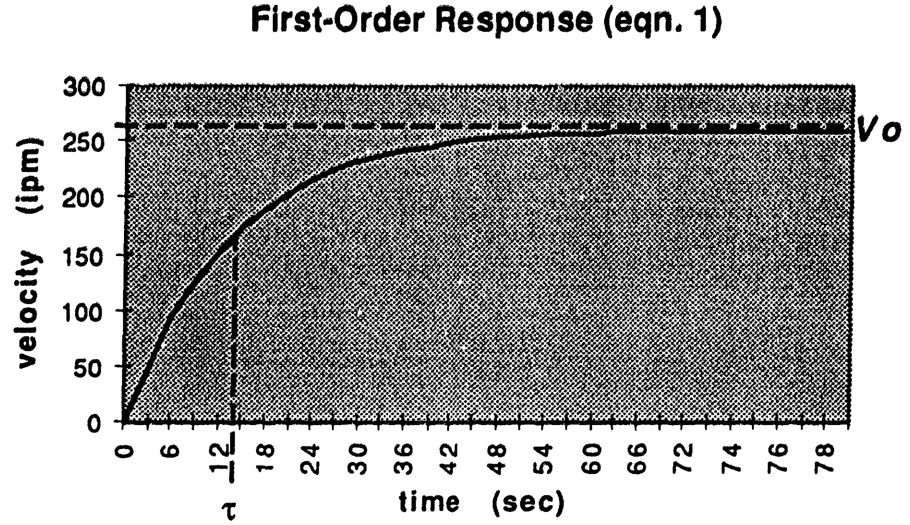


Figure 17: Graphical Representation of Equation (1)

Equations (3) and (4) are approximations of (1) and (2) for cases of long and short times (measured with respect to the time constant). These equations are important because they will be shown to be as accurate and easier to calculate time than (2).

$$t \sim \sqrt{(2\,\tau\, L/V_o)} \qquad t < \tau \qquad (3)$$

$$t \sim \tau + L/V_o \qquad t > \tau \qquad (4)$$

$$t = \sqrt{(L^2 / V_o^2 + 2\,\tau\, L / V_o)} \quad \text{for the entire range (5)}$$

Equation (4) is excellent for long times and makes conservative errors for short times [17, p. 235]. Equation (5), Mabson's equation, applies across the whole range of times [15, p. 33].

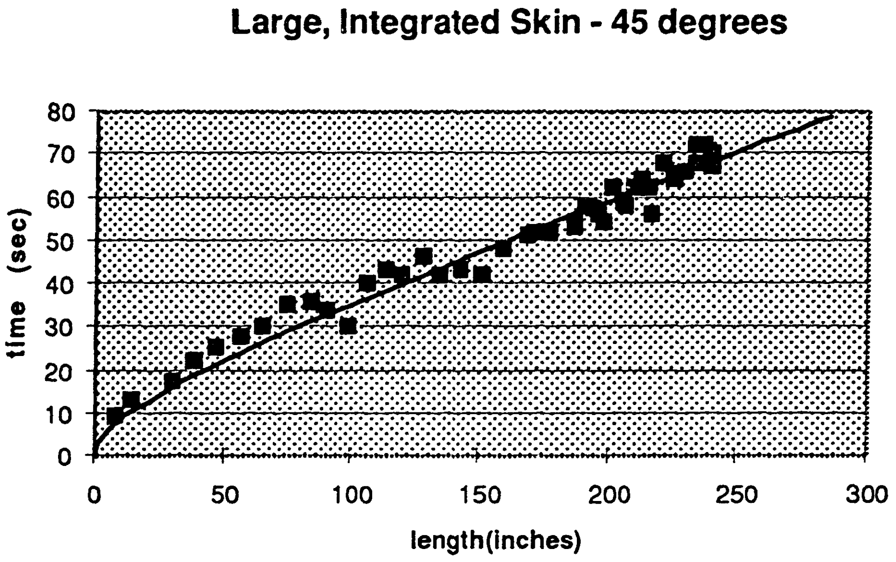


Figure 18: Actual and Predicted Course Lay-up Times

Gutowski and Neoh also outline equations to quantify the complexity of a part [17]. They link the part complexity to Shannon and Weaver's information theory. They go through a series of steps to show that the information contained within a part is directly proportional to the enclosed angle. The key notion is that the part is represented as a collection of aligned fibers and the fibers are thought of as an information storage medium. Neoh describes the physical interpretation of this finding[17, p. 237]:

> *Interestingly, there is a precise physical interpretation for this result [that information stored within a fiber is proportional to the enclosed angle]. If a complex composite part is made by deformation, then the shear required along a fibre to make this part is identical to the enclosed angle, theta.*

Thus, just like there is a physical understanding relating the cost model to the machine controllers, there is a relationship between part lay-up time and the curvature. From this idea they modify the time constant, τ, for complex parts:

$$\tau = \tau_0 + b\hat{I} \qquad (6)$$

$$\hat{I} = \Theta \text{ (the enclosed angle)} \qquad (7)$$

In these equations τ_0 is the time constant without complexity and b is a constant of proportionality with units of time/radian. For more information on shear and fiber mapping, please refer to Tam and Gutowski [21]. So, to account for complexity, one must substitute equation (6) for the time delay into one of the first four equations. In this thesis equations (6) and (7) are only used to map simple curvature features because it is difficult to measure the enclosed angle completely for all but the simplest parts.

Gutowski and Neoh have demonstrated that the physical model outlined in equations (1) through (7) agree with Northrop's detailed Advanced Composites Cost Estimating Manual for a variety of processes and part shapes [17]. **Figure 19** shows a cross-section of several of the shapes for which the model was verified. The model was also verified for parts with complex geometries.

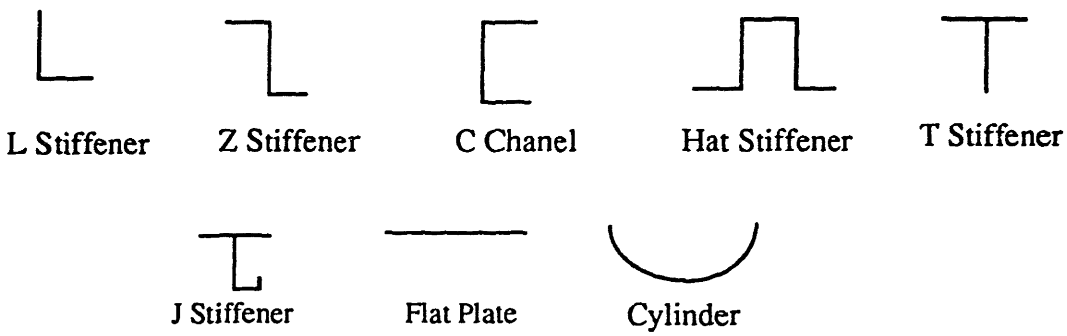


Figure 19: Cross Section of Part Shapes used to Verify Model in [17]

The benefits of the model in equations (1) through (7) are: (1) it presents a detailed model which shows the effects of part features on cost, (2) it gives a physical interpretation for all model coefficients and (3) it is simple to use. Before continuing with specifics on various part orientations, it is useful to summarize the models assumptions and decision variables

3.2.1 Assumptions

The model assumes that the machine operation can be characterized by two properties: a steady state velocity and a time constant. These parameters which are determined by the part shape are mapped into an estimation of machine lay-up time. The time constant depends upon part curvature, cut and adds, and orientation. V_0, the steady state velocity, is a function of ply orientation. τ and V_0 characterize the system for many geometries, but have some limitations with complex geometries. The difficulty is that the part orientation has three axes, while the machine has seven axes. Thus, there is not a one-to-one mapping from part to process. This model has attempted to address this issue by penalizing shapes that activate many axes of motion.

3.2.2 Decision Variables and Parameters

The decision variables in this model are shown in **Table 16**. The length and complexity of the course are input and the time of the course is the output. Units are shown in parenthesis.

Coefficients	
Vo	The steady-state velocity (length/time)
τ,	The system time constant (time). Found when $V=.63V_o$.
b	The complexity proportionality constant (time/radian)
L*	The length needed to reach one time constant, called the critical length. It is the product of tau and V_o.
Inputs	
L	Course length (length)
I, theta	Information map of the course: the enclosed angle mapped by the fibers (radians)
Outputs	
t	The time to lay a course (time)

Table 16: Design Decision Variables are L and I

With the model's assumptions and decision variables outlined, the details of each of the orientations can now be identified. In **Sections 3.3 to 3.6** a large, integrated skin and a large fairing have been used to map part geometry features into process parameters. The 0-, 90- and 45-degree orientations will be discussed and it is shown that there is an adequate mapping of part shape to process parameters using a linear relationship. Then, the return cycle for the machine will be statistically determined.

3.3 0-degree Orientation

The 0-degree orientation has one of the most complicated data-sets due to the width expansion of the large fairing. There is good agreement between the simple courses on the fairing and the integrated skin. **Figure 20** shows a summary data-plot of the 0-degree courses which were timed. More detailed data about each part is given in **Appendix 8**. The courses which are flat or have only normal curvature are represented by a square or a diamond. The complex courses on the fairing are represented by a star pattern and a circle. There are two features which add complexity to the fairing: an increase in width perpendicular to the lay-up direction and a recessed area which has a dip and a rise. These features are shown schematically in **Figure 21.**

Table 17 shows that equation (4), the linear approximation, is as accurate as using equation (5) for the fairing and integrated skin data. The correlation coefficient (in the row marked R^2) is typically higher for the linear equation than for the second-order, Mabson, relation. In fact, agreement with the linear approximation is so good for less complex courses that there is no need to perform the difficult curve-fitting exercises needed with equations (1) and (2).

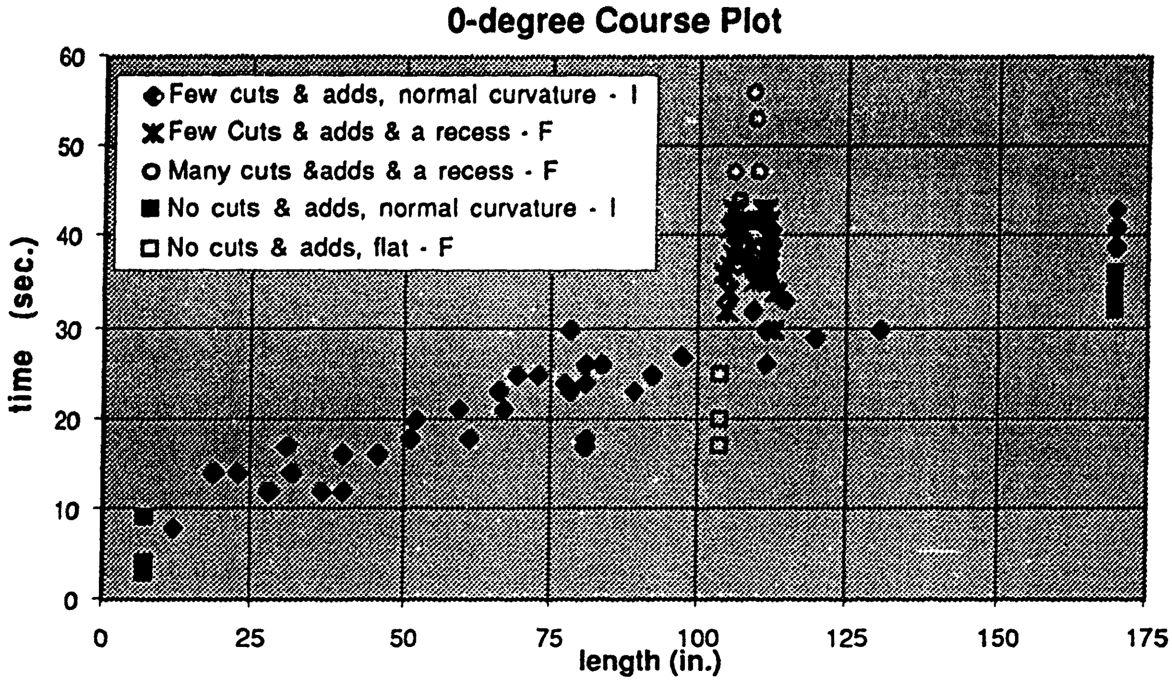


Figure 20: Course times for the 0-degree Orientation

No cuts & adds	linear	Mabson
τ (sec)	3.1	3.59
Vo (ips)	5.71	5.71
R^2	0.9785	0.9771
Few cuts & adds	**linear**	**Mabson**
τ (sec)	9.4	13.06
Vo (ips)	5.71	5.71
R^2	0.855	0.852

Table 17: 0-degree curve fit parameters using equations (4) and (5)

The values in **Table 17** show the curve-fitting parameters for two of the scenarios described in **Figure 20.** The time constant varies from 3 to 13 seconds and the steady state velocity is held at 343 inches per minute (ips x 60). The agreement for the more simple courses is excellent with R^2 above 0.8.

The other two scenarios in **Figure 20**, (1) courses with few cuts and adds and a recess and (2) courses with many cuts and adds and a recess, have poor agreement with the nearly horizontal linear model. The agreement is poor because all of the data points were measured at nearly the same course length. Instead of linear regression, the curve will be shifted via hand-waving. Since, the points with few cuts & adds and a recess have a delay about 10 seconds greater than similar points without a recess, τ is adjusted to 19 seconds. Since the average of the points titled "many cuts & adds" is 12 seconds greater than the points with a recess., τ for this scenario will be 31 seconds.

The process used to curve fit equations (4) & (5) to the parameters, τ and V_O, is simple. First, τ and V_O were found for the least complex courses. Then, V_O was held constant as τ was varied to adjust for complexity changes. Deltagraph 3.5 was used for the linear regressions.

Figure 20 clearly shows that not all courses follow the size scaling equations (1) to (5). The complexity equations (6) and (7) are capable of adjusting τ based on the complexity of the part, but they are difficult to apply in industrial applications since they would require manipulation of the CAD data. Additionally, this would be as time consuming as the NC code simulator which this model is intended to bypass. Therefore, some complexity rules of thumb have been invented to map part complexity to τ .

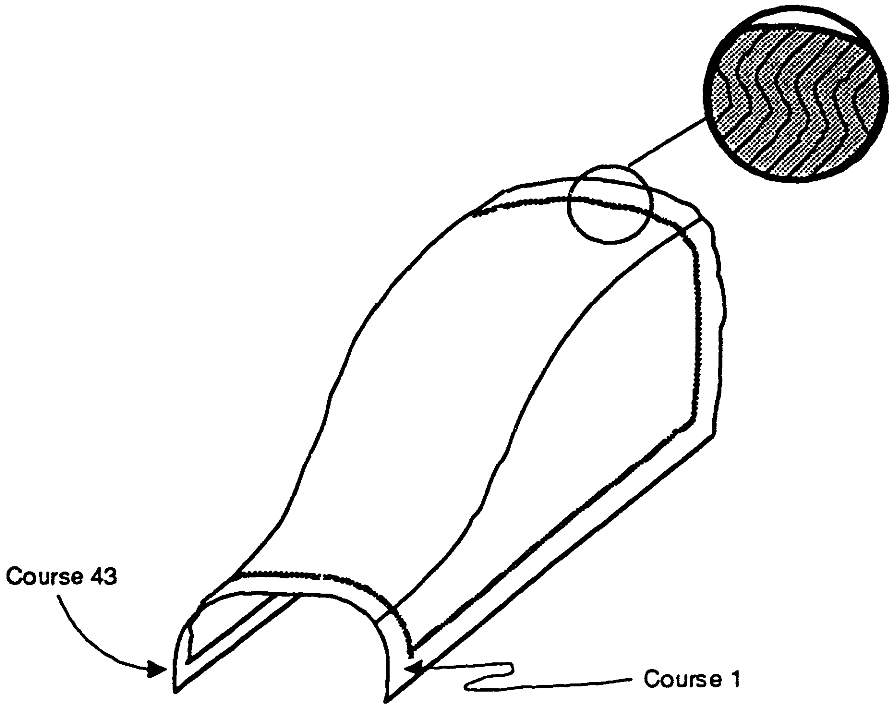


Figure 21: Large fairing with the 0-degree orientation

The following section outlines a method to calculate the time constant for part shapes. The time constant has four components:

- End effects
- Acceleration
- Curvature
- Adds and Drops

The end effects are the delay due to the beginning of material lay up and the end. At the start of the course the tows are fed a distance equal to the minimum cut length as the head is placed against the part surface or the tool. At the end of the course the machine must stop, cut and proceed with the minimum cut length of material. Actual data suggests that this **end-effects delay, τ_E**, is two seconds per end or four seconds in total. This data agrees with the extrapolated intercept shown for the least complex courses in **Table 17.**

After the initial tow length is dispensed, the activated axis or axes accelerate to the steady state velocity in a manner similar to Figure 18, the first order response. This effect is known as the **dynamic delay, τ_D**. Deceleration occurs much more quickly than acceleration and the delay can be ignored. The dynamic delay depends on the limiting axis of acceleration, but it can be approximated for each ply orientation. The best estimate of the dynamic delay of the 0-degree orientation is the difference between the time constant for "few cuts and adds" and τ_E: 6.3 seconds.

The **curvature delay**, τ_C, is caused by the limiting activated axis. The CMI automated tow placement machine has seven axes of motion: x, y, z, i, j, k and c. The first three axes, -x, y, and z, are motions of the arm and carriage, the next three are head movements and the final one is the mandrel axis. The curvature delay for the recess in the fairing is approximately 8 seconds — the difference in time between the courses titled "few cuts & adds" with and without a recess (40 - 32 = 8 sec.). The recess causes the j and x axes to be activated (in addition to the z axis) as the machine maneuvers to negotiate the dip shown in the inset in **Figure 21.**

The expression for the curvature was stated previously:

$$\tau_c = b\Theta \qquad (8)$$

This equation is applied to the head axes and the mandrel axis with the limited amount of data which is available to characterize b. Θ is the enclosed angle of the part feature. For example, the enclosed angle of the recess in **Figure 21** is 180°. The units of b are in [sec/Radian]. The curvature coefficient, b, can be found as a function of the axes activated as shown in **Table 18.** These numbers are not very accurate because they are based on very few data points from these two parts. They should be used with care.

The curvature delay for a course can be calculated for a given part curvature and equation (6). For example, the fairing recess spans π Radians on either side of the part. Three axes are activated with j, pitch, as the primary head axis. Thus, τ_C is calculated to be 8.2 seconds per course for this 2 in. radius part feature. Implicit in this calculation is the realization that x, y, z and c axes contribute less to the time delay than the i, j and k axes for head movement.

Axes Activated	Orientation	b [sec / Radian]	Number of points used to find b	Delay [sec.]	Enclosed Angle of Feature
z, x, j	0-degree	1.3	1	4	π
z, y, k	0-degree	2.7	1	4.2	$\pi/2$
x, y, c, j	90-degree	5.82	3	16.1, 13.1, 25.7	π

Table 18: The curvature equation constant of proportionality

The **cut/add delay,** $\tau_{C/A}$, is the delay for cutting or restarting the tow in the middle of the course. The average increase in time for courses with significant tow adds on the fairing is 9 seconds (49 - 40 seconds). 49 seconds is the average time for the courses labeled "Many cuts & adds & a recess. The cut/add delay, $\tau_{C/A}$, is caused by a significant difference in the width (measured perpendicular to the orientation) across the part. For example, if the large fairing were laid completely flat, the width of the rear of the part would be 123 in. and the width of the front would be 66 in. The 57 in. difference will cause 456 tow adds. The data shows that there is a 9.5 second difference between the courses with a recess, but with and without adds. With 456 tow adds distributed over 45 courses (123 in./2.75 in.), there are 10 tow adds per course. Thus, the delay for an individual add is approximately 1 second.

A few words of caution with this cut and add analysis. The add effect is not observed on the 0-degree build-ups for the stringers on the integrated skins, even though the rear of this part is 2.25 times the front (**Figure** 22). The difference is that the edge of the fairing is parallel to the lay-up direction,, but the integrated skin edge is not. Therefore, all courses at the front of the fairing must extend to the back and significant tow adds (or drops) are required. The edge of the integrated skin is at an angle so that there is really no area increase at the opposite end of the part. Thus, it does not have a noticeable $\tau_{C/A}$.

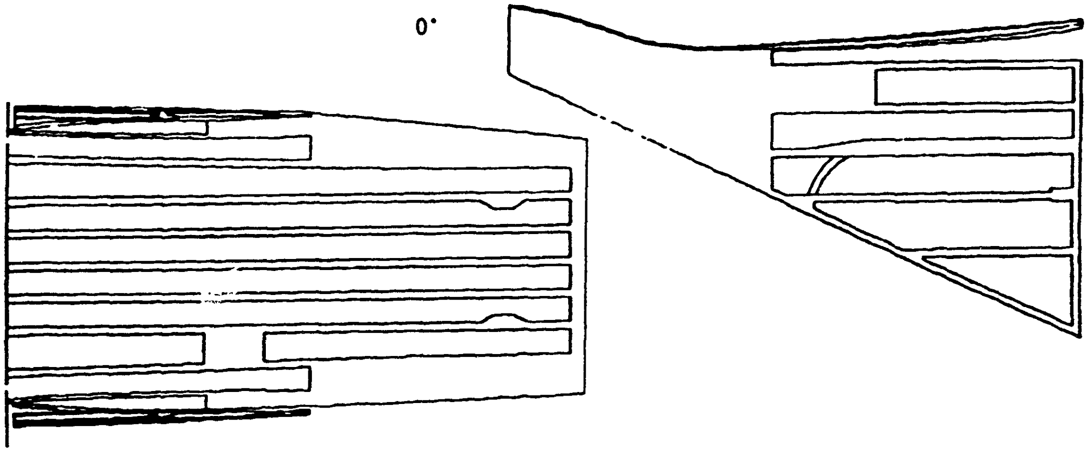


Figure 22: Integrated skin 0-degree orientation ply

In this section four types of delays have been introduced: end effects, dynamic, curvature and cuts and adds. These delays have the effect of shifting the linear size relationship upward as shown in **Figure 23.** Other orientations may now be discussed with ease.

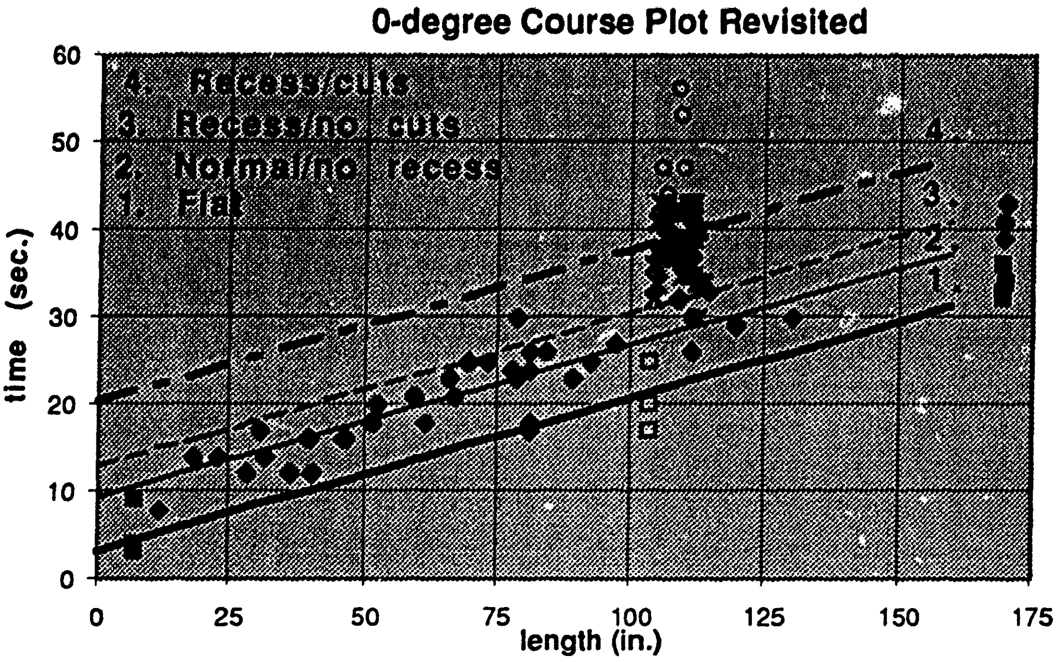


Figure 23: Increased part complexity shifted the curves upward for the 0-degree

3.4 90-degree Orientation

The 90-degree orientation data-set is shown in **Figure 24.** This plot shows full plies for the integrated skin and the fairing on the 90-degree orientation. There is excellent agreement between parts. Integrated skin data was adjusted for the machine override setting which was used at the time of lay-up due to material tack problems. The interesting conclusion of the graph is that size effects (L/V_o) are dominated by time delays (τ).

The 90-degree orientation on the integrated skin and the fairing are both U-shaped. The similarity of the lay-up times between parts supports the assertion of this model that part shape can characterize the lay-up time.

There are two distinct groups of data — with and without a tow inhibited. The parameters for these two scenarios were found using equation (4) and are shown in **Table 19.** The V_o in this table is an upper limit — since the part is delay dominated, V_o is not predictable. As discussed below the angular steady-state velocity is predictable. The model user should not use 26.62 ips for new part estimates, especially hoop plies which are velocity dominated.

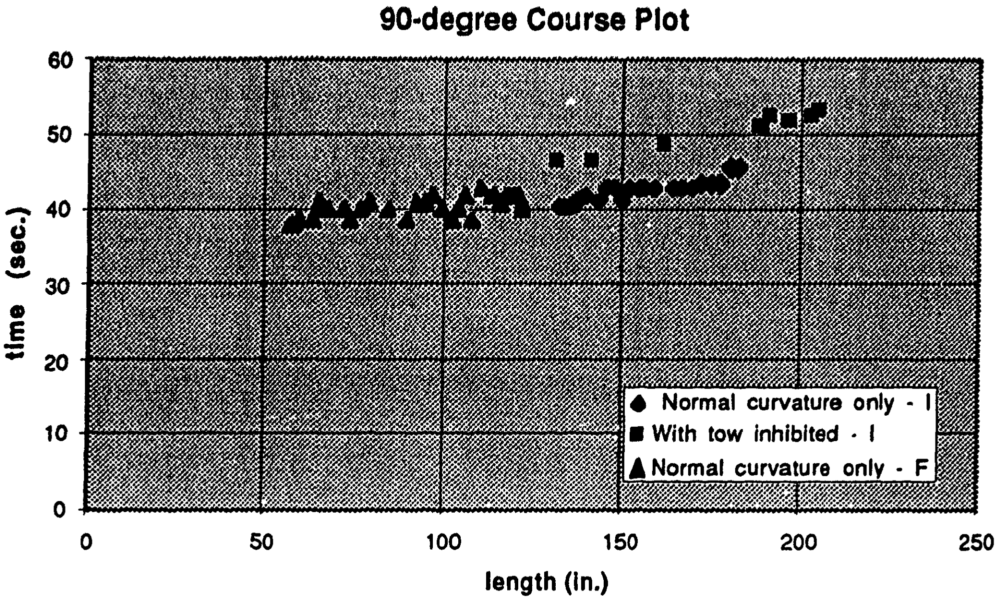


Figure 24: 90-degree ply course times

Normal Curvature Only	linear
τ (sec)	36.83
Vo (ips) - upper limit, do not use	26.62
R2	0.643
With a tow inhibited	**linear**
τ (sec)	43.68
Vo (ips) - upper limit, do not use	26.62
R2	0.968

Table 19: 90-degree curve fit parameters

The machine operator "inhibits a tow" when there is some problem with the dispensing of a fiber. Upon noticing a fiber delivery error, the operator presses the tow inhibit button and the machine continues to lay all other tows in the bandwidth. Then, the operator will manually fill the tow that was inhibited. The data suggests that inhibiting a tow takes 7 seconds. There is little need to plan for operators inhibiting tows beyond the downtime estimates which are discussed in **Chapter 5**. Thus, this data will not be used in the model.

Delay dominated means that the velocity term does not significantly affect the course time. Equation (4) may be written for a U-shaped part to explain this idea in more detail:

$$t = \tau + 3\ [(L/3)/V_0] \qquad \text{where}$$

$$\tau = 2\tau_E + 3\tau_D + 2\tau_C \qquad (9)$$

and this can be calculated. A cross section of the part is shown in **Figure 25**. This figure also explains the delays in equation (9). The machine starts at one end, accelerates to speed only to have to slow down to engage the pitch axis for the turn, the head accelerates again until the next turn, after which the head accelerates. This figure shows figuratively why equation (9) is true. τ_C is found to be 5.9 sec. from equation (9). τ_E is 2 sec. and τ_D is 6.3 sec. from the 0-degree ply data. This gives a τ of 34.7 sec. Then, the estimated time for a 180 in. course length is 41.5 seconds (4% below the value shown in **Figure 24**). Since time delays are 84% of the total lay up time, the data is said to be "delay dominated."

For a hoop ply, equation (4) can be rewritten:

$$t = \tau + \frac{\text{revolutions turned (n)}}{\text{revolutions per unit time }(\dot{n})} \qquad (10)$$

The velocity term has now been rewritten in terms of angular distance and angular velocity. This is appropriate for the 90-degree data because the mandrel axis limits motion. If τ_E and τ_D are removed from the course times in **Figure 24**, the velocity term is about 30 seconds in 180° of rotation. This is a useful way to calculate lay-up times for U-shaped parts and bodies of revolution with the 90-degree ply.

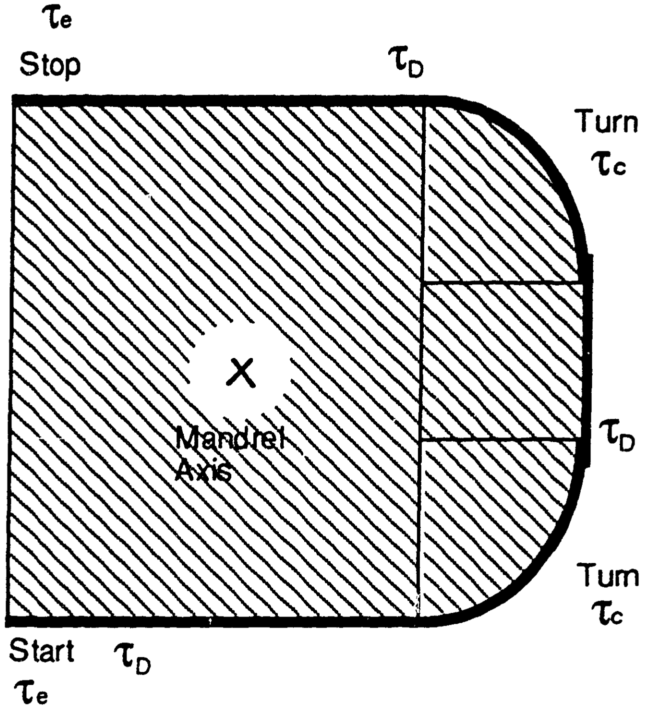


Figure 25: Typical cross-section of fairing and integrated skin

With an understanding of the 0-degree and 90-degree orientations the 45-degree orientation can be easily discussed because it is an extension of the previous two.

3.5 45-degree Orientation

The 45-degree orientation is dominated by the velocity term, L/Vo. The data points are shown in **Figure 27**. The curve-fit parameters are shown in **Table 20**. The first conclusion from the table is that the delay for the simple curvature (labeled flat and normal) is only one second more than the equivalent parameter for the 0-degree ply: good agreement of the data.

The second conclusion is that the steady-state velocity is the projection of the 0-degree velocity on the 45-degree orientation (5.71 cos 45° = 4.03). A velocity vector diagram is shown as **Figure 26.** This conclusion shows that the z-axis is limiting the lay-up speed. Additionally, it shows that the 45 degree data agrees with the 0-degree data.

flat and normal - single	linear
τ (sec.)	10.4
Vo (ips)	4.186
R2	0.934
double curvature	linear
τ (sec.)	25.72
Vo (ips)	4.186
R2	0.918

Table 20: 45-degree orientation parameters

The axes activated during lay up of a 45-degree ply of a flat plate would be the y and the z (arm tilt and carriage). For the two parts which are in the figure, the arm stroke (x) and mandrel axis (c) are also activated during most of lay up. The point here is that with the x, y, z and c axes activated, there is little measurable curvature delay in the time constant. Thus, the head axis is the primary cause of curvature delay, as discussed in **Figure 14.**

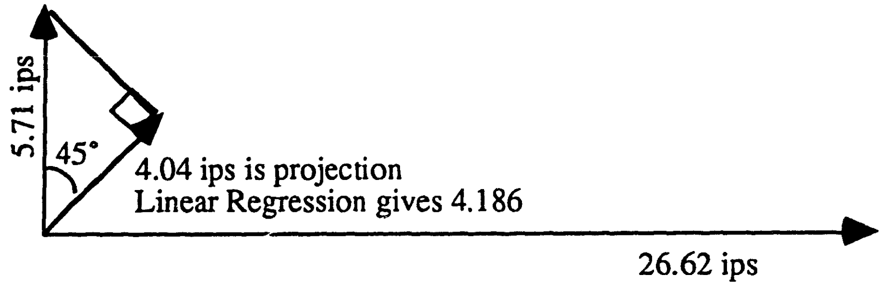


Figure 26: Velocity vector diagram for ATP

Data was taken for two very similar plies on the integrated skin to confirm that there is repetition between parts. **Figure 28** shows measured lay-up times for two different parts. The data for the second part has been shifted to adjust for the operator override of 60 to 100% during the lay up of the integrated skin #2. This figure verifies repetition between parts as well as it shows that the course time can be predicted from the length and part features.

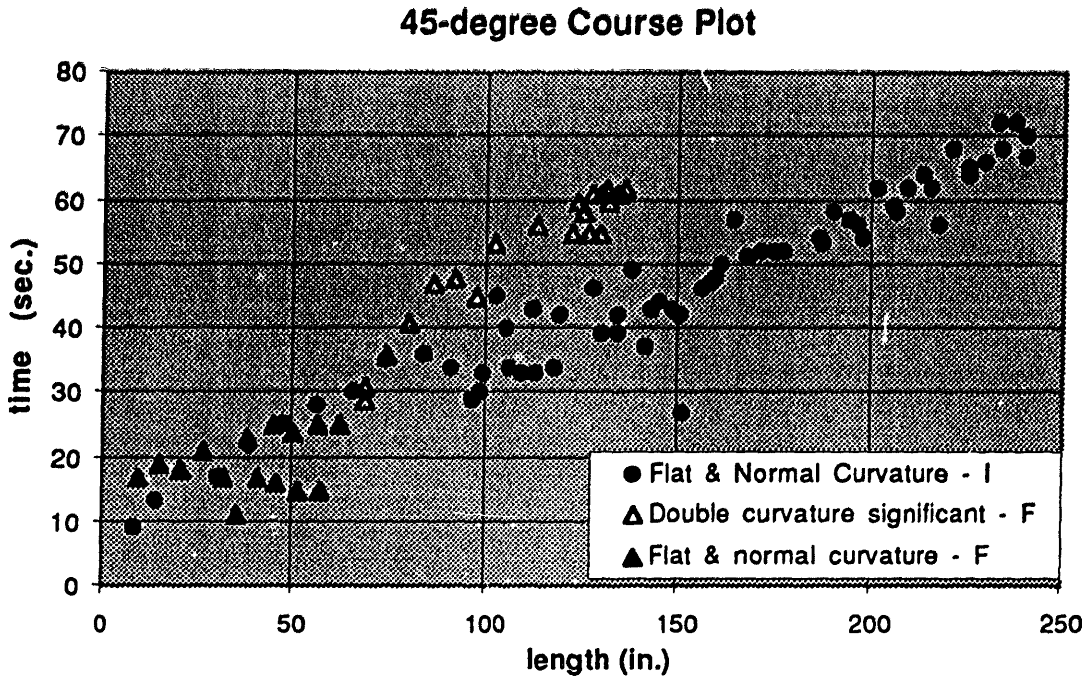


Figure 27: 45-degree ply course times

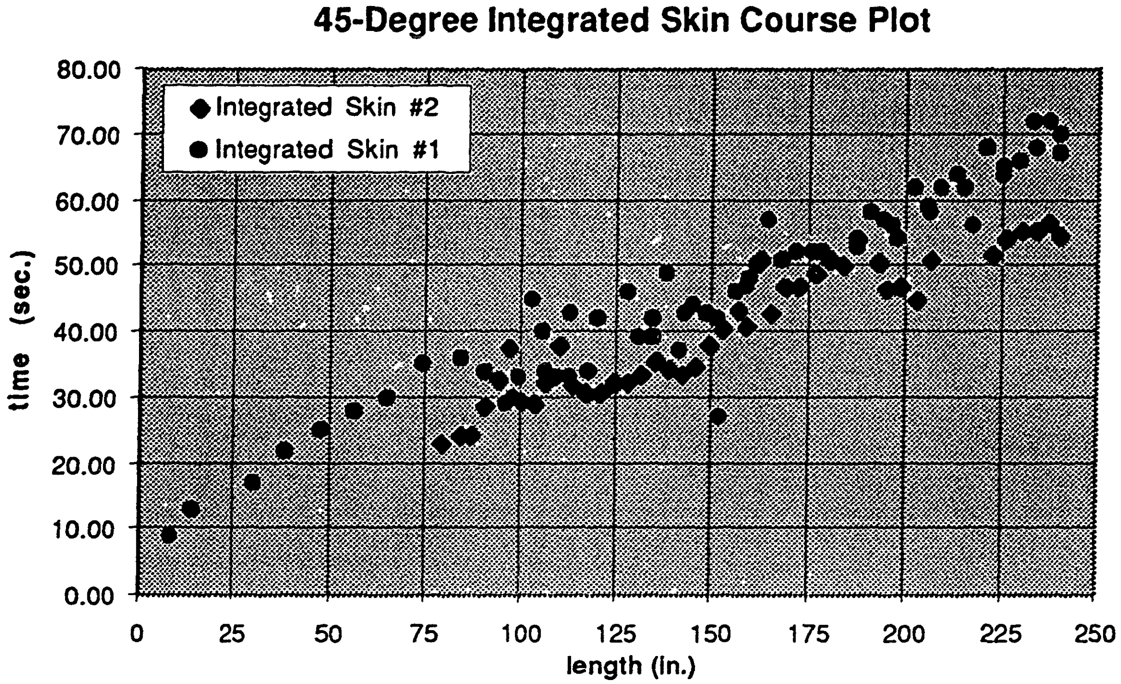


Figure 28: Course times are consistent between parts for integrated skins

3.6 Return

Return data is shown in **Figure 29.** The return sequence is the time at which the head lifts off the part at the end of one course until the head touches the part for the start of another course. The theory which has been outlined above does not apply for the return because the previous course length has no physical link to the return time. Instead, a simple, statistical linear regression gives:

$$t = 8.75 + .0371L$$

The correlation coefficient for this equation is .204; this means agreement is low. Alternatively, an average of this data may be just as accurate. The average return time is 14 seconds and has a standard deviation of 4.3 seconds. The average may be better for parts the size of the integrated skin. The regression equation is probably better for parts smaller and larger than the integrated skin (165 in. [24]).

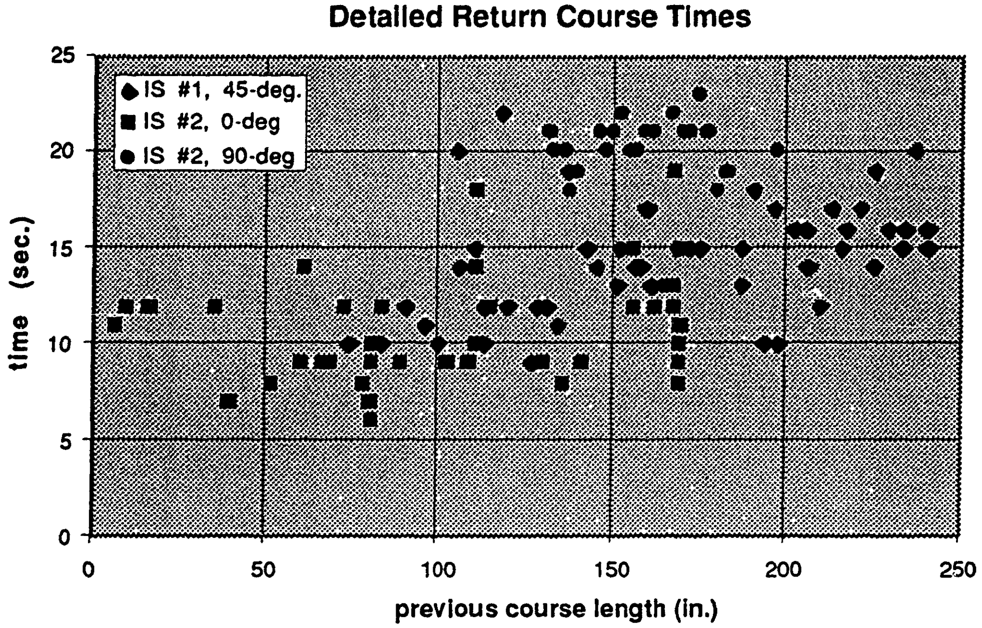


Figure 29: Return times for the BD&SG Viper

3.7 Verification of the Model

In this section the model is compared to some simulations of generic part shapes which were performed at Cincinnati-Milacron [3]. Part shapes are shown in **Figure 30.** The results are shown in **Table 21.** Detailed calculations are in **Appendix 12.**

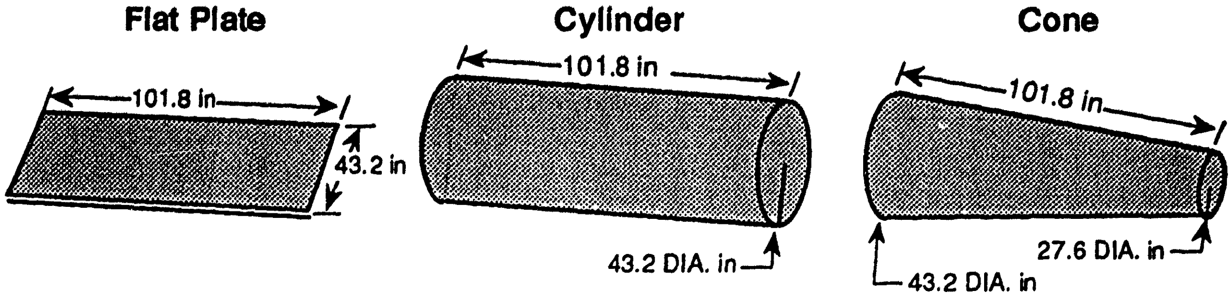


Figure 30: Part shapes considered for verification

Several assumptions were made for this calculation:

- A lay-up setting of 800 ipm (V_0 values are extrapolated)
- A 24 tow machine with 1/8th in. wide tows (3 in. bandwidth)
- Non-cycle time of 30%
- Tow thickness of .0055 in.
- Tow density of .058 lb./in^3

The model predicts lay-up rates that are consistently lower than the CMI simulation (**Figure 31**). This is a desirable because CMI is in the business of selling machines, not estimating times accurately. The rates in the figure are high when compared to the 0.72 lb./hr. lay-up rate found during production at Boeing because the 30% non-cycle time assumption is a very optimistic prediction. The process improvement team found that this factor should be 80% when estimating for production. As shown in **Chapter 4** the model predicts overall lay-up rates accurately when an 80% non-cycle time factor is used.

Don Evans of CMI defines in-cycle time as the time during which the machine is laying material onto the part. Non-cycle time is machine preparation, tool preparation, tool installation, machine alignment, vacuum debulks, ply inspections and machine downtime [3]. The process improvement team found that the majority of the non-cycle time is downtime.

The trends in Figure 31 are very good. The model values follow the shape of the simulation from 0- to 90- to 45-degrees well. The 0-degree ply is typically faster than the 45-degree. The 90-degree ply rate depends on whether the ply is a hoop ply or not. Notice that the hoop ply is a very efficient shape to fiber place.

A note to cost estimators using this model. The calculations for the 45-degree plies were sensitive to the way the length of the courses were estimated. The length calculation can be verified by calculating the weight of the 45-degree ply from the individual lengths. Then, this value can be compared to the weight expected for full coverage of the tool. If the numbers are substantially different, the estimator should recheck his geometry calculations. Of course, it is always wise to check the units in the calculations.

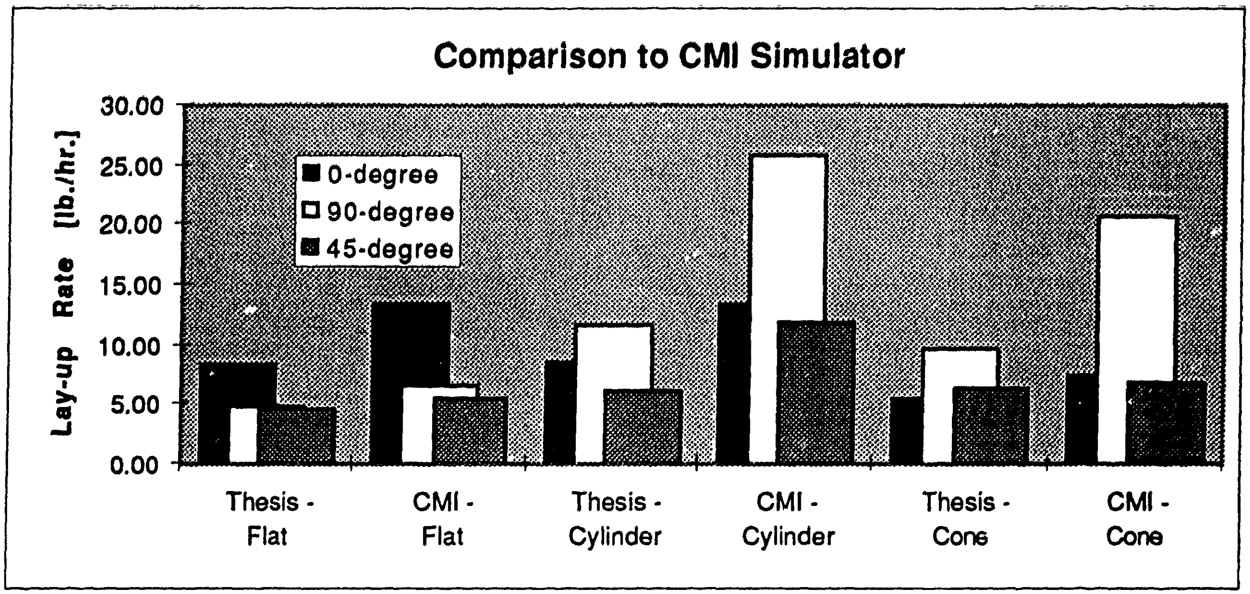


Figure 31: Comparison of CMI estimates vs. Thesis Model

The calculations for these nine plies took just 4 hours and has a reasonable amount of accuracy. Thus, the model performs up to its expectations as an easy tool to apply prior to importing CAD data to the NC code generator — a lengthy process. **Chapter 4** describes how to use this simple, accurate linear model to estimate part fabrication times.

3.8 Chapter Summary

A physical model was introduced and used to determine the time to lay several plies of various shapes. The model uses control theory equations to understand design tradeoffs early and is simpler and less costly to apply than using CAD/CAM software. Data was provided and analyzed for three lay-up orientations as well as the return cycle. Additionally, the primary design features (Curvature and tow cuts/adds) that effect the lay-up rate were honed and put into the model as complexity parameters, τ. This model was found to have lay-up rates below 3rd party estimates performed previously at CMI. The overall lay-up rate numbers were judged to be reasonable estimates when compared with HD division's average lay-up rate. The model also translated part features into lay-up time, although data was sparse. This model can be used to develop intuition about ATP by understanding when a ply will be delay or velocity dominated as well as understanding that curvature and tow restarts add to lay-up time.

Table 21 a summary of the model parameters for easy reference. A discussion of the level of accuracy of each parameter follows the table. These values are rough estimates, but values marked with a * can be used with a higher degree of confidence.

Parameter	0°	45°	90°
V_0 (ips) at 400 ipm setting	5.71*	4.186*	6.67
$\dot{n}$ (seconds / revolution)	—	—	60
$\tau_0 = \tau_E + \tau_D$	9.4 sec.*	10.4 sec.*	10 sec.
$\tau_c = b\Theta$	see below	see below	30 sec. and below
$\tau_{c/A}$ (sec./cut)	1*	1	1

Axes Activated	Orientation	b [sec / Radian]	Number of points used to find b
z, x, j	0-degree	1.3	1
z, y, k	0-degree	2.7	1
x, y, c, j	90-degree	5.82	3

Table 21: Summary of Parameters of the Cost Model

V_0 for 0- and 45-degree are supported with a substantial amount of data. The velocity for 90-degrees is a guess (≈400ipm / 60sec/minute): it is not supported by data. The angular velocity, $\dot{n}$, has very little data support, but it seems to be representative of the fairing and integrated skin data as well as it compares conservatively versus the CMI simulation. It should be used with care and little trust.

The values for τ_0 on the 0- and 45-degree orientations are well-supported with a substantial amount of data. The value for 90-degrees has been extrapolated from the data. Thus, it can be used with a moderate level of trust. This τ may be found to be lower in an experiment with a flat plate on the 90-degree. τ_c is the least trustworthy value in the table. The values of b are limited and very few data points support the predictions. This is definitely the next place to focus research. $\tau_{c/A}$ was determined with the 0-degree orientation and is assumed to be the same for a 45-degree and 90-degree orientation. Since this is a primitive task which is determined from a decent amount of data, it can be used with a moderate level of trust.

With the model and its accuracy established, an example will now be used to outline the process to use this linear model.

4. Guidelines for Using the Cost Model

This section presents a procedure to estimate the time to fabricate a part. The part is a cone with sandwiched honeycomb reinforcement. A sample process plan similar to the one in **section 1.3.2.1** is outlined for this part. The important steps in the process plan are identified using historical data from HD's ATP parts. Then the lay-up time is calculated and the results are compared to the HD average lay-up rate as well as the rate for the V-22 grip. Next the times for the other important process steps are estimated.

4.1 The Part

The part is the hypothetical cone geometry shown in **Figure 32.** The part could be a part for the forward fuselage of an aircraft. It may contain electronics, environmental systems or both. A ply list is shown in **Table 22.** Eight plies of 0-, 90- and 45-degree orientation will be laid. Four plies on each side of the core. There will also be 16 doubler and filler plies that picture-frame the core. There will be a recess for the core. This affects the 0- and 45- degree ply times for the inner skin (ply 1, 2, 4). Tow cut and add delays will be needed for the 0-degree plies on the part due to the increase in width from the front to the back of the part. Also, the operators typically override the speed and acceleration settings to 60% on the first ply and the ply after the core to improve material tack to the tool and core, respectively.

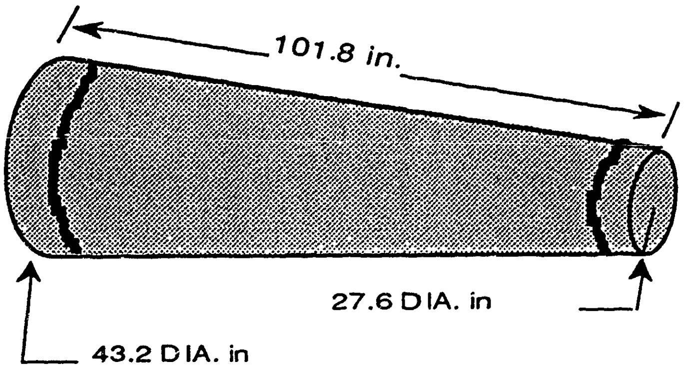


Figure 32: Hypothetical part geometry for part calculation example

Ply Number	Orientation	Comments
1	+45	V dominates, 60%, recess
2	0	Recess and Width Δ
3	90	Hoop ply
4	-45	Velocity dominates & Recess
5	-45	V dominates, 60% Override
6	90	Hoop ply
7	0	Width Δ delay
8	+45	Velocity dominates
16 others	0 degree	Edge Build-up Plies

Table 22: Ply list for the Nose Cone

The part would be fiber placed onto a male tool mounted to a spindle shaft. Some release agent or heat shrink would be applied to the tool for part removal. The tool would break-down for removal of the part and a caul plate may be used during cure for OML surface smoothness.

4.2 The Process Plan

The are 23 steps expected for the process plan of this part:

1. Clean Fiber Placement Bonding Jig
2. Assemble FPBJ
3. Prep the tool face
4. Stack and cut isolation plies
5. Load and align ATP mandrel / clean machine head / install material
6. Apply E-Glass isolation ply
7. Lay inner skin
8. Lay up adhesive film
9. Bag and Debulk
10. Fit the Core
11. Lay up Outer 1st ply (60% override for tack)
12. Bag and Debulk
13. Lay up other outer plies
14. Apply outer copper shielding ply
15. Install caul plate (for surface smoothness)
16. Vacuum bag and leak check
17. Transport to autoclave
18. Cure in autoclave
19. Disassemble FPBJ
20. Transport part to inspection
21. Non-destructive testing
22. Rework if necessary
23. Trim, package and ship to assembly

Now that the steps have been outlined, the steps which significantly affect the fabrication rate will be determined.

4.2.1 The Important Steps

The important steps in this process can be determined from historical data of labor breakdowns of ATP parts at HD. The steps are "important" because they dominate the time to fabricate the part. This section attempts to establish the "vital few" process steps which determine the cost of a part. Characterizing the vital few from the trivial many is also known as the 80/20 rule. **Figure 33** gives a typical example of a labor breakdown for a tow-placed part. The figure suggests that the integrated skin lay up follows this "80/20 rule" because 95% of the part cost is characterized by 11 steps. Pareto charts of labor hours of other ATP parts are given in **Appendix 13.**

The labor breakdown of this cone would be similar to the breakdown in **Figure 33.** There are some differences which can be identified from **Appendix 13**. The lay-up percent of fabrication time could be expected to be 30% for inner and outer plies. It is more than the integrated skin because of the lack of stringers, but less than the fairing because of tool assembly. Assembly and disassembly of the tool would be similar to the aft at about 20% combined. Tool preparation is the next step at 10%; vacuum bag and leak about 8%; and core placement would be next at 7%. **Figure 33** suggests that cutting copper shielding and isolation ply packs would also be 7%. Installing copper shielding and isolation plies would be 5%. Inspection would be the final 4% which sums to a total of 91% of the recurring part fabrication time. The times to accurately estimate labor hours are only needed for eight tasks. This makes the model very simple when compared to ACCEM which lists 63 steps for a J-stringer [25].

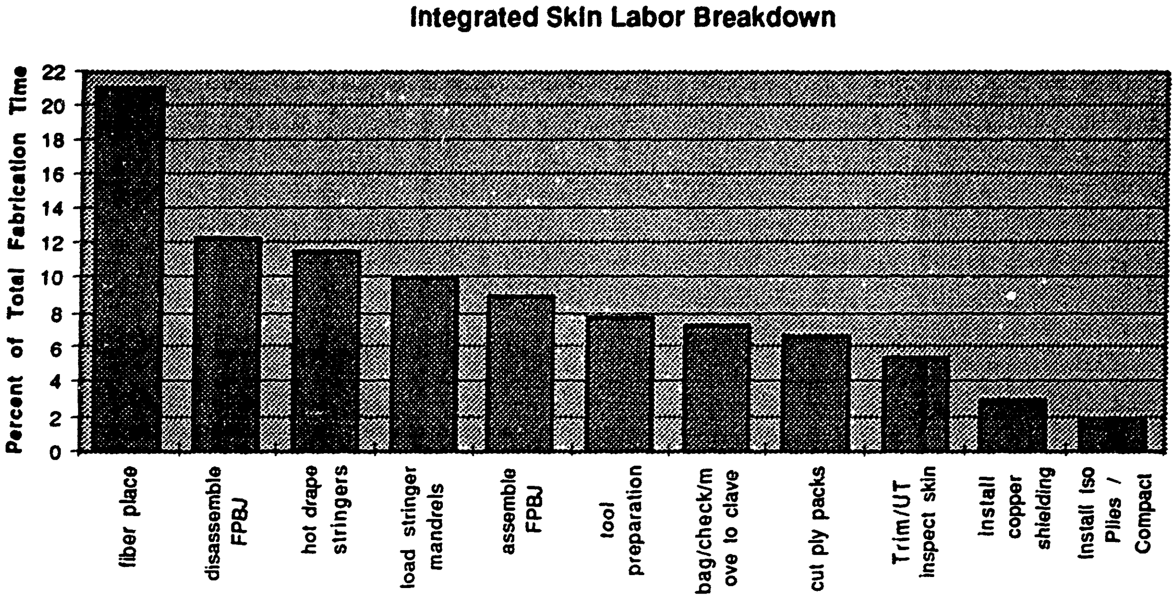


Figure 33: A labor breakdown identifies the important steps which dominate costs

4.3 *Estimating the time for lay-up*

As shown in **Figure 33** and **Appendix 13**, the time to tow place a part dominates the fabrication time for ATP parts. Thus, this step should be estimated with utmost accuracy. It will be estimated using the model from **Chapter 3**.

Since this calculation is an estimate for production, the velocity settings and other assumptions will reflect a production scenario. There are six major assumptions for this calculation:

- A lay-up setting of 400 ipm (V_0 values are extrapolated)
- A 24 tow machine with 1/8th in. wide tows (3 in. bandwidth)
- Downtime of 80%
- Tow thickness of .0055 in.
- Tow density of .058 lb./in^3
- The 1st ply & the ply after core installation will be at 60% override

The results of this calculation are shown in **Table 23**. The overall lay-up rate for the part is 1.75 lb./hr. This number compares favorably with HD's average lay-up rate of 0.72 lb./hr. because helicopter's average is weighed down by several smaller parts. It also compares very favorably with the lay-up rate for the V-22 grip which was 0.76 lb./hr. for an 48 inch long, 83 lb. part.

The time given in the table is the time to lay-up the part. If it is assumed that the tow placement machine has two operators, which is often the case, the contribution to the fabrication rate is 43.7 hours.

Ply Number	Orientation	Ply time(min)	Weight (lb.)	Comments
1	45	96.19	3.6	Velocity dominates, 60%, recess
2	0	78.66	3.6	Recess and width Δ
3	90	61.50	3.6	Hoop ply, no recess
4	-45	73.09	3.6	Velocity dominates & recess
5	-45	96.19	3.6	V dominates, 60% Override
6	90	61.50	3.6	Hoop ply
7	0	67.34	3.6	Width Δ delay
8	45	62.27	3.6	Velocity dominates
16 others	0 degree	44.66	0.6	Edge Build-up Ply

Totals	1311.26	38.14
Total Time (hours)	21.85	
Lay-up Rate (lb./hr)	1.75	

Table 23: Summary table of the ply times calculated for the Cone-Shaped Part

This calculation was performed on an excel spreadsheet in three hours. In fact, the calculation of the build-up plies was first performed on the subway to school. This model is simple to use, accurate and efficient. A person familiar with the linear equations and who has a feel for the delays on the machine will have no problem estimating part costs as well as comparing the effect of design features on manufacturing costs.

4.4 Estimating time for the remaining important steps

With the lay-up time calculated, the time for the remaining steps can be determined. These remaining steps are (in order of expected contribution to the overall costs):

- Assemble and disassemble the tool
- Place the core
- Prepare the tool
- Vacuum bag and leak check
- Cut and install copper shielding and isolation ply packs
- Inspection

The times for these steps will be approximated from experience on the production floor. Then these numbers will be compared to the expectations described in **Section 4.2.1**. Any discrepancies with the data will be addressed.

A male tool for this part would require some assembly and disassembly. Disassembly is for part removal and tool cleaning. Assembly would take approximately two employees 2 eight-hour shifts. Disassembly could occur in one shift for a total of 48 hours.

The core must be placed on adhesive tape on the part surface. One person could lay each of the two halves of the core in 1 shift. The total time for the core placement would then be 16 hours. This does not include any adjustments for variation. Since core placement is a manual operation, the time to place this core can vary substantially. This variation will not affect the 16-hour average, but it should be considered for planning purposes.

Tool preparation is cleaning and preparing the surface of the tool. Assuming there are three surfaces of the tool which need cleaning and preparation and each takes six hours, the total time is 18 hours.

Vacuum bag and leak check can be a challenging task because the part will be ruined if the bag leaks during the autoclave cycle. This process involves cutting the bag to shape, taping the layers which allow for release and vacuum to flow, installing the caul plate and folding and taping the outer bag. It will take several people one-half hour to install the caul plate. The rest could take two shifts with some overtime and an extra person for one shift. Thus, the time to vacuum bag this part would be about 30 hours.

Cutting ply packs is an automated process which requires some set-up time, but it is expected that each could be done in two hours. Copper shielding and isolation plies are hand lay-up which are labor intensive. Ply packs would be one man-hour each. The hand lay-up of the plies could be estimated at 3 hours each for a total of 6 man-hours.

Post-cure inspection would be performed with an automated ultrasound inspection machine. There could also be a 10 minute inspection after each ply. The ply inspection would be 4 hours and the post-cure would be 2 man-hours (assuming no rework).

Task	Estimated MH	% of total	Expected %
Assemble and disassemble the tool	48	28.0	20
Lay-Up Inner & Outer Skins	43.71	25.5	30
Vacuum bag and leak check	30	17.5	8
Tool Preparation	18	10.5	10
Core Installation	16	9.3	7
Hand-lay copper and isolation plies	6	3.5	5
Inspection	6	3.5	4
Cut copper shielding and isolation ply packs	4	2.3	7
Totals	171.7	100	91
Tasks not estimated (10%)	17.2		
Total Estimated Hours	188.9		
Part Weight (lb.)	38.14		
Fabrication Rate (lb./MH)	0.20		

Table 24: Result of Fabrication Rate Estimates

There are several discrepancies between estimated and expected values in **Table 24**. The tooling assembly and disassembly contributes more to the cost than the lay-up. This is acceptable for estimates because tooling assembly and disassembly for a complex tool can be substantial. Vacuum bag is higher than expected because the original expectation did not consider the installation of the caul plate. Cutting ply packs is somewhat lower than expected, but the difference is insignificant considering calculation accuracy. A user at a plant site could improve the accuracy of these numbers by reviewing historical data of similar parts and through interviewing knowledgeable employees.

The estimated fabrication rate of the part is about one-half that of the V-22 grip. This is reasonable because the grip does not have the substantial tooling assembly and disassembly that this part has with a lay-up/curing tool. It also agrees well with many of the parts which HD fabricates with tow placement.

4.5 Chapter Summary

In this chapter the physical model was used in conjunction with estimates from experience to estimate the fabrication time to lay a part simply. The process is as follows:

- Understand the part geometry, especially features that add complexity
- Determine the important tasks which significantly affect the cost
- Estimate the lay-up step using the linear cost model of **Chapter 3**
- Estimate the time for the remaining steps
- Check to make sure the result is reasonable

The rate which was determined would be a reasonable estimate with which to decide on the feasibility of the part. Additionally, if this were a real example, the result shows areas for improvement in design. The tool design could be changed to reduce assembly and disassembly costs. The speed setting on the full plies which are not subject to material tack problems could be increased to 800 ipm for a substantial gain. Improved fixtures for vacuum bag and leak check may expedite this task. The point is that this model can be a tool to determine feasibility, compare design tradeoffs and plan improvement.

5. Manufacturing with Automated Tow Placement

The manufacturing portion of this thesis addresses some important issues which overlap into design, but addresses other managerial issues more deeply: competitors and suppliers, planning, and process improvement.

The first section is an executive summary of the observations from the author's October benchmark study of automated tow placement technology. It is followed by a discussion which uses historical data to determine capacity — a good idea for machines with the repetition of a CNC machine. A description of fiber placement downtime and HD's efforts to identify and reduce downtime precedes the final subsection which looks at ways to improve the operation.

The data in this section shows that no company is the dominant competitor in ATP applications, instead it shows that many companies do a few things well and all have room for improvement. Data-driven capacity planning is used to make recommendations at the HD to reduce future capital equipment expenditures worth millions of dollars. Finally, a structured improvement process is introduced which helped Boeing employees improve their tow placement operation.

5.1 The Status of ATP

This section discusses the results of a seven-day study of the companies in **Table 1**. The reader should be aware that the author's biases are included in the conclusions. An attempt to remove these biases has been made, but no formal scrubbing and review procedure was followed. Detailed observations can be found in **Appendix 10**. Conclusions can be categorized into five groups:

- Manufacturing
- Design
- Management
- Capacity Planning
- Suppliers

Bell and Boeing lead production because they tow placed parts for the EMD phase of the V-22 Osprey. Boeing leads part design because they are already laying up several large, integrated structures. Northrop has very complete and innovative management programs. Boeing seems to have the most realistic capacity planning data. Finally, Cincinnati-Milacron leads other suppliers at production, software and lay-up efficiency for parts longer than about 100 in.

5.1.1 Manufacturing

5.1.1.1 Production

Bell and Boeing lead in production because they have been manufacturing parts for over a year during the EMD phase of the V-22 Osprey Program. Bell had manufactured 30 units of the V-22 grip in October. Boeing had fabricated at least 5 integrated skin sections, 20 fairings, 10 large skins and 10 angles by December of 1995. Bell and Boeing lead because they have identified and solved problems which only arise during manufacturing.

The other competitors are at a variety of stages. In December, Boeing Seattle was beginning to validate and verify their machine. McDonnell-Douglas had been validating their machine with test parts, but had not completed validation in October. Northrop completed their on-plant validation at the end of October.

5.1.1.2 Programming

I observed three stages of software development:

1. Initial
2. Debugging
3. Efficiency

Initial development is where the original code and user interface is developed. Debugging software allows consistent control of the machine with repetition of parts. Efficiency is when the developer observes production and learns to: (1) reduce machine movement and, (2) avoid isolated out-of-control situations observed during production.

I did not observe any aircraft manufacturer which had superior programming methods. All followed a similar procedure of importing a CAD file to the software's NC code generator. The software then developed code with a user-entered set of input parameters. None modified the code generator's output.

Cincinnati-Milacron leads the suppliers with well-designed NC code. CMI has finished debugging Acraplace (NC Generation and Simulator Software) and is presently working to improve the lay-up efficiency with advanced NC techniques. ADC's code is debugged, but it has not had the continuous improvement which CMI has been executing over the past year. Ingersoll does not seem to be past the debugging stages with their software.

5.1.2 Design

5.1.2.1 Part Selection & Producibility

Boeing leads because they have several co-cured structures designed for tow placement. Bell is close behind with the V-22 grip — a small, integrated structure. MDA and Northrop have parts for the F-18 which have been converted from hand lay-up to fiber placement. All competitors know tricks to improve a part's producibility. For example, Boeing, Northrop and MDA all showed me charts which suggest you should align cutouts with fiber orientation and stagger cutouts through plies to maintain minimum cut length.

Boeing's design efforts are exceptional. They have two large, co-cured fuselage skins and a large fairing co-cured with its core. The longest is 251 inches along the zero degree orientation [24]. Their efforts to integrate parts and design for tow placement for the large, integrated skin reduced the recurring costs to 49% of FSD: a hand-laid, non-integrated structure[24]. Finally, they employed the author to write a producibility guide which links design and manufacturing. I did not see similar efforts at other companies.

The V-22 grip is also impressive. Despite its small size, it has a lay-up rate that compares to Boeing's cabin side skins. Bell integrated 1200 details on FSD into a single part on EMD. Additionally, the grip is a body of revolution; my studies suggest this is a very efficient shape to fiber place. The result of these efforts and equipment tailoring (see section below) is that recurring costs of the EMD part are 25% of FSD costs.

The parts for the F-18 have been converted to fiber placement from hand-layup. Thus, they are not integrated, but they have been cleverly converted to achieve the results of designing for the process. Northrop had designed a side skin for the empennage section. They were in the process of converting the engine inlet ducts to fiber placement. Since the duct was to be manufactured in several parts, I believe they do not gain the efficiency of laying up a body of revolution. MDA plans to manufacture the horizontal stabilator for the F-18 E/F.

It is important to mention that F-18 parts were not integrated as a means to reduce risk, and not because the companies were incapable of doing so. Despite this, Bell and Boeing have learned more because they have experience co-curing and integrating parts.

5.1.2.2 Tooling

No company had a distinct advantage in tooling. The author prefers the carbon fiber or aluminum lay-up tools to Invar because they reduce the capital investment in tooling and equipment. Additionally, their reduced inertia allows the fabricator to buy a smaller machine which accelerates more quickly and lays shorter tows significantly faster.

Boeing was the only company to use Invar tooling. This is a neat, but expensive technology to have mastered. Boeing also used an aluminum lay-up tool for the fairings. I applaud this decision. It has a nice lay-up surface, does not face the stressful temperature changes of the autoclave, and it is light and inexpensive.

Bell had an interesting tooling arrangement for the V-22 grip. They installed an internal bladder into the center of the part and sandwiched the part between two steel tools. Then, the part was cured in a press with the bladder pressurized.

MDA used polymer lay-up tools and carbon fiber curing tools. The horizontal stabilator tool had sharp angles which cause severe tow bridging (if the machine could lay the tows). These angles were the result of a miscommunication between design and tooling. The sharp corners were in the process of being removed.

Northrop-Grumman had carbon fiber lay-up and curing tools. The technology for these tools looked very similar to hand-lay up tools. They were ready for operation.

5.1.3 Management

Northrop-Grumman has a unique systems perspective to management with several excellent programs:

- The "Paperless Factory"
- Mechanics inspect their own work
- Focus on the whole system

They were implementing three programs during the visit in October. They had seen exceptional results on all programs, but some were being re-implemented because workers had reverted to old procedures during schedule pressure of EMD of the F-18E/F.

The "Paperless Factory" is a client-server network which links together material in the factory to improve material flow while reducing the need for an I.E. staff to perform this function. Additionally, it communicates quality information to management and employees so they can build in quality while reducing the inspection staff. They redistributed the displaced inspection staff whenever possible, rather than laying people off. Second, mechanics were being trained to inspect their own work to link the problem with the source. They faced some resistance because floor workers feared they would be held accountable for their mistakes. Finally, managers considered the system: all portions of the factory, not just lay-up or assembly.

Bell stood out because they had a cost-conscious culture. Bell manufacturing technology employees had excellent data about the part cost and they were using it to improve.

Boeing had a formal continuous improvement process for the fiber placement machine which was quite effective. Engineers and operators followed a seven-step process to reactively improve production problems with fiber placement.

Although the author did not visit the Mesa facility, a MDA employee explained that Mesa effectively applies lean manufacturing principles to build helicopters. They learned the principles from auto assemblers and commercial aircraft assembly. They effectively outsourced by delegating responsibility to their suppliers. These changes were learned out of necessity to compete with Boeing and Airbus because MDA did not have economies of scale or government support. Their return on sales is twice that of Boeing's, and Wall Street seems to approve because their stock price increased substantially during 1995.

5.1.4 Capacity Planning

Boeing and Bell lead in capacity planning because they are able to use historical data to make realistic projections of present machine capacities. Much of the literature discusses ATP lay-up rates of 10 to 15 lb. per hour. The data in this thesis is a factor of ten lower. One lb./hr. is a high laydown rate for planning tool-in to tool-out times. For estimates in this document, the author assumed that the lay-up rate is the time from tool installation to removal, but it does not include these activities. Thus, a company using these numbers must have a second mandrel (C-axis) and good coordination of the machine with the parts.

Realistic estimates are needed for planning so limited resources are allocated reasonably. For example, Northrop expects to lay 10 lb../hr on 30 different parts for the F-18E/F. Although there is improvement from employee learning and procedure changes, my calculations suggest that achieving a rate of 3 lb./hr. before 1998 will be exceptional.

5.1.5 Suppliers

The Cincinnati-Milacron and the ADC machines have more production experience than Ingersoll. CMI has used their production experience to improve their product, especially software. I am unfamiliar with Ingersoll or ADC's improvement efforts. Ingersoll and ADC have a roll-pitch-roll head design. CMI has a yaw-pitch-roll head design. The roll-pitch-roll head has large part, long-term promise, but the yaw-pitch-roll is a proven design. Future studies should quantify the efficiency of each head type for various applications.

CMI is clearly the production leader with superior software and proven reliability. The CMI machine is the author's choice for parts in the 100-inch to 300-inch range (0-degree orientation) because of these features. Additionally, the pneumatic conformable roller allows the CMI machine to navigate more complex part geometries than other suppliers. CMI should consider modifying software to improve equipment tailoring, reducing the number of contact points in the fiber delivery system and modifying the head to allow for 180-degree rotation.

Ingersoll may be better suited for fabrication of extremely long parts like commercial aircraft fuselage structures and large military applications (possibly missiles or rockets) because the head can rotate instead of returning the full part length (There was an average of 15 seconds difference on a 165-inch long part between head rotation and unit return). The Ingersoll machine may eventually have more uptime because of reduced resin build-up due to a fiber delivery system design that has limited contact with the tows. Ingersoll's non-conformable roller severely limits part geometries.

For smaller parts (<100 inches), ADC is an excellent choice. It is easier to incorporate the equipment tailoring ideas on an ADC machine as well as it requires substantially less initial investment and floor space. Finally, it can achieve full rates faster than Ingersoll or CMI.

The discussion in this section assumes a purchaser would buy a single machine. There are network externalities associated with the purchase of the following machines. For example, having one brand of machine in a facility allows interchangeable operations, programming and maintenance personnel skills. Additionally, standard brands and machine sizes could reduce the spare parts inventory as well as maintenance tooling.

5.1.6 Summary Tables and Charts

There are three tables with explanations in this section. The first compares the software capabilities of each of the machines. The second compares the equipment capabilities. The last identifies several other dimensions of participant companies as well as a summary perception of their corporate cultures. Each table is followed by an explanation.

5.1.6.1 Software

Feature	Ingersoll	ADC / Maclean-Andersen	CM
Off-line Programming System Name	OPS	Autoplace	Acraplace
NC code generator	standard	standard	standard
Monitoring	yes	yes	optional
Finite Element Module	no	no	optional
Control Module	standard	standard	standard
Simulator with collision avoidance	standard	standard	standard

Table 25: Equipment Supplier Software Capabilities

Table 25 outlines the software capabilities of the three brands of machines. All modules had NC code generation, equipment monitoring and control, and a simulator with collision avoidance. Cincinnati-Milacron was the only manufacturer who had an finite element analysis interface capability.

5.1.6.2 Equipment Capabilities

Table 26 (next page) has accumulated information on manufacturers' fiber placement equipment capabilities. The following paragraphs are a description of the contents of the rows and why they are important. The fewer turns in a tow path, the less contact the tow will have with the delivery system. Less contact with a delivery system will reduce resin build-up and, hence, machine downtime. Tow wandering is tows which are displaced sideways at the beginning or the end of a course. Wandering is undesirable because tows overlap or cause gaps in the laminate. A 360 degree bi-directional head is beneficial because the machine does not have to go through the return cycle.

Roll-pitch-roll and the yaw-pitch-roll are distinct head designs and have a significant affect on the lay-up rate as well as on the areas over which a machine can access a concave part. The conformable compaction roller made a significant difference in the machine's ability to conform to various part surfaces. Variable tow thickness and width allows for improved lay-up rate. Individual tow cut and add is a nice feature as it is necessary for providing nearly complete coverage of plies on thin fuselage structures.

The operator position was an important feature for safety and convenience. Dual spindles allowed for increased lay-up rate. Refrigerated creels improved the out-time of the tows. The capability of the tow to lay slit tape or towpreg allowed the design team more flexibility with material choice. Large spools in the creel reduce the tension on the tow, thus reducing restart errors. The more axes, the more degrees of freedom and more complex parts can be fabricated, but there may be a tradeoff with lay-up rate. Tool location shows the method to locate the tool. This is important because it sets up the repeatability of part manufacture and it determines how difficult tool set-up will be. An automated hockey puck locator is quicker and more accurate than an operator "eyeballing" cross-hairs. The higher the acceleration, the faster the machine reaches the lay-up rate setting. Finally, the number of operators is inversely proportional to equipment productivity.

Feature	***MDA***	***Bell***	***BD&SG***	***Northrop***	***GE***	***BCAG***
tow path	6 turns	4 turns	7 turns	6 turns	6 turns	6 turns
tow wandering observed	yes	yes	no	no	no	yes
bi-directional head	yes, all directions	yes, all directions	only on 0 degree	only on 0 degree	only on 0 degree	yes, all directions
head type	roll-pitch-roll	roll-pitch-roll	yaw-pitch-roll	yaw-pitch-roll	yaw-pitch-roll	roll-pitch-roll
compaction roller	solid rubber	fluted rubber	rubber with pneumatic bladders	rubber with pneumatic bladders	rubber with pneumatic bladders	solid rubber
tow thickness variable*	yes	yes	limited	limited	limited	yes
tow width variable*	yes	yes	no	no	no	yes
tow cut & add	individual	full bandwidth	individual	individual	individual	individual
operator position	*ride on machine*	stand by machine	isolated control panel	panel or hand-held control	panel or hand-held control	ride on machine & hand control
spindle	single	single	single	dual	dual	single
refrigerated creel	yes	yes	yes	yes	yes	yes
tow capability	slit tape and towpreg	slit tape and towpreg	towpreg	slit tape and towpreg	slit tape and towpreg	slit tape and towpreg
>3" dia. spools	no	yes	no	yes	no	no
production experience	no	yes	yes	no	CMI's is limited	no
number of axes	7	6	7	7	7	7
tool location (coordinate reference)	hockey puck.	square chuck	cross hairs	cross hairs	cross hairs	hockey puck
acceleration rates	40 in/sec^2	30 in/sec^2	40 in/sec^2	40 in/sec^2	40 in/sec^2	40 in/sec^2
# of operators	2	1	2	1	1or 2	2

Table 26: Benchmark Equipment Status

5.1.6.3 Company Comparison

	BD&SG, Helicopters	*MDA*	*Bell Helicopters*	*Northrop*	*BCAG, Seattle*
ATP Supplier	CM	Ingersoll	ADC /Maclean-Andersen	CM	Ingersoll
shop type	union	union	non-union	non-union	union
culture highlight	technical focus, risk-takers	concerned with accuracy	cost conscious, persevering	system and work flow focus	tech. theorists, long-term focus
primary purchase reason	part production	R&D	part production	part production	R&D

Table 27: Comparison of Companies who use ATP

Table 27 outlines the participants' business. In general non-union shops can change more quickly. Culture — a shared set of beliefs which affect internal integration and external adaptation - affect a company's ability to compete. The primary reason for purchase is noted because the people who were focused on R&D purchased Ingersoll machines, primary producers did not.

This section summarized the status of tow placement technology with several aircraft manufacturers. One of the common short-comings of all manufacturers is that none seemed to have a realistic understanding of the capacity and the flow times of parts through their machines. The next section addresses the issue of capacity planning.

5.2 Capacity

The purpose of this section is to show the reader how to use historical data to understand present capacity. Present capacity planning is first discussed. Then, the purchase of a smaller, used tow placement machine is discussed for increasing capacity rather than purchasing new equipment. In the next section, statistical data is used to prioritize learning in the factory.

5.2.1 Present Lay-up Rate and Efficiency

While at Boeing, the author used historical data to understand the present capacity and to plan for future capacity. Although this seems trivial, it had not been done at Boeing or any of the other companies compared in the previous section. Additionally, there is not a lot of historical data for this technology since it is so new. For proprietary reasons numbers have been disguised. In this section the present capacity is discussed. Then, a measure of efficiency is established to understand how far the tow placement technology has to go to exploit its abilities as a technology.

Present capacity can be determined from a statistical average of historical lay-up times. We first assume that the time to lay all fiber-placed parts is 700 hours with a standard deviation of 150 hours. With a 50 work-week year, a five-day work week and three shifts, there are 5625 hours available on the machine. A 7-day operation with staggered lunches will have 8400 hours available. The results are shown in **Table 28.**

Available Time (Hours)	*Capacity (# of Sets)*	2σ	*Adjusted Time (Hours)*	*95% Sure Delivery (# of Sets)*
5625	8	106	5812	7.74
8400	12	86.6	8573	11.78

Table 28: Capacity calculations

The table shows the number of sets available per machine for two work configurations. Columns two and five emphasize the effect of uncertainty and variation: fewer aircraft sets can be delivered when uncertainty is introduced. The standard deviation in column 3 is 150 hours divided by the square root of the capacity (the population deviation). The adjusted time and delivery values are calculated from the following equations:

$$\text{Adjusted Time} = \text{Set Average (700 hours)} \times \text{Capacity} + 2\sigma$$

$$95\%\ \text{Sure Delivery} = \frac{\text{Available Time}}{\text{Adjusted Time}} \times \text{Capacity}$$

This method is a simple way to calculate the capacity of the fiber placement machine while accounting for uncertainty and variation. A key point is that the capacity of the machine is lower when variation is introduced. Additionally, if there is substantial variation, the 5-day a week schedule allows for flexibility to meet delivery with overtime. Of course, overtime is expensive. So is having capital equipment sit idle if it is a plant bottleneck.

An efficiency for a tow-placement machine can be defined knowing the average lay-up rate and the speed setting. HD efficiency is 3.4%. This is low compared to Flory and Bernardon's expectation (35%) and an ideal: no acceleration, no return and no downtime — just constant velocity. The ideal is not attainable — no machine can work without acceleration, deceleration or time between plies — but, it is a good incentive system to judge improvements. An average efficiency can be read from this table by looking at the 400 ipm setting and scanning across to a lay-down rate of .72 lb./hr.

bandwidth	2.75	inches
tow thickness	0.0055	inches
tow density	0.058	lb/cubic inch

Laydown Setting (ipm)	Laydown Rate (lb/hr.)		
	100%	35%	3.40%
100	5.26	1.84	0.18
200	10.53	3.68	0.36
300	15.79	5.53	0.54
400	21.05	7.37	0.72
500	26.32	9.21	0.89
600	31.58	11.05	1.07
700	36.84	12.90	1.25
800	42.11	14.74	1.43

Table 29: Lay-up rate efficiencies

Bernardon and Flory included acceleration effects which would reduce their lay-up rate below the ones shown for 35% in **Table 29**. The table shows us that there is substantial room for improvement toward the ideal: major gains in lay-up rate will come from improving the lay-up efficiency, just as Flory and Bernardon found [4]. **Table 30** shows that a one-inch bandwidth machine with a 10% efficiency can lay faster than the example above.

bandwidth	1	inches
tow thickness	0.0055	inches
tow density	0.058	lb/cubic inch

Laydown Setting (ipm)	Laydown Rate (lb/hr.)		
	100%	35%	10.00%
100	1.91	0.67	0.19
200	3.83	1.34	0.38
300	5.74	2.01	0.57
400	7.66	2.68	0.77
500	9.57	3.35	0.96
600	11.48	4.02	1.15
700	13.40	4.69	1.34
800	15.31	5.36	1.53

Table 30: Efficiency gains are key to improved lay-up rates

In conclusion this section has shown a method to calculate capacity as well as introduced an efficiency measure which shows how tow placement technology can be substantially improved by reducing downtime.

5.2.2 The Purchase of a Used Machine

Fiber placement capacity data showed that Boeing's planned equipment additions would not meet expected production levels. The next two sections discuss the results of a search for inexpensive capacity additions: purchasing used equipment and improving existing capacity.

The first step to increase capacity was to look at low-cost capacity acquisition. General Electric has a twelve-tow CMI Viper which is presently for sale. **Table 31** shows the main features of this machine which are compared to a new automated tow placement machine. The net present value (12%, 2 years) of purchasing a GE machine now versus a new machine 24 months in the future is $500,000. Since GE would benefit from selling this machine at any price, Boeing may be able to pay substantially less than $2.5 million. Additionally, the machine will probably be for sale two years into the future for a net savings of $1.25 million. Finally, the smaller machine can be tailored to lay smaller parts more efficiently.

There are two elements to this machine purchase: (1) technical constraints and (2) Boeing culture constraints. Technically, the skins manufactured at Boeing exceed the GE Viper's tool weight limit. Thus, the GE machine can only lay the angles and the fairings. The used machine lay-up rate should at least equal the rate of the existing machine for three reasons:

1. The GE machine can accelerate faster,
2. The machine can be tailored to smaller parts,
3. The present machine lays 12 tows with the angles.
4. The workers may learn faster with dedicated parts

The GE Viper has increased acceleration on short courses because the mandrel and the machine inertias are smaller than the larger machine. These smaller inertias could offset the reduction of the smaller width compaction roller. Of course, Boeing could buy a new machine with a 24 tow head, but with a mandrel weight limit to increase the accelerations for short courses. The machine should be tailored to fabricate parts with short courses by sacrificing accuracy to increase cut speed. The smaller compaction roller on the GE machine could reduce drag angle downtime because the majority of downtime is caused by manual tow fill due to roller non-compliance over tight radii. Third, the present machine only lays 12-tows at a time on the angle, so the smaller bandwidth GE machine will be able to match it. Finally, technicians and managers may advance down the learning curve more quickly when they see more of the same type of parts.

General Electric "Viper"	**CMI "Viper" Purchased New**
12-tow head	24-tow head
4' stroke	5' stroke
28.5' spindle bed	same, variable for additional cost
Dual 7' Diameter Spindles, 11 feet each	Dual 12' diameter Spindles
20,000 pound tool capacity	variable
$2.5 million asking price	$3.75 million
Flexible price due because GE committed	Low flexibility on price
Available Now	18-month lead time

Table 31: Comparison of the GE and a New CMI fiber placement machine

There are two aspects of this equipment purchase that are interesting to highlight: one technical and the other cultural. There is one strong technical negative: the reliability of the used machine must be evaluated in depth. Boeing (or anyone else) should seriously evaluate this risk prior to purchasing a used machine.

Culturally, members of Boeing had very different responses to purchasing used equipment. This was a very new idea which many people had not considered. Some people were excited, others seemed cautious, but interested and others openly rejected the idea. The most important lesson to learn is that introducing new ideas is not only a technical decision, but also a social decision.

The section shows that there could be a substantial savings by introducing used equipment intelligently rather than purchasing only new equipment. This could be an excellent way to reduce costs in the changing defense business environment.

5.3 *Identifying and Reducing Downtime*

This section discusses the application of a continuous improvement team to reduce downtime at HD. Tow placement problems are introduced first, and then the events and results of the team are discussed.

Tow placement is an advanced manufacturing system with robotics, feedback control and computer numerical control software systems. It is a complex merging of technologies into a machine system. The system is represented in the block diagram in **Figure 34** shown with the process and the product. The block titled *Process* is the interface between the machine and the part. This figure is a nice framework to begin addressing machine downtime. This section will show that most of the problems occur at the material/machine interface.

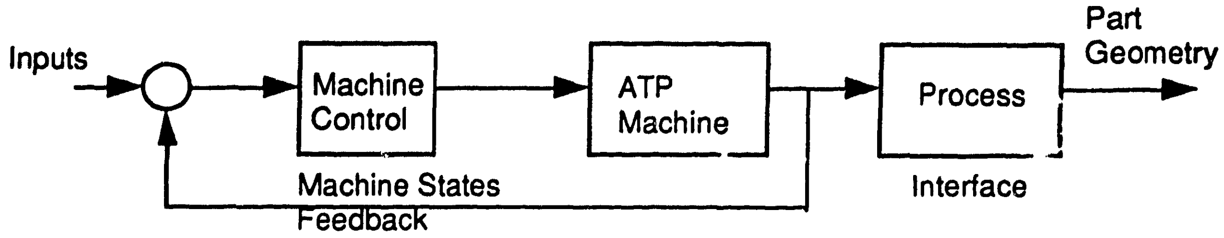


Figure 34: A Block Diagram of ATP Lamination

5.3.1 Problems which occur on Tow-Placed Parts

This section lists some of the problems which occur on a part and the next describes problems with the interface. Boeing inspected plies for several items during the fiber placement laydown [8] as are shown in **Table 32**. The parts at HD consistently passed inspection for these criteria. Thus, the process is robust to part geometry. The challenge is to lay those high-quality parts rapidly.

Wrinkled Tows	Tows that have been folded over onto itself in the fiber direction. This causes the fibers to be kinked.
Folded Tows	One that folds onto itself reducing the width.
Twisted Tows	A tow has rotated 180° on the fiber axis causing a gap.
Puckers	A raised portion of a tow which results in wrinkled tows when compacted between plies or by the next ply covering.
Bridged Tows	A tow that does not stick to the tool or part beneath it because of the part contour.
Gaps	Any spaces between tows which are not specified by design.
Fuzz balls	Loose or frayed fibers which have formed into a ball and are entwined with a tow or on the part surface.

Table 32: Problems which inspection looks for on HD parts

5.3.2 The Continuous Improvement Team

After spending a month in Philadelphia, the author suggested that they start a continuous improvement team so employees could develop tacit knowledge and continuous improvement skills to reduce the downtime experienced with fiber placement. Boeing managers agreed to the idea and a cross-functional group of employees volunteered to be members of the team. Thus, they set up their first meeting to learn a seven-step process to reactive problem solving.

5.3.2.1 The Seven-Step Process

The seven-step process which this team followed is [36, p. 74]:

1. Select Theme
2. Collect and Analyze Data
3. Analyze Causes
4. Plan and Implement Solution
5. Evaluate Effects
6. Standardize Solution
7. Reflect on process and next problem

Once reducing downtime was verified as the theme by team members, the team collected information on 21 sources of downtime. These sources are shown in **Table 34** and the whole form is included as **Appendix 10.**

CCR/Chute	Creel/Compactor	Mat'l/maint/cleaning	Other Operations	Miscellaneous
1) Tow Jammed in chute	5) Tow pull out	9) Material spool change	13) Hand lay-up plies	18) Lunch/shift change
2) Tow jammed in cut anvil	6) Broken tow	10) Machine Maintenance	14) Core installation	19) Programming errors
3) Stuck cutter	7) Compactor wrap	11) Clean delivery system	15) Vacuum bag/ compaction	20) Other
4) Tow burn through	8) Stringer	12) Manual tow fill (gaps)	16) Inspection	21) Non-working hours
	8a) Stringer on Part		17) Tool change-out	

Table 33: Sources of Downtime for V-22 EMD Fiber Placement

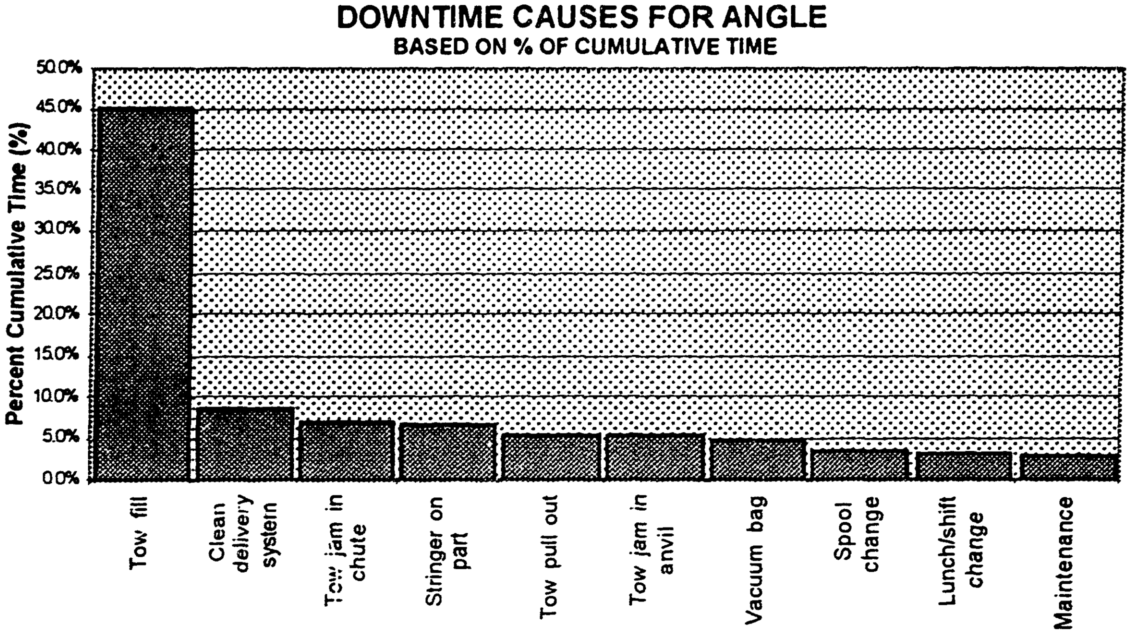


Figure 35: Pareto Chart of Causes vs. Time

The sources in **Table 33** were tabulated for two parts: an angle and a large, integrated skin structure. Downtime was 44.6% of the total lay-up time for the skin and 43.8% for the angle.

The sources of downtime for the angle are shown in **Figures 35 and 36.** Figures for the integrated skin are shown in **Appendix 10.** Although tow pull-out, tow fill and tow jam in chute occurred with similar frequency, the manual tow fill operation dominated the downtime. Eliminating manual tow fill from the angle lay-up would reduce lay-up time by 20%. This would have the effect of increasing the lay-up rate by 25%.

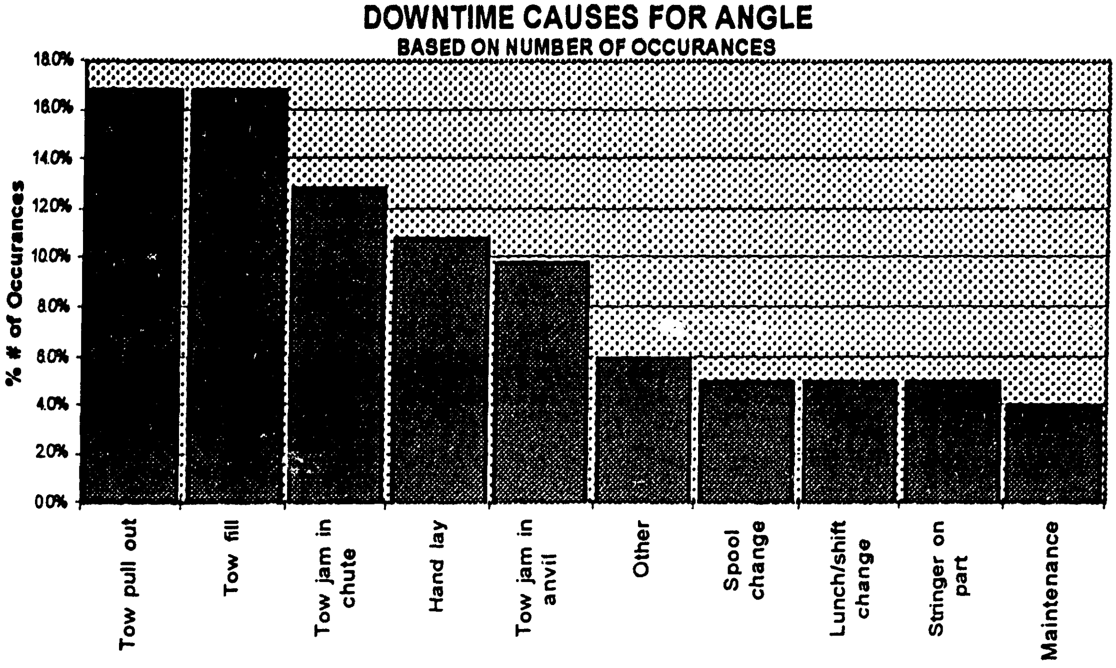


Figure 36: Pareto Chart of Causes vs. Frequency

5.3.2.2 Downtime Recommendations

The process improvement team used the figures above to plan solutions to reduce downtime. The "plan and implement solution" stage of the seven step process was the last stage the process improvement team executed while the author was in Philadelphia. This stage was not completed in December, 1995. **Table 34** outlines the recommendations the team made and their estimated effects. The discussion related to this table is below.

Recommendation	% of downtime for part	% of total time for part	set gain per machine
Design			
Large, Integrated Structure	22	10%	0.30
Angles	45	20%	0.45
Redirect Rollers (All parts)	7		0.45
Smaller bandwidth roller (A)	25	11%	0.25
Reduce Stringers (All Parts)	8		0.52
Total			**1.96**

Table 34: Downtime Recommendations

Integrated Skin Recommendations

The integrated skin has gentle double curvature on the forward edges of the part. The team is presently investigating three alternatives to reduce the manual tow fill in this area: remove the double curvature, add excess length to the part (which would be trimmed) to reduce the steepness of the area change, or decide not to fill the gaps. The first two options would require an expensive tool change. All require a review with the IPT.

Angle Recommendations

The manual tow fill on the angle is caused by the roller non-conformance on the 3/8th inch radius corner which is in the center of the length of the part. There are several ways the team thought they could reduce this problem. First, this radius could be increased with a design change. This is unlikely because it requires the change of an expensive, long-lead time invar tool. Instead, a smaller bandwidth roller is more feasible and could improve roller conformance to the tight radius which should eliminate most of the tow fill on the 0 and 45 degree plies. Segmented rollers were not an option because Boeing has had tow control difficulties with them.

The team thought they could also fix several quick items. A second set of redirect rollers has been purchased. This reduces the fiber delivery cleaning time because rollers can be cleaned off-line. Savings are estimated to be 70% of all cleaning time. Boeing is also working with the material supplier to reduce spool stringers — frayed tows which tangle during despool and cause the tow to break. If all downtime recommendations work 100%, the machine capacity could be increased by 2 sets. Realistically, 75% of these solutions may work for a 1.5 shipset gain. There is a net present value (12%, 4 years) of over $3 million for Boeing to eliminate the need for the additional purchase of 1 machine.

5.4 Improving the Operation

Since there is a substantial opportunity to reduce costs, it is worthwhile to look further to improve production on the BD&SG, HD, Viper. The author assembled a few ideas here, including the downtime reductions discussed above.

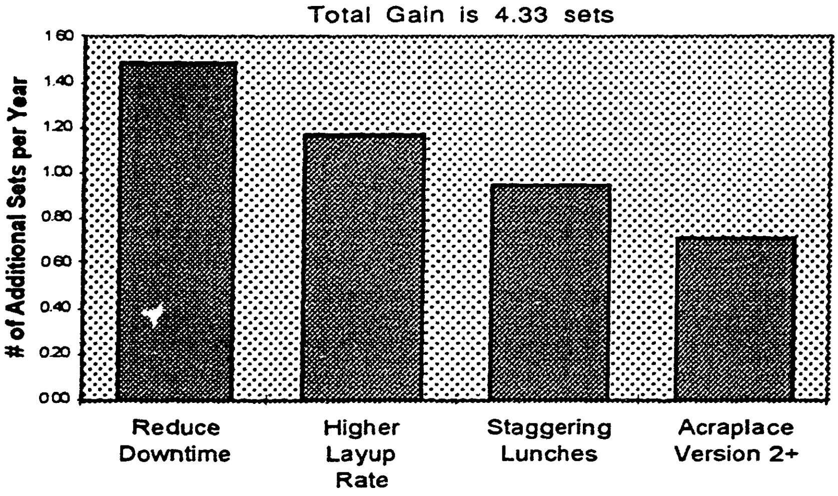


Figure 37: Increasing Production Rates

Figure 37 describes four ways to increase throughput. The gains are determined from the 0.72 lb./hr. rate calculated for all parts on the machine. The "higher lay-up rate" column is an expected improvement if the machine lay-up setting is changed from 400 to 800 ipm. It uses the chart in **Appendix 3** and assumes an average course length of 25 inches (a conservative estimate). Staggering lunches is the gain of 1.5 hours on the machine per day in a 3-shift, 360 day operation. Finally, the gains from Acraplace are one-half of the lower of the range estimated by CMI's programmer [34]. All that is needed to achieve the gains on Acraplace is to take the original CAD files processed on NC code software Acraplace 1.0 and re-process them on version 2.0.

5.5 Chapter Summary

This chapter began by outlining the status of tow placement technology. Capacity calculations showed that it is useful to use historical data to plan capacity and that variation has an effect of reducing capacity. Capacity calculations also showed the need to improve the rate to reduce future capital expenditures. Next, an improvement team found ways to improve the lay-up rate substantially. Finally, other simple ideas to improve the lay-up rate even further were discussed. There are several lessons to take from this section:

- The ATP lay-up rates in the literature are not useful for capacity planning
- Learning curves should be planned

These lessons could improve the operation of tow placement equipment in a factory. They could also be generalized for other technologies: (1) a machine's capacity must be well understood to plan production and (2) encouraging learning is one of management's most critical tasks.

6. Summary and Conclusions

This section summarizes the main points in this thesis as well as introduces items for study. This thesis is written primarily to meet the need for a tow placement knowledge base which can be used to make decisions. Data and a model were introduced which quantify the link between manufacturing and design. The status of tow placement technology was compared for six companies.. Finally, a discussion on capacity exposed the importance of finding and using accurate information from the plant to understand present capacity as well as plan improvements.

The introduction section outlined the need for tow-placement data and was linked to the helicopter industry, composites processing and composites design. The industry was seen to be undergoing dynamic change due to reductions in defense spending. This is forcing a consolidation among defense suppliers and driving changes in the organization, management, technology and people. Technology change caused Boeing to introduce Automated Tow Placement to reduce the labor cost in lay-up as well as assembly (with integrated parts). The basics of the tow placement system were introduced: the material/machine interface (minimum cut length, fiber delivery system and downtime), controls (machine axes and steering), and software (controls and CAD/CAM interface). Finally, advanced composites aircraft structure design was introduced along with the tow-placed parts at HD.

The design section introduced six reasons to fiber place a part:

- Reduced Scrap
- Improved Lay-up rate
- Part Size and Complexity Capability
- Improved Accuracy and Repeatability
- Material Cost
- Business Strategy

The primary advantage appears to be making large, complex parts with a consistent-quality CNC machine. Improved strategy and scrap reduction are also high on benchmark manager's lists of advantages. Presently, lay-up rates are not substantially above other processes (hand, filament winding or tape-laying). Finally, material costs do not seem to be substantially reduced with ATP beyond the savings from scrap.

In **Chapter 2** a detailed discussion of a concurrent design process was demonstrated with data from literature, a case study of the V-22 grip and a designed simulation using CMI's Acraplace NC code generator. The process had three steps:

1. Select the part for the process
2. Tailor the equipment to the part
3. Design for the process

Skins, fairings and surfaces of revolution were found to be efficient shapes to tow place. Then, a process to integrate a part was suggested which calls for understanding the function prior to designing the form. Equipment tailoring introduced ideas to match a small part with a small, tailored tow placement machine rather than settling on only large parts or inefficient manufacturing of small parts. The "Design for the Process" section introduced the primary factors affecting the lay-up rate: (1) material, (2) orientation, (3) course length, (4) curvature and (5) tow cuts and restarts.

Chapter 3 introduced a physical model whose coefficients have a physical interpretation. It was found to be a simple tool to predict lay-up times prior to importing the CAD file into the NC code generator. The model was found to characterize the part size and complexity by combining engineering knowledge and statistics. Parameters for three orientations were determined from actual plant data. The model was compared with results from CMI's Acraplace simulator. It was generally found to have good agreement, but the data was insufficient to characterize hoop plies. Additionally, it seemed to understate the lay-up time of parts with many courses.

Chapter 4 showed that the model can be used to estimate the most time-intensive step of the fabrication process. The lay-up rate compared favorably with rates at HD and Bell at 1.75 lb./hr. The fabrication rate for a honeycomb-core reinforced cone structure was estimated to be 0.2 lb./hr. Although this fabrication rate estimate seems conservative, it is reasonable. Additionally, the estimate could be improved through predicting other important tasks more accurately. Finally, this process and this model are simple to use and can provide an accurate cost estimate of a part in one or two working days.

The manufacturing chapter outlined the status of tow placement technology. Bell and Boeing were production leaders because they have the most experience producing parts for the V-22 program. Boeing leads part design because they have successfully designed and manufactured three large, integrated ATP parts. Northrop-Grumman had a systems view to integrate tow placement into its composites fabrication plant. Finally, CMI seems to lead other suppliers because of its advanced software, production experience, and on-going improvement.

The average lay-up rate at HD was found to be 0.72 lb./hr., well below typical estimates shown in the literature. This information can be used to determine the present capacity for the tow placement machine as well as to plan an educated learning path to march tow placement into the future. The plan is a simple one: reduce downtime, increase the lay-up rate setting, stagger operator lunches and recompile NC code for Boeing's Viper. The improvements as well as a suggestion to use a used tow-placement machine could reduce BD&SG's future capital expenditures by over $3.5 million.

Downtime was found by a process improvement team to be 44% of the total time averaged across two very different parts: the angle and the integrated skin. Both were found to have a significant amount of manual tow placement due to a mismatch between the part shape and the machines capabilities. The team worked under a Total Quality Management Seven-Step Process to identify this downtime.

The process improvement team reinforced a key learning: change is difficult. Technological change often affects peoples lives. BD&SG, HD employees are presently developing a mindset to consider used equipment and to improve. The process improvement team made excellent progress during the internship and they have continued to induce change at HD since that time. This team showed that change is not only difficult, but also possible.

The complexity of the aerospace industry amplifies the difficulty of change. Since delays are long due to low production volumes, it is difficult to connect a change with its results.

Aerospace managers are learning to simplify the path toward reducing costs in a new, competitive environment as was done in **Chapter 5** by using data to improve operations and reduce downtime. A key learning is that a manager must respond to changes in the external environment (i.e., the DoD's cost focus) while being aware of competitors (by benchmarking inside and outside the corporation) and reducing waste internally.

In conclusion a variety of methods were considered to improve the understanding of the link between design and manufacturing. A final lesson is that a manager should use data to help the business improve, but improvement can only happen when the employees at all levels and within all functions become involved.

6.1 Future

This thesis identified three major areas for future studies: design, cost modeling and equipment improvement.

The design section discussed the integration of a part without establishing the ideal part size. Several additional pieces of information were needed to help determine this size:

1. The cost of a splice (or the total cost of a fastener)
2. The increase in tooling assembly and disassembly hours
3. An understanding of complexity and part size's effect on fabrication rates
4. Material out-time considerations

The most important of these is the total cost of a fastener. Fastener cost would allow the reduction of assembly hours to be compared with the increases in fabrication time which occur from co-curing and part integration. The integrated skin had 10% of all recurring costs in tow placement and an equal amount in tooling assembly/disassembly.

The physical model is still unfinished in an industrial tow placement application because further data is needed to characterize several of the parameters. A follow-up to this study should attempt to create robust complexity parameters using substantial experimental data with a variety of part shapes and, possibly, across machines. Specifically, data is needed for the hoop ply on the 90-degree orientation as well as for the curvature relation, equation (6).

Finally, all companies who participate in production with tow-placed parts should work to improve the lay-up rate by reducing the significant downtime observed with fiber placement. This complex technology has potential far beyond today's capabilities.

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19. Ein Teck Neoh, Greg Dillon, and T.G. Gutowski, Complexity Scaling Laws for Composites Fabrication Cost, Working Paper, Department of Mechanical Engineering MIT, March 1994.

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28. Data provided by one of the Benchmark participants anonymously.

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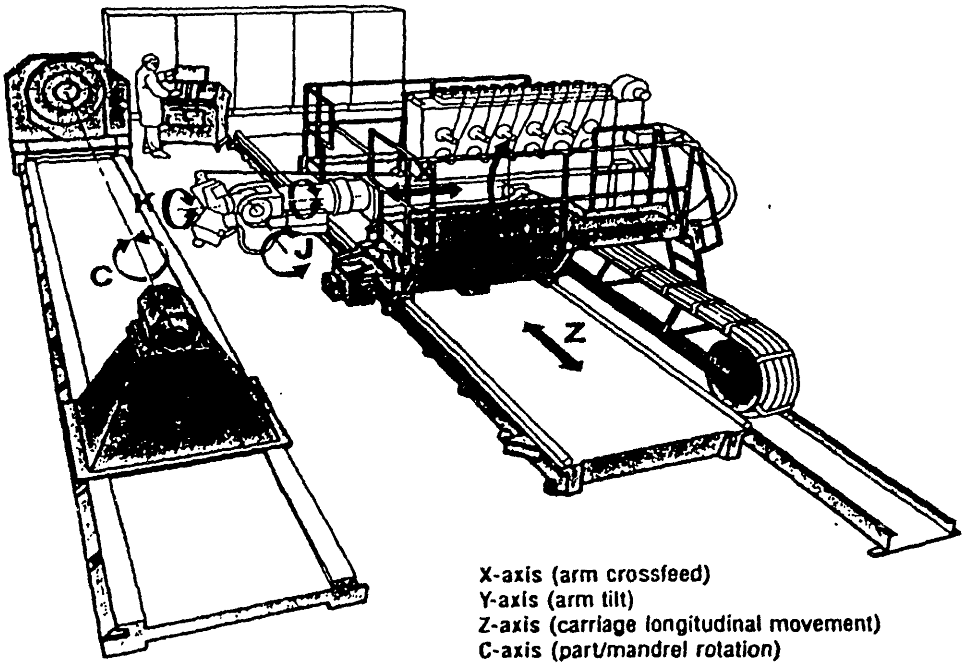
Appendix #1: CMI Machine Axes



X-axis (arm crossfeed)
Y-axis (arm tilt)
Z-axis (carriage longitudinal movement)
C-axis (part/mandrel rotation)
I-axis (head yaw)
J-axis (head pitch)
K-axis (head roll)
A-axis (redirect roller angular position)
Q-axis (tow restart linear position)

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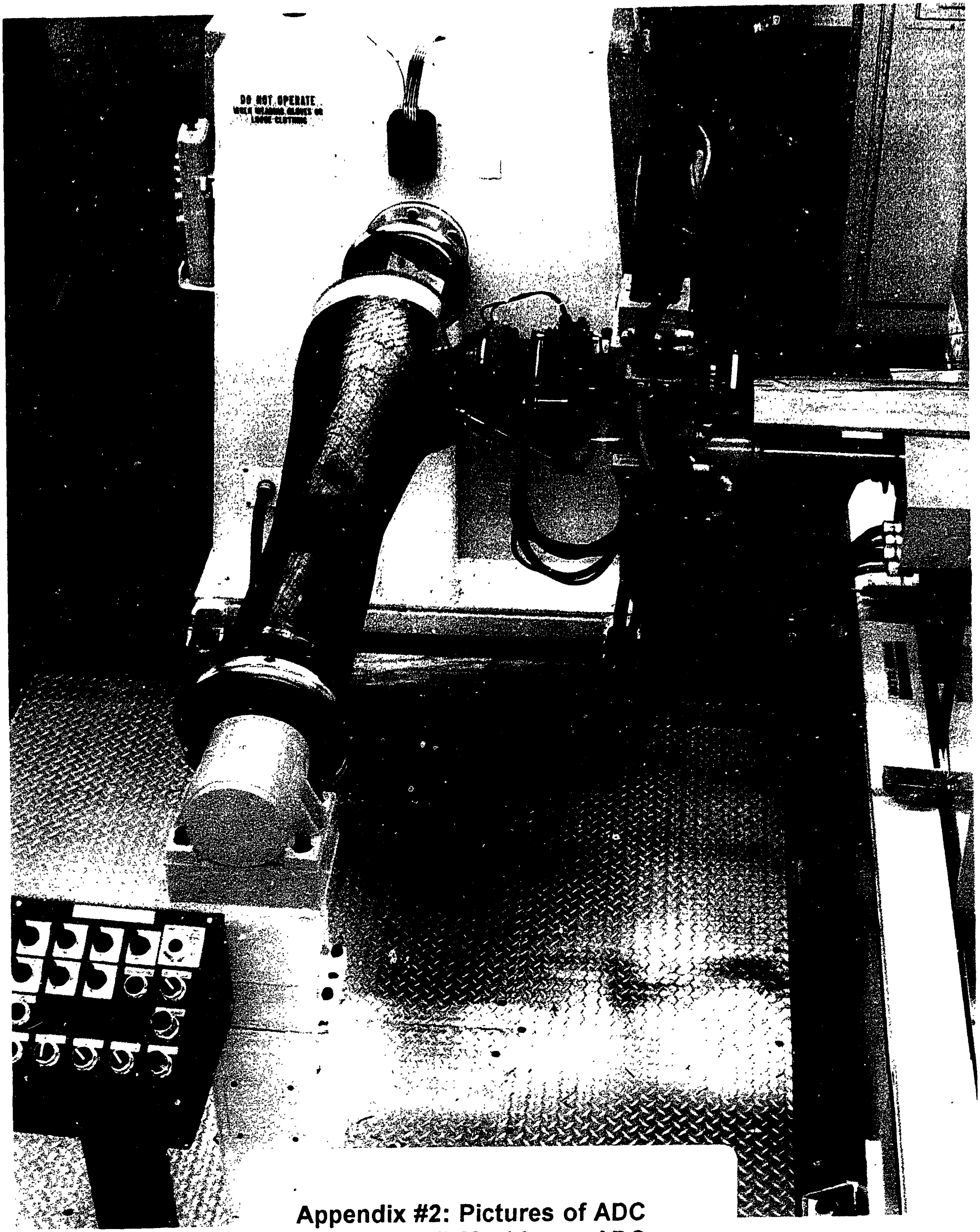
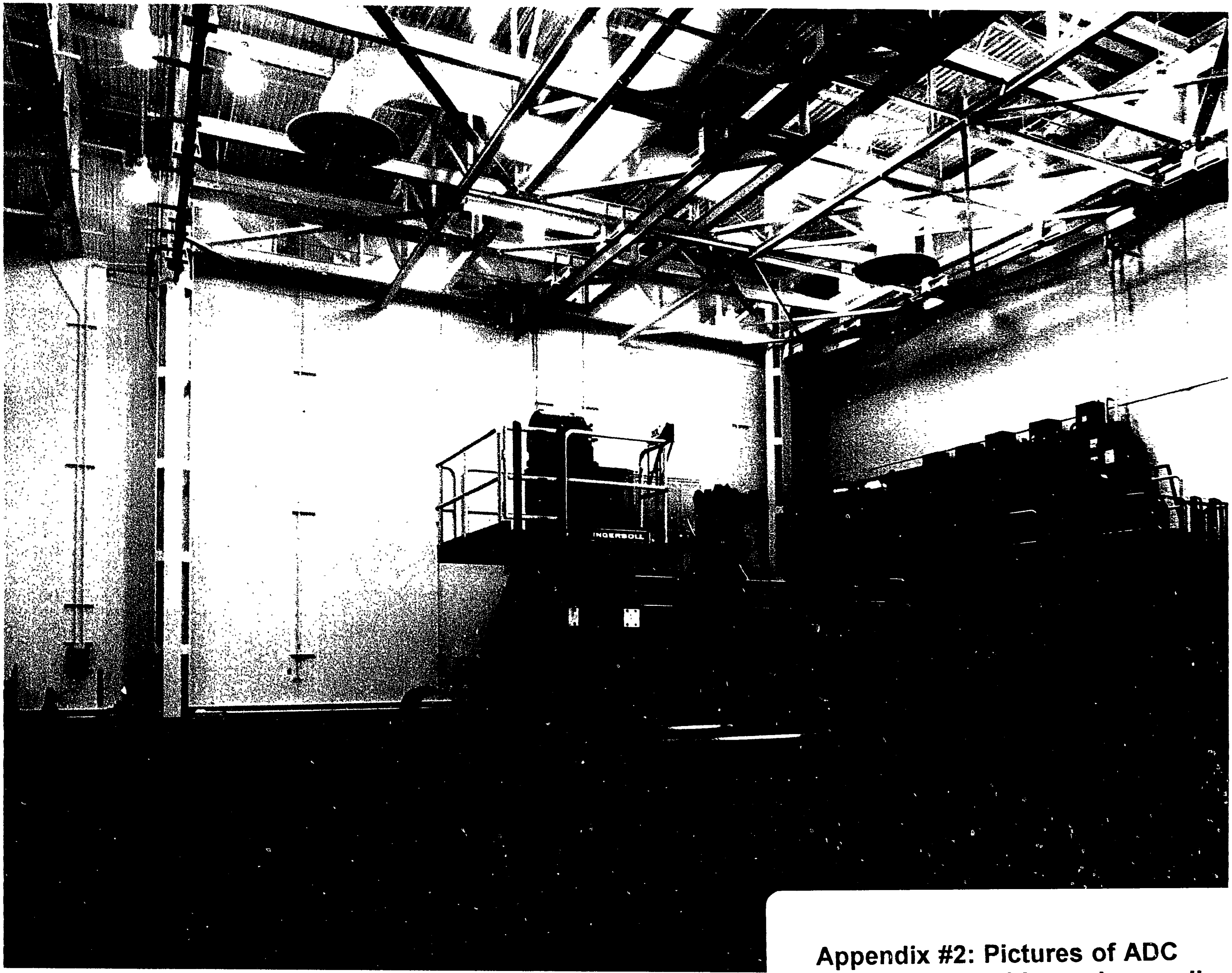


Appendix #2: Pictures of ADC and Ingersoll Machines - ADC



Appendix #2: Pictures of ADC
& Ingersoll Machines - Ingersoll

Appendix #3: CMI Chart for lay-up speed and course length

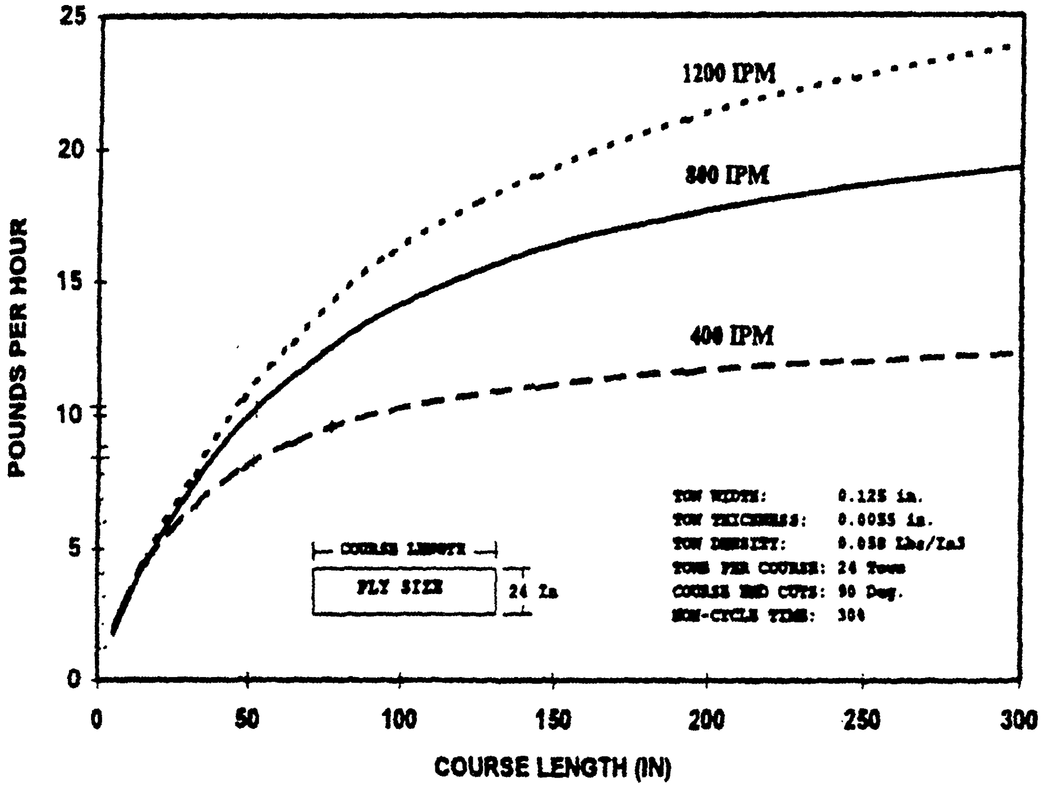


Figure 20 Programmed Lay-Down Rates

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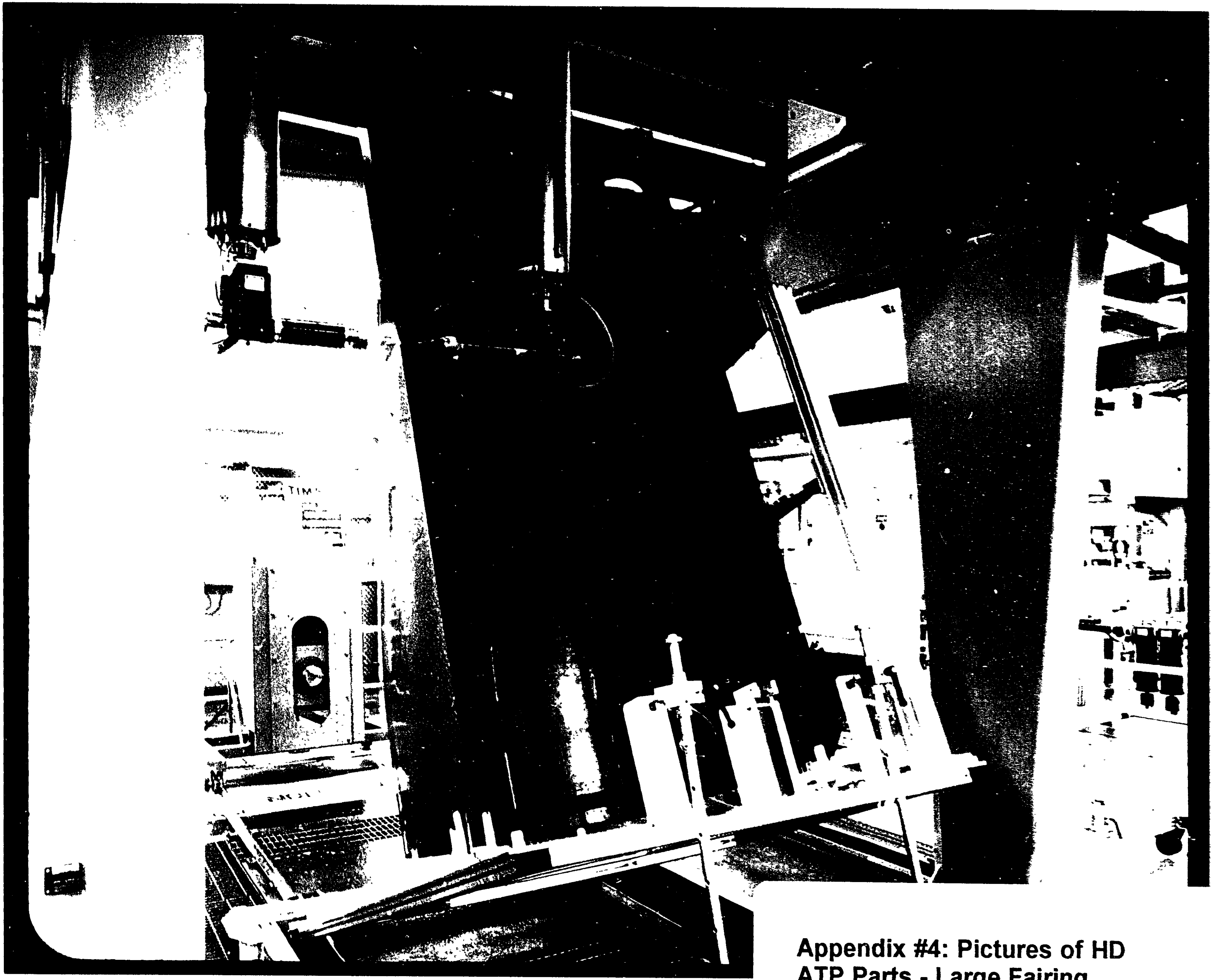
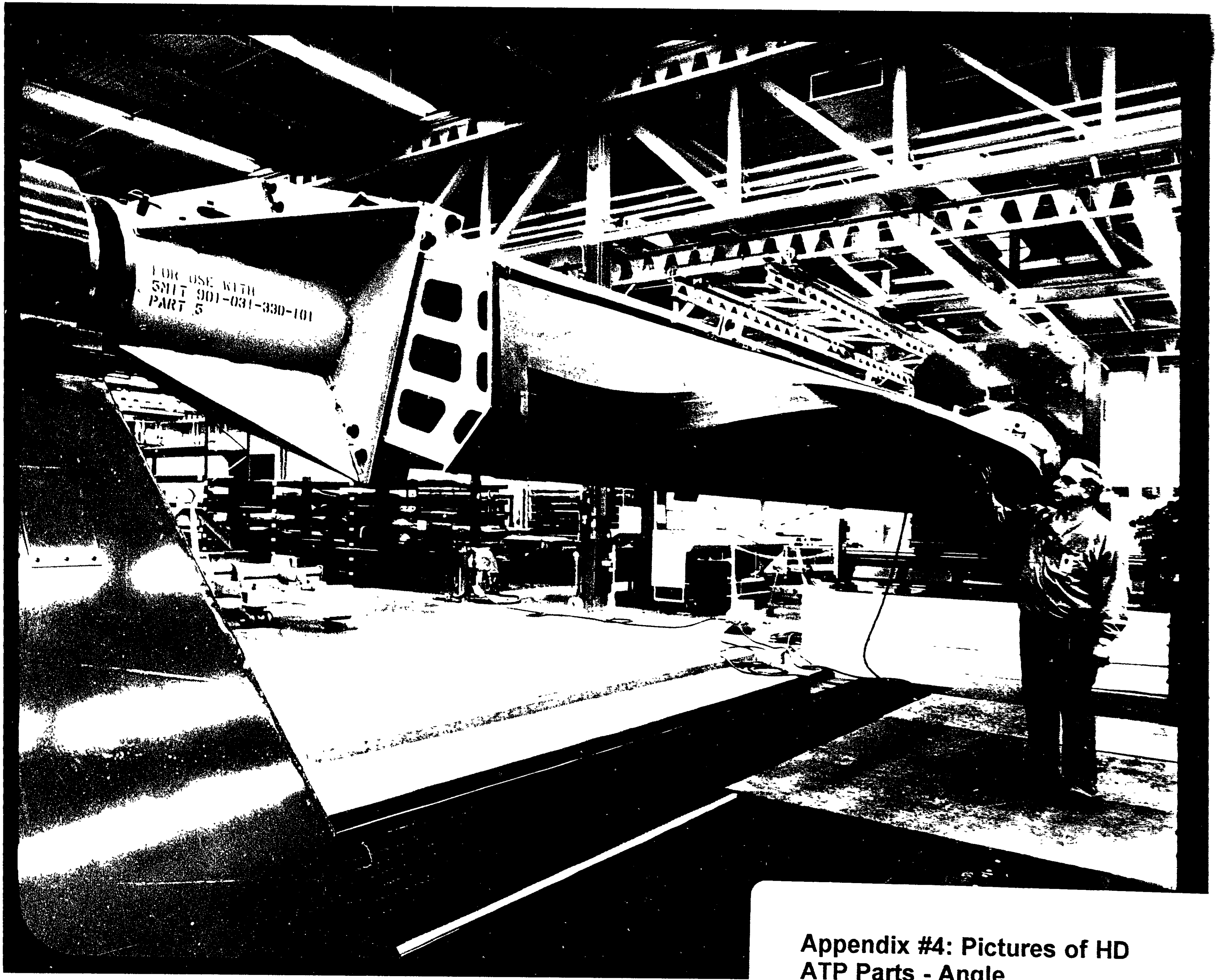
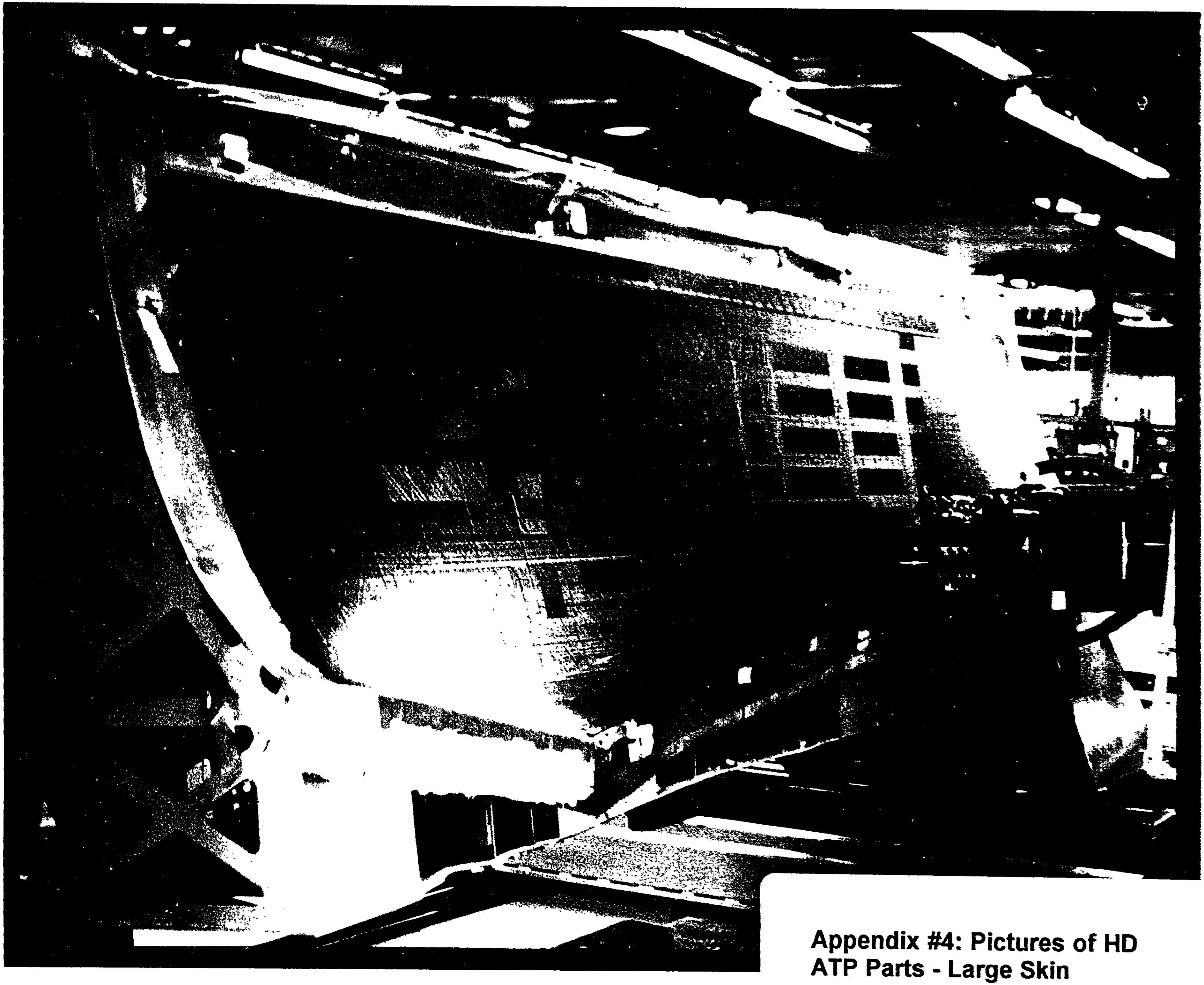


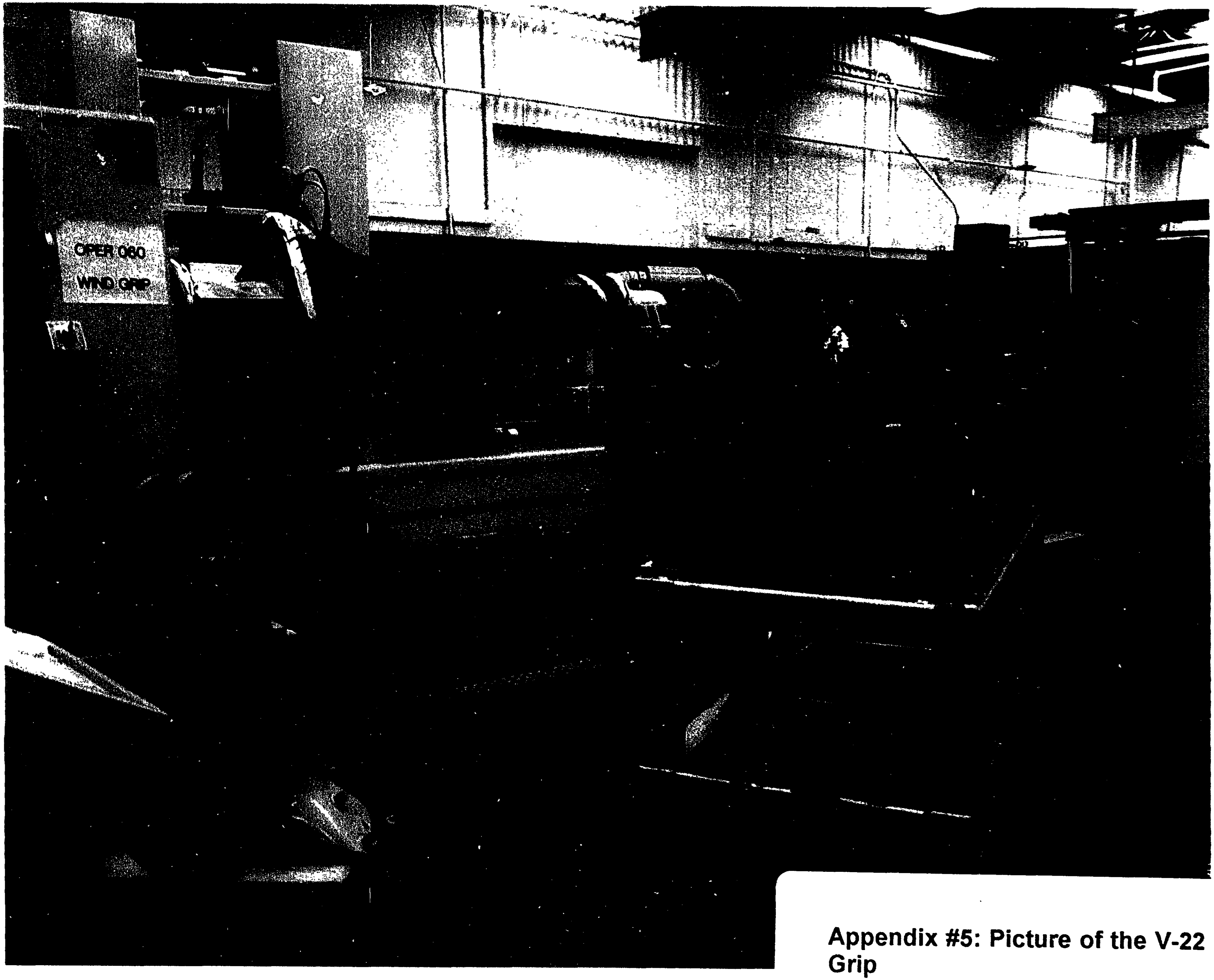
Appendix #4: Pictures of HD ATP Parts - Large Fairing



Appendix #4: Pictures of HD
ATP Parts - Angle



Appendix #4: Pictures of HD ATP Parts - Large Skin



Appendix #5: Picture of the V-22 Grip

Appendix #6: CMI Axes Capabilities

Cross-feed (X-axis)

max. speed	1800 ipm
acceleration	30 in/sec^2
Repeatability	.002 in
Accuracy	+/- .002 in/ft (software compensated, +/-.005 in overall) +/-.005 in/ft (uncompensated, +/-.015 in overall)
Travel	*48 in (Stroke Length)*

Arm Tilt (Y-axis)

max. speed	2.22 rpm
acceleration	15 deg/sec^2
Repeatability	20 arc-sec
Accuracy	+/- 40 arc-sec
Travel	*30 degrees*

Carriage (Z-axis)

max. speed	2000 ipm
acceleration	40 in/sec^2
Accuracy	+/- .002 in/ft (software compensated, +/-.005 in overall) +/-.005 in/ft (uncompensated, +/-.015 in overall)
Travel	*342 inches (28.5 ft.)*

Head Yaw (I-axis)

max. speed	8800 degrees/min.
acceleration	115 deg/ sec^2
Repeatability	50 arcsec
Accuracy	+/- 100 arcsec
Min. Travel	*200 degrees*

Head Pitch (J-axis)

max. speed	6300 degrees/min.
acceleration	115 deg/ sec^2
Repeatability	50 arcsec
Accuracy	+/- 100 arcsec
Min. Travel	*100 degrees*

Head Roll (K-axis)

max. speed	8800 degrees/min.
acceleration	115 deg/ sec^2
Repeatability	50 arcsec
Accuracy	+/- 150 arcsec
Min. Travel	*180 degrees*

Mandrel (C-axis)

max. speed	41.7 rpm	laydown speed varies as a function of distance from center
spindle		
acceleration	38.2 deg/sec^2	
Repeatability	18 arc-sec	
Accuracy	+/- 36 arc-sec	
Max. Diameter	144 inches	
Max. Length	342 inches (28.5 ft.)	
Max. Weight	40,000 lb	
Max. Inertia	200,000 in-lb/ sec^2	
Max. Shaft Dia.	12"	

Material Requirements

Tow impregnated with thermoset resin wound without twists on a cylindrical core.

Width	.125 +/- .015"
Tow Thickness (uncured)	.006 to .015 inches

Must De-spool without stringers

Max Spool Dia.	8 inches
Max. Spool Weight	25 lb.

Slight Tack: sticks to itself, but not a vertical tool

Application Specifications

Max. # of tows	24
Fiber Bandwidth	3 inches
Fiber placement Speed	200 to 1200 ipm (I have 100 in my DOE)
Material Laydown Rates	2.0 to 65 lb/hr
Ply Orientation Accuracy	+/- 5 degrees
Minimum Cut Length	*6.3"*
Nominal Compaction Force	100 lbf

Appendix #7: Results of Designed Simulations

The three surfaces are a cylinder, a cylinder with double curvature and a flat plate. The control parameter settings for both experiments are in the following table. The cylinder DOE does not have the restart speed setting. The flat plate experiment does not have the rise height variation. The important parameters were determined using a normal probability plot of the parameter effects. Control parameter values were chosen as extreme values which would be observed at the machine.

control parameter	minus	plus
length	14.824	250
rise height	0	10% of length
cutout	5% of length	15% of length
cut speed	25 ipm	150 ipm
lay speed	100	1200
restart speed	150	300

The ply tables below give substantial information about the results of the experiment. In general:

Layup Time = average time + effect magnitude 1*setting 1+effect magnitude 2* setting 2 + ...

For example, you may use the results of the 0 degree, short ply to estimate the layup speed for a ply with a 150 ipm cut speed, 650 lay speed (halfway between 100 and 1200) and no double curvature. The equation for the result is:

$$\text{Layup Time} = 3.58 - 0.79*(0) - .38*(+1) + .41*(-1) = 2.79 \text{ minutes}$$

Cylinder IBL / 11-15-95

5 2^4 factorial experiments were completed with the intent to determine which numerical control parameters and design features affected layup time significantly. The experiments were:

- 0 degree orientation, short
- 0 degree orientation, long
- 45 degree orientation, short
- 90 degree orientation, short
- 90 degree orientation, long

Layup time was most significantly effected by the layup speed, double curvature and cut speed. The greater the layup speed and the cut speed, the faster the ply is laid up. The less contour, the better. On the long plies the layup speed and the contour were the most significant. Cut speed was most significant on short plies, except the 90. Lay speed and contour were about the same magnitude. There were some interesting interactions between lay speed and contour or cut speed and contour. The 45 degree orientation, long simulation was not executed because Acraplace Version 1.0 would not execute the path generation file.

Baseline Runs

	Control Parameters					0 degrees		45 degrees		90 degrees	
	length	rise height	cutout	cut speed	lay speed	time	courses	time	courses	time	courses
1	250	0	none	70	600	8.1	14			21.1	91
2	250	0	15%	70	600	8.48	14			21.8	91
3	250	0	5%	70	600	8.48	14			21.4	91
4	14.824	0	none	70	600	2.08	14	2.48	13	1.57	7
5	14.824	0	15%	70	600	2.37	14	3.37	13	1.65	7
6	14.824	0	5%	70	600	2.35	14	3.32	13	1.62	7
7	250	10%	none	70	600	24	31	28.6	17	23.7	95
8	250	10%	15%	70	600	24.4	31	31.9	17	25.8	95
9	250	10%	5%	70	600	24.4	31	30.3	17	24.2	95
10	14.824	10%	none	70	600	2.68	16	3.32	17	1.82	7
11	14.824	10%	15%	70	600	3.18	14	4.15	17	1.93	7
12	14.824	10%	5%	70	600	3.18	16	4.28	17	1.92	7

0 degree orientation, short

Average Time = 3.58 minutes

Major effects	**magnitude**	**higher setting effect on time**	**comments**
cut speed	-.79	reduces	
lay speed	-.38	reduces	
contour	.41	increases	

0 degree orientation, long

Average Time = 27.14 minutes

Major effects	**magnitude**	**higher setting effect on time**	**comments**
lay speed	-10.6	reduces	
cut speed	-5.47	reduces	
cut/contour interaction	-2.01	reduces	
cut/lay interaction	1.88	increases	
lay/contour interaction	1.90	increases	
contour	8.44	increases	

45 degree orientation, short

Average Time = 5.01 minutes

Major effects	**magnitude**	**higher setting effect on time**	**comments**
cut speed	-1.242	reduces	
lay speed	-.300	reduces	
cut/contour	-.192	reduces	
contour	.502	increases	

90 degree orientation, short

Average Time = 2.11 minutes

Major effects	magnitude	higher setting effect on time	comments
lay speed	-.27	reduces	
cut speed	-.15	reduces	
contour	.16	increases	

90 degree orientation, long

Average Time = 28.07 minutes

Major effects	magnitude	higher setting effect on time	comments
lay speed	-4.42	reduces	
cut speed	-1.98	reduces	
lay/contour	-.70	reduces	
cutout	.51	increases	
contour	2.1	increases	

Flat plate IBL / 9-5-95

6 2^4 factorial experiments were executed with the intent to determine which numerical control parameters and design features affected layup time significantly. The experiments were:

- 0 degree orientation, short
- 0 degree orientation, long
- 45 degree orientation, short
- 45 degree orientation, long
- 90 degree orientation, short
- 90 degree orientation, long

Layup time was most significantly effected by the layup speed and the cut speed. The average time of longer plies was longer than the equivalent orientation short plies, but the shortest time of a long ply was very close to the longest time of a short ply.

There is a tradeoff between the number of courses and the number of cuts. More courses add time because the ply must stop and go to the clear plane, but cutouts slow the machine down due to adds and drops. When the cutout is the width of a full course, the machine goes back to the clear plane position and adds a course. When the cutout was less than the width of a full course, the machine did not add a full course and it saved time: the 90 degree, short had an average speed of 1795 inches of tow per minute and the 0 degree course laid 1036"/min.

Baseline Runs

	Control Parameters					0 degrees		45 degrees		90 degrees	
	length	cutout	cut spd	lay speed	restart speed	time	courses	time	courses	time	courses
1	14.824	5%	70	600	200	3.5	17	3.57	14	1.47	6
2	14.824	15%	70	600	200	3.5	17	3.50	17	1.55	6
3	250	5%	70	600	200	9.17	17	22.45	79	22.73	96
4	250	15%	70	600	200	9.03	17	23.55	85	23.95	104
5	14.824	none	70	600	200	2.5	17	2.75	14	1.80	6
6	250	none	70	600	200	8.57	17	21.12	74	22.07	92

0 degree orientation, short

Average Time = 3.93 minutes

Major effects	magnitude	higher setting effect on time	comments
cut speed	-.81	reduces	
lay speed	-.47	reduces	
restart speed	-.21	reduces	

0 degree orientation, long

Average Time = 19.27 minutes

Major effects	magnitude	higher setting effect on time	comments
lay speed	-12.4	reduces	
cut speed	-3.46	reduces	
lay/cut interaction	2.70	increases	

45 degree orientation, short

Average Time = 4.34 minutes

Major effects	magnitude	higher setting effect on time	comments
cut speed	-1.12	reduces	
lay speed	-.36	reduces	
restart speed	-.17	reduces	
cutout/cut interaction	-.12	reduces	

45 degree orientation, long

Average Time = 36.63 minutes

Major effects	magnitude	higher setting effect on time	comments
lay speed	-10.6	reduces	
cut speed	-7.27	reduces	

90 degree orientation, short

Average Time = 2.27 minutes

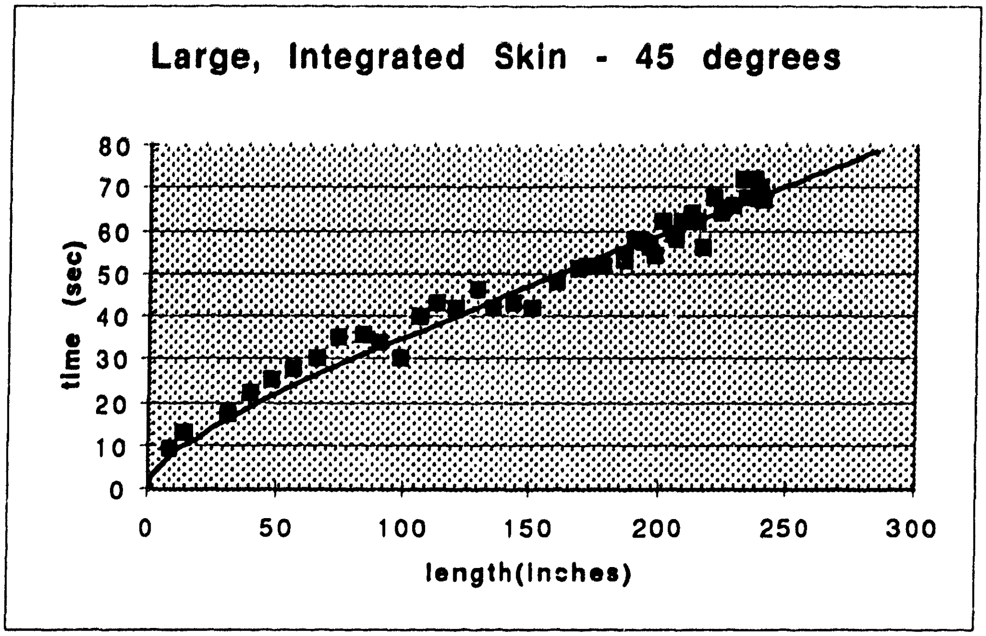
Major effects	magnitude	higher setting effect on time	comments
lay speed	-.70	reduces	
cut speed	-.33	reduces	

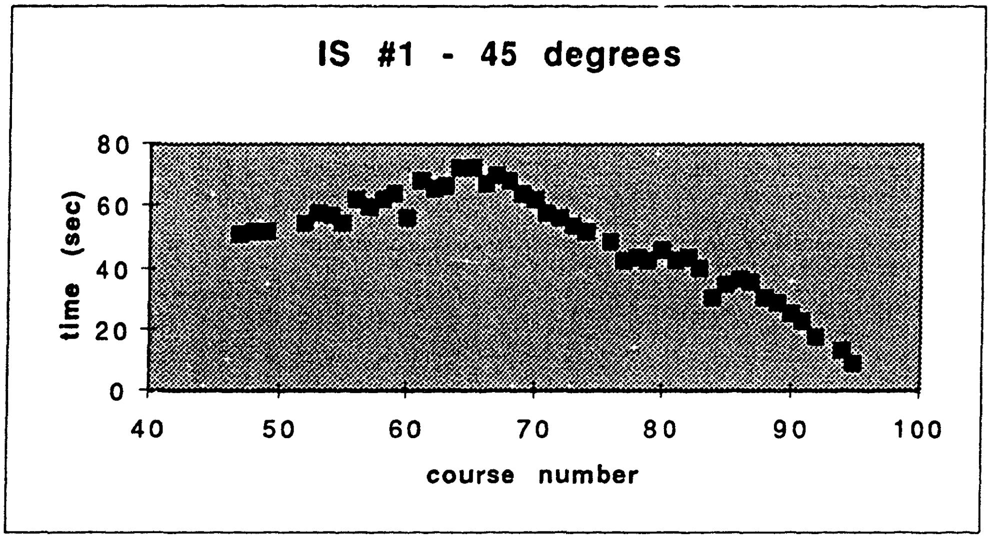
90 degree orientation, long

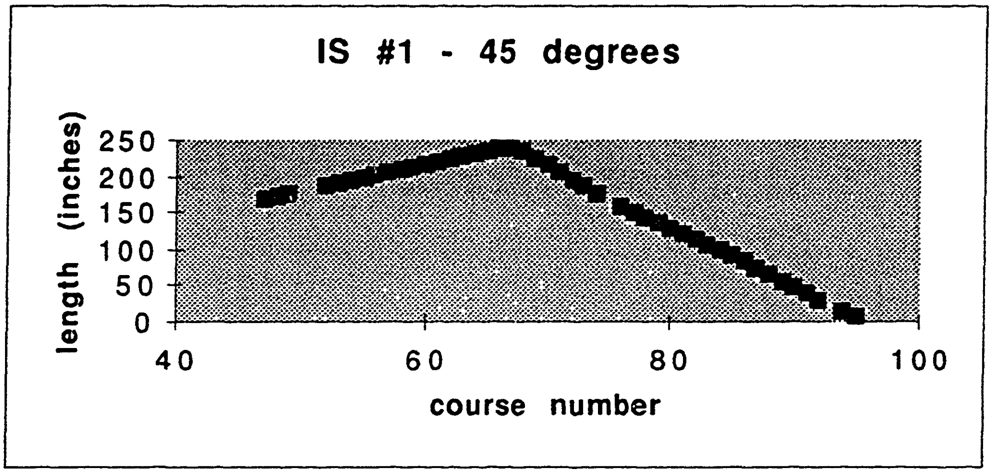
Average Time = 35.41 minutes

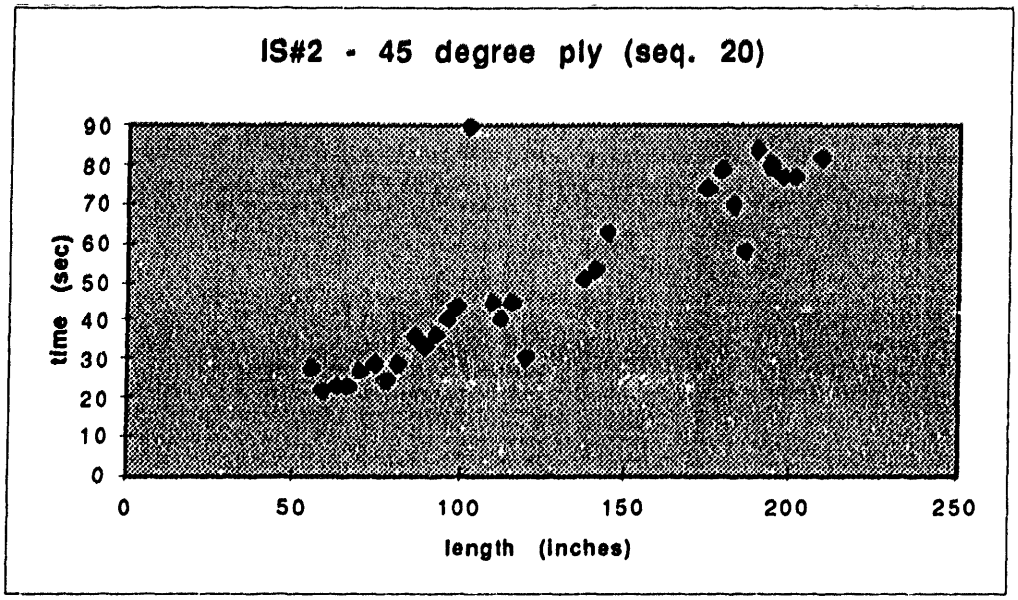
Major effects	magnitude	higher setting effect on time	comments
lay speed	-11.4	reduces	
cut speed	-4.45	reduces	
restart speed	-1.13	reduces	

Appendix #8: BD&SG ATP Course Data





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time (sec)
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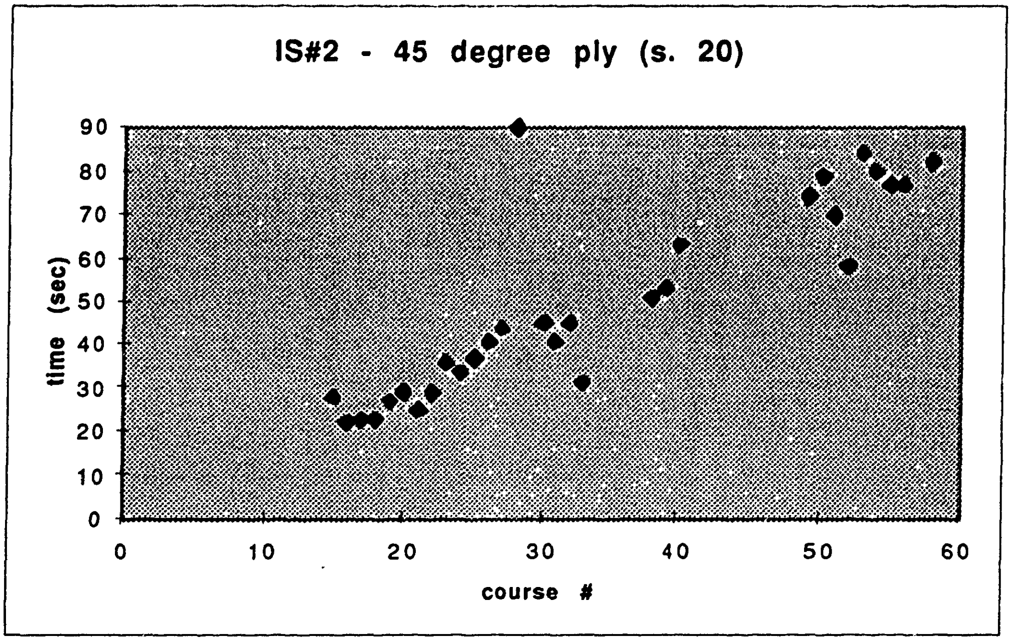
30
40
50
60
70
80
90
0
50
100
150
200
250
length (inches)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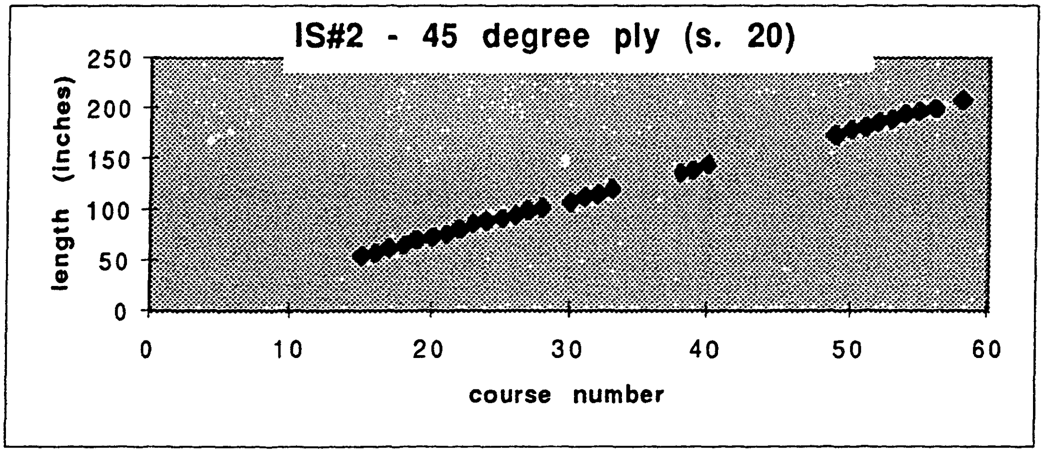
20
30
40
50
60
70
80
90
0
10
20
30
40
50
60
course #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length (inches)
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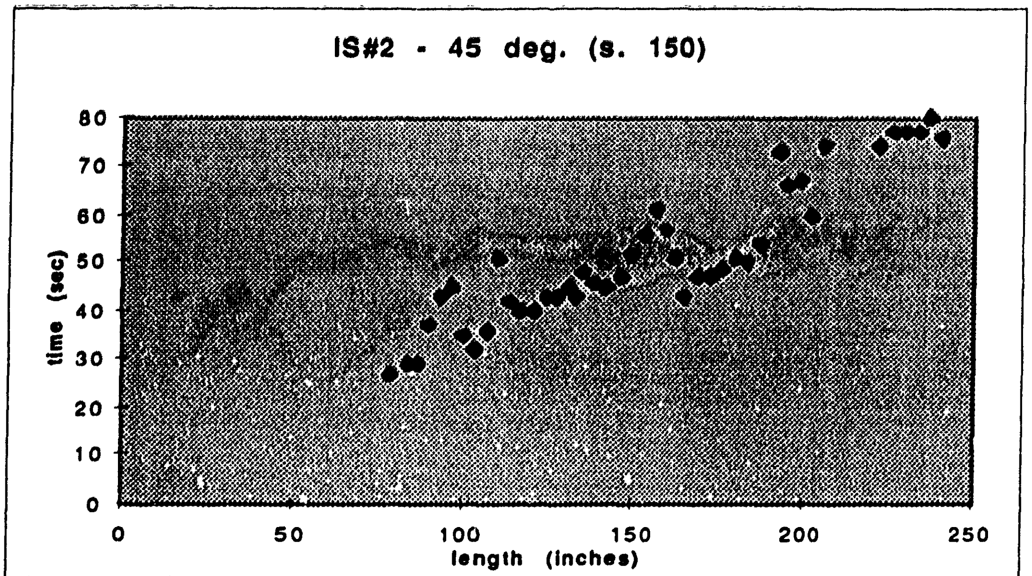
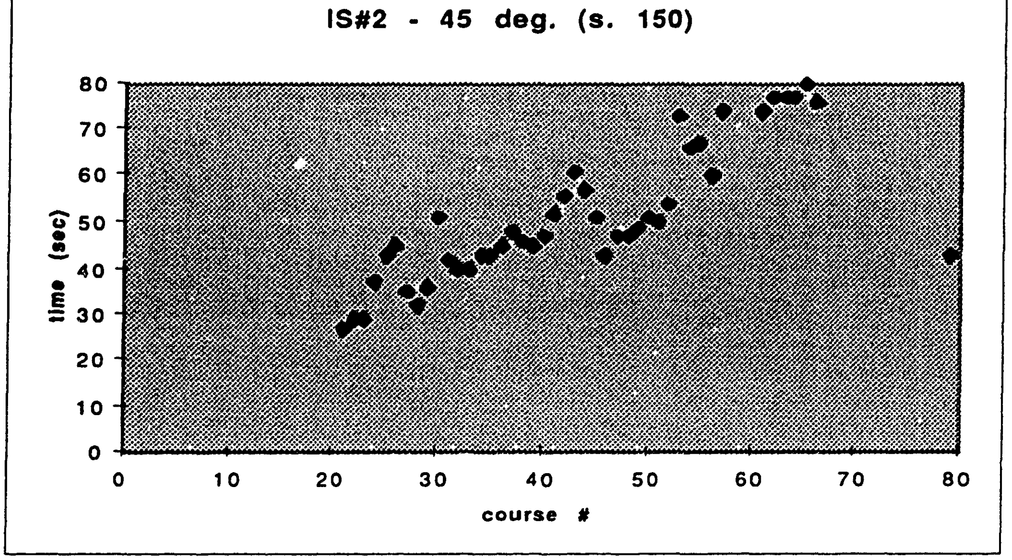
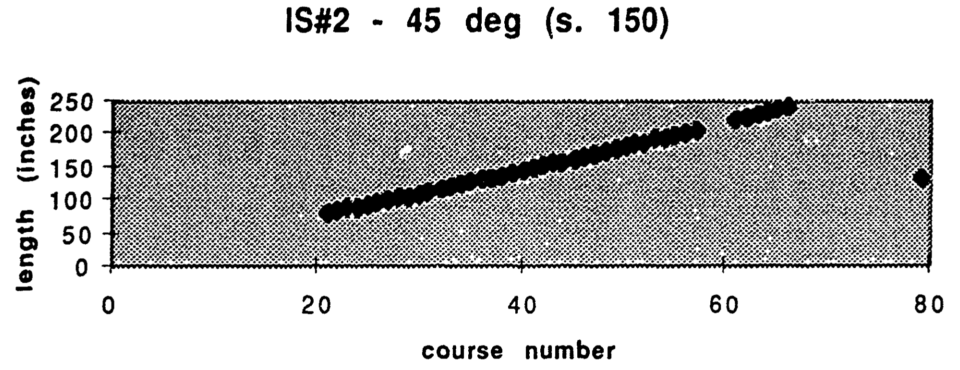
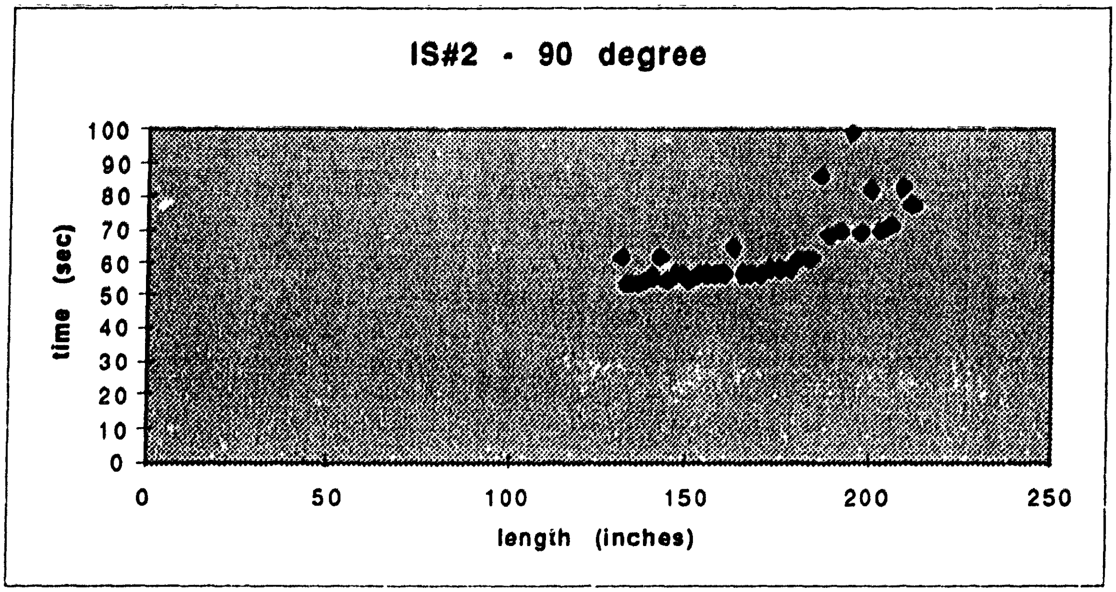
100
150
200
250
0
10
20
30
40
50
60
course number



Note: much of this ply was laid with override between 60 - 100%



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time (sec)
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10
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0
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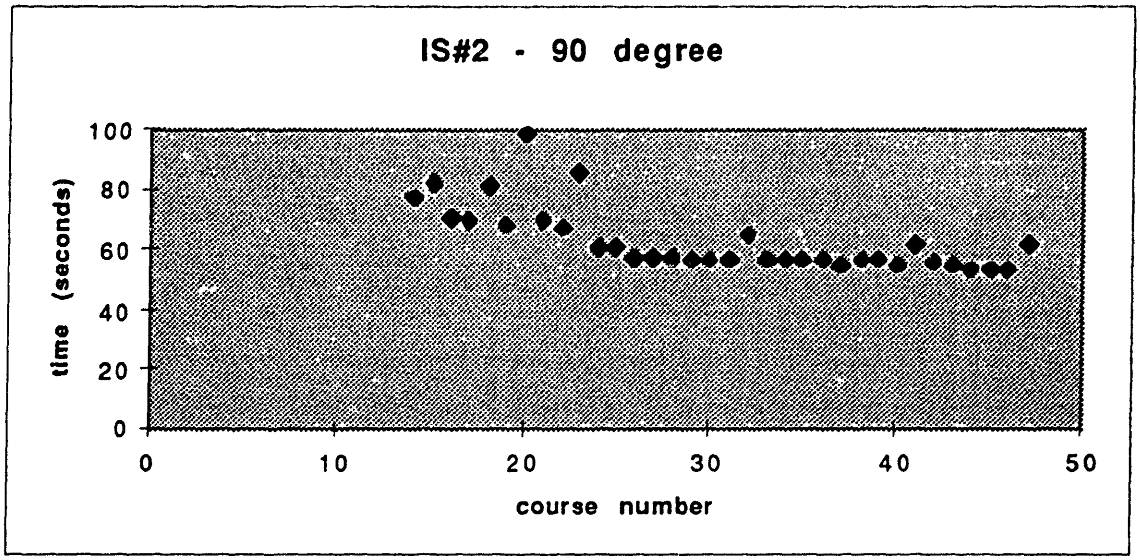
100
150
200
250
length (inches)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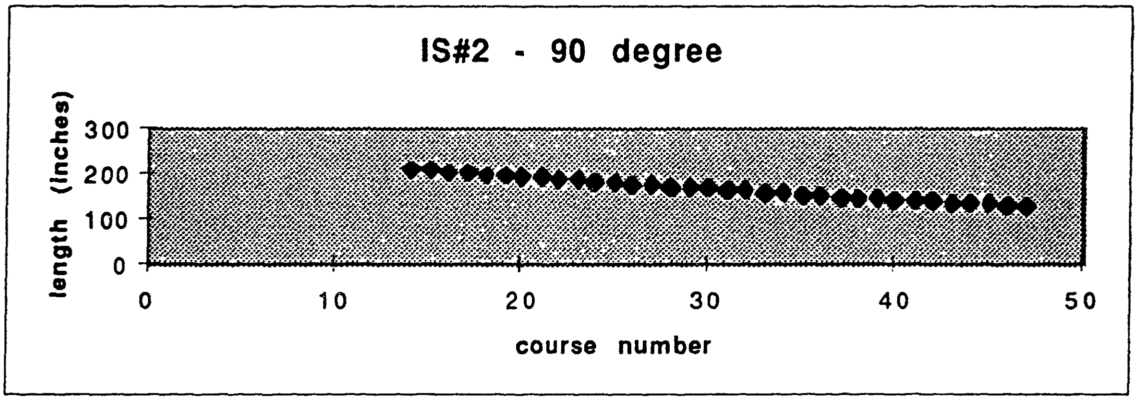
60
40
20
0
0
10
20
30
40
50
course number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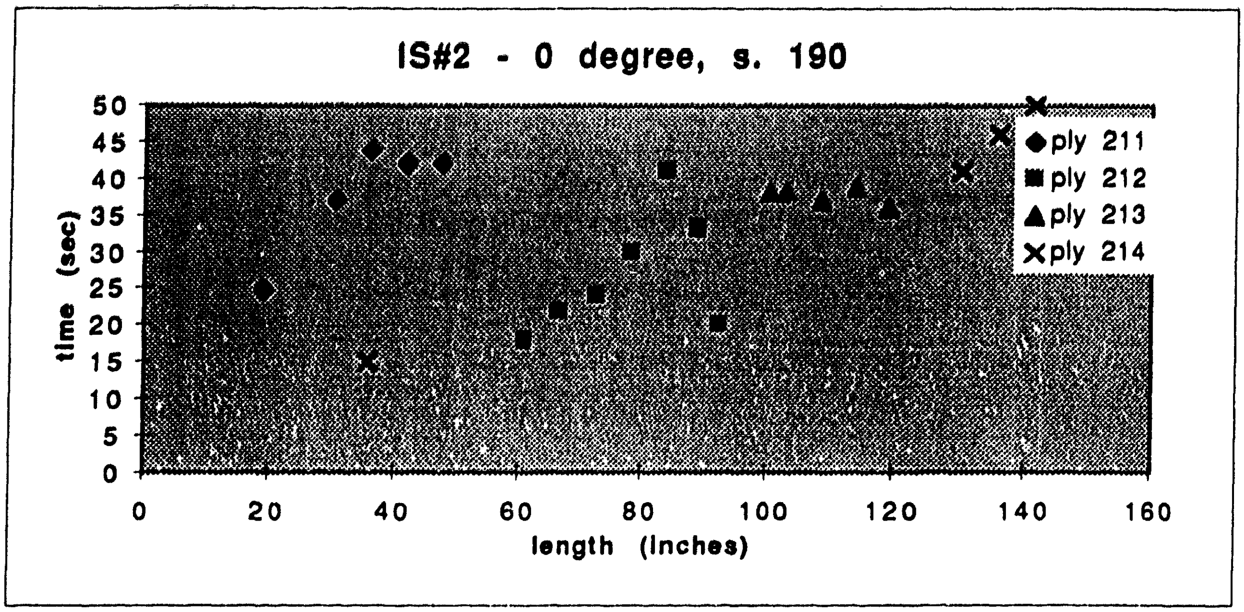
0
10
20
30
40
50
course number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10
15
20
25
30
35
40
45
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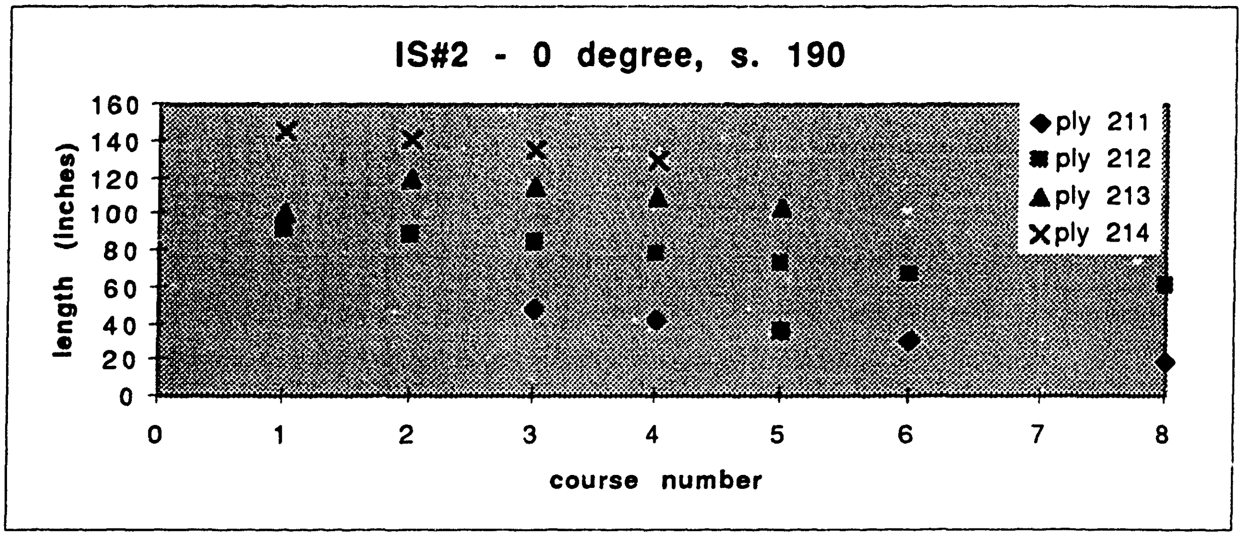
120
140
160
◆ply 211
■ply 212
▲ply 213
✕ply 214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80
100
120
140
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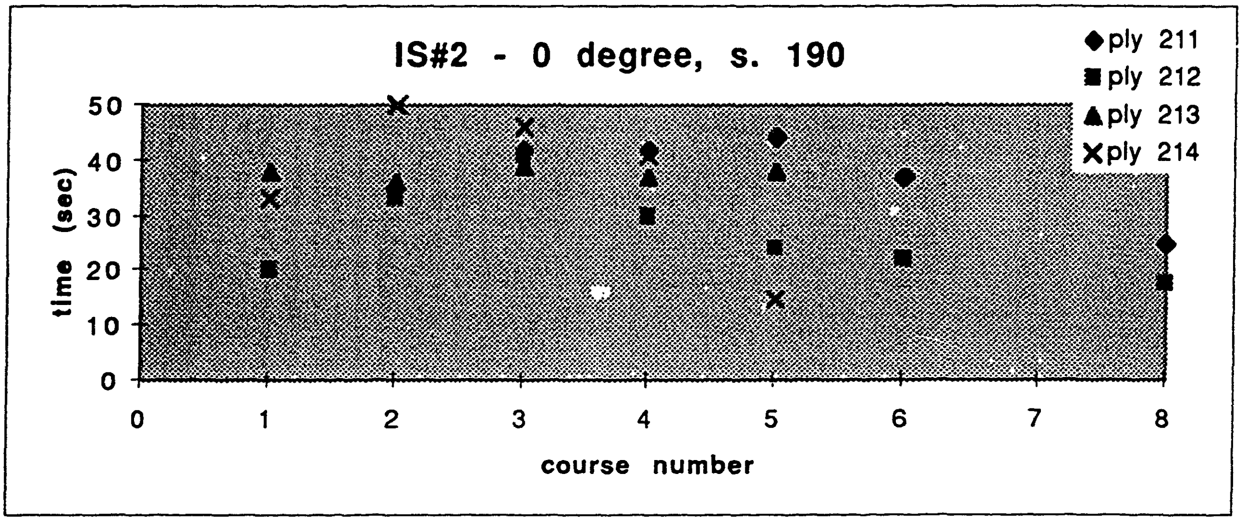
▲ply 213
✕ply 214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time (sec)
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20
30
40
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course number
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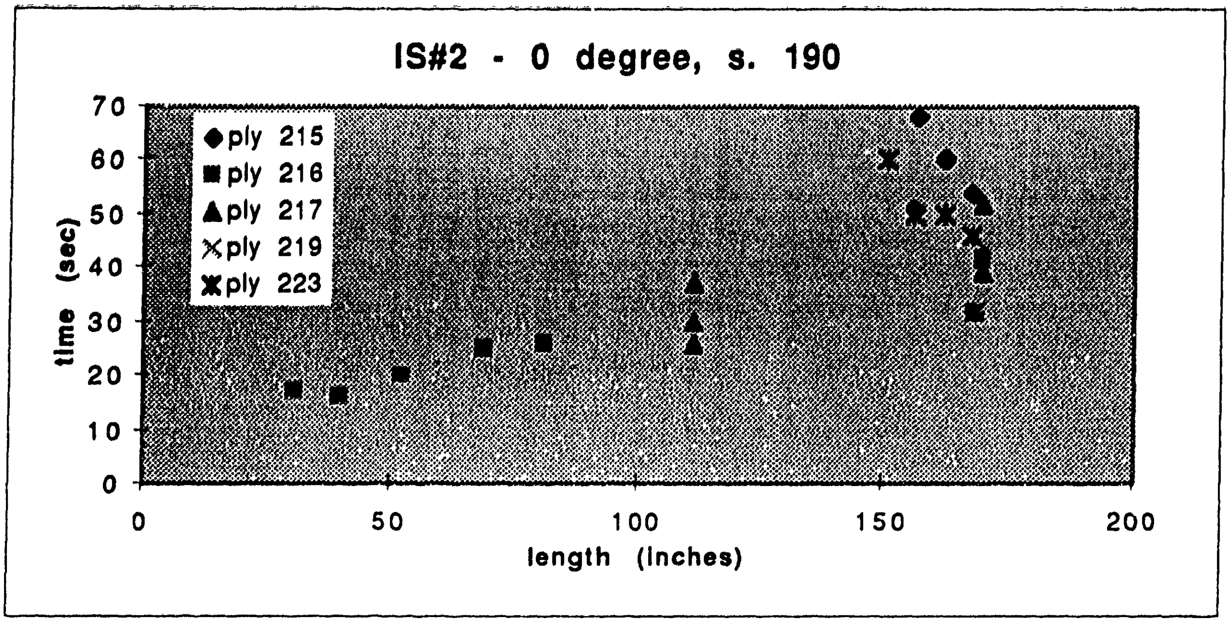
▲ply 213
✕ply 214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length (inches)
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40
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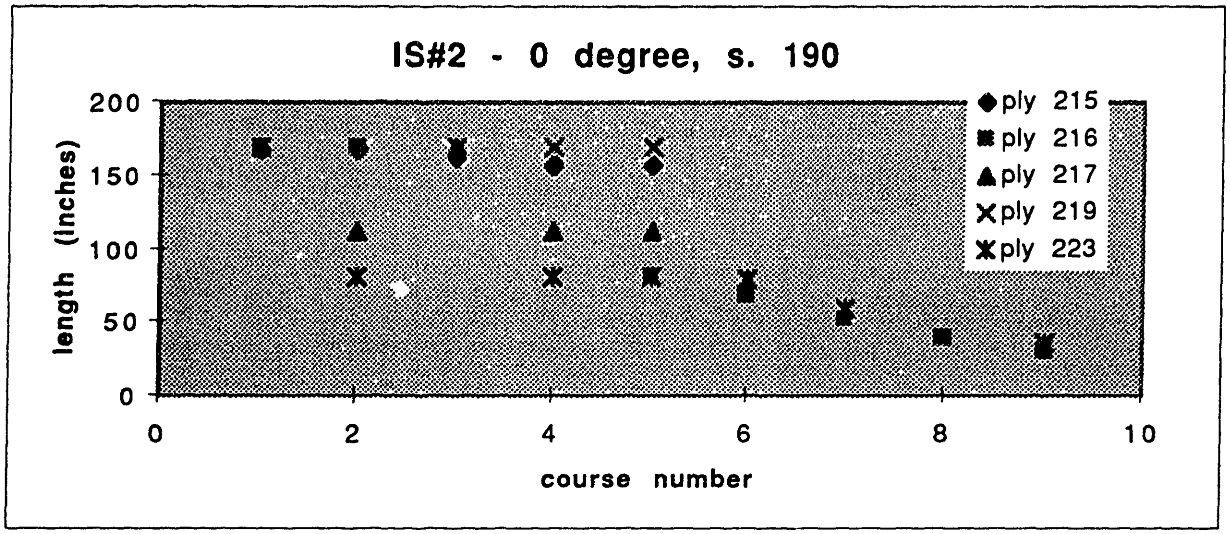
■ply 216
▲ply 217
×ply 219
✱ply 223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length (inches)
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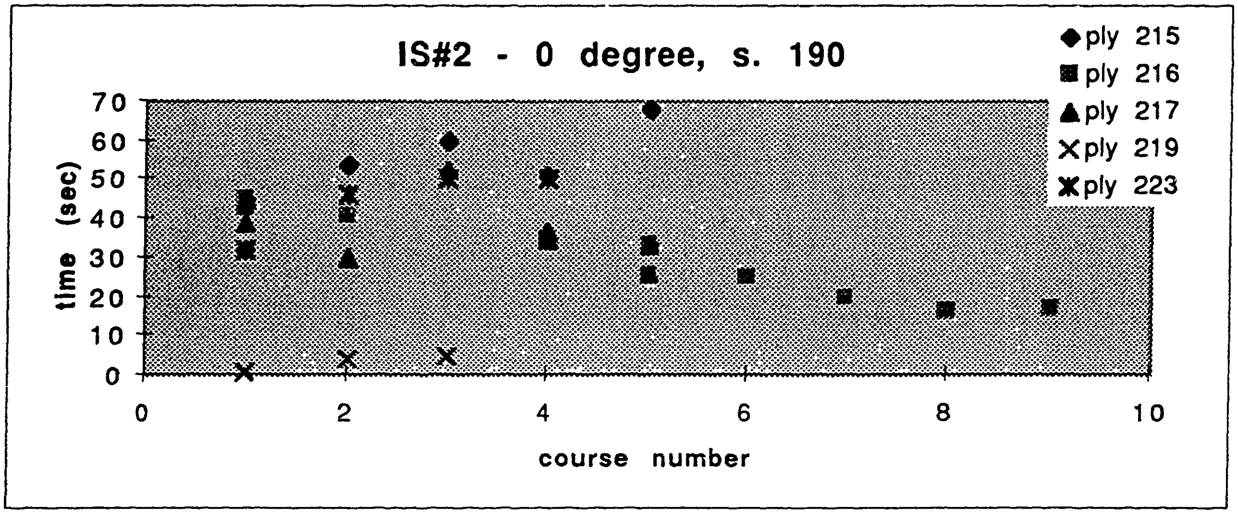
▲ply 217
×ply 219
✱ply 223


IS#2 - 0 degree, s. 190
time (sec)
course number
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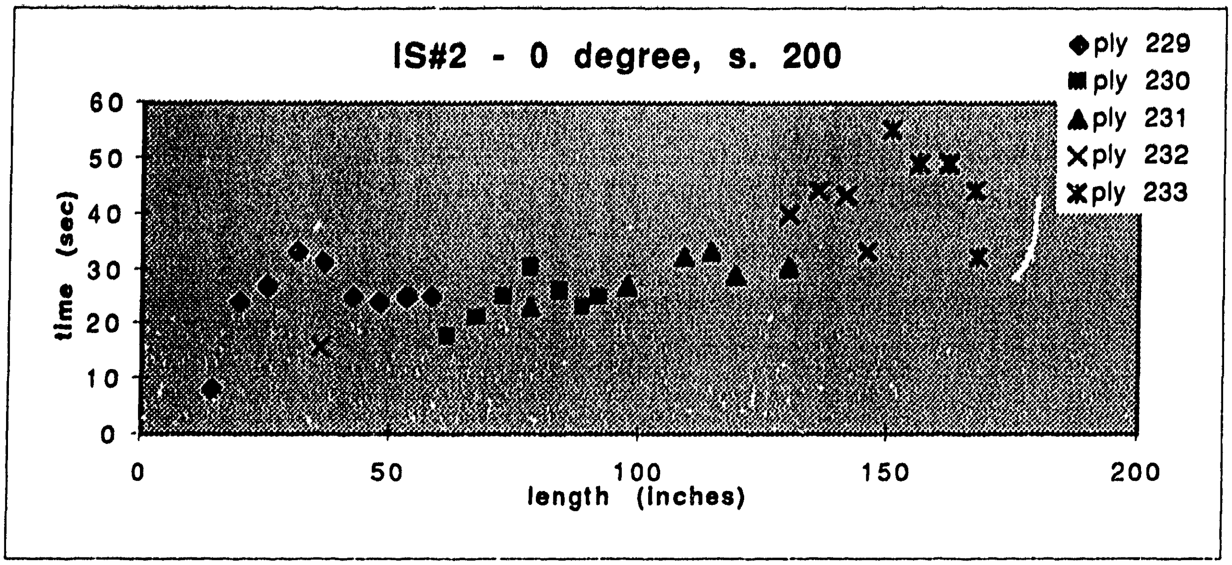
10
20
30
40
50
60
70
0
2
4
6
8
10
◆ply 215
■ply 216
▲ply 217
×ply 219
✱ply 223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60
length (inches)
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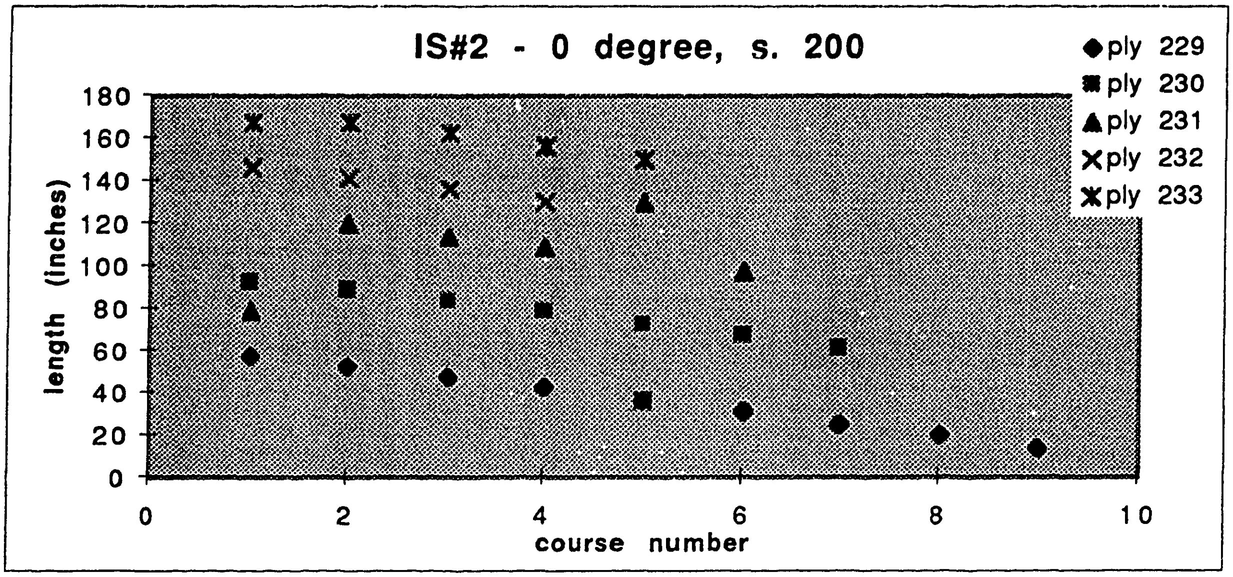
50
100
150
200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100
120
140
160
180
course number
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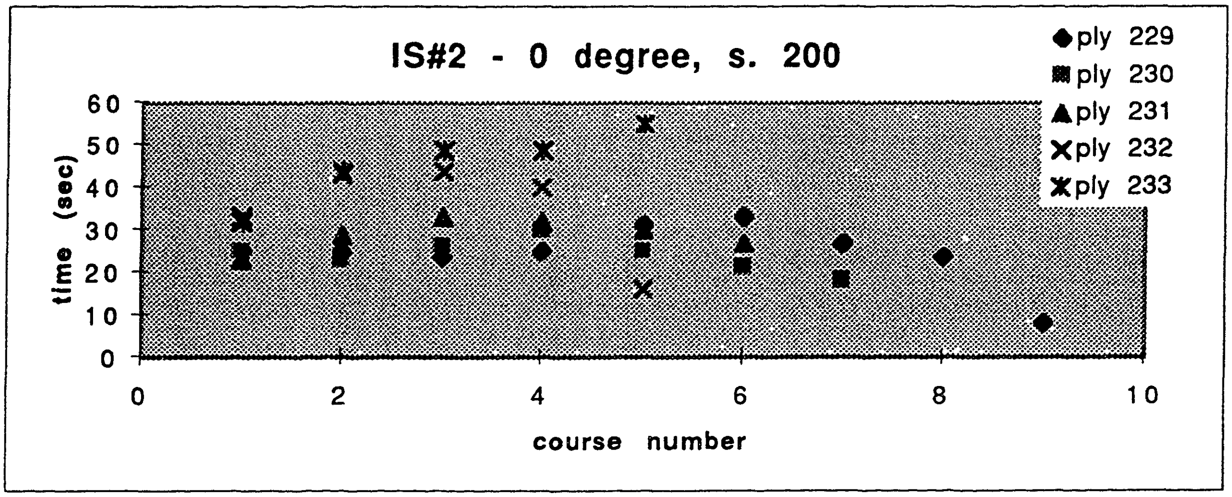
2
4
6
8
10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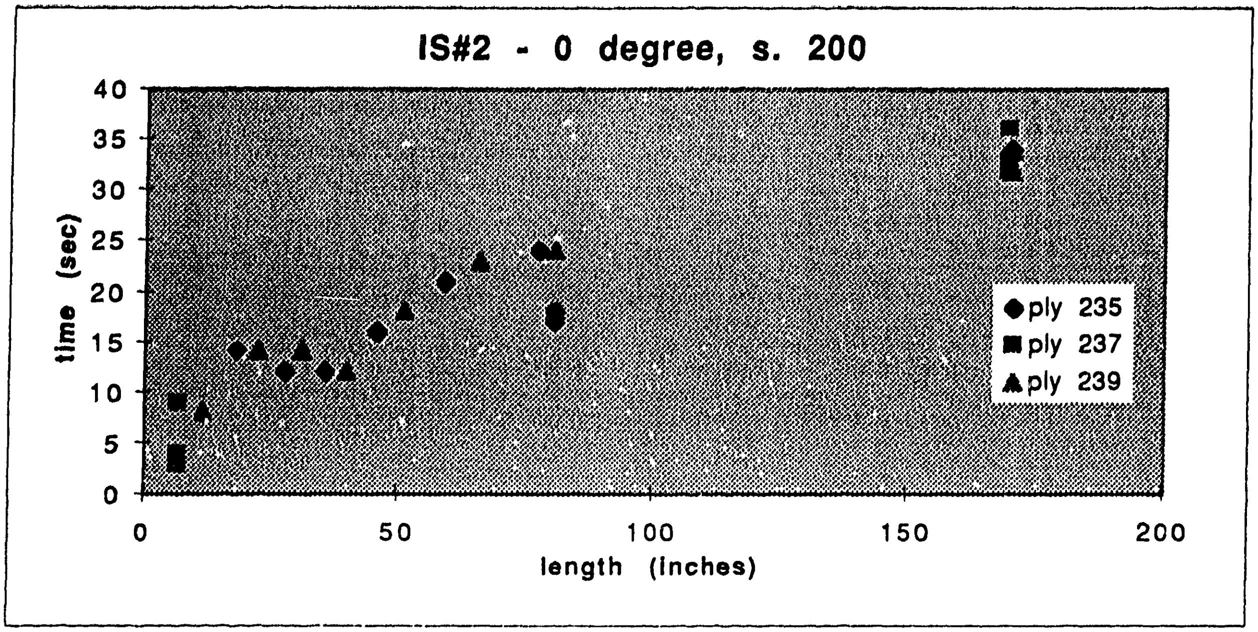
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length (inches)
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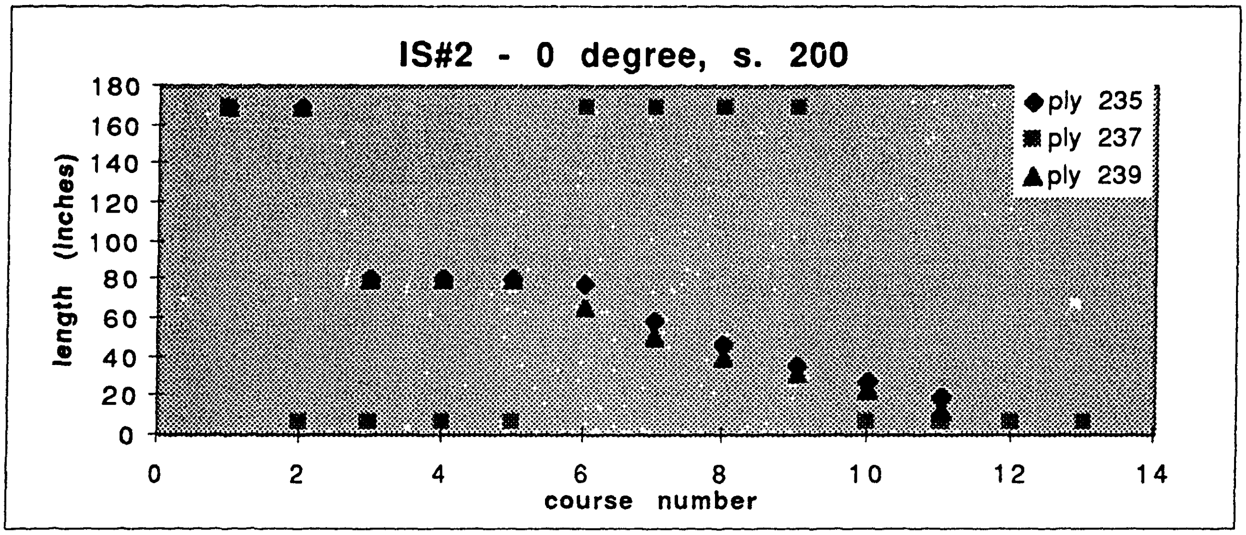
■ply 237
▲ply 239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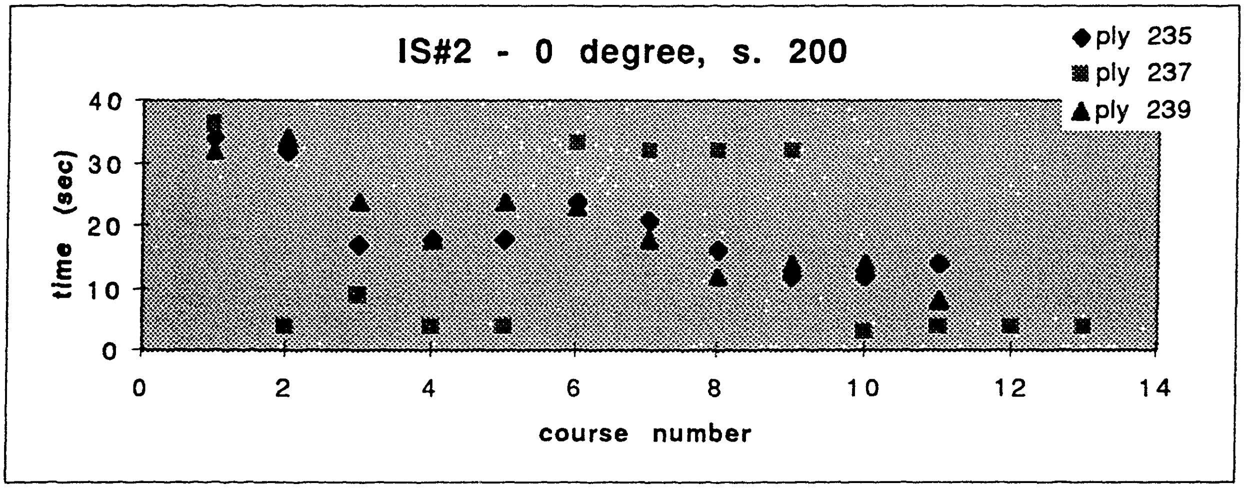
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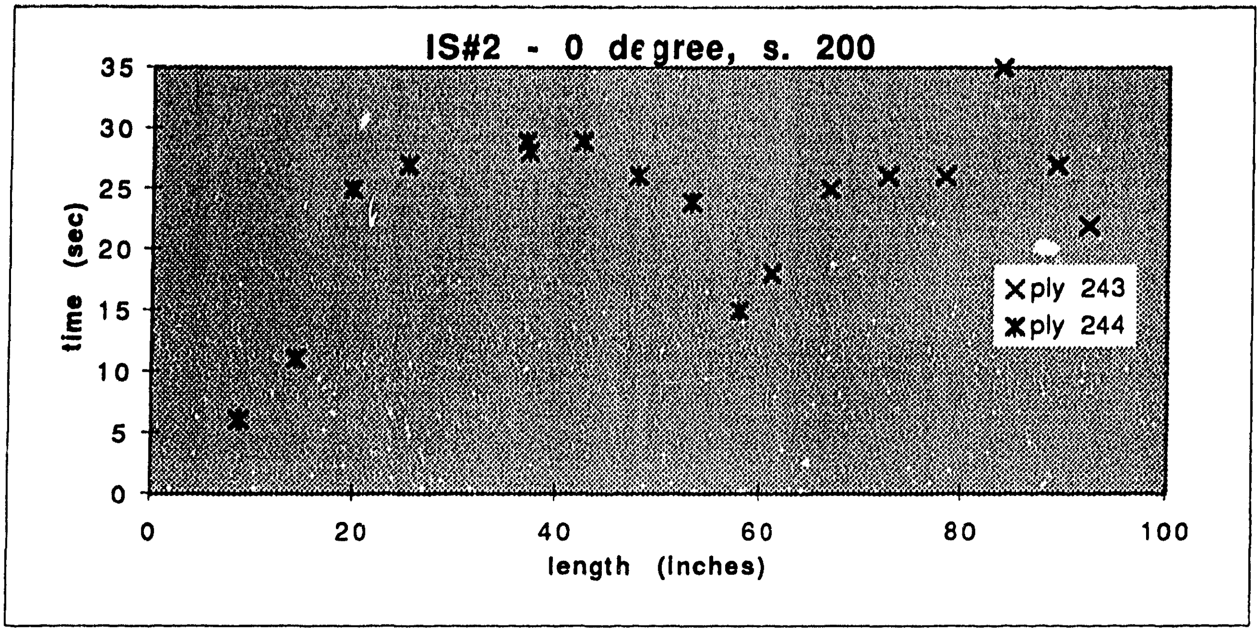
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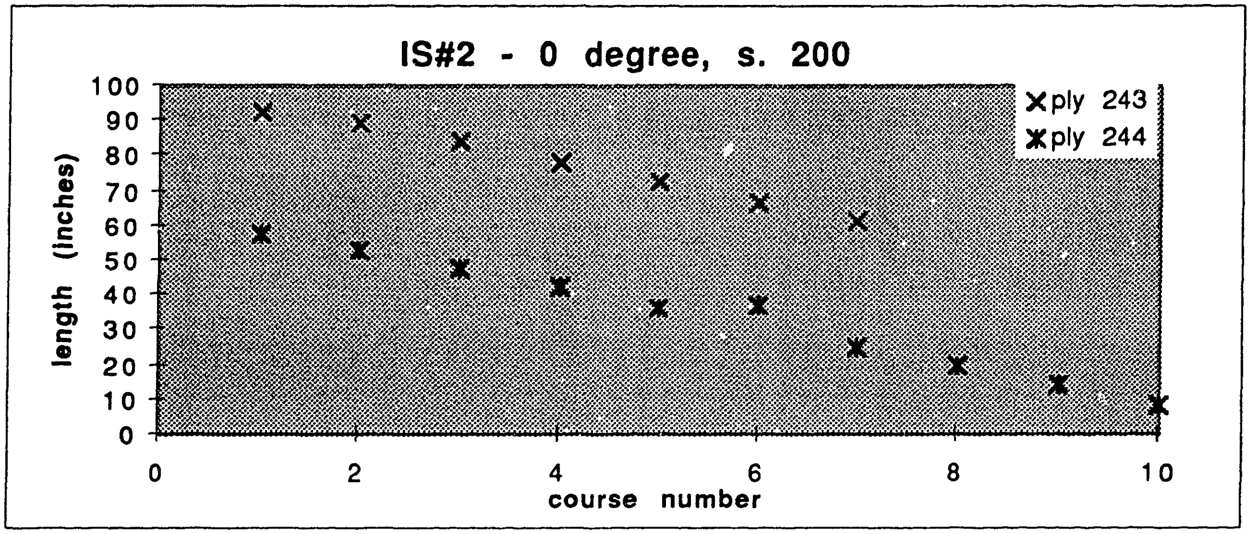
60
80
100
ply 243
ply 244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course number
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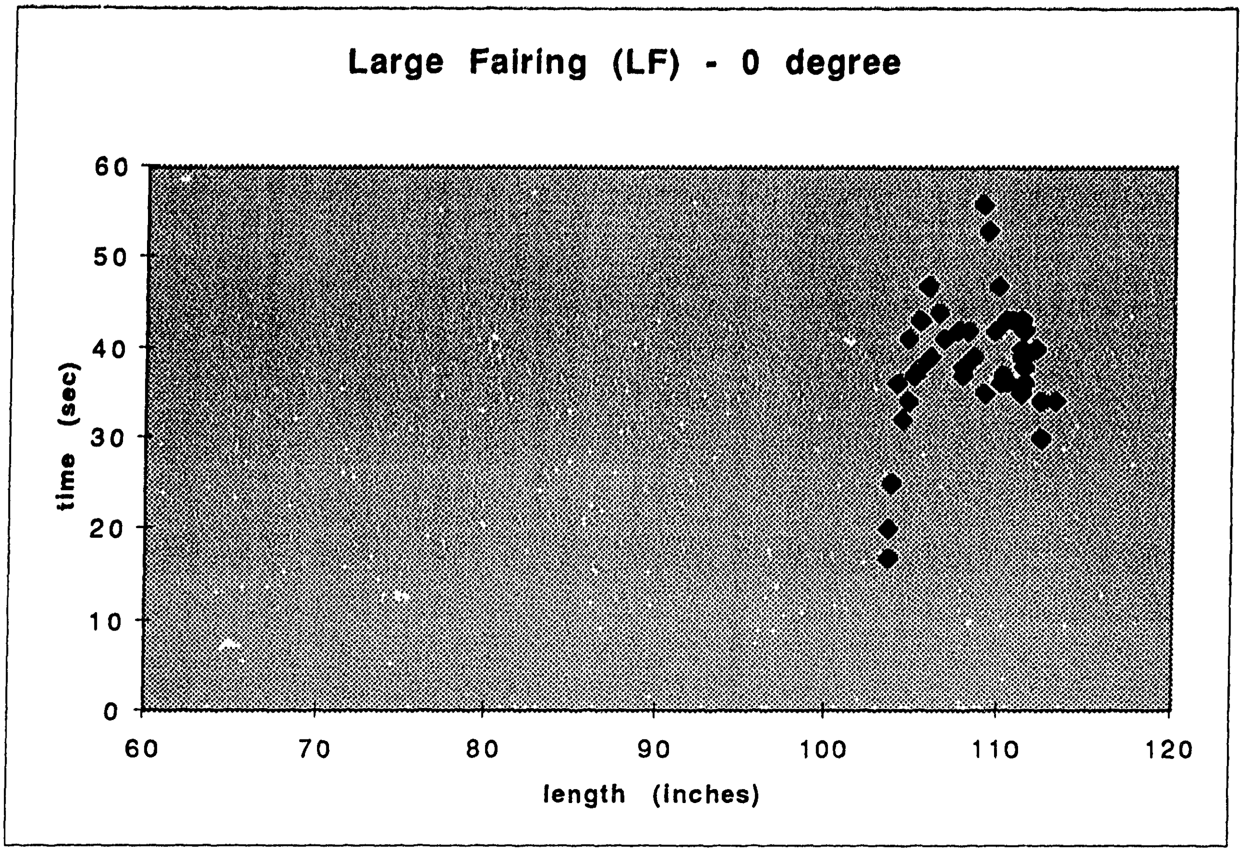
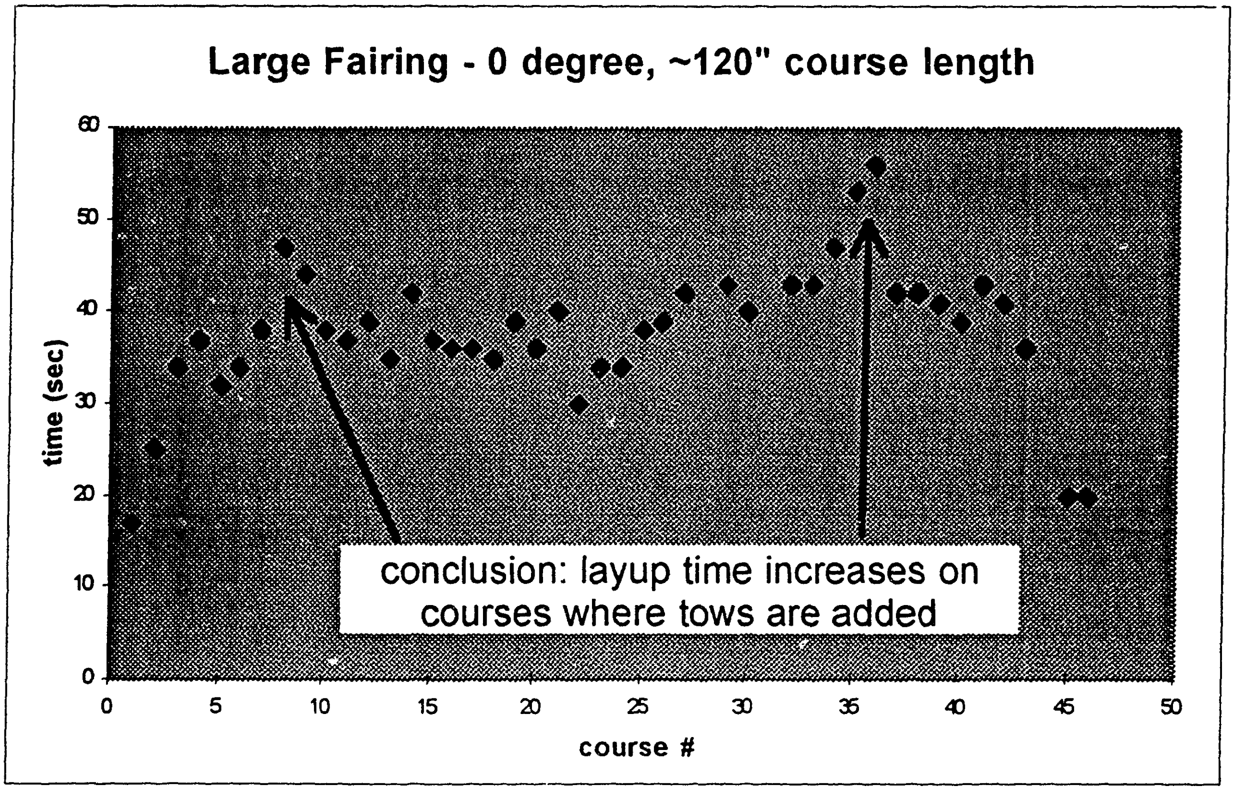
8
10
ply 243
ply 244

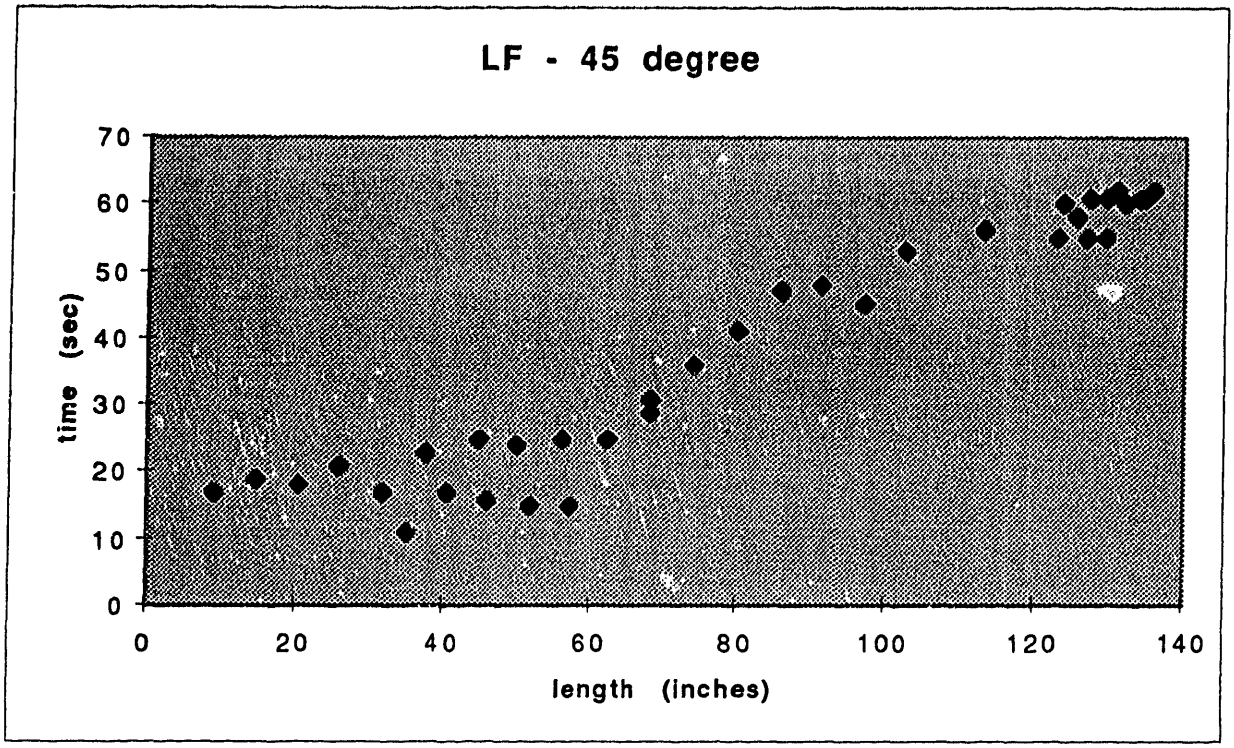


Large Fairing (LF) - 0 degree



Large Fairing - 0 degree, ~120" course length

conclusion: layup time increases on courses where tows are added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50
60
70
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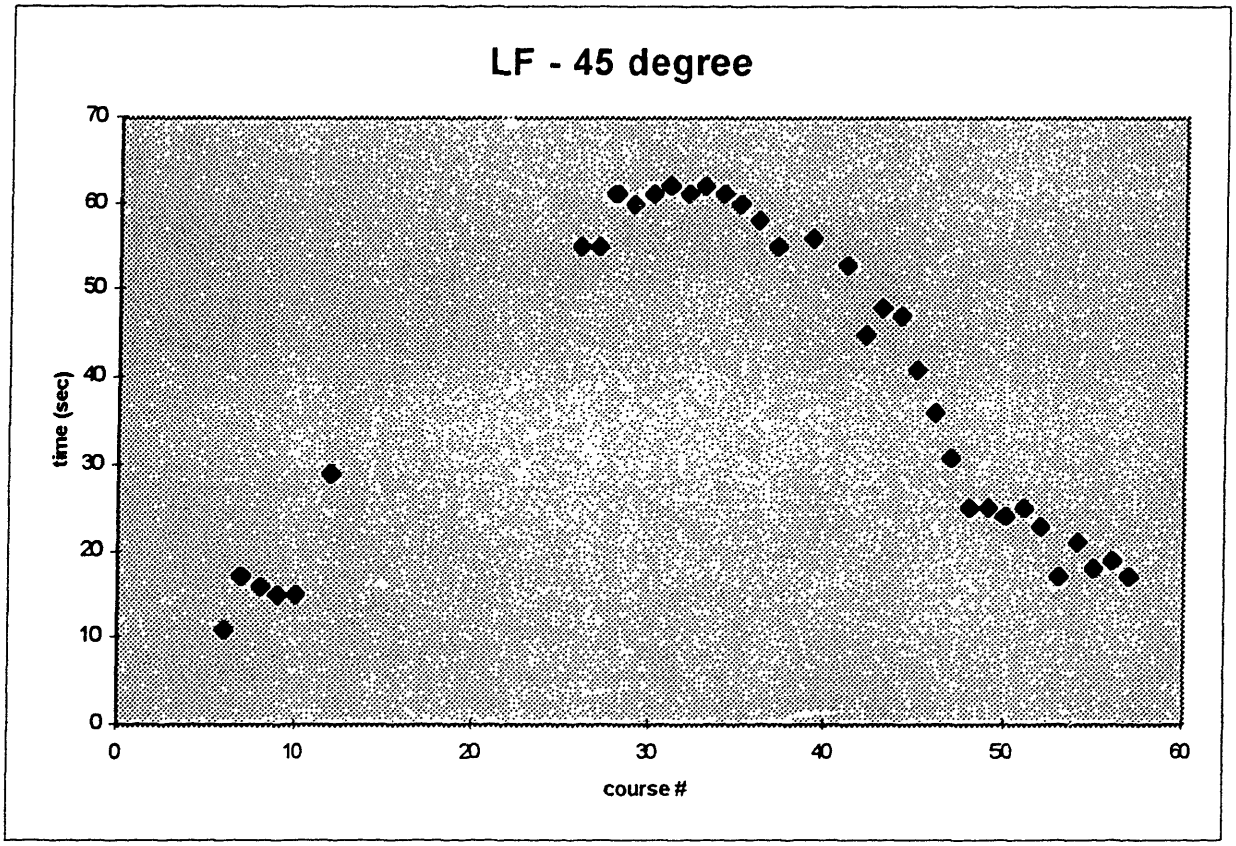
20
40
60
80
100
120
140
length (inches)


LF - 45 degree
time (sec)
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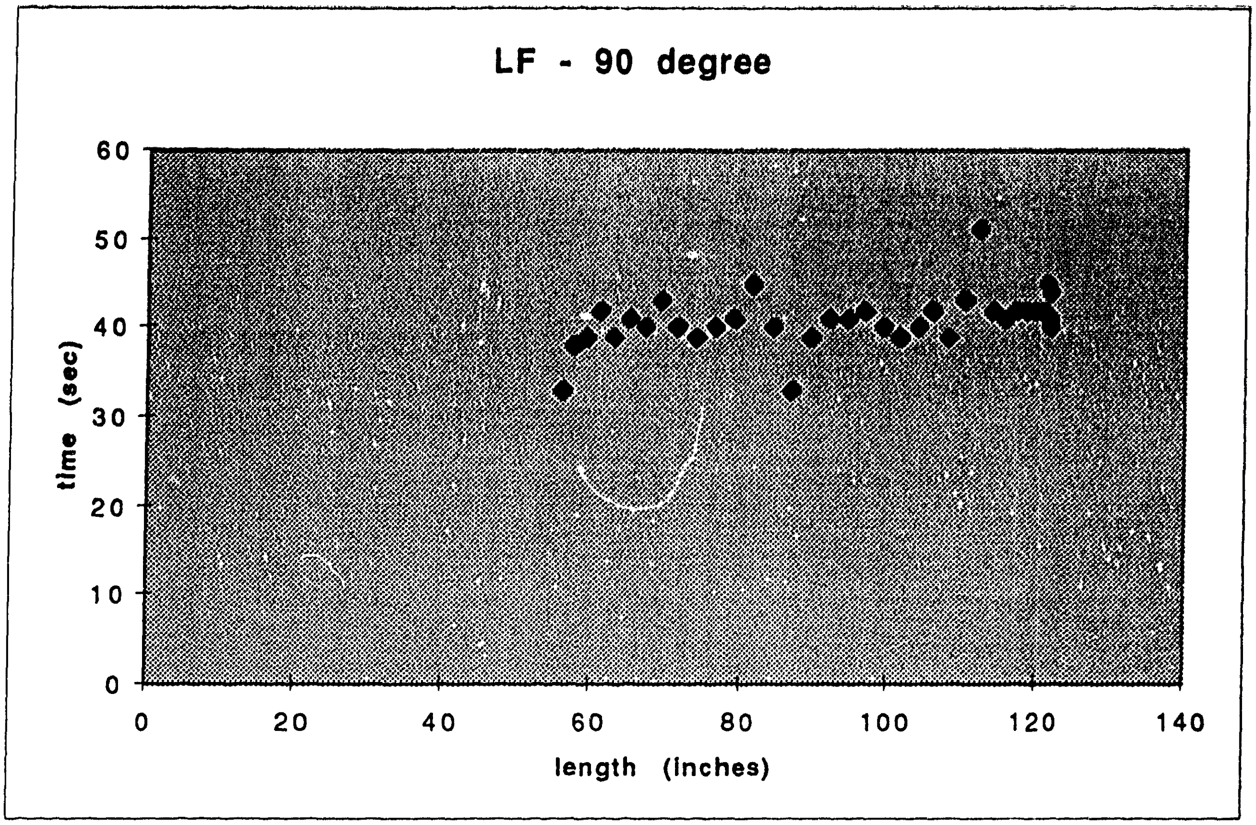
10
20
30
40
50
60
70
0
10
20
30
40
50
60
course #


LF - 90 degree
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40
30
20
10
0
length (inches)
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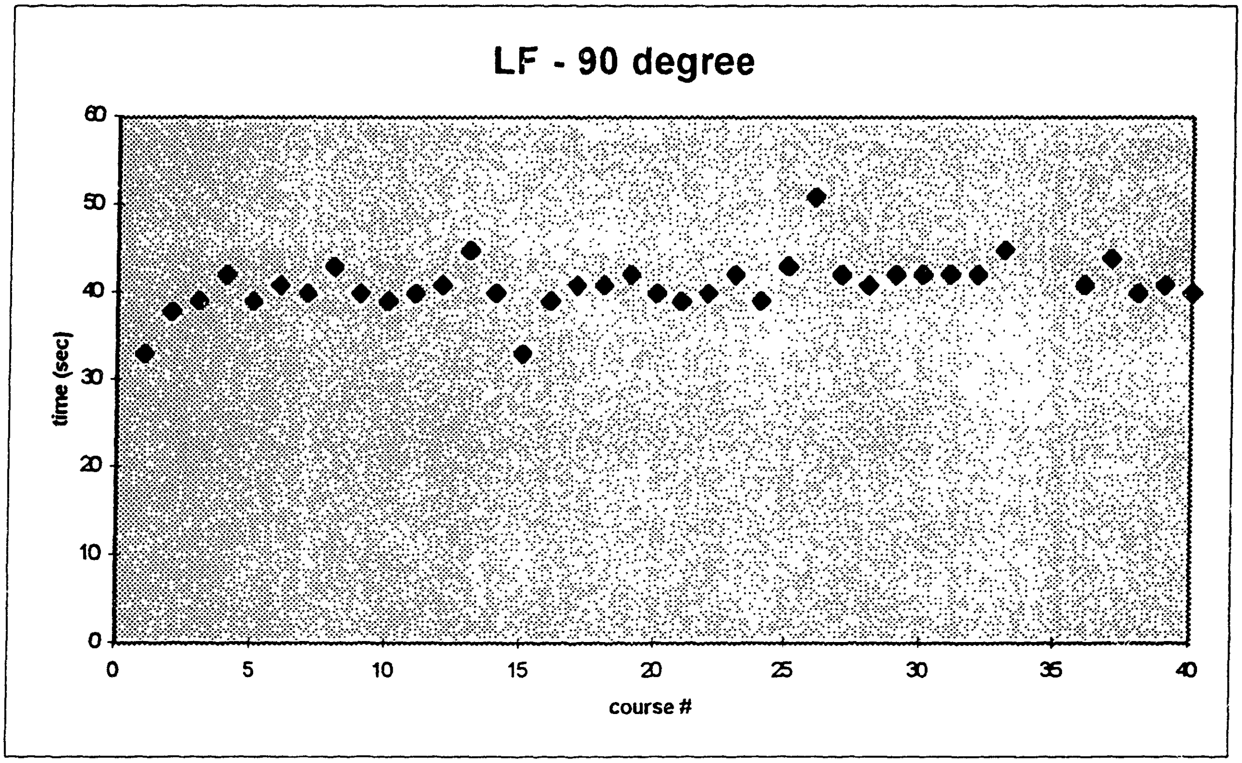
20
40
60
80
100
120
140


LF - 90 degree
time (sec)
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course #
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Appendix #9: Detailed Benchmark Observations

The following are detailed notes from my benchmarking trip. I have attempted to clean them up so they are readable and understandable without eliminating my initial thoughts on the location. The observations sections are arranged into six sections per participating company:

- Manufacturing
- Design
- Programming
- Tooling
- Management
- Culture

MDA-Tuesday, October 17, 1995

- Drew Mallow - project manager, materials
- John Kowalski - designer
- Alan Rouge - floor engineer, operator, producibility
- John Henderson - Programmer
- Dee Gil - CRAD program funding

Sum - They seem to have a stronger machine/material competence than the CM owners. Mostly because Hercules pioneered fiber placement. Their focus is proving out the machine's accuracy and repeatability. They are redesigning portions of the delivery system and debugging NC program. BH proved their accuracies and machine code during the summer/fall of 1994. MDA has not verified the machine making production part runs. Boeing learned substantial lessons during production.

Development/Validation

They have been involved in the development of the fiber placement machine with Hercules and Northrop since the early '80s. Hercules had converted a CM tape layer to invent fiber placement. See the discussion in Northrop's section about the Hercules/MDA/Northrop agreement. Cincinnati-Milacron hired a bunch of Hercules people to build their machine.

They are presently at the validation stage of the machine. Add tolerances are .08" and cut tolerances are .04". Hand-lay tolerances are .10". A mylar introduces .02 to .04" error. They have several test tools. The tapered square tool has 1/8", 1/2" and 3/4". It tests radius' and hoop plies. They added an adapter to offset tool to verify the coordinate tracking of the machine.

Thinner material twists more than thicker material (i.e.. .0055 vs. .010"). The MDA machine can cut on the fly, but they are not familiar with accuracy so they do not attempt it. The .0055" needs functionality and reliability on redirect rollers: the tows "walk" off the roller. The center roller is too small. CM's larger diameter, pneumatic roller is better in tension than Ingersoll's. Fiber steering is more a function of material than machine.

Management/Strategy

Why they decided to buy a fiber placement machine:

- To stay technologically competitive (primary driver), not cost savings. Cost savings on the F-18E/F would not justify buying a fiber placement machine.
- Ergonomics - FP can make parts a human or other machines cannot.

Automation

- Autoclave - has a 12' diameter capability
- Tape Laying - have not been successful implementing tape layers in the past.
- Automated Cutter - they have reciprocating and ultrasonic cutters.
- OLT - recently began to use these.
- Trim - They manufacture and use AUSS waterjet. They sell their waterjets to Boeing and Northrop.

They have had many bad experiences with automation. Thus, they are spending substantial time validating the equipment. Part of why their automation may have failed is that equipment is not purchased dedicated to one program: C17, T45, F-18, etc. If the machine was dedicated to a program and required to work, they would probably make it work. Program management does not take ownership when equipment is distributed [Pat Dolan was V-22 program manager who carried reigns for Boeing].

In the CRAD program Hercules has a capabilities and future applications push. Northrop's push is to determine candidate parts. MDA has been spending "excess cash" to avoid being a takeover target [when assets are worth more than the buying price].

Manufacturing

F-18E/F is their first production application (targeted). Alliant builds the horizontal stabilator (Mike Douberly is the Navy contact who favors Hercules/Alliance. He left the Navy due to a conflict of interest). Upkeep for the machine includes staff, material, tooling, test and inspection.

Material - Drew Mallow

Drew's background is in materials. They are using IM7/977-3 at .182" wide. 10 mil. Towpreg is cheaper for IM7. Northrop is using 1, 12k tow of AS4 for a .157" width and .068" thickness (a "natural thickness" is lower cost). Toughened resins like 8552, 977-3 and E7T1 have less resin buildup on fiber delivery surfaces than untoughened like 3501-6. Material qualification costs $2 to 10 million. Thinner material twists more than thicker material (i.e.. .0055 vs. .010"). They are on their third iteration of cutter coating. Band cuts are less reliable than individual.

parts	size	material	notes
F-18E/F Horizontal Stabilator			sandwich w/ chamfered core
C17 Landing Gear Pod Fairing	10' x 10' x 5'	AS4/3501-6	sandwich w/ chamfered core
T45 Horizontal Stabilator		/8552-1A	replaced a part with fatigue problem
CRAD project w/ Northrop	various	various	
Pratt & Whitney Cowling			ARPA

Parts

On their parts with core, they oversize the core. This allows them to lay-up on a male, drop into a female and keep the bag on the complex side of the part. All of these parts were subcontracted and they are bringing work in house to be fiber placed. Unions do not understand this; they think fiber placement will eliminate jobs. The F-18E/F parts for EMD are hand-laid. Their first window for production is in the first month of 1997: LRIP for F-18E/F.

They lay up the stabilators as one piece end to end. This:

- reduces end effects and improves lay-up efficiency
- reduces tool installation
- reduces probe setup

Installation and setup benefits may not be realized if you have a dual spindle like Northrop. He expects one operator to be able to run the machine in the future (the machine will be fault-tolerant). They have a freezer and tool storage space in the lay-up room (room similar to Northrop's). They store spare material in the creel so they do not need to make extra trips to the freezer.

Status of ATP at MDA

Production procedures are not finished at present. They are validating the machine's accuracy: cuts and adds, etc. Cut tolerance depends on tow thickness. Design is concurrent. Tools need to be refabricated to eliminate sharp angles and abrupt contour. The lay-up tools are metal interior with plastic surfaces and cure tools are graphite. The software is not completely debugged at present. They presently have an engineer operating the machine. I did not meet the operators.

The Present Machine/Equipment

- 32 tow head, .182" tow and 5.82" bandwidth
- Minimum Cut Length is 4"
- Maximum part length is 37'
- 20 feet diameter tool capability
- Spindle has 80 ton capacity or 80,000 lb.
- Single Spindle
- 10 ton overhead Crane
- Presently one shift operation.
- Operators/Training - Operators are union and hand-picked (need intelligence). 4 are trained, 3 have a good process focus.
- On-site design, programming and simulation work station
- GE Fanuc controls and servos (matched).
- The machine is in a new room on its own.

The gyroscopic head on the Ingersoll machine is good for thicker materials. They are presently combining their gyroscopic head with the redirect roller concept for a 10th generation head design.

Machine Evolution - from the present

- Fiber Path - adding redirect rollers
- Debug NC program
- More reliable tensioning system
- NC parameters/producibility
- Automated spool replacement and loading in creel

At the Machine - Alan Rouge

Observations - The machine stops to make cuts. I felt scared when the head was moving forward and I was on the machine. The whole creel moves since it does not have a telescoping arm. There is consistent tow wandering at the beginning of each course. There also appears to be a substantial amount of tow wrinkling, but the ply seems to have been on the machine for some time (the tool is a flat plate and the laminate is the MDA insignia). They are validating and verifying the machine. Alan says the Ingersoll machine is rigid and more accurate than Cincinnati's machine. They have 1/10" tolerances on hand-laid, .08" cut tolerance and .04" add tolerance. They have observed no backlash on their machine with GE FANUC controllers and servos.

The Ingersoll head has a straight, airy fiber path

Design - John Kowalski

Unigraphics CAD system. Version 9, switching to version 10. RASNA 3d solid modeling tool does complex modeling. It is generations beyond FEA: it does fatigue analysis accurately. FEA does not analyze fatigue. Hewlett-Packard monitor, series 75 workstation.

The F-18E/F horizontal stabilator was hand-laid. It is two inner and outer skins sandwiching honeycomb cores. It has a torque box for connection to the spindle which rotates it. The torque box is made of hand-laid cloth and titanium ribs. These "bearing ribs" are highly loaded. They co-bond the skins and the honeycomb. This eliminated a splice plate which reduced assembly cost [some integration].

Concerns with fiber placement: primarily minimum cut length. You should design your ply drops for fiber placement. Make the edges parallel or perpendicular to the fiber path. You should also end plies at different locations (ramp), otherwise the tows will pull up.

Designers determine the method of manufacture, tow overlap (0,50,100%), guide paths, starting points and controlled angle or offset path programming. He gets together with NC programmers to discuss these parameters. Their design process looks like:

Design

1. Define part boundaries
2. Define cutouts
3. Build a ply table
4. Determine ply orientation limits: offset, hoop or control angle
5. Build a cutout table
6. Determine material - fiber, resin, thickness
7. Translate geometry to curvefit (text file)

NC programming

1. Generate Paths - also, compaction modeling (band narrowing)
2. NC code generation - post processor
3. Simulation
4. Intelligent Front End - arranges head location

He has a feel for where it will drop tows. Usually, they use 50% overlap for the best accuracy to expected ply boundary. Eventually, they plan to make a design manual for fiber placement. Hand-laid and fiber placed parts are analyzed the same way. Fiber placed parts have gaps that get resin rich. Mechanical tests show hand-laid and FP parts are structurally similar, but they have not done ice tests [Boeing had trouble with ice damage on fiber placed parts]. They always use a metal leading edge to avoid ice damage. It is easy to convert from hand-laid to fiber placement [they did little integration].

What parts are good for fiber placement?

- The bigger the better [my data shows an asymptote, tool complexity increases, but DFA with part integration drives the big push]
- Parts that have a complex mold line. Ply steering is a main benefit since you can follow a changing fiber axis and a load path [like the drag angle]

  - Parts where drops and lands are minimized
  - Cutouts should be aligned with fiber axis
- Ply lengths should be multiples of tow lengths
  - Wing with center holes - *see figure* - long courses which cross whole wing, but go around a hole without cutouts [would this stress the matrix & separate fibers? CM talked of study at Virginia Tech.]
  - Co-cured parts (stiffeners, ribs,etc.-eliminate fastener line and build up for stress concentrations)
  - Inlet Ducts
  - Laminates with hybrid materials.
  - Basically - skins, ducts and fairings [Bell added body of revolution]

Programming - John Henderson

The Off-line programming systems has similar features, but names are different:

Acraplace	OPS
fixed axis	controlled angle
parallel path	offset path

Ply angle mapping is where the designer can specify a fixed fiber axis in specific areas only. Hercules old programming system allowed you to program each path. It was called the Hercules design module.

They spend lots of time with gaps, overlap and accuracy. 0 indicates no overlap, a 1 indicates 100% overlap (same as CM). The OPS has a ply table which specifies the lay-up type for each ply: hoop, controlled (fixed) angle or offset path (parallel).

By the time the part gets down to the NC programmer, the only concern is producibility. For example, the Ingersoll machine lays 45 plies in the downward direction better than upward. Thus, they set it at 135 instead of 45 when possible. Other aspects:

- Path generation fills area between boundaries. Iterates to add and drop tows.
  - ◊ unit normal
  - ◊ feedrate
  - ◊ tow cut and add
  - ◊ x, y, z
- Generate NC files
- Simulation with collision avoidance

He learns the most significant effects from talks with Ingersoll who talks to Selma (the programmer). The machine has an intelligent front end that takes NC data and generates movement of the axes - x,z,j,e,b,a,c. John calls the IFE a post-post processor. It determines the orientation of the head. The simulation and the intelligent front end are similar. The program sets up collision pairs before the IFE or the simulation. The NC programmer or the operator sets the program parameters.

Process parameters

- Compaction force
- Compaction temperature offset
- Temperature at slow speed
- Tow tension [normally at .5 lb. w/CM, but Seattle did 2 lb. test]
- Creel temperature
- Head temperature

- Ribbonizer temp

Process time depends on part size and complexity. For example, the P&W cowling takes about 1 week for all plies at 8 hours/day. John recommends producibility improvements to the design team. The program [OPS] is really teaching him the idiosyncrasies of the NC system, not really producibility. For example:

- Concave tools with a corner are hard to lay up
- Sharp radii are tough
- On a cutout, the roller rolls right across, it does not retract
- The clear plane is there at the start and the end
- He specifies any extra retract distance for safety

Tooling

They do not use Invar. The F-18E/F stabilator tool is metal interior with plastic surfaces. Cure tools are graphite. The female tool is a "splash" of male master. Lay-up tools for validation were predominantly steel.

They have a "hockey puck" for automated coordinate reference between the machine and the tool. This is similar to a coordinate measurement machine. Once the puck is located on the tool, the designer identifies the exact location in the CAD program.

Future

- Production part pictures and drawings as well as size
- Pictures and/or drawings of production tools and their materials
- Brochure for the Ingersoll machine
- Specifications for their machine (1 page specifics)

Cincinnati-Milacron - Wednesday, October 18, 1995

- Don Evans - Process Engineer
- Joe Beard - Lab Supervisor
- Mark Trudan - Software Engineer
- Robert Harper - Technician
- Randy Kapesser- Product Manager

Presentation #1

Customers Report the Advantages of Fiber Placement are:

- Fiber Steering - allows non-geodesic paths & eliminates hand lay-up
- Individual Tow Cut and Add
- In-process compaction
- Higher Productivity in some cases

- Better Quality and Repeatability
- Reduced scrap: 7-10% vs. 50% with a Gerber or AGFM cutter
- Unitized Structures

Viper Features:

- 24 Tow Capability
- 7 axis motion
- bi-directional electronic tensioners (when dispensing and retracting)
- world coordinate system
- off-line programming system

5 dimensions of the CM machine:

1. System Machine
2. Fiber delivery system
3. Off-line programming system
4. Machine control (A975F, A975C used on tape layers)
5. Customer service (local, service parts, re-manufacture and retrofit)

Presentation #2 - at GLCC

History of fiber placement at CM -see slides in GLCC. Complete production system:

- Off-line programming system
- machine & control
- Fiber Delivery System
- Knowledge and experience

Some parts which have been made: Comanche upper tail cone, 747/767 cowling. A process Engineer defines the process steps. Where are machines? 1 at Northrop-Grumman, 1 at Boeing Helicopters, 1 at Thiokol, 2 at Cincinnati-Milacron (1 for GE blades, 1 leased from GE), 1 being built for Raytheon. What they do at CM:

- Part Making
- Machine Supplier
- Tooling
- Productivity Studies - i.e.. slowdown regions for Northrop
- Performance system supplier

CM is an experienced supplier and an experienced producer of FP parts. They provide:

- NC programming
- Machine
- machine controls
- fiber delivery system
- process knowledge
- service and support

The GE90 fan blade video

- >600 plies at the base
- < .100" at the edge
- The root is 3"+
- Lay 2 blades at a time, root to root
- 0,45,-45 orientations
- Initial Zeros were laid at a reduced feedrate
- Completed blade was 35 lb. (same as hand-laid part)
- They have a dual mandrel - safety interlocks for safety
- GE90 used a significant # of debulking operations, but fewer than hand-laid
- A big advantage was reduced scrap

The following is GEAE's position regarding the sale of the fiber placement machines.

"The use of fiber placement technology for the manufacture of the GE90 composite fan blade was successfully demonstrated. The machines performed the lay-ups at an acceptable quality level and demonstrated savings in both labor hours and material input. GEAE's decision to not introduce the machine into production was purely an economic decision based on high efficiency demonstrated by the hand lay-up process versus the cost required for recertification and machine acquisition, which offset savings projected over the next several years."

Manufacturing - They make parts to sell machines (risk reduction).

Feasibility Studies - mostly to sell machines

- Generic or specific parts
- Design for fiber placement to increase productivity
- Making the software more efficient for fiber placement. This is beyond Selma/Ingersoll who are proving their programming system.
- Cycle time determination

Why they are making parts:

- Equipment development
- Proof of concept
- Limited production runs - risk reduction
- Test articles
- Further process and machine development

Development is customer driven. They are developing:

- FEA interface
- Increase productivity through (1) laying more material per pass, (2) laying faster and (3) reducing downtime
- In-process monitoring/Inspection
- For the head: segmented roller, straight chutes, well-organized head package
- FP lay-up rate is lower than tape lay-up or filament winding

The market and competitors

They expect fiber placement could be as common as profiling in the aircraft business, but it is coupled tightly to the success of composite parts. Their installed base will depend on implementation as well as the supplier technology and military contracts. Boeing Fredrickson took 10 years for their tape layers to be implemented in production capability. CMI has an installed base of 30 tape layers (Ingersoll is substantially less). They need to educate people about this technology. CASA uses 3 tape layers. Competitors are Ingersoll, ADC, alternative processes like tape laying, pultrusion, filament winding and hand lay-up.

Answers to Questions

Hoop plies must start at course beginning or inhibit a tow and replace. Thus, may not be as productive as expected and head reliability is critical.

Reference: Dr. Michael Hires at Virginia Polytechnic, wrote paper which discusses steering around a cutout vs. tow adds and drops.

Design - producibility - Don Evans

Slide with #/hr vs. course length, bandwidth was 24"

tow width	.125"
tow thickness	.0055"
tow density	.058 lb./in^3
laydown rate	800 ipm
course end cuts	0,45, 90 degree
non-cycle time	30%

Steered courses are slower than all three because the machine speed is limited by the slowest axis: i,j,k. The part radius limits motion because the fast movement of the axis to maintain normal forces may result in slower roller movement.

CMI has drawings for course length vs. probability of stoppage and #/hr vs. course length with feedrates called out. At higher rates the curved chute may build up faster so operators turn down the feedrate below 800 ipm (good for tack)

Feedrates

Cincinnati-Milacron usually lays the first ply at 400 ipm and the next plies at 800. The cut speed can be changed based on accuracy of cut and reliability of the cut.

As laydown rate increase the chute buildup increases. The 400 ipm used at Boeing may help reduce chute buildup. Problems observed during fiber placement

1. tow bridging - observed on ADC/Maclean Anderson
2. tow wrinkling - observed on Ingersoll/ADC
3. tow wandering - observed on Ingersoll/ADC
4. tow twist - observed more on CM (thinner tows)
5. fuzz - observed more on CM (3501-6)
6. stringers - observed more with towpreg
7. tack - less important for Ingersoll/ADC due to straighter fiber path

Improvements with downtime for GE blade. They changed: speeds, feeds, forces, programming (changed by putting the start point at the widest portion and lay to smaller width portion because cuts are more consistent than restarts) and step size.

Programming - Mark Trudan

The programmer can define slowdown regions like on the F-18 side skin cutouts. Process regions can be specified in CATIA to slow down the feedrate. This was developed for Northrop's F-18 side skin.

Radial error correction - a feature in the post-processor (NC generation). It adds data process points around corners. This is ***similar to Professor Gutowski's theta/delta theta - see the drawing in the logbook.*** The parallel ply on a complex contour will be completely different than a fixed angle ply. Path lay-up types:

- parallel
- fixed
- limited parallel
- helix

Release 2 has a feature called smart retract. It only pulls back as much as needed and will follow the surface for contoured parts a specified distance away (uses collision avoidance). This can save up to 15% of retract time for complex parts.

There really are 3 types of delays: (1) contour, (2) control delays and (3) end effects. Retract is also a delay. Bi-directional lay-up is more efficient for long length courses.

Tooling

Their average time to install a tool is 30 minute to install a flat plate and align it. It is 1 hour for a large tool. Check the mandrel acceleration rate in the operating manual.

Tool location is performed by placing cross-hairs on the tool and having two operators manually align. Bob Meier knows machine dynamics. He is available at computer area.

Bell Helicopter - Wednesday, October 19, 1995

Equipment suppliers, manufacturing engineers and managers can learn a lot from Bell.

- Dan McIlroy - Manager, Manufacturing Research and Development
- Kevin Sewell - Chief, Rotor Technology, MR&D
- Ron Measom- Senior Engineering Specialist, MR&D
- Chuck Baskin - Group Engineer, V-22 Rotor Design
- Jim Lang- Group Engineer, Materials Engineering

Initial Impressions

Bell is in business to make money. There is a lot to learn here as a concurrent engineering case study. Their fiber placement is equivalent to a Motorola success story. Additionally, they have the first cost conscious culture I have seen in the aerospace (or equipment supplier) industry. They quoted part size and the amount of hours for each and every part. Floor workers had this information. One drawback, some employees spoke of the Navy as obnoxious rather than a customer with important needs.

They drove this project home with perseverance and developed the process/equipment when it was not yet developed to make small, thick parts efficiently. Bell realized the CM or Ingersoll machines would not laydown quickly with this part because individual tow restart and cut is slower. Also, towpreg has more tension on the roll: more stringers with tackier (non E7T1-2) material. They specifically designed this machine to cut at full speed, stop and then back up to start the next course. These cuts are needed so the grip will expand into the bonding tool when the silicone rubber bag pushes the IML into the tool to form the OML surface. The restart is low friction with larger diameter spools, E7T1-2 resin (first BP, now Fiberite), slit tape for width control and straight fiber paths.

There were other steps to increase the laydown rate (final laydown times for the grip. 110 hours for an 85 lb. part). They doubled the tow thickness (to .015" from .0075"). Manufacturing convinced designers to shift the coverage area (allow non-exact ply boundaries but maintain fiber weight & orientation). This allowed them to increase fiber bandwidth to 1" (8 tows laid with a bandcut. This allows steering but no individual cut).

The Automated Dynamics delivery system is similar to a polar winder or the Ingersoll delivery system. There are very straight tow paths and lots of air. The straight chute has the capability for tows up to .028" thick. This allows for easy switching of material thickness. Their machine did not have the capability to change tow width easily. Neither does the Cincinnati machine. The Ingersoll machine and the AD/MA machine both have substantial tow wandering at the start, then it smoothes out.

The programming software is a DOS-based off the shelf shell that was tailored for their application. It seems less flexible than the Viper's or the Ingersoll machine, but it works.

Summary - Bell concurrently designed the part, chose and qualified the material, developed the equipment and the manufacturing process. They implemented a system that is substantially cheaper than the other two brands. This fiber placement machine is more dedicated versus the flexible manufacturing systems made by CM and Ingersoll. This is more like a transfer press or some other equipment in the auto industry.

Development - Ron Measom

They evaluated .25, .5 and 1.0 inch bandwidth. Since only the cure thickness really mattered and build-up shapes did not have to be exact (fiber volume is what they needed), they went with a 1" bandwidth. Tow adds and drops were slow and unreliable since they had short courses.

Their lay-up mandrel is actually smaller then the IML so the part can be expanded by the silicone rubber bag. The part is longer than the bond tool because the steel tool has a higher coefficient of thermal expansion. The tool was made of steel to reduce cost. The diametric CTE of the grip is actually higher than that of steel. Due to the high content of ± 5 degree fibers, the diametric CTE is resin dominated. The linear CTE is very low, but since the part shrinks slightly away from the steel, the part matches the tool.

The material was chosen based on trials with a 28" (smaller) grip. Back then, slit tape had fluff - an area with no resin. This clogged the machine. Towpreg had more consistent resin and thickness. Then, they decided to pre-lay two plies together. This increased the lay-up rate and the randomness of the dry spots eliminated the problem. Tape was also thicker and easier to manage. It will take .028" thick tape. They change cutters once or twice a month (about 2 parts per cutter life). They decided to use a 6" diameter spool to reduce tow drag. This will reduce stringers because you have more leverage (torque = force x distance; with torque constant force on tow is reduced).

Management/Strategy - Dan McIlroy

The rotor craft business is a narrow niche of the $8-9 billion helicopter market. They have 50% of the civil market. They have a broad product line which ranges from light to medium helicopters (the V-22 is a "heavy" helicopter). Most of their sales are light and medium weight helicopters.

They have a continuous quality improvement focus. It is mostly based on reactive problem solving. For example, they rotor blade is very sensitive to twist. They have +-15 minutes. They analyzed what manufacturing process effects the twist and determined it to be the press. When the blade comes out of twist, it increases vibration. They want a robust product early in the product line. Another example, scoring on couplings. All scored couplings were from one grinder: the one which used an aluminum oxide grinding wheel (vs. SG abrasive). They rectified this. They are mating machines, equipment and methods. They must treat manufacturing support test as important as design tests.

They make most of their money on spare parts. Jim Lang spoke of a commercial which showed that the cost of a Jeep Cherokee is the same as the V-22 Yoke.

Marcelling Case Study - Kevin Sewell

They have observed marcelling in the V-22 yoke. Marcells are a problem because designers reduce allowables because fibers cannot carry loads as well across wavy plies. They had this same problem with the V-22 grip, but it is fixed. Marcelling occurs in the autoclave and is more prominent among thicker parts. They performed two L4 designed experiments to determine an improved process for the autoclave. They started with smaller arrays to gain an understanding. Then, they replicated their best and worst cases to reduce marcelling and porosity. Marcelling (fiber waviness) is caused by high viscosity resin pushing the fibers while trying to flow under pressure. Ramping temperature slower and introducing pressure later (after viscosity drops) solved the problem.

The V-22 Wing Skins

They averaged 1250 hours to hand-lay the V-22 wing skin on the FSD program and 650 hours to tape lay the wing skins on EMD. Other benefits from tape laying are reduced inclusions, reduced FOD and increased repeatability (quality). This is a 400 lb. part. Large pieces are easier to automate.

Automation - Dan McIlroy

- Cutting – Ultrasonic (AGFM @ 1250 ipm) and reciprocating cutters (@ 300 ipm) and an NC core profiling machine.
- Layup
  - ◊ Laser Optical Layup Templates to assist hand-layup
  - ◊ Spindle winder - wound the spindle and yoke bands
  - ◊ Helical and Polar Winders
  - ◊ Fiber Placement - In the future they may fiber place the spindle
  - ◊ Tape Lay-up - laid the V-22 wing skin
- Cure – presses and autoclaves
- Trim – abrasive waterjet, robotic
- Inspection – Robotic Ultrasonic through transmission
- Assembly - mechanized installing of stringers on wingskins

Polar winders provide the bulk of unidirectional material for spar and yoke fabrication. Helical winders wind around a surface of revolution.

Why automate?
- The machine tool must negotiate the geometry
- Improved lay-up rate, quality, repeatability, and reduced setup times
- Step function improvement in lay-up rate

They do not buy expensive machines for experiment. Only for application. They do have RTM, autoclave and inexpensive equipment for experiment. Since they have a small company, they must be confident of the payout of the project - machines increase capital cost and expense of a program. They perform detailed sensitivity analysis when evaluating capital projects. For example, they look at 100% tooling cost overruns.

They invest to protect their core businesses: (1) rotor blades and (2) transmissions/gears. Since core is an important aspect of rotor blades, they will do their own core profiling rather than purchasing a profiled part from Hexcel. Additionally, CNC gear grinding equipment is key [one problem I see - competencies are not maintained through technology, but people]. They place 5 factors above financials:

- Reliability
- Safety
- Product Line
- Future (Strategy)
- Quality

They have 50% of the commercial marketplace. Their commercial assembly is in Canada. They do perform component manufacturing in FT. Worth for the civil market. Bell full scale tests every transmission and rotor blade. Competitors do not.

History of Automation at Bell

1975 - first filament winder
1980 - NC filament winder
1983 - Ingersoll tape layer. It took 10 years to implement software
1992 - ADC/Maclean-Anderson fiber placement for the V-22 grip on EMD.

Filament winders are ideal for parts with a constant cross section like a drive shaft.

Success in Automation

What is the key to their application of many technologies? Perseverance. For example, consider the grip at the start. There were many obstacles, but they knocked each one out one by one for 2 years developing the head and the process and 1 more year for developing the part. They were less successful with the waterjet because it has low tolerances and is more difficult than hand routers. They have not patented many ideas since they are not in the equipment supplier business and patents are expensive. They also had obstacles when they first started filament winding: it was a wet process that is messy. It was also mechanically controlled (vs. NC). Then, they had a hand filament winder. Tape laying took 10 years to take hold due to software difficulties.

They iterated to find a solution. They linked the pain and the cause close together in time and space to have satisfactory reactive problem solving. Their boss' motto is "failure is not an option." He will throw resources, etc. at something to make it work.

Manufacturing

Automated Dynamics modified a 5 axis Maclean Anderson filament winder. It worked better subcontracting this because Bell is in the application business. They develop machines, tools, etc. for manufacturing parts, not selling equipment [that is how we did it in the oil industry - a low cost, commodity product].

Material for the grip - Kevin Sewell

IM7/E7T1 material is slit tape. Towpreg induces more tension which causes bridging and restart problems. Tape is wider than tows: 1/8" tow with 1/2" backing strip. This reduces stringers 100%. 5 lb. spools reduce downtime and out time. There is a knockdown for gaps, but on a thick part this does not matter [testing treats it as a continuum anyway].

Filament winders have an increased tack tow which causes stringers. Kevin demonstrated this by having me pull on a tow on a filament winder. It stuck, then released, stuck, then released, etc. as it fed out. You throw away the ends of a filament wound part.

Material - Jim Lang

The materials group supplies material for FP. All are very new: material, equipment, process, integral part design. They chose IM7/E7T1-2 and went about qualifying it while others were working on the part and equipment design. E7T1 is a low flow material, has toughened resin, and 50 ksi in a compression impact. They wanted a toughened resin with a cure temperature above 250 degrees (IM6/E77-3 in FSD) for better mechanical properties in hot/wet performance greater than 180 degrees Fahrenheit. Their primary screening test was a short beam shear fatigue test.

The material they chose had good fiber placement attributes: low flow and low tack. E7T1-2 flows at temperatures above 100 degrees F. Therefore, it conforms well, but does not have high tack. Also, it is good for cavity mold press cure since it has low tack and intermediate debulking.

They started evaluating E7T1-2 during the LH program in the mid-80's. The goal of this program was to have a 7,500 pound flyaway weight aircraft. On this program they characterized material properties. They bought slit tape for width control. IM7 tape is cut to 1/8". Slit tape is specification #299-947-350. The qualification report is 901-930-072 for IM7GP/E7T1-2. A fuselage structure is much different than the thick grip. With the grip, there is enough safety factor to allow laps and gaps. The V-22 EMD Materials Test Plan is 901-991-017, rev. D.

Qualifying Material

- Control slit tape dimensions and shipping temperature
- Coupon Tests (material characterization)
- Actual structure test (point design allowables)
- Full Scale test (3 for yoke and 1 for inboard blade)

They developed materials, manufacturing process, equipment and design concurrently. The IPT did not have full buy in with management. People felt they were wasting time in the meetings which they did not always need to attend. Support for the IPT faded. An agenda communicated prior to a meeting allows people avoid attending meetings unnecessarily.

Navy did not want to use E7T1-2 or ADC fiber placement. Bell knew they would use this material. Navy wanted a Hercules machine (A Navy person pushed Hercules' products). They proved out the structure, but they did not show the Navy material's comparison because they did not want to give the Navy ammunition. The Navy was obnoxious & demanding.

Material choices - Jim Lang

1. 12K roving - non-controlled, Fiberite
2. towpreg - .125"+-.01-.015
3. split tape - roving sent to Web Converter, then Bell. .125+-.002"

Their MRP system usually accounts for scrap. The computer normally buys 25 to 50% extra. They buy uni-tape which can be used as tape or tow on several different parts. If they need tow, they send it out to convert it into slit tape. The yoke star pattern causes a lot of scrap: it is a 188 lb. part, but they buy 540 lb. of raw material

The Present Machine/Equipment

- 8 tow head, .125" tow, 1" bandwidth
- Tow thickness is .075", doubled is .150", available is .28"
- MCL is 2.1"
- Maximum part length is 15'
- Material is slit tape
- 4' Diameter tool capability
- Single spindle
- 2 shift operation
- The two machines are in a room with filament winders and other hand lay-up.
- Operators/Training - one operator stands near head while it is operating

The operator usually sets the machine at 62 to 70% on feedrate override. The machine uses nitrogen for heating and cooling (E7T1-2 does not need to be cooled at the head). The z axis can move at 400 ipm. They have a very straight fiber path from the creel to the part. I never saw the head stop for jams or cleaning while I was there. The machine cuts purely on the fly. They have locator strips for X-ray. I do see tow wandering at the start of most courses.

Design - Chuck Baskin

Rotor inertia is good so helicopters can hover to the ground with engine failure and have several tries to fan the blades at landing (basically, rotating the blades slows the landing speed). This makes lightweight composite blades which only give pilots one try to land during an emergency less desirable.

The quality of the FSD grip was lower: laminate quality, porosity and wrinkling. Cost was also higher. Design and manufacturing development wanted automation. For automation:

- They redesigned the part to eliminate one of the higher loads
- They smoothed out radiuses and wall-section variation
- They chose a head width which accommodated the curvature
- They reduced tight radii

Originally, they thought they would not fiber place, but they designed the part for fiber placement as well as hand-layup just in case the technology was ready. For example, they designed plies so that single or double plies would be acceptable. Soon, they found that fiber placement would be feasible. They defined plies in 3d space then generated machine commands from CATIA. Additionally, they produced the mandrel with this information. Engineering wanted to completely define the ply, not have a ply interpreted by manufacturing engineering. Once cross-sections were defined, it took six months of iteration between the groups to get acceptable plies. They did this using IPT's, but it was their first try and there was some friction.

Chuck learned that the simpler you make the ply, the better off you are. They knew they wanted to lay as long of course lengths as possible. Therefore, they allowed a deviation from theoretical angle of ± 5 degrees. The software was capable of generating paths within this tolerance. They did not reorder ply orientation for cutouts on this part.

Programming - Ron Measom

ICAD is their 3d CAD package. They translate this to an IGES file. They combine the IGES file with a *.ply and a *.pis (a series of parameters like bandwidth, angle, strip length, tolerance, etc.) and enter it into the computer machine control module from ADC. This generates a points file (path), mandrel file, boundary file and a KNT file which is the NC code. Autoplace is run on a 486 machine (vs. SGI workstation for Acraplace). The software is a shell that has been modified for their application.

Northrop-Grumman • Friday, October 20 and Monday, October 23, 1995

ITAR limited some of the discussion and what I could take home. Still got very good information. Equipment suppliers, manufacturing engineers and managers have the most to learn from these guys.

- Flerida Uldrich - MR&D
- Bob Young - Manager of Automation .
- Tim Coyle - Manager of Composite Center of Excellence
- Rick Price - Designer
- Soeman Saha - Affordability Management
- Steve Span, Dennis Van Winkle, Jim, Keith and Randy - NC programming
- Joe Loughmiller - Operator

Initial Impressions-

One good thing they did was to convert parts from F-18C/D to F-18E/F cleverly. They have not integrated these parts, though. They were good at maintaining the minimum cut length by distributing windows through the plies. They did not align window edges with tow directions, even though they recommended it. They hand laid a section that was short, thick and complex. I wonder if they could design this portion out.

A great idea is the paperless factory: a system which gives workers and managers information on delivery schedule, statistical control, and work cell financial performance. It also eliminates the humongous paper trail so common in defense firms. It will reduce the need for support workers handling paper as well as free up I.E. folks from arranging schedules.

Another good idea is their "pull system" which they implemented, lost on F-18E/F and are trying to re-implement. Bob Young had an excellent system focus that I did not see other people mention as explicitly.

Finally, I like their idea to train workers to inspect their own work. Many of these changes are possible because they are a non-union shop.

The managers are forward thinking, on top of emerging issues and aware of resistance to change. They are adopting automation and quality management concepts with the goal of continuous improvement. They seem to have the second best cost focus next to Bell Helicopters, but their quality focus seems greater than Bell's.

Development - Bob Young

In 1986 they had a memo of agreement with Hercules and MDA for the head. They had looked at tows and material. They designed their own head to fit on a Cybotech gantry robot. By 1990, the agreement faded because each company felt it had special technology and did not want to share. MDA and Hercules continued to develop the machine that would become the Ingersoll machine.

During development, they also laid thermoplastic preforms on FP machine, then cured the part to consolidate. The challenge with thermoplastics is that they did not stick together or to the tool. Layup time for thermoplastic parts is 3x thermosets because thermoplastics do not stick (low tack). They know this from experience laying up PEEK.

How they helped Hercules: They had helped Hercules with cutters. Hercules did not have the software expertise that Northrop had. They had already written a program for the 7 axis gantry robot for a duct.

In 1990 they had

- A 7 axis gantry robot
- Software, programming, tooling and equipment development
- They felt they led the industry in this technology
- Experience laying thermoplastics (AS4/PEEK), BMI and epoxy
- They wanted to develop a thorough understanding of FP technology
- Development was funded internally and by CRAD
- Fiber placed flat panels, over core.
- Wound ducts w/ flat tools lying on the ground

The Duct

It was evaluated for production on the F-18E/F at Hercules and Northrop. They qualified materials - allowables and consistencies, specifications, the manufacturing process, inspection and training (inspection, operators and designers).

Inspection

MDA and Northrop specified guidelines that say no gaps are allowed, but some overlap is OK. This guideline is designed so inspectors will not spend an excessive amount of time. The reason for their rule on gaps is to maintain part allowables even with hand layup. 1/10" was acceptable over some large distance. Gaps must not be aligned. They stagger or alternate plies to avoid this alignment of gaps.

They have made lots of parts over the last 10 years. They have lots of experience despite lack of production.

Their production material is AS4/977-3. They have used towpreg (Hercules licenses resin from Fiberite) as well as split tape. Presently, they are using split tape. Early problems with towpreg were cost and width control. Early problems with split-tape were (1) fuzzing - fibers at the edges of the tow width come off [sounds like stringers] and (2) cellophane tape was not removed when material was taped and heated to splice the split tape together at the supplier. A benefit of slit tape is that it is tackier than towpreg, but it is less susceptible to stringers.

They are presently leaning toward slit tape because:

- Fuzzing has been eliminated
- Slit tape has more accurate width control (wide tows jam, thin create gaps)
- Slit tape is cheaper

They bought the CM machine specifically for the F-18E/F (they expect 30 parts). At present, they will make the 2 aft fuselage side skins as well as the ten (5 x 2) pieces for the engine inlet ducts. They will do R&D on this machine when capacity is available.

Great Lakes Composite Consortium Presentation (and videos) - Flerida Uldrich

The objective for the F-18E/F fuselage skin and ducts is to move the FP technology from R&D into production at Northrop. They are taking a conservative route by not doing part integration, but by proving out the technology on parts that could also be hand-laid [as opposed to Boeing who has designed parts which can only be fabricated on FP].

For a risk reduction project, they fiber placed 3 BMI ducts for the YF-23. Both Northrop and Hercules had their own path programs and both worked acceptably. The Northrop gantry machine laid three ducts and Hercules FPM#2 laid 3 ducts. They had hat stiffeners [they predominantly use hat stiffeners since hats are cheaper, but Northrop mechanically fastens ($) the hat stiffeners (vs. the cocured J stiffeners at Boeing)].

The testing they did on the ducts was for fuel pressure and hammershock:

- Fuel Pressure - a pressure from the fuel bladder which is next to the inlet duct.
- Hammershock - the projectile hits and penetration causes magnification of the pressure front the radiates out and around the composite (imagine a water droplet filmed under a strobe with high-speed photography).

Material

- Fiber: AS4
- Resin: 977-3, resin content is 32%.
- Width: .182 +- .002"
- Process Specification - overlap at end of tow, gap allowances depend on part complexity

F-18E/F Fuselage Side Skin Development - Bob Young

The Program - They are making 10 F-18's for E,F EMD.

The Part - Since the part has lands with sharp joggles and complex cuts, it was a good candidate for fiber placement. The part has no core. It is integrally stiffened with hat stiffeners (see the picture). They avoid core due to problems with core migration and core crushing.

Operators - Northrop is using NC machine operators. They thought it was easier to teach people how to make composites than to teach operators a process focus which is needed for automated equipment. [this is opposite of BH who uses 3 composites fabricators and 1 clave operator to run the fiber placement machine]. They will probably have other people bag parts, not the fiber placement operators [this is what BH does].

The process - The process to make the GLCC part was:

Full plies were fiber placed at Cincinnati-Milacron, but small buildup plies were fiber placed because many courses were below the machines minimum cut length.

1. Skins were packaged for shipment
2. Hat stiffeners were added at Northrop in Hawthorne
3. The skins and stiffeners were cocured in Hawthorne's autoclaves

A layup of 6 pounds per hour was calculated from the machine's log. They expect 10 pounds per hour during production [I expect less since those development pieces were full plies without cutouts - adds and drops will reduce the layup speed].

Lessons Learned and applied to the FA-18E,F production parts:

They effectively modified ply stacking to maintain cutouts as well as the machines minimum cut length. There are three effects of this:

1. Shoulder and land regions were unchanged
2. The ply sequence was changed
3. Windows were redistributed throughout the plies
4. Part is 100% tow placeable

Analysis suggests the part strength will be unaffected. The did not verify strength experimentally, yet.

Cost Analysis of the Developmental Trial at Cincinnati-Milacron

They simulated the production environment in Cincinnati with their operators. Labor costs were 62% of the hand-laid version & material cost was thought to be lower due to a lower buy to fly ratio for fiber placement (hand-laid is 2:1 where fiber placement is expected to be 1.5:1).

Management/Strategy - Tim Coyle

Organization at Northrop, Hawthorne Plant. The General Manager is the highest ranked in the facility. The Vice President's are below the GM. Tim Coyle's boss is the Vice President. Tim's title is the Manager of the Composites Center of Excellence.

Background/Experience. Tim has a degree in Biology and Chemistry and an MBA from Pepperdine. His experience at Northrop is in R&D and Production. In R&D he was in QA in the 1970's. Then, he joined Manufacturing Technology for several years. Then, he switched to the production side of the business. He began with 6 years in assembly. In 1986 he began working with composites and he has managed the CCE for 3 years.

Over capacity in the industry

Even within Northrop there is over capacity: there are 4 composites manufacturing centers and corporate only wants 2. He expects the Hawthorne facility to stay open as the manufacturer of smaller, complex fighter aircraft. Hawthorne's noteworthy equipment is their tow placement and autoclave. The B2 facility in Pico Rivera is well suited for manufacture of large, cutting-edge technology aircraft. Presently, the industry is at 30-40% utilization of capacity.

Northrop Commercial Business

Their commercial business is nearby. They make 747 fuselage section structures and ship them to Boeing in Seattle. They recently purchased Vought and merged with Grumman. Vought is in Dallas. Vought's manufacturing capabilities fit well with commercial fuselage fabrication because they have metal bonding and an assembly footprint with requisite equipment.

Future of Tow Placement

They have 30 F-18E/F parts lined up for tow placement. They are planning to buy another machine during LRIP. The biggest advantage is direct layup (see Soeman Saha's diagram). A person lays at best 1 pound per hour. They expect 10 pounds per hour from fp. In Cincinnati they measured 3-3.5 pounds per hour with a stopwatch.

Work Flow

Their bottleneck is the after cure area: trim, drill and NDT. These areas are skill oriented and there are only a few trim bays. Additionally, it is hard to motivate people when they are downsizing. They have a bottleneck with people sealing cocured honeycomb panels.

Switching from Gerber cutters to draw knife

They had reciprocating "Gerber" cutters which cut 7 plies at once which broke down once a day. They were not working 1/2 of the time. The machines were old and did not have spare parts or software to support them. Tim was prepared to spend about $2 million to buy new machines. Then, one of their I.E.'s went to SAMPE and saw CEI (cutting edge machines). They did some test cutting and bought 3 machines for $500,000. This improved the cutting capacity as well as the work flow. Now his biggest problem is material handling.

Materials Handling

Composite materials have a limited shelf life and inventory is a big cost. For example, they recently purchased CEI prepreg cutting machines which are faster than the old "Gerber" reciprocating material cutters. The Gerber's cut 7 plies at a time, but this batch production required a lot of inventory. Raw inventory under the "push" system was $1.5 to 2 million. The faster machines and reduced variation allowed them to go to a pull system until schedule pressures with the F-18E/F caused them to go back to their old ways. Under the pull system, inventory was reduced to 1/3 of original values ($666,666). This translates into a reduction of 30% of direct cost.

They are benchmarking Levi Strauss and Langendorf bread to learn how to improve their material handling. They want to know how to load the area with people to keep the machine loaded. They are looking for the paradigm shift, not just the incremental improvement. Langendorf is similar. They have (according to Bob Young):

- perish time (out time)
- cook in batches (autoclave)
- QA issues
- the recipe changes

They also reduced their clave batch size since autoclaves are not a bottleneck. They have 5 or 6 cure cycles a day. They are also working to combine cure cycles [simplify and standardize - like material with tow placement]. Out time is actually the primary driver for thermoplastics: they do not parish.

During 1994 they started playing "the Kanban game." This demonstrates the benefits of the pull system vs. the push system. In this game you sign 5 cards, then you pass them to the next guy. Then, he signs 5 cards and push them forward. The guy with the long name or arthritis ends up being the bottleneck. Then, you sign one card only when the person in front of you asks for one. This allows them to substantially reduce inventory.

They expect to implement a system in the future called the "Paperless Factory." It may not save workers time, but it will reduce the direct support staff required to process the paper: I.E., Manufacturing Engineering, Planning, etc. Presently, this is done with shortage meetings. The system will give daily reports for him and it will share financial and quality information with employees and management.

They are facing a large barrier to implementing the paperless factory. The company is non-union, but there is still a poor incentive system. Their seniority system does not reward workers for doing a good job. Efficiencies are one extreme and piece parts are another. They have a standard system which tells people how long they have to make a part. People are not rewarded for taking less sick time. Managers with lots of experience do not like making decisions with data, their intuition and experience built over the years is how they make their decisions. They overcome the barriers with persistence and mild threats. If he goes down to the floor and talks directly with the workers, the managers below him are often offended.

Their present focus is on improving quality by building quality in. They are training workers to document their own defects. The people are rewarded because they do not have to have inspectors looking over their shoulder. In the old days they linked the defect rate to pay by having inspectors whose job depended on defects being present. To avoid more barriers he has reassured inspectors that they will be hired as workers and he tries to be straight with people - for example, he will tell people when and how many workers will be laid off.

Present Efforts

The driver of these efforts is to reduce costs to stay in business. They do not want to reduce costs by outsourcing because they want to maintain their competencies.

- Capacity is at 30-40% utilization.
- Quality - Workers inspect own work. Use SPC on trim, drill & countersink.
- Pull System

Automation - Tim Coyle and Bob Young

OLT - these are beginning to replace Mylar and hard templates. They see a 50% cost reduction with this.

Trim - they are buying a 3 head waterjet: it has a waterjet, a router and a measurement fitting [Boeing's trim cell has these]. They have a 5 axis NC router for metal and non-metal honeycomb.

Paperless Factory is a MRP system on a client/server network with SUN servers. A work flow monitoring and control system. It provides instant feedback about material coordination, statistical control, etc. They face resistance because it infringes upon everyone's work privacy. See initial impressions on Northrop for more discussion.

See book on composite manufacturing at their facility. Everyone is tied to the process on page 3 when making composites. The goal is to do this process as efficiently as possible: reduce risk and reduce cost. Automation helps both of these by improving repetition and reducing labor cost. Then, you automate for strategy reasons: to direct where you want to be in 10 years. Always consider automation in a system (T,I,OE).

Presently, they are automating trim and drill because they are bottlenecks and are the most labor intensive. They previously automated:

- ply cutting - draw knife vs. Gerber - 7 plies at a time, lost parts, WIP on ice
- layup - fiber placement, I am not sure about others
- trim - gantry with waterjet, router and measurement

Match manufacturing process with product and business strategy - They are creating a flexible system to adjust for outputs and flex for a differentiated product in this business.

Management (Financial) - Soeman Saha

Soeman is an "Affordability Manager". Ext. 1-4998. Part affordability evaluation must be done on a part by part basis. The charts on the following pages show there are many dimensions.

Labor

std. hours	Hand Layup	std. hours	Tow Placement
60	Cut Plies Kit Stove Freezer Layup Debulk	30	Layup Tows
40	Vacuum Bag Cure Trim Finish NDT	40	Vacuum Bag Cure Trim Finish NDT
100		70	

Material

Fiber/Resin	Fabric ($/lb.)	Split-Tape ($/lb.)	Towpreg ($/lb.)
AS4/3501-6	33	35	35
AS4/8552	41	42	43
AS4/977-3	58	60	96
IM7/977-3	80	84	120
Buy to Fly Ratio	2:1	1.5:1	1.5:1

The improved buy to fly ratio happens at layup only (tow placement has no losses due to cutting). Double numbers at EMD. Scrap happens at several stages:

1. Gerber cutting
2. Excess Trim
3. Scrapped Parts
4. Shelf Life
5. Damaged Parts

Accounting is assessed to direct labor [this overstates the cost of labor versus machines]. The employee/worker is 10% of the direct cost of the airplane. They will not lay people off as they buy new machines. They will just not re-hire people. You must design the part with tow placement in mind. To do this you need to consider:

1. Equipment Capabilities
    - speed
    - tow cut and add
    - return speed
    - # of stations
    - minimum land width
2. Head Capabilities
    - Axis
    - roller width

- tow width
- tow thickness
- number of tows
- minimum land width

The Present Machine/Equipment

- 20 tows of .157" width for a 3 inch bandwidth. Expandable to 32 tows: just replace the head and the delivery system. Wiring is already there.
- MCL is 4.1"
- 12 feet diameter tool capability by 39 feet in length
- Spindle has 80,000 lb capacity
- Dual Spindles
- 4 ton crane, switching to 11 ton in February 1996.
- Headstock and tailstock move electronically
- 2, 10 hour shifts with maintenance in the evening is expected.
- 6 operators by early 1997. NC operator with layup and bagging qualifications.
- The machine is in a new room on its own. Room for expansion to 2 machines with 3 spindles. Then, share the spare spindle.

They have 2 stations primarily to eliminate tool setup and removal time. They can also do bagging on the second spindle.

System Focus

Batch processing does not consider the whole system. That is one of the problems with the ACT program. When designing and manufacturing, think of the whole process: layup, cure, trim and inspection. Also, simplify the system:

input ---------> system -------------> output

The system has some elements. Minimize the elements. Ideally, cure the part individually.

Material

Why use split tape?

- More accurate
- De-spools easier
- Less sensitive to temperature (towpreg spoils at room temperature)
- Cheaper

Design - Bob Young

There are two types of design with ATP:

- Converting hand-laid parts to ATP

- Design for ATP

Converting hand-laid parts to ATP is tougher than direct design for fiber placement. He has several recommendations:

- Align windows with the fiber path - this makes the part stronger and reduces adds/drops. To do this you should design the EOP, generate paths with NC and go back and align windows with paths
- Distribute cutouts throughout the ply - you test the homogenous product as a hole, not individual plies anyway.
- Align cuts perpendicular to the fiber path

To design a fiber placed part you really need to imagine the layup. You need to understand how the machine lays courses, adds and drops, etc. Additionally, we may want to consider integral stiffeners within the skin, not just cocured. Like a piece of foam in a skin and fiber place around them.

CAD programs are limited to 0/45/90 due to mental models and analysis packages.

Design - Rick Price

CAD is Unigraphics on HP workstation. They have Integrated Product Definition Teams. Fiber placement designers meet together to discuss tricks and lessons learned. A fighter skin has many ply drops. Many skins go from 35 plies to 8. The minimum cut length is 4.1" according to Rick Price [Robert Harper thought MCL shorter] but they design for 4.5".

The **Aft Center Fuselage Side Skin** is just below and in front of the vertical stabilizer. The part is 70 inches long and 45 inches high. See the picture and the drawing of the part. The ply layup is 5 plies, then cloth hand layup in lower aft corner, then 23 plies are laid to the top of this. Section E-E in the drawing showed 26 .28 inch plies vs. 17 .128" plies. This thickness difference and the plies' small sizes were the reason they decided to hand-lay this part. It may be reasonable to tow place these if they are all 0 or 90 degrees.

See the ply stacking plot for the aft fuselage side skin. Arrange cutouts on several plies to increase the course length (at least beyond the minimum cut length). One difficulty with this is it is more difficult to analyze a laminate with FEA. You use analysis to reduce cost and avoid testing. Testing is for verification, not design.

The **engine inlet ducts** are fiber placed in 5 pieces and assembled into the passage. They did not align windows on this part. They are redistributing cutouts between plies.

They first fiber placed the inlet ducts at Hercules, but they had 4 fiber placed plies on the inner and outer skin and hand-laid the detailed plies between. This is unfortunate because full plies are easy to lay by hand and the fiber placement machine is good at detail.

They are not integrating parts, yet. They wanted to prove the technology while keeping the same parts as the test airplanes. The risk of integrating was too high. In an emergency they could also be hand-laid. Thus, they are integrating the machine with the existing F-18 design. The goal right now is not cost reduction, but process validation: is tow placement structurally equivalent to hand layup?

They do not have the ability to understand the affects of contour on ply orientation. Hand layup allows +-7.5 degrees. Thus, they have had CM program the plies with 7.5 degrees of limited parallel plies. They are presently in the process of jumping windows from one ply to another with the ducts. 22 plies are in the middle and front (square portion) of the duct. 17 plies are at the rear (round portion) of the duct. F-18E/F hat stiffeners are mechanically attached due to problems with allowables on cocured parts.

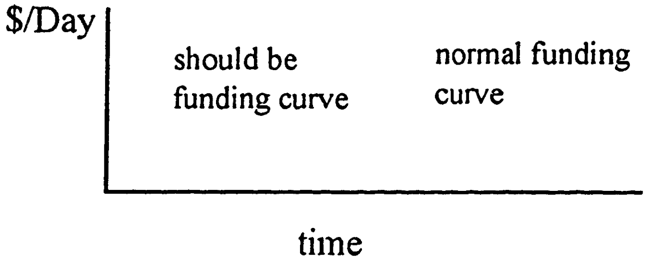
Programming - Dennis Van Winkle

- Programming facilities are in a refinished room nearby
- Acraplace run on Silicon Graphics Indigo 2, 150 MHz

They recommend you avoid editing the output because the next person who attempts to make the NC code will not be able to replicate the previous one. Thus, you edit the input for layup efficiency, not the output. They will use Version 2.01 of Acraplace to generate paths and NC code from the points file supplied by a Unigraphics Ufunct file. The Ufunct converts archetypes (circles, lines, splines and curves) from a Unigraphics CAD file to a set of points in a surface. They plan to generate a park code so they can use a laser template projected onto the tool and part surface between plies on the machine.

For Program Efficiency they will use (1) minimum away, (2) course reordering and (3) limited parallel program settings. Otherwise, their job is to analyze fixtures and avoid collisions. They will learn feedrate settings by trial and error. They are presently using CM's settings.

Designers specify boundaries, fiber axes, start points and orientation. This limits programmers ability to write efficient programs, but they will discuss this at IPT meetings for LRIP on F-18E/F. They were not involved on EMD IPT. Programmers believe funding should come early in the project to eliminate overstaffing & rework at end. Here is a drawing representing this:



Tooling - Bob Young and Rick Price

They try to avoid concave layup tools. Concavity should not be an issue. They can layup on a male tool and drop into a female tool. Besides, fighter skins need the cure tool on the OML for surface smoothness. They do not combine the bond and the layup tool because they do not want the tooling tied up when they want to lay tow. They do not make multiple parts on one tool for this same reason. Additionally, they do not want the inventory.

The **Aft Fuselage Side Skin tool** has a steel cage, a graphite egg crate interior structure and a BMI tool. The **Engine Inlet Ducts** have aluminum tools. They are stiff and rigid to meet dynamic requirements.

Rick Price is impressed with the software. CAD data with 3d geometry becomes NC code. The ducts are laid up and bonded on male tools. Skins are laid up on a male and bonded on a female. Tool surface is driven by the surface that needs to be the smoothest inside on ducts, outside on skins.

Appendix #10: Process Improvement Data Collection Form

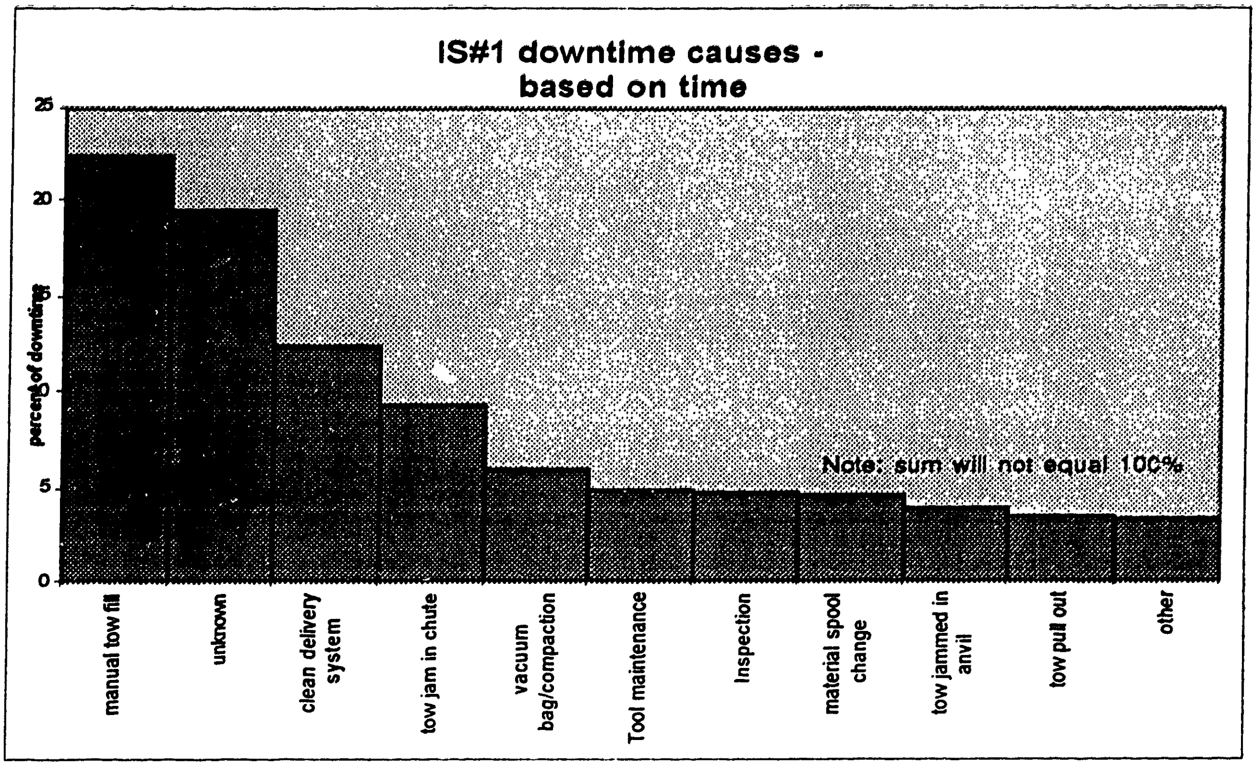
Part Name			
Part Number		**DCN**	

Fiber Placement Record

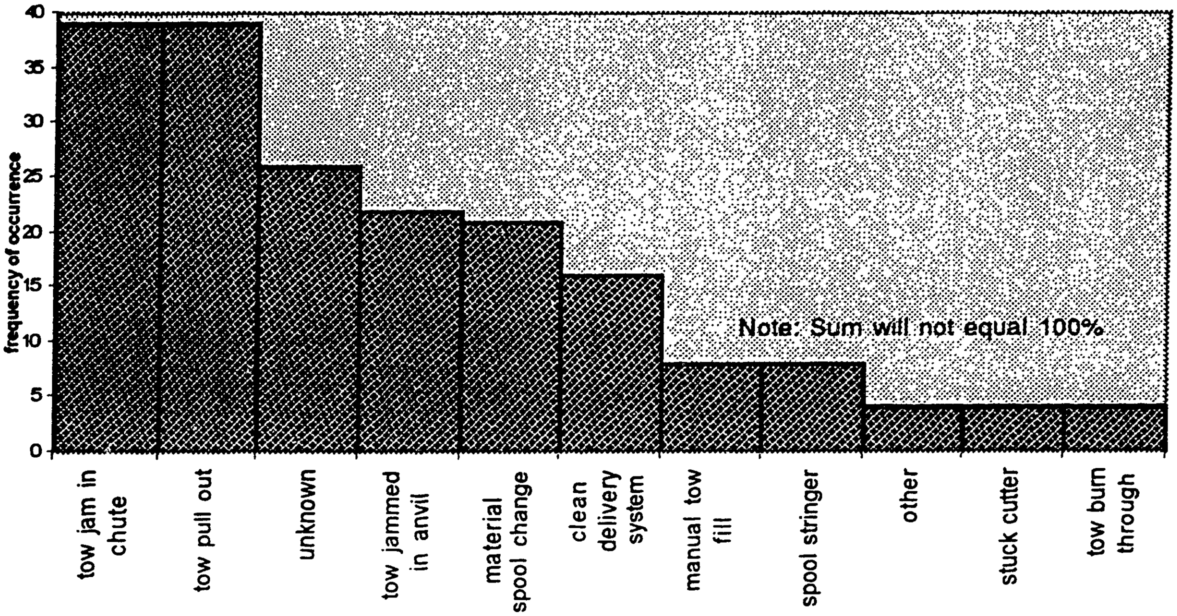
Stop Time	Start Time	Tow #	**Alert message** (Check one if applicable) EOP = End of program FDE = Fiber delivery error TRP = Tow restart problem CTS = Cannot take slack	Cause # (See Below)
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	
			( ) EOP ( ) FDE ( ) TRP ( )CTS ( ) Other ____________	

CCR/Chute	Creel/Compactor	Mat'l/maint/cleaning	Other Operations	Miscellaneous
1) Tow Jammed in chute 2) Tow jammed in cut anvil 3) Stuck cutter 4) Tow burn through	5) Tow pull out 6) Broken tow 7) Compactor wrap 8) Stringer 8a) Stringer on Part	9) Material spool change 10) Machine Maintenance 11) Clean delivery system 12) Manual tow fill (gaps)	13) Hand lay-up plies 14) Core installation 15) Vacuum bag/ compaction 16) Inspection 17) Tool change-out	18) Lunch/shift change 19) Programming errors 20) Other 21) Non-working hours

Process Improvement Charts for the Integrated Skin


IS#1 downtime causes - based on time

IS#1 downtime causes - based on frequency of occurrence



Appendix #11: Detailed Calculations for the Scrap Estimate

	purchase weight	material cost ($/lb)	total material cost ($)	disposal weight (lb)	disposal cost ($/lb)	total disposal cost	total cost ($)
towpreg	69.3	57	3950.1	6.3	50	315	4265.1
fabric	94.5	55	5197.5	31.5	50	1575	6772.5
savings per skin			1247.4			1260	2507.4

WACC scenarios

WACC (%)	probability	savings per month ($)	DCF Factor	present value	expected value
15	0.15	20,059.20	19.72	395,477.03	59,321.55
12	0.45	20,059.20	10.89	218,495.91	98,323.16
9	0.4	20,059.20	6.01	120,538.77	48,215.51
	1				205,860

Production Scenarios

aircraft per month	savings per month ($)	probability	WACC (%)	DCF Factor	present value	expected value
6	30,088.80	0.1	12	10.89	327,743.87	32,774.39
4	20,059.20	0.5	12	10.89	218,495.91	109,247.96
2	10,029.60	0.4	12	10.89	109,247.96	43,699.18
		1				185,721.53

Appendix #12: Model Verification Calculations

	0-degree	90-degree	45-degree
FLAT			
Width	43.2	101.8	150
# of Courses	15	34	50
Length	101.8	43.2	varies
Volume (in3)	24.2	24.2	24.2
Weight (lb.)	1.4	1.4	1.4
$\tau_E + \tau_D$	9.4	10	10.4
τ_c or $\tau_{c/a}$	0	0	0
Vb	11.42	13.33	8.372

	0-degree	90-degree	45-degree
length (in.)	101.8	43.2	
length term (sec)	18.31	13.24	
return time(sec.)	12.53	10.35	
# courses	15	34	
laydown (sec.)	274.71	450.19	510.52
return (sec.)	187.90	351.99	340.72
non-cycle (30%)	138.78	240.65	255.37
total (sec.)	601.40	1042.83	1106.61
total (min)	10.02	17.38	18.44
total (hours)	0.17	0.29	0.31
Thesis rate (#/hr)	8.40	4.84	4.57
CMI rate (#/hr)	13.5	6.6	5.6
% of CMI rate	62	73	82

dominating factor calculation		
0	**90**	
141	340	delay
133.7	110.2	V
274.7	450.2	total

45-degree calculation flat

course #	start distance	length	# of courses at this length	laydown time	time for one or both	return for one or both
1	1.5	6.3	2.0	11.2	22.3	18.0
2	4.5	9.0	2.0	11.5	23.0	18.2
3	7.5	15.0	2.0	12.2	24.4	18.6
4	10.5	21.0	2.0	12.9	25.8	19.1
5	13.5	27.0	2.0	13.6	27.3	19.5
6	16.5	33.0	2.0	14.3	28.7	19.9
7	19.5	39.0	2.0	15.1	30.1	20.4
8	22.5	45.0	2.0	15.8	31.6	20.8
9	25.5	51.0	2.0	16.5	33.0	21.3
10	28.5	57.0	2.0	17.2	34.4	21.7
11	31.5	61.1	2.0	17.7	35.4	22.0
12	34.5	61.1	1.0	17.7	17.7	11.0
13	37.5	61.1	1.0	17.7	17.7	11.0
14	40.5	61.1	1.0	17.7	17.7	11.0
15	43.5	61.1	1.0	17.7	17.7	11.0
16	46.5	61.1	1.0	17.7	17.7	11.0
17	49.5	61.1	1.0	17.7	17.7	11.0
18	52.5	61.1	1.0	17.7	17.7	11.0
19	55.5	61.1	1.0	17.7	17.7	11.0
20	58.5	61.1	1.0	17.7	17.7	11.0
21	61.5	61.1	1.0	17.7	17.7	11.0
22	64.5	61.1	1.0	17.7	17.7	11.0
		1400.8			510.5	340.7
bandwidth		3				
thickness		0.0055				
density		0.058				
weight laid		1.34				

	0-degree	90-degree	45-degree
CYLINDER			
Width	135.7	101.8	240
# of Courses	46	1	80
Length	101.8	4613.8	varies
Volume (in3)	76.0	76.1	76.1
Weight (lb.)	4.4	4.4	4.4
$\tau_E + \tau_D$	9.4	10.0	10.4
τ_c or $\tau_{c/a}$	0	0	0
Vb	11.42	30	8.372

	0-degree	90-degree	45-degree
length (in.)	101.8		
course laydown time (sec.)	18.31		
return time(sec.)	12.53	0.00	
# courses	46	34	
laydown (sec.)	842.45	1030.00	1244.00
return (sec.)	576.23	14.00	717.57
non-cycle (30%)	425.61	313.20	588.47
total (sec.)	1844.29	1357.20	2550.04
total (min)	30.74	22.62	42.50
total (hours)	0.51	0.38	0.71
Thesis rate (#/hr)	8.60	11.67	6.21
CMI rate (#/hr)	13.5	25.7	12
% of CMI rate	64	45	52

dominating

factor calculation

0	90	
432.4	10.0	delay
410.1	1020	V
842.5	1030	total

45-degree calculation cylinder

course #	start distance	length	# of courses at this length	laydown time	time for one or both	return for one or both
1	1.5	6.3	2.0	11.2	22.3	18.0
2	4.5	9.0	2.0	11.5	23.0	18.2
3	7.5	15.0	2.0	12.2	24.4	18.6
4	10.5	21.0	2.0	12.9	25.8	19.1
5	13.5	27.0	2.0	13.6	27.3	19.5
6	16.5	33.0	2.0	14.3	28.7	19.9
7	19.5	39.0	2.0	15.1	30.1	20.4
8	22.5	45.0	2.0	15.8	31.6	20.8
9	25.5	51.0	2.0	16.5	33.0	21.3
10	28.5	57.0	2.0	17.2	34.4	21.7
11	31.5	63.0	2.0	17.9	35.9	22.2
12	34.5	69.0	2.0	18.6	37.3	22.6
13	37.5	75.0	2.0	19.4	38.7	23.1
14	40.5	81.0	2.0	20.1	40.2	23.5
15	43.5	87.0	2.0	20.8	41.6	24.0
16	46.5	93.0	2.0	21.5	43.0	24.4
17	49.5	99.0	2.0	22.2	44.5	24.8
18	52.5	105.0	2.0	22.9	45.9	25.3
19	55.5	111.0	2.0	23.7	47.3	25.7
20	58.5	117.0	2.0	24.4	48.8	26.2
21	61.5	123.0	2.0	25.1	50.2	26.6
22	64.5	129.0	2.0	25.8	51.6	27.1
23	67.5	135.0	2.0	26.5	53.1	27.5
24	70.5	141.0	2.0	27.2	54.5	28.0
25	73.5	144.0	1.0	27.6	27.6	14.1
26	76.5	144.0	1.0	27.6	27.6	14.1
27	79.5	144.0	1.0	27.6	27.6	14.1
28	82.5	144.0	1.0	27.6	27.6	14.1
29	85.5	144.0	1.0	27.6	27.6	14.1
30	88.5	144.0	1.0	27.6	27.6	14.1
31	91.5	144.0	1.0	27.6	27.6	14.1
32	94.5	144.0	1.0	27.6	27.6	14.1
33	97.5	144.0	1.0	27.6	27.6	14.1
34	100.5	144.0	1.0	27.6	27.6	14.1
35	103.5	144.0	1.0	27.6	27.6	14.1
36	106.5	144.0	1.0	27.6	27.6	14.1
totals		5190.6			1244.0	717.6
bandwidth		3				
thickness		0.0055				
density		0.058				
weight laid		4.97	reasonable			

	0-degree	90-degree	45-degree	Comments
CONE - Chapter 3	**0-degree**			
Width	135.7/86.7	102	169.64	
# of Courses	46	1	57	
Length	102	3786	varies	34 courses pn 90-
Volume (in3)	62.4	62.4	62.4	
Weight (lb.)	3.6	3.6	3.6	
$\tau_E + \tau_D$	9.4	10	10.4	
τ_c or $\tau_{c/a}$	9	0	0	cuts on zero
Vb	11.42	30	8.372	30 sec/revolution

	0-degree	90-degree	45-degree	dominating factor calculation		
length (in.)	102					
course laydown time (sec.)	27.33					
return time(sec.)	12.53	0.00		**0**	**90**	
# courses	46	34		846.4	10.0	delay
laydown (sec.)	1257.26	1030.00	1001.79	410.9	1020	V
return (sec.)	576.57	0.00	581.62			
non-cycle (30%)	550.15	309.00	475.02	1257	1030	total
total (sec.)	2383.98	1339.00	2058.44			
total (min)	39.73	22.32	34.31			
total (hours)	0.66	0.37	0.57			
Thesis rate (#/hr)	5.47	9.73	6.33			
CMI rate (#/hr)	7.5	20.7	6.9			
% of CMI rate	73	47	92			

90-degree course lengths		
course	Diameter	length
1	43.2	135.7
2	42.7	134.2
3	42.3	132.8
4	41.8	131.3
5	41.3	129.8
6	40.9	128.3
7	40.4	126.9
8	39.9	125.4
9	39.4	123.9
10	39.0	122.4
11	38.5	121.0
12	38.0	119.5
13	37.6	118.0
14	37.1	116.5
15	36.6	115.0
16	36.2	113.6
17	35.7	112.1
18	35.2	110.6
19	34.7	109.1
20	34.3	107.7
21	33.8	106.2
22	33.3	104.7
23	32.9	103.2
24	32.4	101.8
25	31.9	100.3
26	31.5	98.8
27	31.0	97.3
28	30.5	95.8
29	30.0	94.4
30	29.6	92.9
31	29.1	91.4
32	28.6	89.9
33	28.2	88.5
34	27.7	87.0
Hoop Length		3786.0

45-degree calculation cone 800

course #	start distance	length	# of courses at this length	laydown time	time for one or both	return for one or both
1	1.5	6.3	2.0	11.2	22.3	18.0
2	4.5	11.0	2.0	11.7	23.4	18.3
3	7.5	18.0	2.0	12.6	25.1	18.8
4	10.5	25.0	2.0	13.4	26.8	19.4
5	13.5	32.0	2.0	14.2	28.4	19.9
6	16.5	39.0	2.0	15.1	30.1	20.4
7	19.5	46.0	2.0	15.9	31.8	20.9
8	22.5	53.0	2.0	16.7	33.5	21.4
9	25.5	60.0	2.0	17.6	35.1	22.0
10	28.5	67.0	2.0	18.4	36.8	22.5
11	31.5	74.0	2.0	19.2	38.5	23.0
12	34.5	81.0	2.0	20.1	40.2	23.5
13	37.5	88.0	2.0	20.9	41.8	24.0
14	40.5	95.0	2.0	21.7	43.5	24.5
15	43.5	102.0	2.0	22.6	45.2	25.1
16	46.5	109.0	2.0	23.4	46.8	25.6
17	49.5	116.0	2.0	24.3	48.5	26.1
18	52.5	123.0	2.0	25.1	50.2	26.6
19	55.5	130.0	2.0	25.9	51.9	27.1
20	58.5	137.0	2.0	26.8	53.5	27.7
21	61.5	144.0	2.0	27.6	55.2	28.2
22	64.5	144.0	1.0	27.6	27.6	14.1
23	67.5	144.0	1.0	27.6	27.6	14.1
24	70.5	144.0	2.0	27.6	55.2	28.2
25	73.5	144.0	3.0	27.6	82.8	42.3
totals*		3688.6			####	581.6
bandwidth		3				
thickness		0.0055				
density		0.058				
weight laid		3.53				

	0-degree	90-degree	45-degree	0-deg	Comments
CONE- Chapter 4	no recess	full ply	full	recess	
Width	135.7/86.7	102	169.64	135.7/86.7	
# of Courses	46	1	57	46	
Length	102	3786	varies	102	
Volume (in3)	62.4	62.4	62.4	62.4	
Weight (lb.)	3.6	3.6	3.6	3.6	
$\tau_E + \tau_D$	9.4	10	10.4	9.4	
τ_c or $\tau_{c/a}$	9	0	0	17.2	cuts on zero
Vo	5.71	60	4.186	5.71	60 sec/rev
length (in.)	102			102	
course laydown time (sec.)	36.26			44.46	
return time(sec.)	12.53	0.00		12.53	
# courses	46	34	44	46	
laydown (sec.)	1668.12	2050.00	1493.98	2045	
return (sec.)	576.57	0.00	581.62	576.57	
non-cycle (80%)	1795.75	1640.00	1660.48	2098	
total (sec.)	4040.44	3690.00	3736.08	4719	
total (min)	67.34	61.50	62.27	78.66	
total (hours)	1.12	1.03	1.04	1.31	
Thesis rate (#/hr)	3.22	3.53	3.49	2.76	

	45-degree	0-degree	45 -
CONE	60%, recess	build-up ply	recess
Width	169.64	135.7/86.7	169.64
# of Courses	57	46	57
Length	varies	102	varies
Volume (in3)	62.4	62.4	62.4
Weight (lb.)	3.6	0.6	3.6
$\tau_E + \tau_D$	17.3	9.4	10.4
τ_c or $\tau_{c/a}$	8.2	0	8.2
Vo	3	5.71	4.186
length (in.)		8	
course laydown time (sec.)		10.80	
return time(sec.)		9.05	
# courses	44	75	44
laydown (sec.)	2624.67	810.08	1854.78
return (sec.)	581.62	678.51	581.62
non-cycle (80%)	2565.03	1190.87	1949.12
total (sec.)	5771.32	2679.46	4385.52
total (min)	96.19	44.66	73.09
total (hours)	1.60	0.74	1.22
Thesis rate (#/hr)	2.26	0.77	2.97

45-degree ply time calculation (100%)

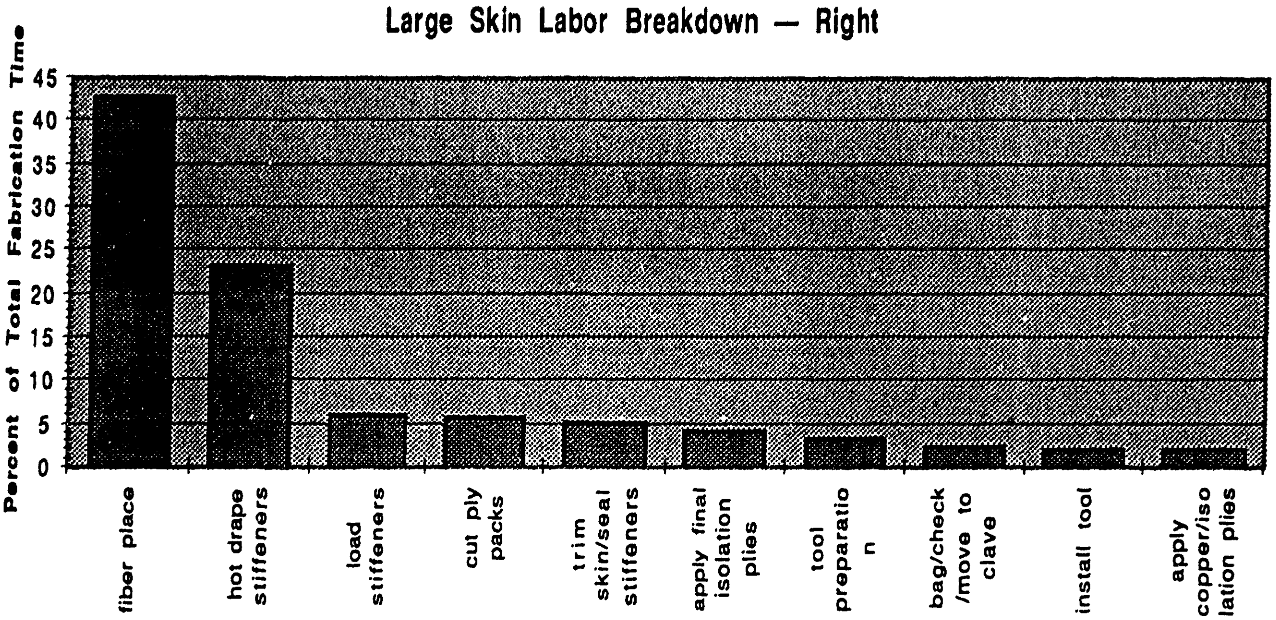
course	start point	length	# of courses at this length	laydown time	time for one or both	return for one or both
1	1.5	6.3	2.0	11.9	23.8	18.0
2	4.5	11.0	2.0	13.0	26.1	18.3
3	7.5	18.0	2.0	14.7	29.4	18.8
4	10.5	25.0	2.0	16.4	32.7	19.4
5	13.5	32.0	2.0	18.0	36.1	19.9
6	16.5	39.0	2.0	19.7	39.4	20.4
7	19.5	46.0	2.0	21.4	42.8	20.9
8	22.5	53.0	2.0	23.1	46.1	21.4
9	25.5	60.0	2.0	24.7	49.5	22.0
10	28.5	67.0	2.0	26.4	52.8	22.5
11	31.5	74.0	2.0	28.1	56.2	23.0
12	34.5	81.0	2.0	29.8	59.5	23.5
13	37.5	88.0	2.0	31.4	62.8	24.0
14	40.5	95.0	2.0	33.1	66.2	24.5
15	43.5	102.0	2.0	34.8	69.5	25.1
16	46.5	109.0	2.0	36.4	72.9	25.6
17	49.5	116.0	2.0	38.1	76.2	26.1
18	52.5	123.0	2.0	39.8	79.6	26.6
19	55.5	130.0	2.0	41.5	82.9	27.1
20	58.5	137.0	2.0	43.1	86.3	27.7
21	61.5	144.0	2.0	44.8	89.6	28.2
22	64.5	144.0	1.0	44.8	44.8	14.1
23	67.5	144.0	1.0	44.8	44.8	14.1
24	70.5	144.0	2.0	44.8	89.6	28.2
25	73.5	144.0	3.0	44.8	134.4	42.3
totals*		3688.6			1494.0	581.6
bandwidth		3				
thickness		0.0055				
density		0.058				
weight laid		3.53				
average length		80.2				

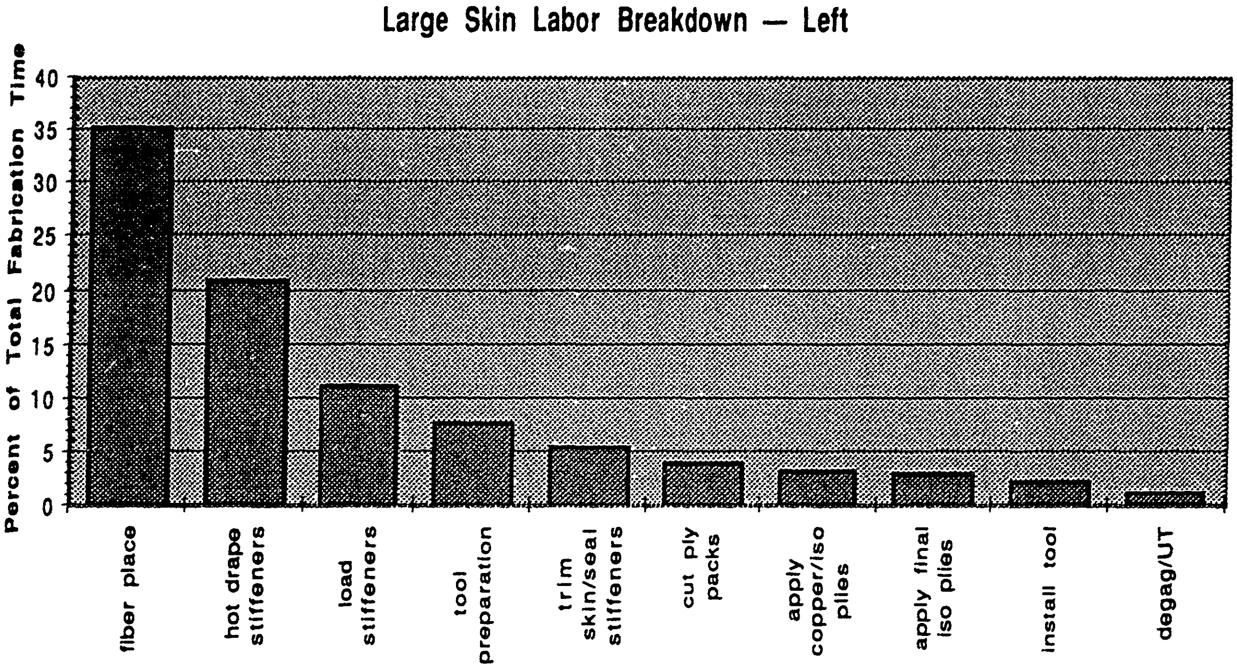
45-degree ply time calculation (60%)

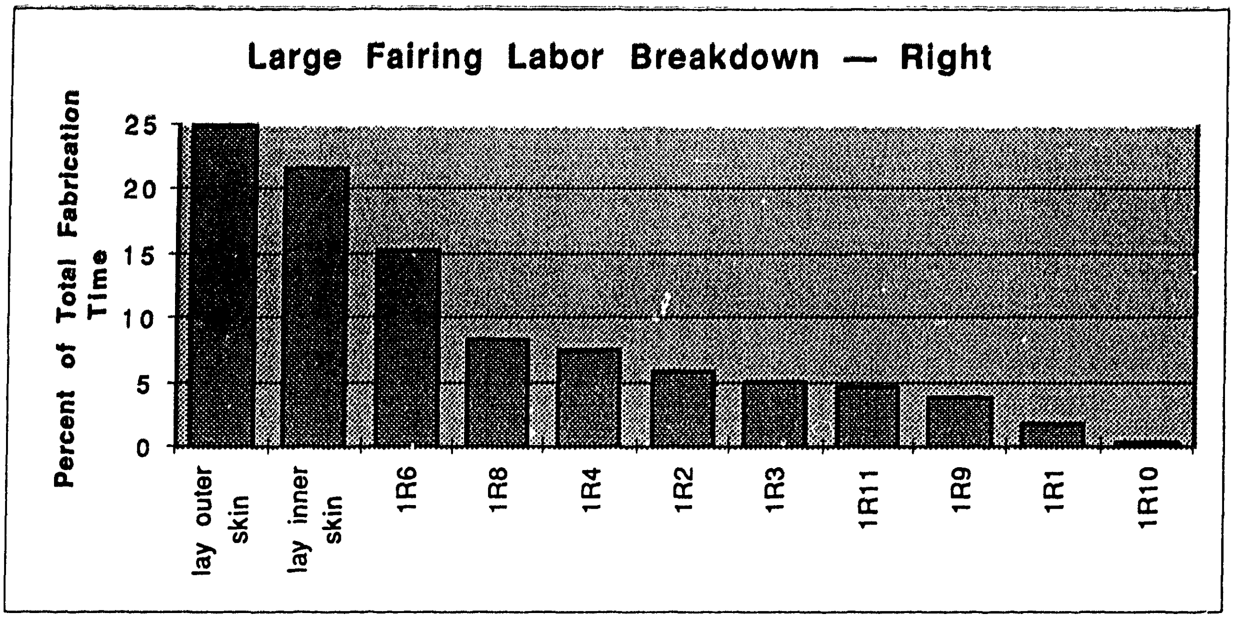
course	start point	length	# of courses at this length	laydown time	time for one or both	return for one or both
1	1.5	6.3	2.0	19.4	38.9	18.0
2	4.5	11.0	2.0	21.0	42.0	18.3
3	7.5	18.0	2.0	23.3	46.7	18.8
4	10.5	25.0	2.0	25.7	51.3	19.4
5	13.5	32.0	2.0	28.0	56.0	19.9
6	16.5	39.0	2.0	30.3	60.7	20.4
7	19.5	46.0	2.0	32.7	65.3	20.9
8	22.5	53.0	2.0	35.0	70.0	21.4
9	25.5	60.0	2.0	37.3	74.7	22.0
10	28.5	67.0	2.0	39.7	79.3	22.5
11	31.5	74.0	2.0	42.0	84.0	23.0
12	34.5	81.0	2.0	44.3	88.7	23.5
13	37.5	88.0	2.0	46.7	93.3	24.0
14	40.5	95.0	2.0	49.0	98.0	24.5
15	43.5	102.0	2.0	51.3	102.7	25.1
16	46.5	109.0	2.0	53.7	107.3	25.6
17	49.5	116.0	2.0	56.0	112.0	26.1
18	52.5	123.0	2.0	58.3	116.7	26.6
19	55.5	130.0	2.0	60.7	121.3	27.1
20	58.5	137.0	2.0	63.0	126.0	27.7
21	61.5	144.0	2.0	65.3	130.7	28.2
22	64.5	144.0	1.0	65.3	65.3	14.1
23	67.5	144.0	1.0	65.3	65.3	14.1
24	70.5	144.0	2.0	65.3	130.7	28.2
25	73.5	144.0	3.0	65.3	196.0	42.3
totals*		3688.6			2222.9	581.6
bandwidth		3				
thickness		0.0055				
density		0.058				
weight laid		3.53				
average length		80.2				

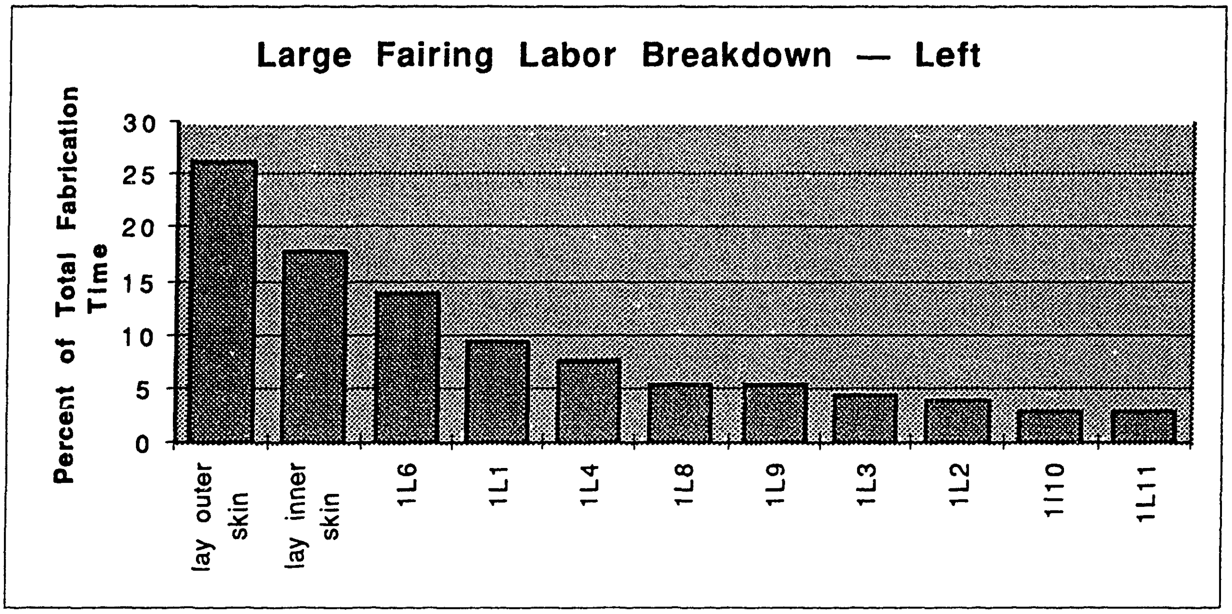
Hoop Length for the 400 ipm cone is the same as for the 80 ipm cone.

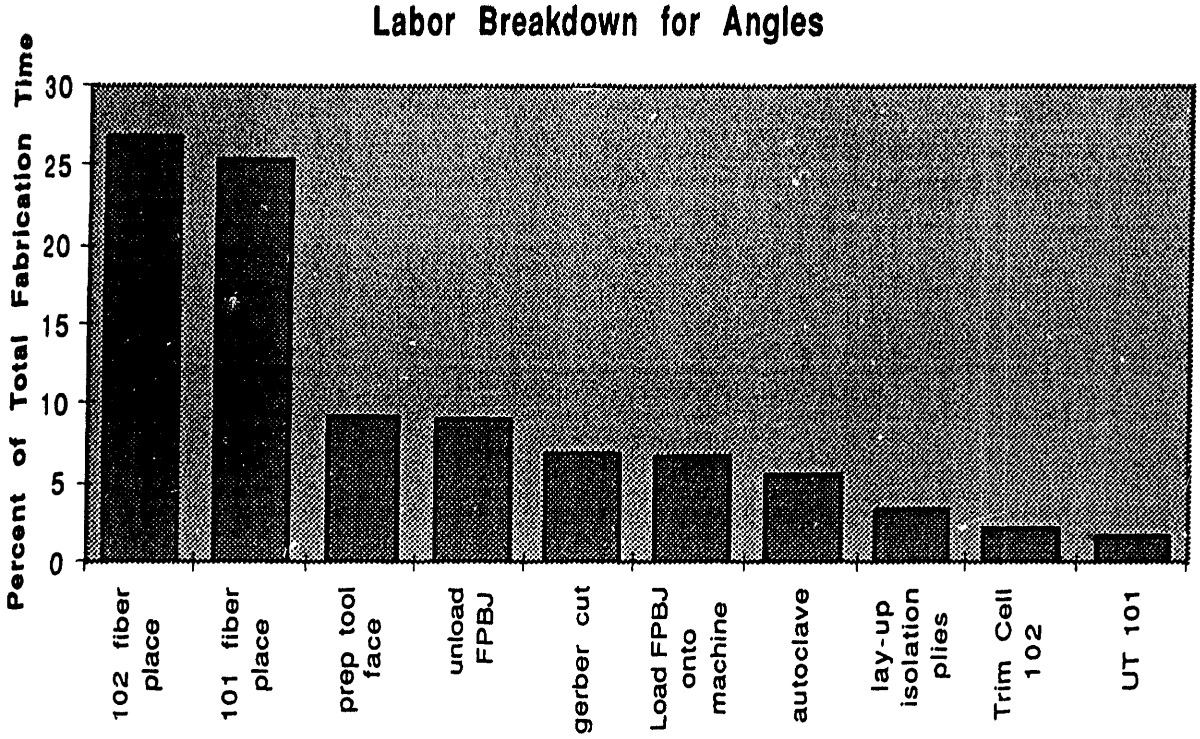
Appendix #13: BD&SG Part Labor Breakdowns






Large Fairing Labor Breakdown — Right
Percent of Total Fabrication Time
25
20
15
10
5
0
lay outer skin
lay inner skin
1R6
1R8
1R4
1R2
1R3
1R11
1R9
1R1
1R10


Large Fairing Labor Breakdown — Left
Percent of Total Fabrication Time
30
25
20
15
10
5
0
lay outer skin
lay inner skin
1L6
1L1
1L4
1L8
1L9
1L3
1L2
1l10
1L11


Labor Breakdown for Angles
Percent of Total Fabrication Time
30
25
20
15
10
5
0
102 fiber place
101 fiber place
prep tool face
unload FPBJ
gerber cut
Load FPBJ onto machine
autoclave
lay-up isolation plies
Trim Cell 102
UT 101