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COST ANALYSIS OF COMPOSITE FAN BLADE MANUFACTURING PROCESSES

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FINAL REPORT

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Prepared for

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16. Abstract

A rigorous analysis was conducted to estimate the relative manufacturing costs for large high technology fan blades prepared by advanced composite fabrication methods using seven candidate materials/process systems. These systems were identified as laminated resin matrix composite (RMC), filament wound resin matrix composite (RMC/FW), superhybrid solid laminate (SH), superhybrid spar/shell (SH/S-S), metal matrix composite (MMC), metal matrix composite with a spar and shell (MMC/S-S), and hollow titanium (HT). The costs were calculated utilizing analytical process models and all cost data are presented as normalized relative values where 100 was the cost of a conventionally forged solid titanium (ST) fan blade whose geometry corresponded to a size typical of 42 blades per disc. Four costs were calculated for each of the seven candidate systems to relate the variation of cost on blade size. Geometries typical of blade designs at 24, 30, 36 and 42 blades per disc were used. The impact of individual process yield factors on costs was also assessed as well as effects of process parameters, raw materials, labor rates and consumable items.

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FOREWORD

This program was conducted by the Materials Technology Laboratories under Contract Number NAS 3-21352 for the Lewis Research Center of the National Aeronautics and Space Administration. The program manager was Dr. C. F. Barth with technical support provided by Mr. W. E. Winters (RMC, RMC/FW, SH, and SH/S-S systems), Mr. J. N. Fleck (MMC, MMC/S-S, and HT systems), and Mr. T. S. Stelson, Cost Models. This work was conducted within the Materials Development Department, Dr. I. J. Toth, Manager, and has been assigned the TRW internal project number 512-004046-88.

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1.0 INTRODUCTION

There currently exists a number of promising candidate material/process systems for fabricating advanced turbine engine fan blading, involving metal or resin matrix composite structures, combinations of these technologies, and several design approaches incorporating hollow titanium components. The metal matrices include both aluminum and titanium alloys while various organic materials, such as polyimides, are employed as resin matrices. Reinforcement fibers commonly utilized in fan blade designs include boron, borsic (silicon carbide coated boron fibers), glass, kevlar, and graphite. A variety of promising materials combinations, design concepts, and fabrication methods have been under evaluation and development. Although each method offers potential for significant improvement in engine performance levels, considerable technical effort remains to be expended in all cases to permit actual production of man-rated flight quality hardware. The fact has also been recognized that simultaneous development efforts in all possible technology areas on a full-scale basis would involve significant research and manufacturing technology efforts. A desirable alternative to this situation would be to analyze each materials/process system and define process cost data to assess the potential relative cost effectiveness of the various systems. In addition the matematical models would permit identification of major costs drivers within each materials/process system. These data would then permit making an informed decision regarding the cost-life cycle effectiveness of fan blades perpared by each of the candidate procedures. A well-directed effort can then be efficiently focused on those critical process cost driver elements to complete development of the more promising fabrication methods.

Seven materials/process combinations were selected by NASA-Lewis for analysis on this program. The specific combinations are as follows:

1. Resin Matrix Composite (Coded RMC)
2. Resin Matrix Composite-Filament Wound (Coded RMC/FW)
3. Super Hybrid (Coded SH)
4. Super Hybrid-Spar/Shell (Coded SH/S-S)
5. Metal Matrix Composite (Coded MMC)
6. Metal Matrix Composite-Spar/Shell (Coded MMC/S-S)
7. Hollow titanium (Coded HT)

All of these systems, with the exception of the hollow titanium, employ the common feature of providing controlled directional reinforcement of the airfoil section. Elimination of the midspan shroud improves aerodynamic efficiency and reduces weight. The titanium blade can be selectively reinforced as well to eliminate its midspan shroud.

Since each of the advanced systems are in the early developmental stages, much more work is needed to realize engine performance improvements. In particular, considerable effort is required in developing cost-effective manufacturing procedures consistent with quality constraints. All seven systems involve advanced fabrication processes for which very little actual manufacturing experience exists. Hence, manufacturing cost projections for large fan blades produced by any of the seven materials/process systems are currently open to conjecture. The overall intent of this program has been to quantitatively analyzed these systems and define practicable manufacutring processes for each. Within this overall objective, the prime intent was to identify the operations in each manufacturing process that were likely to be major cost drivers. These data would be extremely valuable in pinpointing areas where future research emphasis should be concentrated.

This study utilized a cost-modeling technique previously developed by TRW and used on a previous NASA program (1). The technique involved development of detailed process simulation models for each system and subsequent calculation of projected costs for large-scale component manufacture resolved into individual processing elements. Large fan blade designs for discs having 24, 30, 36, and 42 blades were included in the analysis. The estimated manufacutring costs for the 28 possible combinations (seven material/processes and four sizes) were normalized relative to several large solid titanium fan blades (coded ST) in current production. This report summarizes the model development, assumptions involved, and relative manufacturing costs predicted from the analysis.

2.0 BACKGROUND

The NASA-Lewis Research Center and the Air Force are currently conducting a series of programs dealing with the design, fabrication and evaluation of various polymeric and metal matrix composite fan blades for potential use in high bypass, subsonic commercial turbine engines. Large fan blades represent one of the most promising composite materials applications in aircraft engines, and current efforts are primarily directed towards establishing resistance to bird strikes or foreign object damage (FOD) using whirling arm test rigs. Although testing of prototype hardware is in progress, it is important to determine the relative costs of manufacturing aircraft composite fan blades with respect to the current solid titanium components for commercial engines such as the JT9D and CF6.

One of the most important advantages offered by the advanced technology fan blade materials/process systems is the opportunity to eliminate the midspan shrouds. Shroudless fan blades of adequate stiffness provide for significant increases in aerodynamic efficiency. Improvements in specific fuel consumption have become highly desirable in that fuel has become the major life cycle cost item in the operation of both military and commercial aircraft (2). Other factors which provide advantages over current forged solid titanium fan blades are summarized in Figure 1. Weight reduction is also important in that not only the disc requirements can be reduced but this affects favorably other engine components such as shafts, bearings, engine supports, containment rings, etc.

The seven specific materials/process combinations previously identified by NASA-Lewis will be analyzed on this program. The estimated manufacturing cost data will be analyzed on this program. The estimated manufacturing cost data will be compared with baseline data derived from forged and machined solid titanium large fan blades in current production.

The following sections will present a digest of background data relative to the various systems under examination on this program.

2.1 Solid Resin Composite Fan Blade

The solid resin composite fan blade was the first of the all composite blades to be developed being first introduced by Rolls Royce in the late 1960's. Since then many design and material iterations have occurred both in the U.K. and USA. This design still remains the simplest and most readily fabricated composite fan blade approach. Figure 2 depicts a typical large fan blade manufactured by the RMC process.

Basically, the solid resin blade is a laminated structure incorporating one or more fiber materials oriented and configured in such a way as to completely fill the airfoil envelope and provide strengthening and stiffening in the appropriate direction and amount. The root retention system is of a splayed fiber incorporating metal or composite wedges and either metallic pressure pads or a cylindrical or pin type outsert bonded in place. Erosion and foreign object damage protection are provided by appropriate selection of compositing materials and their fiber orientation, a leading edge protection scheme of stainless steel or wire mesh/ electroformed nickel, and an outer coating of polyurethane.

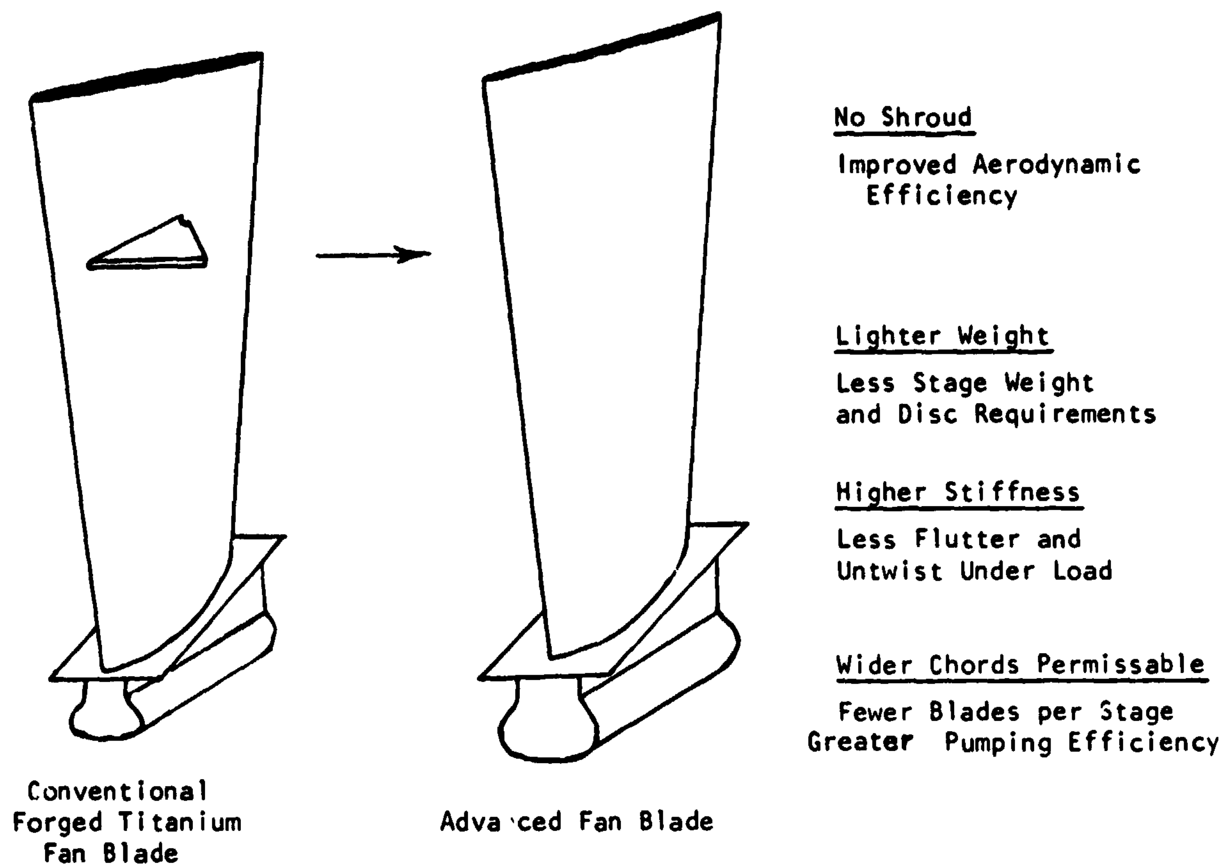

Figure 1. Advantages of Shroudless Large Fan Blades as Compared with the Current Forged Titanium Component.

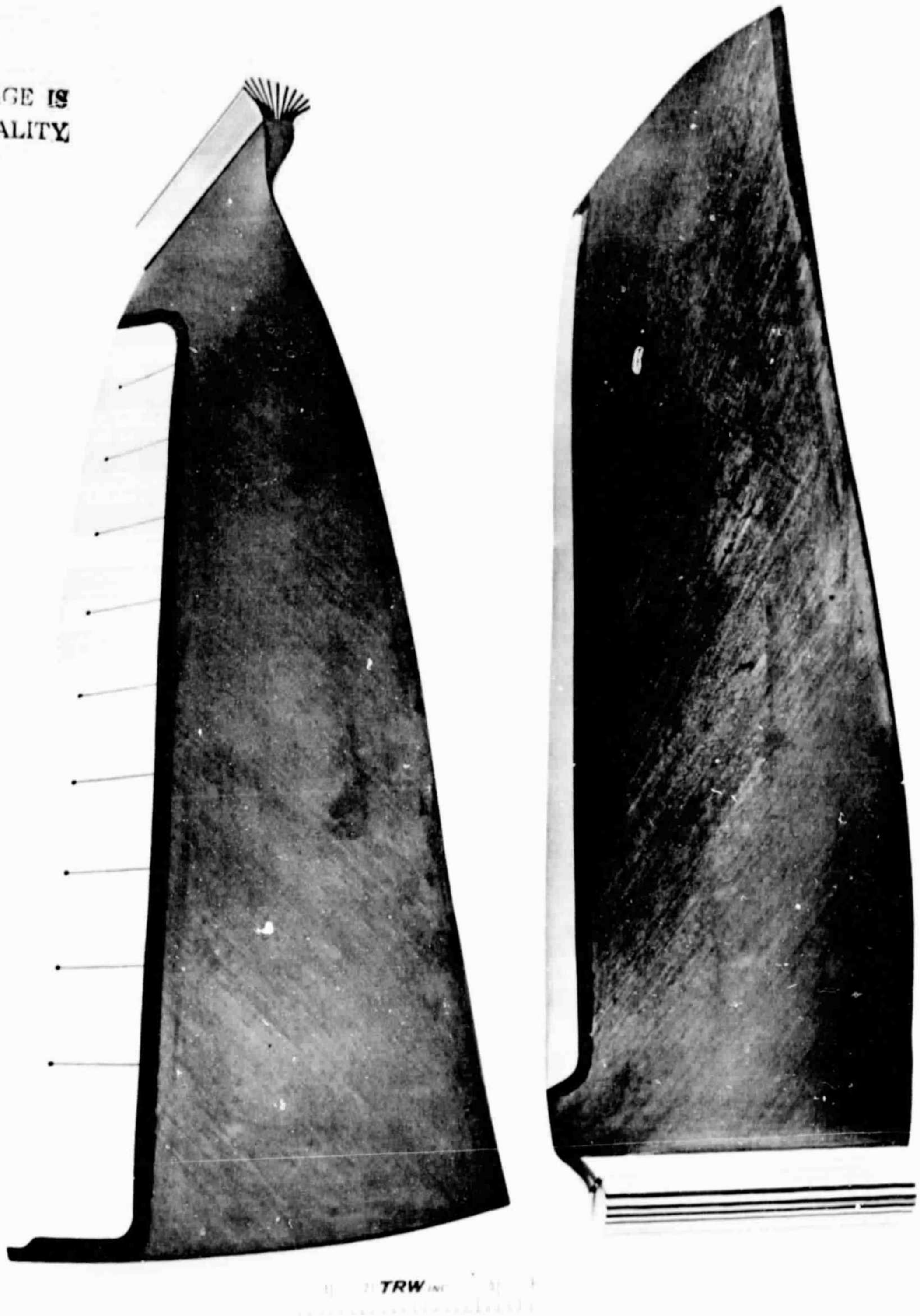

Figure 2. TRW Fabricated Solid Graphite/Epoxy JT9D Fan Blades.

The composite construction materials may be of monolithic design using graphite/epoxy or may be a combination of fiber reinforcing materials such as graphite, glass, boron or Kevlar/epoxy in an interply or intraply configuration. Pratt & Whitney Aircraft designs (3) have favored a shell/core construction in which the larger angle plied layers are placed on the external surfaces of the airfoil to achieve maximum torsional stiffening while radial unidirectional and smaller/shorter members are located nearer the mid-chord location to accept bending and radial loading. This design is, however, subject to residual fabrication stresses resulting from thermal anisotropic material behavior.

General Electric designs (4)(5)(6) are generally of hybrid material, interspersed orientation design incorporating a variety of materials strategically located to perform specific functions.

From a manufacturing standpoint, the solid composite blade is perhaps the most straightforward following several basic unit operations:

o Ply shape generation - starting with readily available unidirecitonal fiber pregreg, as many as several hundred different ply shapes are cut by a variety of means, such as by hand, steel rule die, laser, water jet, or numerically controlled oscillating single point cutter tool (6).

o Assembly - The plies are precisely assembled onto a flat or contoured lay up tool either by hand, using a variety of manufacturing aids such as template locators or optical systems for positioning, or by automated methods (6).

o Molding - The assembly is then cured and consolidated in a precision closed die mold controlling the time/temperature/pressure parameters to achieve a sound composite structure.

o Finishing - The necessary machining of the blade root and tip are followed by installation of root pads or outserts, a leading edge protection system and erosion resistant coating.

o Inspection - As in any aircraft primary structural element, the resin composite fan blade is subjected to numerous inspections from incoming raw material receiving inspection, through in-process inspection controls to finished blade dimensional and nondestructive methods of evaluating quality.

While the number of processing steps outlined above are relatively few, the fabrication sequence is very involved and complex and extreme care must be exercised in establishing the procedures if high quality hardware is to be produced at minimum cost. The selection of the specific approaches to the various operations must be made on far reaching considerations and ramifications. For instance, ply generation can be performed over a spectrum of approaches ranging from hand cut out to fully automated cutting and stacking. The method selected is dependent upon the size of the manufacturing run, the capital equipment investment, the number of other blades or components which can use the same facilities as well as the efficiency and precision with which the method can perform the operation. Such factors were considered in the cost analysis.

2.2 Filament Wound Fan Blades

The concept of a filament wound fan blade offers many distinct advantages over other composite designs. A unique approach involving the winding of two blades simultaneously has been demonstrated by Fiber Science Inc. (24). A representative RMC/FW blade is presented in Figure 3. A distinct advantage is the use of a wrap-around pin root design which precludes complicated splayed-fiber approaches. A particularly desirable feature is the elimination of the cost of prepregging the reinforcement since the fabrication is usually conducted by wet winding methods. However, this requires closer control of the process and may cause resin rich or non-homogeneous areas in the final blade, thus placing greater emphasis on quality control. Another advantage is the ease of fabrication automation. Filament winding operations are readily programmed to perform the necessary unidirectional and geodesic winding patterns with little or no operator control. Projected material and fabrication costs should thus be minimized.

One of the problems associated with filament wound blades is the inability of achieving tight leading and trailing edge radii. For higher tip speed blades such as for the F-103 engine, both leading and trailing edges become extremely thin compared to lower speed fans such as QCSEE. Also, the FOD resistance of the filament wound blade has not proven totally satisfactory to date. However, the amount of development in this area has not been comparable to other composite blade concepts and the filament wound blade offers a most interesting addition to the cost analysis of the proposed program which cannot be overlooked.

2.3 Superhybrid Composite Fan Blade

Superhybrid composites represent a unique combination of resin and metal matrix composite materials integrated to take best advantage of mechanical properties with minimum weight penalty. Generally, a sandwich construction is used in which the core member is graphite/epoxy and the shell material is boron/aluminum overlaid with titanium shim stock. The various members are adhesively bonded into an integral structure. The concept has demonstrated good impact resistance (13) and offers protection of the resin and metal matrix from environmental efforts. TRW experience with superhybrids corroborates the findings of others and has been directed toward the up-grading temperature capability over the low temperature matrix resins and adhesives ordinarily used in superhybrid composites.

There are two basic types of superhybrid fan blade design, a solid laminate and a spar/shell configuration. Each will be discussed briefly.

2.3.1 Solid Laminate Superhybrid

This concept is essentially the same as a solid resin or metal matrix laminated blade except the outer members are replaced with B/Al composite material and Ti. Pratt and Whitney (14) has been successful in fabricating these blades which are currently being tested. One design incorporates a titanium mid-chord layer to maximize strength in this high shear stress area of the blade.

Figure 3. Representative Resin Matrix Composite Fan Blade Produced by the Filament Winding Process.

The fabrication of a superhybrid blade is complicated somewhat over a solid composite blade in that the titanium and B/Al members must be preformed to the precise airfoil contour before assembly and final bonding with the graphite epoxy core. Procedures for stretch forming titanium and hot forming B/Al monotapes are readily available although these represent added operations and cost over a monolithic construction. The concept does, however, offer the potential of surviving foreign object impacts with the proper proportion and location of constituent composite materials.

2.3.2 Spar/Shell Superhybrid

The concept of the superhybrid has been integrated with a spar/shell design by General Electric (15) designated TICOM and TICOR. Two specific configurations are being investigated: the first incorporates a leading edge spar while the second utilizes an internal spar surrounded on all sides of the airfoil with superhybrid composite. The concept offers considerable flexibility in placing sufficient solid titanium at or near the leading edge to provide the necessary FOD resistance. The spar can, in fact, be designed such as to provide equivalent leading edge FOD performance to conventional forged solid titanium fan blades. One of the distinct advantages is the use of a conventional root attachment system. The concept does, however, offer minimal weight savings compared to an all titanium blade. A typical representative experimental superhybrid blade with both a titanium spar and shell is presented in Figure 4.

Manufacturing costs independent of material cost can be expected to be higher than a solid resin laminate blade. The starting block is a precision forged or machined titanium backbone which for practical purposes incorprates essentially the same operations (and therefore cost) of a conventional titanium fan blade. To this is bonded the superhybrid composite materials requiring preforming operations of the metal composite members as described above.

2.4 Diffusion Bonded B/Al Composites

There are three principal design concepts for fiber-reinforced metal composite fan blades, viz, all-composite, selectively reinforced ("patch"), and spar/shell. In some respects, the latter can be regarded as a special case of selective reinforcement. Each of these approaches has its proponents, and, indeed, each has certain advantages to offer.

2.4.1 Solid Laminate Design

Both Pratt & Whitney and General Electric are actively pursuing the development of all composite blades. For example, a B/Al first stage F100 fan blade is being developed by P&WA under an Air Force Contract (18). This B/Al blade includes an integral titanium cover skin and a single aluminum wedge plus external titanium pads in the dovetail area.

A similar blade, the fan blade for SCAR engines, is currently under development. This blade design features stainless steel mesh bulking plies in the dovetail area. TRW also has produced the all-composite CF6 B/Al fan blade shown in Figure 5 under NASA sponsorship (19). This particular blade uses a multiple-wedge root and no cover skin.

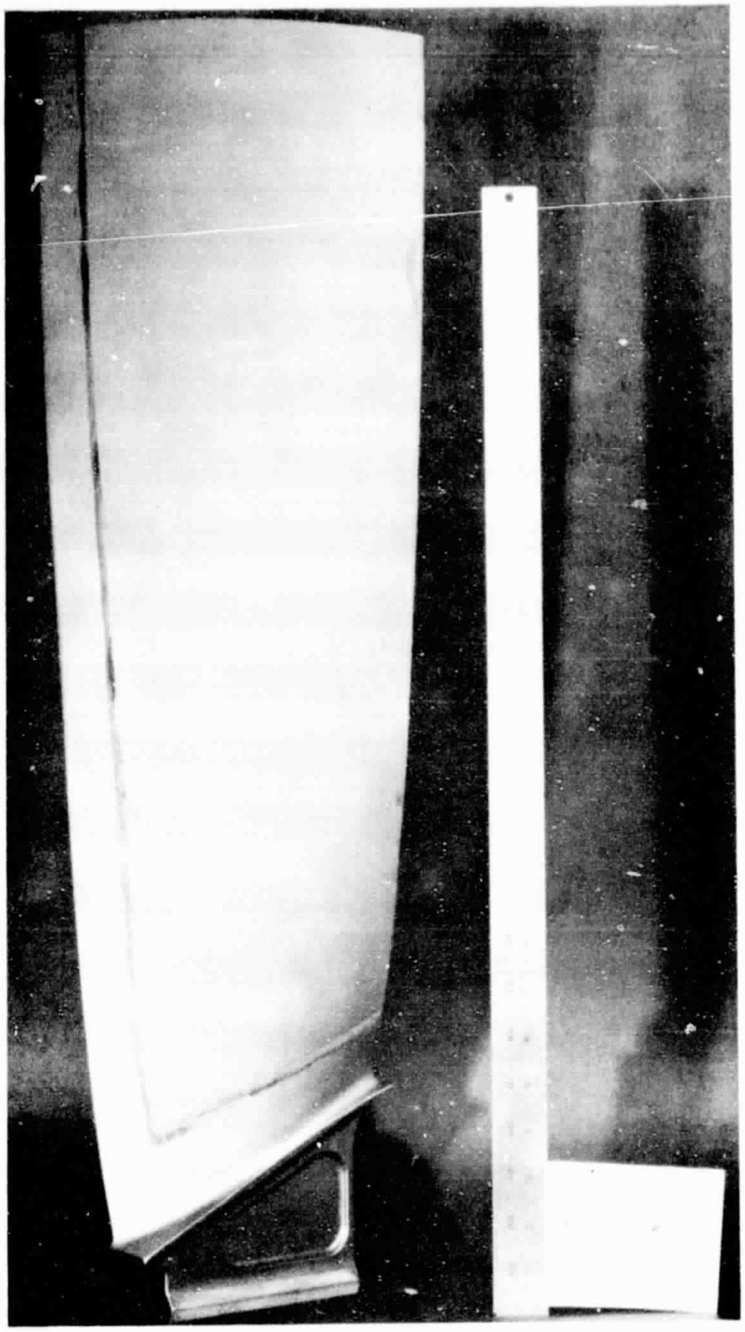

Figure 4. A Typical Superhybrid Fan Blade Design with a Spar and Shell.

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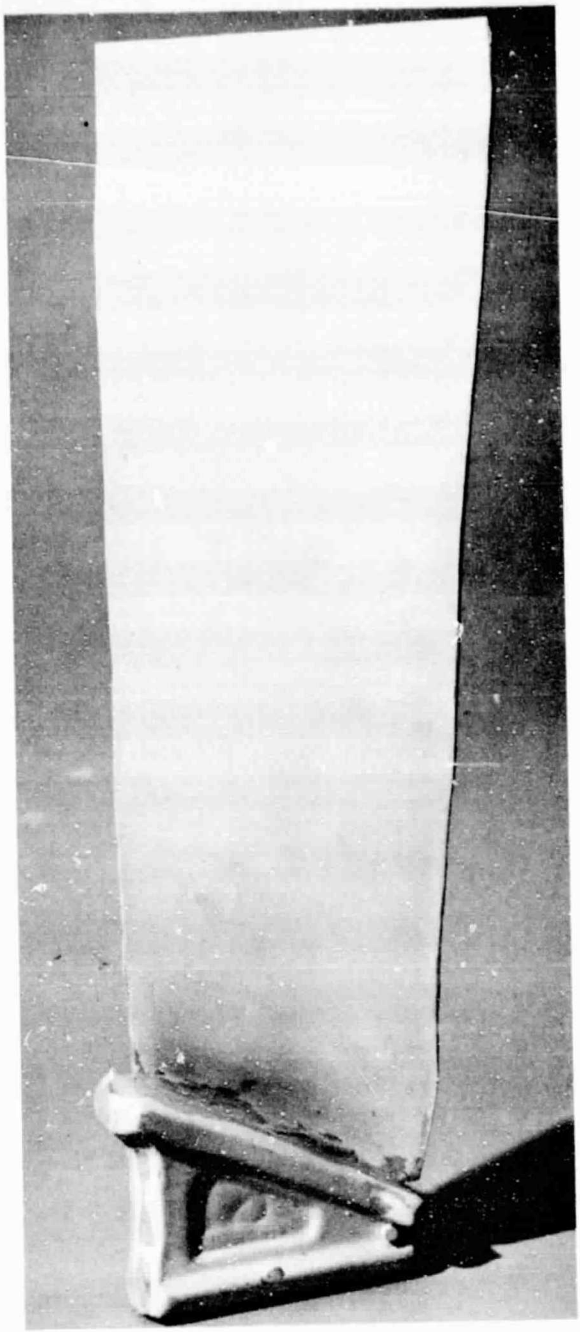

Figure 5. CF-6 Boron-Aluminum Fan Blade.

It is apparent that specific blade design features such as root attachment variations and leading edge protection can have a significant impact on manufacturing processes and, hence, cost. Regardless of the design selected, there are additional factors to be considered in terms of analyzing the manufacturing process. The first is the form of the starting material and the second is the type of bonding process to be used.

Almost all complex metal matrix blades are built up from a monotape of some type, just as polymeric blades are assembled from prepregs. For B/Al there are three principal types of monotape available, i.e., plasma sprayed, resin-bonded and diffusion bonded. Each particular variety of monotape has its own unique advantages.

Once a type of monotape has been selected, the next decision involves preforming of the individual plies. Usually, a simple blade can be prepared without difficulty from flat plies. However, TRW has demonstrated that air-bonded blades can have properties equivalent to those for vacuum-bonded blades (22).

No final determination has yet been made regarding air versus vacuum bonding, and some blades, such as F100 (18), are being vacuum bonded while others, such as the CF6 (23), are being air bonded.

It is apparent that the type and form of the starting material as well as the bonding process will have significant impact on final estimated blade cost. Thus, for a meaningful cost analysis, one must work with a frozen design and processing sequence. For this study the process selected was the one which produced consistent quality blades. This process is presented later in section 3.3.

2.4.2 Spar/Shell Design Concepts

The spar/shell concept was first applied to polymeric composites by Hamilton Standard Division of United Technologies Corporation (16). It has subsequently been extended to metal matrix blades such as QCSEE (17). This particular blade design is shown in Figure 6. As developed for this blade, the spar/shell design required the following components, all of which are subsequently bonded together:

- Titanium spar
- MMC shell pressure surface
- MMC shell suction surface
- shaped honeycomb filler, leading edge
- shaped honeycomb filler, trailing edge
- leading edge sheath

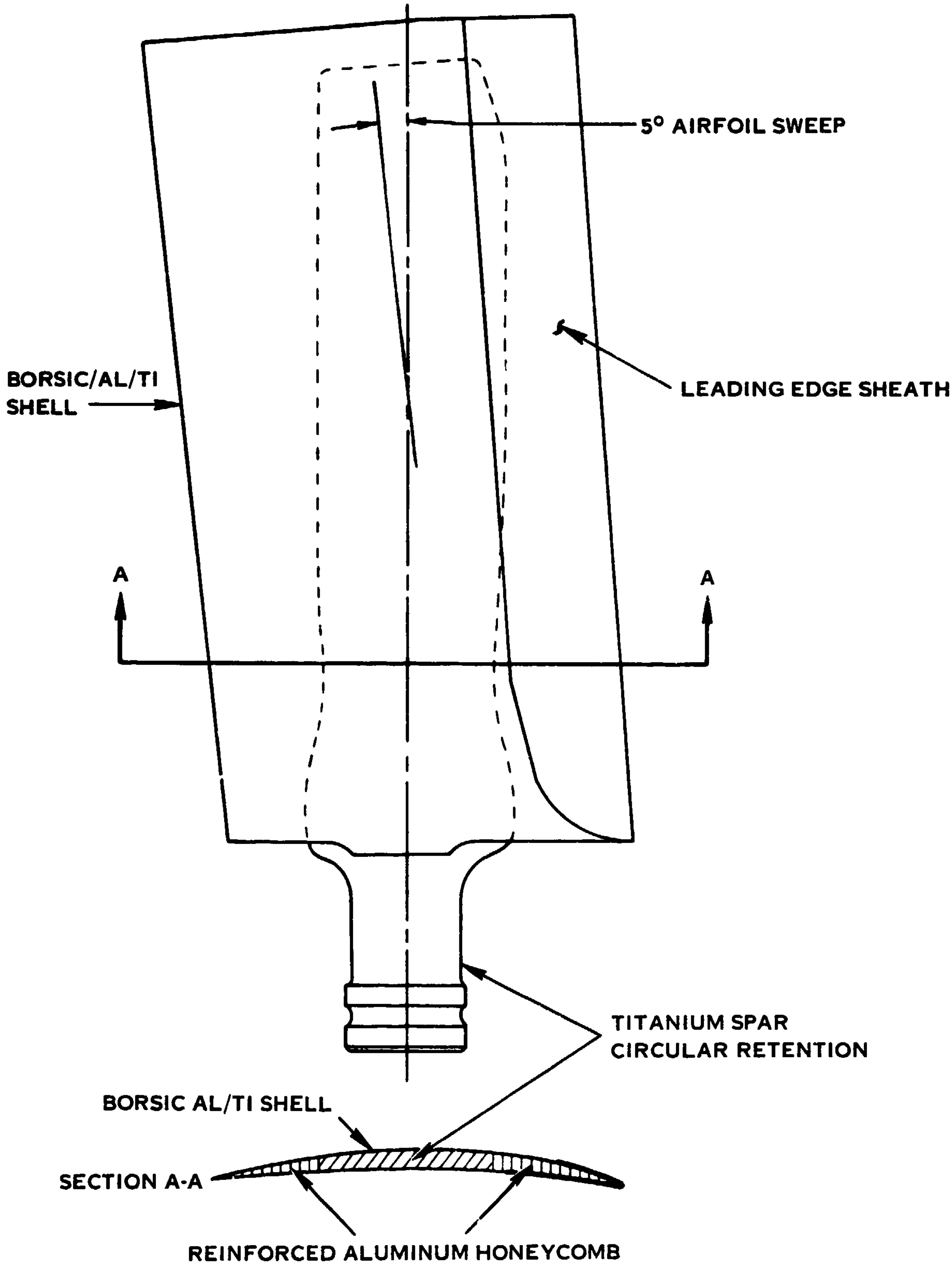

Figure 6. Hamilton Standard QCSEE Type FOD Blade Design Configuration. (17)

The complexity of these various components is a function of the overall blade design, of course. For example, some designs do not use the honeycomb filler, In the advanced designs, it is conceivable that the spar could be hollow. In any event, the analysis of manufacturing costs need only address the fabrication of various elements plus the final assembly operation. If deemed of value, alternative processing schemes such as diffusion bonding in lieu of adhesive bonding or even direct, one-step fabrication can also be addressed.

2.5 Hollow Titanium Blades

Three basic fabrication techniques have evolved for producing hollow titanium fan blades. These techniques may be described as the super-plastically deformed diffusion bonded method (SPF/DB), the "picture frame" insert process (PF), and the lamination and consolidation (LC) approach. Within these categories there can be numerous variations in process details. The later method is basically similar to the lamination procedures previously described relative to the composite materials/process system.

The SPF/DB method incorporates two precisely fabricated components, one for the suction side of the airfoil, which contain the desired internal cavity geometries. Leachable cores are placed within these cavities and the assembly is diffustion bonded in a hot pressing operation. Process variations include the method employed in fabrication of the matching components, the location of the bond line, fabrication procedures for the leachable cores, core materials, and the leaching techniques. Advantages of the process include accurate control of cavity geometry and internal radius development, microstructure comparable to a conventional forging, precise control at external dimensions, lack of significant transverse interfaces, and great flexibility for cavity design options. On the other hand, disadvantages include high tooling costs for manufacturing the matched "halves," stringent dimensional requirements for the cavities and core inserts, lack of flexibility in changing an existing design due to the tooling costs, difficulties in the inspection of the bond line integrity, and the fact that three precise fabrication sequences are required to produce one airfoil. The last consideration involves three costly die assemblies to produce the airfoil components and complete the joining operation.

The "picture frame" concept is similar to the selective reinforcement process used to stiffen areas of a structure. In this case, a conventionally fabricated solid fan blade has either cavities generated from one surface or a through hole cut out of the airfoil using conventional or nontraditional machining procedures. Assembled packs composed of core inserts, oriented reinforcement plies of materials such as borsic/titanium monotapes, filler plies and titanium cover skins are placed into the cavities. Subsequent hot pressing consolidates the inserted material and produces the basic external airfoil envelope. The cores are removed by chemical or electrochemical leaching operations. One major advantage of this approach is that only an initial blade preform has to be produced instead of two as in the case of SPF/DB. A second advantage is that machining the cavities allows much greater flexibility for altering the internal geometry should design changes be required after the hand tooling has been produced. Disadvantages include requirements for more filler plies, development of internal radii during the hot pressing operation, a larger number of joints, and the presence of joints transverse to the long axis of the airfoil. Concern over joints or bond interfaces is only a valid consideration when the diffusion bonding or consolidation processes are not properly conducted.

The third production method comprises a layup and consolidation type operation basically similar to the RMC and MMC production methods. Laminations are die cut with internal passageways and are laid up in an assembly with the leachable cores. The assembly is hot pressed to fully consolidate the blade to the desired external airfoil envelope. This technique offers even greater design flexibility than the other two because complex passageways and core designs can be readily accommodated by varying the geometry of the core components without modification to the major process tooling. Also, selective reinforcement can be easily incorporated into the processing sequence by substituting existing titanium plies with the desired number of borsic/titanium monotape stiffening plies. This option can also be utilized in elimination of the midspan shrouds without the requirement of increasing the chord thickness to maintain airfoil regidity. As a result of the preceding features, the lamination method is attractive due to its fundamentally simple one-step consolidation process and extremely high design flexibility. The large number of interfaces, requirements for internal radius development, and the inspection techniques required are major disadvantages of this method of hollow titanium blade manufacture.

As with superhybrid concepts for composite airfoils, similar combinations of processing technologies can be made in the case of HT fan blade fabrication procedures. One option is the root/stalk method. Conventional forging is used to produce a root and approximately the lower one-third of the airfoil as an integral component. Lamination procedures are then used to develop the remaining hollow portion of the airfoil. The layup is then diffusion bonded to the forged airfoil stalk. One argument favoring this approach is that critical areas immediately above the platform are incorporated in the basic monolithic forging, thus eliminating concerns over potential delamination problems.

An example of a diffusion bonded hollow fan blade is illustrated in Figure 7 in which the root and midspan areas were not produced to near-net configuration to permit the option for evaluating several designs for these areas.

3.0 TECHNICAL APPROACH

Determination of fabrication costs of fan blades using the six candidate composite systems and the hollow titanium system was made using the TRW-developed process analysis and cost modeling technology. The overall technical approach to the problem is reviewed in detail to define the assumptions and constraints used in the model development.

3.1 Component Selection

Selection of a specific fan blade configuration can confer unequal advantages to a particular material/process system. Hence, the selection process included definition of reasonable conditions relative to design features of hypothetical fan

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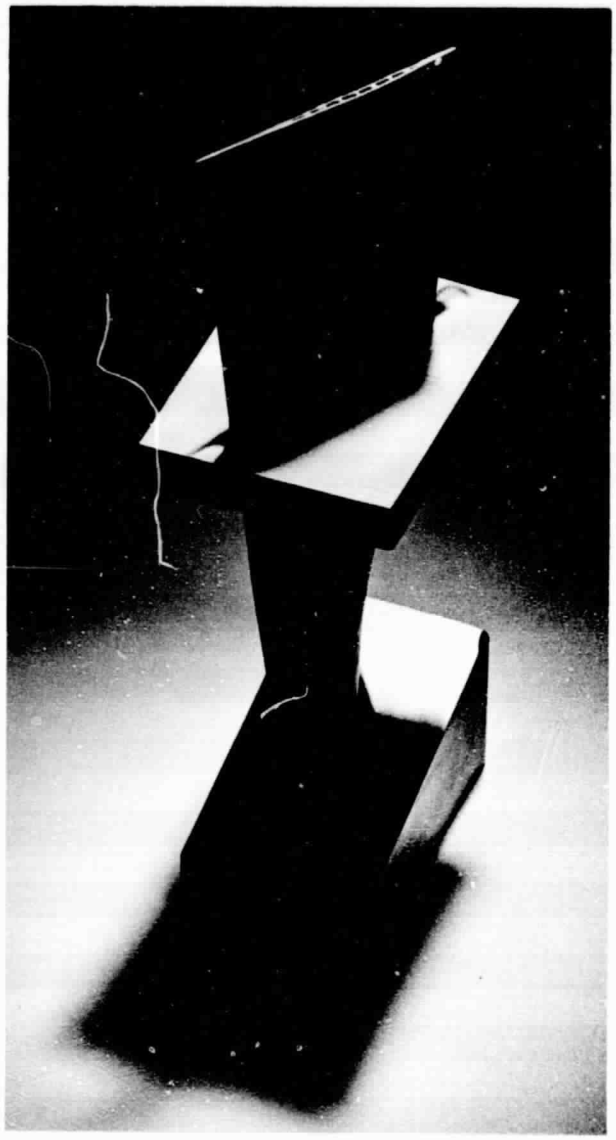

Figure 7. Diffusion Bonded Hollow F100 Titanium Fan Blade Produced by TRW.

blades to be manufactured. A hypothetical blade geometry was selected for each size category according to average design values to avoid the danger of conferring particular advantages to either designs from engine primes or specific material/process combinations. Since major property and performance differences exist between titanium, aluminum and resin matrix fan blades, slight design differences may be incorporated in the various hypothetical blade designs to optimize airfoil configuration for each material class and avoid the problem of unfair comparison.

From an economic viewpoint, the two factors in the blade geometries which have the greatest impact on cost are the maximum airfoil thicknesses and overall blade volume. For blades manufactured by a consolidated lamination process, the blade volume determines the amount of raw material that is required, and the maximum airfoil thickness determines the number of plies which must be cut and laid up.

The blade geometries to be used in this study were selected from average trends in dimensions of previous large high-bypass ratio engine first stage fan designs. An overall airfoil length of twenty-five inches was used as being typical for these blades. The number of blades per disc to be used in the cost analysis was selected to be 24, 30, 36, and 42 blades per disc. This variation in design was studied to determine if different materials/process systems had cost advantages over the others at these different blade/disc ratios. A baseline value of 30 blades/disc was used for the final analysis, and the other cost values were determined by varying the inputs to the cost models.

Blade dimensions were plotted for four large high-bypass ratio engine designs to determine the dimensions to use for the cost study. Dimensions from a JT9D solid titanium blade (46 blades/disc), a CF6 solid titanium blade (38 blades/disc), a CF6 boron/aluminum blade (36 blades/disc), and a resin matrix composite JT9D blade (30 blades/disc) were used. These data are presented in graphical form in Figures 8 and 9. It is remarkable to note the consistency of the data. Least squares linear estimates of the data from the four designs are also plotted in Figure 8 and 9 to establish the blade geometries to be used in the study. These are listed in Table 1 as follows.

Blade volumes were calculated using an ellipse formula:

$$V = \frac{25\pi}{8} \left(CW_T\ CL_T + CW_B\ CL_B\right)$$

where: V = blade volume

CW_T = maximum chord width at the blade tip

CL_T = chord length at the blade tip

CW_B = maximum chord width at the airfoil base

CL_B = chord length at the airfoil base.

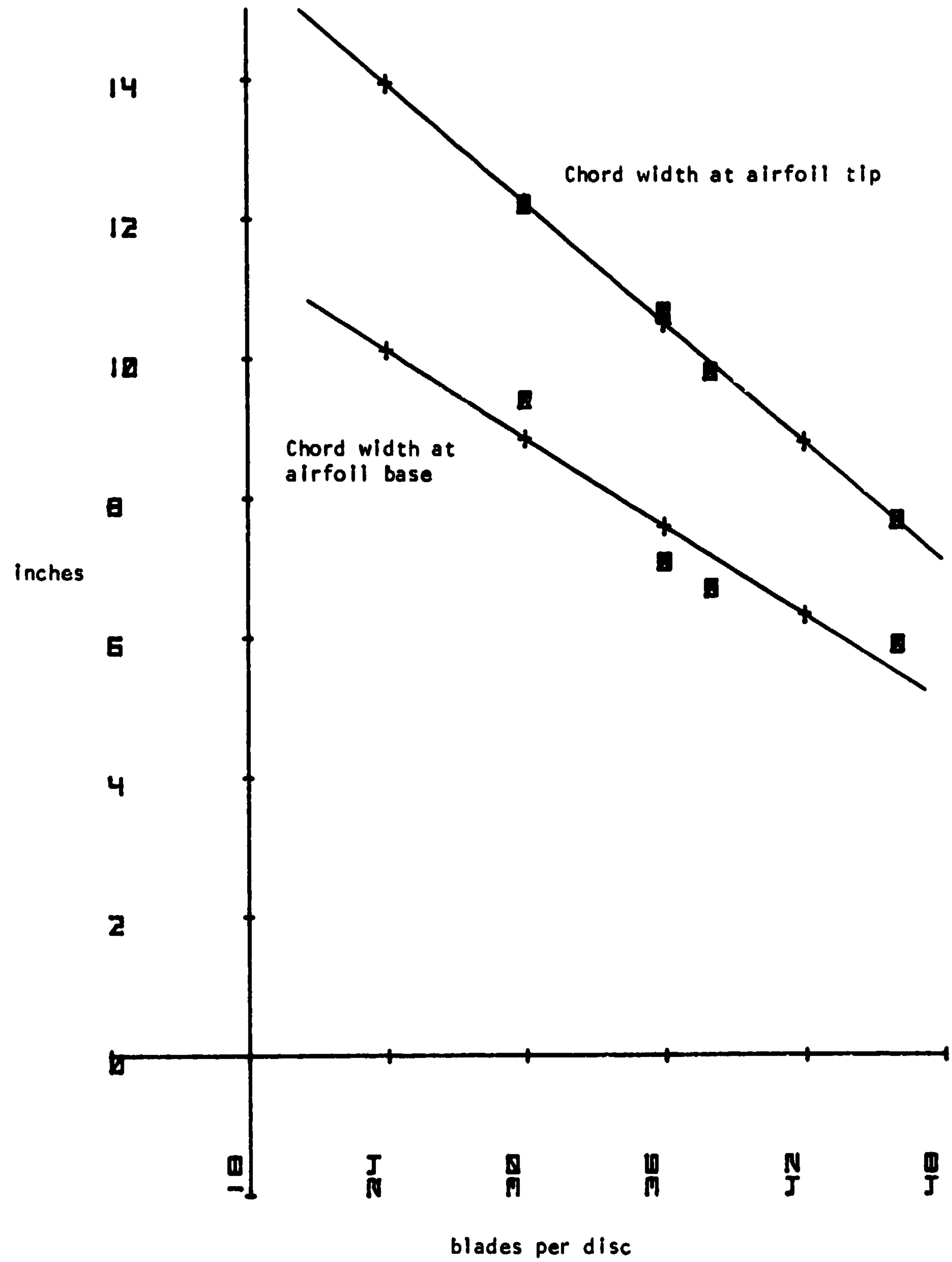

Figure 8. Chord Width at the Airfoil Tip and Base for First Stage Fan Blades from Large High Bypass Ratio Engine Designs.

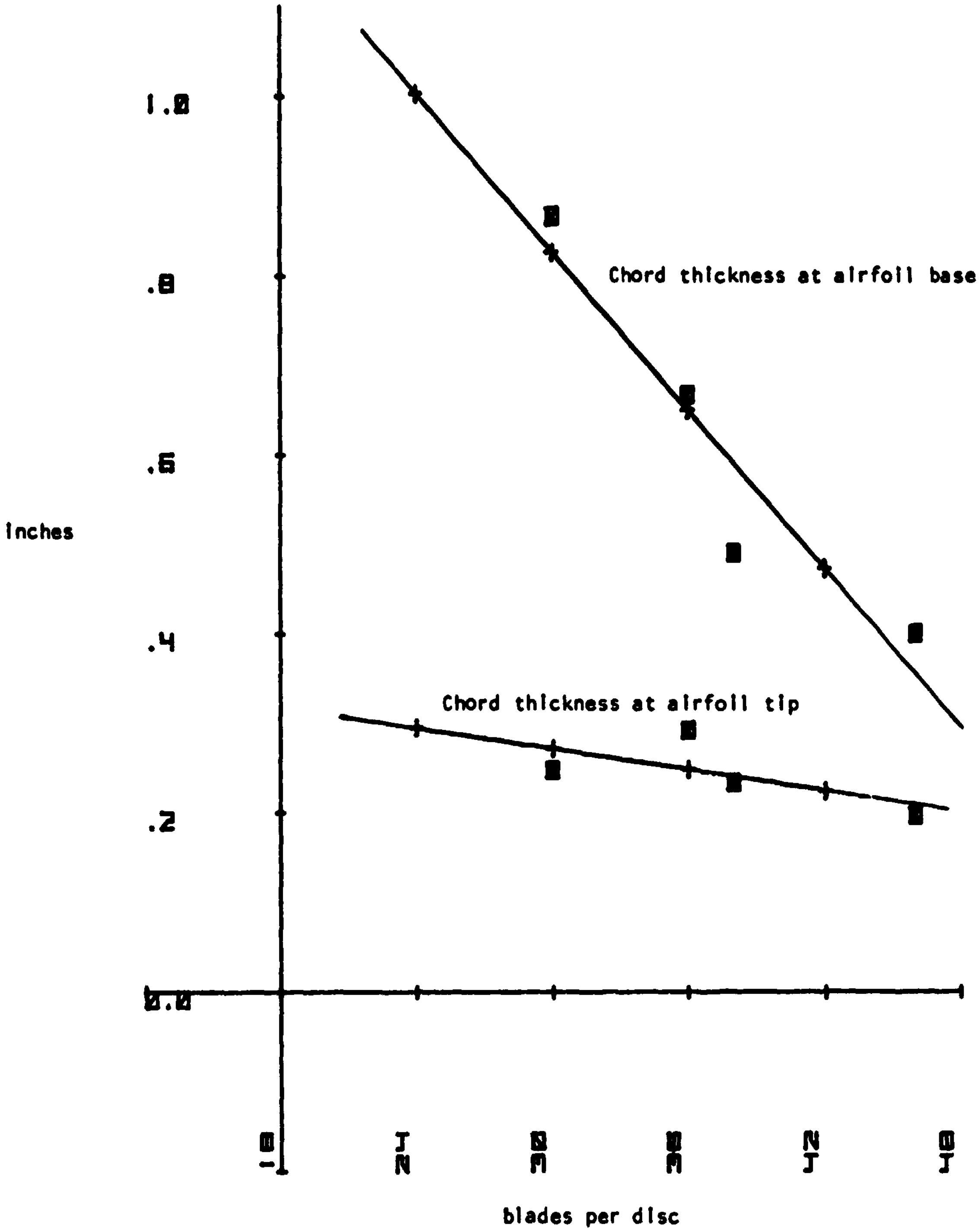

Figure 9. Maximum Chord Thickness for Airfoil Cross Section at the Airfoil Base and Tip of First Stage Fan Blades for Large High-Bypass Ratio Engine Designs.

TABLE 1

Blade Geometries for Various Blade/Disc Combinations to be Used in the Cost Calculations

	Chord at Airfoil Base		Chord at Airfoil Tip	
Blades/Disc	Width (in.)	Thickness (in.)	Width (in.)	Thickness (in.)
42	6.32	0.473	8.80	0.225
36	7.59	0.650	10.51	0.249
30	8.85	0.826	12.23	0.272
24	10.12	1.003	13.94	0.295

The ellipse formula overestimates the volume of the airfoil, but this amount of overestimation is almost equal to the root volume, making the formula able to predict blade volumes fairly accurately. The volumes generated which are the ones to be used in the cost calculations are presented in Table 2.

TABLE 2

Blade Volumes for Various Blade/Disc Ratios Used in the Cost Calculations

Blades/Disc	Blade Volume (cu. in.)
42	49
36	74
30	104
24	140

It should be noted that these blade dimensions were selected to have a minimal biasing effect towards any one of the various systems. The least flexible of the manufacturing system is the RMC/FW process. The original RMC/FW blade was designed for a low speed paddle-like fan, and its geometry was characterized by a large pitch thickness and large leading and trailing edge radii. This original design was tailored to the filament winding process, while the overall geometries used in this study considered all of the materials/process systems under study, putting all systems on a comparable basis.

3.2 Basic Process Assumptions

Necessary constraints and assumptions were imposed upon this study to establish reasonable boundary conditions on the program such that meaningful and credible results could be developed. These constraints are imposed in such a manner as to not compromise the general validity of this study and are presented below:

1. The production rate shall be 833 blades per month or 10,000 pieces annually;

2. A minimum of 500 engine sets have been previously manufactured to develop the learning curve;

3. Capital equipment, permanent tooling, and fixturing have been amortized during the initial production sequences described in (2) above;

4. Costs associated with maintaining capital equipment, die resinking due to wear, mold making facilities, etc., during the production run are included in the overhead burden;

5. Consumable item costs will be included on a per blade cost contribution; and

6. Process yields for operations involving manufacturing of these high technology parts have matured at least to levels comparable to those presently observed for similar state-of-the-art techniques.

As can be seen, the above basic assumptions define the magnitude of the production run and are also consistent with accepted manufacturing practices.

3.3 Process Definition

Extensive discussions were held within TRW and between NASA and TRW personnel throughout the duration of this project to define projected manufacturing methods that would be used to model each of the systems studied. Whenever an individual process closely approximated that of the standard conventionally forged titanium blade, the methods, allowances, tolerances, and inspection routines that were used for the forged blade were adopted for use for these processes. For example, whenever a titanium root was encountered, the manufacturing sequence that would be used for a forged titanium blade root was used. Certain root attachment designs, such as the pinned root used on the RMC/FW blade design, bear little resemblance to any present production fan blade. For processes of this type, assumptions and manufacturing methods were selected which would produce blades of the quality comparable to those presently in production.

Each of the manufacturing routings that were developed for each of the materials/process systems can be summarized by the flow chart in Figure 10. All of the blade designs except for the RMC/FW blade incorporate die cut laminations. For these processes, the sheet material is aligned and cut, the

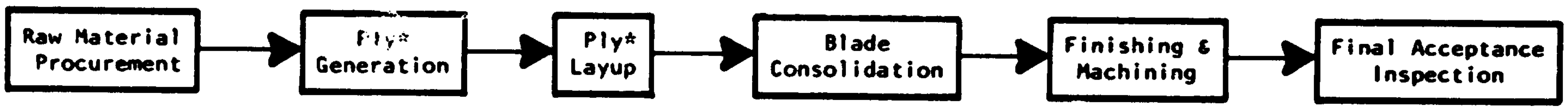

Figure 10. Basic Fabrication Flow Chart for the Manufacture of Fan Blades from Laminated Composite Materials/Process Systems.

*These processes are replaced by filament winding for the RMC/FW blade.

plies are collated, and then these are laid up. The blade is consolidated and sized by some type of press operation, then it goes through some type of finishing operation, specific to the particular materials/process system involved. This would include root machining, applying a leading edge protection, blending operations, and shelf attachment. Instead of the layup and consolidation of laminations, the RMC/FW blade uses an NC controlled filament winding process which generates the basic blade shape.

The individual manufacturing steps for the processes were selected such that they would give enough detail to adequately describe the sequence but be general enough to avoid unnecessary complications. Past experience in process modeling has demonstrated that when process elements are resolved into fine detail, these subelements can readily and accurately be defined with respect to process costs. This particular technique is effective in minimizing the impact of potential errors in the individual sub-sections on the overall cost estimate. In the present study, the resolution process was continued until one of two limits were reached. The first limit was that possible errors in cost and process estimates would exert a negligible influence on the total estimated manufacturing cost. The second limit involved reliability of the projected process element itself in that details were not resolved below the magnitude of the uncertainty associated with the process sub-element definition.

3.3.1 Resin Matrix Composite (RMC) Processing

The design selected for the RMC system includes the use of a solid graphite-epoxy airfoil with fiberglass-epoxy to be used as a diluent and a strain reliever. The pre-impregnated hybrid selected for the majority of the laminations was a ten mil thick 80/20 hybrid of AS graphite and S-glass. Prepreg diluent laminants of S-glass will be used for ten percent of the overall airfoil, and the root plies will be stamped from 5 mil thick Uni-S-glass. The plies will be die cut with angular fiber alignment of 0°. + 35°, and -35°.

The root is of a straight splayed design which has a precision machined titanium dovetail outsert. The platform will be molded from chopped 80/20 hybrid which is offal from the die cutting operation and subsequently bonded to the airfoil. Leading edge protection will be provided by a stainless steel mesh which is bonded onto the leading edge and then nickel plated. The last step of the manufacturing process consists of coating the airfoil with polyurethane for erosion protection.

Certain process details, such as the specific angular arrangement of the plies do not influence assembly costs as all plies must be aligned with respect to the standing axis regardless. The overall yield of the ply cutting operation is relatively independent of the orientation of a given ply because a certain amount of angular reinforcement must be provided.

A detailed process flow chart is presented in Figure 11.

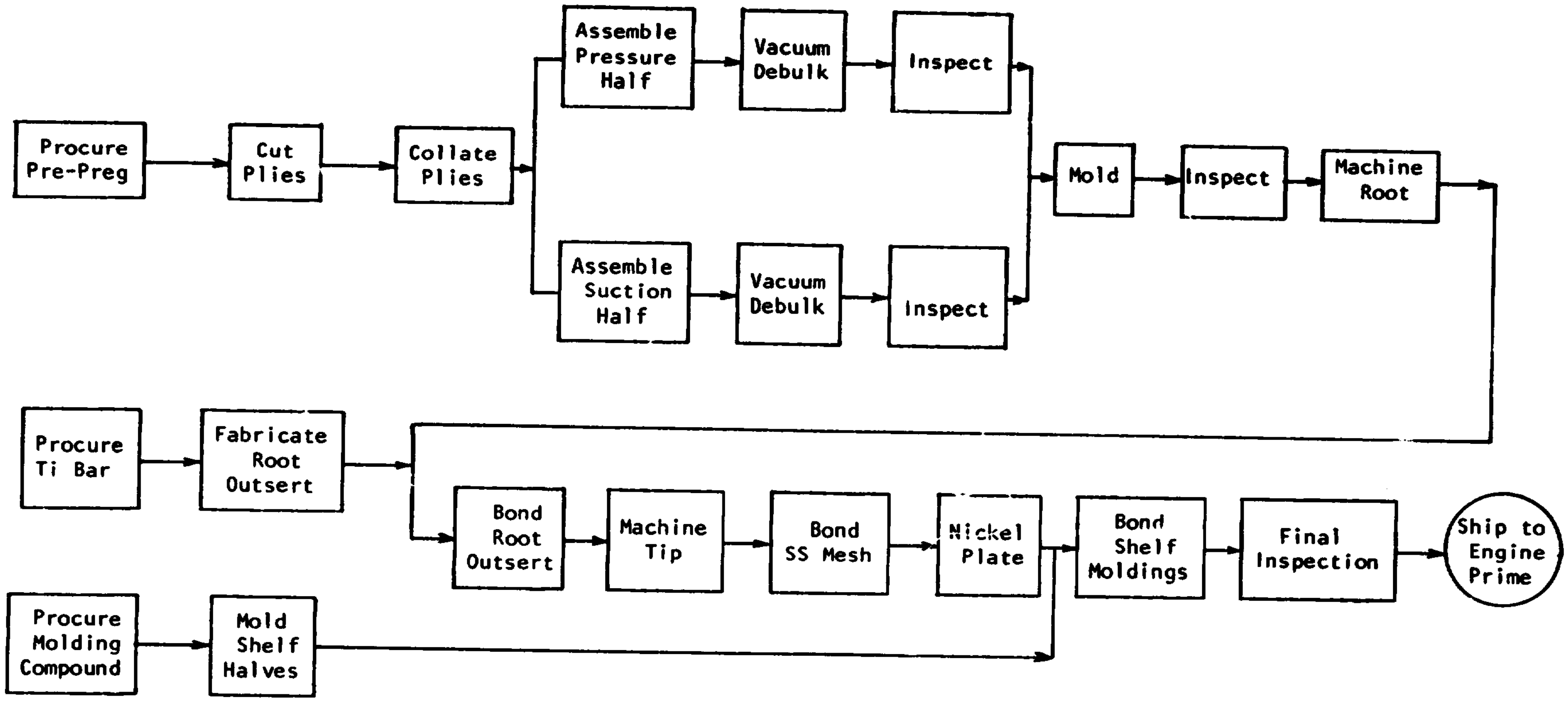

Figure 11. Process Flow Chart for a Solid Resin Composite (RMC) Fan Blade.

3.3.2 Filament Wound Resin Matrix Composite (RMC/FW) Processing

The filament wound blade will be made from strands of Union Carbide T-300 filament material which contains 6000 individual filaments. The blade will have an internal wedge and sleeve to be used as a winding mandrel and a pin type root attachment. The blade will have no hollow cavities and it will be wound in two steps as a spar and shell. The blade will be wet wound using the epoxy resin Apco 2434. The wet filament winding eliminates the costly prepreg process and greatly reduces the cost of the blade.

It should be mentioned that the filament wound blade made by Fiber Science (24) was for a low-speed paddle-like fan. The large leading and trailing edge radii which this design had could be easily wound on their filament winding apparatus. A filament wound blade with smaller leading and trailing edge radii that would be associated with the blade geometries selected in this study will be difficult to fabricate by filament winding but a cost analysis was performed assuming that it was possible to manufacture a large fan blade of the configuration defined in this report.

The blades will be wound two-at-a-time joined at the tips to reduce set-up costs. After winding the two attached blades will be molded simultaneously and then separated. A metal sleeve will be wound into the root to accept the root locking pin. The hole will be finish machined for this locking pin using the airfoil as the reference surface. This arrangement loosens tolerance requirements for the winding and molding operations. Shelf halves and a tip cap will be molded from a glass molding compound, and then bonded to the blade. A stainless steel mesh will be adhesively bonded to the leading edge to improve FOD resistance, and the mesh will be nickle plated, finishing the manufacturing sequence. A flow chart describing the manufacture of this blade is presented in Figure 12.

3.3.3 Superhybrid (SH) Processing

The superhybrid blade utilizes both metal and resin matrix composite materials and represents an attempt to incorporate advantages of both materials in a single structure.

The superhybrid/solid laminate blade will have one central titanium centerply and two three mil titanium plies on both the pressure and suction sides of the blade's airfoil exterior. Beneath the titanium outer shell will be two plies of 50/50 boron aluminum with 5.6 mil boron fibers. The remainder of the blade volume between the centerply and the outer metal matrix plies will consist of the same 80/20 hybrid resin matrix composite used for the RMC blade. All metal plies will be assembled using adhesive bonding with FM-1000 film. The leading edge of the airfoil will be protected by a titanium wrap-around leading edge which will also be adhesively bonded.

The root will be of a straight splayed design with a bonded-on titanium dovetail root outsert. The wedges which will spread the plies at the root will be made from uniglass. The platform will be molded from chopped offal from the hybrid die cutting operation and the platform halves will be adhesively bonded to the airfoil. The process flow chart is presented in Figure 13.

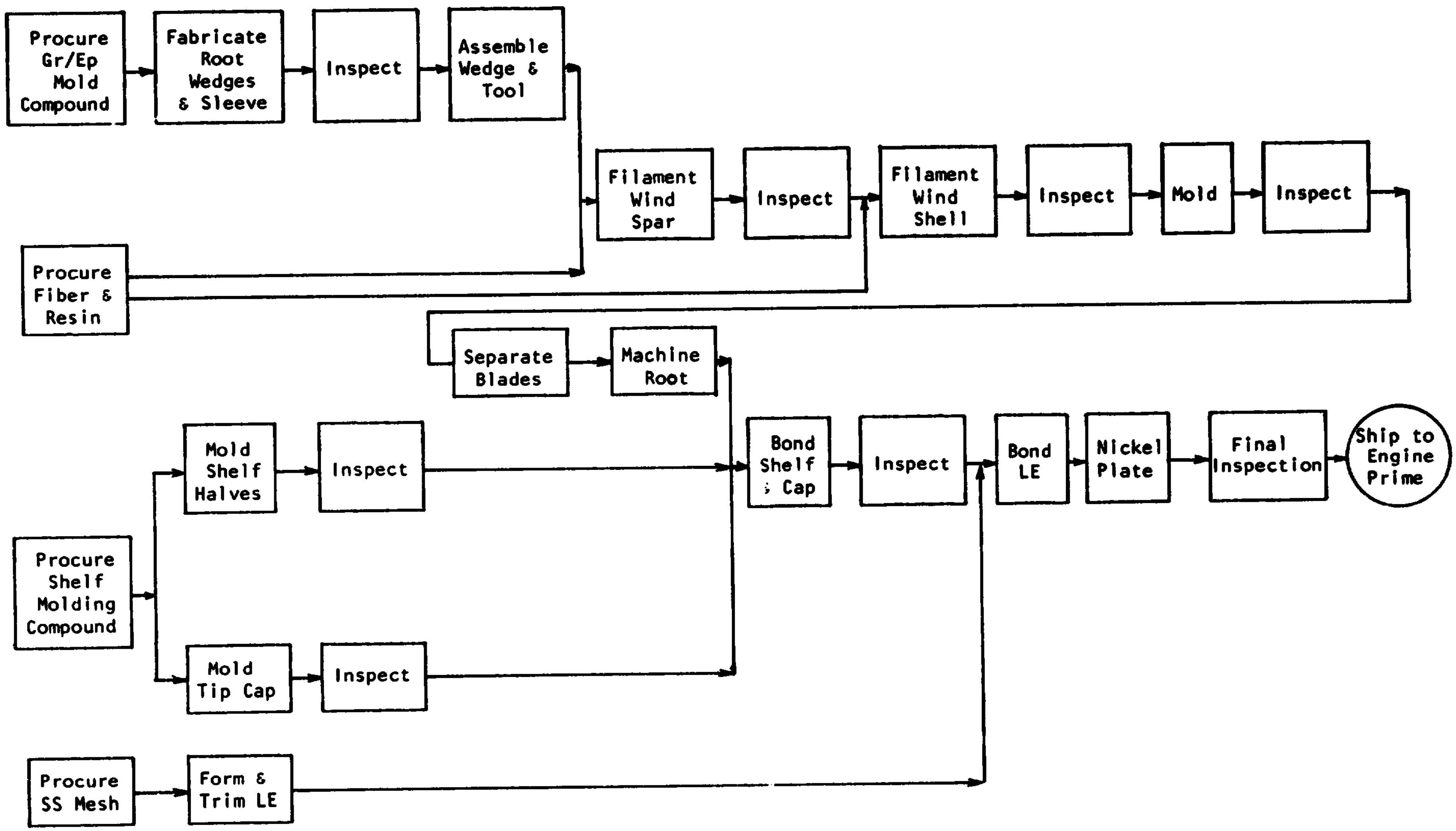

Figure 12. Process Flow Chart for a Filament Wound Composite (RMC/FW) Fan Blade.

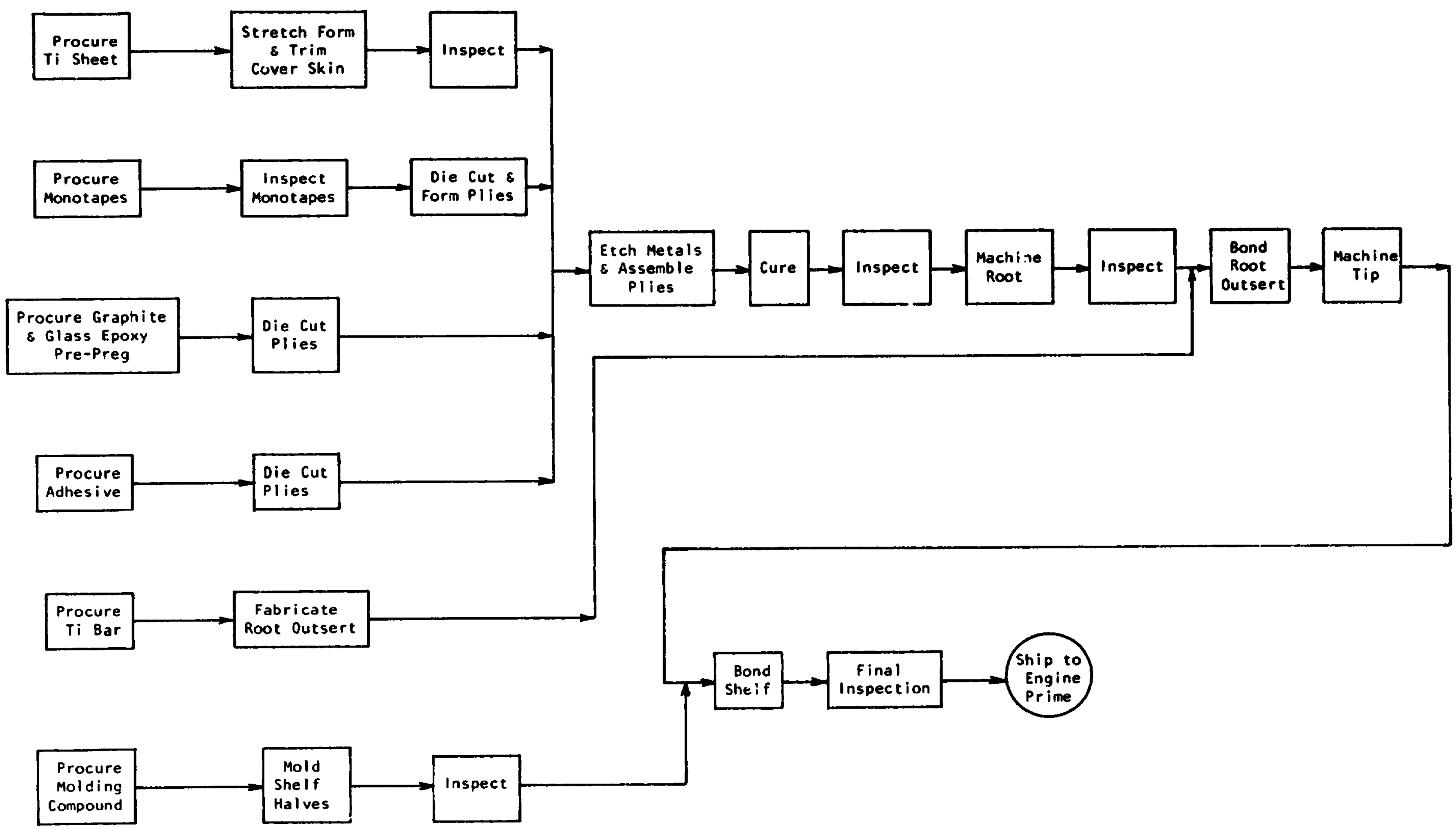

Figure 13. Process Flow Chart for a Superhybrid-solid Laminate (SH) Fan Blade.

3.3.4 Superhybrid/Spar-Shell (SH/S-S) Processing

The superhybrid spar/shell design which was selected for study is similar to that of the G.E. TICOR blade. The spar is manufactured of titanium using conventional forging technology. The leading edge of the spar is also the leading edge of the airfoil for increased FOD resistance. The rest of the exterior of the airfoil will be sheathed by a 0.007 inch thick titanium foil cover skin. The sheath is for erosion protection and will be formed from one of the lower cost titanium sheet alloys such as 3-2 1/2 or 15-3-3-3. Underneath the sheath will be two stiffening plies of 5.6 mil 50/50 boron aluminum plies. The remainder of the blade volume will be filled with laminations of 10 mil thick 80/20 AS/S-glass resin matrix composite. The root configuration will be machined into the spar and will be identical to a conventional solid titanium fan blade.

The pressure and suction laminations will be die cut and assembled separately. Then the etched and cleaned spar, suction and pressure lamination assemblies, and cover skin will be molded into the basic blade shape. The only finishing operations required after molding will be a simple deflashing operation to remove the flash from the resin, a blend of the joints in the airfoil, and the finish machining of the root. A flow chart describing the manufacturing routing is presented in Figure 14.

3.3.5 Metal Matrix Composite (MMC) Processing

The bulk of the Metal Matrix Composite (MMC) blade will be made from pre-consolidated boron-aluminum monotapes. The monotapes will be 0.010 inch thick and have boron fibers which are 0.008 inch in diameter. It was determined that the most cost effective method of monotape acquisition was to go to an outside vendor whose specialty was monotape production for procurement. An outside vendor who produced more monotape than would be required for the assumed 10,000 blade per year production quantity could justify the capital expenditures required for the sophisticated equipment and still produce monotape for a reasonable cost. The capital equipment cost for sophisticated machinery was prohibitive for in-house production of monotapes at the assumed volume level and the labor content of monotape fabrication using simpler machinery would involve excessive labor costs.

Ply configurations are die cut from the monotape and stacked to generate the general airfoil shape. No preforming will be necessary. Stock for the basic root form is provided with the addition of aluminized titanium root blocks. The aluminization is necessary for air bonding. A titanium cover skin will be required for erosion protection, and it must also be aluminized for diffusion bonding in air.

After the blade is consolidated by a diffusion bonding process, it goes through several finishing operations. The leading and trailing edges are trimmed undersize and subsequently coated with a thick layer of titanium. This trim and coat operation is necessary to remove the flash which could occur

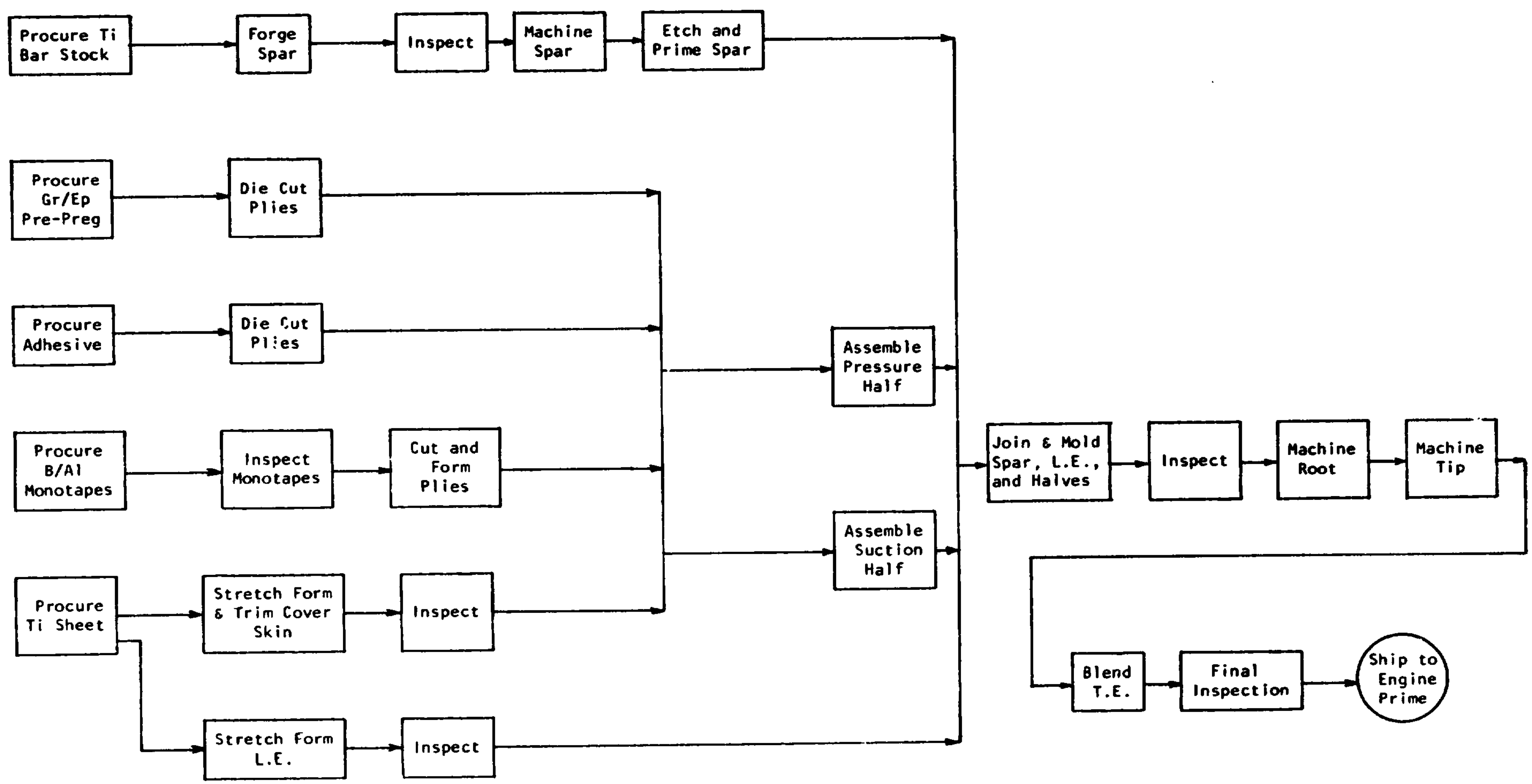

Figure 14. Process Flow Chart for a Superhybrid-Spar/Shell (SH-S/S) Fan Blade.

where the edges of the monotape join. The blade is now ready for finishing operations similar to those required for a conventionally forged blade. These would include a root machining operation, a tip cut operation and airfoil blending operations. A detailed routing for the MMC blade is presented in Figure 15.

3.3.6 Metal Matrix Composite/Spar-Shell (MMC/S-S) Processing

The metal matrix composite/spar-shell blade will be constructed entirely by a lamination process. It will have a titanium spar made from laminations of titanium foil. Hollow cavities with an internal rib structure will be produced inside the spar using leachable iron PM cores. The hollow cavities are situated in areas where there are low operational stress levels, reducing the weight of the blade with minimal strength penalties. There will be a titanium cover skin for erosion protection, and the bulk or remainder of the blade volume will consist of laminations of 10 mil thick boron aluminum monotape. The root attachment will be similar to the root on a conventionally forged blade and will be incorporated in the spar design.

The manufacturing sequence begins with the die cutting of the titanium plies, and the cold press and sintering of the leachable iron PM cores. These components are assembled and tack-welded together and sealed in a HIP can. The spar is HIPped, removed from the HIP can, and all rough edges are smoothed in a blending operation. The spar is then etched and aluminized for the air bonding consolidation process. The spar, the boron aluminum monotape plies, and the aluminized cover skin are assembled and diffusion bonded by a hot pressing operation in air, generating the final blade shape. Finishing operations occurring after this stage are similar to the other metal matrix blades except for the leaching operation. The leading and trailing edges are trimmed undersize and coated to size with titanium in the same manner as the MMC blade. The root is machined using the airfoil as a reference followed by a blending operation. After the exterior of the blade is finished, the cores are leached out in an acid bath creating the hollow cavities. The cores are left in during the trim, blending, and machining operations to increase the rigidity of the blade and ease the bonding difficulties that could result with hollow cavities that could potentially collapse. A detailed flow chart of the processing sequence that was selected for the MMC/S-S blade is presented in Figure 16.

3.3.7 Hollow Titanium (HT) Processing

The processing sequence of the Hollow Titanium blade is very similar to the sequence of the MMC/S-S blade and is presented in Figure 17. This blade design also uses the leachable iron core concept. Instead of having a hollow titanium spar and titanium cover skin with the bulk of the blade volume being boron/aluminum, the hollow titanium blade will be entirely constructed of titanium sheet without selective reinforcement. The titanium alloy to be used will be one of the potentially least cost sheet alloys such as 3-2 1/2 or 15-3-3-3. Because the cost of titanium foil on a weight basis is extremely sensitive to its thickness, the foil used in the laminations will be as thick as possible for cost savings. The average thicknesss selected for the laminations is 0.016 inch. Thinner laminations are used where fill and blade contours are

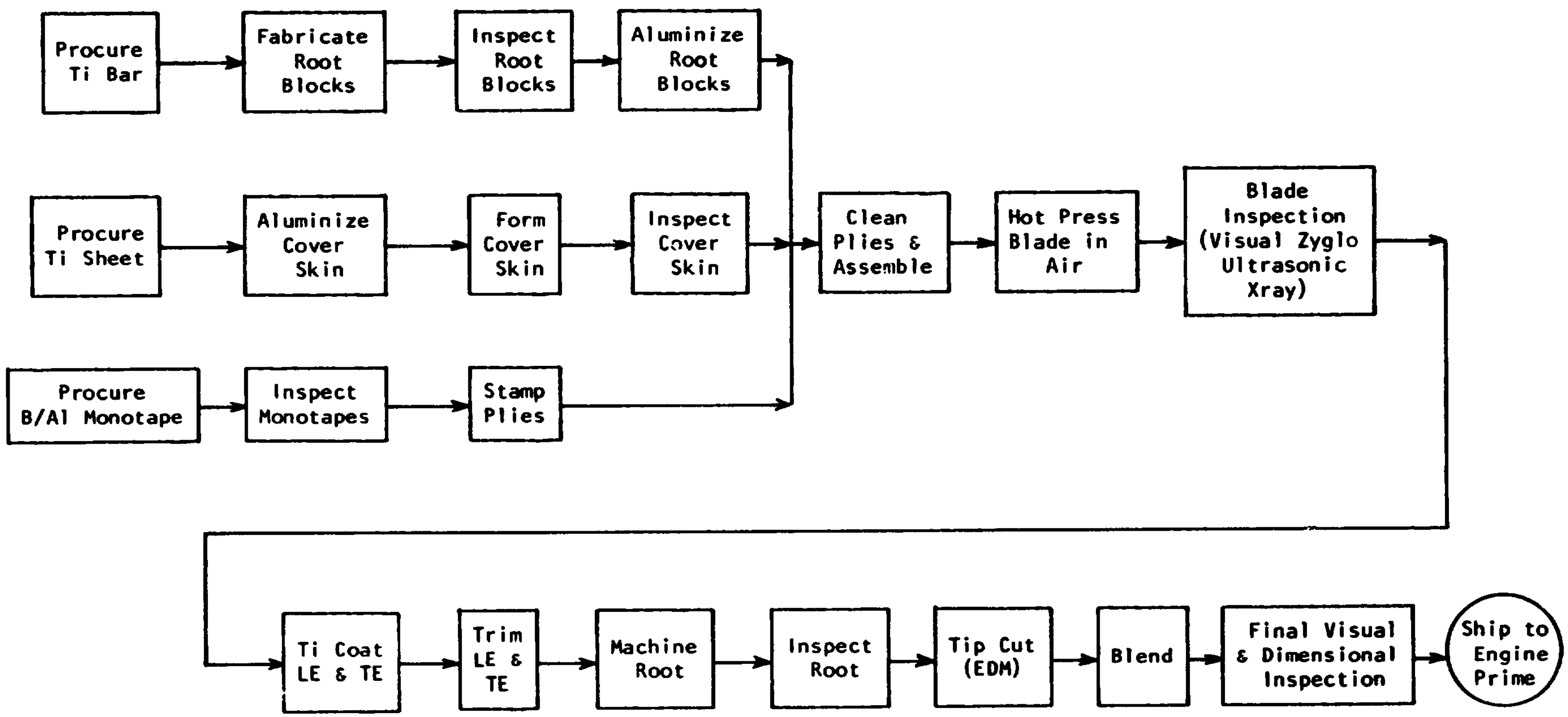

Figure 15. Process Flow Chart for a Metal Matrix Composite (MMC) Fan Blade.

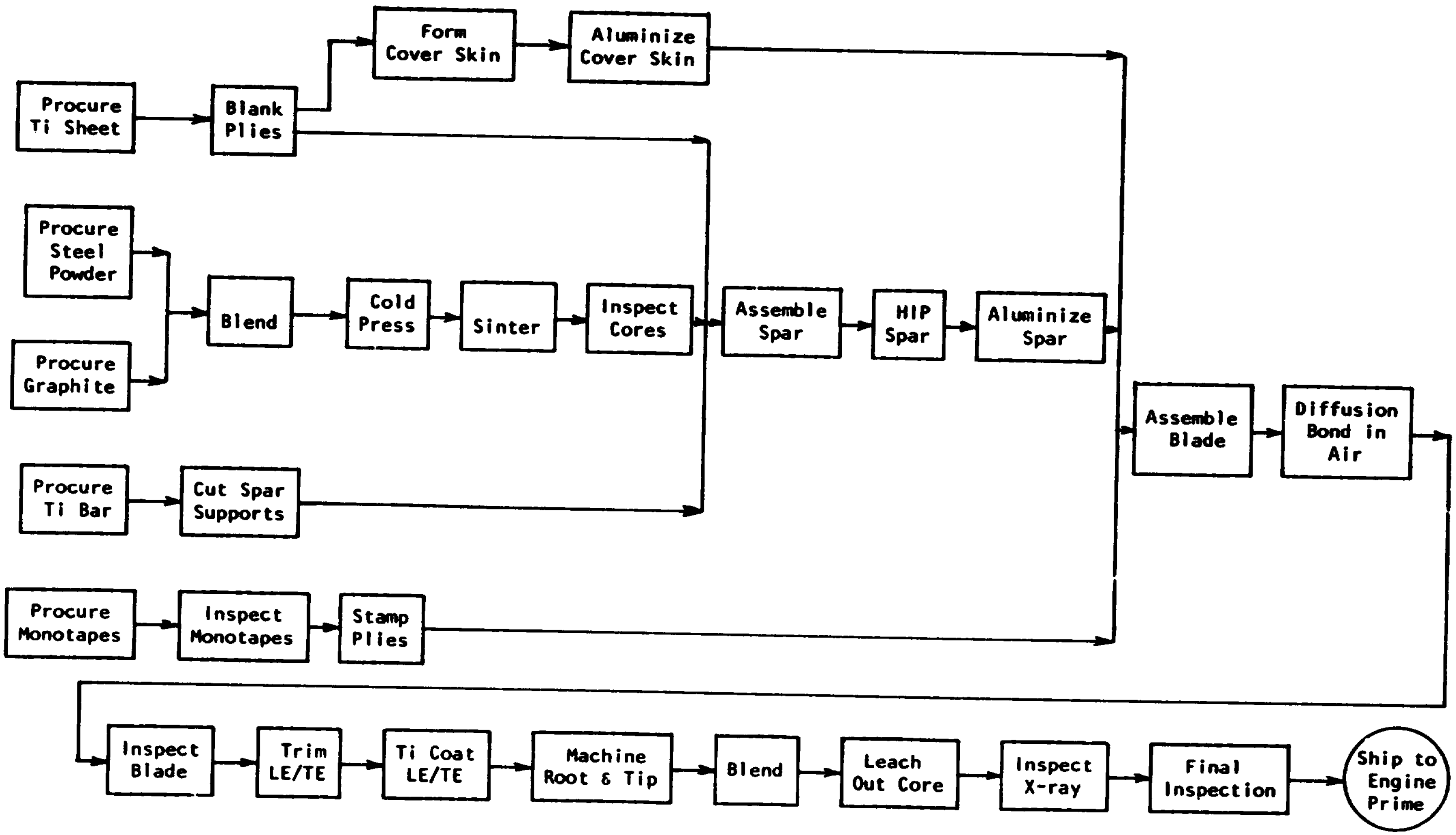

Figure 16. Manufacturing Process Flow Chart for a Metal Matrix Composite Blade with a Spar and Shell (MMC/S-S).

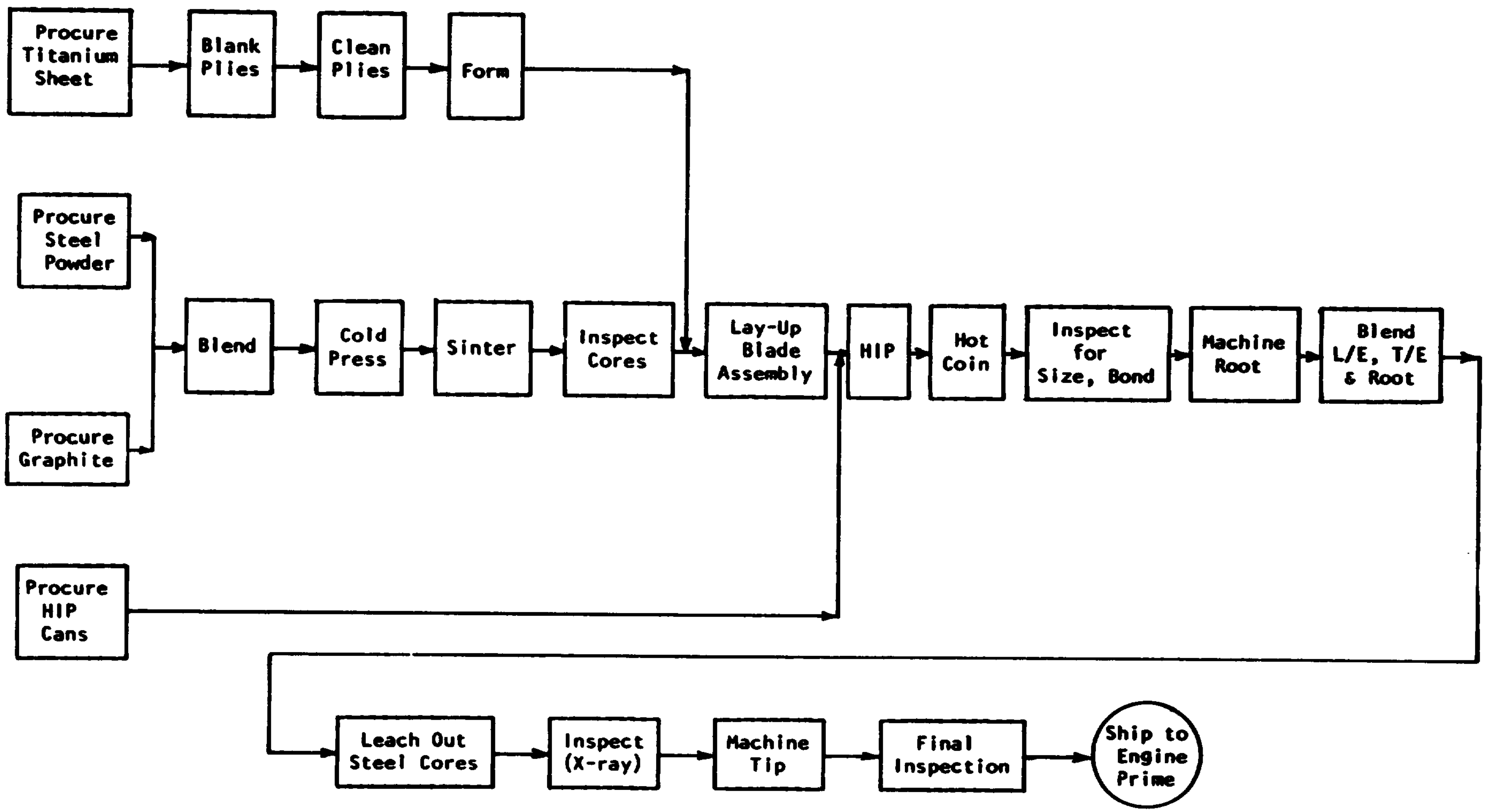

Figure 17. Manufacturing Process Flow Chart for a Laminated Hollow Titanium (HT) Blade.

critical to account for ply drop at highly contoured airfoil sections, and thicker laminations are used towards the center of the blade where these factors are of less concern.

The hollow titanium blade will be manufactured by a diffusion bonding process. Die cut titanium foil laminations will be stacked with PM iron core inserts. This assembly will be canned and HIPped and then subjected to an isothermal sizing operation to bring the blade to its basic shape. The root will be machined, the tip will be cut to size, and the airfoil will be blended. The processing is completed by removing the iron core inserts by an acid leach process.

4.0 ECONOMIC ANALYSIS

This section describes the economic analysis performed on estimating manufacturing costs for seven advanced material/process combinations for large, advanced fan blade designs. Prior to discussing the detailed analysis performed, the methodologies utilized in the cost modeling procedure will be outlined. This background information will provide a basis for credibility for the cost estimates.

4.1 Cost Model Methodologies

The TRW-developed cost modeling technologies were extensively used to establish the projected manufacturing cost presented in this report. There are two basic elements to the modeling process; the models themselves and the complex influence of yield factors.

4.1.1 Process Models

The most general process equation which can be used to describe costs associated with elements of a batch manufacturing process can be defined as:

$$K = \frac{LOH}{nm} (\Sigma t) + C \qquad (1)$$

where: K = cost per part for the process

LOH = labor and overhead rate

n = number of parts per batch

m = number of batch processes simultaneously operated by one worder

t = time to complete one operation

C = raw material costs per part.

When applying this general model to the various manufacturing steps for the seven systems, equations specific for each process element derived can be developed. In many cases in this study, a large proportion of the fabrication steps were relatively straightforward and equation (1) was adequate. The models were developed only to the detailed extent justified by the reliability of the available input data. Hence, in many instances, trivial cost contributions were absorbed as part of the overhead burden rates utilized. This assumption is valid because it was uniformly applied to all systems and the total impact on relative cost estimates was negligible. Further, equipment use and tooling consumption have also been included in the overhead burden, a common industry practice.

4.1.2 Yield Factors

Fallout, or rejects, occur for nearly all manufacturing processes. There are a variety of reasons including machine errors, operator errors, inconsistent materials, and tool breakage. Another factor involves economics in that excessive fallout is undesirable for obvious reasons but control of a process to produce zero rejects can also be uneconomical for most operations. Realistic cost estimates must address this important consideration and make adjustments according to expected process yields. There are two independent approaches to examination of yield factor impact on costs. The first involves consideration of simple, or straight, yield factors for each individual process step. This concept has been identified as the "uncoupled yield factor" and is useful in examining costs for a process element independent of the other process elements. The second concept, "coupled yield factor," is more complex and has been developed to consider real manufacturing conditions existing on a production line during steady-state part throughout. One or more manufacturing steps may be followed by an inspection which then determines part acceptability. Hence, the yield factor is defined in the coupled system of one or more manufacturing steps and the ensuing inspection procedure.

4.1.2.1 Simple Yield Factors

As outlined above, this "uncoupled yield factor" concept involves defining the true costs to process a part through a given step independent of the preceding or following process sequence. The cost defined represents that incurred to pass one good part through the particular cycle under consideration. This relatively straightforward concept is expressed by the equation:

$$K_{ap} = \frac{K_{ip}}{Y_i}$$

where: K_{ap} = process cost for one acceptable part

K_{ip} = process cost for i^{th} operation at 100% yield

Y_i = yield factor for i^{th} operation

This simplistic approach is valid only when an individual process element is being examined and is not applicable in determining total part costs by summing elemental process costs.

4.1.2.2 Coupled Process Yield Factor Development

A more complex expression for yield factors was derived for quantitatively defining the effect of many discrete yield factors on total manufacturing costs. In real manufacturing situations, accept/reject criteria are imposed during inspection operations which are performed following one of more processing steps. Thus, a yield is defined for the combined coupled system of process and inspection steps. The inspection can produce one of three results: the part is acceptable; it is unacceptable and must be scrapped; or it is unacceptable but can be repaired and recycled. This concept is illustrated in Figure 18.

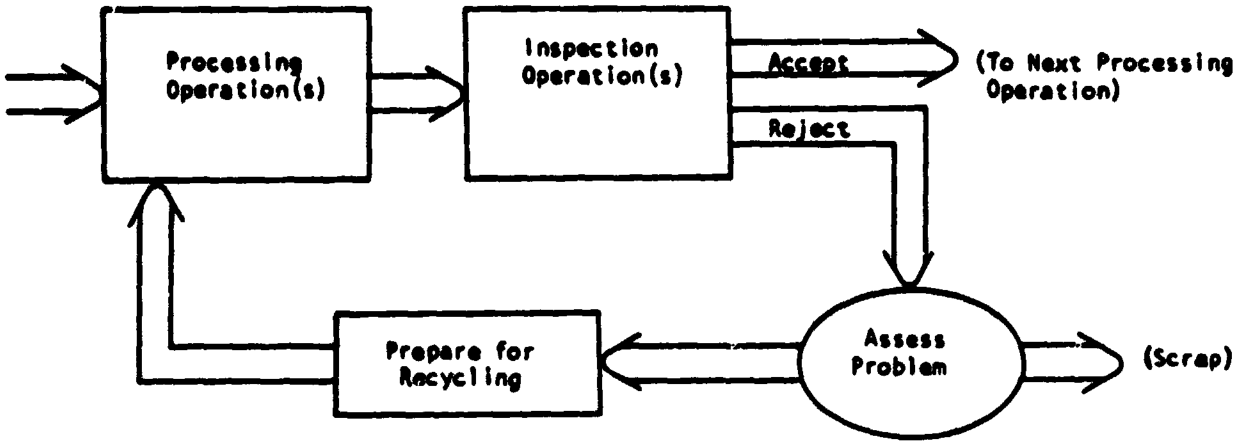

Figure 18. Illustration of Yield Concepts for Process Analysis of an Uncoupled Manufacturing Element.

The process can be treated mathematically by defining:

(a) as the fraction of acceptable parts emerging from inspection;

(b) as the fraction of scrapped parts; and

(c) as the fraction of parts capable of rework repair and recycling through the process. An infinite series can then be defined to describe the total fraction of good parts produced for each part entering the couple processing/inspeciton sequence.

This is given by the equation:

$$a \sum_{n=o}^{\infty} c^n = \frac{a}{1-c}$$

Where n is the number of times a part is recycled with (a) and (c) as defined previously. Similarly, the fraction of scrap parts produced per part entering the sequence is defined as:

$$b \sum_{n=o}^{\infty} c^n = \frac{b}{1-c}$$

and, hence, the total fraction that is recycled is:

$$\sum_{n=1}^{\infty} c^n = \left(\sum_{n=o}^{\infty} c^n\right) - 1 = \frac{c}{1-c}$$

The term K_i is then defined as the overall cost of the sequence to produce one part at 100% yield, the actual costs to produce parts under more realistic conditions can be defined by the following regorous expression:

$$K_y = \frac{K_i \left(\frac{a}{1-c} + \frac{b}{1-c} + \frac{c}{1-c}\right)}{\frac{a}{1-c}}$$

where K_y is now the costs for finite values of b and c, scrap and recycle fallout. This expression is valid for all values of a, b, and c subject to the requirement that:

$$a + b + c = 1$$

This latter constraint is applied to maintain conservation of parts. It assures that parts are not created or lost somewhere in the cycle. Algebraic simplification of the expression for K_y and substituting the a + b + c = 1 constraints reduces the expression to:

$$K_y = \frac{K_i}{a}$$

which is equivalent to the straight yield concept for a single process step.

4.1.2.3 Compounding Yields Factors

Determination of total part cost in the presence of yield factors less than 100% may now be accomplished by a compounding process. It must be recognized that more than one part must be processed by the first operation to provide a good part to enter the next processing cycle. This effect then is compounded over all cycles to arrive at the actual total part cost.

"Actual process/inspection block costs" can also be defined when yield factors are introduced by considering the number of parts that must be produced in a particular block to result in production of one acceptable part for shipment to the customer. The costs are defined by the equation:

$$K_{yi} = \frac{K_i}{\prod_{j=1}^{N} Y_i}$$

where: Π = denotes repetitive multiplication and;

K_{yi} = actual cost of the i^{th} block

K_i = process cost of i^{th} at 100% yield

Y_i = overall yield factor for the i^{th} block

N = total number of blocks in the sequence

The actual block cost method puts heavy weight on the initial blocks of the manufacturing sequence because these preliminary operations must be performed more times than the last few steps. This effect is magnified if the absolute block costs of the first sequence are much larger than the last ones.

4.2 Cost Analysis

This section will examine cost data developed from process models describing the total manufacturing operations established for each of the seven systems analyzed. All resulting estimated total manufacturing cost data were normalized to an index of 100. This index represents the manufacturing costs for large titanium fan blades produced by conventional forging and machining at 42 blades per disc. The index was developed by averaging the standard hours and materials costs for several large titanium fan blades in current production for JT9D and CF6 type engines and equating it to 100. Thus the final blade costs for the other systems are presented as being costs which are percentage values of the production cost of conventional blades. All estimated cost data contained in this report will be presented relative to the actual costs indicated by the normalized indices calculated for the conventionally processed fan blades. An estimate was also made of the manufacturing costs associated with the production of a conventional type blade at the baseline 30 blade per disc size. Forging blades with this large of a plan area is not possible with present forging equipment, but the costs could be calculated using process modeling techniques for comparison purposes. This value becomes 160 in comparison to the index of 100 for the 42 blade per disc size.

4.2.1 Cost Data

Process cost element data developed for the 30 blade per disc size are discussed initially owing to the large volume of information generated for this program. These detailed data are presented in Tables 3 through 9 for the seven systems analyzed. As stated previously, all cost data are presented in normalized form where 100 is the cost of producing a conventionally forged and machined blade for a 42 blade per disc size, and 160 is the cost of producing a similar blade corresponding to a 30 blades per disc size. For clarity, the significance of each column of these tables will be described prior to a detailed analysis of the results. The specific nature of each column is as follows:

Column 1: Manufacturing Steps - The rows in this column represent the basic individual manufacturing steps necessary to describe the total manufacturing sequence in enough detail to give accurate cost estimates. The steps are organized in blocks there major fallout was predicted to occur.

Column 2: Normalized Labor Costs - The figures in this column represent the normalized costs associated with the labor content of each step. These valves are normalized relative to a value of 100 which is the total manufacturing costs incurred while producing one conventionally forged titanium blade at the 42 blades per disc geometry.

Column 3: Normalized Materials Costs - Figures in this column are the normalized costs of raw materials and consumables for each step. These values are also normalized relative to a value of 100 which is the total manufacturing costs incurred while producing one conventionally forged titanium blade at the 42 per disc geometry. Raw materials would include purchased goods such as metal foil, fibers, pregreg, and bar stock. Consumables would include objects such as HIP cans, separaters, parting agents, and solvents. Only the cost of major consumables were used directly. Minor consumables such as general operating supplies were accounted for in the overhead rate.

Column 4: Block Costs - The normalized costs in this column are the sum of columns 2 and 3 and represent the cost of the individual process element block.

Column 5: Yield Factors - The factors tabulated in this column represent the expected or actual yields for each operation in the manufacturing sequence. In some cases, an operation has been assigned a separate yield factor while others illustrate the coupling effects of several manufacturing operations followed by an inspection. In the latter instance, the inspection step identifies the fraction of rejectable parts produced by any or all of the associated manufacturing operations.

Column 6: N (Number of Operations Required) - The data contained in this column reflect the number of times a particular operation must be performed at its point in the manufacturing sequence to yield one acceptable finished large fan blade. The number is derived by compounding all yield factors between this process step and the final operation in the sequence. A simplified example can be provided by considering a two-step manufacturing sequence in which each step has a 0.50 yield factor. Thus, the first operation must be performed four times to yield one acceptable finished part. Hence, the number required for step 1 becomes 4.0. These data therefore reflect the influence of compounded yield factor effects for the entire process sequence.

Column 7: Uncoupled Cost - The influence of the corresponding yield factors on the relative costs of a process are tabulated in this column. The costs are calculated by dividing the data in column four by the corresponding data from column five. Therefore, the relative costs here represent the costs incurred to produce one acceptable part by the process involved, independent of any preceding or succeeding operation. This latter point is significant when total manufacturing costs are later determined.

Column 8: Compound Cost - The compounding effect of yield factors on relative costs for each process/inspection sequence described earlier was utilized to develop the data shown in this column. The relative cost data were calculated by multiplying the costs of an operation at 100% yield (column 4) by the corresponding factor tabulated in column 6. The resulting cost index reflects not only the discrete process step yield/factor, but the influence of compounded yield effects due to fallout occurring downstream in the manufacturing sequence.

The rows of data presented in Tables 3 through 9 are not necessarily presented in sequential order because most of the flow charts (Figures 12 through 18) have branches. The flow charts should be consulted for clarity to explain the actual flow of material through the routing.

The effect of compounding becomes more significant for manufacturing routings which have more steps because there are more places for fallout or scrap to occur. The overall scrap rates for each of the processes examined are approximately equivalent because flow charts are typified by having many parallel branches even though some processes have many more steps than the others, for example, the SH/S-S system. When there are parallel branches there is no compounding type of interactions between the various branches making the individual fallout rate for each branch independent of the other branches.

The estimated total manufacturing costs for the seven material/process systems described in Tables 3 through 9 are summarized for convenience in Table 10.

TABLE 3

Fabrication Costs of a Resin Matrix Composite (RMC) Blade of

the 30 Blades/Disc Geometry

	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Pre-Preg	1.10						
Cut Plies	.86	33.60	36.19	.98	1.25	36.93	45.24
Collate Plies	.64						
Assemble Pressure & Suction Halves & Vacuum Debulk	7.04		7.23	.96	1.23	7.54	8.89
Inspect	.19						
Mold	1.32		4.10	.95	1.18	4.31	4.84
Inspect	2.78						
Machine Root	.75		1.44	.97	1.12	1.48	1.61
Inspect	.69						
Fabricate Root Outsert	4.57	3.76	9.23	.98	1.11	9.42	10.24
Bond Root Outsert	.82	.08					
Machine Tip	.53		.53	.97	1.09	.55	.58
Bond SS Mesh	.92	.13	1.05	.92	1.14	1.15	1.20
Nickel Plate	1.77		1.77	.95	1.11	1.86	1.96
Mold Shelf Halves	2.40		2.40	.94	1.17	2.55	2.81
Bond Shelf Moldings	.69		.69	.96	1.10	.72	.76
Final Inspection and PU Coat	.99	.05	1.04	.95	1.05	1.10	1.10
							79.23

TABLE 4

Fabrication Costs of a Filament Wound Resin Matrix Composite (RMC/FW) Blade of the 30 Blades/Disc Geometry

	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Gr/Ep Mold Compound	.08	.37					
Fabricate Root Wedges & Sleeve	.83	.93	2.84	.94	1.28	3.02	3.64
Inspect	.63						
Assemble Wedge & Tool	.18	.02					
Fiber & Resin	.12	6.54	8.63	.95	1.20	9.09	10.36
Wind Spar	1.65						
Inspect	.12						
Fiber & Resin	.12	4.97					
Wind Shell	1.25		6.46	.95	1.14	6.80	7.37
Inspect	.12						
Mold	.58						
Separate Blades	.10		3.51	.95	1.09	3.70	3.83
Inspect	2.83						
Machine Tip	.50		.70	.97	1.03	.72	.72
Inspect	.20						
Procure Shelf Molding Compound	.08	.22					
Mold Shelf Halves	1.24		2.76	.93	1.12	2.97	3.10
Inspect	1.22						
Bond Shelves	.49		.69	.96	1.04	.72	.72
Inspect	.20						
Procure SS Mesh	.04	.14					
Bond SS Mesh	.79		1.09	.92	1.09	1.19	1.19
Inspect	.12						
Nickel Plate & P.U. Cost	1.77	.05					
Final Inspection	.83		2.65	.90	1.11	2.94	2.94
							33.85

TABLE 5

Fabrication Costs of a Superhybrid (SH) Blade of the 30 Blades/Disc Geometry

	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Ti Sheet	.14	3.86					
Stretch Form & Ti Cover Skin	1.23		5.40	.92	1.31	5.87	7.07
Inspect	.17						
Fabricate B/Al Monotapes	.72	4.14	5.98	.95	1.26	6.29	7.53
Die Cut and Form Plies	1.12						
Procure Gr & Glass Pre-Preg	.31	30.11	31.20	.98	1.23	31.83	38.37
Die Cut Plies	.78						
Procure Adhesive	.07	3.31	3.41	.98	1.23	3.47	4.19
Die Cut Plies	.03						
Etch Metals & Assemble Plies	8.15		8.15	.97	1.20	8.40	9.78
Cure	1.32		4.10	.95	1.17	4.31	4.79
Inspect	2.78						
Machine Root	.75		1.44	.97	1.11	1.48	1.60
Inspect	.69						
Fabricate Root Outsert	4.57	3.76	9.23	.98	1.10	9.42	10.15
Bond Root Outsert	.82	.08					
Machine Tip	.69		.69	.98	1.07	.71	.74
Mold Shelf Halves	2.40		2.40	.94	1.19	2.55	2.86
Bond Shelf and L.E.	1.21		1.21	.94	1.12	1.28	1.35
Nickel Plate	1.77		1.77	.95	1.11	1.86	1.96
Final Inspection	.33		.33	.95	1.05	.35	.35
							90.74

TABLE 6

Fabrication Costs of a Superhybrid Composite Fan Blade With a Spar and Shell (SH/S-S) of the 30 Blades/Disc Geometry

	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Gr/Ep Pre-Preg Die Cut Plies	.15 .43	14.05	14.63	.98	1.26	14.93	18.43
Procure Adhesive Die Cut Plies	.04 .03	.92	.99	.98	1.26	1.01	1.25
Fabricate B/Al Monotapes Cut and Form Plies	.25 1.12	2.77	4.14	.93	1.33	4.45	5.51
Assemble Section & Pressure Halves	2.21		2.21	.96	1.24	2.31	2.74
Fabricate Ti Spar Etch and Clean Spar	28.13 .31	17.14	45.58	.95	1.25	47.93	57.09
Procure Ti Sheet Cut and Form Plies Etch and Prim Plies	.12 .71 .26	2.80	3.89	.97	1.23	4.01	4.78
Join and Mold Blade Inspect Blade	1.16 2.38		3.54	.95	1.19	3.72	4.21
Machine Root	15.88		15.88	.96	1.13	16.54	17.94
Machine Tip	.44		.44	.98	1.08	.45	.48
Blend Airfoil	1.17		1.17	.99	1.06	1.18	1.24
Final Inspect	.17		.17	.95	1.05	.18	.18
							113.85

TABLE 7

Fabrication Costs of a Metal Matrix Composite (MMC) Fan Blade of the 30 Blades/Disc Geometry

	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Fabricate Root Blocks Aluminize Root Blocks	2.49 .18	1.79	4.46	.98	1.35	4.55	6.02
Procure Ti Sheet Stretch Form Cover Skin Aluminize Cover Skin	.09 .18 .23	4.45	4.95	.97	1.36	5.10	6.73
Procure B/Al Die Cut Plies	.78 1.05	40.31	42.14	.95	1.39	44.36	58.57
Layup Plies	3.35		3.35	.99	1.32	3.38	4.42
Hot Press Blade	2.64		2.64	.97	1.31	2.72	3.46
Inspect	2.78		2.78	.95	1.27	2.93	3.53
Trim LE & TE	.92		.92	.99	1.20	.93	1.10
Ti Coat LE & TE	2.53		2.53	.99	1.19	2.56	3.01
Machine Root	16.18		16.18	.96	1.18	16.85	19.09
Machine Tip	.69		.69	.98	1.14	.70	.79
Blend LE & TE	1.20		1.20	.99	1.12	1.21	1.34
Final Inspection	.74		.74	.90	1.11	.82	.82
							108.88

TABLE 8

Fabrication Costs of a Metal Matrix Composite Blade with a Spar and Shell (MMC/S-S) of the 30 Blades/Disc Geomety

	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Form Cover Skin	.27	4.45	4.95	.97	1.36	5.10	6.73
Aluminize Cover Skin	.23						
Procure Powder & Tubing		.38					
Cold Press	.09						
Sinter	.18		1.28	.98	1.43	1.31	1.83
Coin	.23						
Inspect Cores	.40						
Procure Ti Foil		7.00	7.23	.99	1.42	7.30	10.27
Stamp Plies	.23						
Cut Spar Supports	.01	.42	2.21	.99	1.42	2.23	3.14
Layup Spar & Can	.84	.94					
HIP Spar	1.45		1.45	.95	1.41	1.53	2.04
Decan & Aluminize Spar	.37		.37	.99	1.34	.37	.50
Procure B/Al Monotapes	.58	29.95					
Stamp Plies	.81		31.95	.95	1.39	33.63	44.41
Clean Plies	.61						
Assemble Blade	2.01		2.01	.99	1.32	2.03	2.65
Diffusion Bond	2.30		5.08	.93	1.31	5.46	6.65
Inspect	2.78						
Trim LE & TE	.92		3.45	.98	1.22	3.52	4.21
Ti Coat LE & TE	2.53						
Machine Root	16.18		16.18	.96	1.19	16.85	19.25
Machine Tip	.69		.69	.98	1.15	.70	.79
Blend	1.20		1.20	.99	1.12	1.21	1.34
Leach Core	.66		1.95	.98	1.13	1.99	2.20
Inspect for Core Removal	1.29						
Final Inspection	.74		.74	.90	1.11	.82	.82
							106.83

TABLE 9

Fabrication Costs of a Hollow Titanium (HT) Fan Blade of the 30 Blades/Disc Geometry

	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Ti Sheet	.16	75.37					
Blank Plies	1.03		79.76	.97	1.35	82.23	107.68
Hot Form Plies	2.12						
Clean Plies	1.08						
Procure Powder & Tubing		.38					
Cold Press Cores	.09						
Sinter	.18		1.28	.99	1.32	1.29	1.69
Coin	.23						
Inspect Cores	.40						
Layup & Tack Blade	2.47		2.47	.99	1.31	2.49	3.24
Can	1.54	.94	4.41	.95	1.29	4.64	5.69
HIP	1.93						
Isoforge	2.30		2.30	.99	1.23	2.32	2.83
Inspect	3.47		3.47	.98	1.21	3.54	4.20
Machine Root	16.22		16.22	.96	1.19	16.90	19.30
Blend A/F and Root	6.06		6.06	.99	1.15	6.12	6.97
Leach Cores	.66		1.95	.98	1.16	1.99	2.26
Inspect	1.29						
Machine Tip	.88		.88	.98	1.13	.90	2.20
Final Inspection	.74		.74	.90	1.11	.82	.82
							156.88

TABLE 10

Result of the Cost Analysis for
Blade Geometries for a 30 Blade/Disc Design

System	Individual Normalized Blade Cost	Percent of Forged Titanium Blade Cost
RMC	79.23	49.5%
RMC/FW	33.85	21.2%
SH	90.74	56.7%
SH/S-S	113.85	71.2%
MMC	108.88	68.1%
MMC/S-S	106.83	66.8%
HT	156.88	98.1%
ST	160.00	100.0%

The cost figures presented in Table 10 are displayed to two decimal points. These figures are not necessarily significant to two decimal places, in all cases, but the calculations carried the same number of decimal places for consistency and to include all of the cost data generated, no matter how small. This avoided the omission of the smaller cost items avoiding inaccuracies that would have developed when large numbers of small cost operations become a significant proportion of the total cost incurred when summed together.

All of the blades have a lower manufacturing cost than the solid forged titanium blade. As can be seen in the above table, the RMC/FW blade has the lowest apparent cost and the RMC is about double the cost of the RMC/FW blade. The MMC, MMC/S-S, SH and the SH/S-S are all essentially equivalent in cost and these four blades fall into the next highest cost category. The highest cost is for the HT blade.

The low cost of the RMC/FW blade can be explained by its radically different design and fabrication sequence. The other blades closely approximate the geometry of a forged titanium blade without the midspans. The RMC/FW blade has a different root design which is pinned and has a simpler geometry and tolerance requirements. Also the fiber winding process can be readily assumed to be highly mechanized with an NC type winding machine. Any type of mechanization of this degree of sophistication for the other systems would not have been warranted by the 10,000 blade per year production quantity, but the high degree of mechanization was easily justified by pre-existing filament winding technology. Also, the raw materials for the RMC/FW blade were the lowest of any of those examined. Thus it was the most inexpensive due to its simplified root form, high degree of mechanizaiton in the filament winding process, and its relatively low raw material cost.

As for the other systems the major cost driver was found to be associated with raw material costs. This can be easily appreciated by considering the data presented in Figure 19. In this figure, the cross-hatched region represents the cost of raw materials, be it pregreg, titanium bar and sheet, boron fibers, aluminum sheet or adhesives. The rest of the bars in Figure 19 represent the labor content associated with the manufacturing sequence. The labor content is equivalent for the laminated systems because they all are basically manufactured using the same basic process as depicted earlier in Figure 10.

Because these laminated systems are all so extremely raw material sensitive, a perturbation was made by substituting the cost of different higher quality and more expensive raw materials into the manufacturing cost models. First Ti-6Al-4V was substituted for the lower cost 3-2.5 or 15-3-3-3 titanium sheet alloys used for laminations and cover skins. Thin Ti-6Al-4V is extremely expensive when required in thin sheet gauges due to its work hardening characteristics during rolling operations. A graph illustrating this concept is presented in Figure 20.

The boron fiber market also has interesting characteristics. At a national production rate of 100,000 pounds per year, it was estimated that boron fiber would cost $85 per pound. If 1,000,000 pounds were produced annually, the cost would be approximately $35 per pound. This cost reduction results from the implementation of capital equipment that cannot be justified at the lower production rate. The material requirements for the production rate analyzed in this program are not enough to justify the capital equipment needed for the 1,000,000 pound per year production. This program utilized the $35 per pound figure, assuming a large demand for boron fiber existed from other sources. However, if the 10,000 blade quantity was the only materials requirement, the cost would then be at the $85 per pound level, and labor costs to manufacture the monotape would also be higher.

A substitution in the cost of the raw material inputs was made to examine the effect of higher cost materials. Two substitutions were made simultaneously. First the potentially lower cost easier-to-roll titanium alloys were replaced with conventional Ti-6Al-4V which is relatively expensive in thin foil form. Secondly, the $35 per pound boron fibers were replaced with $85 per pound fibers under the assumption that these were the only MMC blades being manufactured. The results of these substitutions are listed in Table 11.

TABLE 11

The Effect of Replacing the 3-2.5 and 15-3-3-3 Titanium Sheet with High Cost Ti-6Al-4V, and Replacing 1,000,000 lb/yr Boron Production Rate Costs with Those Corresponding to 10,000 lb/year

Material/Process System	Cost with Lower Cost Materials	Cost with More Expensive Raw Materials
SH	91 (61% raw materials)	105 (59% raw materials)
SH/S-S	114 (42% raw materials)	124 (42% raw materials)
MMC	109 (51% raw materials)	176 (47% raw materials)
MMC/S-S	107 (56% raw materials)	166 (50% raw materials)
HT	157 (66% raw materials)	170 (69% raw materials)

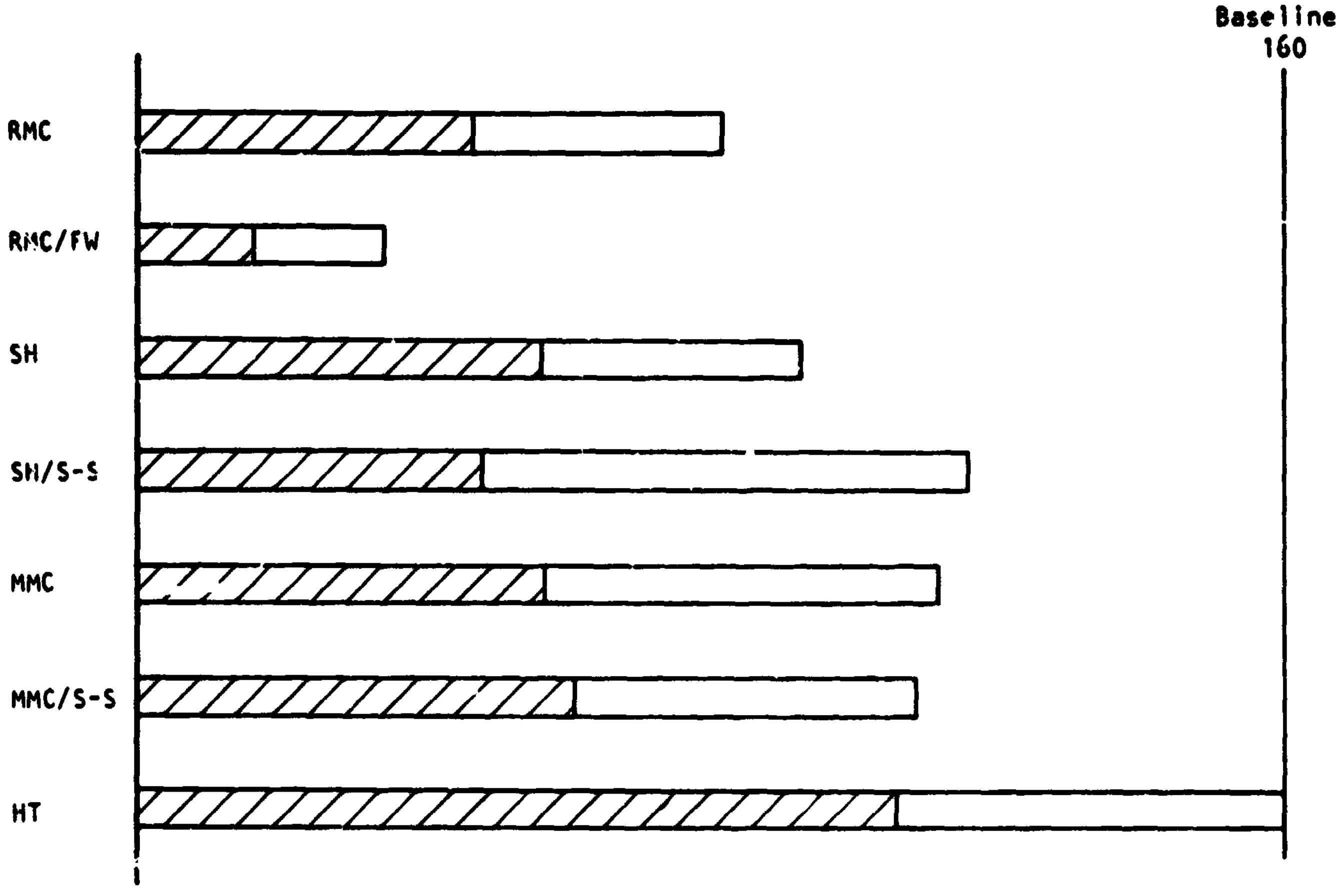

Figure 19. The Final Results of the Cost Analysis for the Seven Advanced Materials/Process Systems for a Blade Size Corresponding to 30 Blades per Disc. The Cross-Hatched Area Represents Raw Materials Costs.

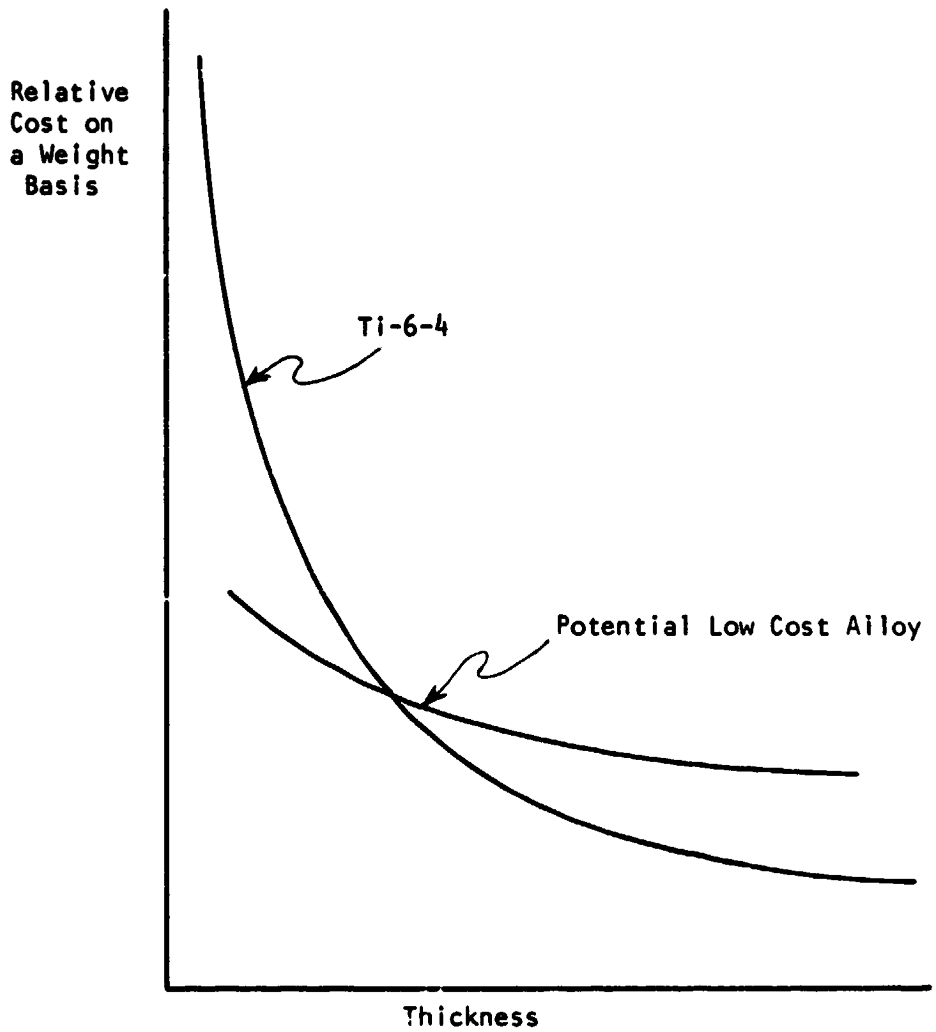

Figure 20. The Variation of Cost on a Weight Basis as a Function of Thickness for Ti-6Al-4V and Potential Low Cost Alloys Such as Ti-15V-3Cr-3Al-3Sn or Ti-3Al-2.5V.

The blade whose cost is most sensitive to these substitutions is the MMC blade. There is a 61% increase in cost, and the resulting cost of the three metal systems is approximately the same with these substitutions.

Cost analyses similar to those presented in Tables 3 through 9 were performed for each of the materials/process systems for the remaining three blade geometries typical of blade per disc ratios of 24, 36, and 42. The detailed cost tabulation tables for these calculations are presented in the Appendix. The overall results of these calculations are presented in tabular form in Table 12 and in graphical form in Figure 21.

TABLE 12

Relative Cost of Individual Fan Blades

	Blades/Disc			
System	24	30	36	42
RMC	101.49	79.23	62.39	46.93
RMC/FW	39.72	33.85	28.85	26.07
SH	106.49	90.74	67.43	55.06
SH/S-S	130.48	113.85	99.72	87.27
MMC	135.35	108.88	87.33	72.57
MMC/S-S	127.75	106.83	88.17	72.83
HT	190.04	156.98	120.85	93.96
ST		160.00		100.00

The most realistic cost comparisons are made on the basis of full fan sets for an engine. Stage costs for each material/process combination for the four blade/disc ratios are presented in tabular form in Table 13 and are graphically illustrated in Figure 22. These data reflect the conomic influence of blade geometry, primarily chord width and thickness, on an overall engine basis. The

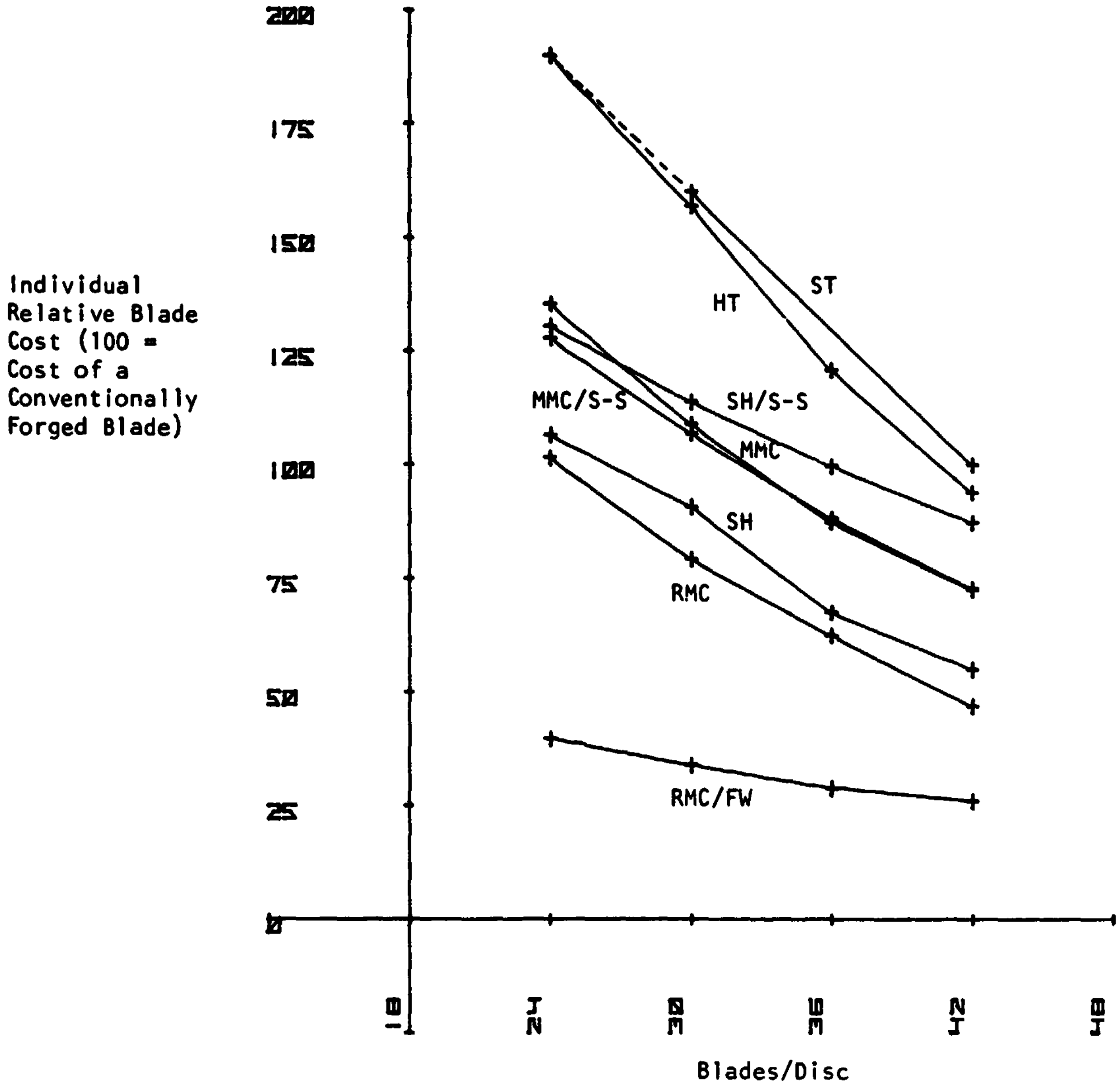

Figure 21. Relative Manufacturing Costs for Individual Fan Blades for Large High-Bypass Engines.

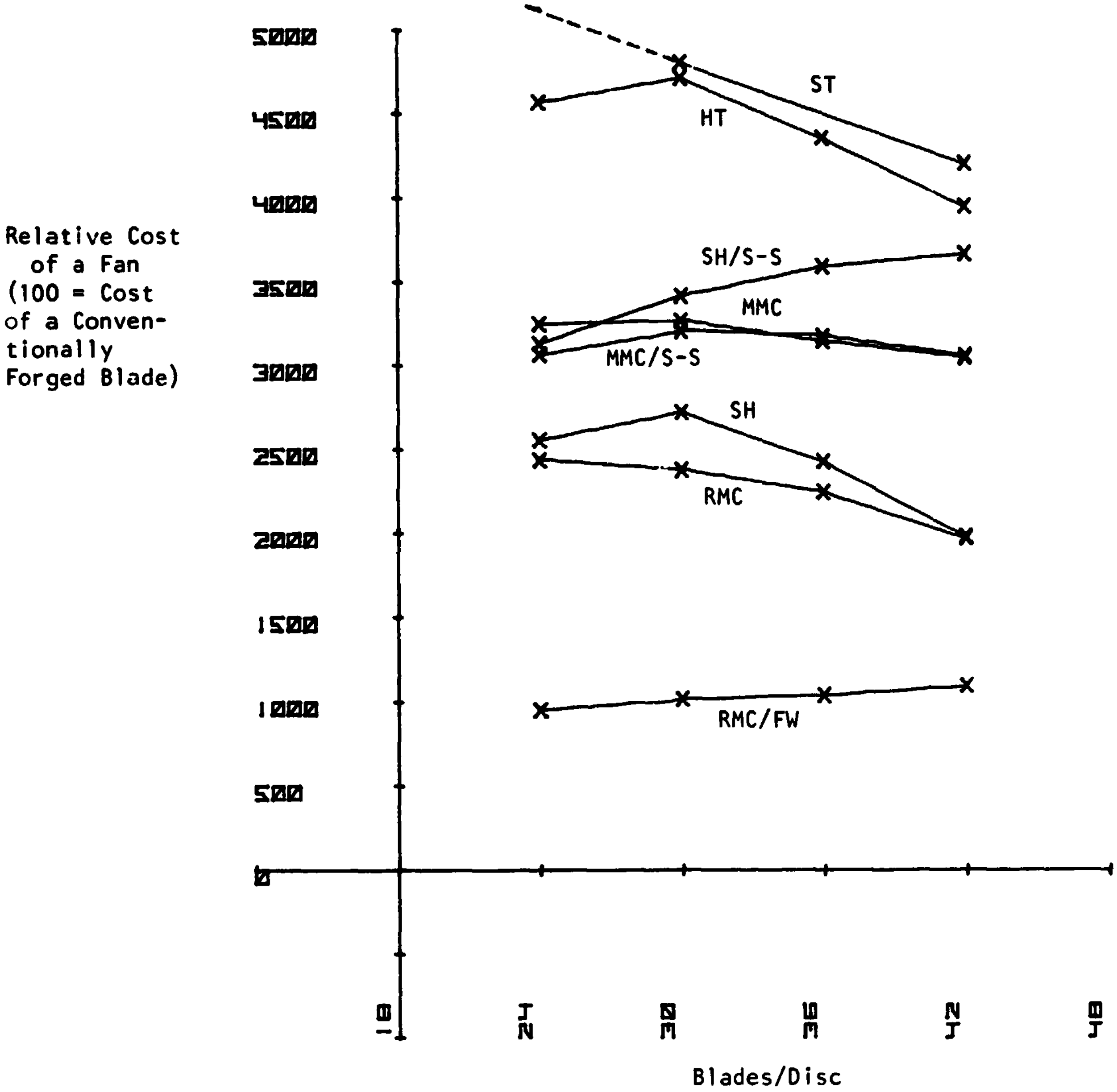

Figure 22. Relative Manufacturing Costs for an Entire Fan for Large High-Bypass Engines.

TABLE 13

Relative Costs of the Blades for an Entire Fan Set

System	Blades/Disc 24	30	36	42
RMC	2,436	2,377	2,246	1,971
RMC/FW	953	1,016	1,039	1,095
SH	2,556	2,722	2,427	1,982
SH/S-S	3,132	3,416	3,590	3,665
MMC	3,248	3,266	3,144	3,048
MMC/S-S	3,066	3,205	3,174	3,059
HT	4,566	4,709	4,351	3,946
ST		4,800		4,200

data show RMC/FW, MMC and MMC/S-S fan costs are relatively independent of their blade per disc ratios. In these cases, higher costs for individual blades in the larger sizes are essentially offset by the fewer blades required per fan set. The RMC, SH and HT blades exhibit sharp scale-up effects and are best utilized at the 42 blade per disc ratio from an economic viewpoint only. Other factors such as flutter and FOD resistance may not allow for this size of blade. Fan sets with larger more expensive blades may be required. An overall observation is that no major crossover effects were observed for the various material/process combinations as a function of blade size, with the single exception of the SH/S-S blade at the 24 blade per disc ratio. Here the SH/S-S cost estimates for a full engine set drop slightly below that for the MMC system.

The advantage of looking at the cost of an entire fan is that each materials/process system can be rated by the cost of the most desirable fan as opposed to the cost of a blade for one specific geometry. These data can be compared between the various systems for economic assessment; however, it should be recognized that all candidate systems are less costly than a full set of conventionally forged titanium blades.

5.0 CONCLUDING REMARKS

For every one of the seven candidate materials/process systems that were analyzed in the study, the resulting manufacturing costs were less than the costs associated with those incurred while manufacturing comparable conventionally forged and machined solid titanium fan blades with midspan supports. This finding occurred at 42 blades per disc which corresponds to present fan blade production, as well as the trend of projected costs at all of the other blades per disc ratios examined.

Several similarities between the various proposed fabrication methods exist which account for the major portion of this indicated cost savings. None of the proposed advanced fan blade fabrication methods include midspan supports in their design. This allows the omission of several expansive precision forging and machining operations necessary to produce a conventional fan blade. Also, every one of the candidate systems has only one consolidation or press operation to generate the basic blade shape which would replace the multistep forging and finishing operations typical of present manufacturing methods.

It should also be emphasized that the calculated costs of the seven advanced manufacturing methods are extremely raw material intensive. Consequently, any change in the cost of the required raw materials will have a significant effect on the finished cost of a blade. Thus, in selecting one of the proposed systems for full-scale fan blade manufacturing, a very important consideration would be the stability of supply and the projected raw material costs. As an example, Figure 20 illustrates the relative cost of titanium sheet on a weight basis for varying thicknesses for Ti-6-4 and projected costs for more easily rolled alloys such as 15-3-3-3 or 3-2.5 if these alloys were available in volume quantities. If these prices fluctuate by 10% or more, it can result in a significant impact on cost for the systems which use titanium sheet. Thus the supply market for the individual raw materials for a fan blade manufacturing process should be a major consideration due to its large impact on final blade cost.

This report is the result of a study whose primary emphasis is on economics. Technical considerations were included during the generation of the proposed manufacturing routing so as to not sacrifice the quality or performance of the blade. Thus the blade fabrication systems were rated for their economic not their technical merit. For example, various designs of the RMC/FW blade prepared by filament winding have yet to pass FOD resistance tests, a condition shared with all other candidate systems. However, the basic fabrication process modeled in this report is relatively independent of blade internal design or fiber orientation. Hence, a future change in design which might be satisfactory with respect to FOD would not change the basic validity of the process model. The reason for the insensitiveity of cost to internal blade design is that the external envelope and blade volume is essentially invariant for each of the four blade sizes evaluated. Therefore, the amount of raw materials and winding time are constant. The only major source of possible cost variations would be due to changes in the raw material utilized in the winding process.

Selection of the most desirable materials/process system should compare the cost of a whole fan set instead of the cost of an individual fan blade. The fan selected should be the one which exhibits the greatest performance from a technical viewpoint, i.e., superior flutter and FOD resistance. Present forging press capacities limit the plan area that can be conventionally forged to those blade sizes now being manufactured, e.g., 42 blades per disc. Forged titanium fan blades having larger plan areas would require either larger capcity forging presses or further development of the isothermal forging process. The material utilization efficiency for blades machined from the solid or oversize forgings would be very low and prohibitive in cost, particularly as the cost of titanium alloys continues to rise. This essentially limits the design of current blades to those having approximately 42 blades per disc. Present RMC and RMC/FW technology demonstrates that a fan with a low number of blades per disc is necessary for adequate flutter resistance. Thus, likely RMC and RMC/FW blade designs will have large chord widths and thicknesses. Likewise, HT blades such as those being designed for energy efficient engines are also dimensionally large requiring fewer blades in a disc. Hollow designs also tend to require large chord thicknesses to provide adequate stiffness and facilitate the fabrication of hollow passages. Therefore, the blade per disc ratios which produce the fan with the most effective technical design should be determined for each candidate advanced materials/process system before selecting and comparing the economic values presented in this report.

6.0 CONCLUSIONS

Manufacturing process models were developed to describe fabrication sequences for each of the seven candidate advanced large fan material/process combinations. These models were then used to prepare detailed manufacturing cost estimates for each of the systems. These cost estimates involved two major assumptions. The first assumption was that the manufacturing process was mature in that development work had been completed prior to the 10,000 piece per year production rate. The second assumption was that the technical aspects of the blade performance had been solved and a particular design would perform in an engine. Secondary assumptions involved amortization of tooling and special capital equipment and the availability of raw materials in the desired quantities.

The Results of the study lead to the following conclusions:

1. All the composite blades were lower in production cost than forged titanium blades.

2. The filament wound resin (RMC/FW) blade gave an 80 percent cost savings over the forged titanium blades.

3. The resin laminate blade (RMC) gave a 50 percent cost savings over forged titanium blades.

4. The two superhybrid blades (SH and SH/S-S) and the two B/Al blades (MMC and MMC/S-S) gave similar cost savings of about 33 percent.

5. The hollow titanium blade was about equal in cost to the forged blade.

7.0 REFERENCES

1. Stelson, T.S., Blake, D.E., Barth, C.F., "Cost Analysis of Advanced Turbine Blade Manufacturing Processes," NASA CR-135203, NASA Contract NAS-20378, TRW ER-7930, October 1977.

2. "Aerospace Cost Savings - Implications for NASA and the Industry," Committee Chairman, M. A. Siegel, 1975.

3. Premont, E.J. and Stubenrach, K.R., "Impact Resistance of Composite Fan Blades," NASA CR-134515, May 1973.

4. General Electric Company Aircraft Engine Group (C. Steinhagen), "Impact Resistance of Composite Fan Blades," NASA CR-134707, December 1974.

5. Oller, T.L., "Fiber Composite Fan Blade Impact Improvement Program," NASA CR-135078, December 1976.

6. Harrison, R.W., Murphy, G.C., et al, "Low Cost FOD-Resistant Organic Matrix Fan Blades," First Interim Report, June 1974 through Twelfth Interim Report, March 1977.

7. More, E.R., "Manufacturing Methods for Composite Fan Blades," AFML-TR-76-138, August 1976.

8. Reinhart, W.H., "Process Development for Large Graphite/Epoxy Fan Glades," TRW TM-4661, October 1972.

9. United Aircraft Corporation, Pratt & Whitney Aircraft Division, Hartford, Connecticut, NASA Contract NAS3-15335 (1972-1974).

10. Cavano, P.J. and Winter, W.E., HPMR Polyimide/Graphite Fiber Composite Fan Blades," NASA CR-135113, December 1976.

11. Whitaker, R.A., "Process Development for Resin Matrix Guide Vanes," TRW ER-7422, September 1970.

12. United Technologies Pratt & Whitney Aircraft Group, Hartford, Connecticut, "Resin Composite JT9D Fan Exit Vanes," NASA Contract NAS3-21037, Initiated September 1977.

13. Chamis, C.C., "High Velocity Impact of Superhybrid Composites," NASA/AF FOD of Composites Workshop, Dayton, Ohio, Novermber 1974.

14. Dennis, A.J., "Superhybrid Composite Fan Blades," United Technologies, Pratt and Whitney Aircraft Division, Hartford, Connecticut, NASA Contract NAS-20379, Initiated October 1976.

15. Oller, T.L., "Metal Spar/Superhybrid Shell Composite Fan Blades," General Electric Company Aircraft Engine Group, NASA Contract NAS3-20402, Iniated Ca. June 1977.

16. Graff, J. et al, "Impact Resistance of Spar-Shell Composite Fan Blades," NASA CR-134521, July 1973.

17. Graff, J. et al, "Fiber Composite Fan Blade Impact Improvement," NASA CR-135001, February 1976.

18. Randall, D. G., "Boron-Aluminum Fan Blade Development Program," Progress Reports under F33615-76-C-5318 (through October 20, 1977).

19. Oller, T. L. et al, "Impact Resistant Boron/Aluminum Composites for Large Fan Blades," NASA CR-135274, December 1977.

20. Doble, G. S. and Melnyk, P., "Fabrication of Boron-Aluminum Fan Blades for SCAR Engines," Progress Reports under NASA Contract 3-20360, 1977.

21. Stabrylla, R. G. and Carlson, R. G., "Boron-Aluminum Fan Blades for SCAR Engines," NASA CR-125184, June 1977.

22. Del Brosso, E. T. et al, "Development of Air Bonded FOD Resistant Metal Matrix Fan Blades," AFML-TR-77-13, February 1977.

23. Doble, G. S., Progress Reports under NAS3-20115, 1977.

24. Yao, S., "Filament Wound Spar Shell Graphite Epoxy Fan Blades," NASA CR-134899, February 1976.

APPENDIX

TABLE A1

Fabrication Costs of a Resin Matrix Composite (RMC) Fan Blade for a 24 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Pre-Peg	1.39	46.82					
Die Cut Plies	1.17		50.12	.98	1.25	51.14	62.65
Collate Plies	.74						
Assemble Pressure & Suction	7.96						
Halves & Vacuum Debulk			8.16	.96	1.23	8.50	10.04
Inspect	.20						
Mold	1.23		4.10	.95	1.18	4.32	4.84
Inspect	2.78						
Machine Root	.74		1.43	.97	1.12	1.47	1.60
Inspect	.69						
Fabricate Root Outsert	5.23	6.24	12.37	.98	1.11	12.62	13.73
Bond Root Outsert	.82	.08					
Machine Tip	.53		.53	.97	1.09	.55	.58
Bond SS Mesh	.92	.14	1.06	.92	1.14	1.15	1.21
Nickle Plate	1.77		1.77	.95	1.11	1.86	1.96
Mold Shelf Halves	2.58		2.58	.94	1.17	2.74	3.02
Bond Shelf Moldings	.69		.69	.96	1.10	.72	.76
Final Inspection and PU Coat	.99	.06	1.05	.95	1.05	1.11	1.10
							101.49

TABLE A2

Fabrication Costs of a Resin Matrix Composite (RMC) Fan Blade for a 36 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Pre-Preg	.79	24.05					
Die Cut Plies	.64		25.94	.98	1.25	26.47	32.43
Collate Plies	.46						
Assemble Pressure & Suction	5.87						
Halves & Cacuum Debulk			6.07	.96	1.23	6.32	7.47
Inspect	.20						
Mold	1.32						
Inspect	2.78		4.10	.95	1.18	4.32	4.84
Machine Root	.74						
Inspect	.69		1.43	.97	1.12	1.47	1.60
Fabricate Root Outsert	3.91	1.97	6.78	.98	1.11	6.92	7.53
Bond Root Outsert	.82	.08					
Machine Tip	.53		.53	.97	1.09	.55	.58
Bond SS Mesh	.92	.14	1.06	.92	1.14	1.15	1.21
Nickel Plate	1.77		1.77	.95	1.11	1.86	1.96
Mold Shelf Halves	2.50		2.50	.94	1.17	2.66	2.93
Bond Shelf Modings	.69		.69	.96	1.10	.72	.76
Final Inspection and PU Coat	.99	.04	1.03	.95	1.05	1.08	1.08
							62.39

TABLE A3

Fabrication Costs of a Resin Matrix Composite (RMC) Fan Blade for a 42 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Pre-Peg	.50	15.42					
Die Cut Plies	.46		16.75	.98	1.25	17.09	20.94
Collate Plies	.37						
Assemble Pressure & Suction	4.20						
Halves & Vacuum Debulk			4.40	.96	1.23	4.58	5.41
Inspect	.20						
Mold	1.32		4.10	.95	1.18	4.32	4.84
Inspect	2.78						
Machine Root	.74		1.43	.97	1.12	1.47	1.60
Inspect	.69						
Fabricate Root Outsert	3.25	.96					
Bond Root Outsert	.82	.08	5.11	.98	1.11	5.21	5.67
Machine Tip	.53		.53	.97	1.09	.55	.58
Bond SS Mesh	.92	.14	1.06	.92	1.14	1.15	1.21
Nickel Plate	1.77		1.77	.95	1.11	1.86	1.96
Mold Shelf Halves	2.46		2.46	.94	1.17	2.62	2.88
Bond Shelf Moldings	.69		.69	.96	1.10	.72	.76
Final Inspection and PU Coat	.99	.04	1.03	.95	1.05	1.08	1.08
							46.93

TABLE A4

Fabrication Costs of a Filament Wound Resin Matrix Composite (RMC/FW) Fan Blade for a 24 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Gr/Ep Mold Compound	.09	.44					
Fabricate Root Wedges & Sleeve	.83	.98	2.97	.94	1.28	3.16	3.80
Inspect	.63						
Assemble Wedge & Tool	.18	.02					
Fiber & Resin	.14	9.53	12.20	.95	1.20	12.84	14.64
Wind Spar	2.21						
Inspect	.12						
Fiber & Resin	.14	5.96					
Wind Shell	1.38		7.60	.95	1.14	8.00	8.66
Inspect	.12						
Mold	.58						
Separate Blades	.11		3.52	.95	1.09	3.71	3.84
Inspect	2.83						
Machine Tip	.50		.70	.97	1.03	.72	.72
Inspect	.20						
Procure Shelf Molding Compound	.09	.29					
Mold Shelf Halves	1.24		2.84	.93	1.12	3.05	3.18
Inspect	1.22						
Bond Shelves	.50		.70	.96	1.04	.73	.73
Inspect	.20						
Procure SS Mesh	.05	.14					
Bond SS Mesh	.79		1.10	.92	1.09	1.20	1.20
Inspect	.12						
Nickel Plate & PU. Coat	1.77	.06	2.66	.90	1.11	2.96	2.95
Final Inspection	.83						
							39.72

TABLE A5

Fabrication Costs of a Filament Wound Resin Matrix Composite (RMC/FW) Fan Blade for a 36 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Gr/Ep Mold Compound	.07	.33					
Fabricate Root Wedges & Sleeve	.83	.72	2.58	.94	1.28	2.74	3.30
Inspect	.63						
Assemble Wedge & Tool	.18	.02					
Fiber & Resin	.10	4.27					
Wind Spar	1.21		5.90	.95	1.20	6.21	7.08
Inspect	.12						
Fiber & Resin	.10	3.97					
Wind Shell	1.13		5.32	.95	1.14	5.60	6.06
Inspect	.12						
Mold	.58						
Separate Blades	.11		3.52	.95	1.09	3.71	3.84
Inspect	2.83						
Machine Tip	.50						
Inspect	.20		.70	.97	1.03	.72	.72
Procure Shelf Molding Compound	.06	.16					
Mold Shelf Halves	1.24		2.68	.93	1.12	2.88	3.00
Inspect	1.22						
Bond Shelves	.50						
Inspect	.20		.70	.96	1.04	.73	.73
Procure SS Mesh	.03	.14					
Bond SS Mesh	.79		1.08	.92	1.09	1.17	1.18
Inspect	.12						
Nickel Plate & P.U. Coat	1.77	.05	2.65	.90	1.11	2.94	2.94
Final Inspection	.83						
							28.85

TABLE A6

Fabrication Costs of a Filament Wound Resin Matrix Composite (RMC/FW)
Fan Blade for a 42 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Gr/Ep Mold Compound	.06	.27	2.47	.94	1.28	2.63	3.16
Fabricate Root Wedges & Sleeve	.83	.68					
Inspect	.63						
Assemble Wedge & Tool	.18	.02					
Fiber & Resin	.09	2.53	3.82	.95	1.20	4.02	4.58
Wind Spar	.88						
Inspect	.12						
Fiber & Resin	.09	2.76	3.61	.95	1.14	3.80	4.12
Wind Shell	.64						
Inspect	.12						
Mold	.58						
Separate Blades	.11		3.52	.95	1.09	3.71	3.84
Inspect	2.83						
Machine Tip	.50		2.48	.97	1.03	2.56	2.55
Inspect	1.98						
Procure Shelf Modling Compound	.06	.13					
Mold Shelf Halves	1.24		2.65	.93	1.12	2.85	2.97
Inspect	1.22						
Bond Shelves	.50		.70	.96	1.04	.73	.73
Inspect	.20						
Procure SS Mesh	.03	.14					
Bond SS Mesh	.79		1.08	.92	1.09	1.17	1.18
Inspect	.12						
Nickel Plate & P.U. Coat	1.77	.05	2.65	.90	1.11	2.94	2.94
Final Inspection	.83						
							26.07

TABLE A7

Fabrication Costs of a Superhybrid (SH) Fan Blade for a 24 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Ti Sheet	.18	4.41	5.99	.92	1.31	6.51	7.85
Stretch Form & Ti Cover Skin	1.23						
Inspect	.17						
Procure B/Al Monotapes	.82	4.73	6.67	.95	1.26	7.02	8.40
Die Cut and Form Plies	1.12						
Procure Gr & Glass Pre-Preg	3.90	33.69	38.66	.98	1.23	39.44	47.55
Die Cut Plies	1.07						
Procure Adhesive	.08	3.49	3.60	.98	1.23	3.67	4.43
Die Cut Plies	.03						
Etch Metals & Assemble Plies	9.24		9.24	.97	1.20	9.53	11.09
Cure	1.32		4.09	.95	1.17	4.31	4.79
Inspect	2.77						
Machine Root	.74		1.43	.97	1.11	1.47	1.59
Inspect	.69						
Fabricate Root Outsert	5.23	6.24	12.29	.98	1.10	12.54	13.52
Bond Root Outsert	.82						
Machine Tip	.69		.69	.98	1.07	.70	.74
Mold Shelf Halves	2.40		2.40	.94	1.19	2.55	2.86
Bond Shelf and LE	1.21		1.21	.94	1.12	1.29	1.36
Nickel Plate	1.77		1.77	.95	1.11	1.86	1.96
Final Inspection	.33		.33	.95	1.05	.35	.35
							106.49

TABLE A8

Fabrication Costs of a Superhybrid (SH) Fan Blade for a 36 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Ti Sheet	.10	3.30	4.80	.92	1.31	5.22	6.29
Stretch Form & Ti Cover Skin	1.23						
Inspect	.17						
Procure B/Al Monotapes	.52	3.56	5.20	.55	1.26	5.47	6.55
Die Cut & Form Plies	1.12						
Procure Gr & Glass Pre-Preg	.22	16.43	17.23	.98	1.23	17.58	21.19
Die Cut Plies	.58						
Procure Adhesive	.05	2.85	2.93	.98	1.23	2.99	3.60
Die Cut Plies	.03						
Etch Metals & Assemble Parts	7.31		7.31	.97	1.20	7.54	8.77
Cure	1.32		4.10	.95	1.17	4.32	4.80
Inspect	2.78						
Machine Root	.74		1.43	.97	1.11	1.47	1.59
Inspect	.69						
Fabricate Root Outsert	3.91	1.97	6.70	.98	1.10	6.84	7.37
Bond Root Outsert	.82						
Machine Tip	.69		.69	.98	1.07	.70	.74
Mold Shelf Halves	2.40		2.40	.94	1.19	2.55	2.86
Bond Shelf and LE	1.21		1.21	.94	1.12	1.29	1.36
Nickel Plate	1.77		1.77	.95	1.11	1.86	1.96
Final Inspection	.33		.33	.95	1.05	.35	.35
							67.43

TABLE A9

Fabrication Costs of a Superhybrid (SH) Fan Blade for a 42 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Ti Sheet	.07	2.75					
Stretch Form & Ti Cover Skin	1.23		4.22	.92	1.31	4.59	5.53
Inspect	.17						
Procure B/Al Monotapes	.33	2.98	4.43	.95	1.26	4.66	5.58
Die Cut and Form Plies	1.12						
Procure Gr & Glass Pre-Preg	.14	12.21	12.76	.98	1.23	13.02	15.69
Die Cut Plies	.41						
Procure Adhesive	.03	2.20	2.26	.98	1.23	2.31	2.78
Die Cut Plies	.03						
Etch Metals & Assemble Plies	5.25		5.25	.97	1.20	5.41	6.30
Cure	1.32		4.10	.95	1.17	4.32	4.80
Inspect	2.78						
Machine Root	.74		1.43	.97	1.11	1.47	1.59
Inspect	.69						
Fabricate Root Outsert	3.25	.96	5.02	.98	1.10	5.12	5.52
Bond Root Outsert	.81						
Machine Tip	.69		.69	.98	1.07	.70	.74
Mold Shelf Halves	2.40		2.40	.94	1.19	2.55	2.86
Bond Shelf and LE	1.21		1.21	.94	1.12	1.29	1.36
Nickel Plate	1.77		1.77	.95	1.11	1.86	1.96
Final Inspection	.33		.33	.95	1.05	.35	.35
							55.06

TABLE A10

Fabrication Costs of a Superhybrid Fan Blade With a Spar and Shell (SH/S-S) for a 24 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Gr/Ep Pre-Preg Die Cut Plies	.18 .43	18.54	19.15	.98	1.26	19.54	24.13
Procure Adhesive Die Cut Plies	.05 .03	1.04	1.12	.98	1.26	1.14	1.41
Procure B/Al Monotapes Die Cut & Form Plies	.30 1.12	3.15	4.57	.93	1.33	4.91	6.08
Assemble Suction & Pressure Halves	2.21		2.21	.96	1.24	2.30	2.74
Fabricate Ti Spar Etch & Clean Spar	29.17 .32	23.30	52.79	.95	1.25	55.57	66.13
Procure Ti Sheet Cut & Form Plies Etch & Prime Plies	.14 .71 .26	3.21	4.32	.97	1.23	4.45	5.31
Join & Mold Blade Inspect Blade	1.16 2.38		3.54	.95	1.19	3.72	4.21
Machine Root	16.43		16.43	.96	1.13	17.11	18.57
Machine Tip	.44		.44	.98	1.08	.45	.48
Blend Airfoil	1.17		1.17	.99	1.06	1.18	1.24
Final Inspection	.17		.17	.95	1.05	.18	.18
							130.48

TABLE A11

Fabrication Costs of a Superhybrid Fan Blade with a Spar and Shell (SH/S-S) for a 36 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Gr/Ep Pre-Preg Die Cut Plies	.12 .43	10.19	10.74	.98	1.26	10.96	13.53
Procure Adhesive Die Cut Plies	.03 .03	.78	.84	.98	1.26	.86	1.06
Fabricate B/Al Monotapes Die Cut & Form Plies	.20 1.12	2.40	3.72	.93	1.33	4.00	4.95
Assemble Suction & Pressure Halves	2.21		2.21	.96	1.24	2.30	2.74
Fabricate Ti Spar Etch & Clean Spar	27.16 .32	12.34	39.81	.95	1.25	41.91	49.87
Procure Ti Sheet Cut & Form Plies Etch & Prime Plies	.09 .71 .26	2.39	3.45	.97	1.23	3.56	4.24
Join & Mold Blade Inspect Blade	1.16 2.38		3.54	.95	1.19	3.73	4.21
Machine Root	15.24		15.24	.96	1.13	15.88	17.22
Machine Tip	.44		.44	.98	1.08	.45	.48
Blend Airfoil	1.17		1.17	.99	1.06	1.18	1.24
Final Inspection	.17		.17	.95	1.05	.18	.18
							99.72

TABLE A12

Fabrication Costs of a Superhybrid Fan Blade with a Spar and Shell (SH/S-S) for a 42 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Gr/Ep Pre-Preg Die Cut Plies	.09 .43	2.98	7.50	.98	1.26	7.65	9.45
Procure Adhesive Die Cut Plies	.02 .03	.64	.69	.98	1.26	.70	.87
Procure B/Al Monotapes Die Cut & Form Plies	.15 1.12	1.99	3.26	.93	1.33	3.51	4.34
Assemble Suction & Pressure Halves	2.21		2.21	.96	1.24	2.30	2.74
Fabricate Ti Spar Etch & Clean Spar	26.45 .31	8.23	34.65	.95	1.25	36.47	43.40
Procure Ti Sheet Cut & Form Plies Etch & Prime Plies	.07 .71 .26	2.02	3.06	.97	1.23	3.15	3.76
Join & Mold Blade Inspect Blade	1.16 2.38		3.54	.95	1.19	3.73	4.21
Machine Root	14.69		14.69	.96	1.13	15.30	16.60
Machine Tip	.44		.44	.98	1.08	.45	.48
Blend Airfoil	1.17		1.17	.99	1.06	1.18	1.24
Final Inspection	.17		.17	.95	1.05	.18	.18
							87.27

TABLE A13

Fabrication Costs of a Metal Matrix Composite (MMC) Fan Blade for a 24 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Fabricate Root Blocks Aluminize Root Blocks	2.79 .18	2.02	4.99	.98	1.35	5.09	6.74
Pro'ure Ti Sheet Stretch From Cover Skin Aluminize Cover Skin	0.10 .18 .23	5.01	5.52	.97	1.36	5.69	7.51
Procure B/Al Die Cut Plies	1.08 1.28	55.81	58.17	.95	1.39	61.23	80.86
Clean & Layup Plies	4.09		4.09	.99	1.32	4.13	5.40
Hot Press Blade	3.30		3.30	.97	1.31	3.40	4.32
Inspect	2.78		2.93	.95	1.27	3.08	3.72
Trim LE & TE	.92		.92	.99	1.20	.93	1.10
Ti Coat LE & TE	2.53		2.53	.99	1.19	2.56	3.01
Machine Root	16.73		16.73	.96	1.18	17.43	19.74
Machine Tip	.69		.69	.98	1.14	.70	.79
Blend LE & TE	1.20		1.20	.99	1.12	1.21	1.34
Final Inspection	.74		.74	.90	1.11	.82	.82
							135.35

TABLE A14

Fabrication Costs of a Metal Matrix Composite (MMC) Fan Blade for a 36 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Fabricate Root Blocks Aluminize Root Blocks	2.14 .18	1.53	3.85	.98	1.35	3.93	5.20
Procure Ti Sheet Stretch Form Cover Skin Aluminize Cover Skin	.07 .18 .23	3.81	4.29	.97	1.36	4.42	5.83
Procure B/Al Die Cut Plies	.54 .81	28.06	29.41	.95	1.39	30.96	40.88
Clean & Layup Plies	2.60		2.60	.99	1.32	2.63	3.43
Hot Press Blade	2.31		2.31	.97	1.31	2.38	3.03
Inspect	2.78		2.78	.95	1.27	2.93	3.53
Trim LE & TE	.92		.92	.99	1.20	.93	1.10
Ti Coat LE & TE	2.53		3.53	.99	1.19	2.56	3.01
Machine Root	15.57		15.57	.96	1.18	16.22	18.37
Machine Tip	.69		.69	.98	1.14	.70	.79
Blend LE & TE	1.20		1.20	.99	1.12	1.21	1.34
Final Inspection	.74		.74	.90	1.11	.82	.82
							87.33

TABLE A15

Fabrication Costs of a Metal Matrix Composite (MMC) Fan Blade for a 42 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Fabricate Root Blocks	1.80	1.27	3.25	.98	1.35	3.32	4.39
Aluminize Root Blocks	.18						
Procure Ti Sheet	.06	3.18					
Stretch From Cover Skin	.18		3.64	.97	1.36	3.75	4.95
Aluminize Cover Skin	.22						
Procure B/Al	.34	17.78	18.78	.95	1.39	19.77	26.10
Die Cut Plies	.66						
Clean & Layup Plies	1.90		1.90	.99	1.32	1.92	2.51
Hot Press Blade	1.98		1.98	.97	1.31	2.04	2.59
Inspect	2.78		2.78	.95	1.27	2.92	7.25
Trim LE & TE	.92		.92	.99	1.20	.93	1.10
Ti Coat LE & TE	2.53		2.53	.99	1.19	2.56	3.01
Machine Root	15.02		15.02	.96	1.18	15.65	17.72
Machine Tip	.69		.69	.98	1.14	.70	.79
Blend LE & TE	1.20		1.20	.99	1.12	1.21	1.34
Final Inspection	.74		.74	.90	1.11	.82	.82
							72.57

TABLE A16

Fabrication Costs of a Metal Matrix Composite Fan Blade with a Spar and Shell (MMC/S-S) for a 24 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Form Cover Skin	.18	5.06					
Aluminize Cover Skin	.23		5.47	.97	1.36	5.64	7.44
Procure Powder & Tubing		.47					
Cold Press	.09						
Sinter	.18						
Coin	.23		1.37	.98	1.43	1.40	1.96
Inspect Cores	.40						
Procure Ti Foil	.05	9.01					
Die Cut Plies	.17		9.23	.99	1.42	9.32	13.11
Cut Spar Supports	.06	.57					
Layup Spar & Can	.84	.94	2.41	.99	1.42	2.43	3.42
HIP Spar	1.45		1.45	.95	1.41	1.53	2.04
Decan & Aluminize Spar	.37		.37	.99	1.34	.37	.50
Procure B/Al Monotapes	.78	40.56					
Stamp Plies	1.03		43.14	.95	1.39	45.41	59.96
Clean Plies	.77						
Assemble Blade	2.55		2.55	.99	1.32	2.58	3.37
Diffusion Bond	2.30						
Inspect	2.78		5.08	.99	1.31	5.46	6.65
Trim LE & TE	.92						
Ti Coat LE & TE	2.53		3.45	.98	1.22	3.52	4.21
Machine Root	16.76		16.76	.96	1.19	17.46	19.94
Machine Tip	.69		.69	.98	1.15	.70	.79
Blend	1.20		1.20	.99	1.12	1.21	1.34
Leach Core	.66						
Inspect for Core Removal	1.29		1.95	.98	1.13	1.99	2.20
Final Inspection	.74		.74	.90	1.11	.82	.82
							127.75

TABLE A17

Fabrication Costs of a Metal Matrix Composite Fan Blade with a Spar and Shell (MMC/S-S) for a 36 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
From Cover Skin	.18	3.85	4.26	.97	1.36	4.39	5.79
Aluminize Cover Skin	.23						
Procure Powder & Tubing		.28					
Cold Press	.09						
Sinter	.18		1.18	.98	1.43	1.20	1.69
Coin	.23						
Inspect Cores	.40						
Procure Ti Foil	.02	4.76	4.95	.99	1.42	5.00	7.03
Die Cut Plies	.17						
Cut Spar Supports	.06	.30	1.86	.99	1.42	1.88	2.64
Layup Spar & Can	.56	.94					
HIP Spar	1.45		1.45	.95	1.41	1.53	2.04
Decan & Aluminize Spar	.37		.37	.99	1.34	.37	.50
Procure B/Al Monotapes	.41	21.44					
Stamp Plies	.62		22.94	.95	1.39	24.15	31.89
Clean Plies	.47						
Assemble Blade	1.55		1.55	.99	1.32	1.57	2.05
Diffusion Bond	2.30		5.08	.93	1.31	5.46	6.65
Inspect	2.78						
Trim LE & TE	.92		3.45	.98	1.22	3.52	4.21
Ti Coat LE & TE	2.53						
Machine Root	15.57		15.57	.96	1.19	16.22	18.53
Machine Tip	.69		.69	.98	1.15	.70	.79
Blend	1.20		1.20	.99	1.12	1.21	1.34
Leach Core	.66		1.95	.98	1.13	1.99	2.20
Inspect for Core Removal	1.29						
Final Inspection	.74		.74	.90	1.11	.82	.82
							88.17

TABLE A18

Fabrication Costs of a Metal Matrix Composite Fan Blade with a Spar and Shell (MMC/S-S for a 42 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Form Cover Skin	.18	3.21	3.61	.97	1.36	3.72	4.91
Aluminize Cover Skin	.22						
Procure Powder & Tubing		.24	1.14	.98	1.43	1.16	1.63
Cold Press	.09						
Sinter	.18						
Coin	.23						
Inspect Cores	.40						
Procure Ti Foil	.02	3.15	3.34	.99	1.42	3.37	4.74
Die Cut Plies	.17						
Cut Spar Supports	.06	.20	1.76	.99	1.42	1.78	2.50
Layup Spar & Can	.56	.94					
HIP Spar	1.45		1.45	.95	1.41	1.53	2.04
Decan & Aluminize Spar	.37		.37	.99	1.34	.37	.50
Procure B/Al Monotapes	.27	14.20	15.24	.95	1.39	16.04	21.18
Stamp Plies	.44						
Clean Plies	.33						
Assemble Blade	1.10		1.10	.99	1.32	1.11	1.45
Diffusion Bond	2.30		5.08	.93	1.31	5.46	6.65
Inspect	2.78						
Trim LE & TE	.92		3.45	.98	1.22	3.52	4.21
Ti Coat LE & TE	2.53						
Machine Root	15.02		15.02	.96	1.19	15.65	17.87
Machine Tip	.69		.69	.98	1.15	.70	.79
Blend	1.20		1.20	.99	1.12	1.21	1.34
Leach Core	.66		1.95	.98	1.13	1.99	2.20
Inspect for Core Removal	1.29						
Final Inspection	.74		.74	.90	1.11	.82	.82
							72.83

TABLE A19

Fabrication Costs of a Hollow Titanium (HT) Fan Blade for a 24 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Ti Sheet	.22	99.08					
Die Cut Plies	1.09		103.78	.97	1.35	106.99	140.10
Hot Form Plies	2.24						
Clean Plies	1.15						
Procure Powder & Tubing		.46					
Cold Press Cores	.09						
Sinter	.18		1.36	.99	1.32	1.37	1.80
Coin	.23						
Inspect Cores	.40						
Layup & Tack Blade	2.89		2.89	.99	1.31	2.92	3.79
Can	1.54	.96	4.43	.95	1.29	4.66	5.71
HIP	1.93						
Isoforge	2.30		2.30	.99	1.23	2.32	2.83
Inspect	3.47		3.47	.98	1.21	3.54	4.20
Machine Root	16.76		16.76	.96	1.19	17.46	19.94
Blend A/F & Root	6.61		6.61	.99	1.15	6.68	7.60
Leach Cores	.66		1.95	.98	1.16	1.99	2.26
Inspect	1.29						
Machine Tip	.88		.88	.98	1.13	.90	.99
Final Inspection	.74		.74	.90	1.11	.82	.82
							190.94

TABLE A20

Fabrication Costs of a Hollow Titanium (HT) Fan Blade
for a 36 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Ti Sheet	.12	52.37					
Die Cut Plies	.77		55.65	.97	1.35	57.37	75.13
Hot Form Plies	1.58						
Clean Plies	.81						
Procure Powder & Tubing		.31					
Cold Press Cores	.09						
Sinter	.18		1.21	.99	1.32	1.22	1.60
Coin	.23						
Inspect Cores	.40						
Layup & Tack Blade	1.88		1.88	.99	1.31	1.90	2.46
Can	1.54	.94	4.41	.95	1.29	4.64	5.69
HIP	1.93						
Isoforge	2.30		2.30	.99	1.23	2.32	2.83
Inspect	3.47		3.47	.98	1.21	3.54	4.20
Machine Root	15.57		15.57	.96	1.19	16.22	18.53
Blend A/F & Root	5.51		5.51	.99	1.15	5.57	6.34
Leach Cores	.66		1.95	.98	1.16	1.99	2.26
Inspect	1.29						
Machine Tip	.88		.88	.98	1.13	.90	.99
Final Inspection	.74		.74	.90	1.11	.82	.82
							120.85

TABLE A21

Fabrication Costs of a Hollow Titanium (HT) Fan Blade for a 42 Blades/Disc Geometry

PROCESS STEP	LABOR	MATERIALS	BLOCK COST	YIELD	N	UNCOUPLED COST	COMPOUND COST
Procure Ti Sheet	.08	34.67					
Die Cut Plies	.61		37.26	.97	1.35	38.41	50.30
Hot Form Plies	1.26						
Clean Plies	.64						
Procure Powder & Tubing		.25					
Cold Press Cores	.09						
Sinter	.18		1.15	.99	1.32	1.16	1.52
Coin	.23						
Inspect Cores	.40						
Layup & Tack Blade	1.38		1.38	.99	1.31	1.39	1.81
Can	1.54	.92	4.39	.95	1.29	4.62	5.66
HIP	1.93						
Isoforge	2.30		2.30	.99	1.23	2.32	2.83
Inspect	3.47		3 47	.98	1.21	3.54	4.20
Machine Root	15.02		15.02	.96	1.19	15.65	17.87
Blend A/F & Root	4.96		4.96	.99	1.15	5.01	5.70
Leach Cores	.66		1.95	.98	1.16	1.99	2.26
Inspect	1.29						
Machine Tip	.88		.88	.98	1.13	.90	.99
Final Inspection	.74		.74	.90	1.11	.82	.82
							93.96