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STRUCTURES PERFORMANCE, BENEFIT, COST STUDY

FINAL REPORT

by
E. Feder

UNITED TECHNOLOGIES CORPORATION
PRATT & WHITNEY AIRCRAFT GROUP
COMMERCIAL PRODUCTS DIVISION

Prepared for

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PRATT & WHITNEY AIRCRAFT GROUP
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UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
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16. Abstract
Aircraft engine structures were studied to identify the advanced structural technologies that would provide the most benefits to future aircraft operations. The following procedure was used. First, a series of studies identified engine systems with the greatest potential for improvements. Based on these studies six advanced generic structural concepts were selected and conceptually designed. Quantitative assessments were made of the benefits of each concept in terms of thrust specific fuel consumption, weight, cost, maintenance cost, fuel burned and direct operating cost plus interest. The probability of success of each concept was also determined. The concepts were ranked and the three most promising were selected for further study. This consisted of identifying and comprehensively outlining the advanced technologies required to develop these concepts for aircraft engine application. Analytic, fabrication and test technology developments are required. The technology programs outlined emphasize the need to provide basic, fundamental understanding of technology to obtain the benefit goals.

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ABSTRACT

Aircraft engine structures were studied to identify the advanced structural technologies that would provide the most benefits to future aircraft operations. The following procedure was used. First, a series of studies identified engine systems with the greatest potential for improvements. Based on these studies six advanced generic structural concepts were selected and conceptually designed. Quantitative assessments were made of the benefits of each concept in terms of thrust specific fuel consumption, weight, cost, maintenance cost, fuel burned and direct operating cost plus interest. The probability of success of each concept was also determined. The concepts were ranked and the three most promising were selected for further study. This consisted of identifying and comprehensively outlining the advanced technologies required to develop these concepts for aircraft engine application. Analytic, fabrication and test technology developments are required. The technology programs outlined emphasize the need to provide basic, fundamental understanding of technology to obtain the benefit goals.

1.0 INTRODUCTION

During the design of a new engine system many structural trade-offs must be made with respect to individual component design, fabrication procedure, and geometric arrangement within the total engine system configuration. The availability of critical structural technologies and design trade-offs that are made can affect engine performance and operating cost. For example, performance related structural aspects include: bearing arrangement and critical shaft speeds, engine case and rotor deformations due to thrust loads, maneuver loads and thermal transients and their effects on wear and clearances, and the engine's ability to withstand severe transient environments such as engine surge, foreign object damage and blade loss. Critical trade-offs and available technologies also affect engine performance under cruise conditions. For example, decisions made regarding compressor blade and vane aspect ratio, aerodynamic loadings, number of stages, and both the type and length of the burner have a direct influence on structural rigidity and therefore the operating clearances of the engine. The magnitudes of these clearances in turn affect engine performance and direct operating costs.

In all of the above examples, availability of critical structural technologies and structural trade-offs have a direct impact on ownership costs for the engine system.

Pratt & Whitney Aircraft has completed a number of cost/benefit/ feasibility studies under NASA-sponsored programs. Recently, these have included:

- o NASA Contract NAS3-19445, Preliminary Compressor Design Study for an Advanced Multistage Axial Flow Compressor (AMAC)
- o NASA Contract NAS3-20630, Engine Component Improvement Program-Performance Improvement (ECI-PI)
- o Trade studies conducted as part of NASA Contract NAS3-20628, Energy Efficient Engine Preliminary Design and Integration Studies Program
- o Trade studies conducted as part of NASA Contract NAS3-20646, Energy Efficient Engine Component Development and Integration Program
- o NASA Contract NAS3-17804, Cost/Benefit Study of Advanced Materials Technologies for Aircraft Turbine Engines (MATE)
- o NASA Contract NAS3-20072, Cost/Benefit Analysis of Advanced Materials Technologies for Future Aircraft Turbine Engines (MATE).

This report presents a program for the evaluation of advanced generic structural concepts. This is the first application of a performance/cost/-benefit study for engine structures proposed under NASA sponsorship.

The program has several objectives. The first is to adapt methods used in previous cost/benefit/feasibility studies to evaluate structural concepts. The second objective is to identify advanced structural concepts which will benefit airline operation in the 1990's, and the third is to identify and outline the advanced technologies whose development will provide the greatest benefit for advanced aircraft engines in the 1990's.

To accomplish these objectives the base engine, which is the Energy Efficient Engine, was assessed to determine the areas with the greatest potential for improvement. Trade studies were conducted to determine the relative importance of weight, cost, maintenance cost, and performance on airline operating costs. Based on these studies, six advanced generic structural concepts were selected and conceptually designed. The base engine was reconfigured as required to optimize the benefits of each advanced concept. The benefits of each advanced concept were quantitatively determined and their probability of success assessed. Based on these studies the best of these concepts were selected, their required technological advances identified, and programs for these technology developments outlined.

2.0 SUMMARY

The primary objective of this program was to identify and outline advanced technologies for aircraft engines which would provide the maximum economic benefits for advanced aircraft in the 1990's. To accomplish this goal a disciplined methodology, which was developed for this purpose, was used. The methodology consists of identifying and assessing advanced generic structural concepts and determining their requisite technologies. An outline of the programs is presented below.

Before selecting the advanced concepts a qualitative overview was conducted to determine which engine system provided the greatest potential benefit to future engines. The Energy Efficient Engine was used as the base engine. Also, engine parameters such as thrust specific fuel consumption, weight, cost, and maintenance cost were reviewed to determine their relative contribution to life cycle performance and ownership cost.

Based on these studies and the criteria that the advanced concepts be innovative, advanced (i.e., technologically beyond the base engine) and provide significant benefit to future aircraft engines, six advanced concepts were identified and conceptually designed. These are:

- Geared fan
- Hybrid turbine blade
- Layerglazed™ disk
- Composite drum rotor
- Composite high pressure compressor blade
- Folded burner

Quantitative benefit assessments were made of each advanced concept in terms of thrust specific fuel consumption, weight, cost, maintenance cost, fuel burned and direct operating costs plus interest. The entire base engine was reconfigured, as required, to maximize these benefits. Also, the probability of success of each concept was determined. Based on this study the advanced concepts were ranked in terms of their benefit potential and the top three were selected for further study. These are:

- Geared fan
- Hybrid turbine blade
- Layerglazed™ disk

A wide range of technologies, required for these concepts, were identified and development programs outlined. The most beneficial advanced technologies are listed below in order of their ranking. They are analytic programs because they are the most generic technologies and thus provide the greatest application and potential benefits to future engine developments.

1. Life Prediction - advanced turbine blades
2. Life Prediction - advanced disks
3. Flutter - high speed turbine blades
4. Heat Generation and Dissipation - advanced gears

It is recommended that these technologies be developed in order to benefit future aircraft operations.

3.0 STRUCTURAL CONCEPT SELECTION AND ASSESSMENT

3.1 Concept Development

3.1.1 Base Engine Studies

A qualitative overview was conducted to determine which engine system provided the greatest potential benefit to future engines. The Energy Efficient Engine (NASA Contract NAS3-20646) was chosen as the base engine for this study.

Various areas of the base engine system were systematically assessed to determine where changes in components or structural design will lead to improved life cycle performances and/or decreased ownership costs. Engine factors such as thrust specific fuel consumption, weight, cost and maintenance cost were reviewed to determine their relative contribution to life cycle performance and ownership cost. Further breakdown of these factors was made to determine which areas of the engine offer the most promise of improvement. The engine aero-mechanical configuration characteristics were assessed and the characteristics providing significant benefit to the life cycle performance and ownership costs were identified.

The relative benefits due to improving thrust specific fuel consumption, weight, cost and maintenance cost were assessed. The study is based on a "rubber" engine procedure which allows the aircraft to be reconfigured to maximize the benfit due to a change of these parameters. Table 1 shows the equivalence of 1% thrust specific fuel consumption to weight, cost and maintenance cost in terms of fuel burned and direct operating cost plus interest for the domestic and international missions defined in Table 2. This study is based on 1979 dollars and $1.50 per gallon of fuel. The study clearly shows that thrust specific fuel consumption is the most important parameter for benefit improvement. Projected increased cost of fuel makes thrust specific fuel consumption even more important. The concepts selected and the methods for maximizing their benefits reflected these trades.

To determine the engine systems with the most potential for improvement, a weight, cost and maintenance cost study of the major engine systems was conducted. The results are listed in Table 3. All other parameters being equal, the component with the greatest weight and/or cost and/or maintenance cost has the greatest potential for improvement. This study provided useful guidelines during the concept selection period.

3.1.2 Concept Selection Criteria

The advanced generic structural concepts selected had to conform to very specific criteria to fulfill the contractual as well as the philosophical requirements of this program. Specifically, they had to be structural, innovative, technologically advanced, and provide significant benefit to future aircraft engines.

TABLE 1
BENEFIT TRADE FACTORS

1% thrust specific fuel consumption is equivalent to:

	Fuel Burned		Direct Operating Cost + Interest	
	Domestic	International	Domestic	International
Weight - lb/engine	1300	1310	1070	1220
kg/engine	589.6	594.2		
Cost - $/engine			197,000	265,000
Maintenance Cost $/engine flight hour			13.60	13.50

TABLE 2
ENERGY EFFICIENT ENGINE
STUDY AIRPLANE CHARACTERISTICS

	Domestic Trijet	International Quadjet
No. of Engines	3	4
Range - (Nautical Miles)		
Design Mission	3000	5500
Typical Mission	700	2000
Passengers		
Design Mission	400	510
Typical Mission	55% load factor	55% load factor
Design Take-off Gross Weight (TOGW)		
- (lbs)	510,000	750,000
- (kg)	231,330	340,192
Cruise Mach No.	0.80	0.80
Initial Cruise Altitude (ft)	35,000	33,000
(m)	10,668	10,058
Take-off Field Length (ft)	8,000	11,000
(m)	2,438	3,352

TABLE 3
COMPONENT POTENTIAL
FOR BENEFIT IMPROVEMENT

	Weight Total kg (Pounds)	Weight Change (Percent)	Cost Change (Percent)	Maintenance Cost Change (Percent)
Fan	771 (1700)	21.2	12.9	9.1
Low Pressure Compressor	199 (440)	5.5	6.0	4.3
Intermediate Case and Bearings	435 (960)	12.0	8.8	1.9
High Pressure Compressor	353 (780)	9.7	11.9	12.0
Diffuser/Burner	288 (635)	7.9	9.6	9.4
High Pressure Turbine	340 (750)	9.3	10.1	19.7
Turbine Intermediate Case and Bearings	151 (335)	4.2	5.2	6.2
Low Pressure Turbine	703 (1550)	19.3	20.3	18.1
Mixer/Exhaust	97 (215)	2.7	2.7	0.4
Controls/Accessories/ Misc./Assem/Diagram/ Test/Line Maint.	299 (660)	8.2	12.5	18.9
Total	3,640 (8025)	100	100	100

The "advanced" criterion required the proposed concept to employ technologies beyond the baseline engine. Several worthwhile concepts were not selected for this study because they represented technologies similar to those used in the base engine.

Long-term developments projected into the 1990's and corresponding risk levels were accepted to meet the requirement of significant benefit. This is a difficult requirement since aircraft engines represent mature technologies where advances tend to be evolutionary rather than revolutionary. It is worthwhile to note that the significant improvements obtained by the base engine relative to current engines result from careful applications of many advanced concepts which individually provide only small benefits.

3.1.3 Concepts Selected

The concepts selected are identified in Figures 1 through 6 and consist of a mix of critical engine components whose improvement were assessed to provide significant benefits to future engine development. The concepts are (1) geared fan, (2) hybrid turbine blade, (3) Layerglazed™ disks, (4) composite drum rotor (5) composite high pressure compressor blade, and (6) folded burner.

Each concept was assessed individually and selected on its own merit. Particular attention was paid to ensure that each concept conforms to the criteria discussed previously and, when possible, provide complementary benefits. Thus the geared fan provides major performance benefits and, as defined in this program, requires long range technology development. The hybrid turbine blade and Layerglazed™ disks complement each other at their critical interface, that is the turbine blade attachment. The two composite structures provide major weight savings, and represent high technology in an area which will become increasingly important to future aircraft engines. In addition, when used in conjunction with the hybrid turbine blade and Layerglazed™ disk, additional benefits are feasible as will be discussed in the appropriate section later in the text. The folded burner provides a major system change producing a shorter, stiffer and potentially lighter engine with greatly improved rotor dynamics characteristics. A more detailed description of each advanced concept is provided in Section 3.4.

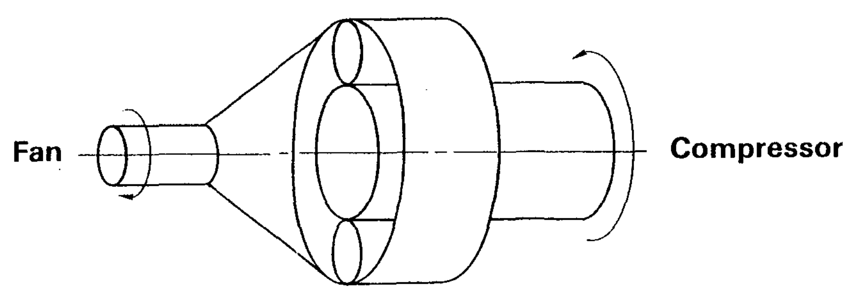

Figure 1 Geared Fan Concept. This concept maximizes efficiency by allowing the optimum combination fan tip speed and low pressure rotor speed.

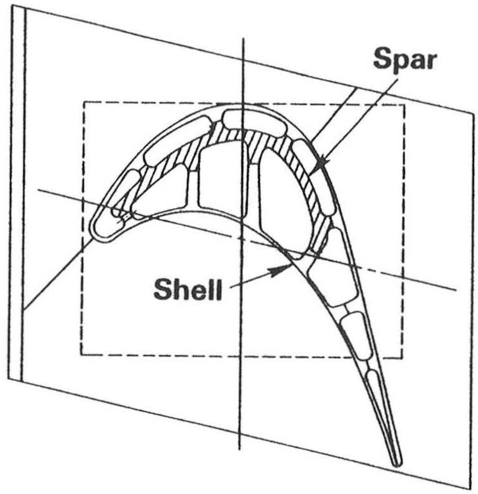

Figure 2 Hybrid Turbine Blade Concept. The blade has superior strength, lower weight and improved internal cooling compared to base engine technology turbine blades. The hybrid nature of the blade permits each component of the blade to be optimized.

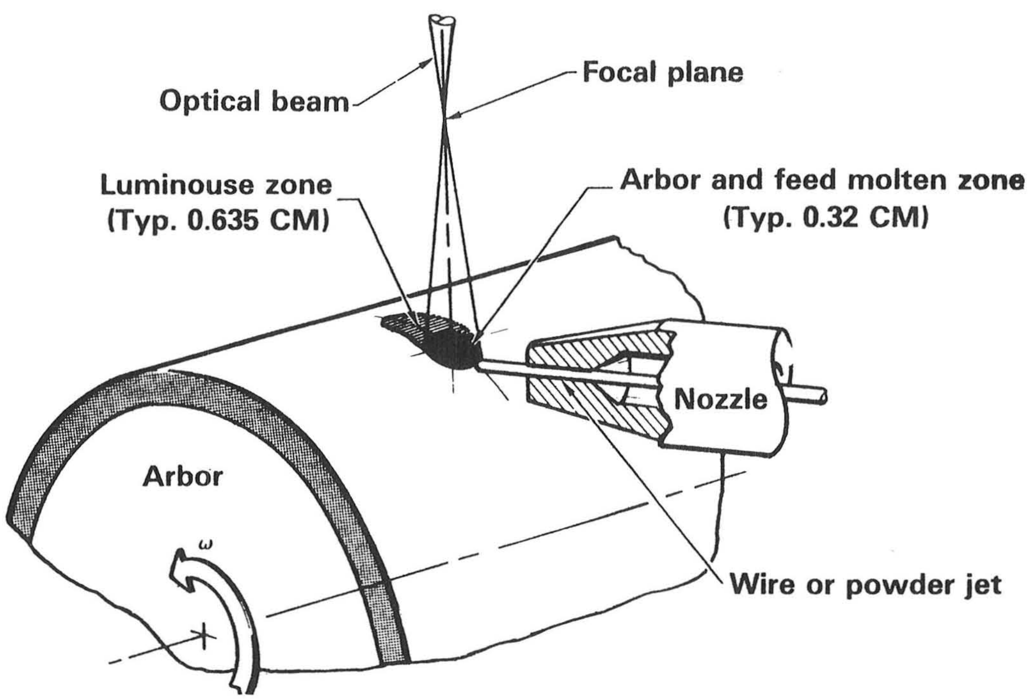

Figure 3 Layerglazed™ Disk Concept. Layerglazing™ produces a high strength, homogeneous, structure by depositing thin layers of material, via metal powder feed, on a rotating disk, and melting the powder with a high intensity laser beam.

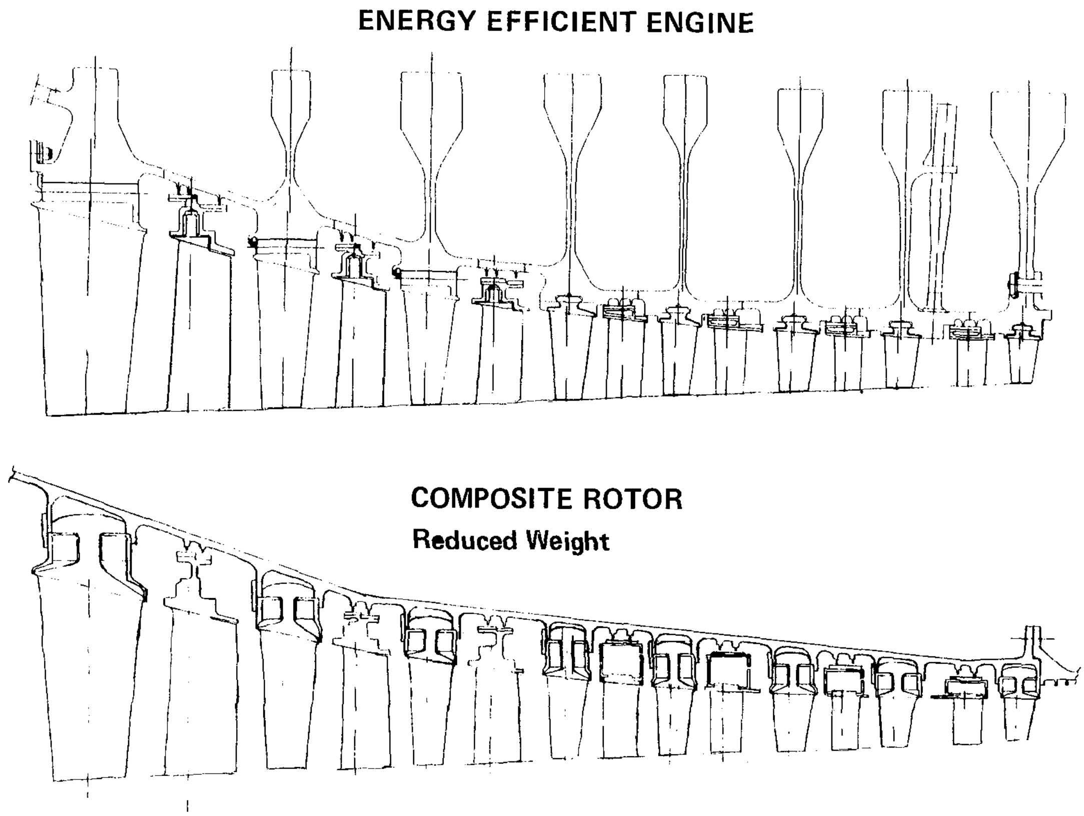

Figure 4 Composite Drum Rotor Concept. The concept requires no deep profile disks, while the base engine drum rotor requires nine.

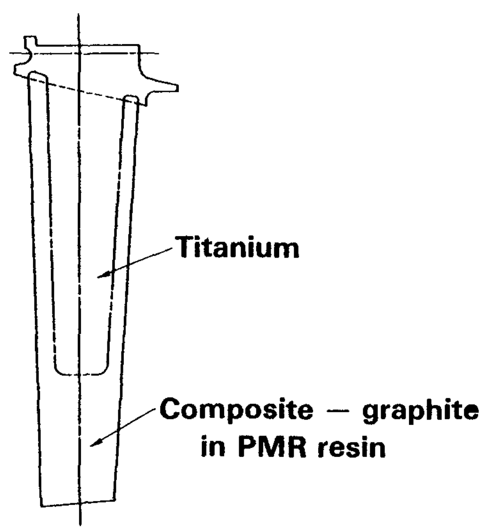

Figure 5 Composite High Pressure Compressor Blade. Frequencies of adjacent blades can be varied by changing the geometry of the titanium spar, without changing the external aerodynamic shape of the airfoil. The result is a stage with improved vibration characteristics.

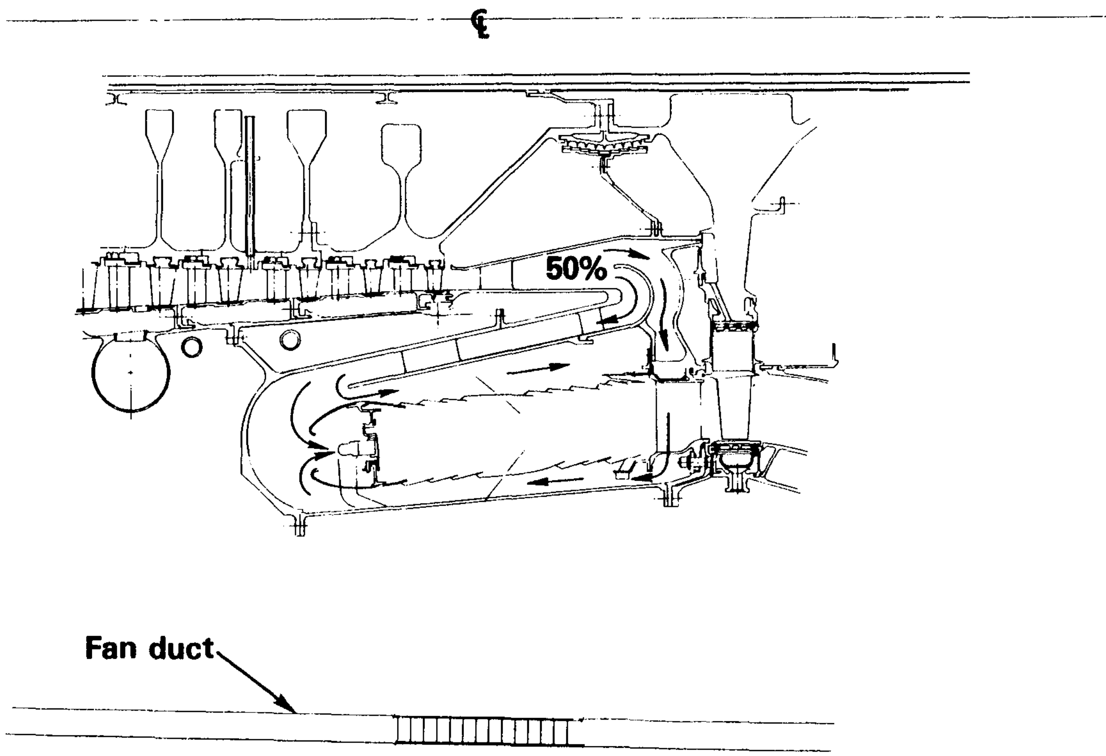

Figure 6 Folded Burner Concept. This concept reduces engine length significantly. The resulting decrease in rotor length directly increases rotor stiffness, which improves rotor dynamics.

3.1.4 Redefinition of Engine Configuration

The base engine for the study will be the Energy Efficient Engine, which is the flight propulsion system design being utilized in the NASA Energy Efficient Engine Component Development and Integration Program, Contract No. NAS3-20646. A cross section of this engine is shown in Figure 7. The Energy Efficient Engine is a twin-spool, direct drive, mixed-flow configuration consisting of a hollow shroudless single stage 1.74:1 pressure ratio fan, a four-stage 1.8:1 pressure ratio low pressure compressor, a ten-stage 14:1 pressure ratio high pressure compressor, a two-stage carbureted combustor, a high rim speed single stage high pressure turbine, a four-stage offset low pressure turbine. The overall mechanical arrangement features a short, stiff, straddle-mounted high pressure rotor combined with a short, three bearing low pressure rotor, resulting in two major engine support frames and five main-shaft bearings located in two bearing compartments.

The baseline engine aero-mechanical configuration was redefined to maximize the benefit of incorporating the advanced concepts. To obtain the maximum engine benefit, alternate ways of incorporating each advanced concept was investigated. This process involved extensive use of existing computerized engineering analyses, and experience gained in previous preliminary engine design studies. The engine redefinition included such changes to the engine as: component efficiencies, cooling airflow, component configuration, geometry, rotor speed and number of stages required. Care was taken that only changes directly related to the incorporation of the advanced concepts were made.

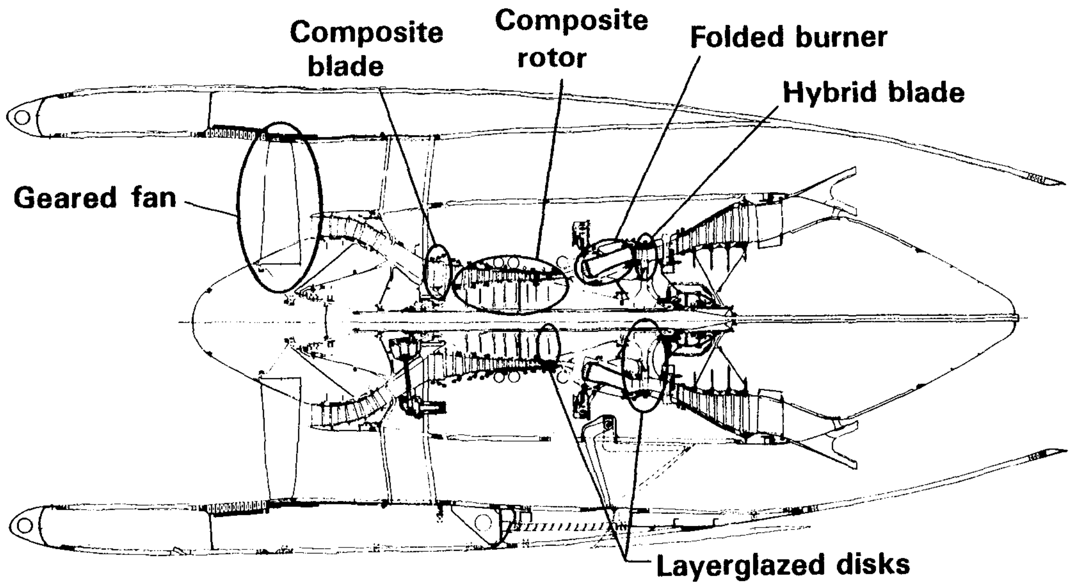

Figure 7 Base Engine for the Study. Concepts studied under the program will be evaluated in the Energy Efficient Engine configuration.

The most attractive redefined engine configuration was selected by trading the impact of the efficiency differences with engine price, maintenance cost and weight differences between the alternate approaches. The redefined engine will form the basis for the benefit and feasibility analysis of the advanced concepts.

3.2 Engine-Aircraft Performance Assessment Procedure

3.2.1 Base Airplane

Two advanced study airplane designs were used in the benefit evaluation to ascertain the effect of different mission types. One is a 440 passenger domestic trijet and the other is a 510 passenger international quadjet. The study airplane definitions are from the Energy Efficient Engine Component Development and Integration Program (NAS3-20646). Aircraft characteristics include high aspect ratio wings, supercritical aerodynamics, and advanced lightweight composite structures technology. The overall airplane characteristics are shown in Table 2. The aircraft are designed for the full specified payload and range, but the economic analysis is conducted for the typical mission payload and range, as shown in Table 2.

3.2.2 Engine Performance

The effect of incorporating each advanced structural concept in the engine was evaluated for its impact on the performance of the particular engine component involved and the entire engine. Generally, engine component efficiencies, pressure losses and cooling airflows were affected. This required reoptimizing the baseline engine cycle and determining the corresponding effect on the overall engine performance (thrust specific fuel consumption and thrust specific fuel consumption retention). The engine cycle was redefined at constant high pressure turbine rotor inlet temperature with the bypass ratio adjusted to provide approximately equal core and fan stream exhaust pressures, for the base engine mixed flow exhaust configuration. These cycle effects and changes to engine performance were determined by analyzing the inlet, engine component, and nozzle performance characteristics.

Changes to nacelle drag, which affects the installed engine performance were evaluated based on changes in overall engine length and diameter. These engine geometry changes were determined on the basis of the component redesign, cycle refinement and performance change. For example, overall engine geometry are directly affected by component redesigns such as blade aspect ratio changes and revisions in the number of compressor or turbine stages. Cycle bypass ratio refinement will affect overall engine diameter because of the fan size (total airflow) change relative to the rest of the engine. Performance changes due to component efficiency or cooling airflow differences require resizing the engine to the thrust level required by the study airplane. This scaling affects both engine length and diameter. Techniques developed from previous detailed design efforts that identified and accounted for scaling limitations in each engine component were included in these analyses.

3.2.3 Engine Weight

Changes to the engine weight resulting from the incorporation of the advanced concepts were used in the airplane performance assessment. The redefinition of the base engine including the cycle re-optimization provided the basic input into the engine weight analysis.

Changes to engine weight were obtained from a component analysis technique used for preliminary studies, which has been verified through actual engine experience. This procedure was used to analytically modify well-established component designs to reflect study component weight differences attributable to changes in size, aspect ratio, number of stages, materials, speed, temperature, pressure, etc. Changes to the nacelle weight were evaluated based on the engine geometry changes discussed above.

3.2.4 Airplane Analysis

The airplane analysis determined the impact of the changes in engine performance, including performance retention, weight, and geometry on aircraft take-off gross weight and fuel burned. A well developed trade factor technique derived from consideration of airplane aerodynamics, flight mechanics, propulsion integration, and weight estimation was the basis for this analysis. Trade factors for changes in engine and nacelle weights, performance (thrust specific fuel consumption), and drag were applied independently to determine the effect of each engine change on take-off gross weight and fuel burned. Individual effects were then combined to evaluate the total effect of the advanced concepts on take-off gross weight and fuel burned.

The changes in airplane take-off gross weight reflect a "rubber" airplane analysis, i.e. improvements to the engine configuration allow further improvements to the airplane configuration. For example, an advanced engine structural concept which reduces engine weight will result in a fuel savings which reduces aircraft weight and aircraft structural component weight, permitting reductions in wing size and engine thrust requirements. Consequently, the initial engine weight benefit "snowballs" in its impact on the aircraft benefit.

3.3 Engine-Aircraft Ownership Cost Assessment Procedure

3.3.1 Engine First Cost

Changes in engine first cost for the redefined engine incorporating an advanced generic structural concept were determined from manufacturing cost changes. These changes were estimated in a similar manner to weight changes, using similarly developed analytical techniques from previous studies. In addition to those items which were considered to obtain component weight differences, cost estimating allowed for differences between advanced and baseline technology components in the areas of fabrication, tooling, quality control, and inspection. Advanced manufacturing projections were based on previous studies and accumulated experience. Resulting first cost changes were expressed in terms of fixed year dollars.

3.3.2 Engine Maintenance Cost

Maintenance cost changes for the redefined engine were evaluated using a statistical analytical approach. This approach was predicated on average part lives determined for various failure modes by careful analyses of well documented field experience obtained from years of in-service operation with various engine models. Service lives for the redefined engine components were predicted by adjusting the field experience based average part lives for similar components. This adjustment process evaluated the interaction of several different modes of failure to determine the mode which will control replacement life. Total maintenance labor and materials requirements changes caused by the redefined engine were then estimated based on changes in service life, repair interval, field inspection repair characteristics, and shop repair. These differences in maintenance requirements were converted into maintenance materials and labor cost differences using spare parts cost differences and standard labor rates.

3.3.3 Airline Economic Analysis

The economic system analysis evaluated the effect of changes in engine maintenance cost and first cost to the changes in the aircraft take-off gross weight and fuel burned described in the previous section, in order to assess the airline economic effect. The life cycle ownership costs determined in this analysis were expressed as direct operating costs plus interest. A well developed trade factor technique derived from considerations of total airline economics was the basis for this analysis, and includes crew cost, fuel cost, airframe and engine depreciation, airframe and engine maintenance cost, insurance cost, and overhead cost. These trade factors reflected the specific engine and airplane to which each advanced engine structural concept was applied. Trade factors for changes in engine and nacelle weights, performance (thrust specific fuel consumption) including performance retention, maintenance cost, and first cost were applied independently to determine the effect of each engine change on a given economic parameter. Individual effects were then combined to evaluate the total effect of the advanced concept on that parameter.

Direct operating cost plus interest is an extension of direct operating cost in that it includes the "cost of money". In other words, it includes an expected return to the airline for their investment in the aircraft/engine system. Direct operating cost plus interest is an appropriate substitution for return on investment and includes all of the engine related terms in return on investment, and is therefore an appropriate parameter for evaluating the effect of engine changes on an airline's economics.

3.4 Advanced Structural Concept Design Description and Engine Redefinition

3.4.1 Geared Fan

A major performance benefit can be obtained by a high bypass ratio geared fan engine. This approach achieves the increased propulsion efficiency of a high bypass ratio engine without the performance and weight penalties associated with a direct drive fan engine design which operates at a non-optimum fan speed and reduced low pressure turbine rotor speed. In this study, the engine components are similar to the preliminary geared fan study of the base engine, Energy Efficient Engine Preliminary Design and Integration Studies, NASA-CR-135396 except that advanced technologies were assumed.

A geared fan arrangement was carefully evaluated during the preliminary engine definition phase of the base engine program. It was not selected in spite of a large thrust specific fuel consumption gain, because the gearbox reliability, maintenance cost and performance retention risks were assessed to be too great for the time period of application.

In this study the geared fan concept deals with long term technology advances, and the projected improvements in gearbox technology make it an excellent concept for evaluation. Furthermore, the risk factor can be reduced by developing advanced gear concepts required to design a practical geared fan concept. These advanced concepts will be used to upgrade the 99.2% gear efficiency used during the base engine study to a target efficiency of 99.5%. Selection of the geared fan concept was also based on the important spin-off of gearbox technology for the advanced turbo-prop engine. Major performance gains are projected for the turbo-prop engine. Advances in gearbox technology will also be vitally important to the success of the turbo-prop engine.

The star gear arrangement shown in Figure 8 was assessed to be the most efficient. The outer ring turns with the fan. The intermediate gear centerlines are stationary relative to the static structure and turn about their own axis. The inner gear, rotating at the opposite direction to the fan gear, rotates at the low pressure rotor speed.

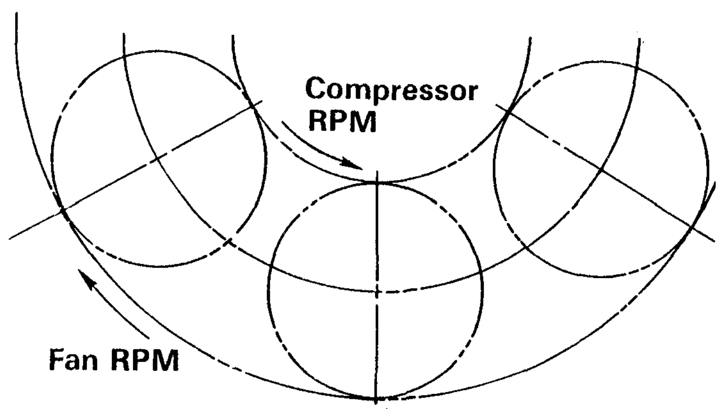

Figure 8 Geared Fan Star Gearbox. This design was found to be the most efficient. The outer ring turns with the fan. The intermediate gear centerlines are stationary relative to the static structure and turn about their own axes. The inner gear rotates at the low pressure rotor speed in the opposite direction of the fan gear.

To achieve the technology goals for the geared fan concept, a program tailored to technology advances projected for the 1990's was assumed. For example, improved gear lubrication, shown in Figure 9, will be evaluated. The oil flows directly into the center of the intermediate gears, through the roller bearings and out of passages drilled through the gear teeth. This provides more efficient cooling which in conjunction with a higher allowable operating temperature will reduce the oil cooling requirements.

Other advanced concepts, which will be incorporated, include higher strength gear teeth, scoop scavenging of the oil, hollow roller bearings to increase roller contact, molybdenum disulfide sputter coated roller bearings for longer life, better surface finish of the gear teeth, higher gear tooth contact ratios, polygon splines and buttress gear teeth.

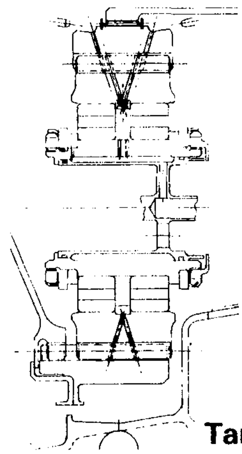

Figure 9 Geared Fan Improved Gear Lubrication Method. Oil flows directly into the center of the intermediate gears, through the roller bearings and out of passages drilled through the gear teeth. This provides more efficient cooling.

The changes to the engine cycle used in the benefit assessment, shown in Table 4, reflect the projected efficiency increase and better cooling arrangement. A small increase of the fan bypass ratio relative to the base engine study was made to correspond to the efficiency increase.

TABLE 4
ASSESSMENT SUMMARY RELATIVE TO BASE ENGINE

Concept	Change in Cruise Thrust Specific Fuel Consumption (percent)	Change in International Direct Operating Cost + Interest (percent)	Probability of Success
Geared Fan	-4.2	-2.19	75
Hybrid Turbine Blade	-2.2	-1.49	50
Layerglazed™ Disk	-0.7	-0.40	50
Composite Drum Rotor	0	-0.04	50
Composite Compressor Blade	0	-0.04	50
Folded Burner	-0.3/+0.2	-0.50/-0.11	90

3.4.2 Hybrid Turbine Blade

A high pressure turbine blade was designed which has superior strength lower weight and improved internal cooling compared to base engine technology turbine blades. A hybrid arrangement permits optimizing each component of the blade for its application. Thus, the blade centrifugal load is carried by the inner spar whose material properties are selected for high strength at the relatively low inner temperature (See Figure 2). Weight reductions, and therefore reduced blade pull stress, are achieved by the material selection.

The spar and shell construction permits the attachment axis to be perpendicular to the disk face, eliminating the stress distribution factor due to skewed attachments. Up to 50% greater attachment stress result from conventional construction where the blade load is transmitted by the outer shell.

Further reduction of the blade load stress is obtained by reducing the weight of the blade tip abrasive cap and blade platform. The cap weight is reduced by increasing the abrasive content. Platform weight will be reduced by making it from silicon carbide reinforced ceramic which is hot pressed to the turbine blade. This material is about one third the weight of the platform material of conventional blades.

Further benefits for the selected design are obtained by improving the cooling of the turbine blade. The three piece spar and shell construction provides for the multi-pass airflow arrangement shown in Figure 10. Passage size can be designed for optimum airflow velocities. Thus, the airflow velocity on the concave side is lower than for the convex side, providing greater cooling on the side with the lower external air velocity. Cooling air impingement on the leading edge is provided without the root inserted impingement tube required by a conventional designs. To reduce flow losses and increase heat transfer in the internal passages turning vanes and flow trips will be used.

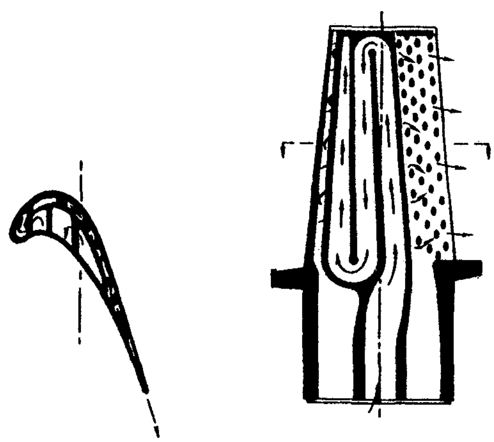

Figure 10 Hybrid Turbine Blade Cooling Design. The three piece spar and shell construction uses a multi-pass airflow design.

To realize the full potential of this concept the base engine was changed extensively. The overall pressure ratio was increased to 45 to 1 because the hybrid turbine blade can withstand higher cooling air temperatures from the high pressure compressor. The base engine pressure ratio is 38.6 to 1. A ten percent increase of the high pressure rotor speed was made possible by the higher strength and decreased weight of the turbine blade. The blade pull parameter AN^2 (area x speed squared) was also increased ten percent. This increase was acceptable because of the hybrid turbine decreased weight. Thus, the turbine attachment stress was not increased beyond the base engine stress.

Further base engine revisions were required to obtain the higher overall pressure ratio and increased AN^2 efficiently. The fan diameter, fan speed, total airflow and bypass ratio were matched to the 45:1 overall pressure ratio. A fifth stage was added to the low pressure compressor to provide the higher pressure ratio. The extra compressor stage required modifications to the low pressure compressor inlet and exit hub tip ratio, and inlet and exit root diameters.

The high pressure compressor flowpath was redesigned as required by the ten percent speed increase and to stay within base engine technology. This was accomplished by reducing the front end hub tip ratio and adjusting the rest of the high pressure compressor stages to match the first stage.

The diameter of the high pressure turbine was also decreased, as required to obtain the ten percent speed increase and a ten percent AN^2 increase. The burner geometry was adjusted to match the decreased diameter turbine. This required a small increase in burner length to maintain the required burner volumetric heat exchange rate.

An extra stage was added to the low pressure turbine to match the decreased diameter high pressure turbine. Adding the extra stage was based on an extensive trade study comparing the extra stage with longer or steeper transition ducts. These ducts, in addition to extra weight and cost, provide a performance loss.

The base engine changes provided significant performance benefits relative to the base engine in the low pressure compressor, high pressure compressor, high pressure turbine and low pressure turbine. Increasing the overall pressure ratio provided an engine performance improvement. The increased high pressure rotor speed permits the rotor diameter to be decreased, resulting in weight and cost benefits. Higher performance results in scaling the revised engine down to the baseline thrust providing further weight and cost benefits. Partially offsetting these gains are an increase in engine length and in the number of parts. These changes are due primarily to the extra low pressure compressor and turbine stages.

3.4.3 Layerglazed™ Disks

An advanced fabrication technology, the Layerglaze™ process, will be used to manufacture a superior last stage high pressure compressor disk and the high pressure turbine disk. Layerglazing^{TM} produces a high strength, homogeneous, structure by depositing thin layers of material, via metal powder feed, on a rotating disk, and melting the powder with a high intensity laser beam. The Layerglaze^{TM} process is shown in Figure 3.

In addition to homogeneity, Layerglazing^{TM} provides the potential of very high fatigue properties by radically limiting the size and number of inclusions in the material. The inclusions consist primarily of ceramic particles mixed in the metal powder. The size of the inclusion can be reduced by fine mesh screening the metal powder. The number of inclusions are reduced during the Layerglaze^{TM} process by a resonant coupling between the ceramic powder and the laser beam radiation which cause many of the ceramic particles to evaporate. Inspection has shown that the defects in the Layerglazed^{TM} metal are generally spherical voids rather than the ceramic inclusion found by using other powder metal processes. The voids could be removed by a subsequent laser beam remelt.

Other advantages of the Layerglaze^{TM} process, such as inspection during fabrication, repair, mechanical working, grading of material and heat treatment are illustrated in Figure 11. Integrating inspection with the fabrication process is feasible since the disk is build up layer by layer. In other structures this type of inspection could only be accomplished by destroying the disk. With this type of inspection method, repair and/or removal of inclusions as they are formed is feasible. Mechanical working of the material during the fabrication process is also possible. Grading of materials and heat treatment as the disk is fabricated can provide the strength, ductility, and heat resistance to meet specific requirements. Materials having different coefficients of expansion, in conjunction with proper heat treatment, can be used to pre-stress the disk. While not all materials can be Layerglazed^{TM}, research is in progress to extend this technology.

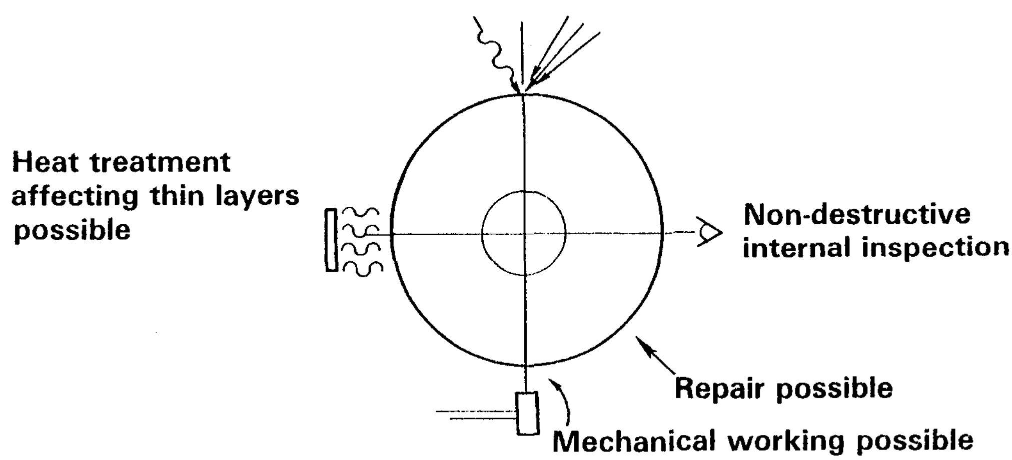

Figure 11 Additional Advantages of the Layerglaze^{TM} Process. The Layerglaze^{TM} process also permits inspection, repair, mechanical working, grading of material and heat treatment during fabrication.

Simple substitution of the disks would provide significant weight savings by using the higher strength of the Layerglazing™ to reduce disk material. However, to optimize the benefit from this concept, the base engine cycle was changed in a similar manner to the hybrid turbine blade. The overall pressure ratio was increased to 45 to 1 and the high pressure rotor speed was increased ten percent.

Since the high pressure turbine blade material in this case is the same as the base engine hardware, the AN^2 (area x speed squared) parameter was held constant to avoid an increase in the blade's stress level. This increases turbine Mach number, causing a small performance decrease which is accounted for. More cooling is required for the turbine blades since the cooling air from the compressor is hotter than from the base engine. This is also accounted for in the assessment. Otherwise, the revision to the entire base engine cycle is generally the same as described for the hybrid turbine blade.

3.4.4 Composite Drum Rotor

Composite ring reinforced rotors provide major weight reduction and reduced centrifugal growth due to the superior strength and stiffness properties of composites. The weight reduction decreases the requirement for titanium, which may become a critically scarce material for future engines. The decreased centrifugal growth provides the potential for smaller blade clearances which improves engine performance.

An innovative blade attachment arrangement, shown in Figure 12, allows the entire blade pull to be carried by the composite ring. Assembly of a typical stage is accomplished by loading the first compressor ring, the blades and finally the second composite ring axially onto the rotor. The assembly is held in place by a retaining ring. Circumferential motion is prevented by slots in the titanium rings bonded to the composite rings. With this arrangement, the titanium rotor is required to carry only its own loads, i.e., its own centrifugal load, torque and vibration. In addition, the material of each composite ring can be matched to the temperature requirement of each stage.

The blade pull load is transmitted directly to the composite rings. In conventional designs, which have the composite encapsuled in the titanium, the load path is more complex and thus requires additional material. The direct load path also provides for a simple and economical blade attachment geometry.

Since the composite rings are not encapuslated in the titanium rotor, a simple quality control procedure can be used during their fabrication. A ring can be fabricated which is twice the width required for the individual rings. This ring, shown in Figure 13, is then cut in half, ensuring a matched pair of composite rings to carry the blade pull. There are no filaments in the center of the ring, so no filaments are severed when the ring is cut.

For this study the entire drum rotor of the high pressure compressor used composite rings. As shown in Figure 4, composite rings require no deep profile disks necessary in an all titanium design. The base engine drum rotor requires 9 disks to carry the centrifugal loading.

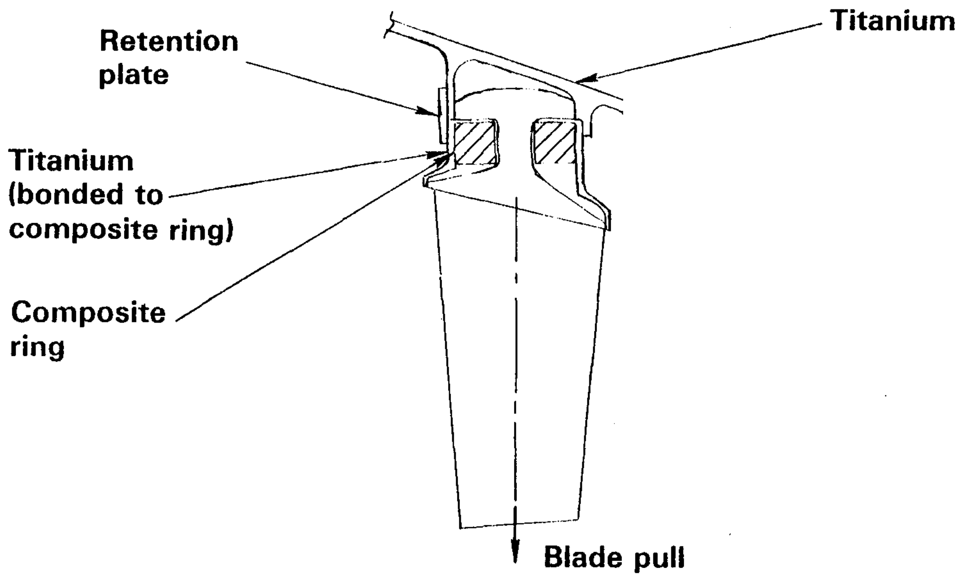

Figure 12 Composite Drum Rotor Blade Attachment Method. The entire blade load is carried by the composite ring.

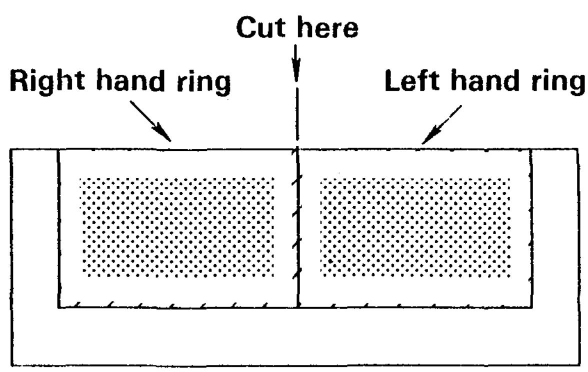

Figure 13 Composite Drum Rotor Ring Fabrication Method. A ring is fabricated which is twice the width required for the individual rings and then cut in half, producing a matched pair of composite rings.

Several studies were completed evaluating engine cycle changes to increase the benefits for this concept. These studies investigated the effects of using the superior properties of the composite drum rotor to increase the high pressure rotor speed by ten percent. This increase required additional changes to the engine cycle. The high pressure turbine diameter had to be decreased to keep the turbine tip speed constant. An extra stage had to be added to the low pressure turbine to provide proper flowpath alignment with the high pressure turbine. Variations of this arrangement which included transition ducts and omitting the extra turbine stage were evaluated. While these studies indicated large weight saving potential, the new engine components were less efficient than the base engine. As a result the fuel burned and direct operating cost plus interest increased. Therefore, the final benefit evaluation is based on a simple substitution of the composite drum rotor for the base engine titanium rotor.

It is important to note that if the drum rotor was considered in conjunction with the hybrid turbine blade and Layerglazed™ disks the benefits due to increasing the rotor speeds could be realized. The higher strengths of the hybrid turbine blade and Layerglazed™ disks permits the high pressure turbine diameter to remain constant at the increased speed thus eliminating the alignment problem.

The philosophy of the benefit assessment was to evaluate each concept on its individual merit. Thus, unjustified credit for advances in other engine components were not taken. However, the above indicates that greater benefits for the composite drum rotor are potentially available when used in conjunction with other advanced components.

3.4.5 Composite High Pressure Compressor Blade

Since the first stage of the high pressure compressor is critical in establishing the overall efficiency, cost, weight and length of the compressor, a composite inlet stage rotor blade was selected. The preliminary study shown in Table 4 was based on assuming a 10% speed increase. This was used to significantly increase the first stage performance by decreasing the blade hub tip ratio and increasing the aspect ratio. Hub tip ratio was decreased to 0.45 from the 0.56 ratio of the baseline engine, and blade aspect ratio was increased from 1.3 to 4.0.

These aerodynamic and structural changes were made possible by the high stiffness to weight ratio of the composite materials used. These materials have improved vibration characteristics, allowing the twice per revolution (2E) resonance with the blade first bending mode to be designed below idle. The low blade weight was also be used to to decrease the compressor disk size. The smaller disk permitted a further decrease in the compressor flowpath, providing even lower hub tip ratios.

While the base engine first stage high pressure compressor is more advanced than those in current aircraft engines, the revised design provided significant improvements compared to the base engine.

The spar and shell construction shown in Figure 5 can be readily mistuned. By changing the geometry of the titanium spar, frequencies of adjacent blades can be varied without changing the external aerodynamic shape of the airfoil. While mistuning effects require further study, there is considerable evidence that mistuning decreases the potential for flutter. Mistuning technology developments may also have an important spin-off in designing advanced engine fans.

Further advantages of the composite blades are: weight saving, decreased blade containment requirements, potential decreased engine length resulting from increased aspect ratio and reduced requirements for titanium for the blades and compressor disk.

As with the composite drum rotor, various engine cycles incorporating a ten percent increased high pressure compressor rotor speed were evaluated. Corresponding, changes to the compressor hub tip and aspect ratios were investigated. These trades resulted in large weight benefits, but performance losses increased direct operating cost plus interest. As a result of these studies, the final benefit assessment is based on installing the composite blade into the base engine flow path. The higher strength to weight ratio allows the blade width to be reduced. Thus, the final composite blade hub tip ratio is the same and the aspect ratio is greater than the base engine compressor blade.

The discussion regarding the ten percent speed increase in the previous section on the composite drum rotor also applies to this concept. Thus greater benefits than obtainable in the study shown in Table 4 would be realized if the other engine components are improved to permit the speed increase.

3.4.6 Folded Burner

A folded burner (actually a folded diffuser) provides for a shorter and stiffer engine, which for future engine applications may become critically important. The trend in future engines is to decrease weight and increase rotational speeds. Thus, critical speed problems may become a limiting factor in engine designs. Shortening the engines by using the folded burner concept may solve these critical speed problems. Another important application is in scaling down engines for reduced thrust. A burner requires a certain length for efficient combustion, and so takes up a proportionally larger amount of space when an engine is scaled down, preventing engine length from decreasing at the same scale rate as the rest of the components. As a result, critical speed problems increase as the engine size is reduced because rotor diameter decreases, but rotor length does not also decrease proportionally, decreasing rotor stiffness. A shorter engine, using a folded burner, can solve this problem because it allows engine length to decrease more than other components.

The folded burner, shown in Figure 6, achieves a significant reduction of engine length. The resulting decrease in rotor length directly increases rotor stiffness, which increases the critical speed of the rotor. Rotor dynamic response characteristics improve in terms of reduced rotor vibration amplitudes, response to maneuver loads and blade loss. Reduced rotor deflection allow blade tip clearances to be set tighter, increasing engine performance.

Additional benefits for the folded burner include reduced nacelle drag due to shorter length, potential for decreasing shaft diameter which decreases the bearing DN (diameter x rotational speed), improved pattern factor of flow to the turbine since the diffuser acts as a mixing chamber, decreased maintenance cost since the burners are more accessible, and for some applications the potential of reduced engine weight due to the shorter length.

Component improvements directly attributable to the folded burner were not identified. Therefore, the engine flow path, with the exception of the burner arrangement, is the same as the base engine.

To provide insight on some of the possible performance benefits of folded burners, it was assumed that the high pressure compressor and turbine tip clearances will be reduced by three mils. This was a judgement estimate based on the hypothesis that an advanced engine, with a conventional burner arrangement, will have a critical speed problem. This hypothesis is reasonable since advanced engines will be lighter and rotate faster than current engines. Incorporating the folded burner into the hypothetical engine produces a shorter and stiffer shaft. It was assumed that the stiffer shaft will raise the critical speed outside the operating range of the engine. The resulting decrease of vibration amplitude was estimated to be three mils.

3.5 Benefit Assessment Results

Table 5 shows the results of the benefit assessment. Note that two sets of performance cost figures are shown for the folded burner benefit assessment results. The first set corresponds to an engine with a high pressure rotor clearance decrease of three mils. The second set of numbers assumes no clearance changes. Fuel burned and direct operating costs plus interest were determined for a domestic and international mission defined in Table 2.

TABLE 5
PERFORMANCE, BENEFIT, COST ASSESSMENT OF THE ADVANCED CONCEPTS

	Geared Fan	Hybrid Turbine Blade	Layer-glazed™ Disks	Composite Drum Rotor	Composite High Pressure Compressor Blade	Folded Burner
Thrust Specific Fuel Consumption (%)	-4.2	-2.2	-0.7	0	0	-0.3/+0.2
Weight (lbm)	+371	-265	-155	-104	-50	+51/+80
kg	168	120	70	47	22	23/ 36
Cost ($)	+95,000	+18,000	+16,000	+4,000	+5,000	+13,000/ +15,000
Maintenance Cost ($/EFH)	+2.87	+3.34	+2.01	+0.50	+1.25	-0.36/-0.26
Fuel Burned						
- Domestic (%)	-4.36	-2.69	-0.88	-0.10	-0.13	-0.67/-0.07
- International (%)	-4.91	-3.02	-0.99	-0.11	-0.15	-0.78/-0.09
Direct Operating Cost + Interest						
- Domestic (%)	-1.53	-1.13	-0.27	-0.03	-0.02	-0.41/-0.09
- International (%)	-2.19	-1.49	-0.40	-0.04	-0.04	-0.50/-0.11

3.6 Risk Assessment Method

The probability of success for each advanced concept was assessed using a quantitative analytical procedure developed for this purpose by Pratt & Whitney Aircraft. A degree of risk was assigned to the six factors in Table 6.

TABLE 6
CONCEPT RISK ASSESSMENT METHOD

		Degree of Risk		
		A	B	C
Primary Factors				
State of the Art	1.	Traditional	Advanced	Revolutionary
Design Approach	2.	Traditional	Advanced	Revolutionary
Fabrication Process	3.	Traditional	Advanced	Revolutionary
Present Status	4.	Production Feasibility	Component Feasibility	Laboratory Feasibility
Secondary Factors				
Alternate Approaches	5.	Three or More	Two	One
Nature of Concept	6.	Static/ Low Stress	Static/ High Stress	Rotating

Overall probabilities were defined in terms of the following categories:

- o Very High 90%
- o High 75%
- o Medium 50%
- o Low 25%
- o Very Low 0-10%

These factors were combined quantitatively as shown in Table 7 to determine the overall probability of success for each concept.

TABLE 7
EVALUATION FACTOR QUANTIFICATION
METHODOLOGY FOR RISK

1) BASELINE RISK (PRIMARY FACTORS 1-4)

FACTOR EVALUATION	PROBABILITY OF SUCCESS LEVELS
(4A's) or (3A's + 1B).	90%
(3A's + 1C), (1A + 3B's), (2A's + 2B's), or (2A's + 1B + 1C)	75%
(4B's), (3B's + 1C), (1A + 3C's), (2B's + 2C's), (2A's + 2C's), (1A + 2B's + 1C), or (1A + 1B + 2C's).	50%
(4C's) or (1B + 3C's).	25%

2) BASELINE RISK REFINEMENT FOR SCORES OF 25% OR THREE PRIMARY FACTORS = C (SECONDARY FACTORS 5 AND 6)

FACTOR EVALUATION	SUCCESS LEVELS
(2A'S) or (1A + 1B).	Probability remains at same level
(2B'S), (1A + 1C), or (1B + 1C).	Reduce probability 1 level*
(2C'S).	Reduce probability 2 levels*

*Probability of success levels below 25% are either 10% or 0%.

3.7 Risk Assessment Results

The risk assessment method yielded the results shown in Table 8.

3.8 Selection of Concepts for Further Evaluation

The results of the risk and benefit assessments were combined to rank the advanced concepts. The results of these assessments are summarized in Table 9. It can be clearly noted that the benefits for the first three concepts are considerably greater than the last ones. Therefore, the geared fan, hybrid turbine blade and Layerglazed™ disk were selected for further study.

TABLE 8
ADVANCED CONCEPT PROBABILITY OF SUCCESS

Degree of Risk	Geared Fan	Hybrid Turbine Blade	Layer-glazed™ Disks	Composite Drum Rotor	Composite High Pressure Compressor Blade	Folded Burner
State of the Art	B	C	C	B	B	A
Design Approach	B	B	B	B	B	B
Fabrication Process	A	C	B	B	B	A
Present Status	B	B	C	B	B	A
Alternate Approaches	C	B	B	B	B	A
Nature of Concept	C	C	C	C	C	A
Probability of Success (%)	75	50	50	50	50	90

TABLE 9
CONCEPT BENEFIT/RISK RANKING

Concept	Change in Thrust Specific Fuel Consumption (Percent)	Change in International Direct Operating Cost Plus Interest (Percent)	Probability of Success (Percent)
Geared Fan	-4.2	-2.19	75
Hybrid Turbine Blade	-2.2	-1.49	50
Layerglazed™ Disks	-0.7	-0.40	50
Composite Drum Rotor	0	-0.04	50
Composite High Pressure Compressor Blade	0	-0.04	50
Folded Burner	-0.3/+0.2	-0.50/-0.11	90

4.0 REQUISITE TECHNOLOGIES

Overview

Considerable advances in the stage of the art will be required for a wide range of technologies to develop the three advanced concepts selected. These requirements comply with the programs objective which was to identify advanced technologies beneficial to future aircraft operations. The benefits were quantitatively assessed in the previous section. These assessments provide a major advantage over conventional planning for technology developments where benefits can usually be qualitatively estimated.

Concurrent analytic, fabrication and test technology developments will be required. To show the relationship of these technologies to each other and to each advanced concepts, overall development schedules were prepared. Nominally, technology development descriptions apply to the individual advanced concepts. However, generic developments are the primary objectives. The programs were designed to provide basic and fundamental understanding of each technical discipline. This approach was essential to solve the high technology problems for each advanced concept. Thus, the technology developments described in the following sections are with almost no exception generic and are not restricted to the applicable concept.

The format used to outline the technology developments accomodates the requirement of showing their context with the advance concept and their generic nature. Overall development schedules show the context. Self sufficient description of each requisite technology can be used out of context with the advanced concept thus indicating their generic nature. The technology descriptions provide individual objectives, current state of the art, technical problems and schedules. The basic knowledge obtained will be generically applicable to a wide range of future high technology engine developments. Since the first year is critical to long range development programs, the first year plan is described in greater detail where required.

4.1 Geared Fan

4.1.1 Program Objective

The objective of the geared fan program is to develop the technology required to design a 99.5% efficient, 29,828 kW (40,000 horsepower) fan drive reduction gearbox system suitable for aircraft engine application.

4.1.2 State of the Art

Geared fan aircraft engines have been developed and are in commercial service. However, these engines are about an order of magnitude smaller than required for this program and have considerably lower efficiencies. To achieve the goals of this program further advances in the state of the art in gearbox and bearing technologies are required.

4.1.3 Technical Problems

Gearbox - Constructing an aircraft engine gearbox of greater power capability and increased size than those presently in commercial service will present problems in the extrapolation of current design and manufacturing criteria. The high power levels will also impose structural deflections that must be accommodated to permit gear and bearing load sharing and alignment control to maximize reliability. Often, the same factors that maximize structural integrity and mechanical reliability tend to be in conflict with transmission efficiency goals. A concentrated effort will therefore be required to achieve the reliability and efficiency goals.

Reducing frictional losses, or increasing efficiency beyond the current state of the art presents certain technical problems. For example, gear tooth contact sliding speed must be minimized without seriously impacting load capacity. Oil churning and scavenge losses must be minimized in spite of a need to operate at higher gear and bearing pitch line speeds. Innovative approaches must be explored to separate the lubrication function from cooling to reduce viscous oil shearing losses.

Bearings - Critical to the durability of the gearbox is the fatigue life of the pinion support cylindrical roller bearings. Data is not currently available for such bearings that are heavily loaded, designed with outer races integral with the gear, and operating in 93 °C (200°F) Type I, Type II, or advanced 204 °C (400°F) engine oil. The angular contact ball bearing supporting the fan is also critical to the durability of the power gearbox system. This bearing must operate at thrust levels in excess of those experienced in state of the art turbofan low pressure rotor applications. Meeting these requirements will necessitate use of unusual combinations of larger contact angles, increased ball sizes and tightened raceway curvatures. Appropriate rig test programs are to be conducted to investigate these pinion roller bearing and fan ball bearing problems and to provide necessary design data.

4.1.4 Program Approach

The approach required to develop the geared fan is outlined in the schedule shown in Figure 14. A description of the development plan and milestones is given below.

Heat Generation and Dissipation Model

State of the Art Model - Initially, the current capability of the industry to predict heat generation in reduction gearing will be updated consistent with the increased speed requirements of the subject program. This will include gear tooth and bearing friction and viscous shear modeling. This model will also deal with the fluid mechanics of the oil flow as it departs the various gear meshes and bearings, travels to the scavenge outlets and to the pumps taking into account viscous drag and churning effects. In addition, a simplified heat generation dissipation or thermal model representing the current state of the art will be defined to permit prediction of component operating temperatures and thermal gradients. These heat generation and dissipation state of the art models will be defined for the conventional jet oiling and scavenging system.

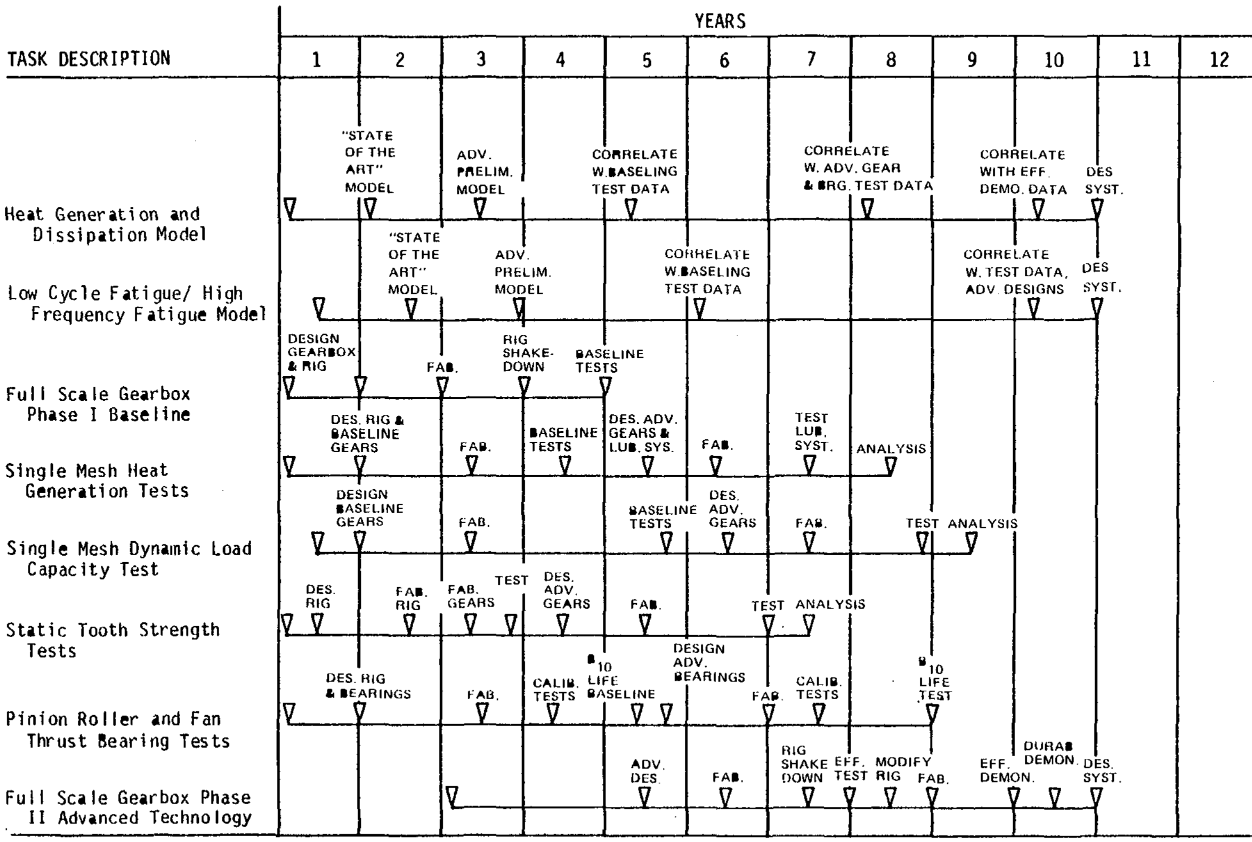

Figure 14 Geared Fan Development Program.

Advanced Preliminary Model - The gear tooth and bearing friction models will be improved through incorporation of the latest advances in the understanding of elastrohydrodynamics. Models will be developed for advanced concepts such as pulse jet oiling and integral cooling of components via radial oil passages in the gear teeth and bearing inner races. The fluid drag and scavenge model will be developed to include an air circulation assist system, tangential scoop scavenging and compartment wall wipers. The thermal or dissipation models will be advanced accordingly to provide at least two dimensional capability for all the concepts referred to in the context of the advanced heat generation model mentioned above.

Correlate With Baseline Test Data - Data predicted by the heat generation and dissipation models for the conventional jet oiling and scavenge system will be compared to rig test data. Modifications will be made to the models, as necessary, to develop agreement with the experimental data.

Correlate With Data From Tests on Advanced Gears and Bearings - As data becomes available from advanced component rig tests the appropriate elements in the advanced heat generation and dissipation models will be correlated and upgraded to develop the necessary correspondence.

Correlate With Data From Efficiency Demonstration Test of Full Scale Gearbox - The gearbox heat generation and dissipation models will be used to predict the transmission efficiency of the full scale gearbox and the operating temperature of its components. This data will be compared to that obtained experimentally from the full scale demonstration rig test of the reduction gearbox. Modifications will then be made to the analytical models, as necessary, to provide satisfactory correlation with the observed test data.

Design System - The fully correlated advanced reduction gearbox analytical models for heat generation and dissipation will subsequently be integrated with the existing design system. This will provide a design optimization capability fully accounting for the influence of mechanical power transmission efficiency related parameters and associated temperature levels and thermal gradients of the gearbox and its components.

Low Cycle Fatigue/High Frequency Fatigue Model

State of the Art Model - Initially, the current capability of the industry to predict the dynamic behavior of gears relating to the high frequency fatigue characteristics of gear teeth and support structures will be evaluated consistent with the increased speed and power requirements of the subject program. Specific needs for improvement will be detailed and plans laid for realizing those improvements. In large, high speed gearboxes diametral and/or torsional mode resonance may be limiting. Analytical modeling of gear rings is needed to identify any trouble areas. Also, a simplified analysis will be developed for the large fan drive ring gear system focusing on thermally and dynamically induced stresses using state of the art low cycle fatigue modeling capability. If this study identifies potential low cycle fatigue related effects that should be considered in the gearbox design then a plan will be identified and detailed for realizing improvements in the low cycle fatigue model.

Advanced Preliminary Model - The plans to improve the high frequency fatigue and low cycle fatigue models, as identified in the State of the Art phase, will be executed. The following capabilities should be added to the state of the art model:

- o Effect of flexibility of pinion gear support system
- o Effect of tooth profile errors
- o Effect of tooth damping (model such concepts as transverse slot in tooth or gear rim filled with Coulomb damping material)
- o Dynamic model of multi-pinion star gear system (present analysis limited to multi-pinion planetary system)
- o Effect of bearing flexibility

Correlated With Baseline Test Data - Stress level and frequency data predicted by the high cycle fatigue/low cycle fatigue models will be compared to corresponding data obtained experimentally from both component rig and full scale gearbox tests. Modifications will be made to the models, as necessary, to develop reasonable agreement with the experimental data.

Correlated With Test Data From Advanced Designs - As stress and frequency data become available from both advanced component rig tests and full scale gearbox tests the advanced analytical models will be correlated and upgraded to develop a high degree of correspondence. High cycle fatigue life data will be acquired during the single gear mesh load capacity tests that will permit full correlation with the model. If the low cycle fatigue analytical studies indicate that this should be an area of concern to the design of the fan drive ring gear system then the test plan would be modified accordingly to allow experimental data to be obtained to adequately correlate the analytical model.

Design System - The fully correlated advanced reduction gearbox high cycle fatigue/low cycle fatigue analytical models will subsequently be integrated with the overall design system. This will provide a design capability fully accounting for the influence of high compressor fatigue/low compressor fatigue related parameters permitting rational compromises to be made with competing efficiency and weight factors for realization of an optimum gearbox configuration.

Full Scale Gearbox, Phase I - Baseline

Design - Apply existing technology to gearbox configuration use back-to-back loading system for rig design so drive system power need only be that required to cover mechanical losses.

Fabrication - Apply state of the art technology.

Rig shakedown - Assemble rig, mount on test stand, align with drive system and conduct rig and drive shakedown tests at low loads over the complete program speed range.

Baseline tests - conduct rig tests over the complete and speed and load range toward the target efficiency range of 98 to 99%.

Single Mesh Gear Heat Generation Tests

Design test rig and baseline gears - A new rig is required, for which the basic design exists. This is a four-square type of power recircular rig that can test a single gear mesh, star pinion and sun gear combination, sized and loaded to be identical to the corresponding gears in the full scale gearbox.

Fabricate - The rig will be built, including at least two sets of baseline test gears.

Baseline tests - After rig assembly and test stand shakedown, the baseline gears will be evaluated for mechanical efficiency by measuring heat generation over the complete program load and speed range.

Design advanced gears and lubrication systems - Promising concepts will be analytically screened and the most attractive will be selected for detail design. Concepts of note are: radial cooling passages integral with gear teeth to minimize total oil flow to the mesh, reducing heat generation, higher temperature lubricants, and improved gear materials permitting use of a smaller engine oil cooler, reducing associated losses.

Fabrication - Advanced gears may require advanced fabrication methods, including inspection and quality control improvements.

Test advanced gears and lubrication system - Each gear mesh concept fabricated will be tested to identify heat generation improvements, followed by similar tests on improved lubrication systems. Final tests will measure the heat generation of both gear and lubrication systems.

Analysis - Test data will be reduced, compared to baseline data and correlated with existing analytical models for later incorporation in the power gearbox design system.

Single Mesh Dynamic Load Capacity Tests

Design and fabricate baseline gears - These gears are the same star pinion and sun gear mesh design mentioned in the previous two sections and will be tested in the same rig described in the Single Mesh Heat Generation Test section.

Baseline tests - These tests will be integrated with the heat generation test schedule and will be conducted on up to four gear sets at increasing load until tooth surface scoring damage is noted.

Design advanced gears - Promising concepts will be analytically screened and the most attractive concepts detail designed. Concepts of note are: increased gear tooth contact ratio, buttress tooth shapes of unsymmetrical form, improved surface finish, hollow teeth, powder processing, and sputtered molybdenum disulfide coating.

Fabrication - Completion of this phase would involve the application of advanced methods of fabrication, inspection and quality control.

Test advanced gears - Each gear mesh concept fabricated will be tested to identify the increase in scoring load limits.

Analysis - Test data will be reduced, compared to baseline data and correlated with existing analytical models for later incorporation in the power gearbox design systems.

Static Tooth Strength Tests

Design rigs - A new, but simple static test rig will be designed for determining both ultimate and single direction cyclic fatigue strength of the full size pinion and sun gear teeth. A new rig will also be designed for evaluating the reverse bending fatigue strength of the full scale pinion gear teeth.

Fabrication - Gears for this program will be identical to other program baseline gears and will be fabricated with those for the heat generation and dynamic load capacity tests.

Baseline tests - Tests will be conducted on baseline gears over a range of increasing loads to assess the tooth bending strength characteristics; i.e., static strength limits, and one way and reversed bending cyclic fatigue strength limits.

Design advanced gears - Promising concepts will be analytically screened and the most attractive concepts detail designed. Concepts of note are: alternate materials, alternate concepts such as powder processing, alternate tooth shapes, and teeth with oil cooling passages.

Fabrication - Completion of this phase would involve the application of advanced methods of fabrication, inspection and quality control.

Test advanced gears - Each gear concept fabricated will be tested to identify improvements in bending strength characteristics.

Analysis - Test data will be reduced, compared to baseline data and correlated with existing analytical models for later incorporation in the power gearbox design system.

Pinion Roller and Fan Thrust Bearing Tests

Design test rigs and bearings - New rigs will be designed to test full scale bearing at engine loads and speeds and at endurance overload conditions. The baseline bearing designs will be those developed for the baseline gearbox.

Fabrication - Apply state of the art technology. Procure twenty of the pinion roller bearings for calibration and B_{10} life fatigue testing and two fan thrust bearings for calibration and durability testing.

Calibration tests - After rig assembly and test stand shakedown, the baseline roller and ball bearings will be calibrated by running tests over the complete range of anticipated engine loads, speeds, temperatures and oil flows; measuring thermal and structural performance. The fan thrust bearing will also be tested under loads equivalent to fan blade loss.

B_{10} life baseline test - The group of twenty pinion roller bearings will be subjected to steady state overload accelerated endurance tests to establish the B_{10} rolling contact fatigue life rating. One of the fan thrust bearings will be subjected to a 100 hour cyclic rated load and speed endurance rig test to establish minimum durability.

Design advanced bearings - Promising concepts for improved B_{10} life of the pinion roller bearing will be analytically screened and the most attractive of these will be detail designed. Concepts of note are: advanced higher temperature and corrosion resistant material alternates, powder processing, hollow ended rollers and molybdenum disulfide sputter coated raceways.

Fabrication - Complete fabrication will use the designated improved material and processing with the most advanced dimension and quality control specification available.

Calibration and B_{10} life tests advanced bearings - Thermal calibration rig tests will be conducted to assess operating temperatures, heat generation and wear performance followed by steady state B_{10} life tests in the lubricant and at the temperatures established in the design process. The B_{10} life improvement will be assessed by comparing results to the baseline tests.

Full Scale Gearbox, Phase II - Advanced Technology

Advanced design - Promising concepts for improving transmission efficiency, durability and structural integrity will be analytically screened in conjunction with similar effort conducted in the gearbox component programs. The most attractive configuration will then be detail designed for subsequent fabrication. Concepts of note are, in addition to those already mentioned for the gears and bearings: tangential discharge scoop scavenging for reduced oil churning and improved power transmission efficiency, and polygon splines for improved reliability potential.

Fabrication - Utilize related improved materials, processing, tolerance control and quality control specifications.

Rig shakedown - Assemble rig, mount on test stand and align and conduct rig shakedown tests at low loads over the program speed range.

Efficiency tests - With the gearbox loaded at equivalent sea level takeoff power levels and speeds, measure the losses by oil temperature and flow means in addition to measuring drive power. Conduct efficiency tests at all other load/speed points of interest.

Modify rig - After disassembly, rig component inspection and analysis of the data from the efficiency test, identify any deficiencies and provide design fixes to upgrade performance.

Fabricate fixes - Based on the design fixes, rework rig hardware and reassemble the rig for efficiency testing.

Efficiency demonstration - Run a complete operating point spectrum in the back-to-back test rig facility to demonstrate the improved power transmission efficiency of the upgraded advanced technology gearbox.

Durability demonstration - After partial disassembly of the rig to permit minor adjustments or modification for gear alignment etc., conduct a 150 hour durability demonstration at cyclic rated engine load and speed conditions. Disassemble, inspect and record results.

Design system - Upgrade the gearbox design analysis system by correlating the existing thermal and durability models with the operational and inspection data generated from testing the advanced technology program power reduction gearbox.

Geared Fan First Year Program

The objective of the geared fan first year program is to develop component rig designs and a baseline technology 29,828 kW (40,000 horsepower) fan drive gearbox design with a target efficiency of 98 to 99%.

Figure 15 shows the first year schedule and is discussed below.

Full scale gearbox design - baseline state of the art

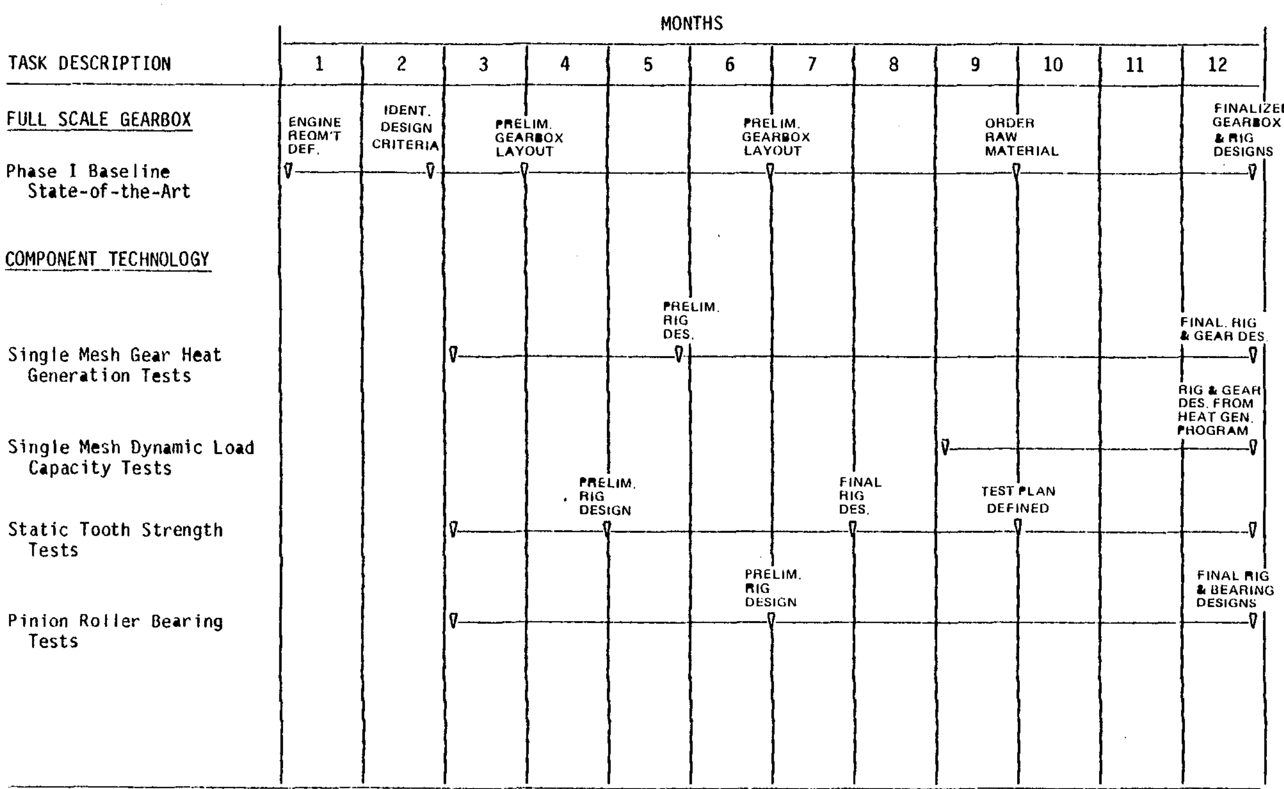

Figure 15 Geared Fan First Year Plan.

Identify design criteria - Overall power gearbox and component design criteria will be established.

Preliminary Gearbox Layout - The gearbox design layout will be defined sufficiently so that preparation of material requirements type and quantities can begin and rig layout work can proceed.

Preliminary Test Rig Layout - The back-to-back load regenerative full scale gearbox test rig layout will be defined sufficiently by so that raw material orders can be prepared.

Order raw material - Placement of all material orders will allow adequate lead time to satisfy second year finished hardware procurement schedules.

Finalize gearbox and rig designs - The design layouts of both the baseline, current stage of the art fan drive gearbox and the associated test rig will be completed.

Component technology rigs & testing

Single mesh gear heat generation tests - The regeneratively loaded four-square rig for testing a single pinion mating with the sun gear will be subjected to preliminary design to permit ordering raw material by the 9th month. This will be followed by definition of the test plan and finalization of the rig and gear designs by year's end.

Single mesh dynamic load capacity tests - This component program will use the same test rig as the one used in the heat generation program. The test gear raw material and test plan definition schedule will, as a result, also be the same as for the heat generation program.

Static tooth strength tests - The test gears and the two rigs for this program, to test gear teeth ultimate strength and one way and two way bending strength, will be designed sufficiently to permit ordering of raw material by the 6th month. The rig designs will be completed by the 8th month and the test plan by the 10th.

Pinion roller and fan ball bearing tests - The bearing rigs will be designed in sufficient detail to allow raw material to be ordered by the 9th month. Enough material will be ordered for two roller bearing rig and one ball bearing rig. The test plan will then be defined and the test bearing and rig designs will be finalized by year's end.

4.2 Hybrid Turbine Blade

4.2.1 Program Objective

To develop an advanced turbine blade which relative to current turbine blades is stronger, lighter, can sustain higher temperatures, and incorporates improved internal cooling.

4.2.2 State of the Art

High technology aircraft engine turbine blades are operating reliably in extremely high stress and high temperature environments. They are made from advanced superalloys which are cast into equiaxed or columnar grain structures. Two piece constructions, bonded by Transient Liquid Phase (TLP[R]) bonds have been developed. High temperature capability is enhanced by sophisticated cooling arrangements which include multi-pass internal cooling, film cooling, and coatings.

4.2.3 Technical Problems

Several important technical problems must be solved to develop the hybrid turbine blade. These are discussed individually in the sections describing the advanced technologies required. These are: life prediction analyses, flutter analysis, the silicon carbide platform, casting, bonding and coating.

4.2.4 Program Approach

Turbine Blade Life Prediction

Objective: To develop analysis capabilities to determine the thermomechanical fatigue life and defect sensitivity of an advanced turbine blade. The analysis shall apply to multipiece constructions, such as a spar and shell geometry.

Objective

The current state of the art life prediction analysis for monolithic equiaxed or columnar grained superalloy turbine blades is based upon the results of subcomponent testing and an evaluation of accumulated service experience.

Turbine blade life prediction state of the art

The current state of the art life prediction analysis for monolithic equiaxed or columnar grained superalloy turbine blades is based upon the results of subcomponent testing and an evaluation of accumulated service experience.

Turbine blade life prediction technical problems

The fabricated spar and shell turbine blade will consist of a high strength equiaxed or single crystal root and spar bonded to a single crystal oxidation resistant outer shell overlayed with a thermal barrier coating. Spherical or transverse isotropy associated with the equiaxed or directionally solidified turbine blades is no longer present The elastic, inelastic, fatigue and fracture mechanics characteristics of the single crystal alloys are highly anisotropic and must be fully characterized. Crystal orientation mismatch and/or fitup problems can create very intense local secondary stresses at the bond interface resulting in premature bond failure. Calculation procedures for establishing the magnitude of these stresses and the durability of the bond are required. The criticality of bond line defects on component performance must be established through analysis and test. A durable and dimensionally stable coating is required to assure adequate hot corrosion life. Local thinning of the coating due to viscoelastic instabilities or coating cracking must be prevented through effective design and analysis.

Turbine blade life prediction approach

A four part analytical effort is proposed to develop life prediction techniques essential for development of the hybrid turbine blade concept. The required developments are briefly detailed below and presented in Figure 16.

o Fatigue initiation criteria for single crystal material

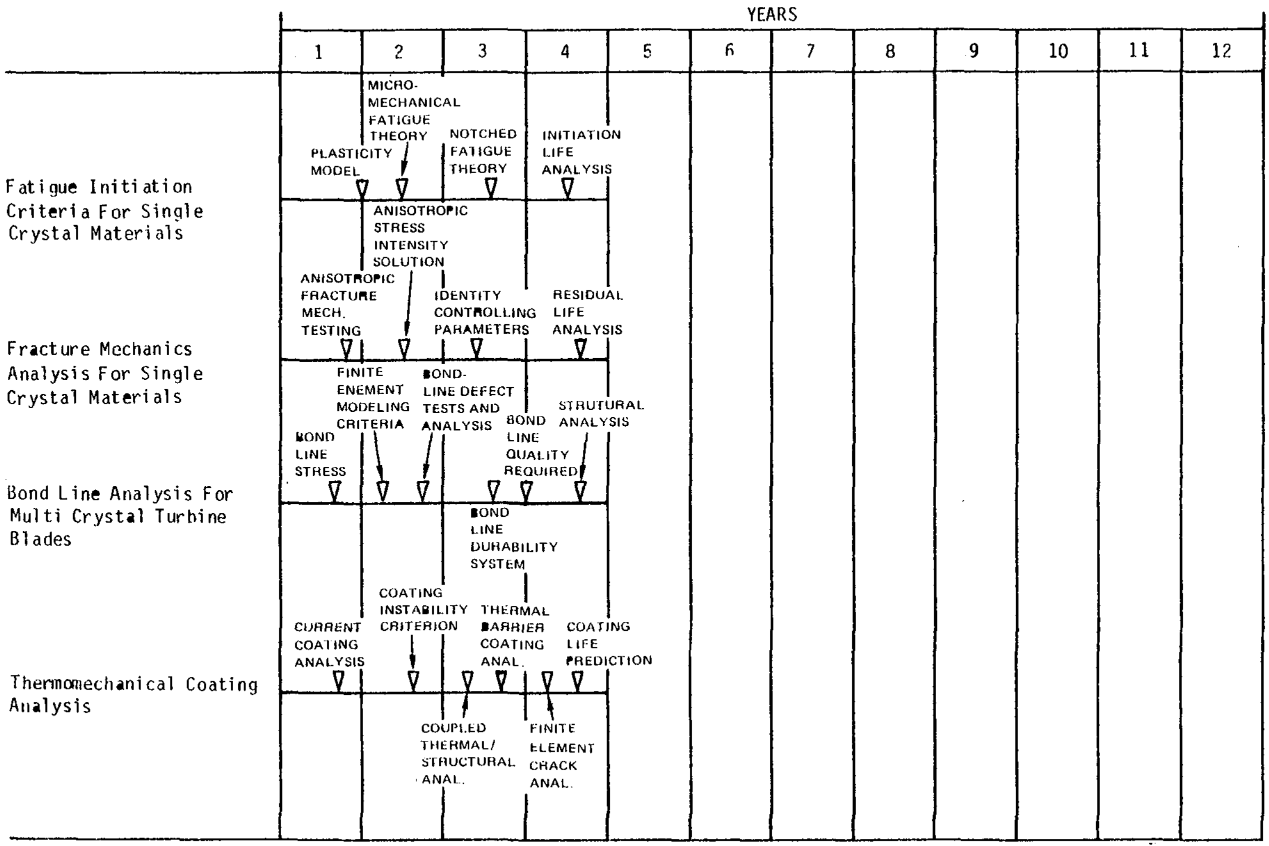

Figure 16 Hybrid Turbine Blade Life Prediction Techniques Development Program.

Plasticity Model - Determines the effect of crystal orientation and stress state (plane strain to plane stress) on the cyclic constitutive behavior of the alloy. Incorporate a constitutive model for the single crystal alloy in a nonlinear finite element code and evaluate local material behavior in the notched fatigue specimen.

Micromechanical Fatigue Theory - Conduct smooth stress and strain controlled fatigue testing to determine the influence of crystal orientation and specimen configuration on low cycle fatigue life. Determine the micromechanical parameters (critical resolved shear stress, slip strain, etc.) controlling the fatigue crack initiation life.

Notched Fatigue Theory - Conduct notched fatigue tests on plane strain and plane stress specimens to calibrate the low cycle fatigue life analysis. Identify the effect of strain gradients, surface preparation on fatigue durability.

Initiation Life Analysis - Calibrate the life prediction against full scale cyclic spin tests of an advanced turbine blade design.

- o Fracture mechanics analysis for single crystal materials

Anisotropic Fracture Mechanics Testing - Conduct smooth and notched crack growth tests to determine the influence of crystal orientation, specimen geometry, stress state (plane strain to plane stress), and bonding type (strain or stress controlled) on crack growth direction and growth rate.

Anisotropic Stress Intensity Solutions - Conduct finite element or boundary integral equation analysis to determine the effect of the crystal parameter on the significant fracture mechanics parameter such as stress intensity factor, strain intensity factor and crack opening displacements.

Identify Controlling Parameters - Determine through correlation of test data the parameters that control the direction and growth of fatigue cracks.

Residual Life Analysis - Conduct benchmark subcomponent tests and detailed structural analyses to determine the residual life of the component in the presence of single and two degree of freedom cracks and casting defects.

- o Bond line analysis for multi-crystal turbine blades

Bond Line Stress - Determine influence on bond interface stresses and strains of crystal orientation, load direction, stress state and component configuration using finite element or boundary integral equation analysis.

Finite Element Modeling Criteria - Conduct analytical studies to determine the appropriate finite element modeling criteria for the interface boundary of two or more anisotropic materials. The presence of misfit strains will be considered.

Bondline Defect Tests and Analysis - Conduct fatigue tests to determine the influence of crystal orientation, specimen geometry, stress state, load directions and load type on the behavior (direction and rate growth) of incomplete bond defects. Finite element, closed form, or boundary integral equation analysis will be performed to determine the effects of the above parameters on fracture.

Bond Line Durability System - Appropriate bond line durability analysis procedures will be developed based on concurrent test and analytic developments.

Bond Line Quality Requirements - Bond line quality requirements will be based upon the evaluation of bond line defect tests using anisotropic fracture mechanics analysis developed in this program.

Structural Analysis - A structural analysis for complex bondline interface of anisotropic materials will be developed.

- o Thermomechanical coating analysis

Current Coating Analysis - Conduct thermoviscoelastic analysis of electron beam vapor deposited NiCoCrALY coating on a packed aluminide substrate to determine the influence of base metal behavior, coating thickness, and the gradation in composition on mechanical behavior during an engine cycle. Relate predicted behavior to the development of coating cracks and/or debonding observed in specimen and engine testing.

Coating Instability Criterion - Develop an understanding of the mechanisms that give rise to dimensional instabilities in the coating (rumpling) and subsequent loss of coating effectiveness.

Coupled Thermal/Structural Analysis - Conduct similar analysis and testing on the thermal barrier coating systems. Develop a combined thermal/thermovisco-elastic finite element analysis that can accurately predict the temperature variation through the blade wall and the influence of the mechanical stress/strain state on thermal conductivity (coupled thermal/structural analysis).

Thermal Barrier Coating Analysis - Determine the influence of base metal behavior, coating thickness, coating composition, etc., on the coating stress/strain behavior during a duty cycle.

Finite Element Crack Analysis - Relate predicted behavior to the development of coating cracks and/or debonding observed in specimen tests.

Coating Life Prediction - Determine, through analysis and test, the conditions that result in propagation of the coating crack into the base metal and development of an analysis procedure for predicting the rate of growth of coating induced surface cracks into a structure subjected to a high thermal stress gradient.

Hybrid turbine blade life prediction first year program

Objective: To initiate the necessary material characterization, subcomponent testing, and analysis activity to understand the mechanisms influencing the initiation and propagation of fatigue and rupture cracks in bonded single crystal spar and shell turbine blades.

The following approach will be used to accomplish this objective.

- Fatigue initiation Criteria for Single Crystal Materials - Conduct cyclic strain controlled tests to determine the constitutive properties of the alloy as a function of orientation and temperature. Results are to be interpreted in terms of existent theories of slip and hardening in face centered cubic materials. Generalization to multiaxial stress states will follow.

  Conduct Smooth Strain and load controlled tests to determine the influence of crystal orientation on fatigue crack initiation life. Results are to be interpreted in terms of existing theories of fatigue for face centered cubic crystalline materials.

  Modify an existing nonlinear finite element code to incorporate the constitutive model for single crystal material.

- Fracture Mechanics Analysis for Single Crystal Materials Utilize existing finite element or boundary integral equation codes to determine the effect of crystal orientation on stress/ strain intensity solutions, strain energy release rates and crack opening displacements for relatively simple structural configurations; i.e., center cracked plates, edge cracked plates, two degree of freedom surface cracks in plates, subjected to bending and tension loading, cracks emanating from simple notches, etc.

  Conduct both smooth isothermal load controlled crack growth tests and smooth strain controlled thermomechanical crack growth tests to determine the effect of crystal orientation on the crack growth rate and direction of growth. Relate observed behavior to calculated fracture mechanics parameters.

  Initiate "bench mark" crack growth tests using more complicated, component relevant specimen/crack configurations including:

  - Two degree of freedom part through surface cracks in a plate subjected to cyclic load or strain controlled conditions. Similar testing in one way or fully reversed bending will follow.

  - One and two degree of freedom surface cracks emanating from side and center notches in a plate.

  - One degree of freedom through thickness cracks subjected to multi-mode stress and strain controlled loading.

  - One degree of freedom edge cracks subjected to a cyclic thermal stress that varies in the direction of the crack.

- Bond Line Analysis for Spar and Shell Turbine Blade - Conduct finite element or boundary integral equation analysis to establish the influence of crystal orientation (six parameters), and bond plane orientation (two parameters), on bond plane stresses and strains under general loading conditions. Consider simple geometrical situations in this study (bond separating half or quarter space, two intersecting bonds, etc.).

  Conduct analytical studies to determine appropriate finite element modeling criteria to properly represent bond interfaces and the presence of fitup strains in a full blade finite element analysis.

  Initiate simple tensile, creep, and fatigue tests to establish bond strength as a function of crystal orientations and loading conditions.

- Thermomechanical Coating Analysis - Conduct thermoviscoelastic finite element analysis of a state of the art coating/substrate combination to determine the influence of the base metal behavior, coating thickness, and gradation in composition on mechanical behavior in the coating during an engine duty cycle. Assume that the temperature is uniform across the entire structure, but varies with time.

  Initiate development of a coupled thermal/structural finite element analysis to facilitate analysis of a thermal barrier coating.

  Initiate simple material and subcomponent tests to determine parameters controlling initiation of coating debond, and cracking. Consider the current state of the art and advanced thermal barrier coating systems in this study.

Hybrid Turbine Blade Flutter Analysis

Objective

Develop a procedure for predicting flutter of high speed turbine stages with lightweight flexible blades and disks.

Hybrid turbine blade flutter analysis state of the art

Turbine stages have been observed to flutter during high tip speed operation. The general characteristics of the flutter are predictable by a stability analysis which interacts the natural modes of structural vibration with an unsteady aerodynamic analysis derived from incompressible flow theory. But comparative analysis of several stages which fluttered and other stages which did not flutter shows that critical conditions are not accurately predicted. A non-dimensional parameter, reduced velocity has been used with greater success to predict shroudless blade flutter. Reduced velocity is the flow exit velocity relative to the rotor stage divided by the product of chord and lowest mode natural frequency. It was observed that below an empirically derived critical value of reduced velocity flutter does not occur. New shroudless turbine stages are, therefore designed to have their reduced velocities lower than this critical value.

Hybrid turbine blade flutter analysis technical problems

Hybrid turbine blade construction provides a performance benefit because more efficient construction permits operation at higher tip speeds. Higher tip speeds will generally be accomplished by higher Mach numbers, with a greater portion of the passage containing supersonic relative flow. Chords for blades operating in these conditions may be limited by the requirement that they can not be permitted to flutter. Fan flutter has been more accurately predicted than turbine flutter and is known to be very sensitive to changes in velocity which represent a transition from subsonic to partially supersonic flow. Therefore it is probable that the current critical reduced velocity criteria for flutter stability evaluation will not provide a reliable basis for high speed turbine stage design. Current procedures for engine stage flutter analysis recognize that unsteady aerodynamic load acting on a vibrating blade control its stability but assume that the critical mode of vibration will be a natural mode of the structure in a vacuum. Turbine blade flutter correlation experience indicates that the critical unsteady aerodynamic load is applied near the trailing edge. Reactions to this load induce chordwise bending and spanwise torsional moments. Deformations caused by these moments are directly proportional to hollow airfoil wall thickness. Hybrid construction turbine blades will have thinner walls than current cooled blades and will therefore experience more aerodynamic load induced deformation and trailing edge motion in the flutter mode. Therefore, a more comprehensive flutter analysis method is required to design the hybrid turbine blade because the critical mode may be significantly different than a natural model of vibration of the stage in a vacuum.

Hybrid turbine blade flutter analysis approach

The Euler differential equations define aerodynamic systems where flow is partially subsonic and partially supersonic. These equations have been solved numerically to successfully simulate the steady aerodynamics of a high speed turbine stage. This model can be linearly perturbed to provide a description of an unsteady compressible aerodynamics system. Unsteady boundary conditions describing airfoil surface velocity, shock motion and axial wave propagation can be written to complete the definition of vibrating cascade aerodynamics. Numerical procedures for solving these equations to find unsteady pressures on the airfoil surface are cumbersome but a time marching technique shows considerable promise. Analyses of strips at several radii can be combined with an air load sensitive blade structural dynamics model to form a system of homogeneous equations having determinable complex eigen values. The real parts are the responsive frequencies of the aeroelastic stage and the imaginary parts are levels of aerodynamic damping. The sign of the lowest difference between aerodynamic damping and inherent structural damping is indicative of stage stability. Specifically, the development program (Figure 17) will include:

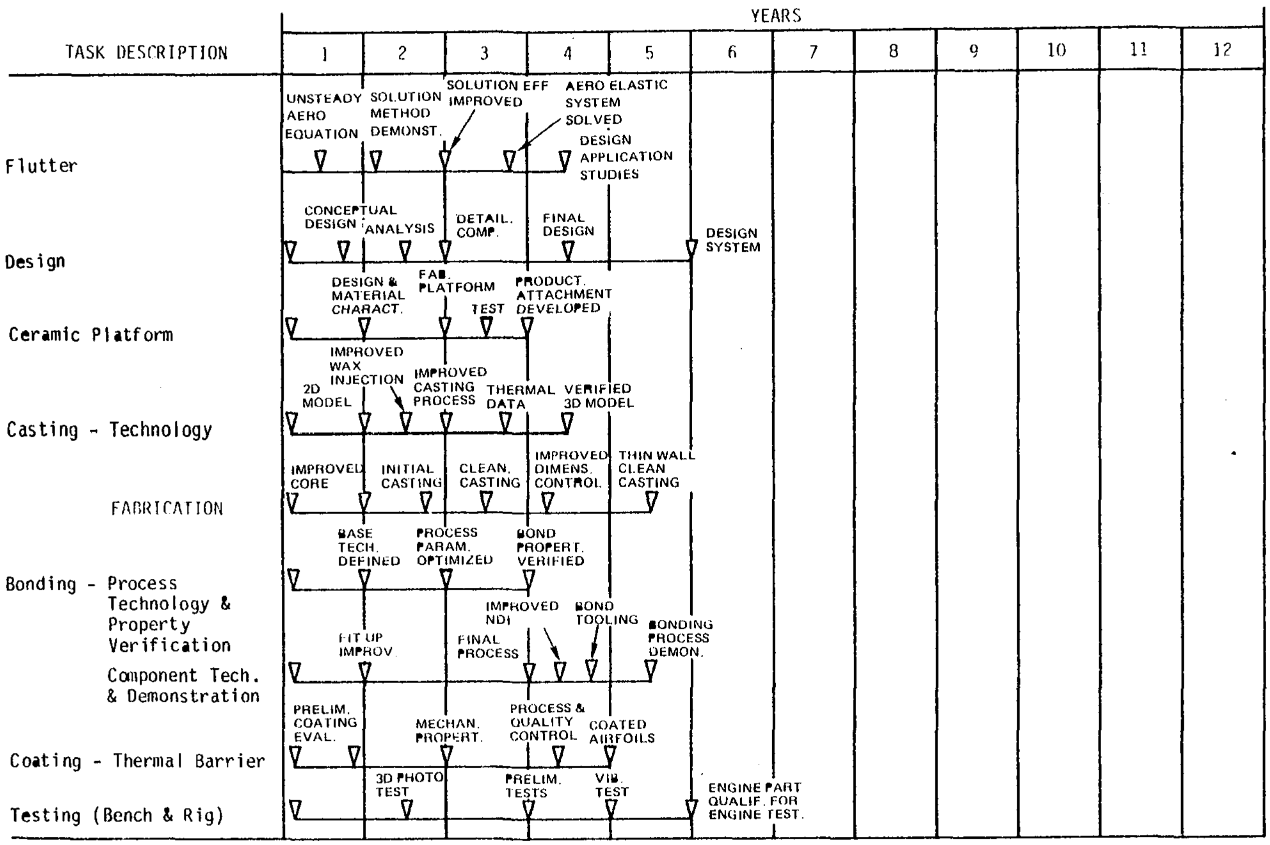

Figure 17 Hybrid Turbine Blade Development Program.

Unsteady Aerodynamic Equations - Equations defining the unsteady aerodynamic characteristics and boundary conditions will be written and the solution technique will be outlined.

Solution Methods Demonstrated - The aerodynamic solution procedure will be programmed, debugged and substantiated by application to known limit cases.

Solution Efficiency Improved - Techniques for improving solution efficiency will be investigated and incorporated in the computer program.

Aeroelastic System Solved - An expanded computer program will be developed to find the eigen values of a system including the unsteady aerodynamic equations and interactive structural dynamic equations.

Design Application Studies - Application studies will be conducted to demonstrate the sensitivity of stage aeroelastic stability to advanced design parameters.

Hybrid Turbine Blade Ceramic Platform

Objective

To develop a ceramic platform suitable for advanced high technology turbine blades.

Hybrid turbine blade ceramic platform state of the art

Silicon carbide reinforced glasses have been developed with exceptional performance characteristics. They exhibit high strengths, high fracture toughness, oxidation stability and low density. Specifically:

- Bend strength over 689,480 KPa (100,000 psi) at 1,000 °C (1832 °F)
- Excellent creep properties to 1,093 °C (2000 °F)
- High fracture toughness and impact resistance at 1,000 °C (1832 °F) (K_{1C} = 385,279 KPa-cm $^{1/2}$ (22,000 psi-in. $^{1/2}$))
- Densities less than one third that of superalloys 2.5 g/cc (0.09 lbs/in^3)
- Low thermal expansion 5.4 x 10 $^{-6}$ cm/°C (1.2 x 10^{-6} in/°F)

Hybrid turbine blade ceramic platform technical problems

The replacement of current state of the art nickel or cobalt superalloy blades with a spar and shell hybrid turbine blade that has a separately formed platform of a lightweight ceramic composite material represents a significant technical challenge. The recently developed COMPGLAS™ material consisting of silicon carbide fiber reinforced lithium aluminosilicate (LAS) glass-ceramic appears to be ideal for this application, assuming that certain chemical, mechanical, and processing conditions can be properly assessed. Such material properties as chemical interaction between the COMPGLAS™ platform and superalloy blade must be studied as well as fretting fatigue and wear characteristics of the composite rubbing on the superalloy. The problem of fabricating the COMPGLAS™ platform with the fibers in the correct orientation and the attachment of this platform to the superalloy blade must be investigated. And finally, the platform/blade combination must be rig tested in gas turbine environment before the actual use of this material in an engine can be considered.

Hybrid turbine blade ceramic platform approach

A new composite material COMPGLAS™ which consist of silicon carbon fiber reinforced lithium aluminosilicate (LAS) will be developed for this application. Specifically, the development effort (Figure 17) will include:

Preliminary design and material characterization, as outlined in the "First Year Program" description that follows in Figure 18.

Fabrication of model platform - Investigate fabrication process, fiber orientation (unidirectional, cross-plied, or chopped form randomly oriented), and heat treatment.

Testing - Material strength properties, vibration, wear due to fretting, reaction with nickel based superalloys and thermal properties.

Attachment - Final attachment procedure for fabricating the platform around the blade. Some techniques to be investigated include hot pressing the fiber plus glass powder around the superalloy blade in one step, or fabricating sections of the platform separately and pressing into place. Optimum clearance between the low expansion platform and high expansion blade will also be determined.

Hybrid turbine blade ceramic platform first year program

The objective of the ceramic platform first year program is to complete an initial evaluation phase shown in Figure 18 for developing a ceramic turbine blade platform. Specifically:

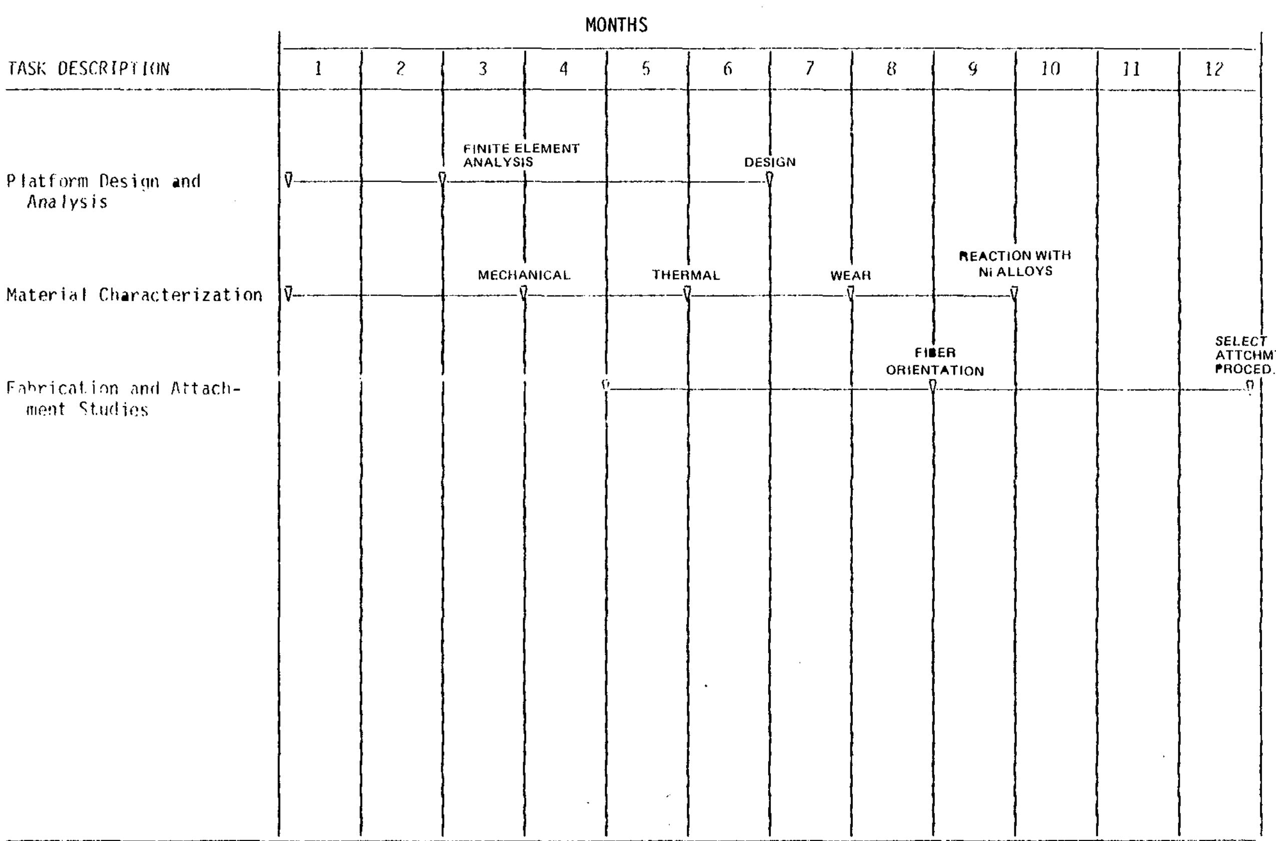

Figure 18 Hybrid Turbine Blade Ceramic Platform First Year Plan.

- Analysis and design

  Apply finite element analysis to the platform to determine the temperature and stress distribution.

  Design the platform - Determine the composite material construction and fabrication process which meet the physical constraints, stress and thermal requirements.

- Material characterization

  Mechanical properties - Strength, ductility, creep, impact, thermal expansion compatibility with nickel superalloy blade and wear due to vibration induced fretting.

  Reaction with nickel alloy - Silicon carbon reacts with nickel based alloys at elevated temperature. At the temperatures for this application reaction is not expected to be a problem but requires investigation.

Fabrication and attachment - Preliminary studies.

Hybrid Turbine Blade Casting

Objective

To develop fabrication capabilities which relative to current technology provide: decreased wall thickness, improved dimensional control, smoother surface finish and fewer oxide defects.

Hybrid turbine blade casting state of the art

The current state of the art of turbine blade castings provides: equiaxed grain structure, columnar grained superalloys, single crystal of near primary orientation and airfoil thickness 2.0 cm (0.80 in.) to 0.5 cm (0.20 in.) (the lower values are highly localized).

Hybrid turbine blade casting technical problems

For the hybrid turbine blade, an equiaxed or columnar grain spar will be designed to carry most of the centrifugal load, thus requiring high strength at relatively low temperatures. The outer shell will consist of a thin wall single crystal alloy selected for maximum oxidation resistance. This arrangement allows considerable alloy design flexibility. However, it will require significant advances in the state of the art of casting technology. For the spar, far greater dimensional control will be required which requires substantial improvement of the traditional ceramic shell mold process. For the outer shell, advances in wax injection technology, dimensional control and master melt cleanliness are required.

Hybrid turbine blade casting approach

While considerable sophistication has been achieved in casting aircraft engine turbine blades, further technological advances (Figure 17) are required for the hybrid turbine blade. These include;

- Casting technology

  Two dimensional models must be refined to better simulate directional solidification of simple shapes. This would include: cylindrical data, rectangular body thermal data, initial simulation and parameter adjustment.

  Improved wax injection procedure by increasing fill speed required. This will require: improved venting, temperature control, pressure control, local die chills, improved core holding, and analytic development of the fluid dynamics of incoming wax.

  Casting cycle process improvements are required such as: lower mold temperature for decreased distortion, improved control of hot zone heat flow, improved control of solidification process.

  Thermal data is required from complex bodies such as: section size changes, multiple bodies, non-axisymmetric shapes, and internal vs. external.

  Verification of a three dimensinal computer simulation model involves: formulating a working model, selecting appropriate process and material parameters, running trial cases and adjusting poorly known parameters to match thermal data.

- Casting fabrication

  An improved core technology will involve the study of options such as: improved core materials, advanced pinning methods, core print closure, and core design beyond the component.

  Initial castings would provide a baseline for: dimensions, crystal quality, and cleanliness.

  Cleaner castings can be obtained via: improved defect detection, improved ingot production, and improved casting processing.

  Improved ceramic molds for better dimensional control can be obtained by improved material, better particle size distribution, firing cycle, drying conditions, obtaining balance between prime coat mobility and back up coat strength, thinner molds, and stronger molds.

Thin walled clean single crystal castings should be obtained by a combination of: improved, analysis, improved design, and improved processing.

Hybrid turbine blade casting first year program

The objective of the hybrid turbine blade casting first year program is to determine the fundamental approach to significant anticipated casting problems associated with the dimensional control and cleanliness of thin walled single crystal airfoils.

The following approach (Figure 19) would be used for the first year program.

- Technology baseline

  Cylindrical simulation trials would vary such parameters as: mold thickness, thermal conductivity, hot zone temperature, withdrawal rate, emissivity, and diameter.

  Rectangular simulation would address: transverse aspect ratio, size/rate effects, and interface curvature.

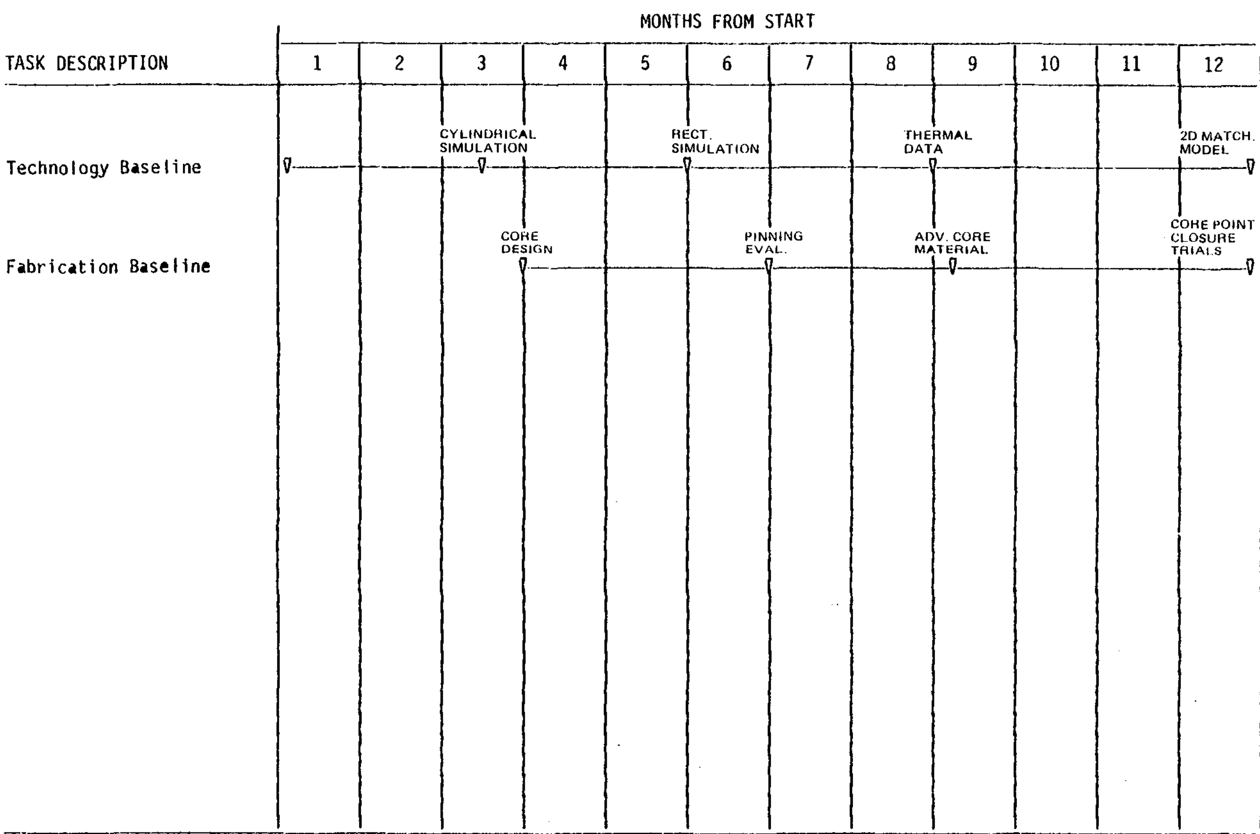

Figure 19 Hybrid Turbine Blade Casting First Year Program.

Thermal data are required on: cylinders, rectangular molds, internal vs. external, and cooling chamber boundary conditions.

A matched two dimensional model would fine tune hot zone profiles, emissivity, and heat transfer coefficients.

- Fabrication baseline

Core design studies would encompass holes in flash beyond part, and braces for additional rigidity.

Core pin studies would incorporate various angles sizes, and shapes.

Advanced core material would be evaluated by sag tests, reactivity tests, leaching tests, and castability evaluation.

Core print closure trials would cover: exit hole design, welding methods, and various filler alloys.

Hybrid Turbine Blade Bonding

Objective

To develop the joining technology required to fabricate advanced multipiece, single crystal turbine blades.

Hybrid turbine blade bonding state of the art

Joining of two piece turbine blades with relatively simple bond planes can be accomplished with TLP^R bonding. Bond tooling for columnar grain blades and process parameters have been established and substantiated, and are near production readiness.

Hybrid turbine blade bonding technical problems

A spar and shell single crystal high pressure turbine blade concept will require substantial advances beyond the current state of the art of superalloy bonding technology, both in basic TLP^R bonding process definition and in component processing optimization. This type of blade configuration presents significantly more difficult bonding problems than current two-piece blades due primarily to the multi-piece construction and the resultant complex bond plane. Thus, bond surface fit-up of the hybrid turbine blade, which is essential to successful bonding, is more difficult to achieve directly by casting. Developments in the areas of pre-bond processing and bond tooling to enhance the fit-up will be therefore required. Also, as a result of the multiple internal bonds, bond inspection is more difficult, requiring fully optimized bonding parameterss, compatible with the selected blade materials and more tolerant of fit-up problems. Improved bond inspection methods along with a carefully controlled, optimized process parameters and bond property characterization will be necessary to assure bond integrity.

Hybrid turbine blade bonding approach

The joining technology for advanced multi-piece turbine blade design requires advances beyond the state of the art in several important disciplines shown in Figure 17. Specifically these include:

- Process technology and property verification

  Base Bond Technology Definition - Define temperature range for selected blade alloys including effects of temperature on base alloy strength, isothermal solidification rates, recrystallization, interaction and boron level. Define bond parameter approach including interlayer compositions, multiple bond cycles, pre-bond cleaning methods, and methods of improving tolerance to fit-up and misorientation.

  Process parameter optimization: bond temperature, cycle time, cycle sequences, interlayer composition for fit-up and misorientation tolerances, pre-bond cleaning method and preliminary bore property screening.

  Bond property verification: bond mechanical properties (creep, tensile, thermal fatigue), bond coatability oxidation, hot corrosion, bond cycle/process effects on base alloys, effects of misorientation, and effects of poor fit-up.

- Component technology and demonstration

  Fit-up improvement: bond temperature effect on fit-up ,HIP bonding, Co-EDM, and candidate die materials.

  Final process methods optimization which include bond fit-up improvement methods selection, tooling concepts, definition of design requirements, and detail alignment methods.

  Improved non-destruction inspection (NDI) methods: survey of current methods, define candidate methods for multipiece blade including methods for internal bonds, improve bond visibility to NDI methods, and demonstrate NDI methods on components.

  Bond tooling: design and fabricate tooling for actual component demonstration.

  Bonding process demonstration: demonstrate optimized processing on actual components, evaluate process reproducibility.

Hybrid turbine blade bonding first year program

The objective of the hybrid turbine blade bonding first year program is to define the general TLP bond processing approaches required to fabricate an advanced multi-piece single crystal turbine blade including bond process parameters, approach to improving bond fit-up, and NDI methods.

The following approach (Figure 20) will be used for the first year program.

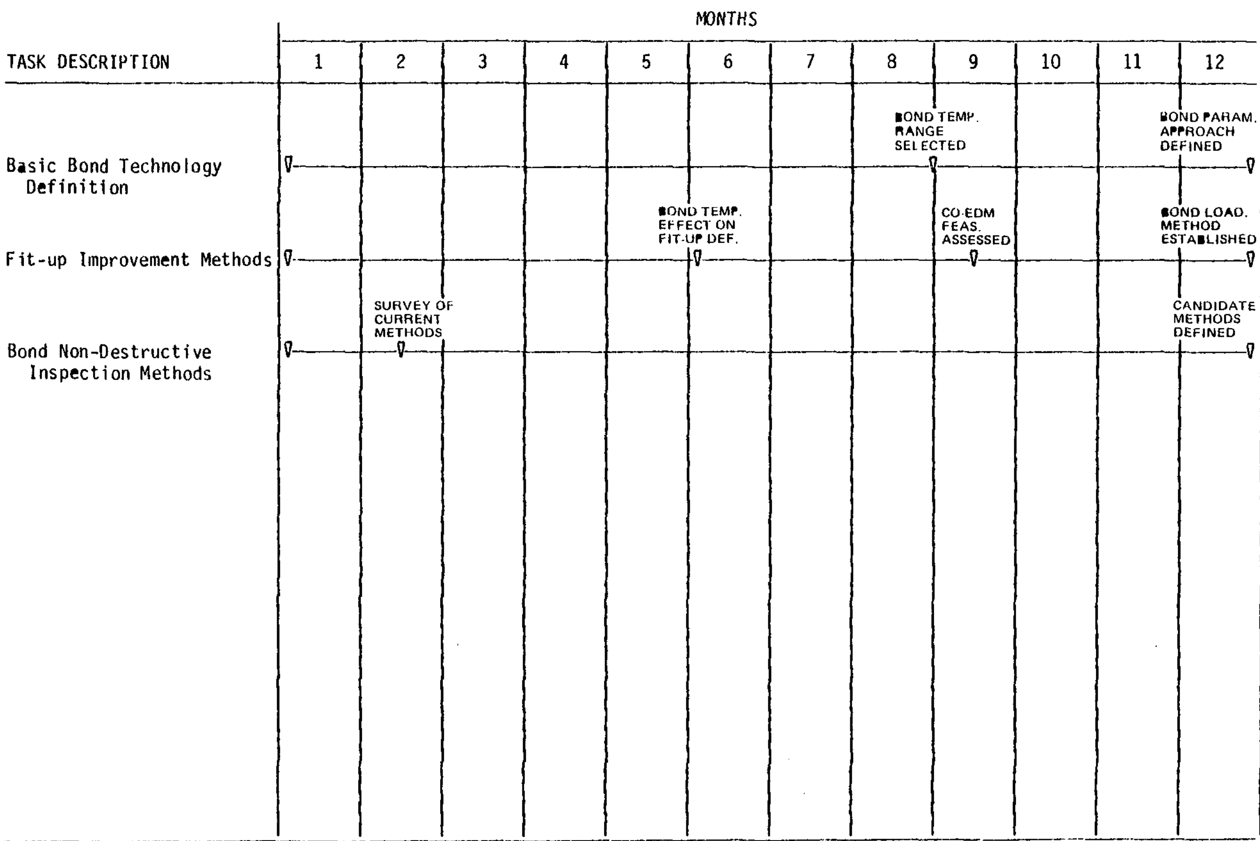

Figure 20 Hybrid Turbine Blade Bonding First Year Plan.

- o Basic bond technology definition

  Bond temperature range selection - Effects of temperature on isothermal solidification, compatability with selected blade materials, temperature vs. alloy strength, temperature effects on recrystallization, temperature vs. die/alloy interaction, diffusion zone characterization vs. temperature, and temperature vs. interlayer boron level.

  Bond parameter approach definition - Effects of interlayer alloy composition on isothermal solidification, microstructure and melting temperature, compatability with selected blade alloys, effect of multiple bond cycles, screening of candidate pre-bond cleaning methods, parameter approach to improve tolerance to fit-up, and approach to improve tolerance due to misorientation.

- Fit-up improvement

  Bond temperature effects on fit-up - Effects of temperatue on base alloy properties, and temperature vs. strain vs. recrystallization.

  Co-EDM feasibility: metal removal rates, effect of detail misallignment, and surface cleaning.

  Bond loading methods: HIP bonding, tooling, candidate die materials, parting agents, and internal support.

- Bond non-destructive inspection methods

  Survey current methods

  Define candidate methods for multi-piece blade - External bond inspection, internal bond inspection, crystallographic misorientation, thermally solidified structure, and approaches to bond visibility enhancement.

Hybrid Turbine Blade Coating

Objective

To develop and demonstrate a thermal barrier coating system for advanced turbine airfoils capable of reliably reducing metal temperature by 37 °C (100°F).

Hybrid turbine blade coating state of the art

Plasma sprayed ceramic thermal barrier coatings have been successfully developed to insulate combustor and after burners in gas turbine engines from the effects of thin high temperature environment. Thermal barrier coatings are at present not available for turbine blades and vanes. However, advanced segmented coatings, suitable for turbine airfoils, have been produced in the laboratory.

Hybrid turbine blade coating technical problems

Developing a suitable thermal barrier coating for turbine blades is considerably more difficult than for the current applications since the thermal gradients and dynamic loadings are more severe for turbine blades. In addition, reliability is a far more serious problem since failure of a turbine blade coating may result in a major engine failure. This requires considerable improvement in quality control and coating deposit reproducibility.

Hybrid turbine blade coating approach

In order to meet the high stress required for coating turbine airfoils applications the coatings will be made up of free standing columns which allow for free expansion and expansion in the plasma of the coating. This permits large stress with little effect on the ceramic columns. In order to develop this process for engine application the following developments (Figure 17) are required.

Coating evaluation - Candidate coating fabrication, spalling resistance - utilize a rapid Jet A fuel fired laboratory jet burner to simulate the turbine engine environment and oxidation erosion tests.

Mechanical property definitions- Physical properties, coating reduction durability versus temperature thickening and coated mechanical properties.

Process methods and quality control - Hardware process definition, post coat processes and quality assurance techniques.

Coated airfoil - Coating process developed for engine testing.

Hybrid Turbine Blade Three-Dimensional Photo-Elastic Investigation

Objective

To design, fabricate and test a three dimensional model of the hybrid turbine blade suitable to correlate test results with analyses.

Hybrid turbine blade three-dimensional photo-elastic investigation approach

Three-dimensional photo elastic stress freeze testing provides visual data of the entire stress field including locations ordinarily not accessible by other methods. This procedure will provide useful information during the initial phase of the hybrid turbine blade development program. Specifically, as shown in Figure 21, it will include:

Initial configuration definition of a plastic 3D model.

Analyses of the model which includes thermal, stress and vibration studies.

Fabrication of the model requiring developments of fabrication technology for making spar and shell construction.

Testing consisting of preliminary vibration tests and inducing centrifugal stresses in the 3D model.

Correlation of test results with analyses.

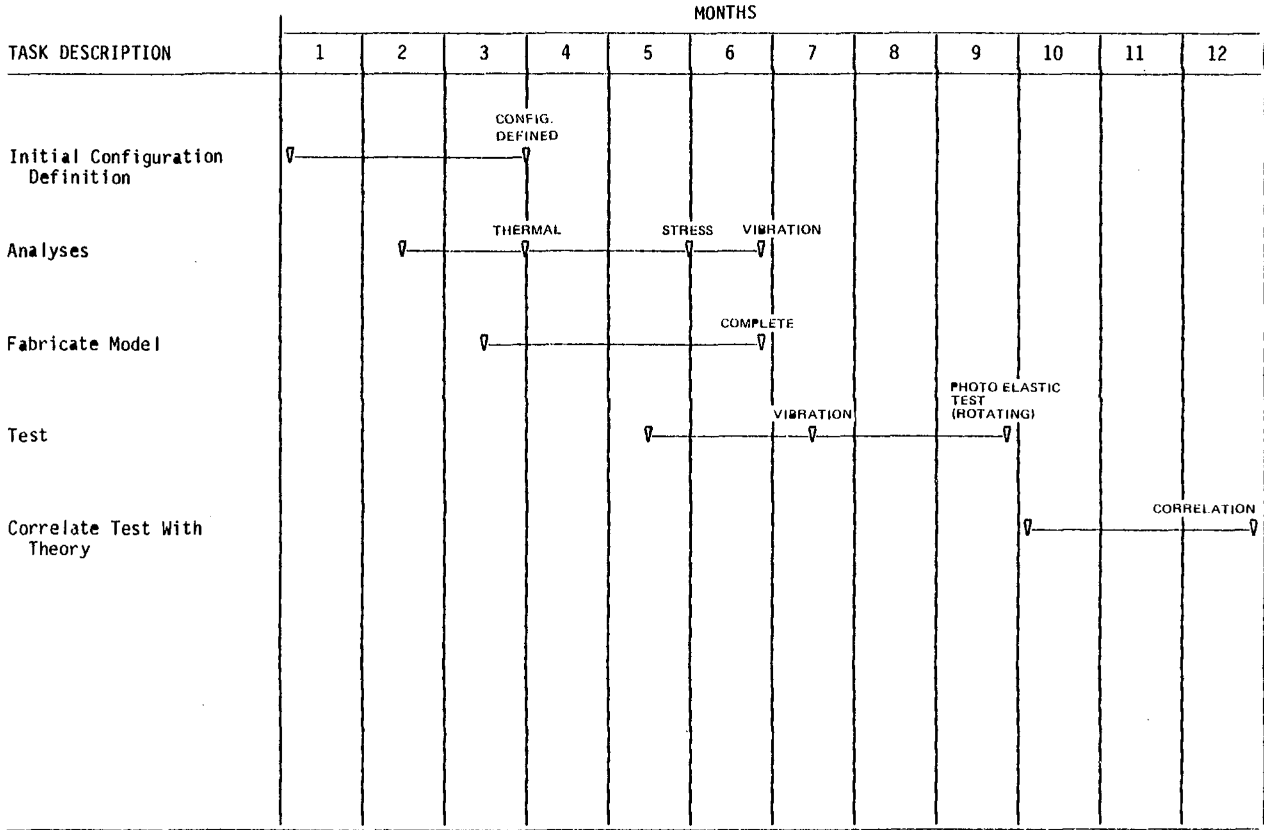

Figure 21 Three-Dimensional Photo Elastic Testing Methods Development Program.

4.3 Layerglazed™ Disk

4.3.1 Objectives

To produce aircraft engine disks having superior strength, ductility and fatigue resistance. This will be accomplished by: producing fine, homogeneous microstructures, eliminating or reducing number and size of defects in the structure and varying structure and physical properties within the disk to optimize each section of the disk for its application

4.3.2 State of the Art

The following developments in Layerglazing™ have been demonstrated: high quality, fully dense bulk part and surface coatings have been fabricated in the laboratory which are suitable for experimental evaluation and testing, alloy families which are suitable for Layerglaze™ processing have been demonstrated, thermal treatment by laser has been accomplished, and the ability to vary metals within the structure has been demonstrated.

4.3.3 Technical Problems

Alloy design is the most difficult problem since more information is required for this type of fabrication. Since the process involves the deposition of liquid layers sequentially, and high shrinkage forces occur upon cooling of the newly-formed solid material, only alloys with adequately high strain capability can be Layerglazed™ without difficulty. Although work to date has clearly indicated that this type of processing produces fine, homogeneous microstructures as anticipated, only moderately high strengths have been achieved in fully successful alloys. In the Layerglaze™ alloys with the greatest strengths demonstrated to date, evidence of phase instabilities has been found after prolonged exposure to temperatures of 537 °C (1000°F.) Attempts to reduce these tendencies by alloying have resulted in some improvements. However, additional basic work is needed, particularly in identifying phases and understanding mechanisms, as well as ambitious alloy design programs to explore the potential of systems based outside the limited range explored to date. It is important to note that the potential for superior properties has been clearly demonstrated.

Technical problems associated with Layerglaze™ fabrication include the ability to deliver a steady level of laser energy consistently to the interaction point and to coordinate this energy with numerically-controlled part manipulation and constant-mass flow powder delivery.

4.3.4 Program Approach

To develop Layerglazed™ disks for aircraft engine applications will require a wide range of developments shown in Figure 22. These include disk life prediction analysis, the Layerglaze™ production process, in-situ process and alloy research. Specifically this includes:

Disk Life Prediction

Objective: To develop analysis capabilities to determine the overspeed, over-temperature, and cyclic fatigue capability of turbine disks of controlled, gradated composition (properties).

Disk life prediction state of the art

Conventional high and low pressure gas turbine disks are machined from highly alloyed nickel or iron base materials that have been either cast and forged, powder atomized and direct hot isostatically pressed, or direct hot isostatically pressed and subsequently thermomechanically worked. The mechanical properties of the conventional turbine disk materials are homogeneous and isotropic on a macroscopic scale. The materials are stable with respect to occasional over-temperatures and can be heat treated successfully without introducing significant levels of residual stress. Experience indicates that the inherent strength and ductility of these alloys ensures adequate overspeed and over-temperature capability if adequate section size is provided to assure dimensional stability and fatigue resistance at normal operating conditions. No special consideration is given to contouring of notch details to improve notch tensile (overspeed) capability. Overspeed or burst testing is usually performed on the final disk design to demonstrate minimum burst tolerance. Inclusions, microsegregation, and microshrinkage, introduced during the manufacturing process are evident on the microscale in conventional disk alloys. The low cycle fatigue capability of the disk, the property most sensitive to microstructural configuration, becomes the critical consideration in the design of a conventional turbine disk. Elaborate and well calibrated design systems, based upon the results of extensive specimen and component fatigue testing, have been established to facilitate the design of critical smooth and notched disk details to prevent fatigue cracking. Cyclic spin or load frame testing of the final product is usually performed to demonstrate minimum predicted fatigue crack initiation life.

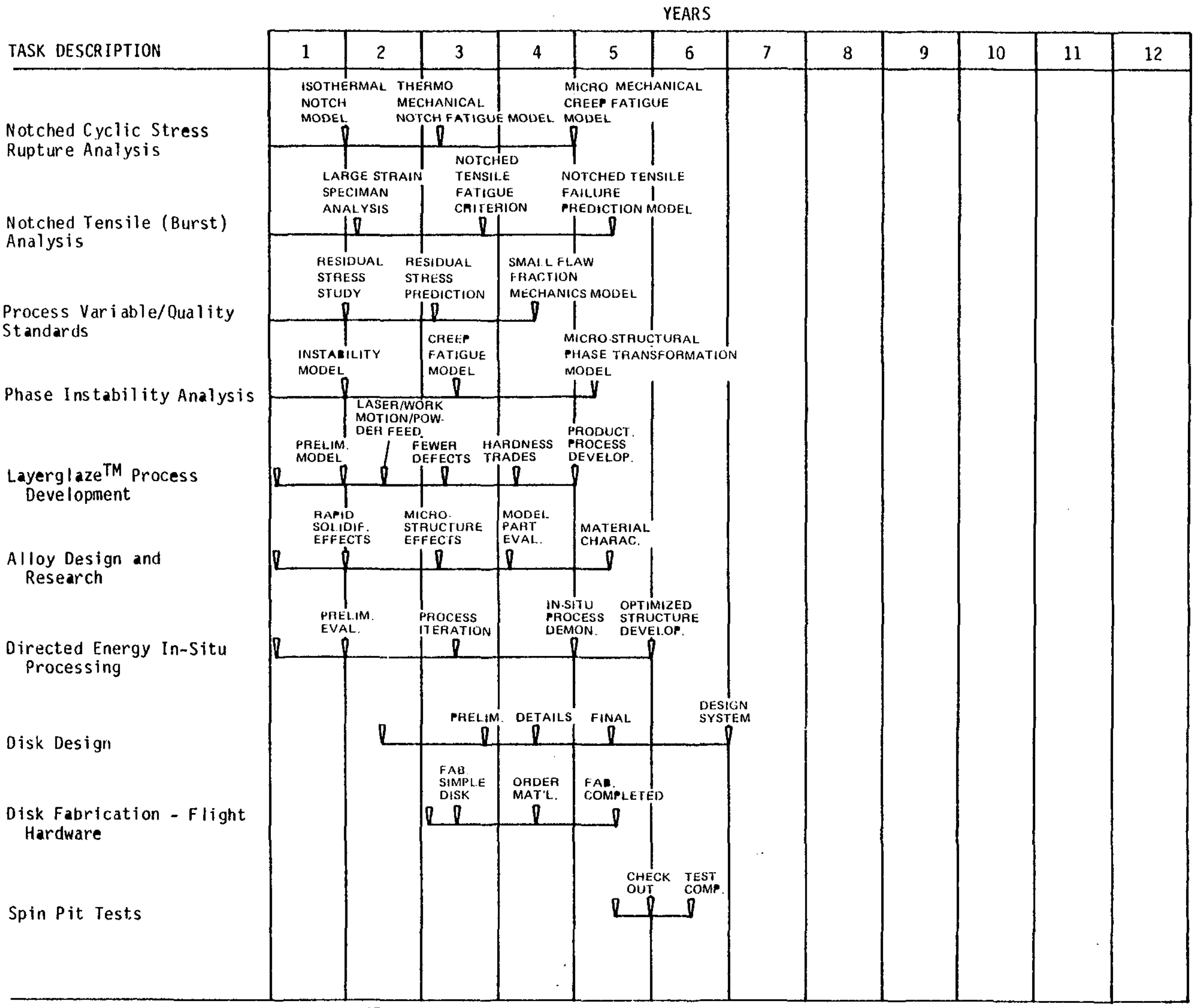

Figure 22 Layerglazed™ Disks Development Program.

Disk life prediction technical problems

Microstructural refinement and process controls attainable with advanced processes such as Layerglazing™ will result in a component with greatly enhanced low cycle fatigue resistance. It is expected, therefore, that notched tensile failure during overspeed, phase instability resulting from occasional over-temperaturing, and cyclic stress rupture of the disk/blade attachment details will become the principal design considerations and require considerable analytical study in the future.

The ability to produce an aircraft engine disk using the Layerglaze™ process will permit the designer to vary the material composition, as well as the design shape, to produce the optimum disk configuration for the particular application.

It will be possible to adjust the alloy composition in the disk rim to minimize the accumulation of cyclic rupture damage. In cooler, higher stressed disks a material with good low cycle fatigue and notched tensile strength would be desirable. The ability to optimize an advanced disk and material configuration is contingent upon the development of analysis capabilities to address the following concerns:

- Obtain an understanding of the effect of material composition, microstructure and properties on the notched low cycle fatigue and notched cyclic stress rupture life of the alloy.

- Obtain an understanding of the effect of material composition, microstructure and properties on the notched tensile capability of the alloy.

- Obtain an understanding of the effect of advanced disk manufacturing techniques on the size and number of fatigue critical intrinsic defects, in particular, determine the nature and behavior of spheroidal inclusions present in the powder feed stock, porosity and voids resulting from feed stock interruptions, porosity and microcracking resulting from variations in the production processes. Small flaw fracture mechanics analysis and the results of this effort will establish process control requirements.

- Develop a predictive procedure to establish the magnitude and distribution of bulk residual stresses in the final machined configuration. Determine the influence of compositional variation, heat treatment schedule and preform to final shape change on residual stress levels.

- Develop a procedure to determine the degradation in material properties and component durability resulting from occasional over-temperaturing and resultant phase instability.

A four part analytical effort is proposed to develop life and strength analysis for effective initiation of the Layerglazed™ concept for disk manufacture. The required developments are briefly described below and shown in Figure 22.

- Notched Cyclic Stress Rupture Analysis

Isothermal Notch Model - Conduct nonlinear finite element analysis to establish the effect of loading history (cyclic or sustained loading), notch type (plane strain vs. plane stress) and notch geometry on the inelastic distribution and time variation in stress and strain in the vicinity of a prototype fatigue notch. Based on these results a simple, cost-effect design model for predicting the variation in local notch conditions will be developed.

Thermo-Mechanical Notch Fatigue Model - Conduct suitable analyses to determine if the design procedure proposed above is satisfactory when the temperature as well as the load varies with time.

Micro-Mechanical Creep Fatigue Model - Obtain suitable test data. The specimen for these tests and test conditions will be based on detailed structural analysis of a turbine disk fir tree arrangement. The tests will investigate smooth fatigue, step load creep, constant strain relaxation and notched ruptures to provide the empirical base required to develop a micromechanical theory of creep/fatigue. The theory will reflect the microstructural basis for cyclic creep rupture failures.

- Notched Tensile (Burst) Analysis

Large Strain Specimen Analysis - Perform large strain, large displacement nonlinear finite element analysis to identify the variation in local plastic stress and strain condition as a function of nominal load. Conduct concurrent tests to verify analysis.

Notched Tensile Failure Criterion - Based on the above analytic and test results propose a failure initiation criterion for the microvolume of material adjacent to a tensile notch.

Notched Tensile Failure Prediction Model - Develop model based on large strain, large displacement nonlinear structural analysis on typical disk notch configurations (bolt holes, rim slots, cooling holes, etc.). The analysis will determine the influence of notch details on disk burst capability.

Process Variables/Quality Standards

Residual Stress Study - Develop a nonlinear finite element program which includes the capability to predict the stress and strain state in a variable composition disk during the manufacturing process. This includes layer build up, heat treatment and reduction to finished state.

Residual Stress Prediction - Use the above analysis to predict the state of residual stresses in a prototype disk and the effect of subsequent engine operation on dimensional stability and durability.

Confirm the prediction by bulk and residual stress measurements on prototype parts.

Small Flaw Fracture Mechanics Model - Develop a model for predicting the behavior of small intrinsic material defects based upon small flaw fracture mechanics theory and the results of a concurrent test program. Testing will investigate specimen with known levels (size and number) of defects. The defects will consist of ceramic inclusions, porosity, voids and microcracks.

Phase Instability Analysis

Instability Model - Develop an analytic model to predict the rate of microstructures transformation. Conduct concurrent thermal stability tests to determine the influence of time/temperature exposure on the precipitation of unstable phases.

Creep Fatigue Model - Modify the creep fatigue micromechanical damage model to reflect the effect of phase instability on damage accumulation rates.

Micro-Structural Phase Transformation Model - Develop model based on the above analyses and concurrent testing of strain controlled creep fatigue tests to verify model predictions.

Layerglaze™ Process Development

Model parts demonstrating Layerglaze™ and in-situ processing described in first year plan (Figure 23) - includes destruction evaluation and mechanical testing.

Laser development requiring increased power and reproducibility as well as optimized coordination of laser power with powder feed and motion of disk being fabricated.

Fewer defects - by reducing the size and number of ceramic inclusion in the powder being Layerglazed™, vaporization of inclusion by coupling with the laser energy and defect removal made possible by in-situ inspection.

Hardness trades - investigate trade between hardness, strength and ductility.

Production process developed - suitable for producing aircraft engine quality disk

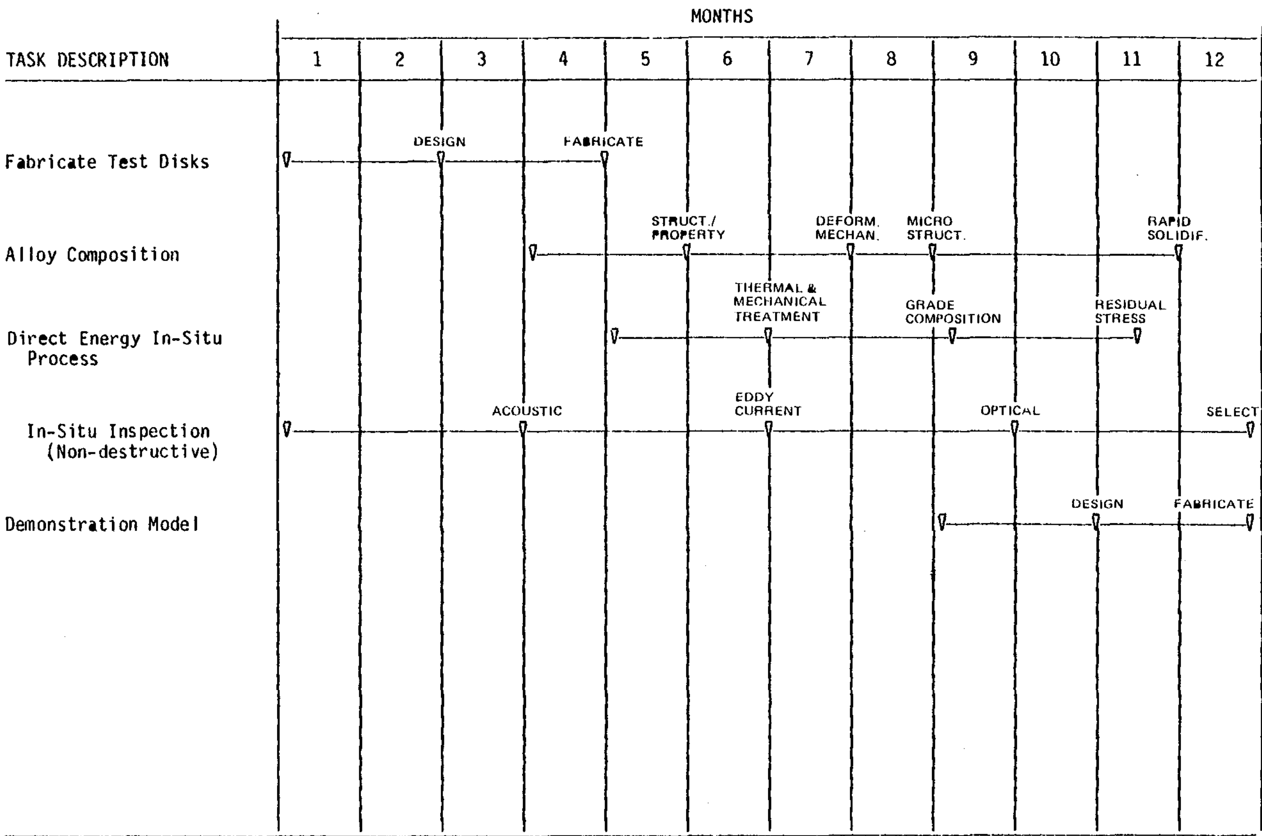

Figure 23   Layerglazed™ Disks First Year Plan.

Alloy design and research

Rapid solidification effect on microstructures, shrinkage forces during cooling and effect on strength enhancement characteristics of alloys used in Layerglaze™ process.

Microstructure effects on mechanical properties of alloys and deformation mechanism.

Model part evaluation - fabricate simple disks to test and evaluate alloy design parameters.

Material characterization - strength, ductility.

Directed energy in-situ processing

Preliminary evaluation - described, in first year plan.

Process iteration - leading to alloy improvements and processing adjustments due to investigation of in-situ inspection, mechanical and thermal treatment, grade composition, control microstructure and residual stress.

In-situ processing demonstrated

Optimized structure, incorporating in-situ processes, developed for turbine disk application.

Disk design

Preliminary design - incorporating state of the art technology.

Details completed - details of parts completed suitable for ordering material.

Final design - iteration procedure incorporating results of experimental and analytical investigation.

Design system - developed for aircraft engine application.

Disk fabrication - flight hardware

Fabricate simplified disk - preliminary fabrication development to investigate feasibility of candidate concepts.

Order material

Fabrication completed - disk available for full scale, instrumented spin pit test.

Spin pit tests

Check out test facilities and instrumentation

Complete qualification test required for full scale engine testing and final design system.

Layerglazed™ Disk First Year Program

The objectives of the Layerglazed™ disk first year program are to: investigate structure/property relationships, investigate the Directed Energy In-Situ Process and fabricate model parts incorporating and demonstrating Directed Energy In-Situ Process developments.

The following approach outlined in Figure 23 will be used for the first year program.

Design and fabricate - Layerglazed™ model parts incorporating single variables.

Alloy composition.

Investigate structure/properly relationships - By mechanical testing and destructive inspection.

Investigate deformation mechanisms - Using various techniques such as fracture surface examination of structure dislocation.

Microstructure - Investigate means for varying and controlling microstructure.

Rapid solidification - Effect on material properties of candidate alloys.

Directed Energy In-Situ Processing - preliminary investigation of processes which are uniquely feasible by the sequential, layer by layer build up of the disk.

Thermal and mechanical treatment of material during Layerglazing™.

Grade composition - Provide smooth, continuous transition of one material to another by continuously varying the mixture of metals in the powder feed.

Residual stress - Investigate means for inducing desirable prestress in material by thermal, mechanical treatment and grading material.

In-situ inspection - One of the major advantages of the Layerglaze™ process in that non-destructive inspection can be performed during fabrication. This provides detailed knowledge of the internal structure which can ordinarily be achieved only by destructive inspection. Three non-destruction inspection procedure will be evaluated. These are:

Acoustic emission process monitoring - Detects the low level acoustic emissions generated during the formation of laser melting and subsequent solidification.

Eddy current methods - Defects the location of defects by monitoring the changes of conductivity and permeability of eddy currents induced in the metal.

Optical methods - A light source such as a laser illuminates the surface. Defects are detected by changes of location, intensity and distribution of the detected beam.

Demonstration model - Fabricate model part incorporating thermal and mechanical treatment, graded microstructure and composition of Layerglazed™ model which has been continuously inspected.

4.4 Recommendations

The advanced concepts selected require a wide range of technology developments. This was expected. The program was designed to provide a disciplined approach to identify long term technology requirements. All the technologies outlined in the previous section will significantly benefit future aircraft operations. These benefits are quantitatively assessed for the applicable advanced concepts. Even more important are the spin off benefits. The technology development programs were designed to provide basic physical understanding providing generic as well as specific applications. The basic knowledge obtained will permit improvements to a variety of advanced concepts.

The technologies outlined were ranked in order of their benefits to future aircraft operation. The factors considered included: potential benefits, importance to the advanced concepts, probability of success, generic applications and engineering judgement. This assessment showed that the analytic technologies provide the greatest benefits. The key factor was that they provide the most generic applications. For long term developments, the analytic advances will benefit many future development programs.

Specifically, all technologies identified should be developed. However, the most important technologies, in order of their ranking, are listed below:

- o Life Prediction - advanced turbine blades
- o Life Prediction - advanced disks
- o Flutter - high speed turbine blades
- o Heat Generation and Dissipation - advanced gears

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