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COST/BENEFIT ANALYSIS (PART 2) OF ADVANCED MATERIAL TECHNOLOGY CANDIDATES FOR THE 1980'S

by

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16 Abstract

The cost/benefit analysis is an effort to evaluate nine new advanced material technologies projects considered for general aviation and turboprop commuter aircrafts through estimated life-cycle costs, direct-operating costs, development costs, risks, and relative values. This analysis included the following activities:

- o Selection of the candidate technologies for future MATE Program projects
- o Development of the property goals for the candidate technologies
- o Determination of the impact of engine weight and fuel consumption on airframe weight and cost
- o Development of the engine and airframe life-cycle and direct-operating cost models
- o Calculation of the potential benefits (life-cycle and direct-operting cost improvements) to a selected engine and airframe based on changes in the engine performance resulting from the proposed incorporation of each candidate technology
- o Estimation of the development cost and risk for each candidate technology
- o Ranking of each candidate technology based on the relative benefits to the aircraft, as well as the associated investments and risks involved.

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FOREWORD

This Cost/Benefit Analysis (Part 2) was prepared for the National Aeronautics and Space Administration, Lewis Research Center. It presents the results of a cost/benefit study conducted to evaluate costs, benefits, and risks for nine candidate material technologies for general aviation aircraft plus small commuter aircraft. These technologies were compared through calculated life-cycle cost, direct-operating cost, and Relative Value. The study was conducted as part of the Materials for Advanced Turbine Engines (MATE) Program under Contract NAS3-20073.

The authors wish to acknowledge the assistance and guidance of C. Blankenship, S. Grisaffe, and R. L. Dreshfield of NASA-Lewis Research Center.

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SUMMARY

This document summarizes the second phase of a two-part cost/benefit analysis (Part 1 is complete, see ref. 1) conducted as part of the NASA Materials for Advanced Turbine Engines (MATE) Program. The objective of this cost/benefit analysis is to analyze the costs, benefits, and risks for each new candidate technology to be considered for future projects. This analysis includes the selection of technologies to be evaluated; development of property goals; assessment of candidate technologies on typical engines and aircraft; sensitivity analysis of the changes in property goals on performance and economics, cost and risk analysis for each technology; and ranking of each technology by Relative Value.

The cost/benefit analysis was applied to a domestic, nonrevenue producing, business-type jet aircraft configured with two TFE731-3 turbofan engines, and to a domestic, nonrevenue producing, business-type turboprop aircraft configured with two TPE331-10 turboprop engines. In addition, a cost/benefit analysis was applied to a commercial turboprop aircraft configured with a growth version of the TPE331-10. The aircraft chosen for that analysis was similar to the Gates Learjet 35/36, the Rockwell 980 Commander, and a 30-passenger Fairchild commuter aircraft. (For the purposes of this study, the effects of the technologies that were developed in previous MATE programs conducted by AiResearch were included in the engines analyzed.)

Cost benefits of nine candidate material technologies, shown in Figure 1, were evaluated. The material technologies were compared by both life-cycle cost and Relative Value. Relative value is a method of comparing technologies by equating benefits (payoffs), development cost, and probability of success. Relative Value is defined as follows:

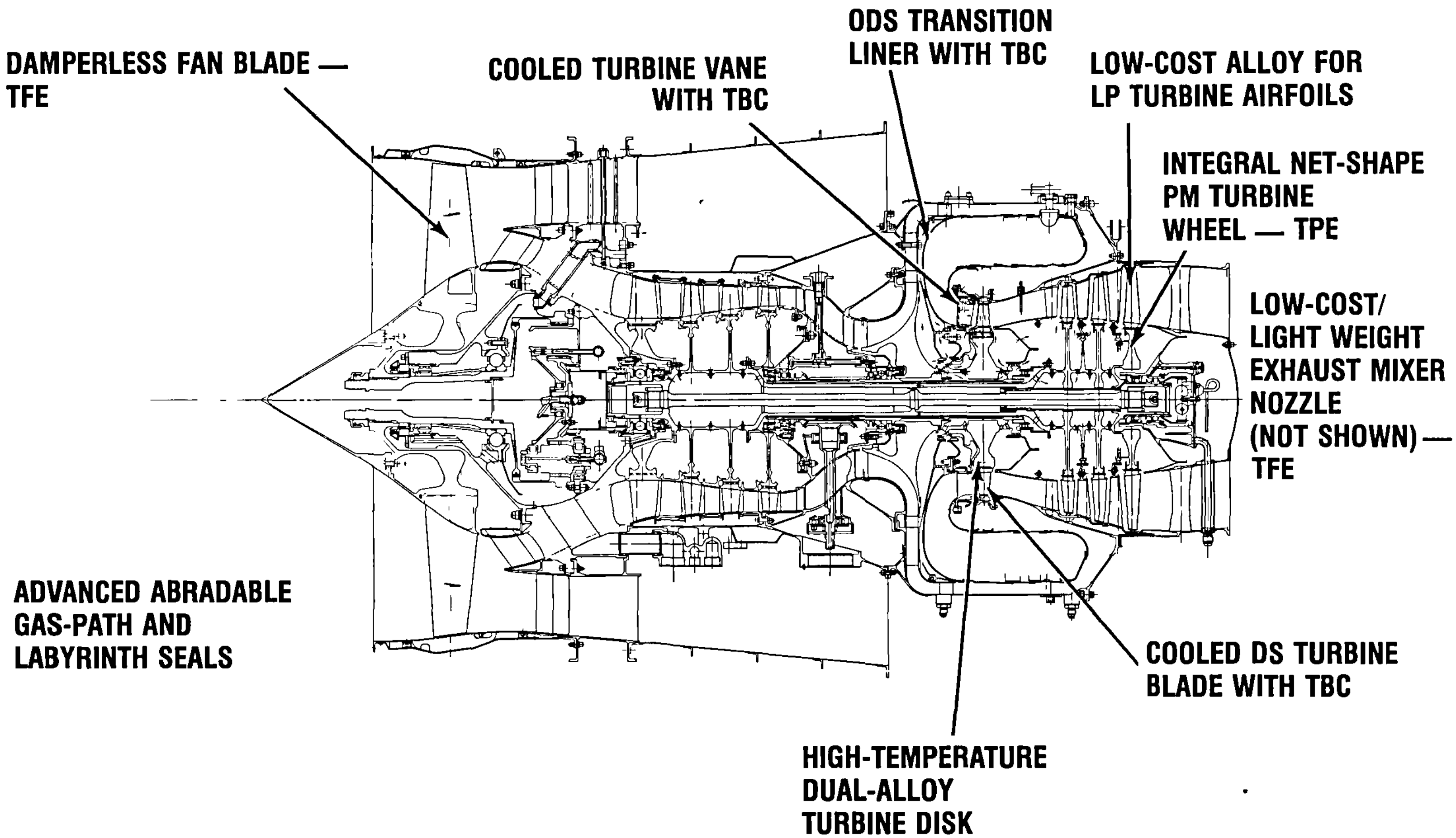


Figure 1. Life-Cycle-Cost Technologies.

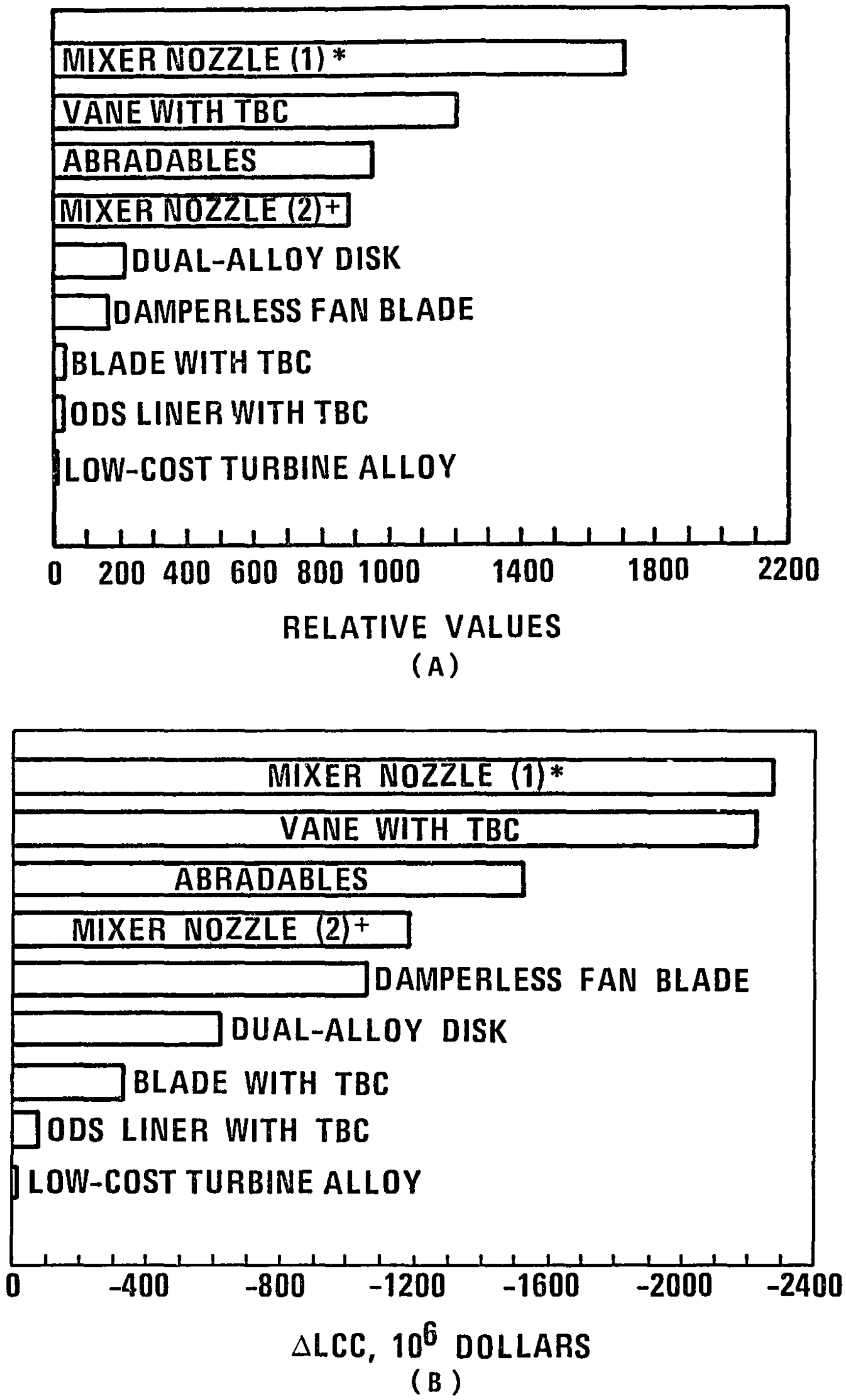
$$\text{Relative Value} = \frac{\Delta\text{Life-Cycle Cost or }\Delta\text{Direct-Operating Cost}}{\Delta\text{Development Cost}} \times \text{Probability of Success} \qquad (1)$$

This approach should not be construed to represent the sole basis for selecting material technologies for engineering development and engine applications. Several other factors, such as engineering judgement or corporate priorities, may be as important as Relative Value in the selection of material technologies for engine application.

Figures 2(A), 3(A), and 4(A) present the ranking of the nine technologies based on Relative Value in the selected application. The low-cost/lightweight exhaust mixer nozzle and the cooled high-pressure (HP) vane with thermal-barrier coating (TBC) rank the highest, followed by the advanced, low-cost abradable turbine gas-path and labyrinth seals. The remaining technologies fall in order as shown in the following figures. The low-cost/lightweight mixer nozzle was analyzed in comparison to the TFE731-3 with a coannular exhaust nozzle (as is currently used on the Learjet 35/36) and to the same engine configured with a welded mixer nozzle.

Figures 2(B) and 3(B) rank the technologies on a straight change in life-cycle cost (ΔLCC). The direct-operating cost (DOC) is summarized in Figure 4(B). This straight benefit ranking does not include either the development cost or the probability of success factor. The high ranking technologies, in terms of benefits only, are the low-cost/lightweight exhaust mixer nozzle, the cooled HP turbine vane with TBC, and the advanced, low-cost abradable turbine gas-path and labyrinth seals.

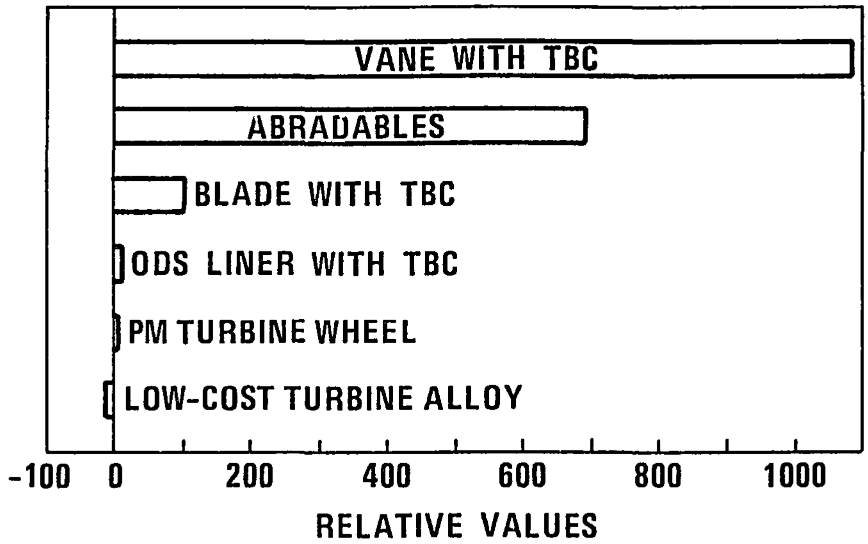
The AiResearch corporate ranking is presented in Table I and follows the Relative Value and ΔLCC/ΔDOC ranking for the top three technologies. The corporate ranking will be discussed in more detail later in this report.



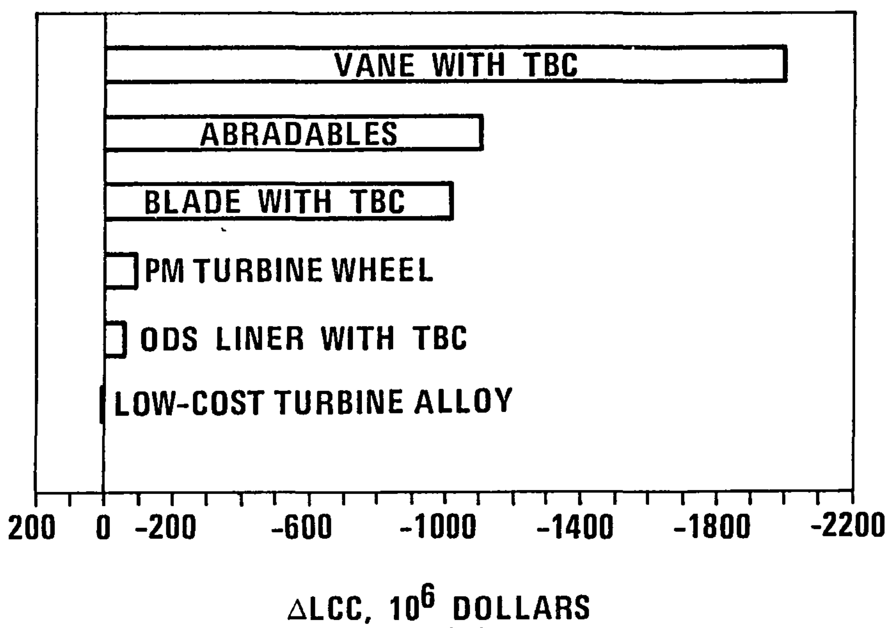
* SUPERPLASTIC FORMED (SPF) MIXER NOZZLE COMPARED TO CONVENTIONAL COANNULAR MIXER NOZZLE.

\+ SUPERPLASTIC FORMED (SPF) MIXER NOZZLE COMPARED TO CONVENTIONAL WELDED MIXER NOZZLE.

Figure 2. Turbofan Aircraft Relative Value and ΔLCC Ranking of the Material Technologies.



(A)



(B)

Figure 3. Turboprop Business Aircraft Relative Value and ΔLCC Ranking of the Material Technologies.

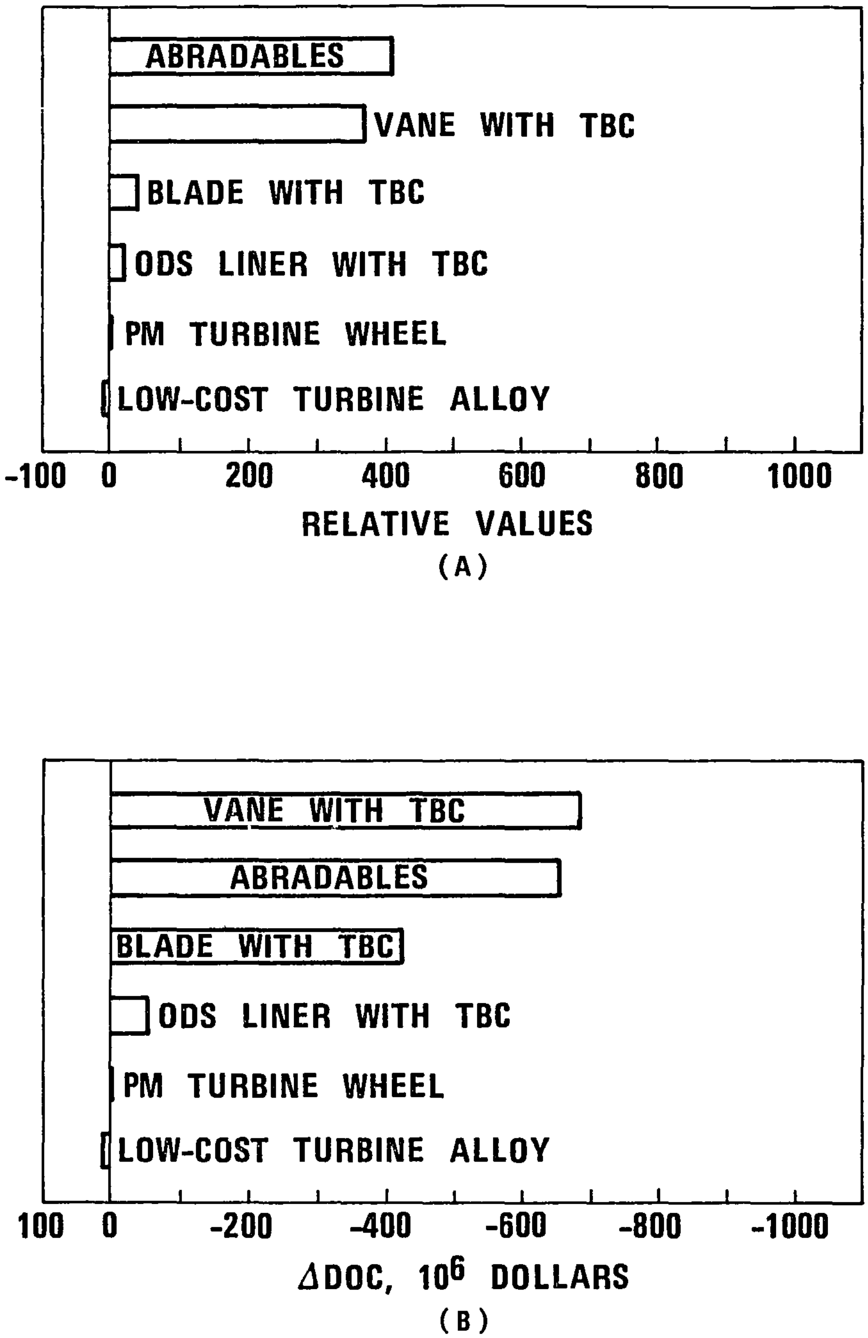


Figure 4. Turboprop-Commuter Aircraft Relative Value and ΔDOC Ranking of the Nine Material Technologies.

TABLE I. AIRESEARCH CORPORATE RANKING OF THE MATERIAL TECHNOLOGIES

1. Low-cost/lightweight exhaust mixer nozzle - TFE only.
2. Cooled HP turbine vane with TBC - TFE and TPE.
3. Advanced, low-cost abradable turbine gas-path and labyrinth seals - TFE and TPE.
4. High-temperature, dual-alloy turbine disk - TFE only.
5. Damperless fan blade - TFE only.
6. Cooled directionally-solidifed (DS) HP turbine blade with TBC - TFE and TPE.
7. Oxide-dispersion strengthened, (ODS) transition liner with TBC - TFE and TPE.
8. Integral net-shape power-metal (PM) turbine wheel - TPE only.
9. Low-cost alloy for low-pressure (LP) turbine airfoils - TFE and TPE.

INTRODUCTION

The NASA MATE Program is a cooperative effort with industry to accelerate the introduction of new materials into aircraft turbine engines. Nine material technologies, which are possible candidates for future MATE projects, were assessed by AiResearch on a cost/benefit basis for their potential benefits in small turbine engines. These advanced technologies are all currently in the exploratory development stage. However, after laboratory feasibility has been adequately demonstrated, their advancement would occur through the improvement of present materials, designs, and process and manufacturing techniques. The verificaiton of the potential benefits of these technologies would be accomplished by hardware fabrication followed by component testing in actual engine environments.

The cost/benefit analysis reported herein is an effort to evaluate each of the nine new material technologies projects considered through estimated life-cycle costs, development costs, risks, and Relative Values. This analysis included the following activities that are described in detail in this report:

- Selection of the candidate technologies for future MATE Program projects
- Development of the property goals for the candidate technologies
- Determination of the impact of engine weight and fuel consumption on airframe weight and cost
- Development of the engine and airframe life-cycle cost models

- Calculation of the potential benefits (life-cycle cost improvements) to a selected engine and airframe based on changes in the engine performance resulting from the proposed incorporation of each candidate technology

- Estimation of the development cost and risk for each candidate technology

- Ranking of each candidate technology based on the relative benefits to the aircraft, as well as the associated investments and risks involved.

This report emphasizes cost/benefits of advanced material technologies for general aviation aircraft. In addition, a cost/benefit analysis of a turboprop-powered commuter aircraft was included in this study because of the growing interest in this type of aircraft.

STUDY APPROACH

The cost/benefit analysis consisted of an evaluation based on life-cycle cost considerations of nine candidate material technologies as possible future MATE projects. The ranking of these candidates was accomplished through the modeling of all of the life-cycle cost factors involved in the acquisition cost, operation cost, and maintenance cost. Figure 5 presents a flow chart illustrating the methodology for this analysis.

The cost/benefit analysis began with descriptions of the candidate technologies which included the capability goals (critical and noncritical property goals that will be feasible for 1990 production technology) for relative strengths, weights, and component life; the probability of success for each goal; the probability of success for producing the component while satisfying all of the goals; the comparisons to current production parts; and the development costs.

Development costs for the selected component technologies were prepared using input from AiResearch materials engineers and AiResearch cost experience with similar efforts. The costs encompassed the effort required to demonstrate, in an engine test, the technical objectives of the new technology.

The technical risk, associated with the technical objectives, was estimated based on primary factors that considered the nature of the material, design approach/application, and current goal status. The effect of secondary factors--such as alternate applications, required material development time, and criticality of component--were also included in the technical risk analysis. An overall probability of success for each technology project was estimated from the risk analysis.

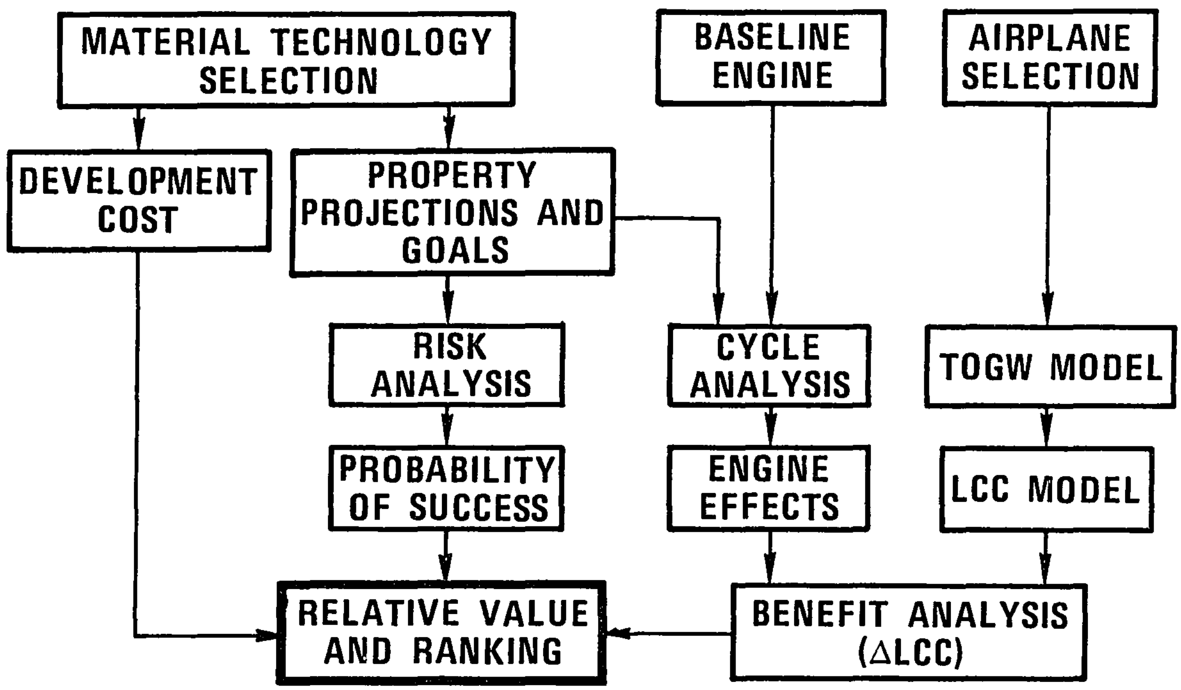


Figure 5. Flow Chart of the Study Approach.

The TFE731 turbofan engine used in the cost/benefit analysis utilizes a geared fan driven by the LP spool. The geared-fan design offers an optimum approach to high-cycle efficiency. The engine cycle was varied, depending upon the nature of the component technology being incorporated, to achieve minimum engine thrust specific fuel consumption. This was accomplished by optimizing the bypass ratio and core pressure ratio, within practical limits, at a constant cruise thrust level. Turbine inlet temperature was varied according to the technology being considered.

The TFE731 turboprop engine used in the cost/benefit analysis is a lightweight single-shaft engine featuring modular design and an integral gearbox and inlet. The engine cycle was optimized for specific fuel consumption at constant shaft horsepower, depending upon the nature of the component technology being incorporated. This was accomplished by optimizing the core flow within the same engine frame size. Turbine inlet temperature was varied according to the technology being considered.

The potential benefits for both engines were assessed through engine cycle analyses (utilizing existing computer models); design analysis for weight, size, and life effects; and cost analyses in the manufacturing and maintenance areas. The aircraft benefits were assessed with inputs from the engine benefits analysis and the life-cycle cost (LCC) models. The engine/aircraft LCC models were utilized to develop sensitivity coefficients for the effects of changes in selected engine parameters (weight, thrust specific fuel consumption, size, cost, life) on total system life-cycle costs. The analysis results are expressed in terms of the benefits resulting from application of each component material technology to the selected engine/aircraft combination. These benefits are expressed as changes in life-cycle cost.

The cost estimating models for the aircraft were based upon a scaled aircraft and engine meeting a fixed payload and range for changes in engine specific fuel consumption and weight. The scalability of the aircraft was determined by utilizing a weight model for the aircraft that partitions the aircraft takeoff gross weight into airframe fixed, airframe variable, installed engine, and fuel and tankage elements. The installed engine weight fraction relates the engine thrust requirements and the thrust/weight ratio to gross weight via the lift-drag ratio. The fuel and tankage fraction relates thrust specific fuel consumption, range, and thrust requirements to gross weight with use of the Breguet range equation (ref. 2).

The following sections present further details of the cost/benefit analysis methodology and results. Appendix B provides a list of abbreviations/symbols used in the following sections.

SELECTED CANDIDATE MATERIALS TECHNOLOGIES

This section provides descriptions, material property and cost goals for each of the candidate material technologies selected for the cost/benefit analysis. These advanced material technologies were chosen because of their potential benefits to the engine/aircraft application. Sharp increases in the cost of fuel over the last five years have led to increased emphasis on the potential of the candidate technologies for reducing fuel consumption. The list of nine technology candidates, as shown below, incorporates input that was collected from vendors, purchasing, performance, stress analysis, materials, etc. to develop the goals required for the cost/benefit analysis. The composite nacelle/inlet components technology, which was originally included in the list, was eliminated since this type of component is already available from at least one vendor as a production component.

- Low-cost alloy for LP turbine airfoils
- Integral net-shape PM turbine wheel
- Damperless fan blade
- ODS transition liner with TBC
- Cooled HP turbine vane with TBC
- Cooled DS HP turbine blade with TBC
- Advanced, low-cost abradable turbine gas-path and labyrinth seals
- High-temperature dual-alloy turbine disk

o Low-cost/lightweight exhaust mixer nozzle

The material property goals were established for each of these candidate advanced material technologies based on projections of current alloy/process technology. The technical and cost goals were established by AiResearch material experts based on a 1990 production status. This assumes a go-forward decision within the MATE II program schedule. The technical material goals are based on two criteria: property goals that must be met to offer a benefit to engine life and/or performance (critical goals), and property goals that must be closely approached to meet the life and performance objectives (noncritical goals). The cost goals are meant to reflect a realistic evaluation of future production costs based on AiResearch experience and published data. A probability of success for each goal is presented to reflect AiResearch's subjective evaluation. A weighing factor was also established for the critical material and cost goals indicating the relative importance of these goals to the success of the technology. The weighing factors and probabilities of success were used in a risk analysis to arrive at a project probability of success for each technology. A subsequent section of this report gives a description of how the risk analysis was performed.

Development costs were estimated for each technology. These estimates are based on all of the costs required to take the candidate technology from its present development status through factory engine demonstration tests, including rig-test costs, and those costs chargeable to incorporation of the technology into an engine.

Brief descriptions and the projected goals for each technology are summarized in the following sections.

Low-Cost Alloy for LP Turbine Airfoils (TFE and TPE)

This project would lead to the production of LP turbine blades and/or stators from a new low-cost, lower temperature capability alloy. These uncooled turbine components would be substituted for more costly, conventional alloy turbine hardware without any loss in performance.

- Capability Goals
  - Critical Goals
    - Δ Creep-rupture strength to be at least 80 percent of the creep-rupture strength of Inco 713LC in the 1000-1300°F range - 60-percent probability of success (30-percent weighing factor).
    - Δ HCF strength to be at least 80 percent of Inco 713LC in the 1000-1300°F range - 60-percent probability of success (25-percent weighing factor).
    - Δ Tensile strength, ductility and impact resistance to be 80 percent of Inco 713LC in the 1000-1300°F range - 60-percent probability of success (10-percent weighing factor).
  - Noncritical Goals
    - Δ Density equivalent to Inco 713LC.
    - Δ Oxidation/corrosion resistance to be at least as good as Inco 713LC up to 1300°F.

- Finished Part Cost Goal - 90 percent of the uncooled LPT blades and stators used in TFE731 and/or TPE331 (assuming conventional Ni-base material costs escalate substantially in the 1990 time frame) - 60-percent probability of success (35-percent weighting factor).

- Estimated Development Cost - $1,500,000.

- Project Probability of Success - 50-percent.

Integral Net-Shape Powder-Metal Turbine Wheel (TPE)

This project would lead to the production of integral net-shape turbine wheels of PM superalloys for use in the 1000-1300°F maximum temperature range where cast inserted blades and forged disks are used today. Primary benefits of the project would be improving the cyclic life and reliability of turboprop engine turbine wheels while reducing the overall cost and weight.

- Capability Goals

  - Critical Goals

    - Δ The low-cycle-fatigue life of the rim area to be ten times that of cast Inco 713LC - 90-percent probability of success (10-percent weighing factor).

    - Δ Wheels will be produced with net-shape blades requiring no finish machining - 70-percent probability of success (30-percent weighing factor).

- Δ Creep-rupture strength to be equal to that of cast Inco 713LC in the 1000-1300°F range - 90-percent probability of success (10-percent weighing factor).

- Δ HCF strength to be equal to that of cast Inco 713LC in the 1000-1300°F range - 90-percent probability of success (10-percent weighing factor).

- Δ Weight of the integral wheel to be 20-percent less than the inserted blades/disk assembly - 90-percent probability of success (10-percent weighing factor).

- o Noncritical Goals

  - Δ Density to be no greater than that of Inco 713LC.

  - Δ Oxidation/corrosion resistance to be equal to that of Inco 713LC up to 1300°F.

- Finished Part Cost Goal - 70 percent of the cost of a TPE331 blade/disk assembly using a forged disk and individual inserted blades - 50-percent probability of success (30-percent weighing factor).

- Estimated Development Cost - $2,500,000.

- Project Probability of Success - 15 percent.

Damperless Fan Blade (TFE)

This project would lead to the production of a hollow damperless titanium fan blade for use in the new TFE76 engine. This candidate technology is more applicable to the new TFE76 low-aspect-ratio fan blade than the TFE731 blade. Therefore, the benefits and engine demonstration test are planned for the TFE76 while the cost/benefit study will utilize the TFE731 engine/aircraft model. The incorporation of this technology would result in a one-percent increase in the fan-stage efficiency.

- Capability Goals
  - Critical Goals
    - Δ Weight of fan blade to be reduced at least 25 percent to avoid vibration problems with damperless fan blade - 75-percent probability of success (35-percent weighing factor).
    - Δ Fan to pass FAA required bird-strike test - 60-percent probability of success (40-percent weighing factor).
  - Noncritical Goals
    - Δ Weight of fan stage to be reduced by at least 10 percent.
    - Δ Part life to be equal to that of production TFE731 fan blade.
- Finished Part Cost Goal - Cost of the total fan stage would be equal to or less than the present TFE76

design - 60-percent probability of success (25-percent weighing factor).

- Estimated Development Cost - $2,800,000.

- Project Probability of Success - 45 percent.

ODS Transition Liner with TBC (TFE and TPE)

This project would lead to production of an oxide-dispersion strengthened (ODS) material transition liner with a TBC. As part of this technology, an appropriate design must be established to facilitate, fabricate, and repair the ODS liner. This technology would utilize less cooling air to produce a longer life component with less thermal distortion. Cooling airflow will be reduced 30 percent.

Capability Goals

- o Critical Goals

  - Δ TBC to provide thermal protection for at least 3000 hours without spallation - 70-percent probability of success (30-percent weighing factor).

  - Δ Durability of the TBC ODS liner must be adequate for 3000 hours - 50-percent probability of success (30-percent weighing factor).

- Finished Part Cost Goal - 200 percent of the cost of the current production components in the TFE731 and TPE731 - 60-percent probability of success (40-percent weighing factor).

- Estimated Development Costs - $1,500,000.

- Project Probability of Success - 60 percent.

Cooled HP Turbine Vane with TBC (TFE and TPE)

This project would lead to the production of a TBC air-cooled HP turbine vane that operates at a 150°F higher turbine inlet temperature while maintaining metal temperatures comparable to those in the current TFE731 and TPE331. The key to this project is the development of a TBC that can function in the vane environment for the required life of the component without spallation.

- Capability Goals

  o Critical Goals

    Δ TBC to provide thermal protection for turbine vanes for 3000 hours plus at least one recoating - 70-percent probability of success (40-percent weighing factor).

    Δ TBC to provide oxidation and corrosion protection for 3000-hours vane life - 70-percent probability of success (20-percent weighing factor).

  o Noncritical Goal

    Coating must be capable of withstanding minor FOD without disbonding.

- Finished Part Cost Goal - 150 percent of the current cooled cast vane segment in the TFE731 or the

TPE331 - 70-percent probability of success (40-percent weighing factor).

- Estimated Development Cost - $1,200,000.

- Project Probability of Success - 65 percent.

Cooled DS HP Turbine Blade with TBC (TFE and TPE)

This project would lead to the production of a TBC air-cooled, DS HP turbine blade that can operate at a higher turbine inlet temperature than an uncoated, cooled DS blade. Technology goal is to develop a variable thickness coating application that will minimize additional centrifugal streses, optimize aerodynamic effects, and provide a TBC that can survive in the HPT blade environment for the required life.

- Capability Goals

  - Critical Goals

    - Δ TBC to provide thermal protection which will allow cooled turbine blade to operate at 40° higher gas temperatures compared to uncoated blade - 60-percent probability of success (40-percent weighing factor).

    - Δ TBC blade to exhibit adequate durability to provide 3000-hour life - 50-percent probability of success (30-percent weighing factor).

- o Noncritical Goals

  - Δ TBC to provide oxidation and corrosion protection for 3000-hour blade life.

  - Δ Coating must be capable of withstanding minor FOD without disbonding.

- Finished Part Cost Goal - 250 percent of the current solid DS turbine blades in the TFE731 - 70-percent probability of success (30-percent weighing factor).

- Estimated Development Cost - $2,000,000.

- Project Probability of Success - 20 percent.

Advanced, Low-Cost Abradable Turbine Gas-Path and Labyrinth Seals (TFE and TPE)

This project would lead to the production of shrouds and/or labyrinth seals that utilize low-cost, sprayed-on abradables. Environment will vary from 1900°F at the HPT shroud to 1000°F at the LPT labyrinth. The incorporation of new abradables at all these locations would result in a 0.5-percent increase in HPT efficiency, a 0.5-percent increase in LPT efficiency, and a 1.0 increase in interstage efficiency.

- Capability Goals

  - o Critical Goals

    - Δ Coating/Blade tip wear ratio equal to at least 15:1 - 60-percent probability of success (35-percent weighing factor).

- Δ Erosion resistance adequate to meet 3000-hour part life - 50-percent probability of success (30-percent weighing factor).

- o Noncritical Goal

  - Δ Coating debris size less than 0.010 inch.

- Finished Part Cost Goal - Equal to current components with existing abradable coatings and a 10 percent or less cost increase for LPT labyrinth and shroud components that are not currently coated. A 25-percent cost increase over the current HPT component (uncoated) would be anticipated - 60-percent probability of success (35-percent weighing factor).

- Estimated Development Cost - $800,000.

- Project Probability of Success - 50 percent.

High-Temperature Dual-Alloy Turbine Disk (TFE)

This project would lead to the production of a dual-alloy PM turbine wheel with a high creep-resistant alloy rim and a high LCF and tensile strength alloy hub. The disk would be used in conjunction with high temperature uncooled inserted HP turbine blades. This technology would allow the air required for rim cooling to be reduced when uncooled turbine blades (DS, SC or ODS) replace conventional cooled blades. This reduction of cooling air is expected to increase HPT stage efficiency 0.6 percent.

- Capability Goals

  - o Critical Goals

    - Δ Creep strength of the rim material to be equivalent to that of forged Waspaloy at 150°F higher rim temperature - 70-percent probability of success (25-percent weighing factor).

    - Δ Tensile strength of the bond joint between the rim and hub alloys to be equal to that of the rim alloy at the bond joint temperature - 80-percent probability of success (20-percent weighing factor).

    - Δ LCF and tensile strength of hub material to be equal to that of Waspaloy - 90-percent probability of successs (25-percent weighing factor).

  - o Noncritical Goal

    - Δ Density of bimetallic disk not to exceed that of current forged Waspaloy disk.

- Finished Part Cost Goal - 135 percent of the machined Waspaloy forging now used in the TFE731-3 engine - 55-percent probability of success (30-percent weighing factor).

- Estimated Development Cost - $1,800,000.

- Project Probability of Success - 60 percent.

Low-Cost/Lightweight Exhaust Mixer Nozzle (TFE)

This project would lead to the production of a low-cost, lightweight superplastic formed titanium mixer nozzle for the TFE731 engine to improve the overall engine performance 4 percent. This component is to replace the current fabricated coannular steel nozzle and will incorporate demonstrated performance improvement design concepts.

- Capability Goals
  - Critical Goals
    - Δ Performance improvement with the compound mixer nozzle to be at least 4 percent - 80-percent probability of success (40-percent weighing factor).
    - Δ Mixer nozzle to add not more than 2 percent to the overall weight of the engine - 80-percent probability of success (35-percent weighing factor).
- Finished Part Cost Goal - Incorporating this mixer nozzle to increase the cost of the engine not more than 2 percent - 70-percent probability of success (25-percent weighing factor).
- Estimated Development Cost - $1,000,000.
- Project Probability of Success - 75 percent.

RISK ANALYSIS

The risk analysis method used is basically the method described in NASA Report CR-134701 (ref. 3) with the added feature that individual probabilities of success and weighing factors have been assigned to each of the critical property goals and the finished part cost goal for the nine candidate technologies.

Several factors were considered in the risk analysis. Those factors that are considered primary factors address the nature of the material, the design approach/application, and the current goal status. Secondary factors that address alternate applications, required material development time, and criticality of the component are also considered. Except for the current goal status, an alphabetical value is assigned to the primary and secondary factors based on the criteria presented in Table II.

The current goal status is determined by applying the weighing factors to the probability of success for each of the critical property goals and finished part cost goals, and summing the weighted individual probabilities of success. An alphabetical value according to the scale defined in Table II is then assigned to the current goal status. The following example shows how the current goal status was determined for the low-cost/lightweight exhaust mixer nozzle technology.

	Probability of Success	Weighing Factor	Weighted Probability of Success
Critical Goals	0.80	0.40	0.32
	0.80	0.35	0.28
Cost Goal	0.70	0.25	0.18
		Current Goal Status	0.78

TABLE II. DEGREE OF RISK CRITERIA

Factors	Degrees of Risk		
Primary Factors	A	B	C
Nature of Material	Traditional	Advanced	Revolutionary
Design Approach/ Application of Material	Traditional	Advanced	Revolutionary
Current Goal Status (Probability of Success)	1.00-0.90	0.90-0.70	0.70-0.0
Secondary Factors			
Number of alternative approaches for application/ opportunities of incremental success for material	3 or more	2	1
Required material Development Time (years)	3	5	7
Critical nature of component to which Material is applied	Static/low stress	Static/high stress	Rotating

A numerical value for both the primary and secondary factors is assigned based on the combination of alphabetical values previously determined utilizing the following schedule:

Primary Factors		Secondary Factors	
AAA	= 1.00	3 A's	= -0
AAB	= 0.95	2 A's, 1 B	= -0.05
ABA, BAA	= 0.90	1 A, 2 B's	= -0.10
AAC	= 0.85	2 A's, 1 C	= -0.15
ABB,BAB,BBA	= 0.80	1 A, 1 B, 1 C	= -0.20
BBB,ABC	= 0.75	3 B's	= -0.25
BAC	= 0.70	2 B's, 1 C	= -0.30
BBC,CBA,BCA	= 0.65	1 A, 2 C's	= -0.35
ACC,CBB,BCB	= 0.60	1 B, 2 C's	= -0.40
CBC,BCC,CCA	= 0.55	3 C's	= -0.45
CCB	= 0.50		
CCC	= 0.45		

The project probability of success is determined by summing the numerical value obtained for both the primary factors and the secondary factors. It should be noted that the secondary factors are algebraically negative.

Table III summarizes the risk analysis for the nine candidate material technologies.

TABLE III. RISK ANALYSIS

	1 Low-Cost Turbine Airfoil Alloy	2 PM LPT Wheel	3 Damperless Fan Blade	4 ODS Trans Liner W/TBC	5 HPT Vane W/TBC	6 HPT Blade W/TBC	7 Abradable and Labyrinth Seals	8 Dual-Alloy Disk	9 Exhaust Mixer Nozzle
Primary Factors									
o Nature of Material	B	B	A	B	B	C	B	B	A
o Design Approach/ Application	A	C	B	B	B	B	A	B	B
o Current Goal Status	C (0.60)*	B (0.72)*	C (0.65)*	C (0.60)*	B (0.70)*	C (0.60)*	C (0.57)*	B (0.73)*	B (0.78)*
Probability of Success	0.70	0.60	0.75	0.65	0.75	0.55	0.70	0.75	0.80
Secondary Factors									
o Alternate Applications	A	C	B	A	A	A	A	A	B
o Required Material Development Time	C	C	B	B	B	C	B	A	A
o Criticality of Component	B	C	C	A	B	C	C	C	A
Probability of Success	-0.20	-0.45	-0.30	-0.05	-0.10	-0.35	-0.20	-0.15	-0.05
PROJECT PROBABILITY OF SUCCESS	0.50	0.15	0.45	0.60	0.65	0.20	0.50	0.60	0.75

*( ) Weighted probability of success for combined critical property and finished part cost goals.

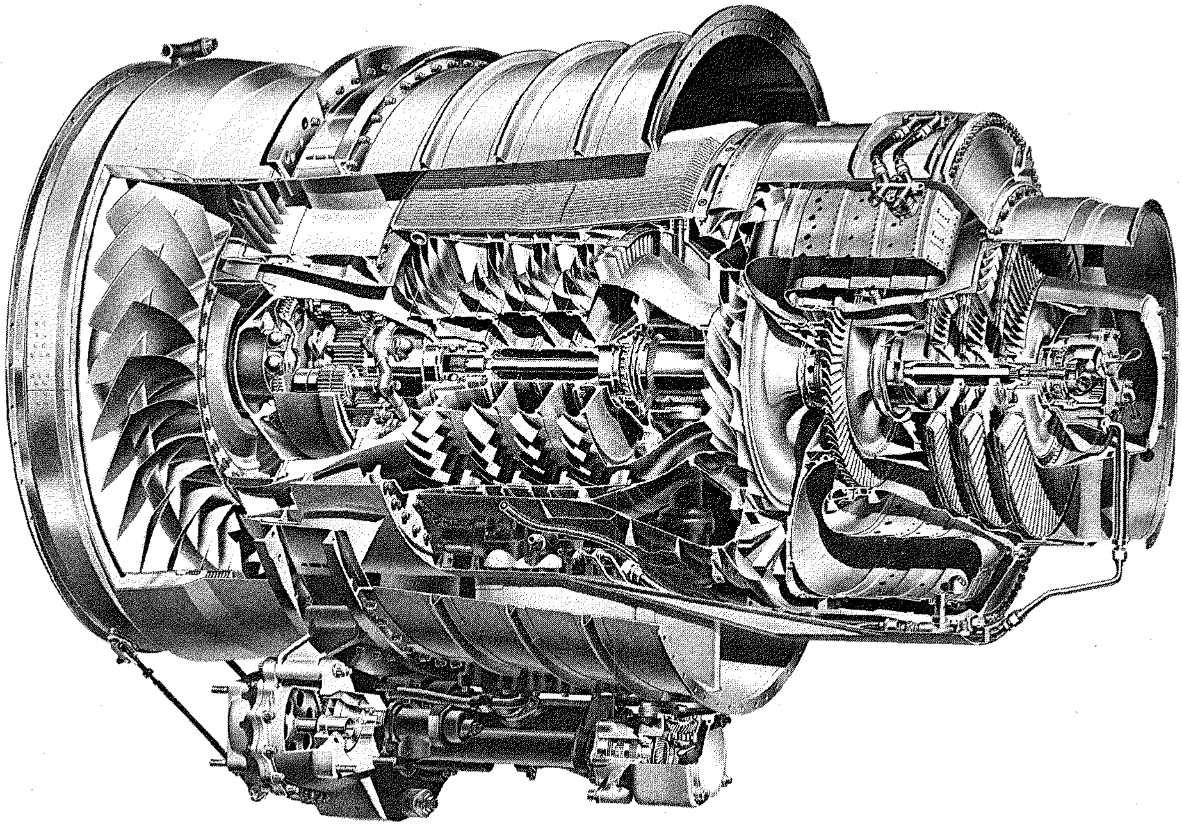
ENGINE CONSIDERATIONS

Baseline Engine Selection

The AiResearch Model TFE731-3 engine (as illustrated in Figure 6), upgraded to include the technology improvements from AiResearch's MATE Projects 1 and 2, was selected as the baseline engine for evaluating the candidate technology projects. The TFE731 engine is currently the powerplant for four domestic aircraft and five foreign aircraft--one military and eight civil aircraft. As in the Cost/Benefit (Part 1) Analysis, a composite twin-engine aircraft representative of the 6800- to 9100-kg (15,000- to 20,000-lb) class was selected as the vehicle for analysis of benefits that could be derived from the candidate projects.

The TFE731-3 engine consists of a geared fan located at the forward end of the engine. The fan is gear-driven by the LP spool. The geared-fan design was selected as the optimum approach for high-cycle efficiency, and it incorporates proven techniques for reducing noise to levels appreciably lower than that of comparably sized turbojets. The LP spool consists of the single-stage fan, coupled through a planetary gearbox to a four-stage compressor and three-stage turbine. The HP spool consists of a centrifugal compressor driven by a single-stage turbine; the accessory gearbox is driven by the HP spool. The reverse-flow annular combustor employs 12 dual-orifice fuel injectors and was designed for low smoke-emission levels below the threshold of visibility, in addition to high-combustion efficiency, reliable ignition and stable operation, and high-durability characteristics over the engine operating range.

The AiResearch Model TPE331 engine (as illustrated in Figure 7) used for both the business and commuter aircraft LCC analysis was upgraded to include the results of the MATE Project 2



+ UNCOOLED DS MAR-M 247 HPT BLADES (PROJECT 1)
+ ABRADABLE COMPRESSOR AND TURBINE SHROUD SEALS (PROJECT 2)
+ INCREASED BYPASS RATIO AND PRESSURE RATIO

Figure 6. Baseline MATE Turbofan Engine.

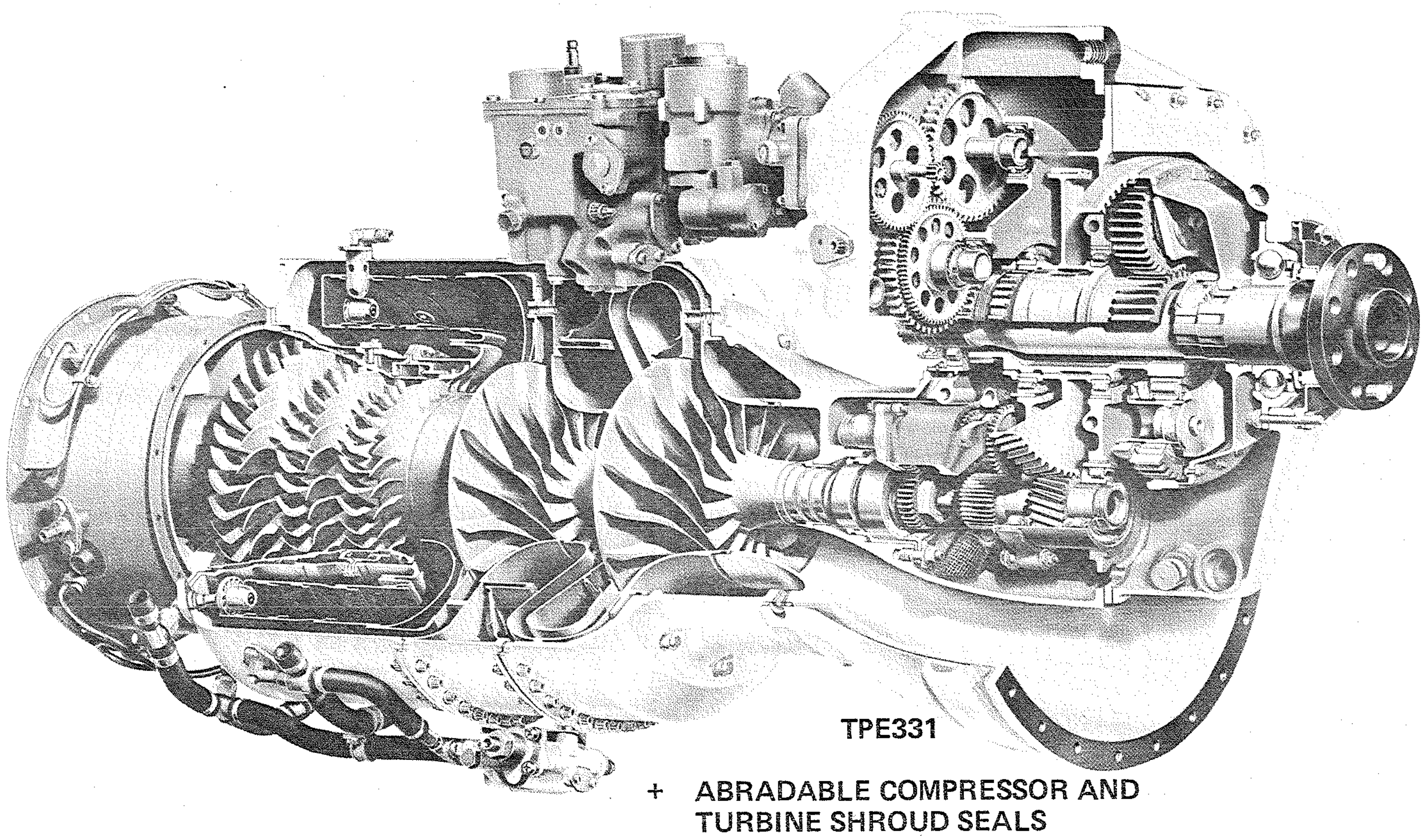


Figure 7. Baseline MATE Turboprop Engine.

Abradable Seals Program. The TPE331 engine is currently the powerplant for thirteen aircraft. The engine was also modified for military applications under the designation T76.

The TPE331 uses a high-pressure-ratio, two-stage centrifugal compressor resulting in a more rugged, more reliable compressor compared to a multistage axial-flow compressor. Added advantages are lower cost and greater flexibility for growth. A three-stage, axial-flow turbine with integral second- and third-stage blades and disks provides a durable and highly efficient turbine. Use of a reverse-flow, annular combustor results in a minimum engine length, minimum weight, low combustor pressure loss, and efficient use of space. The reverse-flow principle shields the turbine first-stage nozzles from the radiant heat transfer from the primary combustion zone. The use of a two-bearing arrangement to support the rotating group results in a compact, easy-to-assemble unit.

Engine Performance

The incorporation of the uncooled DS HP turbine blades developed under Project 1, and the abradable turbine and compressor gaspath seals developed under Project 2 of the MATE Program resulted in a rematch of the TFE731-3 engine in order to achieve a minimum engine thrust specific fuel consumption (TSFC) at the original engine thrust rating (cruise). In addition, the TFE731-3 engine baseline model was updated to include the latest cooling flows and turbine efficiencies. The TPE331 baseline engine was modified to include the effects of the Project 2 abradables by rematching the engine at constant cruise horsepower in order to achieve minimum SFC. The MATE baseline turbofan engine performance and the present TFE731-3 performance are presented in Table IV. The MATE turboprop baseline engine performance for the business and commuter application is shown in Table V.

TABLE IV. COMPARISON OF THE TFE731-3 AND MATE BASELINE PERFORMANCE RATINGS (40,000 FT., 0.8 MACH CRUISE, STANDARD DAY)

Parameter	TFE731-3	MATE Baseline
Thrust, daN (lb)	363 (817)	363 (817)
TSFC kg/hr/daN (lb/hr/lb)	0.833 (0.818)	0.745 (0.732)
Turbine inlet temperature, °C (°F)	977 (1791)	977 (1791)
Bypass ratio	2.7	4.6
Cycle pressure ratio	18	25
Core airflow, kg/s (lb/sec)	5.13 (11.3)	5.04 (11.1)

TABLE V. TPE331 BUSINESS AND COMMUTER MATE BASELINE PERFORMANCE RATINGS

Parameter	MATE Baseline TPE331 Business	MATE Baseline TPE331 Commuter
Altitude, M (Ft)	31,000	15,000
Mach Number	0.46	0.43
Horsepower, KW (SHP)	246 (330)	703 (943)
SFC kg/hr/kw (lb/hr/hp)	0.324 (0.532)	0.338 (0.551)
Turbine inlet temperature, °C (°F)	893 (1639)	1010 (1850)
Cycle pressure ratio	13.7	8.4
Core Airflow, kg/s (lb/sec)	1.38 (3.04)	3.3 (7.3)

Engine Models

Each candidate technology was evaluated by assessing the effect of changes in TSFC, weight, cost, life (TBO), and reliability (MTBF) on the MATE baseline engine configuration by incorporation of the technology. A discussion of the models used to evaluate the changes is presented in the following paragraphs.

Performance Model (Cycle Analysis)

A thermodynamic model of the TFE731-3 engine was used to estimate changes in fuel consumption and thrust resulting from application of the candidate technology. Inputs to the model were changes in turbine inlet temperature, cooling flow, and component efficiency associated with the candidate technology. Where thrust increases resulted from temperature increases, the engine core was scaled down in flow by increasing the bypass ratio until the baseline thrust at the altitude cruise design point was restored. A maximum bypass ratio of 5.3 was selected as a practical limit for purposes of this analysis. Where thrust increases resulted from efficiency improvements and transfer of cooling flow back to working fluid, the complete engine was scaled down in flow for the same bypass ratio until the baseline thrust was restored. TSFC was optimized by varying pressure ratio. A maximum pressure ratio of 25 to 1 was assumed.

Engine performance effects of the candidate technologies were evaluated for the TPE331 in a similar fashion using a thermodynamic performance model. Effects of changes in turbine inlet temperature, cooling flow, and component efficiency resulted in a scaled up, or scaled down core flow in order to maintain a constant cruise thrust. The engine was assumed to have the same frame size.

Weight Model

Scaling of the turbofan engine weight with changes in bypass ratio is accomplished according to the following relationship:

$$\frac{\Delta WE}{WE} = \frac{WE_c}{WE}\left(1 - \frac{BPR_{baseline}}{BPR_{new}}\right) \qquad (2)$$

where: WE = Engine Weight
WE_c = Engine Core Weight
BPR = Bypass Ratio

A weight breakdown for the TFE731 engine showed that 50.5 percent of the total engine weight is core weight. This value is used in Equation (2), above.

Scaling of the turboprop engine weight for changes in core flow is accomplished using the following equation:

$$\frac{\Delta WE}{WE} = 1 - \left[\frac{\dot{M}}{\dot{M}_{baseline}}\right]^{constant} \qquad (2A)$$

where: $\dot{M}$ = Engine Core Flow

The value of the constant in the above equation was determined by AiResearch experience.

Cost Model

The cost model for engine scaling purposes is simply:

Cost is directly proportional to weight (3)

The above approximation is based on very small weight changes for the baseline engine previously described.

Life and Reliability Models

A qualitative approach was used to assess the effects of changes in component life and reliability. Although it was possible to quantitatively estimate stress-rupture life for the rotor and stators, this could not be done for corrosion life, creep-rupture life, and low-cycle-fatigue life because material property data were not available.

Engine Effects of Candidate Technologies

Tables VI and VII summarize the impact of each candidate technology on engine TSFC, weight, cost, life, and reliability utilizing the models previously described. Each technology was evaluated individually; however, it was assumed that necessary changes would be made to the engine in order that the full capability of the technology could be utilized.

The material technology exhibiting the best improvement in SFC is the low-cost/lightweight exhaust mixer nozzle. Performance predictions are based on the NASA/AiResearch QCGAT test results of the QCGAT engine mixer nozzle. Both one-third scale model tests and a sea-level full-scale engine test were run for the QCGAT Program. The 4.0-percent TSFC improvement is relative to the baseline TFE731-3 engine configured with a coannular exhaust nozzle. Since the mixer nozzle is longer and more complex than the coannular exhaust model, weight and cost penalties were assessed to the mixer nozzle. The mixer nozzle, produced by the superplastic forming (SPF) method, was also compared to a mixer nozzle produced by conventional welding methods. This results in a comparison strictly on a materials/manufacturing point of view. Only a slight performance improvement is achieved due to improved contour control of

TABLE VI. TURBOFAN ENGINE EFFECTS OF CANDIDATE TECHNOLOGIES

Candidate Technologies	ΔPerformance TSFC (%)	ΔEngine Weight (%)	ΔEngine Cost (%)	ΔEngine Life TBO (%)	ΔReliability MTBF (%)
Low-Cost Alloy for LP Turbine Airfoils	0.0	0.0	-0.2	-0.1	-0.5
Damperless Fan Blade	-0.95	-1.05	0.0	0.0	0.0
ODS Transition Liner with TBC	0.0	0.0	+0.73	+2.96	+1.8
Cooled HP Turbine Vane with TBC	0.0	-5.8	-4.42	-0.3	-0.9
Cooled DS HP Turbine Blade with TBC	-0.95	0.0	+2.50	-1.7	-4.1
Advanced, Low-Cost Abradable Turbine Gas-Path and Labyrinth Seals	-1.91	0.0	0.0	+0.6	+1.2
High-Temperature, Dual-Alloy Turbine Disk	-0.82	0.0	+0.11	0.0	0.0
Low-Cost/Lightweight Exhaust Mixer Nozzle (Compared to Coannular Nozzle)	-4.0	+2.0	+2.0	0.0	0.0
Low-Cost/Lightweight Exhaust Mixer Nozzle (Compared to Welded Mixer Nozzle)	-0.3	-2.0	-2.98	0.0	+0.9

TABLE VII. TURBOPROP ENGINE EFFECTS OF CANDIDATE TECHNOLOGIES

Candidate Technologies	ΔPerformance TSFC (%)	ΔEngine Weight (%)	ΔEngine Cost (%)	ΔEngine Life TBO (%)	ΔReliability MTBF (%)
Low-Cost Alloy for LP Turbine Airfoils	0.0	0.0	-0.3	-0.3	-2.0
Integral Net-Shape PM LP Turbine Wheel	0.0	-0.5	-0.5	0.0	0.0
ODS Transition Liner with TBC	0.0	0.0	+0.7	+2.3	+6.9
Cooled HP Turbine Vane with with TBC	-0.9	-9.6	-8.9	-0.3	-2.2
Cooled DS HP Turbine Blade with TBC	-1.3	-4.1	-2.6	-1.0	-5.8
Advanced, Low-Cost Abradable Turbine Gas-Path and Labyrinth Seals	-2.4	-2.2	-2.2	+0.4	+0.6

the SPF technique. However, substantial benefits are realized through a reduction in weight and cost, and a reliability improvement.

The cooled HP turbine vane with TBC and the cooled DS HP turbine blade with TBC, offer a higher turbine stage temperature capability to the TFE731-3 and TPE331 baseline engines and, subsequently, a higher engine thrust and horsepower result. In the case of the turbofan engine, the resultant engine thrust was reduced to the baseline thrust at the altitude cruise design point by scaling down the engine core flow by increasing the bypass ratio. TSFC was optimized by varying the cycle-pressure ratio. A pressure ratio of 25:1 was selected, as the maximum, for the cycle analysis. In the case of the turboprop engine, the resultant increase in horsepower was reduced to the baseline level by scaling down the engine based on core flow for a fixed engine frame size. Both the vane and blade with TBC were compared to the baseline components on a constant airfoil life basis. It was assumed that the other turbine components would require minor redesigns, as well as increased cooling, due to the increase in turbine gas temperature. Performance penalties were also assessed because of the increased surface roughness of the TBC. Because the turbofan baseline engine has an uncooled DS, HP turbine blade, performance benefits of a cooled DS blade were subtracted from the cooled DS blade with TBC in order to properly evaluate the TBC technology for the turbine blade. Increases in centrifugal stresses due to the TBC on the blade were taken into account for both the turbofan and turboprop engines. The large reduction in engine cost and weight for the vane with TBC technology is primarily due to the increase in bypass ratio for the turbofan engine and the decrease in core flow for the turboprop engine.

Performance improvements due to the advanced, low-cost abradable turbine gas-path and labyrinth seals are the result of reduced turbine blade tip seal clearance and decreased cooling air leakage through labyrinth seals. Both the turbofan and turboprop baseline engines include MATE Project 2 abradable seal improvements.

The primary benefit of the ODS transition liner with TBC is an improvement in life and reliability. This technology results in a higher engine cost due to the anticipated increase in the transition liner component cost.

The high-temperature dual-alloy turbine disk is used in conjunction with uncooled inserted HP turbine blades. For this reason, it is evaluated for the TFE731-3 engine only, since the baseline turboprop engine has cooled HP turbine blades. Performance improvements result from reduced cooling air to the disk. A cost increase is expected relative to the current machined forging.

The elimination of mid-span dampers for the fan blade technology improves the aerodynamic efficiency of the fan, thereby producing an overall engine performance improvement. The low-aspect-ratio design reduces the fan blade weight and a corresponding reduction in disk weight. This candidate technology is more applicable to the TFE76. Therefore, although the engine demonstration test would be done on the TFE76, the cost benefit study utilizes the TFE731-3 baseline engine model.

The integral net-shape PM turbine wheel reduces the overall cost compared to an inserted blade/disk assembly. Weight would also be reduced through the elimination of the blade/disk attachment. This technology would apply to the turboprop engine only.

The primary benefit of the low-cost alloy for LP turbine airfoils is a reduction in material cost. It was found, however, that the material cost of these components is small relative to the overall manufacturing cost. Overall cost savings, therefore, are minimal. Decreases in life and reliability are the result of the lower temperature capability and the decrease in material strength.

AIRCRAFT CONSIDERATIONS

Aircraft Selection

The turbofan aircraft selected for the cost/benefit analysis is a nonrevenue producing, business-type, twin-engine aircraft in the 6800- to 9100-kg (15,000- to 20,000-lb) gross weight class (as previously discussed in the baseline engine selection section). The aircraft is an all new design based on a composite aircraft similar to the Gates Learjet 35/36 (shown in Figure 8). The aircraft parameters set for the modeling were:

- 4000 potential aircraft
- 600-hours annual utilization
- 25-year service life
- 7710-kg (17,000-lb) takeoff gross weight
- 953-kg (2100-lb) payload
- 3700-km (2300-mi) range

The Rockwell Turbo Commander 980 (Figure 9) was chosen to be representative of a TFE331-10 powered business-type aircraft. The following aircraft parameters were set for the LCC analysis:

- 5200 potential aircraft
- 550-hours annual utilization
- 25-year service life
- 4683-kg (10,325-lb) takeoff gross weight
- 410-kg (905-lb) payload
- 4500-km (2800-mi) range

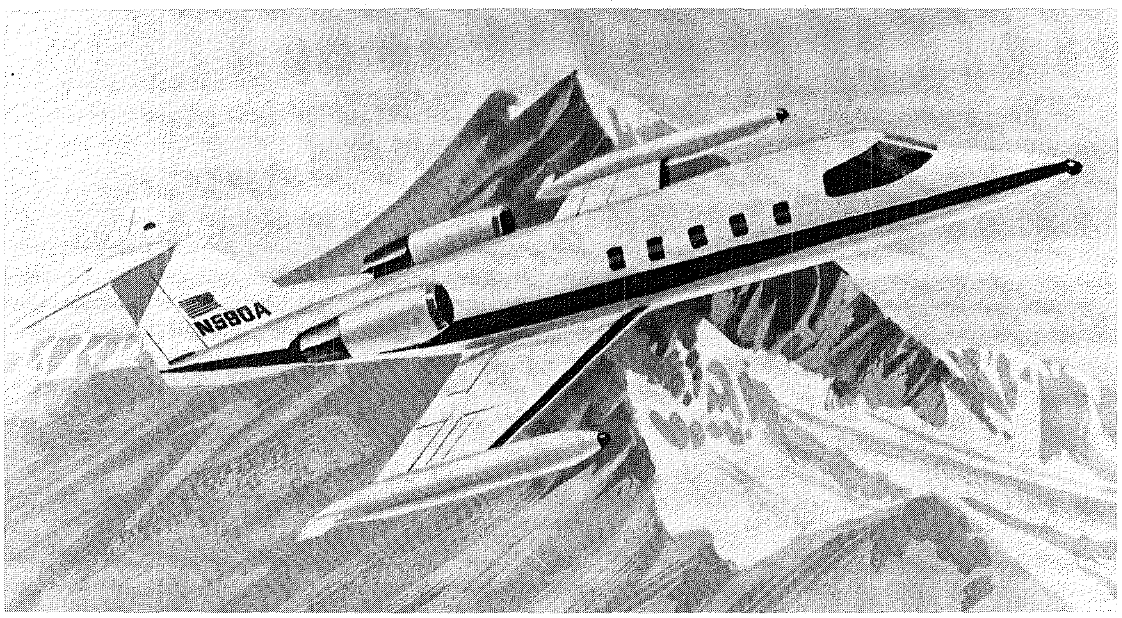
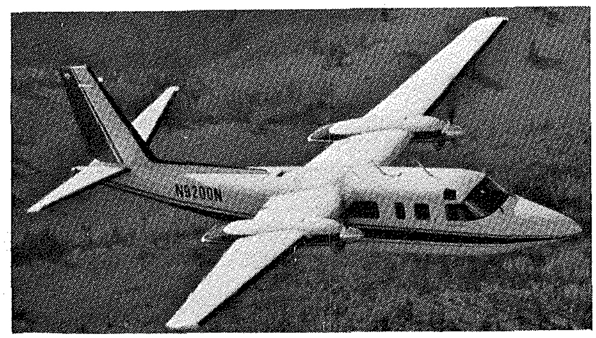
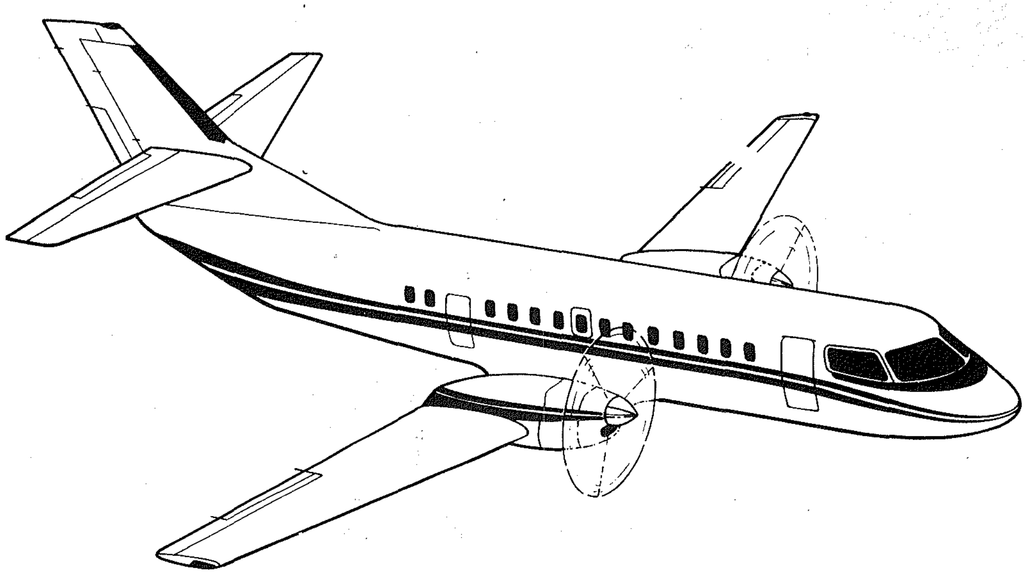


Figure 8. Gates Learjet 35/36.



ROCKWELL TURBO COMMANDER



FAIRCHILD/SAAB-SCANIA SF3000
COMMUTER AIRCRAFT

Figure 9. Turboprop Business Aircraft and Turboprop Commuter Aircraft.

The turboprop-powered commuter aircraft used in the analysis was assumed to be similar to the 30-passenger Fairchild/Saab-Scannia SF 3000 (Figure 9). The following summarizes the aircraft parameters set for this aircraft:

- 1000 potential aircraft
- 3000-hours annual utilization
- 15-year service life
- 10,930-kg (24,100-lb) takeoff gross weight
- 2,721-kg (6000-lb) payload
- 1,590-km (990-mi) range

Aircraft Baseline Life-Cycle Cost/ Direct-Operating Cost

The baseline operating and maintenance parameters for the selected twin-engine aircraft are shown in Tables VIII, IX, and X. Operating costs are established from these parameters for one aircraft and extended for the entire fleet of aircraft and service life, utilizing the LCC models for the business aircraft and the direct-operating cost models for the commuter aircraft as described in Appendix A. Tables XI and XII present the baseline LCC for the turbofan and the turboprop business aircraft. Table XIII summarizes the baseline direct-operating costs for the turboprop commuter aircraft.

TABLE VIII. BASELINE TURBOFAN BUSINESS AIRCRAFT OPERATING AND MAINTENANCE PARAMETERS

Purchase Related	
o Aircraft acquisition cost, $\$(10^6)$	2.63 (includes engine cost)
o Engine acquisition cost, $\$(10^6)$	0.80 (two engines)
o Airframe fixed weight cost, $/kg ($/lb)	357 (162)
o Airframe variable weight cost, $/kg ($/lb)	714 (324)
o Equity, %	40
o Loan interest rate, %	12
o Imputed interest, %	12
o Insurance rate, %	1
o Property tax rate, %	1
Operation Related	
o Annual crew wages, $	70,000
o Annual crew expenses, $	6,400
o Annual hanger cost, $	8,050
o Fuel weight, kg (lb)	2,800 (6,172)
o Annual landing/parking fees, $	1,610
o Annual miscellaneous costs, $	1,400
o Annual utilization, hrs	600
o Fuel price, ¢/liter (¢/gal)	31.7 (120)
o Flight Mach number	0.85
o Maximum sea-level, static thrust, daN (lb)	1,779 (4,000)
o Average cruise thrust, daN (lb)	363 (817)
o Average cruise TSFC, kg/hr/daN (lb/hr/lb)	0.745 (0.732)
o Average cruise L/D	11.15
o Payload, kg (lb)	765 (1,686)
o Cruise range, hrs	6.13
o Service life, years	25
Maintenance Related	
o Annual preflight servicing cost, $	6,300
o Engine inspection cost, $/flt-hr	7
o Annual engine overhaul cost, $	23,710
o Annual engine unscheduled repair cost, $	5,847
o Airframe inspection cost, $/flt-hr	14.80
o Annual airframe overhaul cost, $	24,219
o Annual airframe unscheduled repair cost, $	5,847

TABLE IX. BASELINE TURBOPROP BUSINESS AIRCRAFT OPERATING AND MAINTENANCE PARAMETERS

Purchase Related	
o Aircraft acquisition cost, $\$(10^6)$	1.24 (includes engine cost).
o Engine acquisition cost, $\$(10^6)$	0.26 (two engines)
o Airframe fixed weight cost, \$/kg (\$/lb)	357 (162)
o Airframe variable weight cost, \$/kg (\$/lb)	472 (214)
o Equity, %	40
o Loan interest rate, %	12
o Imputed interest, %	12
o Insurance rate, %	1
o Property tax rate, %	1
Operation Related	
o Annual crew wages, \$	70,000
o Annual crew expenses, \$	6,400
o Annual hanger cost, \$	8,050
o Fuel weight, kg (lb)	1,253 (2,763)
o Annual landing/parking fees, \$	1,610
o Annual miscellaneous costs, \$	1,400
o Annual utilization, hrs	550
o Fuel price, ¢/liter (¢/gal)	31.7 (120)
o Flight speed (k&s)	265
o Maximum sea-level, static power, KW (SHP)	775 (1040)
o Average cruise power, KW (SHP)	246 (330)
o Average cruise SFC, kg/hr/KW (lb/hr/HP)	0.324 (0.532)
o Average cruise L/D	12.7
o Payload, kg (lb)	586 (1292)
o Cruise range, hrs	9.19
o Service life, years	25
Maintenance Related	
o Annual preflight servicing cost, \$	6,300
o Engine inspection cost, \$/flt-hr	7
o Annual engine overhaul cost, \$	10,420
o Annual engine unscheduled repair cost, \$	2,255
o Airframe inspection cost, \$/flt-hr	14.8
o Annual airframe overhaul cost, \$	14,710
o Annual airframe unscheduled repair cost, \$	3,550

TABLE X. BASELINE TURBOPROP COMMUTER AIRCRAFT OPERATING AND MAINTENANCE PARAMETERS

Purchase Related		
o	Aircraft acquisition cost, $\$(10^6)$	3.00 (include engine cost)
o	Engine acquisition cost, $\$(10^6)$	0.50 (two engines)
Operation Related		
o	Airframe depreciation, $/flt-hr	74.38
o	Engine depreciation, $/flt-hr	17.71
o	Airframe insurance, $/flt-hr	12.89
o	Engine insurance $/flt-hr	2.00
o	Crew costs, $/flt-hr	66.82
o	Fuel costs, $/flt-hr	300.75
o	Oil costs, $/flt-hr	0.44
o	Fuel weight, kg (lb)	1,432 (3,157)
o	Annual utilization, hrs	3,000
o	Fuel prices, ¢/liter (¢/gal)	53 (200)
o	Flight speed, kts	269
o	Maximum sea-level, static power, KW (SHP)	1,268 (1,700)
o	Average cruise power, KW (SHP)	703 (943)
o	Average cruise SFC, kg/hr/KW (lb/hr/HP)	0.338 (0.551)
o	Average cruise, L/D	10.36
o	Payload, kg (lb)	2.721 (6,000)
o	Cruise range, hrs	3.19
o	Service life, years	15
Maintenance Related		
o	Airframe maintenance labor cost, $/flt-hr	18.65
o	Airframe maintenance parts cost, $/flt-hr	36.25
o	Engine repair labor, $/flt-hr	0.76
o	Engine repair and maintenance parts cost, $/flt-hr	17.04
o	Engine refurbish labor cost, $/flt-hr	4.89
o	Engine refurbish parts cost, $/flt-hr	12.21
o	Engine inspection cost, $/flt-hr	0.03

TABLE XI. 25-YEAR LIFE-CYCLE COST FOR A BUSINESS FLEET OF 4000 TURBOFAN-POWERED AIRCRAFT

	Airframe $\$(10^6)$	Engine $\$(10^6)$	Total $\$(10^6)$
Acquisition Cost	7320.0	3200.0	10520.0
Fixed Operating Costs			
o Interest on loan	1317.6	576.0	1893.6
o Imputed interest on investment	12737.0	5568.0	18305.0
o Crew wages	7013.0	--	7013.0
o Insurance	915.0	400.0	1315.0
o Taxes	915.0	400.0	1315.0
o Hanger	805.3	--	805.3
o Miscellaneous costs	140.3	--	140.3
Variable Operating Costs			
o Fuel	--	11075.3	11075.3
o Preflight servicing	631.2	--	631.2
o Airframe inspection	887.9	--	887.9
o Airframe repair	584.8	--	584.8
o Airframe overhaul	2421.9	--	2421.9
o Engine inspection	--	841.6	841.6
o Engine repair	--	1169.5	1169.5
o Engine overhaul	--	4742.0	4742.0
o Service bulletin incorporation	--	339.2	339.2
o Crew expenses	644.2	--	644.2
o Landing, parking, catering, etc.	161.1	--	161.1
Total	36494.3	28311.6	64805.9

TABLE XII. 25-YEAR LIFE-CYCLE COST FOR A BUSINESS FLEET OF 5200 TURBOPROP-POWERED AIRCRAFT

	Airframe (10^6)	Engine (10^6)	Total (10^6)
Acquisition Cost	5096.0	1352.0	6448.0
Fixed Operating Costs			
o Interest on loan	917.2	243.4	1160.6
o Imputed interest on investment	6113.1	1621.9	7735.0
o Crew wages	9100.0	--	9100.0
o Insurance	637.0	169.0	806.0
o Taxes	637.0	169.0	806.0
o Hanger o Miscellaneous costs	} 1228.5	--	1228.5
Variable Operating Costs			
o Fuel	--	3793.5	3793.5
o Preflight servicing	598.0	221.0	819.0
o Airframe inspection	1058.2	--	1058.2
o Airframe repair	461.5	--	461.5
o Airframe overhaul	1912.3	--	1912.3
o Engine inspection	--	1001.0	1001.0
o Engine repair	--	586.3	586.3
o Engine overhaul	--	2709.2	2709.2
o Crew expenses	832.0	--	832.0
o Landing, parking, catering, etc.	209.3	--	209.3
Total	28800.1	11866.3	40666.4

TABLE XIII. 15-YEAR DIRECT OPERATING COSTS FOR A FLEET OF 1000 TURBOPROP-POWERED COMMUTER AIRCRAFT

	Airframe (10^6)	Engine (10^6)	Total (10^6)
Operation Costs			
o Depreciation	3347.1	797.0	4144.1
o Insurance	580.1	90.0	670.1
o Crew costs	3006.9	--	3006.9
o Fuel	--	13533.8	13533.8
o Oil	--	19.8	19.8
Maintenance Costs			
o Maintenance labor	839.3	34.2	873.5
o Maintenance parts	1631.3	766.8	2398.1
o Engine refurbish labor	--	220.1	220.1
o Engine refurbish parts	--	549.5	549.5
o Engine inspection	--	1.4	1.4
Total	9404.7	16012.6	25417.3

AIRCRAFT BENEFIT ANALYSIS

Trade Factors

AiResearch has developed a technique for determining aircraft LCC that begins with the formulation of a takeoff gross weight (TOGW) model for the aircraft, and proceeds to the formulation of the cost models for development, acquisition, operation, and maintenance costs for both the airframe and engine. This technique allows airframe weight and cost to be evaluated as changes in engine parameters, especially engine weight and fuel consumption, are considered.

Changing the airplane size and, hence, engine size for the turboprop-powered commuter aircraft requires a direct operating cost (DOC) model. As in the LCC model, the DOC analysis begins with the formulation of a TOGW model.

Sensitivity coefficients of the TOGW model are obtained for changes in engine TSFC and weight. Then, cost models for development, acquisition, operation, and maintenance are prepared, and the baseline costs are formulated as previously noted. A LCC/DOC model is assembled from these models based upon linearized effects of various engine parameters, and LCC/DOC sensitivity coefficients developed for engine TSFC, weight, cost, life (TBO), and reliability (MTBF). When applied to engine design changes, these coefficients will project a change in LCC/DOC.

Descriptions of the aircraft weight models and the various cost models are included in Appendix A of this report.

Sensitivity coefficients for changes in engine weight and fuel consumption are calculated by changing the appropriate elements of the TOGW equation. For instance, sensitivity to changes in engine weight is determined by changing the engine weight in the installed engine weight (IEW) element and calculating a new takeoff gross weight. The aircraft fixed weight element is held constant for the specific aircraft designs since this element represents basically the payload. The new takeoff gross weight is portioned using the original weight fractions established for the aircraft, and new weights and thrust are calculated.

In a similar manner, sensitivity coefficients are calculated for changes in engine fuel consumption. The sensitivity coefficients calculated for changes in engine weight and TSFC for the analysis are tabulated in Tables XIV, XV, and XVI. The new thrust, fuel weight, and other parameters listed in the above tables are utilized in the appropriate LCC and DOC models, presented in Appendix A, to obtain the sensitivity of engine weight and TSFC changes on aircraft LCC and DOC.

In addition, sensitivity to engine cost, time-between-overhaul (TBO), and mean-time-between-failure (MTBF) are also calculated.

The change in LCC and direct-operating cost resulting from a one-percent change in TSFC, engine weight, engine cost, TBO, and MTBF are tabulated in Tables XVII, XVIII, and XIX.

TABLE XIV. SENSITIVITY COEFFICIENTS CALCULATED FOR CHANGES IN ENGINE WEIGHT (ΔTSFC) AND (ΔWE) FOR TURBOFAN AIRCRAFT

Parameter	ΔTSFC = -1%	ΔWE = -1%
ΔThrust	-1.7%	-0.7%
ΔFuel weight	-2.5%	-0.7%
ΔEngine installed weight	-1.7%	-1.7%
ΔAirframe variable weight	-1.7%	-0.7%
ΔAircraft empty weight	-1.8%	-0.8%

TABLE XV. SENSITIVITY COEFFICIENTS CALCULATED FOR CHANGES IN ENGINE WEIGHT (ΔTSFC) AND (ΔWE) FOR TURBOPROP BUSINESS AIRCRAFT

Parameter	ΔTSFC = -1%	ΔWE = -1%
ΔHorsepower	-1.1%	-0.6%
ΔFuel weight	-1.9%	-0.6%
ΔEngine installed weight	-1.1%	-1.5%
ΔAirframe variable weight	-1.1%	-0.6%
ΔAircraft empty weight	-1.1%	-0.7%

TABLE XVI. SENSITIVITY COEFFICIENTS CALCULATED FOR CHANGES IN ENGINE WEIGHT (ΔTSFC) AND (ΔWE) FOR TURBOPROP COMMUTER AIRCRAFT

Parameter	ΔTSFC = -1%	ΔWE = -1%
ΔHorsepower	-0.3%	-0.1%
ΔFuel weight	-1.5%	-0.1%
ΔEngine installed weight	-1.3%	-1.1%
ΔAirframe variable weight	-0.3%	-0.1%
ΔAircraft empty weight	-0.4%	-0.2%

TABLE XVII. CHANGES IN LIFE-CYCLE COST FOR ONE-PERCENT CHANGE IN VARIOUS PARAMETERS FOR THE TURBOFAN AIRCRAFT

Parameter (One-Percent Change)	1980 ΔLCC
Thrust specific fuel consumption (TSFC)	1.20%
Engine weight (WE)	0.47%
Engine cost (CE)	0.17%
Time-between-overhaul (TBO)	0.07%
Mean-time-between-failure (MTBF)	0.02%

TABLE XVIII. CHANGES IN LIFE-CYCLE COST FOR ONE-PERCENT CHANGE IN VARIOUS PARAMETERS FOR THE TURBOPROP BUSINESS AIRCRAFT

Parameter (One-Percent Change)	1980 ΔLCC
Specific fuel consumption (SFC)	0.70%
Engine weight (WE)	0.35%
Engine cost (CE)	0.11%
Time-between-overhaul (TBO)	0.06%
Mean-time-between-failure (MTBF)	0.01%

TABLE XIX. CHANGES IN DIRECT-OPERATING COST FOR ONE-PERCENT CHANGE IN VARIOUS PARAMETERS FOR THE TURBOPROP COMMUTER AIRCRAFT

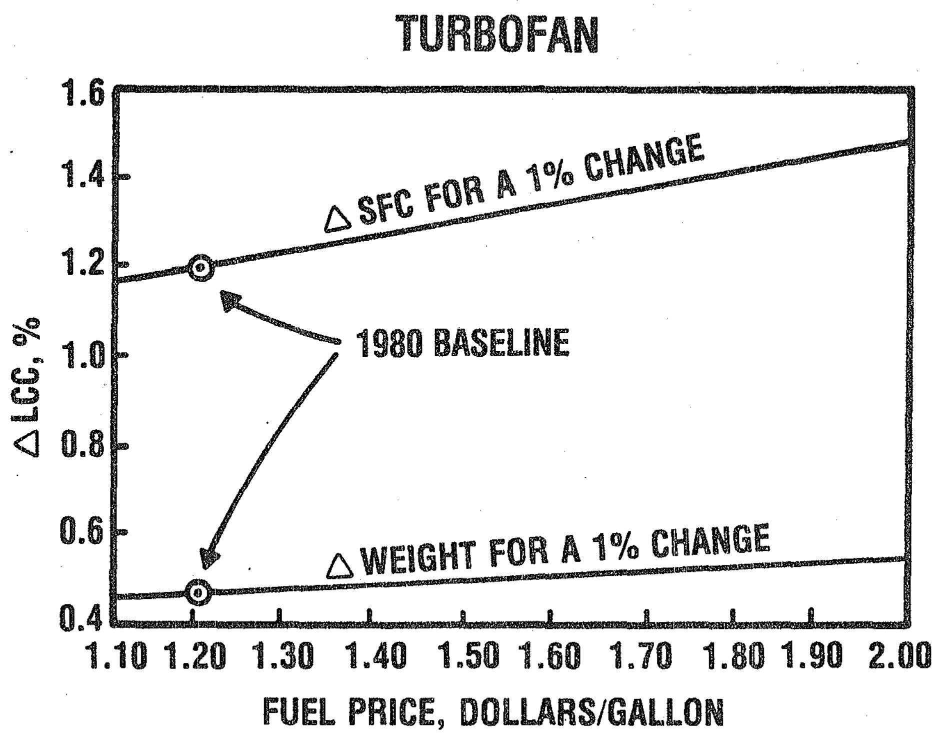
Parameter (One-Percent Change)	1980 ΔDOC
Specific fuel consumption (SFC)	0.86%
Engine weight (WE)	0.13%
Engine cost (CE)	0.09%
Time-between-overhaul (TBO)	0.03%
Mean-time-between-failure (MTBF)	0.03%

As noted in the above tables, SFC followed by engine weight has the greatest influence on LCC and direct-operating cost. Furthermore, as the cost of fuel increases, the effects of changes in SFC and engine weight on LCC and DOC are even more pronounced. Table XX compares sensitivity factors from the Cost/Benefit Analysis (Part 1) (ref. 1) to the current sensitivity factors. As can be seen, the sharp rise in fuel prices has had a major impact on LCC studies.

TABLE XX. COMPARISON OF TURBOFAN BUSINESS AIRCRAFT SENSITIVITY COEFFICIENTS

Parameter (One-Percent Change)	1975 ΔLCC	1980 ΔLCC
Specific fuel consumption (TSFC)	0.91%	1.20%
Engine weight (WE)	0.35%	0.47%
Engine cost (CE)	0.19%	0.17%
Time-between overhaul (TBO)	0.10%	0.07%
Mean-time between failure (MTBF)	0.03%	0.02%

The fuel price used in the current analysis was $0.32 per liter ($1.20 per gallon) and represents 17.1 percent of the total LCC of the turbofan aircraft and 9.3 percent of the total LCC of the turboprop commuter aircraft. A sensitivity analysis was conducted to determine the effect of fuel price on fuel consumption and engine weight sensitivity coefficients. The results of this analysis are shown in Figure 10.



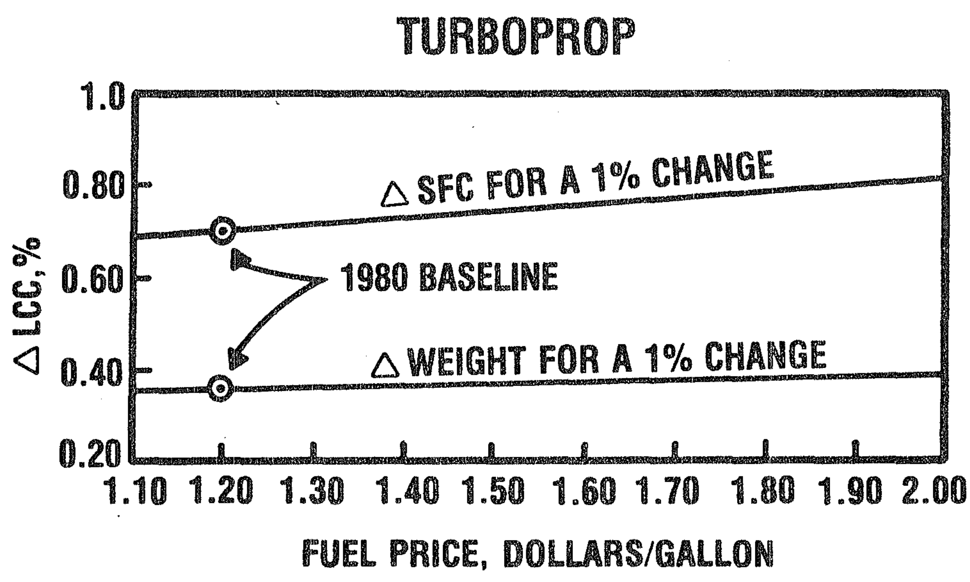


Figure 10. Sensitivity Analysis for the Determination of the Effects of Fuel Prices on SFC and Engine Weight Sensitivity Coefficients.

Aircraft Benefits

The nine candidate material technologies were evaluated against the baseline engine for TSFC, weight, cost, TBO, and MTBF as previously shown. These engine results were then incorporated in the aircraft LCC and DOC models using the factors previously described. The results of this analysis, in terms of change in aircraft LCC and DOC, are listed in Tables XXI, XXII, and XXIII.

TABLE XXI. REPRESENTATIVE TURBOFAN AIRCRAFT LIFE-CYCLE-COST RANKING

Rank	Technology	ΔLCC $\$(10^6)$
1	Low-cost/lightweight exhaust mixer nozzle (compared to coannular nozzle)	-2281
2	Cooled turbine vane with TBC	-2229
3	Advanced abradable gas-path and labyrinth seals	-1529
4	Low-cost/lightweight exhaust mixer nozzle (compared to welded nozzle)	-1186
5	Damperless fan blades	-1056
6	High-temperature dual-alloy turbine disk	-622
7	Cooled turbine blades with TBC	-331
8	ODS transition liner with TBC	-80
9	Low-cost alloy for LP turbine airfoils	-8

TABLE XXII. REPRESENTATIVE TURBOPROP BUSINESS AIRCRAFT LIFE-CYCLE-COST RANKING

Rank	Technology	ΔLCC (10^6)
1	Cooled turbine vane with TBC	-2005
2	Advanced abradable gas-path and labyrinth seals	-1110
3	Cooled turbine blade with TBC	-1021
4	Integral net-shape powder-metal turbine wheel	-98
5	ODS transition liner with TBC	-57
6	Low-cost alloy for LP turbine airfoils	+4

TABLE XXIII. REPRESENTATIVE TURBOPROP COMMUTER AIRCRAFT DIRECT OPERATING COST

Rank	Technology	ΔDOC (10^6)
1	Cooled turbine vane with TBC	-686
2	Advanced abradable gas-path and labyrinth seals	-656
3	Cooled turbine blade with TBC	-424
4	ODS transition liner with TBC	-53
5	Integral net-shape powder-metal turbine wheel	-3
6	Low-cost alloy for LP turbine airfoils	+10

As shown in the above tables, the most significant benefits are from those technologies that produce a significant reduction in fuel consumption (SFC). The greatest reduction in fuel consumption is seen from the low-cost/lightweight exhaust mixer nozzle. The relatively high ranking of the cooled turbine vane with TBC is due to the increased temperature capabilities predicted for this technology. The primary benefits of the advanced abradable gas-path and labyrinth seals are derived from reduction in turbine cooling air and an improvement in turbine efficiency through reduced turbine blade tip seal clearances.

RESULTS AND DISCUSSION

Relative Value Analysis

Since the nine material technologies studied here are currently at different stages in their development cycles, the delta life-cycle costs indicated for these technologies are not necessarily representative of their current investment worth. The indicated benefits need to be qualified by the current estimated development costs and risks associated with each technology. One method of accomplishing this is by utilizing a NASA-developed parameter termed "Relative Value" as defined below:

$$\text{Relative Value} = \frac{\Delta LCC \text{ or } \Delta DOC}{\text{Development Cost}} \times \text{Probability of Success} \quad (4)$$

This parameter was calculated for each of the nine material technologies using the project probability of success developed in the risk analysis, the technology development cost, and the delta life-cycle cost, and direct-operating cost calculated for each technology. The resulting values are shown in Tables XXIV, XXV, and XXVI with the technologies listed in order of decreasing Relative Value.

The highest Relative Value ranking is the low-cost/lightweight exhaust mixer nozzle. The mixer nozzle performance benefits far outweigh the cost and weight penalties imposed comparing it to the current coannular exhaust nozzle. The exhaust mixer nozzle technology also enjoys the highest project probability of success. The exhaust mixer nozzle technology is followed by the cooled turbine vane with TBC and the advanced abradable gas-path and labyrinth seals in the Relative Value ranking. It is interesting to note that the cooled turbine vane with TBC ranks first for the turboprop-powered business aircraft and the advanced abradable gas-path and labyrinth seals ranks first for the turboprop-powered commuter aircraft. This is primarily due to two factors. The

TABLE XXIV. MATERIAL TECHNOLOGIES RELATIVE VALUE SUMMARY FOR TURBOFAN-POWERED BUSINESS AIRCRAFT

Rank	Technology	Relative Value	ΔLCC $\$(10^6)$	Development Cost $\$(10^6)$	Probability of Success (%)
1	Low-cost/lightweight exhaust mixer nozzle	1711	-2281	1.0	75
2	Cooled turbine vane with TBC	1207	-2229	1.2	65
3	Advanced abradable gas-path and labyrinth seals	956	-1529	0.8	50
4	Low-cost/lightweight exhaust mixer nozzle (compared to welded nozzle)	890	-1186	1.0	75
5	High-temperature dual-alloy turbine disk	207	-622	1.8	60
6	Damperless fan blades	170	1056	2.8	45
7	Cooled turbine blade with TBC	33	-331	2.0	20
8	ODS transition liner with TBC	32	-80	1.5	60
9	Low-cost alloy for LP turbine airfoils	3	-8	1.5	50

TABLE XXV. MATERIAL TECHNOLOGIES RELATIVE VALUE SUMMARY FOR TURBOPROP-POWERED BUSINESS AIRCRAFT

Rank	Technology	Relative Value	ΔLCC (10^6)	Development Cost (10^6)	Probability of Success (%)
1	Cooled turbine vane with TBC	1086	-2005	1.2	65
2	Advanced abradable gas-path and labyrinth seals	694	-1110	0.8	50
3	Cooled turbine blade with TBC	102	-1021	2.0	20
4	ODS transition liner with TBC	23	-57	1.5	60
5	Integral net-shape powder-metal turbine wheel	6	-98	2.5	15
6	Low-cost alloy for LP turbine airfoils	-12	+4	1.5	50

TABLE XXVI. MATERIAL TECHNOLOGIES RELATIVE VALUE SUMMARY FOR TURBOPROP-POWERED COMMUTER AIRCRAFT

Rank	Technology	Relative Value	ΔDOC (10^6)	Development Cost (10^6)	Probability of Success (%)
1	Advanced abradable gas-path and labyrinth seals	410	-650	0.8	50
2	Cooled turbine vane with TBC	372	-686	1.2	65
3	Cooled turbine blade with TBC	42	-424	2.0	20
4	ODS transition liner with TBC	21	-53	1.5	60
5	Integral net-shape powder-metal turbine wheel	<1	-3	2.5	15
6	Low-cost alloy for LP turbine airfoils	-30	+10	1.5	50

commuter aircraft is much more sensitive to SFC compared to engine weight and cost, and the MTBF sensitivity becomes more important relative to the other sensitivity coefficients as shown in Tables XVIII and XIX.

AIRESEARCH CORPORATE RANKING

The low-cost/lightweight exhaust mixer nozzle, the cooled HP turbine vane with TBC, and the advanced, low-cost abradable turbine gas-path and labyrinth seals technologies that rank highest on the Relative Value basis and showed the largest reduction in life-cycle cost and direct-operating cost were also highest in the AiResearch priority ranking. The ranking for the ten candidate technologies is presented in Table XXVII.

The low-cost/lightweight titanium exhaust mixer nozzle technology received the highest corporate ranking primarily because of the potential performance improvement gains. Unlike technologies which require higher turbine inlet temperatures (with a subsequent engine redesign) to achieve their greatest performance improvement potential, the exhaust mixer nozzle will replace the current coannular nozzles without any basic engine changes. The cost/benefit analysis results also show that the mixer nozzle manufactured using the SPF method has substantial savings in weight and cost compared to a mixer nozzle manufactured using conventional forming and welding techniques.

Cooled HP turbine vane durability has always been a prime concern in the design and development of high-temperature gas turbine engines. The cooled HP turbine vane with TBC technology would greatly enhance the cooling effectiveness of vanes designed for high-temperature operation. This technology has the highest payoff for vanes designed with sophisticated cooling schemes, since the insulating effect of the TBC is more beneficial with an increase in heat flux through the airfoil wall.

The advanced, low-cost abradable turbine gas-path and labyrinth seals technology ranked high in the AiResearch priority ranking due to the reduced cooling air and improved turbine efficiency benefits. Turbine blade tip seal clearances have a very

TABLE XXVII. AIRESEARCH CORPORATE RANKING OF THE MATERIAL TECHNOLOGIES

1.	Low-cost/lightweight exhaust mixer nozzle - TFE only.
2.	Cooled HP turbine vane with TBC.
3.	Advanced, low-cost abradable turbine gas-path and labyrinth seals.
4.	High-temperature dual-alloy turbine disk - TFE only.
5.	Damperless fan blade - TFE only.
6.	Cooled directionally solidified HP turbine blade with TBC.
7.	Oxide-dispersion strengthened transition liner with TBC.
8.	Integral net-shape power-metal turbine wheel - TPE only.
9.	Low-cost alloy for LP turbine airfoils.

strong influence on turbine performance because of the short turbine blade length of small gas turbine engines. It is felt that this technology would be especially well suited for the current TPE331-10 engine.

A low-cost directionally-solidified (DS) turbine blade was developed under the NASA MATE Project 1 and is currently in production use on the TFE731-3-100 engine. Although the high-temperature dual-alloy turbine disk technology did not rank very high in the Relative Value ranking, it would greatly reduce the amount of cooling air required to cool the disk and blade attachment in designs which incorporate an uncooled HP turbine blade, such as the TFE731-3-100.

The damperless fan blade technology is applicable to new low-aspect-ratio fan blade designs that would not require a mid-span damper. This type of design results in improved aerodynamics and reduced fan stage weight.

The cooled DS HP turbine blade with TBC technology, like the vane with TBC, has its highest payoff in a high-temperature application. The turbine blade with TBC, however, is less attractive because of the higher centrifugal stresses in the blade due to the TBC coating and the higher development risk.

The ODS transition liner with TBC technology would greatly improve the life and reliability of the burner transition liner. However, this technology ranks low, since there is no performance improvement associated with this component and finished part cost would be twice that of current transition liners.

The primary benefit of the integral net-shape PM turbine wheel is to improve the material properties relative to Inco 731LC. This technology has a low ranking because of the high estimated development costs and the very low project probability of success.

The technology receiving the lowest ranking is the low-cost alloy for LP turbine airfoils. This technology actually produces an increase in life-cycle cost and direct-operating cost and would not be a viable candidate unless there is a sharp increase in the price of current nickel-base alloys.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study are summarized in Tables XXVII through XXXIV. The highest ranking technology in both Relative Value and company priority is the low-cost/lightweight exhaust mixer nozzle. The following technologies are recommended for consideration as future MATE projects:

- Low-cost/lightweight exhaust mixer nozzle
- Cooled HP turbine vane with TBC
- Advanced, low-cost abradable turbine gas-path and labyrinth seals
- High-temperature dual-alloy turbine disk
- Damperless fan blade

The remaining candidates, while generally having value, should not be developed at the expense of any of the recommended technologies.

TABLE XXVIII. REPRESENTATIVE TURBOFAN AIRCRAFT LIFE-CYCLE-COST RANKING

Rank	Technology	ΔLCC $\$(10^6)$
1	Low-cost/lightweight exhaust mixer nozzle (compared to coannular nozzle)	-2281
2	Cooled turbine vane with TBC	-2229
3	Advanced abradable gas-path and labyrinth seals	-1529
4	Low-cost/lightweight weight exhaust mixer nozzle (compared to welded nozzle)	-1186
5	Damperless fan blades	-1056
6	High-temperature dual-alloy turbine disk	-622
7	Cooled turbine blade with TBC	-331
8	ODS transition liner with TBC	-80
9	Low-cost alloy for LP turbine airfoils	-8

TABLE XXIX. REPRESENTATIVE TURBOPROP BUSINESS AIRCRAFT LIFE-CYCLE-COST RANKING

Rank	Technology	ΔLCC $\$(10^6)$
1	Cooled turbine vane with TBC	-2005
2	Advanced abradable gas-path and labyrinth seals	-1110
3	Cooled turbine blade with TBC	-1021
4	Integral net-shape powder-metal turbine wheel	-98
5	ODS transition liner with TBC	-57
6	Low-cost alloy for LP turbine airfoils	+4

TABLE XXX. REPRESENTATIVE TURBOPROP COMMUTER AIRCRAFT DIRECT-OPERATING-COST RANKING.

Rank	Technology	ΔDOC $\$(10^6)$
1	Cooled turbine vane with TBC	-686
2	Advanced abradable gas-path and labyrinth seals	-656
3	Cooled turbine blade with TBC	-424
4	ODS transition liner with TBC	-53
5	Integral net-shape powder-metal turbine wheel	-3
6	Low-cost alloy for LP turbine airfoils	+10

TABLE XXXI. REPRESENTATIVE TURBOFAN-POWERED BUSINESS AIRCRAFT RELATIVE VALUE RANKING

Rank	Technology	Relative Value
1	Low-cost/lightweight exhaust mixer nozzle	1711
2	Cooled turbine vane with TBC	1207
3	Advanced abradable gas-path and labyrinth seals	956
4	Low-cost/lightweight exhaust mixer nozzle (compared to welded nozzle)	890
5	High-temperature dual-alloy turbine disk	207
6	Damperless fan blades	170
7	Cooled turbine blade with TBC	33
8	ODS transition liner with TBC	32
9	Low-cost alloy for LP turbine airfoils	3

TABLE XXXII. REPRESENTATIVE TURBOPROP-POWERED BUSINESS AIRCRAFT RELATIVE VALUE RANKING

Rank	Technology	Relative Value
1	Cooled turbine vane with TBC	1086
2	Advanced abradable gas-path and labyrinth seals	694
3	Cooled turbine blade with TBC	102
4	ODS transition liner with TBC	23
5	Integral net-shape powder-metal turbine wheel	6
6	Low-cost alloy from LP turbine airfoils	-12

TABLE XXXIII. REPRESENTATIVE TURBOPROP-POWERED COMMUTER AIRCRAFT RELATIVE VALUE RANKING

Rank	Technology	Relative Value
1	Advanced abradable gas-path and labyrinth seals	410
2	Cooled turbine vane with TBC	372
3	Cooled turbine blade with TBC	42
4	ODS transition liner with TBC	21
5	Integral net-shape powder-metal turbine wheel	<1
6	Low-cost alloy from LP turbine airfoils	-30

TABLE XXXIV. AIRESEARCH CORPORATE RANKING

1	Low-cost/lightweight exhaust mixer nozzle
2	Cooled HP turbine vane with TBC
3	Advanced, low-cost abradable turbine gas-path and labyrinth seals
4	High-temperature dual-alloy turbine disk
5	Damperless fan blade
6	Cooled directionally-solidified HP turbine blade with TBC
7	Oxide-dispersion strengthened transition liner with TBC
8	Integral net-shape powder-metal turbine wheel
9	Low-cost alloy for LP turbine airfoils

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APPENDIX A

AIRCRAFT WEIGHT LIFE-CYCLE COST, AND DIRECT-OPERATING COST MODELS

APPENDIX A

AIRCRAFT WEIGHT, LIFE-CYCLE COST, AND DIRECT-OPERATING COST MODELS

WEIGHT MODEL

In synthesizing the total weight of an aircraft, it is convenient to divide the weight into a number of major components. The AiResearch LCC and DOC models make use of a TOGW model consisting of four major elements: airframe fixed weight (AFFW), airframe variable weight (AFVW), installed engine weight (IEW), and fuel and tankage weight (FTW), all expressed as fractions of TOGW (ref. 4).

The airframe fixed weight consists of the crew and support systems, instruments, and avionics. These items are specified by the aircraft operational requirements and, therefore, do not vary with aircraft size.

The airframe variable weight consists primarily of a structure such as the fuselage, wings, empennage, and landing gear. System weight is also included in the variable weight since system weight tends to scale with structure weight because of the direct influence of size on control actuation and hydraulic pump requirements, lenghts of wiring, piping, etc.

The installed engine weight consists of the bare engine weight and the additional weight due to the installation such as the pylons, connections, and engine oil. Also included in this weight is the starting system.

The fuel and tankage weight consists of the fuel and fuel tanks including any auxiliary fuel tanks. The fuel pumps, pipes, and collector plenums would also be included as part of the tankage weight.

Tables XXXV, XXXVI, and XXXVII are a tabulation of the weight breakdown for the aircraft used in the cost/benefit analysis. The takeoff gross weight can be related to the engine thrust-to-weight ratio and TSFC in the following form:

$$\underbrace{TOGW=F_{FW}(TOGW)}_{AFFW} + \underbrace{F_{VW}(TOGW)}_{AFVM} + \underbrace{\frac{K_1(TOGW)}{L/D(FN/WE)}}_{IEW} + \underbrace{K_2(TOGW)\,1-e^{[-TSFC(T)/L/D]}}_{FTW} \qquad (A1)$$

where:

F_{FW} = airframe fixed weight fraction (AFFW/TOGW)

F_{VW} = airframe variable weight fraction (AFVW/TOGW)

FN/WE = average engine cruise thrust/weight ratio

L/D = aircraft average life (L)/drag (D) ratio at cruise

T = aircraft cruise endurance with all fuel consumed

TSFC = average engine thrust specific fuel consumption at cruise

K_1 = engine installation factor (nacelles, mounts, oil tank, lines, etc.)

K_2 = fuel tankage factor (entrained fuel plus tank, pump, and line weight)

The consumption of all fuel is, of course, unrealistic; but both the useful fuel requirements and the reserve fuel requirements vary with changes in aircraft and engine parameters. Because range-dominated vehicles spend most of their operating time at cruise conditions, sensitivity analysis for changes in engine parameters can be performed by assuming that all operation is at the cruise condition. This approach also assumes that the aircraft performance is not marginal at takeoff; therefore, the takeoff performance with a candidate configuration change should also be evaluated.

TABLE XXXV. REPRESENTATIVE TURBOFAN-POWERED BUSINESS AIRCRAFT WEIGHT BREAKDOWN

Parameter	Weight kg(lb)
Airframe Fixed Weight	
o Instrumentation, Avionics Equipment, Furnishing	435 (959)
o Crew Plus Baggage	176 (387)
o Payload	765 (1686)
TOTAL	1376 (3032)
Airframe Variable Weight	
o Fuselage	739 (1630)
o Landing Gear	245 (540)
o Wing	639 (1410)
o Empennage	141 (310)
o Controls	590 (1300)
TOTAL	2354 (5190)
Installed Engine Weight	
o Engines (2)	655 (1444)
o Engine Installation	296 (652)
TOTAL	951 (2096)
Fuel and Tankage Weight	
o Fuel (includes a 30-minute reserve)	2799 (6171)
o Fuel System (includes usable fuel)	122 (269)
o Auxiliary Fuel Tanks	109 (240)
TOTAL	3030 (6680)
Takeoff Gross Weight (TOGW)	7711 (17,000)

TABLE XXXVI. REPRESENTATIVE TURBOPROP-POWERED BUSINESS AIRCRAFT WEIGHT BREAKDOWN

Parameter	Weight kg (lb)
Airframe Fixed Weight	
o Instrumentation, Avionics Equipment, Furnishing	366 (806)
o Crew Plus Baggage	176 (387)
o Payload	410 (905)
TOTAL	952 (2098)
Airframe Variable Weight	
o Fuselage	585 (1290)
o Landing Gear	150 (330)
o Wing	620 (1367)
o Empennage	95 (210)
o Controls	352 (775)
TOTAL	1802 (3972)
Installed Engine Weight	
o Engines (2)	308 (680)
o Engine Installation	255 (563)
TOTAL	563 (1243)
Fuel and Tankage Weight	
o Fuel (includes reserve)	1253 (2763)
o Fuel System (includes usable fuel)	113 (249)
TOTAL	1366 (3012)
Takeoff Gross Weight (TOGW)	4683 (10,325)

TABLE XXXVII. REPRESENTATIVE TURBOPROP-POWERED COMMUTER AIRCRAFT WEIGHT BREAKDOWN

Parameter	Weight kg(lb)
Airframe Fixed Weight	
o Instrumentation, Avionics Equipment, Furnishing	2206 (4863)
o Crew plus Baggage	254 (560)
o Payload	2721 (6000)
TOTAL	5181 (11,423)
Airframe Variable Weight	
o Fuselage	1742 (3840)
o Landing Gear	390 (860)
o Wing	853 (1880)
o Empennage	204 (450)
o Controls	276 (610)
TOTAL	3465 (7640)
Installed Engine Weight	
o Engines (2)	476 (1050)
o Engine Installation	295 (650)
TOTAL	771 (1700)
Fuel and Tankage Weight	
o Fuel (includes reserve)	1432 (3157)
o Fuel System (includes usable fuel)	82 (180)
TOTAL	1514 (3337)
Takeoff Gross Weight (TOGW)	10,931 (24,100)

The expression for the installed engine weight is based on the free-body diagram for an aircraft at cruise where life is equal to weight, and thrust is equal to drag. Thus, the aircraft lift/drag ratio and engine thrust/weight ratio will allow determination of engine weight if the takeoff gross weight is known, and most importantly, vice versa. A change in engine weight can then be directly related to a change in aircraft weight. The change in aircraft weight will be significantly greater than the change in engine weight, because of multiplicative fuel and structural effects.

The engine installation factor (K_1) is the ratio of installed engine weight to the bare engine weight. As previously noted, the installed engine weight would include the bare engine weight plus the additional weight for installation such as engine mounts, the nacelle, oil tank, and the various service lines.

The fuel tankage factor (K_2) is the ratio of the fuel weight (with reserves) plus the weight of the fuel tanks (including auxiliary tanks), unusable fuel, fuel system components (pumps and lines) to the weight of the usable fuel (with reserves).

The expression for the fuel weight is a variation of the well-known Breguet range equation for distance traveled:

$$R = \left(\frac{V}{TSFC}\right)\left(\frac{L}{D}\right)\left[\ln\left(\frac{WF_{INITIAL}}{WF_{FINAL}}\right)\right] \quad \text{(A2)}$$

where:

R = distance traveled

V = aircraft speed

$WF_{INITIAL}$ = fuel weight at start of cruise

WF_{FINAL} = fuel weight at end of cruise

The above equation is based on a single-segment (all-cruise) mission; however, multisegment missions can be easily incorporated as Nicolai (ref. 2) has shown.

DIRECT-OPERATING COST SENSITIVITY MODEL

The changing commuter airplane size and, hence, engine size, requires a DOC model sensitive to these changes, and their influence on engine cost, life, and reliability.

The baseline direct operating costs are estimated and used in a DOC model formulated in terms of airframe and engine weight, engine performance, and mission parameters -- cruise speed, block time, etc. This DOC model is then perturbed for the weight and performance changes from the weight model. The results are the DOC sensitivities to engine parameter perturbations.

The assumptions implicit in these models are:

- Wing loading = constant
- Power loading = constant
- SHP/Engine wt. = constant
- Nacelle and fuel system weights increase/decrease in proportion to engine and fuel weights, respectively
- SFC and power changes are proportional throughout the operating envelope (However, the baseline fuel was calculated through multisegment mission analysis.)
- Engine cost $\propto HP^{constant}$
- Airframe DOC per Fairchild model

Although these assumptions may appear limiting, they have little or no deleterious effect on the use of the model for the evaluation of differences (sensitivity analysis).

DEVELOPMENT COST MODEL

Engine development costs can be estimated as a function of several engine parameters as has been accomplished by the Rand Corporation. Project Rand (ref. 5), a study prepared for the Air Force, provides several aircraft turbine engine development cost estimating relationships. For turbofan engines, one of the Rand models that relates engine thrust, Mach number, and engine quantity was utilized. This relationship includes those standard variables that have been found to be important in past cost studies, and its mathematical form is:

$$EDC = 2{,}220{,}000\ (MV)^{1.287}\ (QE)^{0.0815}\ (FN_M)^{0.399} \qquad \text{(A3)}$$

where:

EDC = engine development cost

MV = maximum flight Mach number

QE = engine quantity

FN_M = maximum sea-level static thrust

Maximum thrust is considered a measure of the physical size of the engine. Since the major part of the cost of developing an engine is for test hardware, thrust as an index of engine size, reflects the cost of hardware.

Mach number can be considered an indicator of the environment in which the engine must operate, and the operational environment is a strong determinant of the amount of testing required.

For business aircraft development cost, the model prepared by J. R. Humphreys (ref. 6), based on empty weight, can be utilized and its mathematical form is:

$$ADC = 741{,}000\ \left(\frac{ACEW}{1000}\right)^{1.49} \qquad \text{(A4)}$$

where:

ADC = airframe development cost

ACEW = aircraft empty weight

MANUFACTURING COST MODEL

Like development cost, manufacturing cost can also be estimated as a function of aircraft weight and engine thrust. The airframe and engine manufacturing cost inputs to the equations described below are based on acquisition cost (sell price). The airframe manufacturing cost model selected is based on data from several business aircraft manufacturers, and considers only fixed and variable airframe weight. Its mathematical form is:

$$AMC = [(AFFC)(AFFW) + (AFVC)(AFVW)]\ QA \qquad (A5)$$

where:

AMC = airframe manufacturing cost
AFFC = airframe fixed cost per pound
AFVC = airframe variable cost per pound
QA = aircraft quantity

For engine manufacturing cost, the engine manufacturer will choose to input a separate estimate for the specific engine chosen as the baseline. In this case, the engine cost model can merely be a function of the baseline engine cost and changes in thrust where the thrust used can be either the maximum rating, or that at the design point. In this analysis, the design point was chosen as the cruise condition and was used for the analysis. Its mathematical form is:

$$EMC = BEMC \left(\frac{FN}{BFN}\right)^{0.75} (QE) \qquad (A6)$$

where:

EMC = engine manufacturing cost
BEMC = baseline engine manufacturing cost (established by the engine manufacturer)
BFN = average engine baseline cruise thrust

OPERATING COST MODEL

The annual cost of owning and operating the business jet aircraft can be structured into fixed and variable costs as shown below:

Fixed Costs	Variable Costs
Load interest	Fuel
Imputed interest on investment	Airframe maintenance
Depreciation	Engine maintenance
Crew wages	Crew expenses
Insurance	Landing, parking, catering, etc.
Taxes	
Hangar	
Miscellaneous costs	

While these are fixed and variable with respect to aircraft usage, they must be recategorized for evaluation of changes in the engine. Imputed interest on investment is not usually considered in revenue operation because the analyst prefers to examine total return on investment. For nonrevenue operation, imputed interest on the equity investment should be included at the internal rate of return. Depreciation drops out of LCC when acquisition cost is introduced (except for tax effects when calculating cash flow).

The fuel-cost model utilizes the fuel-weight output of the weight model and is:

$$FC = (WF)\left(\frac{FP}{T}\right)(TOH) \qquad (A7)$$

where:

FC = fuel cost

WF = fuel weight

FP = fuel price per pound

TOH = total operating hours (for lifetime)

The life-cycle invariant and cost-sensitive fixed charges are modeled as shown below:

$$CINT = (LYRS)(RINT)\ (1-EQ)\left[\frac{AMC + EMC}{2}\right](QA) \qquad (A8)$$

where:

CINT = interest cost

LYRS = loan years

RINT = interest rate

EQ = aircraft equity

EMC = engine manufacturing cost

$$CINS = (RINS)(AYRS)\left[\frac{AMC + EMC}{2}\right](QA) \qquad (A9)$$

where:

CINS = insurance cost

RINS = insurance rate

AYRS = aircraft life

$$CTAX = (RTAX)(AYRS)\left[\frac{AMC + EMC}{2}\right](QA) \qquad (A10)$$

where:

CTAX = tax cost

RTAX = tax rate

$$FOC = (AYRS)(CHM)(QA) \qquad (A11)$$

where:

FOC = fixed operating costs

CHM = crew, hanger, and miscellaneous costs

$$TOC = CINT + CINS + CTAX + FOC \qquad (A12)$$

where:

TOC = total operating cost

MAINTENANCE COST MODEL

The engine maintenance cost model is comprised of preventive maintenance (inspection), module overhaul, unscheduled maintenance (repair of failures), and incorporation of service bulletins.

The baseline costs for preventive maintenance, module overhaul, and unscheduled maintenance are established from experience on similar applications. The incorporation of service bulletins is assumed to be 5 percent of the sum of the engine preventive maintenance cost, overhaul cost, and unscheduled maintenance cost.

The change in engine life (TBO) and the resultant effect in cost can be determined by using an engine overhaul cost model. The overhaul cost model may be a composite for the whole engine, or it can have separate expressions for each module or component. The basic model for engine overhaul cost (EOC) is:

$$EOC = \sum_{\text{Module}} \left[(BMOC) \left(\frac{BMTBO}{MTBO} \right) \left(1 + \frac{1}{3} \left[\frac{\Delta MMC}{BMMC} \right] \right) \right] \qquad (A13)$$

where:

BMOC = Baseline module overhaul cost (assumed at one-third manufacturing cost)

BMTBO = Baseline module time-between-overhaul

MTBO = Module time-between-overhaul

MMC = Module manufacturing cost

BMMC = baseline module manufacturing cost

The module cost in the equation above is expressed as a fraction of engine cost.

The effect of engine unscheduled maintenance on cost, resulting from changes in reliability (MTBF), can be determined by using an engine repair cost model. The basic model for engine repair cost (ERC) is:

$$EOC = \sum_{Module} (BMRC)\left[\left(\frac{BMMTBF}{MMTBF}\right)\left(1 + \frac{3}{4}\left[\frac{\Delta MMC}{BMMC}\right]\right)\right] \qquad (A14)$$

where:

BMRC = Baseline module repair cost
BMMTBF = Baseline module mean-time-between-failure
MMTBF = Module mean-time-between-failure

The airframe maintenance cost model is comprised of preventive maintenance, overhaul, and unscheduled maintenance costs. The baseline costs for the airframe maintenance cost model are established from experience on similar applications. The following overhaul cost model and repair cost model are used to show the change in airframe maintenance life-cycle cost.

$$AOC = BAOC\left[1 + \frac{1}{3}\left(\frac{\Delta AMC}{BAMC}\right)\right] \qquad (A15)$$

where:

AOC = Airframe overhaul cost
BAOC = Baseline airframe overhaul cost
BAMC = Baseline airframe manufacturing cost

and,

$$ARC = \frac{2}{3}(AOC) \qquad (A16)$$

where:

ARC = Airframe repair cost

The preflight servicing cost for the aircraft is established based on similar application experience.

APPENDIX B

LIST OF ABBREVIATIONS/SYMBOLS

LIST OF ABBREVIATIONS/SYMBOLS

Δ	Change in a value
ACEW	Aircraft empty weight
ADC	Airframe development cost
AFFC	Airframe fixed cost
AFFW	Airframe fixed weight
AFVC	Airframe variable cost per pound
AFVW	Airframe variable weight
AMC	Airframe manufacturing cost
AOC	Airframe overhaul cost
ARC	Airframe repair cost
AYRS	Aircraft life
BAMC	Baseline airframe manufacturing cost
BAOC	Baseline airframe overhaul cost
BEMC	Baseline engine manufacturing cost
BFN	Baseline cruise thrust
BMMC	Baseline module manufacturing cost
BMMTBF	Baseline module mean-time-between-failure
BMOC	Baseline module overhaul cost
BMRC	Baseline module repair cost
BMTBO	Baseline module time-between-overhaul
BPR	Bypass ratio
CHM	Crew, hanger, and miscellaneous costs
CINS	Insurance cost
CINT	Interest cost
CTAX	Tax cost
D	Drag
Delta	Change
DOC	Direct-operating cost
DS	Directionally-solidified
EDC	Engine development cost
EMC	Engine manufacturing cost
EQ	Aircraft equity
ERC	Engine repair cost

F_{FW}	Airframe fixed weight fraction (AFFW/TOGW)
F_{VW}	Airframe variable weight fraction (AFVW/TOGW)
FC	Fuel cost
FN	Average engine cruise thrust
FN_M	Maximum sea-level static thrust
FOC	Fixed operating costs
FP	Fuel price
FTW	Fuel and tankage weight
HCF	High-cycle fatigue
HIP	Hot-isostatically pressed
HP	High pressure
HPT	High-pressure turbine
IEW	Installed engine weight
K_1	Engine installation factor
K_2	Fuel tankage factor
L	Lift
L/D	Lift/drag ratio
LCC	Life-cycle cost
LCF	Low-cycle fatigue
LP	Low pressure
LPC	Low-pressure compressor
LPT	Low-pressure turbine
LYRS	Loan years
M	Engine core flow
MATE	Materials for Advanced Turbine Engines
MMC	Module manufacturing cost
MMTBF	Module mean-time-between-failure
MTBO	Module time-between-overhaul
MV	Maximum flight Mach number
OC	Overhaul cost
ODS	Oxide-dispersion strengthened
QA	Aircraft quantity

LIST OF ABBREVIATIONS/SYMBOLS (CONTD)

QE	Engine quantity
PM	Powder-metal
R	Distance traveled
RINS	Insurance rate
RINT	Interest rate
RTAX	Tax rate
T	Aircraft cruise endurance with all fuel consumed (hours)
TBC	Thermal-barrier coating
TBO	Time-between-overhaul (engine life)
TO	Takeoff
TOC	Total operating cost
TOGW	Takeoff gross weight
TOH	Total operating hours (for lifetime)
TSFC	Average engine thrust specific fuel consumption
V	Aircraft speed
WE	Engine weight
WE_C	Engine core weight
WF	Fuel weight
$WF_{INITIAL}$	Fuel weight at start of cruise
WV_{FINAL}	Fuel weight at end of cruise

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Carpenter Technology Corp.
Attn G. DelCorso
A. Walsh
R/D Lab, Bldg. 68
Reading, PA 19603

Certified Alloys Products
Attn M. Woulds
3245 Cherry Ave.
Long Beach, CA 90807

Cessna Aircraft Co.
Attn A. Kavie
(Turbofan)
Wallace Division
P.O. Box 7704
Wichita, KS 67277

Cessna Aircraft Co.
Attn C. Gonzales
(Turboprop)
Wallace Division
P.O. Box 7704
Wichita, KS 67277

Chromalloy-PMT
Attn R. Elbert
13434 Floyd Circle
Dallas, TX 75243

Climax Molybdenum Co.
Attn Wm. Hagel
P.O. Box 1568
Ann Arbor, MI 48106

Colt Industries
Attn E. Dulis
Crucible Inc, Mat'ls Rsch
P.O. Box 88
Pittsburgh, PA 15230

Colt Industries
Attn J. Moll
Crucible Inc, Mat'ls Rsch
P.O. Box 88
Pittsburgh, PA 15230

Convair Aerospace Div.
General Dynamics Corp.
Attn A.J.K. Carline
P.O. Box 748
Ft. Worth, TX 76101

DCI Inc.
Attn R. Engdahl
318 Victory Drive
Herndon, VA 22070

Defense Marketing Services
Attn D. Franus
100 Northfield St.
Greenwich, CT 06830

Delta Airlines
Attn W.J. Overend
Atlanta Airport
Atlanta, GA 30320

Douglas Aircraft Co.
Attn Library
Mcdonnell Douglas Corp
3855 Lakewood Blvd.
Long Beach, CA 90846

Duradyne Tech. Inc.
Attn R. Horton
8607 Tyler Blvd
Mentor, OH 44060

Engelhard Industries
Attn E. Grider
Route 152
Plainville, MA 02762

Ford Motor Company
Attn C. Feltner
Metallurgical Dept.
P.O. Box 2053
Dearborn, MI 48121

Gates Learjet Corp.
Attn Don Baisden
P.O. Box 7707
Wichita, KS 67277

Gates Learjet Corp.
Attn W.J. Reese
C.L. King
P.O. Box 7707
Wichita, KS 67277

Gates Learjet Corp.
Attn A.M. Heinrich
T. Reichenberger
P.O. Box 7707
Wichita, KS 67207

General Atomics Co.
Attn D.I. Roberts
P.O. Box 81608
San Diego, CA 92138

General Motors Corp.
Attn K. Bly 73-S
Technical Center
Warren, MI 48090

Gould Inc.
Attn R. Szafranski
17000 St. Clair Ave
Cleveland, OH 44110

Grumman Aerospace Corp.
Attn C. Hoelzer C32-5
Bethpage, NY 11714

Hamilton Standard
Attn W. Adamson
Windsor Locks, CT 06096

Howmet Turbine Comp. Div.
Attn W. Freeman
500 Terrace Plaza
Muskegon, MI 49443

Howmet Corporation
Technical Center
Attn L. Dardi
699 Benston Rd.
Whitehall, MI 49461

Howmet Corporation
Technical Center
Attn J. VanderSluis
699 Benston Rd.
Whitehall, MI 49461

Howmet Corporation
Turbine Components Div.
Attn E. Carozza
Mr. Burd
Dover, NJ 07801

Huntington Alloys Div.
International Nickel Co.
Atnn D. Tillack
9501 W. Devon
Rosemont, IL 60018

Huntington Alloys Div.
International Nickel Co.
Attn F. Perry
Huntington, WV 25720

IIT Research Institute
Attn M.A. Howes
10 West 35th Street
Chicago, IL 60616

Intermetco
Attn J. Siergiej
300 Condord Road
Wayland, MA 01778

International Nickel Corp.
Attn L. Curwick
Sterling Forest
Suffern, NY 10901

International Nickel Corp
Attn Library
Sterling Forest
Suffern, NY 10901

Jetshapes, Inc.
Attn C. Phipps
Rockleigh Industrial Park
Rockleigh, NJ 07647

Kawecki Berylco Ind.
Attn R. Gower
E.R. Laich
P.O. Box 1462
Reading, PA 19603

Kelsey Hayes
Attn T. Miles
D. Weaver
7250 Whitmore Lake Road
Brighton, MI 48116

Kelsey Hayes
Attn M. Ziobro
Utica, NY 13503

Kelsey Hayes Co.
Attn W.G. Koby
Heintz Div.
Front St. and Olney Ave.
Philadelphia, PA 19120

Kelsey Hayes Co.
Attn M. Lopacki
Heintz Div.
Front St. and Olney Ave.
Philadelphia, PA 19120

Ladish Company
Attn R. Daykin
Cudahy, WI 53110

Lockheed-California Co.
Attn. T. Sedjwick
Dept. 75-4, Bldg. 63
Plant A-1
P.O. Box 551
Burbank, CA 91503

Lockheed-Georgia Co.
Attn R.H. Lange
Dept. D/72-79
Marietta, GA 30060

McDonnell-Douglas East
Attn R.A. Garrett
Dept. E452, Bldg 106
P.O. Box 516
St. Louis, MO 63166

MCIC
Battelle Memorial Inst.
Attn H. Mindlin
Columbus, OH 43201

Martin Marietta
Attn C.H. Lund
15 N. Windsor Rd
Arlington Hts, IL 60004

METCO Inc.
Attn V. Lanza
1101 Prospect Ave.
Westbury, L.I., NY 11590

METCO Inc.
Attn J. Dailey
1101 Prospect Ave.
Westbury, L.I., NY 11590

METCO Inc.
Attn C. Lewis
3400 A Oak Cliff Rd.
Atlanta, GA 30340

Pan American World Airways
Attn W.B. Hibbs
Pan Am Building
New York, NY 10017

Rand Corp.
Attn J. Richard Nelson
Washington Research Div.
2100 M St.
Washington, DC 20037

Rocketdyne Division
Attn J. Frandsen
Rockwell International
6633 Canoga Ave.
Canoga Park, CA 91304

Rockwell International
Attn W.B. Palmer
Columbus Aircraft Div.
P.O. Box 1259
Columbus, OH 43209

Rockwell International
Columbus Aircraft Div.
Attn E.E. Culp
D. Rosenbaum
P.O. Box 1259
Columbus, OH 43216

Rockwell International
Attn N. Paton
Science Center
Thousand Oaks, CA 91360

Rockwell International
Attn G.E. Mathwig
General Aviation Div.
5001 N. Rockwell Ave.
Bethany, OK 73008

Rockwell International
Atten L.L. McHughes
General Aviation Div.
5001 N. Rockwell Ave.
Bethany, OK 73008

SCM Glidden Metals
Attn K.M. Kulkarni
11000 Cedar Ave.
Cleveland, OH 44106

Sorcery Metals
Attn P. Hanson
Box 1600
Delray Beach, FL 33444

Special Metala, Inc.
Attn J. Pridgeon
Middle Settlement Road
Hew Hartford
New York 13413

Special Metals, Inc.
Attn. S. Reichman
C.J. Burton
Middle Settlement Road
New Hartford
New York 13413

Special Metals, Inc.
Attn W. Castledyne
Udimet Powder Division
2310 S. Industrial Hwy
Ann Arbor, MI 48104

Stellite Division
Cabot Corporation
Attn E. Bickel
1020 West Park Ave.
Kokomo, IN 46901

Sundstrand
Attn N.C. Evans
9841 Airport Blvd.
Los Angeles, CA 98045

Sundstrand
Attn D. Augustine
4747 Harrison Ave.
Rockford, IL 61101

Swearingen Aviation Corp.
Attn J.E. Kirkpatrick
Box 32486
San Antonio, TX 78284

Teledyne Allvac
Attn F. Elliott
P.O. Box 759
Monroe, NC 28110

Teledyne Allvac
Attn R. Kennedy
Wm. Thomas
P.O. Box 759
Monroe, NC 28110

TRW Inc.
Attn I. Toth
23555 Euclid Ave.
Cleveland, OH 44117

TRW Inc.
Attn. J. McCarthy
23555 Euclid Ave.
Cleveland, OH 44117

TRW Inc.
Attn D. Maxwell
23555 Euclid Ave.
Cleveland, OH 44117

TRW Inc.
Attn T. Piwonka
23555 Euclid Ave.
Cleveland, OH 44117

TRW Inc.
Attn. C. Cook
23555 Euclid Ave.
Euclid, OH 44123

Turbine Support Co.
Attn. K. Speirs
4430 Director Drive
P.O. Box 20148
San Antonio, TX 78220

Turbine Support Co.
Attn. M. Dean
4430 Director Drive
P.O. Box 20148
San Antonio, TX 78220

Union Carbide Corporation
Attn. M.S. Wright
Carbon Products Division
P.O. Box 6116
Cleveland OH, 44101

Union Carbide Corporation
ATTn L. Nelson
Carbon Products Division
P.O. Box 6116
Cleveland, OH 44101

Union Carbide Corporation
Attn H.J. Wilder
Applications Mgr.
P.O. Box 6087
Cleveland, OH 44101

Union Carbide Corporation
Attn R. Tucker
Coatings Service Dept.
1500 Polco St.
Indianapolis, IN 46224

United Airlines, Inc.
Attn. MR. R.M. Brannon
P.O. Box 66100
Chicago, IL 60666

United Airlines - SFOEG
Attn J.K. Curry
San Francisco Airport
CA 94128

United Airlines - SFOEG
Attn R.E. Coykendall
San Francisco Airport
CA 94128

United Airlines - SFOEG
Attn J.K. Goodwine
San Francisco Airport
CA 94128

United Tech Rsch Center
Attn B. Thomson
East Hartford, CT 06108

United Tech Rsch Center
Attn Library
East Hartford, CT 06108

Universal Cyclops
Attn L. Lherbier
Mayer St.
Bridgevill, PA 15017

Universal Cyclops
Attn. Wm. Kent
Mayer St.
Bridgeville, PA 15017

Vought Corp.
Attn O.H. Cook 2-53400
P.O. Box 5907
Dallas TX 75222

Hampton Technical Center
Attn W.A. Lovell
3221 No. Armistead Ave.
Hampton, VA 23666

Westinghouse Electric Co.
Attn R.L. Ammon
P.O. Box 10864
Pittsburgh, PA 15236

Vought Corp.
Attn. W.R. Boruff 2-53220
P.O. Box 5907
Dallas TX 75222

Vought Corp.
Attn Library
2-50370/TL 7-67
P.O. Box 5907
Dallas TX 75222

Westinghouse R&D Center
Attn D. Moon
Beulah Rd.
Pittsburgh, PA 15235

Westinghouse Electric Co.
Attn E. Crombie C-210
P.O. Box 251
Concordville, PA 19331

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