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COST/BENEFIT ANALYSIS ADVANCED MATERIAL TECHNOLOGIES SMALL AIRCRAFT GAS TURBINE ENGINES

by

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A DIVISION OF THE GARRETT CORPORATION

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16. Abstract

Cost/benefit studies were conducted on ten advanced material technologies applicable to small aircraft gas turbine engines to be produced in the 1985 time frame. The cost/benefit studies were applied to a two engine, business-type jet aircraft in the 6800- to 9100-Kg (15,000- to 20,000-lb) gross weight class. The new material technologies are intended to provide improvements in the areas of high-pressure turbine rotor components, high-pressure turbine stator airfoils, and static structural components. The cost/benefit of each technology is presented in terms of Relative Value, which is defined as a change in life-cycle cost times probability of success divided by development cost. Technologies showing the most promising cost/benefits based on Relative Value are uncooled single-crystal MAR-M 247 turbine blades, cooled DS MAR-M 247 turbine blades, and cooled ODS 'M'CrAl laminate turbine stator vanes.

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FOREWORD

The cost/benefit studies of technologies described herein were performed by the AiResearch Manufacturing Company of Arizona, a division of The Garrett Corporation, under the technical direction of Neal T. Saunders, Materials and Structures Division, NASA-Lewis Research Center. These studies were performed as a part of the NASA-MATE Program currently being conducted by AiResearch under Contract NAS3-20073. This report was prepared by Don H. Comey, the AiResearch Project Manager, for the cost/benefit studies with the assistance of L. G. Hurst, Documentation Engineer. Materials information was prepared and reviewed by G. S. Hoppin, L. W. Sink, D. V. Sundberg, and J. A. Petrusha of AiResearch. Valuable assistance was provided by R. E. Dennis, the AiResearch Assistant Program Manager for the MATE Program. Overall direction of the Contractor's effort was provided by C. E. Corrigan, MATE Program Manager.

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SUMMARY

This document summarizes a cost/benefit analysis conducted as part of the NASA Materials for Advanced Turbine Engines (MATE) Program. The objective of this cost/benefit analysis was to assess the potential benefits, costs, and risks for several advanced material technologies potentially applicable to general aviation gas turbine engines; and to provide a value ranking of these technologies. The results of the analysis are intended as an aid in selecting future materials technology projects for the MATE Program.

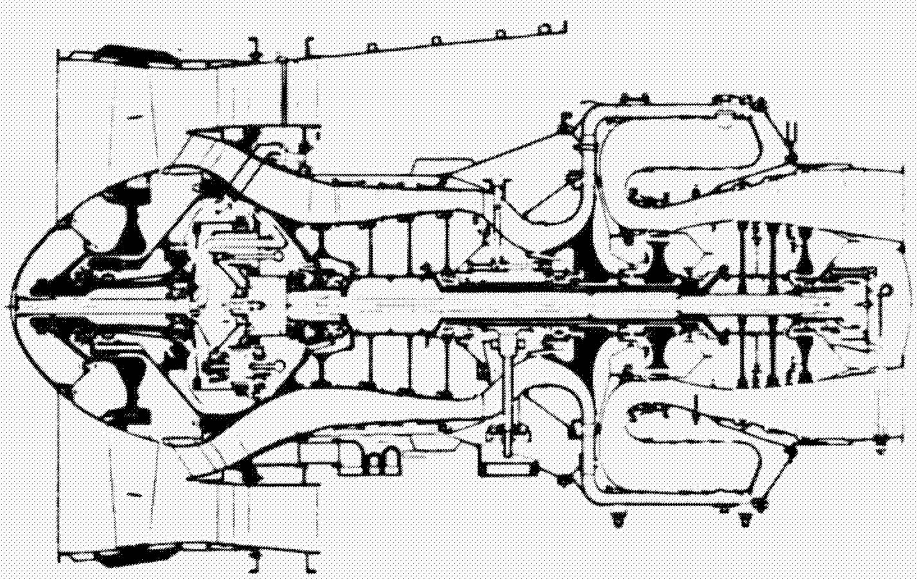
The cost/benefit analysis was applied to a domestic, nonrevenue producing, business-type jet aircraft in the 6800- to 9100-kg (15,000- to 20,000-lb) gross weight class configured with two AiResearch Model TFE731-3 Turbofan Engines. The aircraft chosen for the analysis was an all new design based on an aircraft similar to the Gates Learjet 35/36. For purposes of this study, the engine included the directionally-solidified uncooled high-pressure turbine blade, and the abradable compressor and turbine gas-path seal technologies currently being developed in the MATE Program by AiResearch.

Cost benefits of ten candidate materials technologies were evaluated. They included turbine rotor components, turbine stator airfoils, and static structural components (see Figure 1). The material technologies were compared by both life-cycle costs and Relative Value. Relative Value is a method of comparing technologies by equating benefits (payoffs), development cost, and probability of success. The cost/benefit analysis was based on the general aviation (nonrevenue producing) application; therefore, return on investment (ROI) forecasting techniques were not used. The benefits were determined by applying life-cycle-cost (LCC) forecasting techniques and calculating the Relative Value where:

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

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.

- HPT ROTOR COMPONENTS
  - COOLED DS MAR-M 247 BLADES
  - UNCOOLED SINGLE-CRYSTAL MAR-M 247 BLADES
  - UNCOOLED WIRE REINFORCED 'M'CrAlY BLADES
  - COOLED INTEGRALLY-BLADED DS-CAST MAR-M 247 ROTORS
  - PM RENE' 95 TURBINE DISKS



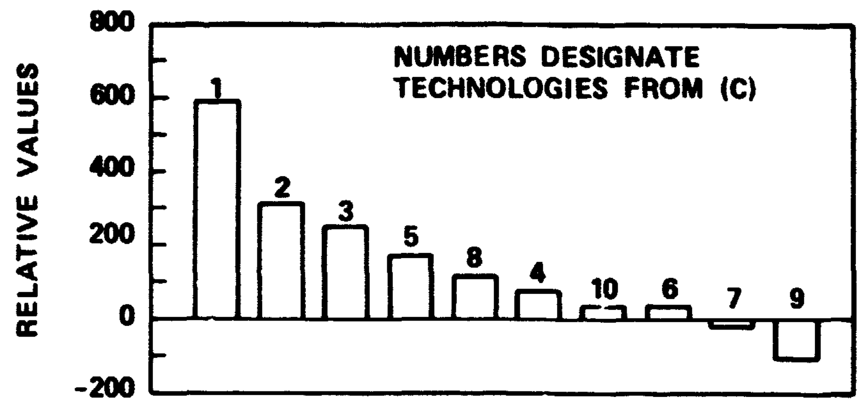
- STATIC STRUCTURAL COMPONENTS
  - LOW-EXPANSION IRON ALLOYS FOR HOT-END STATIC STRUCTURES
  - ABRADABLE SILICONE-RUBBER LPC SHROUDS
- HPT STATOR AIRFOILS
  - UNCOOLED ODS 'M'CrAl VANES
  - COOLED ODS 'M'CrAl LAMINATE VANES
  - UNCOOLED WIRE REINFORCED 'M'CrAlY VANES

Figure 1. - Material Technology Candidates Evaluated.

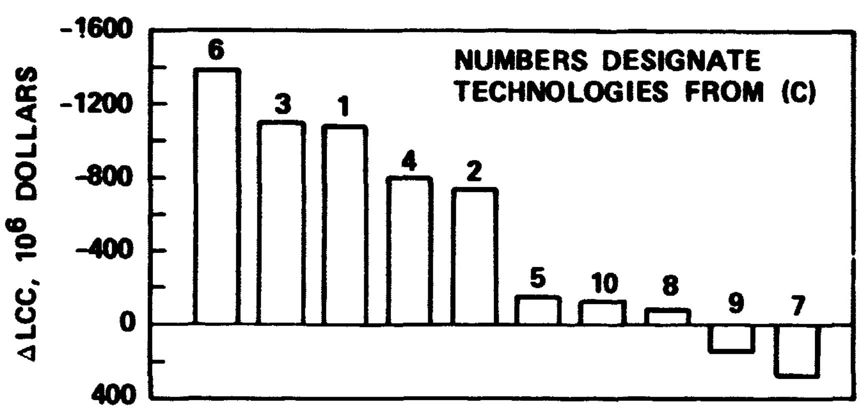
Figure 2(A) presents the ranking of the technologies based on Relative Value in the selected application. Uncooled single-crystal MAR-M 247 turbine blades and cooled DS MAR-M 247 turbine blades rank the highest, followed by cooled ODS 'M'CrAl laminate turbine stator vanes. The remaining technologies fall in order as shown.

Figure 2(B) presents the ranking of the technologies based on a straight change in life-cycle-cost (ΔLCC). This straight benefit ranking does not include either the development cost or the probability of success factor. The high ranking of the uncooled wire reinforced 'M'CrAly airfoils (both blades and vanes) in terms of straight benefits has generated considerable interest in these technologies in spite of a low relative value ranking that is based on a calculated probability of success and an estimated development cost. These factors are influenced by a general lack of experience with this process, so the relative value could change dramatically with added experience. The remaining high ranking technologies, in terms of benefits only, are cooled ODS 'M'CrAl laminate vanes, uncooled single-crystal MAR-M 247 blades, and cooled DS MAR-M 247 blades. These three technologies were ranked highest in Relative Value.

The AiResearch corporate ranking is presented in Figure 2(C). This follows the Relative Value ranking for the top three technologies, and will be discussed later in this report.



(A) RELATIVE VALUE RANKING



(B) ΔLCC COMPARISON

1. UNCOOLED SINGLE-CRYSTAL MAR-M 247 BLADES
2. COOLED DS MAR-M 247 BLADES
3. COOLED ODS 'M'CrAl LAMINATE VANES
4. UNCOOLED WIRE REINFORCED 'M'CrAlY HPT VANES
5. ABRADABLE SILICONE-RUBBER LP COMPRESSOR SHROUDS
6. UNCOOLED WIRE REINFORCED 'M'CrAlY HPT BLADES
7. COOLED INTEGRALLY-BLADED DS-CAST MAR-M 247 HPT ROTORS
8. LOW-EXPANSION IRON ALLOYS FOR HOT-END STATIC STRUCTURES
9. UNCOOLED ODS 'M'CrAl VANES
10. PM RENÉ 95 TURBINE DISKS

(C) CORPORATE RANKING

Figure 2. - Relative Value, ΔLCC, and AiResearch Corporate Ranking of the Ten Material Technologies.

INTRODUCTION

The NASA MATE Program is a cooperative effort with industry to accelerate the introduction of new materials into aircraft turbine engines. Ten 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 for business-type aircraft. These advanced technologies are all currently in the exploratory development stage. But after laboratory feasibility has been adequately demonstrated, their advancement would occur through the improvement of present materials, designs, and process and manufacturing techniques. The verification 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 estimate the life-cycle costs, development costs, risks, and the relative values for each of the ten new materials technology projects considered. This analysis included the following activities that are described in detail in this report:

- o Selection of candidate technologies for future MATE Program projects
- o Development of 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 engine and airframe life-cycle-cost models
- o 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
- o Estimation of the development cost and risk for each candidate technology
- o Ranking of the relative importance 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. Other NASA sponsored studies in the MATE Program have conducted similar cost/benefit studies of advanced material technologies as applied to commercial aircraft (Ref. 1, 2).

STUDY APPROACH

The cost/benefit analysis consisted of an evaluation based on life-cycle-cost considerations of ten candidate materials 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, operating cost, and maintenance cost. Figure 3 presents a flowchart 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 1985 production technology) for relative strengths, weights, and component life; probability of success for each goal; the probability of success for producing the component while satisfying all of the goals; comparisons to current production parts; and the development costs.

Development costs for the selected component technologies were prepared utilizing 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 incorporation date, 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.

The engine used in the cost/benefit analysis utilizes a geared fan driven by the low pressure (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 potential engine benefits were assessed through the above 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 models. The engine/aircraft LCC models were utilized to develop sensitivity coefficients for the effects of

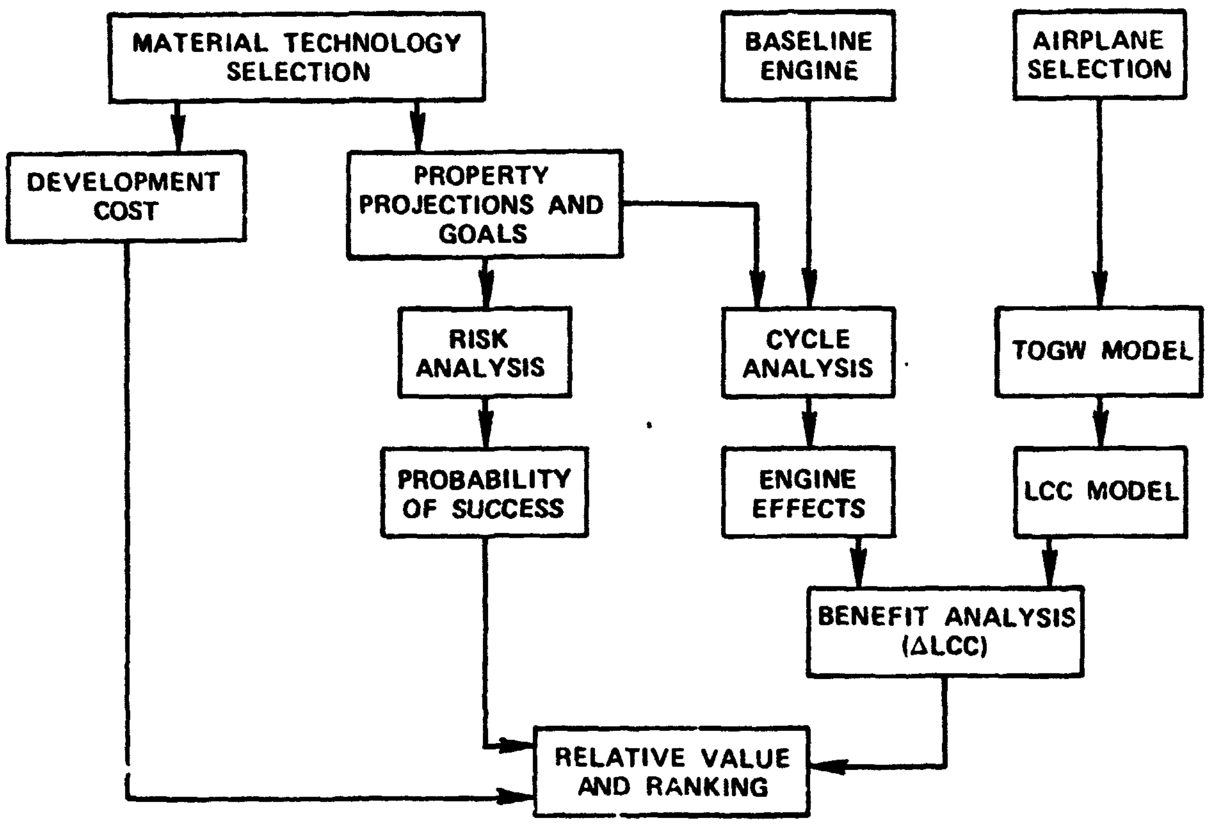


Figure 3.-Flow Chart of the Study Approach.

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 costs (ΔLCC).

The cost estimating models for the business-type aircraft were based upon a scaled aircraft and engine meeting a fixed payload and range for changes in engine thrust 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. 3).

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 MATERIAL TECHNOLOGIES

This section provides descriptions and 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. There was particular emphasis placed on their potential for reducing fuel consumption. Originally, the abradable Genaseal high-pressure turbine (HPT) shroud was considered one of the candidate material technologies, but AiResearch studies have shown that the high-temperature capability of this shroud cannot be fully utilized in near-term AiResearch engines. Since the baseline for comparison already includes the abradable HPT shroud currently being developed in the MATE Program by AiResearch, the Genaseal has been dropped from further consideration at this time due to its higher cost. The current candidates are divided into three basic areas:

- o High-Pressure Turbine Rotor Components
    - Cooled Directionally Solidified (DS) MAR-M 247 Blades
    - Uncooled Single-Crystal MAR-M 247 Blades
    - Uncooled Wire Reinforced 'M'CrAlY Blades
    - Cooled Integrally-Bladed DS-Cast MAR-M 247 Rotors
    - Powder-Metallurgy (PM) René 95 Turbine Disks
- o High-Pressure Turbine Stator Airfoils
    - Uncooled Oxide-Dispersion-Strengthened (ODS) 'M'CrAl Vanes
    - Cooled ODS 'M'CrAl Laminate Vanes
    - Uncooled Wire Reinforced 'M'CrAlY Vanes
- o Static Structural Components
    - Low-Expansion Iron Alloys for Hot-End Static Structures
    - Abradable Silicone-Rubber Low-Pressure Compressor (LPC) Shrouds

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 1985 production status. This assumes a go-forward decision within the present MATE five-year program schedule. The technical material goals are based on two criteria--those property goals that must be met to offer a benefit to engine life and/or performance (critical goals), and those property goals that must be approached reasonably close 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.

High-Pressure Turbine Rotor Components

1. Cooled DS MAR-M 247 Blades. - This project would lead to the production of cooled, directionally-solidified (DS) MAR-M 247 high-pressure (HP) turbine blades cast with an exothermic heating method (Ref. 4) that controls columnar grain growth. This exothermic DS casting process is currently being demonstrated for uncooled blades in AiResearch's Project 1 of the MATE Program. This process would be further developed to produce cooled blades with internally cored passages--the cores to be leached out after casting. The choice of MAR-M 247 is based on the demonstrated response of the alloy to the exothermic DS process. The incorporation of this material technology allows a potential increase in the baseline engine cruise turbine inlet temperature of 150°C (270°F), and the consequently lower fuel consumption.

(a) Capability Goals

- o Critical Goals

  (1) Creep-rupture strength of 0.076-cm (0.030-inch) thick material at least 80 percent of that of 0.178-cm (0.070-inch) diameter bars of DS MAR-M 247 -- 90-percent probability of success (50-percent weighing factor)

  (2) Thermal fatigue resistance equivalent to that of TFE731-3 uncooled DS MAR-M 247 turbine blades -- 80-percent probability of success (20-percent weighing factor)

- o Noncritical Goals

  (1) Turbine blade low-cycle-fatigue (LCF) strength at 760°C (1400°F) equal to that of uncooled DS MAR-M 247 turbine blades

  (2) Transverse stress-rupture strength equal to that of uncooled DS MAR-M 247 turbine blades

  (3) High-cycle-fatigue (HCF) strength at 760°C (1400°F) 90 percent of that of uncooled DS MAR-M 247 turbine blades

  (4) Coatable for 5000-hours part life

(b) Finished Part Cost Goal - 2.5 times that of uncooled DS MAR-M 247 blades -- 80-percent probability of success (30-percent weighing factor)

(c) Estimated Development Cost - $1,300,000

(d) Project Probability of Success - 55 percent

2. Uncooled Single-Crystal MAR-M 247 Blades. - This project would lead to the production of uncooled MAR-M 247 HP turbine blades cast with an exothermic heating method that produces a single crystal in each blade. An improvement of 14°C (25°F) in stress-rupture strength of unmodified MAR-M 247 (Ref. 5) has been demonstrated with single-crystal turbine blades as compared with polycrystalline DS turbine blades of the same alloy and configuration. Alloy modifications made possible by the elimination of alloy constituents normally added for grain boundary strengthening are expected to boost this improvement in stress-rupture temperature capability to 25°C (45°F). The incorporation of this material technology results in a potential increase in cruise turbine inlet temperature of 30°C (54°F).

(a) Capability Goals

- o Critical Goals

  (1) A gain of 25°C (45°F) in creep-rupture strength in the crystal-growth direction compared to DS MAR-M 247 -- 75-percent probability of success (50-percent weighing factor)

  (2) Thermal fatigue resistance equivalent to that of uncooled DS MAR-M 247 turbine blades at a maximum temperature 25°C (45°F) higher -- 80-percent probability of success (20-percent weighing factor)

- o Noncritical Goals

  (1) Turbine blade low-cycle-fatigue (LCF) strength at 760°C (1400°F) greater than that of uncooled DS MAR-M 247 blades

  (2) Transverse stress-rupture strength equivalent to the longitudinal stress-rupture strength of uncooled DS MAR-M 247 turbine blades

  (3) High-cycle-fatigue (HCF) strength at 760°C (1400°F) greater than that of uncooled DS MAR-M 247 turbine blades

  (4) Coatable for 5000-hours part life

(b) Finished Part Cost Goal - 1.5 times that of uncooled DS MAR-M 247 blades -- 80-percent probability of success (30-percent weighing factor)

(c) Estimated Development Cost - $1,100,000

(d) Project Probability of Success - 60 percent

3. Uncooled Wire Reinforced 'M'CrAlY Blades. - This project would lead to the production of uncooled HP turbine blades reinforced with wire filaments. These blades, with high-temperature metal-matrix composite materials would be produced by ply-layup and diffusion-bonding techniques similar in principle to those utilized for producing composite fan blades of boron-aluminum. The 'M'CrAlY sheet utilized would be the most oxidation- and corrosion-resistant composition available in sheet form (e.g. - FeCrAlY). Extensive design and fabrication efforts would be required to produce technically viable turbine blades with this materials system. The blade-root attachment problem will be

particularly difficult to solve, due to expected low shear strength of the material. The incorporation of this material technology would result in a potential increase in cruise turbine inlet temperature of 70°C (126°F).

(a) Capability Goals

o Critical Goals

(1) A gain of 140°C (252°F) in creep-rupture strength over uncooled DS MAR-M 247 blades -- 50-percent probability of success (50-percent weighing factor)

(2) Thermal fatigue life, at 1150°C (2102°F), equal to that of DS MAR-M 247 at 1040°C (1904°F) -- 40-percent probability of success (20-percent weighing factor)

o Noncritical Goals

(1) HCF strength at 760°C (1400°F) equal to that of DS MAR-M 247

(2) LCF life at 760°C (1400°F) 75-percent of that of DS MAR-M 247

(3) Transverse creep-rupture strength properties 50-percent of DS MAR-M 247

(4) Oxidation and hot-corrosion resistance of uncoated parts adequate for 5000-hours life as TFE731 turbine blades

(b) Finished Part Cost Goal - three times that of uncooled DS MAR-M 247 blades -- 20-percent probability of success (30-percent weighing factor)

(c) Estimated Development Cost - $4,400,000

(d) Project Probability of Success - 10 percent

4. Cooled, Integrally-Bladed DS-Cast MAR-M 247 Rotors. - This project would lead to the production of cooled, integrally-bladed HP turbine rotors DS-cast with an exothermic heating method for providing columnar grains in the blades and equiaxed grains in the hub. Small turbine engines frequently employ cast, integrally-bladed turbine wheels. Special casting techniques that force directional solidification of the turbine blades from their tips inward allows the casting of a dual macrostructure turbine wheel. This type of wheel offers the outstanding high stress-rupture

strength typical of directionally-solidified turbine blades, while retaining the normal equiaxed grain structure in the hub. The feasibility of producing 15- to 20-cm (5.9- to 7.9-inches) diameter turbine wheels with this dual structure has been demonstrated with MAR-M 247. Process reproducibility, mechanical property determinations, and design methodology require better definition for utilization of this unique procedure for producing cast turbine wheels. The incorporation of this material technology would result in a potential increase of 150°C (270°F) in cruise turbine inlet temperature.

(a) Capability Goals

- Critical Goals

  (1) Blade mechanical and physical properties equal to uncooled DS MAR-M 247 blades -- 45-percent probability of success (35-percent weighing factor)

  (2) Transition zone between DS and equiaxed grain structures will be at least 1 cm (0.39 inches) radially inward from the wheel rim -- 50-percent probability of success (25-percent weighing factor)

- Noncritical Goals

  (1) The equiaxed grain areas of the turbine wheel would have mechanical and physical properties equivalent to those of a 100-percent equiaxed MAR-M 247 turbine wheel

  (2) Part shall be coatable for 5000 hours life

(b) Finished Part Cost Goal - Four times that of current cooled TFE731-3 HP turbine disk, blades, and seal plate -- 75-percent probability of success (40-percent weighing factor)

(c) Estimated Development Cost - $2,000,000

(d) Project Probability of Success - 15 percent

5. PM René 95 Turbine Disks. - This project would lead to the production of powder-metallurgy René 95 hot-isostatically-pressed (HIP) turbine disks for all of the HP and LP turbine stages. René 95 has the highest strength, below 650°C (1202°F), of the available advanced turbine disk materials. Its cost-effective manufacture into disks requires the near-net-shape powder-metallurgy technology being developed by General Electric as a part of NASA's MATE Program (Ref. 6). The incorporation of

this material technology would result in a 10-percent weight reduction in the machined turbine disks.

(a) Capability Goals

- o Critical Goals

  (1) LCF life of PM disk alloy equal to that of forged Waspaloy -- 70-percent probability of success (30-percent weighing factor)

  (2) Tensile strength 45-percent greater than Waspaloy at 650°C (1202°F) -- 90-percent probability of success (20-percent weighing factor)

(b) Finished Part Cost Goal - 1.25 times that of current Waspaloy TFE731-3 turbine disks -- 20-percent probability of success (50-percent weighing factor)

(c) Estimated Development Cost - $1,300,000

(d) Project Probability of Success - 35 percent

High-Pressure Turbine Stator Airfoils

1. Uncooled ODS 'M'CrAl Vanes. - This project would lead to the production of uncooled oxide-dispersion-strengthened (ODS) turbine stator vanes machined from a solid extrusion, closed-die forging, or other near-net-shape piece, and brazed into a stator ring. Oxide-dispersion-strengthened materials retain useful strengths to temperatures up to 165°C (297°F) higher than the cast nickel and cobalt-base alloys normally used as gas turbine stator vanes. The more advanced ODS alloys (e.g. ODS NiCrAl or FeCrAl) also have very high intrinsic oxidation and corrosion resistance, and should not require surface coating. At metal temperatures up to 1150°C (2102°F), the ODS alloys can be utilized as solid parts not requiring the cooling needed for cast alloys. The incorporation of this material technology would result in an improvement in component useful life and reliability by a factor of two.

(a) Capability Goals

- o Critical Goals

  (1) Longitudinal stress-rupture strength at 1150°C (2102°F) equal to that of INCO 713LC castings at 1000°C (1832°F) -- 80-percent probability of success (40-percent weighing factor)

  (2) Stress-rupture strength in the transverse direction at least 50 percent of that in the longitudinal direction -- 70-percent probability of success (20-percent weighing factor)

o Noncritical Goals

(1) Thermal fatigue life at 1100°C (2012°F) ten times that of INCO 713LC at 1035°C (1895°F)

(2) Brazeable to conventional nickel and cobalt-base superalloy bands

(3) Incipient melting temperature 83°C (150°F) greater than INCO 713LC [i.e., 1371°C (2500°F) versus 1288°C (2350°F]

(b) Finished Part Cost Goal - Two vanes brazed into cast alloy bands will cost two times the cost of the current TFE731-3 cooled 2-vane segment of cast INCO 713LC -- 85-percent probability of success (40-percent weighing factor)

(c) Estimated Development Cost - $1,000,000

(d) Project Probability of Success - 70 percent

2. Cooled ODS 'M'CrAl Laminate Vanes. - This project would lead to the production of cooled HP turbine stator vanes fabricated from photo-chemically machined 0.076 cm (0.030-inch) ODS 'M'CrAl sheet stock diffusion bonded (laminated) together. The ODS material previously described for the uncooled ODS 'M'CrAl vanes would be utilized to produce stator vanes with intricate cooling passages. The incorporation of this material technology would result in a potential increase in cruise turbine inlet temperature of 150°C (270°F).

(a) Capability Goals

o Critical Goals

(1) Bond strength between laminates at least 50 percent of the stress-rupture strength of the sheet material -- 70-percent probability of success (30-percent weighing factor)

(2) Thermal-fatigue life, at 1100°C (2012°F), of bonded laminates at least two times that of INCO 713LC at 1035°C (1895°F) -- 50-percent probability of success (20-percent weighing factor)

(3) Sheet stress-rupture strength ±10-percent isotropic at 1150°C (2102°F) and equal to INCO 713LC castings at 1000°C (1832°F) -- 90-percent probability of success (15-percent weighing factor)

- o Noncritical Goals

  (1) Brazeable to conventional nickel and cobalt-base superalloy bands

  (2) Incipient melting temperature 83°C (150°F) greater than INCO 713LC

(b) Finished Part Cost Goal - Two times that of cooled TFE731-3 2-vane segments cast of INCO 713LC -- 85-percent probability of success (35-percent weighing factor)

(c) Estimated Development Cost - $1,300,000

(d) Project Probability of Success - 30 percent

3. Uncooled Wire Reinforced 'M'CrAlY Vanes. - This project would lead to the production of uncooled HP turbine stator vanes of an 'M'CrAlY matrix composite reinforced with wire filaments. These vanes would be produced by the process previously described for the uncooled wire reinforced 'M'CrAlY blades. The incorporation of this material technology would result in a potential increase in cruise turbine inlet temperature of 150°C (270°F).

(a) Capability Goals

- o Critical Goals

  (1) A gain of 250°C (450°F) in longitudinal (spanwise-direction) creep-rupture strength over 0.178-cm (0.070-inch) thin-section equiaxed INCO 713LC castings -- 50-percent probability of success (30-percent weighing factor)

  (2) Thermal fatigue life at 1150°C (2102°F) equal to that of INCO 713LC at 1035°C (1895°F) -- 40-percent probability of success (35-percent weighing factor)

- o Noncritical Goals

  (1) Transverse stress-rupture strength equal to that of equiaxed IN-100 castings

  (2) Oxidation resistance for 5000-hours part life in a TFE731 Engine

(b) Finished Part Cost Goal - Three times that of cooled INCO 713 TFE731-3 vanes -- 20-percent probability of success (35-percent weighing factor)

(c) Estimated Development Cost - $3,500,000

(d) Project Probability of Success - 25 percent

Static Structural Components

1. <u>Low-Expansion Iron Alloys for Hot-End Static Structures</u>. - This project would lead to the production of more stable HP compressor, combustor, and turbine stator supporting structures fabricated of age-hardenable nickel-iron alloys with thermal expansions approximately half that of conventional, commercially available structural nickel alloys. These alloys have low thermal expansion when utilized below the steady-state operating temperature (candidate alloys are Incoloy 903 and CTX-2), and permit closer control of rotor blade tip/stator clearances resulting in improved component efficiency. Since the alloys do not contain chromium, coatings for oxidation resistance are required. The mechanical properties of these alloys are strongly influenced by thermo-mechanical processing. For this reason welding, brazing, and other thermal treatments performed during static structure manufacture require stringent control to prevent loss of strength and ductility. The incorporation of this technology and the associated alloys would allow a reduction in running clearances that would increase HP compressor and turbine stage efficiencies approximately 1.0 and 0.8 percent, respectively.

(a) Capability Goals

- Critical Goals

  (1) Retain base-alloy (Incoloy 903 and CTX-2) mechanical properties after fabrication and coating processes and after long-time engine operation -- 50-percent probability of success (50-percent weighing factor)

  (2) Coated parts of this alloy to be protected for 5000-hours, and then to be recoatable -- 70-percent probability of success (20-percent weighing factor)

- Noncritical Goal - Tensile and creep-rupture strengths equal to INCO 718

(b) Finished Part Cost Goal - 120-percent of the current INCO 718 TFE731-3 support structures -- 70-percent probability of success (30-percent weighing factor)

(c) Estimated Development Cost - $400,000

(d) Project Probability of Success - 60 percent

2. Abradable Silicone-Rubber LPC Shrouds. - This project would lead to the production of LP compressor shrouds coated with silicone rubber. The most advanced silicone rubbers are environmentally resistant to approximately 230°C (446°F). These materials have demonstrated good abradability in large turbofan engines, and they bond well to compressor casing materials. The incorporation of this technology would result in a 1.2-percent increase in compressor stage efficiency.

(a) Capability Goals

- Critical Goals

  (1) Coating/blade tip wear ratio equal to 15:1 -- 60-percent probability of success (40-percent weighing factor)

  (2) Erosion resistance adequate to meet 5000-hours part life -- 40-percent probability of success (30-percent weighing factor)

- Noncritical Goal - Coating debris size less than 0.025-cm (0.010-inch)

(b) Finished Part Cost Goal - Equal to current sprayed METCO 601 Shroud -- 80-percent probability of success (30-percent weighing factor)

(c) Estimated Development Cost - $400,000

(d) Project Probability of Success - 50 percent

RISK ANALYSIS

The risk analysis method used is basically the method described in NASA Report CR-134701 (Ref. 1) 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 ten 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 incorporation date, and the 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 I.

TABLE I. - 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
Secondary Factors			
Number of alternative approaches for application/ opportunities of incremental success for material	3 or more	2	1
Required technology incorporation date of material (years)	7	5	3
Critical nature of component to which material is applied	Static/low stress	Static/high stress	Rotating

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 following scale is then assigned to the current goal status:

Probability of Success	Alphabetical Scale Value
1.00 - 0.90	A
0.90 - 0.70	B
0.70 - 0	C

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
BBC	= 0.70	2 B's, 1 C	= -0.30
BAC,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 II summarizes the risk analysis for the ten candidate material technologies.

TABLE II. - RISK ANALYSIS.

	HPT Rotor Components					HPT Stator Vanes			Static Structural Components	
	Cooled DS MAR-M 247 Blades	Uncooled Single-Crystal MAR-M 247 Blades	Uncooled Wire Reinforced 'M'CrAlY Blades	Cooled Integrally-Bladed DS-Cast MAR-M 247 Rotor	PM René 95 Turbine Disk	Uncooled ODS 'M'CrAl	Cooled ODS 'M'CrAl Laminate	Uncooled Wire Reinforced 'M'CrAlY	Low-Expansion Iron Alloys for Hot-End Static Structures	Abradable Silicone-Rubber LPC Shrouds
Primary Factors										
o Nature of material	B	B	C	C	B	B	C	C	B	B
o Design approach/ application	B	A	C	C	A	A	C	C	B	B
o Current goal status	B (0.85)*	B (0.8)*	C (0.4)*	C (0.6)*	C (0.5)*	B (0.8)*	B (0.75)*	[illegible] (0.4)*	C (0.6)*	C (0.6)*
o Probability of Success	0.75	0.8	0.45	0.45	0.65	0.8	0.5	0.45	0.7	0.7
Secondary Factors										
o Alternate Applications	A	A	A	B	B	A	A	A	B	C
o Required incorporation Date	B	B	C	C	B	B	C	C	B	B
o Criticality of Component	C	C	C	C	C	B	B	B	A	A
o Probability of Success	-0.2	-0.2	-0.35	-0.3	-0.3	-0.1	-0.2	-0.2	-0.1	-0.2
Project Probability of Success	0.55	0.6	0.1	0.15	0.35	0.7	0.3	0.25	0.6	0.55

*( ) Weighted Probability of Success for combined critical property and finished part cost goals.

ENGINE CONSIDERATIONS

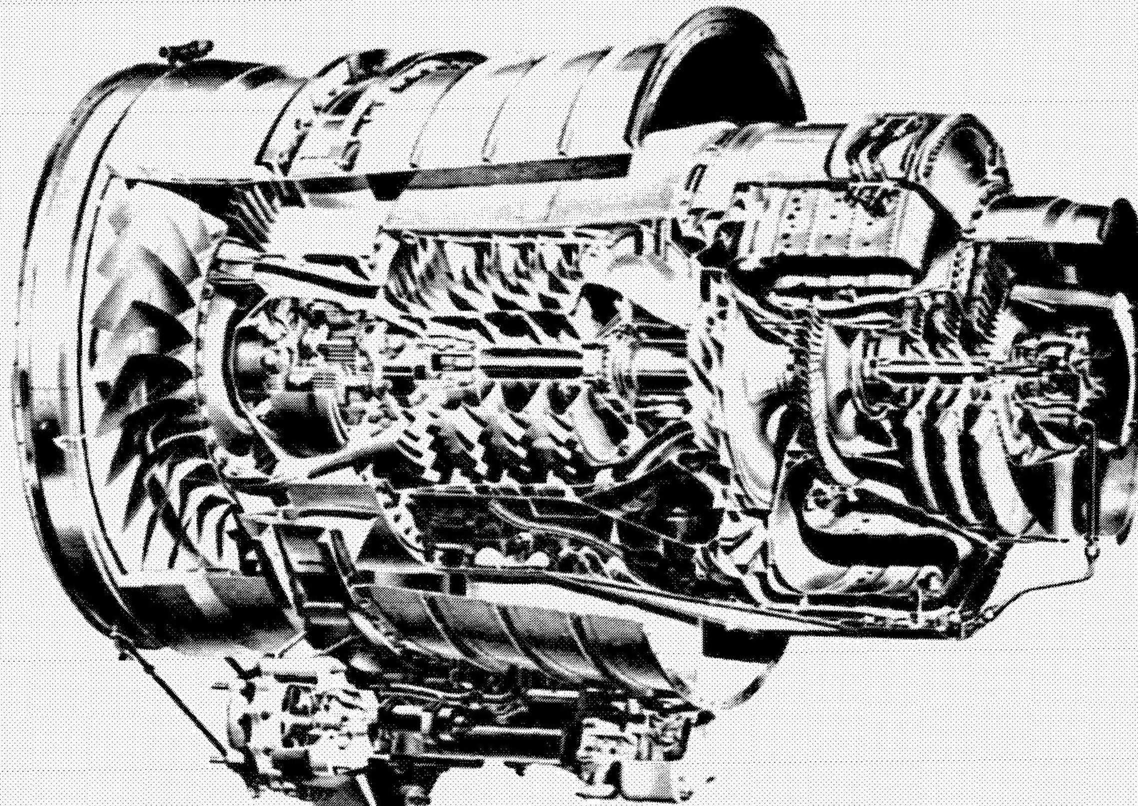
Baseline Engine Selection

The AiResearch Model TFE731-3 Engine (as illustrated in Figure 4), upgraded to include the MATE Projects 1 and 2 currently being developed, 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. Because a constraint was established for this study to focus on domestic aircraft, the choice was between the Lockheed JetStar II and the Learjet 35/36. The TFE731-3 Engine is installed in the Jetstar II (a four-engine aircraft), and the TFE731-2 Engine is installed in the Learjet 35/36 (a twin-engine aircraft). The program utilizes the TFE731-3 Engine; but the application of program benefits to a twin-engined aircraft was believed to be more in accord with the overall objectives of the program. As a result, 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.

Engine Performance

The incorporation of the uncooled DS HP turbine blades presently being developed under Project 1, and the abradable turbine and compressor gas-path seals presently being 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). The effects of these incorporated technologies results in the MATE baseline engine performance presented in Table III. Also shown for comparison is the present TFE731-3 performance.



TFE731

+ UNCOOLED DS MAR-M 247 HPT BLADES (PROJECT 1)

+ ABRADABLE COMPRESSOR AND TURBINE SHROUD SEALS (PROJECT 2)

+ INCREASED BYPASS RATIO AND PRESSURE RATIO

Figure 4.- Baseline Engine

TABLE III. - 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)	0.734 (0.721)
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)	4.9 (10.8)

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 are 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.

Weight Model

Scaling of the 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.

Cost Model

The cost model for engine scaling purposes is:

Cost is 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

Table IV summarizes the impact of each candidate technology on engine TSFC, weight, cost, 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 technologies exhibiting the best improvement in TSFC are the uncooled wire reinforced 'M'CrAlY HPT blades and the uncooled single-crystal MAR-M 247 blades. These HPT blades offer a higher turbine inlet temperature capability to the baseline engine and, subsequently, a higher engine thrust result. 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. The 25:1 pressure ratio was found to be optimum or near optimum for all the technologies studied. The cooled DS MAR-M 247 blades and the cooled integrally-bladed DS-cast MAR-M 247 rotor, although allowing a higher turbine inlet temperature capability, do not offer the improvement in engine TSFC as the other HPT blades. This is because of the penalty imposed on the engine cycle due to the cooling flow requirements, and the slightly lower component efficiency resulting from the cooling flow exit slots. There is no improvement in TSFC when utilizing the powder-metallurgy René 95 turbine disk.

The cooled ODS 'M'CrAl laminate vane and uncooled wire reinforced 'M'CrAlY vane technologies also offer a higher turbine stage temperature capability to the baseline engine and, subsequently, a slight improvement in engine TSFC results. The turbine stage temperature capability with the incorporation of the uncooled ODS 'M'CrAl vanes is the same as the baseline engine; therefore, there is no improvement in TSFC.

The static structural components offer a slight improvement in TSFC which results from the engine cycle optimization due to the improved turbine and compressor efficiency. These efficiency improvements are the result of the better tip clearance control offered by these static structural components.

The reduction in engine weight due to the incorporation of the HPT blade technologies is primarily due to the scaling of the baseline engine for the bypass ratio after the engine core flow was scaled down to restore the baseline altitude cruise thrust. The engine weight reduction for the PM René 95 turbine disk technology is due to the lower weight of the disk compared to the baseline disk weight.

Similarly, the reduction in engine weight, resulting from incorporation of the HPT cooled ODS 'M'CrAl laminate vanes and uncooled wire reinforced 'M'CrAlY vanes is due to the scaling of the engine for bypass ratio. There was no engine weight reduction with the incorporation of the uncooled ODS 'M'CrAl vane technology.

The low-expansion iron alloys show a reduction in engine weight because of the engine scaling resulting from a bypass ratio increase (as a result of the engine cycle optimization study). The abradable silicone-rubber LPC shrouds showed no weight change.

The change in engine cost is attributed to two considerations. The first consideration is the production cost of the technology component compared to the production cost of the present component in the baseline engine. The production cost for the component technology was established by a manufacturing review of the component. Production costs were also assessed and included in the cost/benefit analysis for those companion components that would need upgrading in order to realize the full benefit of the technology. For instance, incorporation of the uncooled single-crystal MAR-M 247 HPT blades would require an upgrading of the HPT stator in order to utilize the higher temperature capability of the blades. The second consideration is the cost effect resulting from the engine weight change due to the change in bypass ratio. As previously noted, for small changes in engine weight, the cost is approximately proportional to the weight. The above two considerations were used to arrive at the change in engine cost.

The large increase in engine cost from incorporation of the cooled integrally-bladed DS-cast MAR-M 247 rotor is due to the production cost being the overriding cost driver. The reduction in engine cost for the remaining HPT blade technologies is due primarily to the cost reduction resulting from the weight decrease for the increased bypass ratio.

The increase in engine cost from incorporation of the uncooled ODS 'M'CrAl and uncooled wire reinforced 'M'CrAlY HPT vanes is due to the increased production cost of the technologies compared to the baseline. The increased production cost of the uncooled wire reinforced 'M'CrAlY vanes was partially offset by the cost reduction associated with the increased bypass ratio. The reduction in engine cost from the incorporation of the cooled ODS 'M'CrAl laminate vanes is due primarily to the cost effect of the increased bypass ratio.

The production cost increase for incorporation of the low-expansion iron alloys for hot-end static structures was offset by the cost reduction associated with the bypass ratio increase.

The improvement in engine reliability (MTBF) was determined by arriving at a qualitative assessment of the component reliability. The component reliability was then used to arrive at the total module reliability. An improvement in engine reliability is noted by an increase in MTBF on Table IV. The greatest improvement in MTBF is in the uncooled HPT stator vanes and HPT blades. The improvement in MTBF for the cooled ODS 'M'CrAl laminate vanes is due to the increase in stress-rupture strength.

The components currently being evaluated, except for the turbine disks, are replaced on an 'on-condition' basis; therefore, the assessment of each candidate technology on life (TBO) was not considered. The delta change on life (TBO) for the integrally-bladed DS-cast rotor and the PM René 95 turbine disk is zero.

TABLE IV.- ENGINE EFFECTS OF CANDIDATE TECHNOLOGIES.

	Δ Performance TSFC (%)	Δ Engine Weight (%)	Δ Engine Cost (%)	Δ Reliability MTBF (%)
High-Pressure Turbine Rotor Components				
o Cooled DS MAR-M 247 blades	-0.7	-4.8	0	0
o Uncooled single-crystal MAR-M 247 blades	-1.1	-4.9	-3.3	+0.9
o Uncooled wire reinforced 'M'CrAlY HPT blades	-2.1	-6.3	-1.4	+1.5
o Cooled integrally-bladed DS-cast MAR-M 247 rotor	-0.7	-4.8	+16.3	0
High-Pressure Turbine Stator Airfoils				
o Uncooled ODS 'M'CrAl	0	0	+3.6	+8.0
o Cooled ODS 'M'CrAl laminate vanes	-0.7	-6.7	-2.1	+4.0
o Uncooled wire reinforced 'M'CrAlY vanes	-0.7	-6.3	+1.7	+2.0
Static Structural Components				
o Low-expansion iron alloys for hot-end static structures	-0.4	-1.1	-0.3	0
o Powder-metallurgy René 95 turbine disks	0	-1.0	-0.15	0
o Abradable silicone-rubber LPC shrouds	-0.4	0	0	+1.5

AIRCRAFT CONSIDERATIONS

Aircraft Selection

Early in the program a decision was made to use a domestic, non-revenue 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 chosen for the analysis was an all new design based on a composite aircraft similar to the Gates Learjet 35/36 (as illustrated in Figure 5). 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

Aircraft Baseline Life-Cycle Cost

The baseline operating and maintenance parameters for the selected composite twin-engine business jet aircraft are shown in Table V. From these parameters the annual direct operating costs are established for one aircraft and extended for a fleet of 4000 aircraft and a 25-year service life utilizing the life-cycle-cost models described in Appendix A. Table VI presents the baseline life-cycle costs. The operating costs are categorized into fixed and variable costs. The fixed costs are independent of the aircraft utilization and include interest, insurance, and taxes. The variable operating costs are a function of aircraft utilization, and would include primarily the fuel, and the aircraft and engine maintenance costs.

A pictorial representation of the contribution of each major life-cycle-cost element is shown in Figure 6 for the business-type aircraft application described herein. The acquisition cost contributes 19.9 percent of the total life-cycle costs. The fixed operating costs contribute 42.8 percent. The variable operating costs consist of 11.3 percent for fuel, 24.6 percent for engine and airframe maintenance, and 1.4 percent for the remaining variable costs.

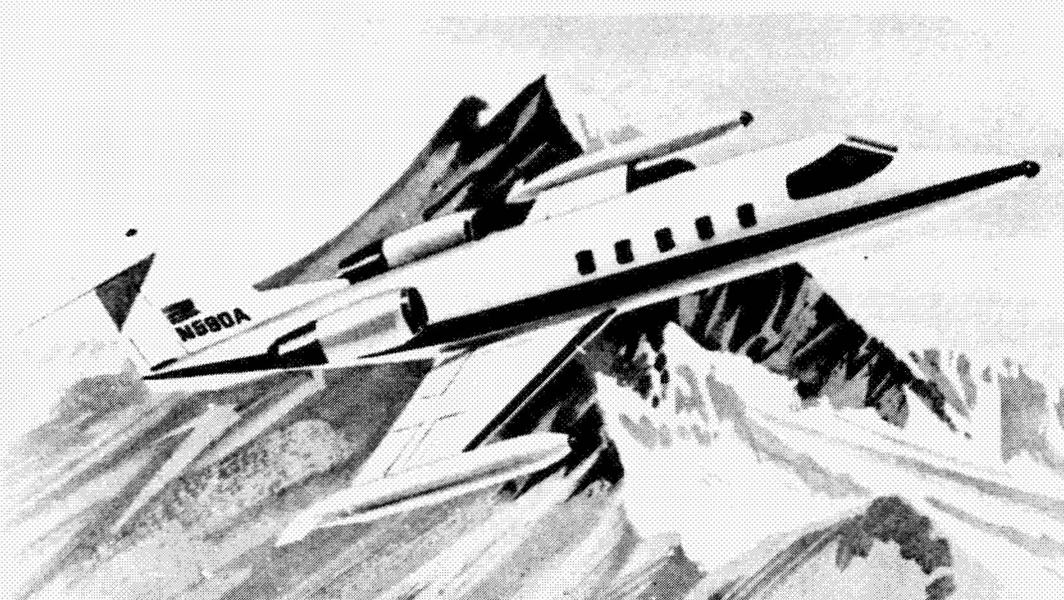


Figure 5.- Gates Learjet 35/36

TABLE V. - BASELINE AIRCRAFT OPERATING AND MAINTENANCE PARAMETERS.

Purchase Related	
o Aircraft acquisition cost, 10^6 $	1.63 (includes engine cost)
o Engine acquisition cost, 10^6 $	0.5 (two engines)
o Airframe fixed weight cost, $/kg ($/lb)	45.35 (100)
o Airframe variable weight cost, $/kg ($/lb)	90.7 (200)
o Equity, %	40
o Loan interest rate, %	8
o Imputed interest, %	8
o Insurance rate, %	1
o Property tax rate, %	1
Operation Related	
o Annual crew wages, $	50,000
o Annual crew expenses, $	4,000
o Annual hanger cost, $	5,000
o Fuel weight, kg (lb)	2,800 (6,172)
o Annual landing/parking fees, $	1,000
o Annual miscellaneous costs, $	1,000
o Annual utilization, hrs	600
o Fuel price, ¢/liter (¢/gal)	10.6 (40)
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)	0.735 (0.721)
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, $	4,500
o Engine inspection cost, $/flt-hr	5
o Annual engine overhaul cost, $	16,300
o Annual engine unscheduled repair cost, $	4,020
o Airframe inspection cost, $/flt-hr	10.55
o Annual airframe overhaul cost, $	16,650
o Annual airframe unscheduled repair cost, $	4,020

TABLE VI. - 25-YEAR LIFE-CYCLE COSTS FOR A BUSINESS JET FLEET OF 4000 AIRCRAFT.

	Airframe $\$(10^6)$	Engine $R(10^6)$	Total $\$(10^6)$
Acquisition Cost	4,520	2,000	6,520
Fixed Operating Costs			
o Interest on loan	542.4	240	782.4
o Imputed interest on investment	3,616	1,600	5,216
o Crew wages	5,000	--	5,000
o Insurance	565	250	815
o Taxes	565	250	815
o Hanger	500	--	500
o Miscellaneous costs	100	--	100
Variable Operating Costs			
o Fuel		3,689.3	3,689.3
o Preflight servicing	450	--	450
o Airframe inspection	633	--	633
o Airframe repair	402	--	402
o Airframe overhaul	1,665	--	1,665
o Engine inspection	--	600	600
o Engine repair	--	804	804
o Engine overhaul	--	3,260	3,260
o Service bulletin incorporation	--	233.2	233.2
o Crew expenses	400	--	400
o Landing, parking, catering, etc.	100	--	100
Total	19,058.4	12,926.5	31,984.9

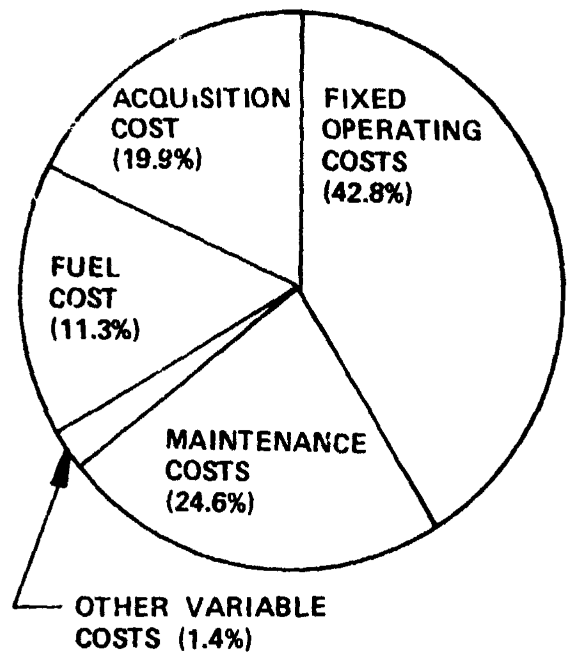


Figure 6. - Representation of the Contribution of Each Major Life-Cycle-Cost Element for the Business-Type Aircraft.

The imputed interest shown on Table VI is the interest which could be earned on the investment dollars if those dollars were not used for aircraft equity investment. An imputed interest rate equal to the typical internal rate of return for manufacturing firms of 8 percent has been assigned to the equity investment. It was also assumed that this investment is amortized on a straight-line basis over the economic life of the aircraft. Negligible salvage value at the end of that lifetime was assumed.

AIRCRAFT BENEFIT ANALYSIS

Trade Factors

AiResearch has developed a technique for determining aircraft life-cycle costs that begin 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, operating, 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.

The analysis begins with the formulation of a weight model for the aircraft. Sensitivity coefficients of this model for changes in engine TSFC and weight are obtained. Then, cost models for development, acquisition, operation, and maintenance are prepared, and the baseline costs are formulated as previously noted. An LCC model is assembled from these models based upon linearized effects of various engine parameters, and LCC 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.

Descriptions of the aircraft weight model 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 since this element represents basically the payload and, therefore, is constant for the specific aircraft design. 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 Table VII.

TABLE VII. - SENSITIVITY COEFFICIENTS CALCULATED FOR CHANGES IN ENGINE WEIGHT (ΔWE) AND (ΔTSFC).

Parameter	ΔTSFC = -5%	ΔWE = -5%
ΔThrust	- 8.5%	-3.6%
ΔFuel weight	-12.3%	-3.3%
ΔEngine installed weight	- 8.5%	-8.2%
ΔAirframe variable weight	-10.8%	-4.7%
ΔAircraft empty weight	- 7.8%	-4.1%

The new thrust, fuel weight, and other parameters listed in Table VII are utilized in the appropriate life-cycle-cost models, presented in Appendix A, to obtain the sensitivity of engine weight and TSFC changes on aircraft life-cycle cost.

In addition, sensitivity to engine cost, time-between-overhaul (TBO), and mean-time-between-failure (MTBF) are also calculated using the appropriate life-cycle-cost models.

The change in life-cycle cost resulting from a one-percent change in TSFC, engine weight, engine cost, TBO, and MTBF are tabulated in Table VIII.

TABLE VIII. - CHANGES IN LIFE-CYCLE COST (ΔLCC) FOR ONE-PERCENT CHANGE IN VARIOUS PARAMETERS.

Parameter (one-percent change)	ΔLCC Percentage
Thrust specific fuel consumption (TSFC)	0.911
Engine weight (WE)	0.345
Engine cost (CE)	0.194
Time-between-overhaul (TBO)	0.102
Mean-time-between-failure (MTBF)	0.025

As noted in Table VIII, TSFC followed by engine weight has the greatest influence on life-cycle cost. Furthermore, as the cost of fuel increases, the effects of changes in TSFC and engine weight on life-cycle cost are even more pronounced.

The fuel price used in the analysis was assumed to be 10.6-cents per liter (40-cents per gallon) and represented 11.3 percent of the total baseline life-cycle cost. A sensitivity analysis was conducted to determine the effect of various fuel prices on the TSFC and engine weight sensitivity coefficients. The results of this analysis are shown on Figure 7. The TSFC sensitivity becomes one-for-one at a fuel price of about 14.3-cents per liter (54-cents per gallon).

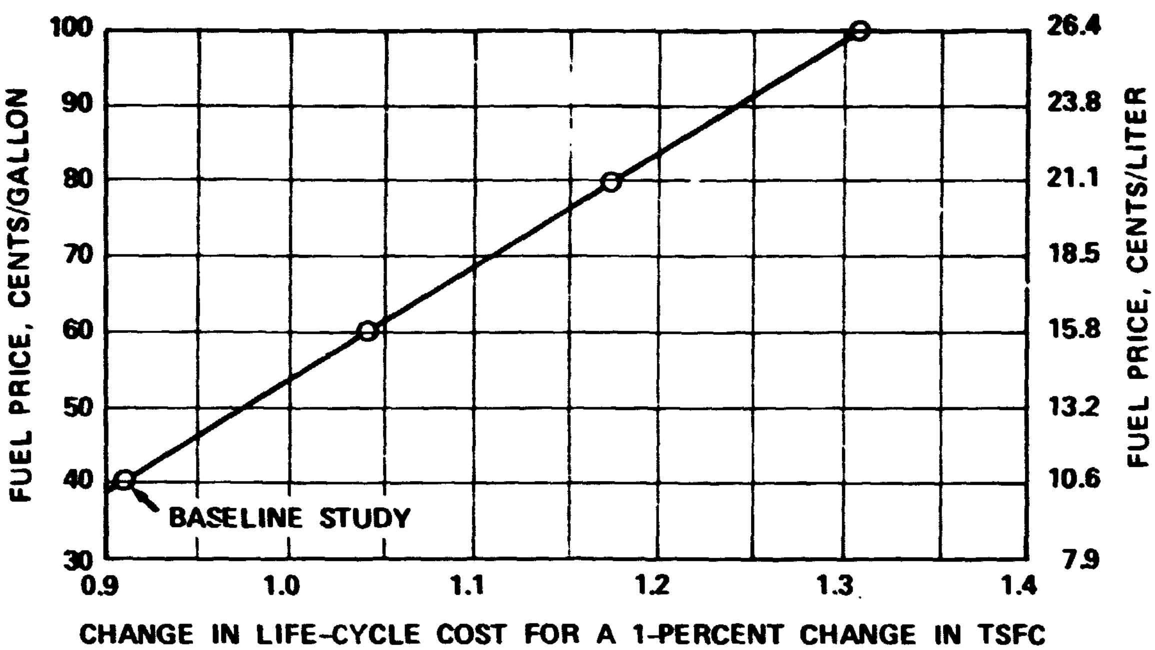
Aircraft Benefits

The ten candidate material technologies were evaluated against the baseline engine for TSFC, weight, cost, and MTBF, as previously shown in Table IV. These engine results were then incorporated in the aircraft life-cycle cost models using the factors previously described. The results of this analysis, in terms of change in aircraft life-cycle costs (ΔLCC), are listed in Table IX.

TABLE IX. - LIFE-CYCLE COST RANKING.

Ranking	Technology	ΔLCC (Dollars x 10^6)
1.	Uncooled wire reinforced 'M'CrAlY HPT blades	-1395
2.	Cooled ODS 'M'CrAl laminate vanes	-1100
3.	Uncooled single-crystal MAR-M 247 blades	-1087
4.	Uncooled wire reinforced 'M'CrAlY HPT vanes	-802
5.	Cooled DS MAR-M 247 blades	-736
6.	Abradable silicone-rubber LP compressor shrouds	-134
7.	PM René 95 turbine disks	-122
8.	Low-expansion iron alloys for hot-end static structures	-71
9.	Uncooled ODS 'M'CrAl Vanes	+152
10.	Cooled integrally-bladed DS-cast MAR-M 247 rotors	+278

As shown, the most significant benefits are associated with the various types of improved airfoils for the high-pressure turbine (except for the uncooled ODS 'M'CrAl vane). The increased temperature capabilities predicted with use of these blades and vanes cause a significant reduction in fuel consumption (TSFC) which has the greatest impact on life-cycle cost.



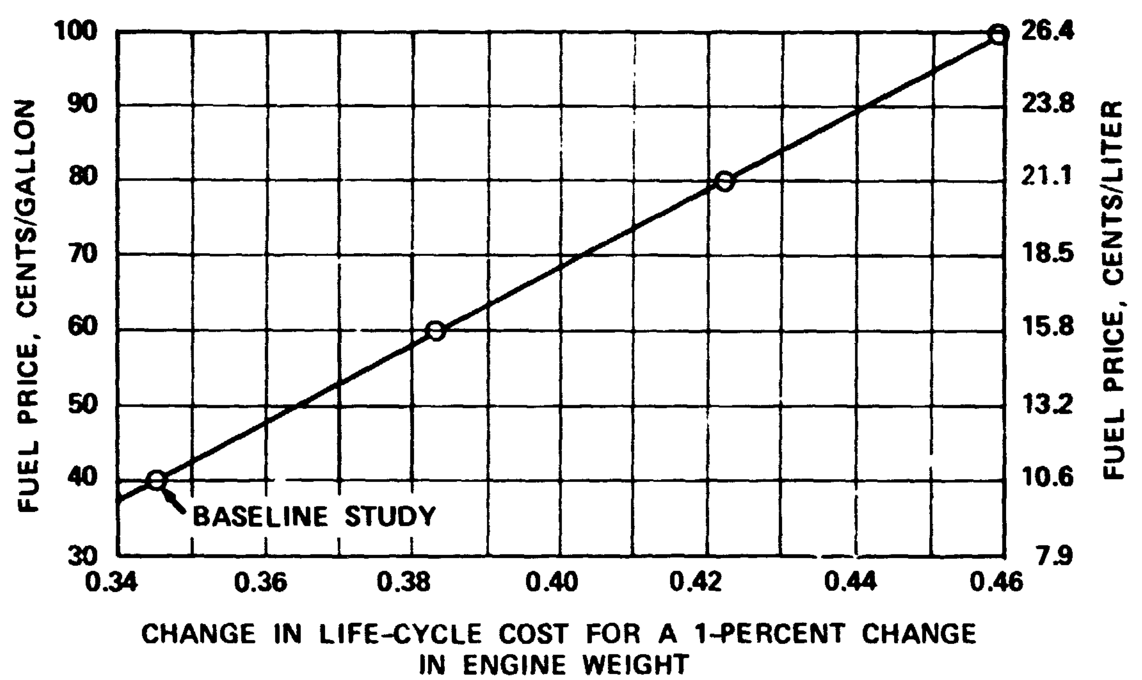


Figure 7.- Sensitivity Analysis for the Determination of the Effects of Various Fuel Prices on TSFC and Engine Weight Sensitivity Coefficients.

The temperature capability of the uncooled ODS 'M'CrAl vanes is the same as the cooled cast INCO 713LC vanes in the baseline engine; therefore, no improvement in TSFC results. The higher production cost of this vane technology actually results in an increase in life-cycle cost. Similarly, the high production cost of the cooled integrally-bladed DS-cast MAR-M 247 rotors offsets the cost reductions due to improved TSFC and increased bypass ratio with the life-cycle costs actually increasing.

RESULTS AND DISCUSSION

Relative Value Analysis

Since the ten materials 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:

$$\text{Relative Value} = \frac{\Delta\text{Life-Cycle Cost}}{\text{Development Cost}} \times \text{Probability of Success} \quad (4)$$

This parameter was calculated for each of the ten materials technologies utilizing the project probability of success developed in the risk analysis, the technology development cost, and the delta life-cycle cost calculated for each technology. The resulting values are shown in Table X with the technologies listed in order of decreasing Relative Value.

The two highest Relative Value rankings are the uncooled single-crystal MAR-M 247 blades and the cooled DS MAR-M 247 blades, followed by the cooled ODS 'M'CrAl laminate vanes. The uncooled wire reinforced 'M'CrAlY HPT blades that showed the highest reduction in life-cycle cost, and the uncooled wire reinforced 'M'CrAlY HPT vanes rank very low on a Relative Value basis because of the high development cost and low project probability of success. The static structural components (i.e., abradable LPC shrouds and the low-expansion structures) increased in ranking on a Relative Value basis compared to the life-cycle cost ranking. This increased ranking directly resulted from the lower development costs and risks currently associated with these technologies. The uncooled ODS 'M'CrAl vanes and the cooled integrally-bladed DS-cast MAR-M 247 HPT rotors obviously rank the lowest on a Relative Value basis because life-cycle cost actually increased with incorporation of these technologies.

TABLE X. - MATERIALS TECHNOLOGY RELATIVE VALUE SUMMARY.

Materials Technology	Relative Value	ΔLCC (10^6 $)	Development Cost (10^6 $)	Probability of Success (%)
Uncooled single-crystal MAR-M 247 blades	593	-1087	1.1	60
Cooled DS MAR-M 247 blades	311	-736	1.3	55
Cooled ODS 'M'CrAl laminate vanes	254	-1100	1.3	30
Abradable silicone-rubber LP compressor shrouds	168	-134	0.4	50
Low-expansion iron alloys for hot-end static structures	106	-71	0.4	60
Uncooled wire reinforced 'M'CrAlY HPT vanes	67	-802	3.0	25
PM René 95 turbine disks	33	-122	1.3	35
Uncooled wire reinforced 'M'CrAlY HPT blades	32	-1395	4.4	10
Cooled integrally-bladed DS-cast MAR-M 247 HPT rotors	<21>	+278	2.0	15
Uncooled ODS 'M'CrAl vanes	<106>	+152	1.0	70

AIRESEARCH CORPORATE RANKING

The uncooled single-crystal MAR-M 247 blade, the cooled DS MAR-M 247 blade, and the cooled ODS 'M'CrAl laminate vane technologies that ranked highest on the Relative Value basis and showed a large reduction in life-cycle cost were also highest in the AiResearch priority ranking. The ranking for the ten candidate technologies is presented on Table XI.

The uncooled wire reinforced 'M'CrAlY HPT airfoil technology, both vane and blade, offers high potential savings in life-cycle costs. This potential, especially of the vane, is responsible for the establishment of their ranking on the AiResearch priority list, in spite of high development costs and low probability of success.

The abradable silicone-rubber LP compressor shroud offers an improvement in compressor stage efficiency by maintaining tip clearance control. Current AiResearch TFE731 engines are not utilizing shrouds for tip clearance control, but rather dimensional tolerance buildup. Since the abradable shrouds offer an improved method for tip clearance control in the current AiResearch TFE731 Engine, this technology ranks high. Low-expansion iron alloys for hot-end structures also offer performance improvements by maintaining tip clearance control in the turbine section.

Integrally bladed disks avoid the complicated firtree attachments that are susceptible to fatigue failure. This configuration also reduces rim loading and, therefore, bore stresses.

The incorporation of the uncooled ODS 'M'CrAl vanes provides an engine cycle improvement since cooling air is no longer required in the vane.

The powder-metallurgy René 95 turbine disk offers ease of fabrication and an attractive alternative when compared to forged Astroloy or forged René 95.

Implications of Results

The uncooled wire reinforced 'M'CrAlY HPT blade and vane technologies both achieve a significant reduction in life-cycle cost. However, these technologies rank low on a Relative Value basis because the high development costs required to incorporate these technologies into the turbine stage, and the projected high production part costs, both drive the Relative Value down. In spite of this, these technologies still appear attractive enough to warrant further study due to the high potential savings. This is especially true of the uncooled vane. The vane technology would not require the extensive development effort necessary for the blades, due to the complex problem of blade attachment.

TABLE XI.- AIRESEARCH CORPORATE RANKING.

1.	Uncooled single-crystal MAR-M 247 blades
2.	Cooled DS MAR-M 247 blades
3.	Cooled ODS 'M'CrAl laminate vanes
4.	Uncooled wire reinforced 'M'CrAlY HPT vanes
5.	Abradable silicone-rubber LP compressor shrouds
6.	Uncooled wire reinforced 'M'CrAlY HPT blades
7.	Cooled integrally-bladed DS-cast MAR-M 247 HPT rotors
8.	Low-expansion iron alloys for hot-end static structures
9.	Uncooled ODS 'M'CrAl vanes
10.	PM René 95 turbine disks

The low Relative Values of the cooled integrally-bladed DS-cast MAR-M 247 HPT rotor and uncooled ODS 'M'CrAl vane technologies are the direct result of these technologies showing an increase in life-cycle cost. This increase in life-cycle cost is due to the high production cost of these technologies compared to the current production costs.

The low Relative Value for PM René 95 turbine disks is the result of a small improvement in life-cycle cost. This technology offers no cost or performance advantage. The only life-cycle cost improvement results from increased reliability and a slight weight reduction.

The abradable silicone-rubber LP compressor shroud and low-expansion iron alloy technologies have median Relative Value due to low development costs and a high project probability of success, which offset the low reduction in life-cycle cost. The reduction in life-cycle cost is due to the decrease in TSFC, which is the result of the tip clearance control offered by these technologies in the compressor and turbine sections.

The probability of success for the cooled ODS 'M'CrAl laminate vane technology is not especially high; however, the moderate development cost and the considerable reduction in life-cycle cost results in a high Relative Value. The low probability of success is due primarily to the high production part cost compared to the present TFE731 cooled 2-vane segments.

The cooled DS MAR-M 247 blades show a high reduction in life-cycle cost, which is due to the improvement in TSFC and engine weight and cost reductions caused by the increased bypass ratio.

The uncooled single-crystal MAR-M 247 blade technology has the highest Relative Value. This is due to the moderate development cost, high probability of success, and a high reduction in life-cycle cost.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study are summarized in Tables XII, XIII, and XIV. The highest ranking technology in both Relative Value and Company Priority is the uncooled single-crystal HP turbine blade. This technology is currently under development as a part of the AiResearch MATE Program. The following technologies are recommended for further consideration as future MATE projects:

- Cooled DS MAR-M 247 blades
- Cooled ODS 'M'CrAl laminate vanes
- Uncooled wire reinforced 'M'CrAlY HPT vanes
- Abradable silicone-rubber LP compressor shrouds
- Low-expansion iron alloys for hot-end static structures

The remaining candidates, while generally having value, should not be developed at the expense of any of the recommended technologies. The possible exception to this conclusion is the uncooled wire reinforced 'M'CrAlY turbine blades. Experience gained through an uncooled wire reinforced 'M'CrAlY vane development effort could change the estimated development cost and project probability of success.

TABLE XII. - LIFE-CYCLE COST RANKING.

Rank	Technology	ΔLCC (Dollars x 10^6)
1.	Uncooled wire reinforced 'M'CrAlY HPT blades	-1395
2.	Cooled ODS 'M'CrAl laminate vanes	-1100
3.	Uncooled single-crystal MAR-M 247 blades	-1087
4.	Uncooled wire reinforced 'M'CrAlY HPT vanes	- 802
5.	Cooled DS MAR-M 247 blades	- 736
6.	Abradable, silicone-rubber LP compressor shrouds	- 134
7.	Powder-metallurgy René 95 turbine disks	- 122
8.	Low-expansion iron alloys for hot-end static structures	- 71
9.	Uncooled ODS 'M'CrAl vanes	+ 152
10.	Cooled integrally-bladed DS-cast MAR-M 247 HPT rotors	+ 278

TABLE XIII. - RELATIVE VALUE RANKING.

Rank	Technology	Relative Value
1.	Uncooled single-crystal MAR-M 247 blades	593
2.	Cooled DS MAR-M 247 blades	311
3.	Cooled ODS 'M'CrAl laminate vanes	254
4.	Abradable silicone-rubber LP compressor shrouds	168
5.	Low-expansion iron alloys for hot-end static structures	106
6.	Uncooled wire reinforced 'M'CrAlY HPT vanes	67
7.	Powder-metallurgy René 95 turbine disks	33
8.	Uncooled wire reinforced 'M'CrAlY HPT blades	32
9.	Cooled integrally-bladed DS-cast MAR-M 247 HPT rotors	< 21>
10.	Uncooled ODS 'M'CrAl vanes	<106>

TABLE XIV. - AIRESEARCH CORPORATE RANKING.

1.	Uncooled single-crystal MAR-M 247 blades
2.	Cooled DS MAR-M 247 blades
3.	Cooled ODS 'M'CrAl laminate vanes
4.	Uncooled wire reinforced 'M'CrAlY HPT vanes
5.	Abradable silicone-rubber LP compressor shrouds
6.	Uncooled wire reinforced 'M'CrAlY HPT blades
7.	Cooled integrally-bladed DS-cast MAR-M 247 HPT rotors
8.	Low-expansion iron alloys for hot-end static structures
9.	Uncooled ODS 'M'CrAl vanes
10.	Powder-metallurgy René 95 turbine disks

APPENDIX A

AIRCRAFT WEIGHT
AND LIFE-CYCLE COST (LCC) MODELS

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APPENDIX A
AIRCRAFT WEIGHT
AND LIFE-CYCLE COST (LCC) 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 model makes 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. 7).

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 structure such as the fuselage, wings, empennage, and landing gear. Systems 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, lengths 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 incl ling any auxiliary fuel tanks. The fuel pumps, pipes, and collector plenums would also be included as part of the tankage weight.

Table XV is a tabulation of the weight breakdown for the composite 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:

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

TABLE XV. - COMPOSITE AIRCRAFT WEIGHT BREAKDOWN REPRESENTATIVE.

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 (6172)
o Fuel System (includes usable fuel)	122 (270)
o Auxiliary Fuel Tanks	109 (240)
TOTAL	3030 (6682)
Takeoff Gross Weight (TOGW)	7711 (17,000)

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 lift (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.

The expression for the installed engine weight is based on the free-body diagram for an aircraft at cruise where lift 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:

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

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, multi-segment missions can be easily incorporated as Nicolai (Ref. 3) has shown.

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. 8), 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. 9), 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
Loan 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:

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

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.

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

where:

AOC = Airframe overhaul cost

BAOC = Baseline airframe overhaul cost

BAMC = Baseline airframe manufacturing cost

and,

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

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
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
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

LIST OF ABBREVIATIONS/SYMBOLS (CONTD)

QA	Aircraft quantity
QE	Engine quantity
R	Distance traveled
RINS	Insurance rate
RINT	Interest rate
RTAX	Tax rate
T	Aircraft cruise endurance with all fuel consumed (hours)
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
WF_{FINAL}	Fuel weight at end of cruise

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