NASA-CR-165225
19810006491

NASA

COST/BENEFIT ANALYSIS OF ADVANCED MATERIALS TECHNOLOGIES FOR FUTURE AIRCRAFT TURBINE ENGINES

by
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August 1980

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA LEWIS RESEARCH CENTER
CONTRACT NAS3-20072

PRATT & WHITNEY AIRCRAFT GROUP
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In reply please refer to:
SSB:AC:nt(9384m) - MERL
Ref. No. PWA 5574-102

January 6, 1981

To: National Aeronautics and Space Administration
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Subject: Project 0 - Cost Benefit Analysis of Advanced Materials Technologies For Future Aircraft Turbine Engines

References: (1) Contract NAS3-20072
(2) NASA Letter, D.M. Thomas to S.S. Blecherman, dated 11 December 1980

Enclosure: Subject Report Final

This Final Report has been prepared in accordance with the requirements of reference (1) and incorporates the changes requested by NASA in the reference (2) letter. Distribution of the Final Report shall be made in accordance with the distribution list submitted under the reference (2) letter.

Sincerely yours,

UNITED TECHNOLOGIES CORPORATION
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Commercial Products Division

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MATE Program Manager

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA-CR-165225		

4. Title and Subtitle	5. Report Date
Cost/Benefit Analysis of Advanced Materials Technologies for Future Aircraft Turbine Engines	August 1980
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
G. E. Stephens	PWA-5755
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
United Technologies Corporation Pratt & Whitney Aircraft Group - CPD East Hartford, Connecticut 06108	NAS3-20072
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics and Space Administration Washington, D.C. 20546	Proj. Comp. Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Program Managers, C. P. Blankenship/S. J. Grisaffe, Materials and Structures Division, NASA-Lewis Research Center, Cleveland, Ohio

16. Abstract

Cost/benefit studies were conducted on six advanced materials technologies applicable to future commercial aircraft gas turbine engines for use in the 1985 to 1990 time frame. The materials technologies studied included thermal barrier coatings for turbine airfoils, turbine disks, cases, turbine vanes and engine and nacelle composite materials. The cost/benefit of each technology was determined in terms of "Relative Value" defined as change in return on investment times probability of success divided by development cost. A recommended final ranking of technologies was based primarily on consideration of "Relative Values" with secondary consideration given to changes in other economic parameters. Technologies showing the most promising cost/benefits were thermal barrier coated turbine airfoils, dual property advanced high pressure turbine disks and low temperature nacelle/engine system composites.

17. Key Words (Suggested by Author(s))		18. Distribution Statement
Materials Technology Fabrication Technology Cost Benefits	Turbofan Engine Subsonic Engine	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	64	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

N81-15006#

FOREWORD

The cost/benefit studies of advanced aircraft gas turbine materials technologies described herein were performed by the Pratt & Whitney Aircraft Group of United Technologies Corporation under the technical direction of Charles P. Blankenship, Materials and Structures Division, NASA-Lewis Research Center. This report was prepared by Guilford E. Stephens, the Pratt & Whitney Aircraft Project Manager. Materials information was prepared by M. J. Blackburn, D. S. Duvall, A. F. Giamei and K. M. Prewo and reviewed by H. A. Hauser of Pratt & Whitney Aircraft. Overall direction of the Contractor's effort was provided by S. S. Blecherman, the Pratt & Whitney Aircraft Materials for Advanced Turbine Engine Program Manager.

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SUMMARY

The primary objective of the study described in this report was to analyze the cost/benefits relationships which potentially could result from the use of the advanced commercial gas turbine materials being considered for NASA's Materials for Advanced Turbine Engine (MATE) program. These studies update previously published cost/benefit studies using the latest state-of-the-art materials and engine cycle information. Comprehensive studies determined estimated payoffs, development costs, and probabilities of success for each of the selected technologies and combined these parameters to establish cost/benefit rankings. Cost/benefit sensitivities to projected material properties were obtained for each technology based on success-oriented (full) and less optimistic (sensitivity) goal levels. The goals are given in Table I.

The relative ranking of materials technologies for either full or reduced goals remained the same and are presented below:

(1) Thermal Barrier Coated Airfoils
(2) Dual Property Advanced Disk
(3) Engine/Nacelle Low Temperature Composites
(4) Silicon-Carbide Reinforced Glass Ceramic
(5) Advanced Fabricated High Pressure Turbine Vane Cluster
(6) High Strength, Low Expansion, Cast Cases

Relative Value* results for all study technologies are compared in Figure 1. Relative Value as used herein represents one way of assessing material technology benefits and ranking the potential benefits of several materials

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*Cost/benefits are measured primarily by "Relative Value" where

$$\text{Relative Value} = \frac{\text{Return on Investment}}{\text{Development Cost}} \times \text{Probability of Success}$$

TABLE 1

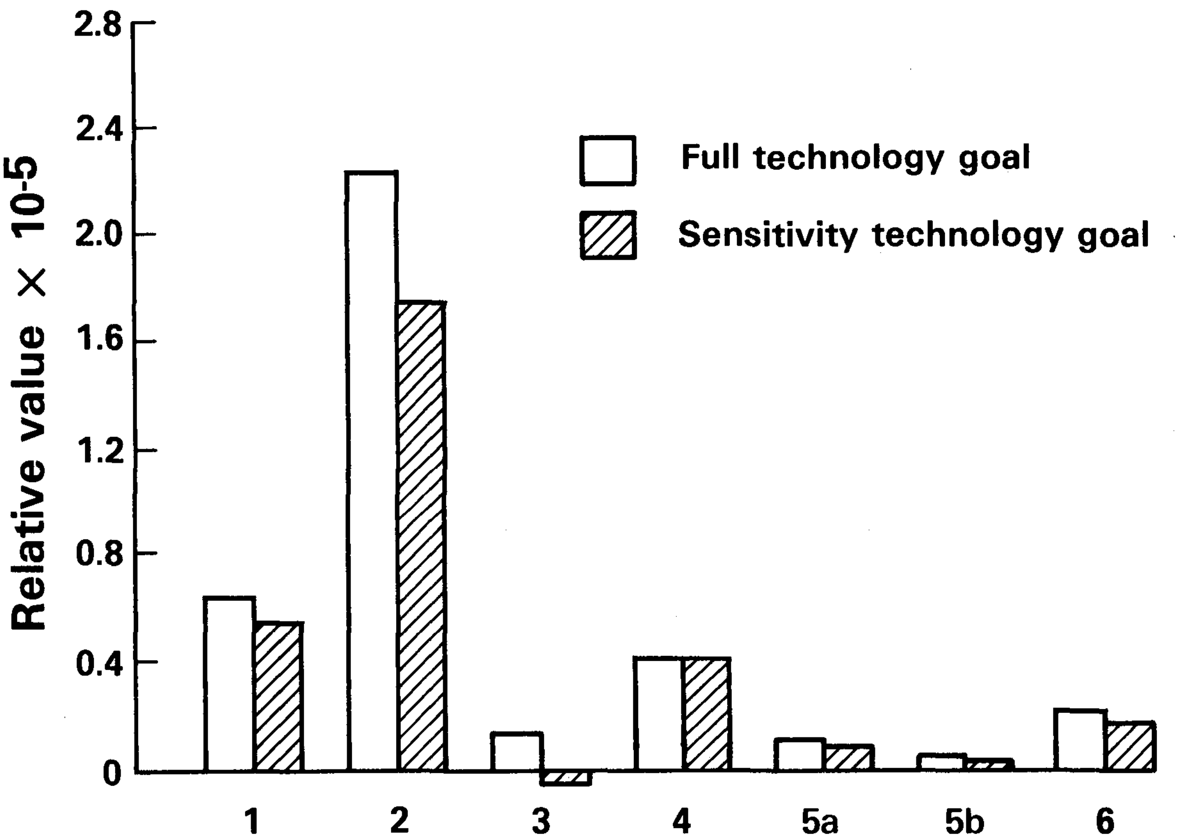
ADVANCED MATERIALS TECHNOLOGY GOALS

Full Goals		Sensitivity Goals
Dual Property Advanced Disk		
• +20% bore LCF strength; +5% yield & U.T.S.; +5% rim stress rupture strength	at $+100^{\circ}F$ vs. MERL 80	-10% rim stress rupture strength
• HIP process cost 2.0X MERL 80		
• Finished disk cost +5% > MERL 80		
Thermal Barrier Coated Airfoils		
• 0.015 inch coating thickness		0.005 inch coating thickness
• Insulative capability $+200^{\circ}F$ > NiCoCrAlY		
• Coating cost 1.5X to 2.0X > NiCoCrAlY		
• Average coated airfoil cost +5% > NiCoCrAlY		
Advanced Fabricated High Pressure Turbine Vane Cluster		
• +100% thermal fatigue strength; • $+250^{\circ}F$ coated oxidation resistance; • $+100^{\circ}F$ creep strength	Vs. PWA 647/ PWA 27	
• Clustered vane set cost equal to PWA 647 single vane set cost		Vane set cost +25% > PWA 647 single vane set cost

TABLE 1 (Cont'd.)

Full Goals	Sensitivity Goals
Engine/Nacelle Low Temperature Composites	
• Total component weight 100 lbs. < aluminum/titanium systems	
• Temperature capability to 500°F	
• Total component cost equal to aluminum/titanium systems	Total component cost +10% > aluminum/titanium systems
High Strength, Low Expansion, Cost Cases	
• Mechanical properties of Inco 718 at 1200°F extended to 1300°F	
• Oxidation/corrosion resistance to 1300°F	
• 40% reduction in modulus X thermal expansion coefficient	20% reduction in modulus X thermal expansion coefficient
• Finished diffuser case cost 5% > Inco 718	
• Finished turbine exhaust case cost 85% > AMS 5616 (Greek Ascology)	
Silicon Carbide-Reinforced Glass Ceramic	
• 1800°F temperature capability	
• Total component weight 180 lbs < nickel-base alloys	
• Finished parts cost 25% > PWA 1455, PWA 655, MERL 220 finished part cost	Finished parts cost 60% > PWA 1455, PWA 655, MERL 220 finished part cost

technologies on the same relative basis. It should not be construed to represent the sole or, necessarily, the prime basis for selecting materials technologies for engineering development and engine application. Other significant factors, which require engineering judgment and often play a major role in program selection priorization, were not included in the Relative Value equation.



1. Dual Property High Pressure Turbine Disk
2. Thermal Barrier Coated Airfoils
3. Fabricated High Pressure Turbine Vanes
4. Engine/Nacelle Low Temperature Composites

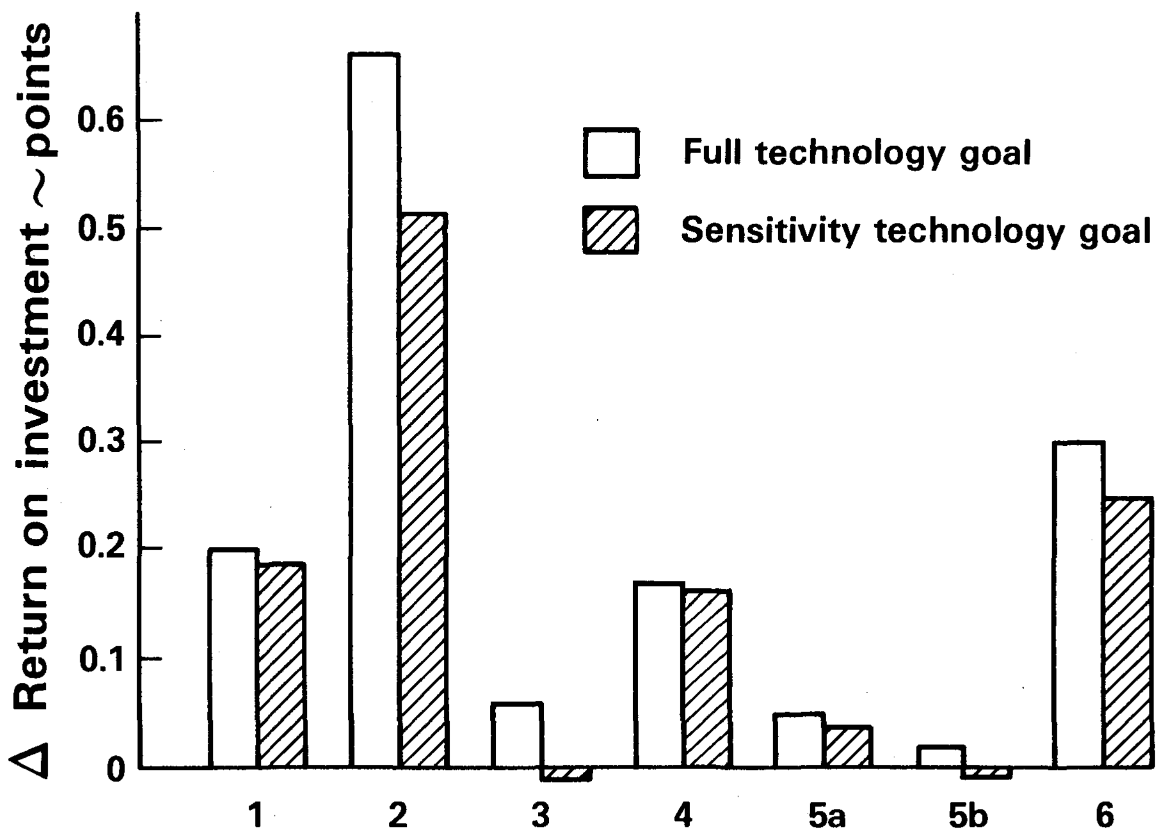
5a. High Strength, Low α Cast, Diffuser Case
5b. High Strength, Low α Cast, Turbine Exhaust Case
6. Silicon Carbide Reinforced Glass Ceramic Static Turbine Components

Figure 1 Comparison of Advanced Materials Technologies on the Basis of "Relative Value" Parameter

The most significant benefits in terms of Relative Value were obtained for three materials listed below:

- Thermal Barrier Coated Airfoils
- Dual Property Advanced Disk
- Engine/Nacelle Low Temperature Composites

Projected economic benefits independent of the probability of success and development cost were also noted for Silicon Carbide-Reinforced Glass Ceramic turbine seals, low turbine airfoils and burner segments. Economic benefits expressed in terms of "Return on Investment" are compared in Figure 2.



1. Dual Property High Pressure Turbine Disk
2. Thermal Barrier Coated Airfoils
3. Fabricated High Pressure Turbine Vanes
4. Engine/Nacelle Low Temperature Composites

5a. High Strength, Low α Cast, Diffuser Case
5b. High Strength, Low α Cast, Turbine Exhaust Case
6. Silicon Carbide Reinforced Glass Ceramic Static Turbine Components

Figure 2 *Comparison of Advanced Materials Technologies on the Basis of "Return on Investment" Parameter*

INTRODUCTION

NASA and industry have recognized the need to investigate and evaluate advanced materials technologies for improved commercial transport engines of the 1980's. Because of concern for the efficient use of our petroleum resources, applications which will make the propulsion system more energy efficient have been given high priority. Also, environmental considerations dictate that the propulsion system be clean and quiet. At the same time, it has been recognized that it is extremely important to thoroughly understand the economic impact on the airlines resulting from these increased energy and environmental constraints.

To help fulfill these needs in the area of materials technology, NASA conceived the MATE (Materials for Advanced Turbine Engine) Program, a cooperative effort with industry, to accelerate the introduction of new materials technologies into advanced aircraft turbine engines. Prior to the initiation of the MATE program, NASA sponsored Pratt & Whitney Aircraft in the "Cost/Benefit Study of Advanced Materials Technologies for Aircraft Turbine Engines' program as reported in NASA CR-134701 (Reference 1). Under that earlier study, Pratt & Whitney Aircraft developed the methodology for calculating the cost/benefits and relative values of new materials technology programs. Cost/benefits were established for twelve advanced materials technologies in that study and subsequently six additional materials technologies in the follow-on cost/benefit study reported in NASA CR-135107 (Reference 2). The technologies evaluated applied to fan blades and cases, compressor and turbine disks, burner liners and turbine blades, vanes and outer airseal/blade tip treatment systems in engines for aircraft of the 1980's. A recent, brief cost/benefit study has demonstrated the potential of erosion resistant coatings on compressor stators and of turbine vane fabrication methods. The results of these studies provided input to select the programs being pursued in the MATE effort.

NASA and Pratt & Whitney Aircraft have recognized the need for periodic updating of the cost/benefit studies during the performance of the MATE program. As a result, the study program summarized in this report has again established costs and benefits for several advanced materials technologies as applied to specific components of an early 1990's technology turbofan engine and a current turbofan engine in representative advanced commercial transport aircraft.

STUDY APPROACH

Advanced materials technologies selected for this study are shown in Table 2. These materials technologies were chosen because of their anticipated potential benefits in the engine/aircraft application with particular emphasis on their potential effects in reducing engine fuel consumption. Materials which will offer significant benefits in combination with reasonable development cost and risk will continue to be considered for incorporation in the NASA MATE effort.

TABLE 2

SELECTED ADVANCED MATERIALS TECHNOLOGIES

- Dual Property Advanced Disk
- Thermal Barrier Coated Airfoils
- Advanced Fabricated High Pressure Turbine Vane Cluster
- Engine/Nacelle Low Temperature Composites
- High Strength, Low Expansion, Cast Cases
- Silicon-Carbide Reinforced Glass Ceramic

The materials technology cost/benefit study approach is shown schematically in Figure 3. First, material property projections and goals were established for the specified technologies. For each material, two levels of properties were defined based on success-oriented (full) and less optimistic (sensitivity) goals. These goal variations permitted a determination of cost/benefit sensitivities in case the developmental phases for each technology were not successful in achieving the expected full goals. The defined goals were then used to estimate the material technology's development program risk and cost. Technology development costs were based on defined program plans and represent the funding estimated to bring a material from its present status through one engine demonstration test and post-test materials analysis. Costs to run the engine or general and administrative costs and fee were not included in these estimates. Technology risk (probability of success) assessments were performed on a uniform basis using a qualitative analytical procedure developed for this purpose. The procedure assigned varying degrees of risk for each of several factors as described in Table 3.

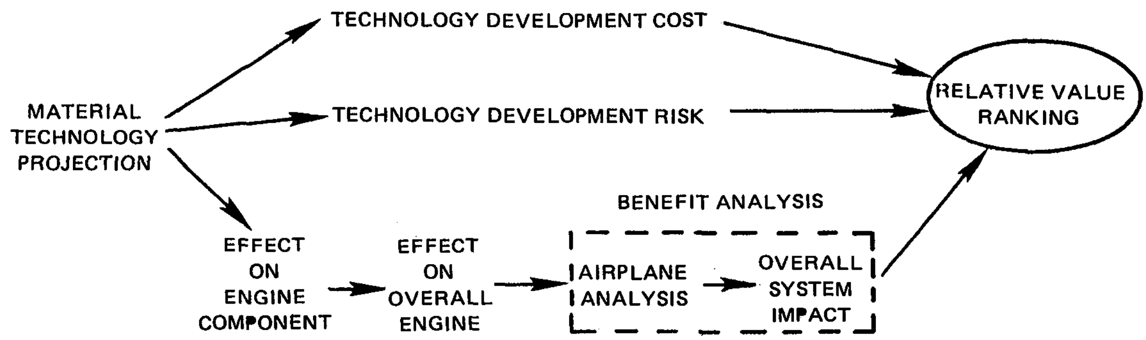


Figure 3 Cost/Benefit Analyses Approach

TABLE 3

TECHNOLOGY DEVELOPMENT RISK ASSESSMENT FACTORS

	Degree of Risk A	B	C
Primary Factors			
1. Nature of Material	Traditional	Advanced	Revolutionary
2. Design Approach/Application of Material	Traditional	Advanced	Revolutionary
3. Current Status of Material	Production Feasibility	Component Feasibility	Laboratory Feasibility
Secondary Factors			
4. Number of Alternative Approaches for Application/Opportunities of Incremental Success for Material	3 or More	2	1
5. Required Technology Incorporation Date of Material (Years)	7	5	3
6. Critical Nature of Component to Which Material is Applied	Static-Low Stress	Static-High Stress	Rotating

The degrees of risk for each factor were combined quantitatively to determine an overall probability of success for each technology. In addition to cost and risk, the property projections and goals were used to estimate the impact of the technology on the engine component to which it was applied and, then, on the overall engine. Overall engine effects, in terms of changes in performance, weight, price, geometry and maintenance cost, were inputs into the benefit analysis. The benefit analysis first determined the impact of the engine effects on the airplane and then on the overall system. These analyses utilized previously developed trade factors that reflect simulations of the pertinent aircraft/economic system. The results of the benefit analysis were expressed as changes in Return on Investment (ΔROI), Direct Operating Cost (ΔDOC), Life Cycle Cost (ΔLCC), and Present Worth (ΔPW). The ΔROI benefit analysis result was then combined with the technology development cost and risk to determine a Relative Value parameter. Finally, a recommended ranking of the material technology was made based primarily on Relative Value.

The terms used in these benefit studies are defined as follows:

ΔROI: the change in return on investment in an aircraft - ROI is proportional to profit divided by investment; a change in profit is due to changes in operating costs for a fixed revenue; investment includes purchase price plus spares. (A positive value is desired.)

ΔDOC: the change in total direct operating cost - includes costs associated with crew, aircraft/engine maintenance, fuel, aircraft insurance, depreciation, burden. (A negative value is desired.)

ΔLCC: the change in the total operating cost of the aircraft over its economic life - includes both direct and indirect operating costs (IOC) and purchase price. (IOC is not affected by advanced materials application.) (A negative value is desired.)

Δ PW: the change in net present value of all initial and future cash savings attributable to an advanced materials technology over the economic life of the total aircraft system; same year introduction for all technologies. (A positive value is desired.)

Relative Value: this is the primary cost/benefit ranking parameter; it equals the benefit in terms of ΔROI times probability of success divided by development cost.

NOTES: (1) Other abbreviations and symbols used in this report are defined on page 42.

(2) More details on the methodology used in this study are given in NASA CR-134701, Reference 1.

Base Engines/Airplane

The base engines for the study are the Energy Efficient Engine (EEE), and the JT9D-7A. The former, the STF505M-7E, is the flight propulsion system design being utilized in the NASA Energy Efficient Engine Component Development and Integration Program, Contract No. NAS3-206646. The parameters for both engines are summarized in Table 4 and cross sections of the engines are shown in Figures 4 and 5.

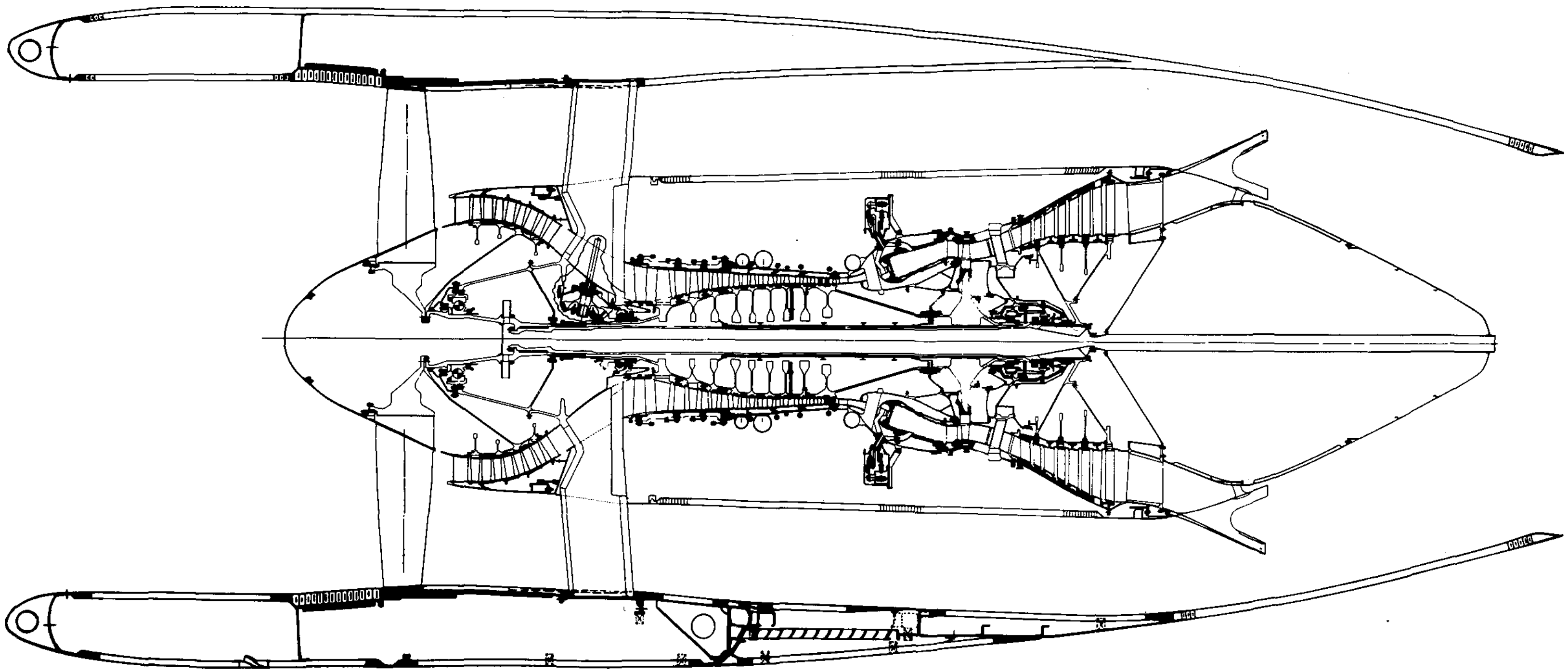


Figure 4 Energy Efficient Engine

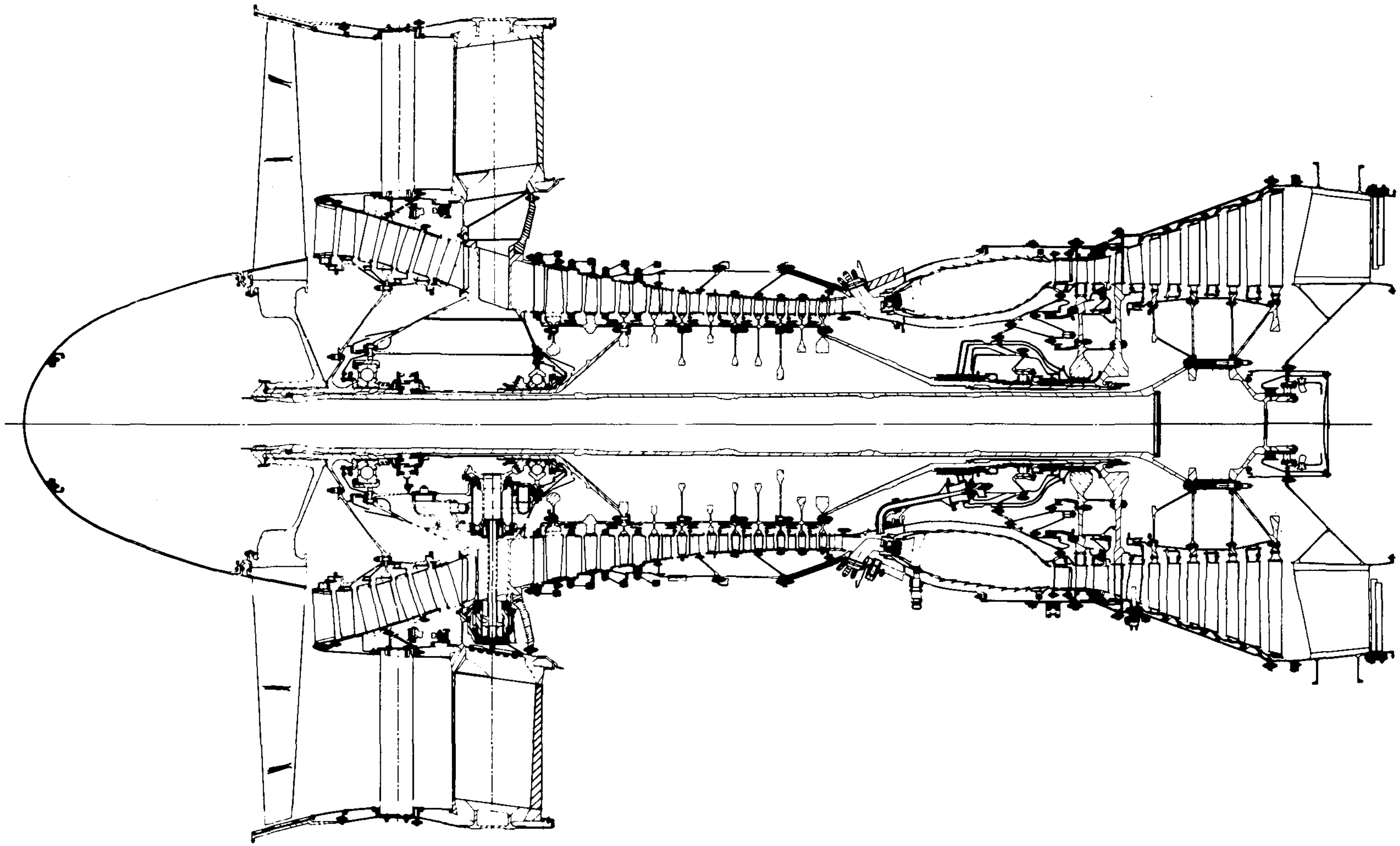


Figure 5 *JT9D - 7A Engine*

TABLE 4

EEE TURBOFAN ENGINE PARAMETERS

	Energy Efficient Engine	JT9D-7A
Base Size		
Thrust - N (Lb.)*	161,240 (36,180)	201,483 (45,210)
Inlet Airflow (Corrected) - kg/sec (lb/sec)	623 (1373)	705 (1554)
Nominal Cycle		
Fan Pressure Ratio	1.74	1.57
Bypass Ratio	6.51	5.13
Overall Pressure Ratio	38.6	24.7
Max. Combustor Exit Temperature ^{o}C (^{o}F)	1435 (2615)	1348 (2458)
Max. Cruise TSFC - kg/hr/N (lb/hr/lb)**	0.0560 (0.550)	0.0668 (0.656)
Weight and Dimensions		
Base Engine Weight - kg (lb)	3640 (8025)	3960 (8730)
Fan Tip Diameter - m (in.)	2.07 (81.35)	2.47 (96.98)
Overall Length - m (in.)	3.22 (126.36)	3.91 (153.58)

*Sea Level Takeoff 28.9^{o}C (84^{o}F) ambient temperature

**10.6 km (35,000 ft.), 0.8 Mn. Standard day with customer air bleed and power extraction.

An advanced domestic tri-jet was selected as the base airplane for the study. The study definition airplane is from the Energy Efficient Engine Program. Aircraft characteristics included high aspect ratio wings, supercritical aerodynamics and advanced lightweight composite structures technology. This aircraft and economic system were exercised under the ground rules presented in Table 5. The aircraft was sized for the design payload and range, but the economic analysis was conducted for the typical mission payload and range.

TABLE 5

AIRCRAFT/ECONOMIC PARAMETERS FOR TURBOFAN EVALUATION

	Energy Efficient Engine		JT9D-7A	
Design Cruise Mach Number	0.80		0.80	
Design Range - km (n. mi.)	5560	(3000)	5560	(3000)
Average Range - km (n. mi.)	1300	(700)	1300	(700)
Design Number of Passengers	440		440	
Number of Engines	3		3	
Takeoff Gross Weight - kg (lb)	23,000	(510,000)	24,500	(545,000)
Load Factor - %	55		55	
Economic Life - Years	15		15	
Operation Hours per Year - hrs.	3580		3580	
Hours per Average Flight - hrs.	2.01		2.01	
Base Return on Investment - %	11.6		11.6	
Fuel Cost - $/liter ($/gal.)	0.40	(1.50)	0.40	(1.50)
Debt Factor	0		0	
Inflation Rate - %	10		10	
Discounting Rate - %	10		10	
Discounting Period - Years	15		15	

ADVANCED MATERIALS TECHNOLOGIES

Six advanced materials technologies were evaluated by assessing the impact of each technology on either the base Energy Efficient Engine or the base JT9D-7A in an advanced domestic trijet, operating in accordance with the ground rules listed in the preceding section. As previously stated, the advanced technologies considered were:

- Dual Property Advanced Disk
- Thermal Barrier Coated Airfoils
- Advanced Fabricated High Pressure Turbine Vane Cluster
- Engine/Nacelle Low Temperature Composites
- High Strength, Low Expansion, Cast Cases
- Silicon Carbide-Reinforced Glass Ceramic Static Turbine Components

A brief description of these advanced technologies follows:

Dual Property Advanced Disk -- A high strength superalloy high pressure turbine disk concept that features a high stress-rupture strength material rim bonded to a high fatigue and tensile strength material bore. The fabrication approach of the dual property disk configuration will utilize current powder metallurgy and hot isostatic processing technology.

Thermal Barrier Coated Airfoils -- An extension of current thermal barrier coating technology, with an expanded application from combustors and augmentors to cooled turbine blade and vane platforms and airfoil surfaces. This technology will provide additional reduced cooling benefits for turbine airfoils and offers significantly improved coating spall resistance through the application of the principles of ceramic structure control to zirconia-based ceramic systems.

Advanced Fabricated High Pressure Turbine Vane Cluster -- A fabrication approach to the economical use of advanced material high pressure turbine vanes which have increased temperature capability over conventional alloys. The proposed fabrication concept encompasses the attachment, either mechanically or metallurgically, of conventional alloy platforms, clustered to minimize leakage, to single crystal airfoils. In addition to allowing a much simplified airfoil detail design, this concept also has the potential to allow vane repair through airfoil replacement and/or platform repair or replacement.

Engine/Nacelle Low Temperature Composites -- An application of composite material and manufacturing technology to major nacelle/engine system components to achieve performance benefits and weight savings. Proposed is the use of graphite/polyimide material for acoustic, aerodynamic and structural application.

High Strength, Low Expansion, Cast Cases -- An alloy extending the 649^{o}C (1200^{o}F) mechanical properties and oxidation/corrosion resistance of Inconel 718 to 704^{o}C (1300^{o}F) was studied for use in advanced engine major cases and structure. The alloy that combines these high strength/high temperature properties with low thermal expansion coefficient provides not only structure with improved compatibility of mechanical and thermal stresses but also cases that contribute to improved tip clearance control.

Silicon Carbide - Reinforced Glass Ceramic -- A type of advanced fiber reinforced glass matrix composite that provides a wide variety of unique properties. Specifically, the silicon carbide fiber system has demonstrated a combination of high strength properties and oxidation resistance. Despite the early development status of this materials technology it promises extensive hot section application in advanced engines and at a significant weight saving.

The baseline for comparing these advanced technologies was assumed to be those technologies that exist in the Pratt & Whitney Aircraft Energy Efficient Engine, a 161,240 N (36,180 lb) thrust engine and in the JT9D-7A, a 201,480 N (45,000 lbs) engine, both assessed for use in an advanced domestic trijet. Therefore, the dual property advanced disk was compared to MERL 80 (nickel-based powder metal disk); the thermal barrier coated airfoils to NiCoCrAlY coating; the advanced fabricated high pressure turbine vane cluster (single crystal alloy airfoil, PWA 647 (Mar-M-509) platform) to a conventionally cast PWA 647 vane; the engine/nacelle low temperature composites to aluminum/titanium systems; the high strength, low expansion, cast cases to Inconel 718 and AMS 5616 cases; and the silicon carbide-reinforced glass ceramic to PWA 1455 (B1900 + Hf) combustor segments, PWA 655 (Inconel 713C) outer airseal and PWA 655 and MERL 220 (specially heat treatable nickel alloy) low turbine vanes. All advanced materials technologies except the advanced fabricated vane cluster and the high strength, low expansion, cast turbine exhaust case use technologies that exist in the Energy Efficient Engine as the basis for comparison.

ADVANCED MATERIALS TECHNOLOGY PROJECTED GOALS

Specific full target goals and sensitivity analysis goals were established for each of the advanced materials technologies under consideration. These goals were based on applying historical developmental experience to projections of current state-of-the-art technology. Projected goals for each technology are summarized in Tables 6 through 11. The percentages and numbers given first are full target goals; the sensitivity (less optimistic) goals are shown in parentheses.

TABLE 6

DUAL PROPERTY ADVANCED DISK TECHNOLOGY
(Energy Efficient Engine Application)

Projected Goals:

- +20% bore LCF strength
  +5% yield & U.T.S.
  +5% (-10%) rim stress rupture strength

  } at +100^{0}F vs. MERL 80

- HIP process cost 2.0X > MERL 80

- Finished disk cost +5% > MERL 80

Estimated Development Cost:

- $1,600,000

Probability of Success:

- 50%

TABLE 7

THERMAL BARRIER COATED AIRFOILS TECHNOLOGY
(Energy Efficient Engine Application)

Projected Goals:

- 0.015 in. (0.005 in.) coating thickness
- Insulative capability +200°F > NiCoCrAlY
- Coating cost 1.5X to 2.0X > NiCoCrAlY
- Average coated airfoil cost +5% NiCoCrAlY

Estimated Development Cost:	Probability of Success:
• $1,500,000	• 50%

TABLE 8

ADVANCED FABRICATED HIGH PRESSURE TURBINE VANE CLUSTER TECHNOLOGY
(JT9D-7A Application)

Projected Goals:

- +100% thermal fatigue strength
+250°F coated oxidation resistance
+100°F creep strength } vs. PWA 647/PWA 27
- Clustered vane set cost 0% (25%) > PWA 647 single vane set cost

Estimated Development Cost:	Probability of Success:
• $2,000,000	• 50%

TABLE 9

ENGINE/NACELLE LOW TEMPERATURE COMPOSITES
(Energy Efficient Engine Application)

Projected Goals:

- Total component weight 100 lbs < aluminum/titanium systems
- Temperature capability to 500^{O}F
- Total component cost 0% (10%) > aluminum/titanium systems

Estimated Development Cost:

- $2,000,000

Probability of Success:

- 50%

TABLE 10

HIGH STRENGTH, LOW EXPANSION, CAST CASES TECHNOLOGY
(Diffuser Case: Energy Efficient Engine Application)
(Turbine Exhaust Case: JT9D-7A Application)

Projected Goals:

- Mechanical properties of Inco 718 1200^{O}F extended to 1300^{O}F
- Oxidation/corrosion resistance to 1300^{O}F
- 40% (20%) reduction in modulus X thermal expansion coefficient
- Finished diffuser case cost 5% > Inco 718;
- Finished turbine exhaust case cost 85% > AMS 5616 (Greek Ascoloy).

Estimated Development Cost:

- $2,000,000

Probability of Success:

- 50%

TABLE 11

SILICON CARBIDE - REINFORCED GLASS CERAMIC TECHNOLOGY
(Energy Efficient Engine Application)

Projected Goals:

- $1800^{o}F$ temperature capability
- Total component weight 180 lbs < nickel-base alloys
- Finished parts cost 25% (60%) > PWA 1455, PWA 655, MERL 220 finished part costs

Estimated Development Cost:	Probability of Success:
• $3,500,000	• 25%

TECHNOLOGY DEVELOPMENT COST AND RISK ASSESSMENT

Based on the established goals, development costs and probability of success were estimated for each materials technology. Development costs were defined as all costs required to take the technology item from its present status through rig test and one engine demonstration test. Costs to run the engine were not considered. Probability of success was based on a risk analysis that was conducted for each technology. It quantifies, in percentage, the likelihood of achieving the technology goals. The development cost and probability of success values were considered the same for both full and sensitivity analysis results, since both the cost and risk analyses essentially address mean values of the two levels of property projections and goals. Resulting values of these parameters for the technologies under investigation are included in Tables 6 through 11.

Risk assessment methodology details are described in Table 2 of NASA Cr-134701, Reference 1. Risk assesment results for the current study are given in Table 12.

TABLE 12

TECHNOLOGY DEVELOPMENT RISK ASSESSMENT SUMMARY

Material Technology	Risk Factors (as defined in Table 2)						Prob. of Success
	1	2	3	4	5	6	%
Dual Property Advanced Disk	B	B	C	B	B	C	50
Thermal Barrier Coated Airfoils	B	C	C	A	B	C	50
Advanced Fabricated High Pressure Turbine Vane Cluster	B	C	C	B	B	B	50
Engine/Nacelle Low Temperature Composites	B	B	C	B	A	A	50
High Strength, Low Expansion Cast Cases	B	B	C	C	B	B	50
Silicon Carbide Reinforced Glass Ceramic	C	C	C	A	A	B	25

TECHNOLOGY COMPARISON STUDY APPROACH

The base engines for this study are the Energy Efficient Engine, a 1984 start-of-development advanced technology engine, and the JT9D-7A, a current production engine. The benefit of each advanced materials technology was determined by substituting it for the base engine current materials. The application of the full goal level technology to the base engine was done assuming that technology is the critical or limiting technology. The effects on the engine components were then determined. Overall engine effects were subsequently established based on these component changes. These benefits were then used to establish aircraft system economic parameters.

An identical approach was used for the reduced technology level sensitivity analysis goals. Results were then compared to full goals for each materials technology.

TECHNOLOGY IMPACT ON COMPONENTS/ENGINE

Following the approach outlined above, the impact of each advanced technology item as a component and the engine was established. Table 13 summarizes these impacts for the full materials technology goals, with sensitivity analysis results presented in parentheses.

TABLE 13

IMPACT OF ADVANCED MATERIAL TECHNOLOGY ON EEE OR JT9D PERFORMANCE, WEIGHT, COST AND DIMENSIONS

Application	Materials Technology	Performance (TSFC) Percent	Δ Engine Weight Percent	Δ Engine Price Percent	Maintenance Cost $/OP. HR.	Δ Engine Length Percent
A	Dual Property Advanced Disk	-0.9(-0.9)‡	+0.81(+1.20)	+1.10(+1.17)	-0.56(-0.49)	+3.09(+3.09)
A	Thermal Barrier Coated Airfoils	-2.1(-1.8)	-2.2(-1.22)	+0.22(+0.59)	-1.36(-0.64)	+0.95(+1.58)
B	Advanced Fabricated High Pressure Turbine Vane Cluster	-0.2(-0.1)	0 (0)	+0.59(+0.95)	-0.15(+1.80)	0 (0)
A	Engine/Nacelle Low Temperature Composites	-0.5(-0.5)	-1.25(-1.25)*	0 (+0.22)	0 (-0.05)	0 (0)
A	High Strength, Low α Cast Diffuser Case	-0.08(-0.06)	-0.19(-0.19)	+0.15(+0.15)	-0.56(-0.56)	0 (0)
B	High Strength, Low α Cast Turbine Exhaust Case	-0.2(-0.1)	+0.46(+0.46)	+1.83(+1.83)	+0.20(+0.20)	0 (0)
A	Silicon Carbide-Reinforced Glass Ceramic	-1.1(-1.1)	-2.2(-2.2)	+2.34(+4.17)	+0.27(+2.18)	+3.09(3.09)

NOTES ‡ Sensitivity study goal results are shown in parentheses
o A decrease in any parameter is a benefit.
* -0.92(-0.92) based on engine + nacelle weight
A Energy Efficient Engine
B JT9D-7A

MATE materials technologies, offering improved properties, permit cycle changes that result in increased high spool rotor speed and/or increased compressor or combustor discharge temperature relative to the Energy Efficient Engine base. Cycle sensitivity studies were conducted which showed that the maximum potential for improved cycle performance is associated with increased cycle pressure ratio rather than increased combustor exit temperature. This becomes most apparent when the effects on component performance of scaling the engines to constant thrust are accounted for. The effects of a cycle pressure ratio increase on the benefits of the advanced technologies are given in detail in the following paragraphs.

(1) Dual Property Advanced Disk -- (Figure 6)

When the proposed advanced disk replaces the current technology MERL 80 disk in the Energy Efficient Engine single stage high pressure turbine (HPT) an increase in cycle pressure ratio to 45:1 from the base engine level of 38.6:1 was used. Small cycle pressure ratio increases beyond 45:1 could have been assumed without exceeding the property targets of the advanced material but the increasingly smaller blades of the high compressor rear stages would create significant efficiency penalties.. The increased compressor discharge temperature that accompanies the increased cycle pressure ratio dictated increased airfoil coolant flows, hence some high pressure turbine efficiency penalty and increased blade cooling dilution effect. The impact of the cooling airflow increase diminished but does not, however, counteract the cycle pressure ratio benefit.

The increased cycle pressure ratio, accomplished by supercharging the low pressure compressor, increases primary airflow which, for the same fan diameter and fan pressure ratio, decreases bypass ratio. The increased primary airflow results in increased primary jet velocity, hence increased jet noise and mixing losses. Increasing fan size (bypass ratio), returning the primary jet velocity to the base engine level, overcomes these deficiencies in the advanced technology engine but the resultant total airflow increase causes the cruise thrust to be excessive. The entire engine is therefore scaled down at constant bypass ratio to the base engine cruise thrust, since, to maintain aircraft systems consistency, the engine must be sized to the same cruise thrust.

As indicated above, the increased cycle pressure ratio had a beneficial effect in lowering fuel consumption; it had the opposite effect on engine weight. At the full goal condition the weight reduction derived from the smaller primary stream size was more than offset by the weight increases of an additional low pressure compressor stage, longer inter-turbine transition duct and a longer, larger diameter low pressure turbine. The net weight increase was more pronounced at the sensitivity goal level because of rim width increase reflecting a loss of critical properties. The engine price is the result of balancing the increased processing cost of the two-powder HIP concept vs. the cost decrease associated with a smaller engine. Engine maintenance costs, assuming no change to high pressure turbine design life, were reduced by the smaller engine.

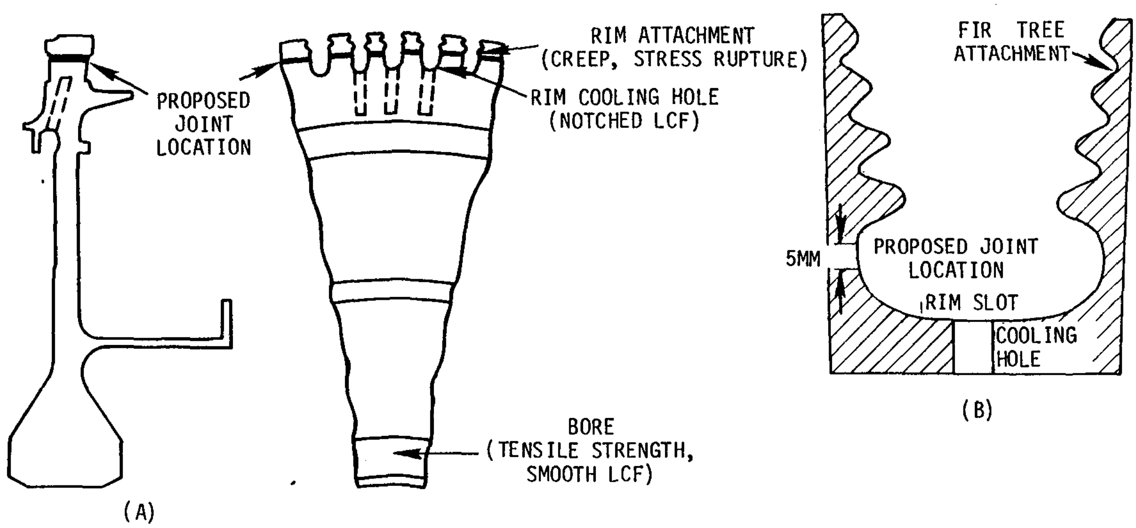


Figure 6 *Dual Property Advanced Disk*

(A) Property Requirement vs. Location

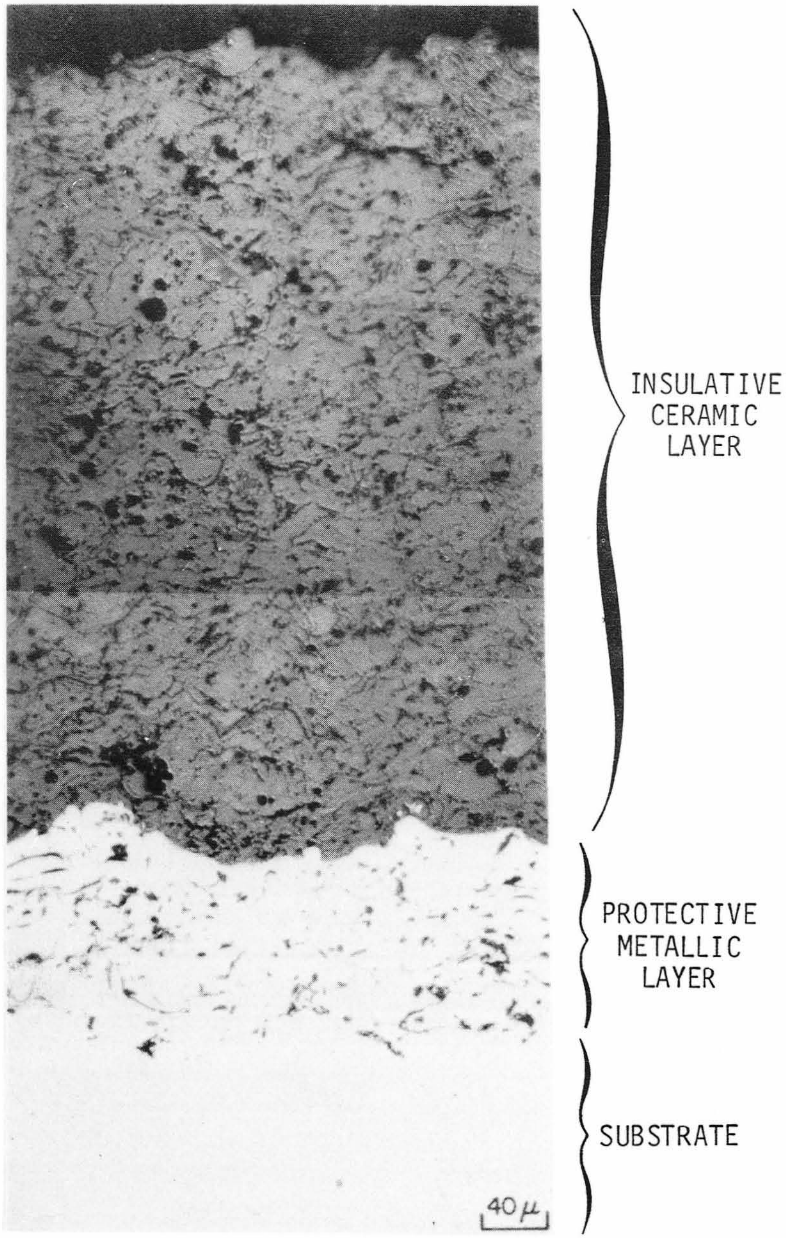
(B) Enlarged View of Proposed Joint Location

(2) Thermal Barrier Coated Airfoils -- (Figure 7)

Adding thermal barrier coating to the single stage high pressure turbine vane and blade airfoils of the base Energy Efficient Engine adds an insulative capability not available before. To realize the maximum potential performance benefit for this technology at the full goal level, the cycle pressure ratio was increased to 45:1 and the cooling airflow reduced to match the airfoil and coating lives of the base engine. Although a greater increase in cycle pressure ratio (smaller cooling airflow reduction) is possible with this technology, 45:1 was seen as a practical limit for the reason stated in the advanced disk discussion. As a result of the reduced cooling airflow, high pressure turbine efficiency was improved and since combustor exit temperature has been held constant, there was a decrease in the blade and vane cooling dilution effect and an increase in high pressure turbine exit temperature.

The efficiency improvement and decrease in dilution effect when added to the increased cycle pressure ratio resulted in substantially more energy being available in the engine primary gas stream. Like the disk technology above, but to a greater degree, application of the thermal barrier coating technology resulted in a smaller core engine (higher bypass ratio). Unlike the disk technology, a net weight reduction was realized. The sensitivity goal level, reflecting reduced insulative capability (reduced coating thickness), required increased cooling airflow but retained the increased cycle pressure ratio. Measurable fuel consumption savings and weight savings resulted from these less optimistic goal levels. The cost increase of the higher cycle pressure ratio exactly offset the cost decrease of the smaller core, constant thrust engine; the reported price increase recognizes the cost of the coating and the labor to apply it. Maintenance costs, reflecting the base engine scrap lives and strip/recoat frequency, are decreased due to the substantial effect of scaling to constant cruise thrust.

(A)



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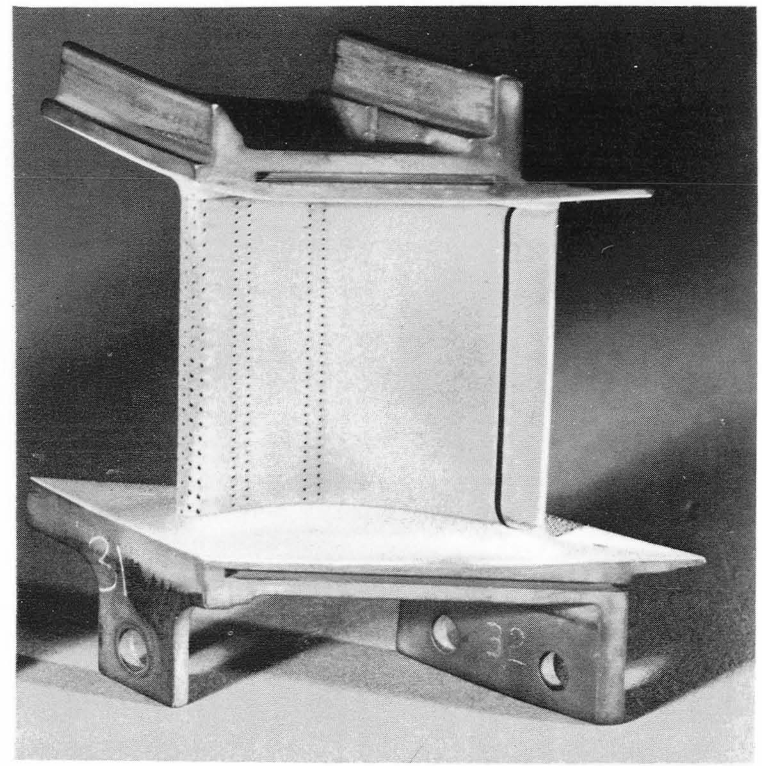

Figure 7 *Thermal Barrier Coated Airfoils*

(A) Coating System Microstructure

(B) Typical Coated Vane

(3) Advanced Fabricated High Pressure Turbine Vane Cluster -- (Figure 8)

Substituting clustered fabricated vanes for conventionally cast PWA 647 vanes results in cost/benefit factors which are influenced most heavily by raw material, processing, and maintenance costs in addition to some modest performance improvement. The JT9D-7A was selected as the base engine for this advanced technology that highlights the performance advantage of clustered vane sets. The 66 vane cascade of the -7A allows the clustering of 3 vanes (22 clusters) within a small circumferential arc (16^{0}). To cluster the 24 vanes of the Energy Efficient Engine into 2 vanes per cluster encompasses 30^{0} of arc, introducing potentially high platform stresses. The full technology goal concept, the use of a soft braze to bond the 3 single cyrstal vanes to single PWA 647 inner and outer platforms introduces, at the present time, a measurable price increase. The fabrication cost of even a simple single crystal airfoil exceeds the current raw material cost of cobalt-rich PWA 647; the projected increasing cobalt cost trend and the decreasing cost of single crystal airfoils to be expected with continued process development should ultimately eliminate the cost difference.

The processing cost impact of the single crystal airfoil works to counter beneficial maintenance cost factors (i.e. independent platform life, simplified strip and recoat, etc.) resulting in modest maintenance cost savings at the full goal condition. A small performance improvement is realized from reducing inter-platform leakage and from reducing airfoil cooling airflow (increased temperature capability single crystal material).

The inability to develop an acceptable soft braze procedure, resorting instead to a permanent airfoil-to-platform bond eliminated the economical, individual vane replacement technique. The sensitivity goal level is therefore based on a configuration of 66 individual vanes with single crystal airfoils permanently bonded to PWA 647 platforms.

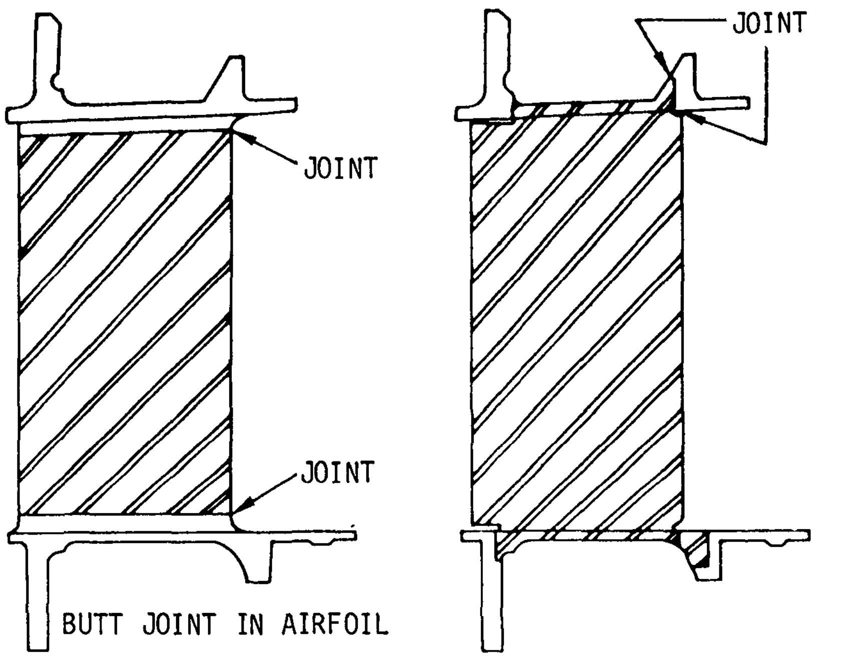

Figure 8 *Advanced Fabricated High Turbine Vane Cluster Schematic Representation of Two Basic Design Approaches*

(4) Engine/Nacelle Low Temperature Composites -- (Figure 9)

The substitution of a fiber-reinforced polyimide composite system for the aluminum/titanium system in the structural core cowl of the Energy Efficient Engine resulted in performance and weight savings. Composite materials used in the core cowl created an increased stiffness component compared to the current aluminum construction, thereby reducing engine ovalization and backbone bending through improved core cowl load sharing. Increased concentricity between rotating and stationary components and decreased case deflections will lead to improved blade tip clearances and improved thrust specific fuel consumption.

A weight reduction recognizing both the low density of the composite system and some influence of load sharing on engine backbone weight has been identified. Further study, optimizing the cowl load sharing capability of a composite of 2 to 3 times the metallic system stiffness, would reveal additional weight saving from the engine backbone. Further study is also needed to establish a clearer component cost picture. The study would give attention to such things as fabrication to near net shape and, most importantly, reduction of labor intensive operations in the manufacturing process. The attainment of full goal level benefits were measured solely by the ability to produce the composite core cowl at no cost increase over the aluminum/titanium component it replaces. The sensitivity goal level recognized a 10% component cost increase (.22% engine price increase). Maintenance cost trends followed the engine price trends and for the same reason.

The introduction of a composite core cowl to the Energy Efficient Engine created weight, cost, and maintenance cost impacts on aircraft economics that were modest when compared to the performance impact. Load sharing, a feature unique to the core cowl, was the most significant benefit. Potential for greater economic benefits exists through the use fiber-reinforced composite systems. Figure 9 identifies some of the many engine and nacelle locations where composites can result in a weight reduction of approximately 600 pounds.

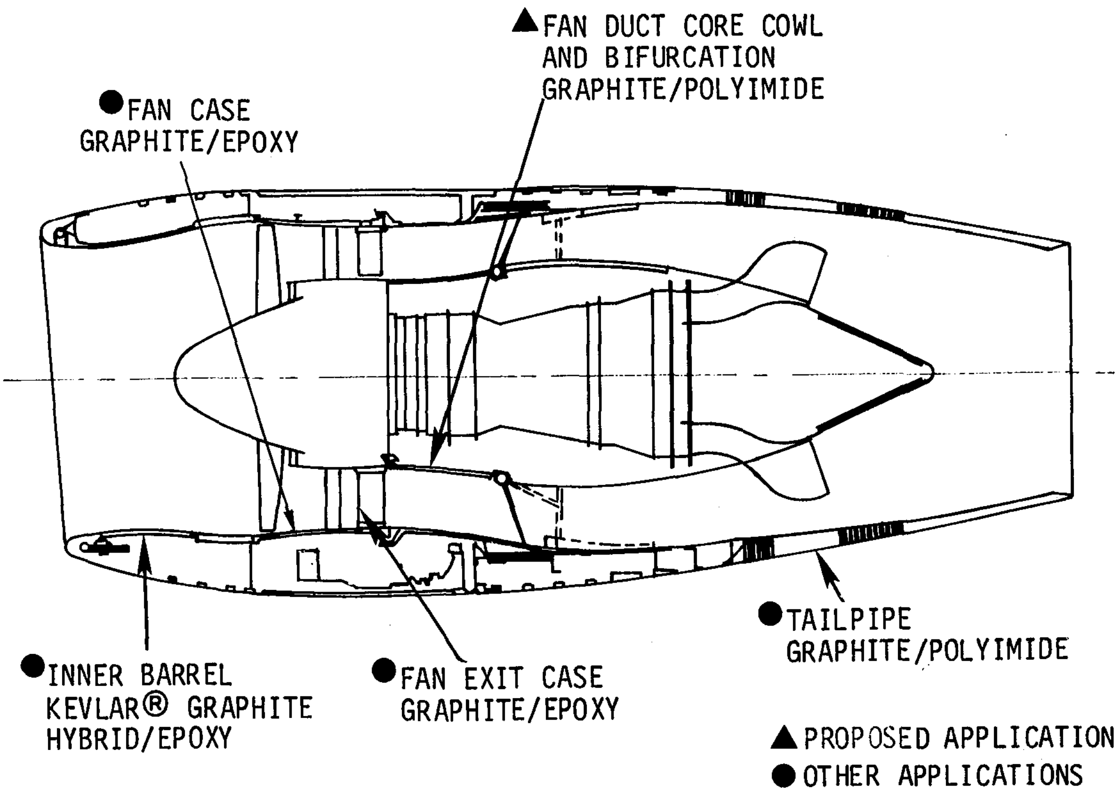

Figure 9 Engine/Nacelle Low Temperature Composites-Energy Efficient Engine Applications

(5) High Strength Low Expansion Cast Cases -- (Figure 10)

The use of such a material to replace Inco 718 in the Energy Efficient Engine diffuser case and AMS 5616 in the JT9D-7A turbine exhaust case was to improve the compatibility between thermal and mechanical stresses within the cases and to improve blade tip clearances in nearby stages. The key to accomplishing both objectives was to incorporate in the advanced technology material high strength combined with low coefficient of thermal expansion; the JT9D-7A turbine exhaust case application, in particular, benefits from these properties.

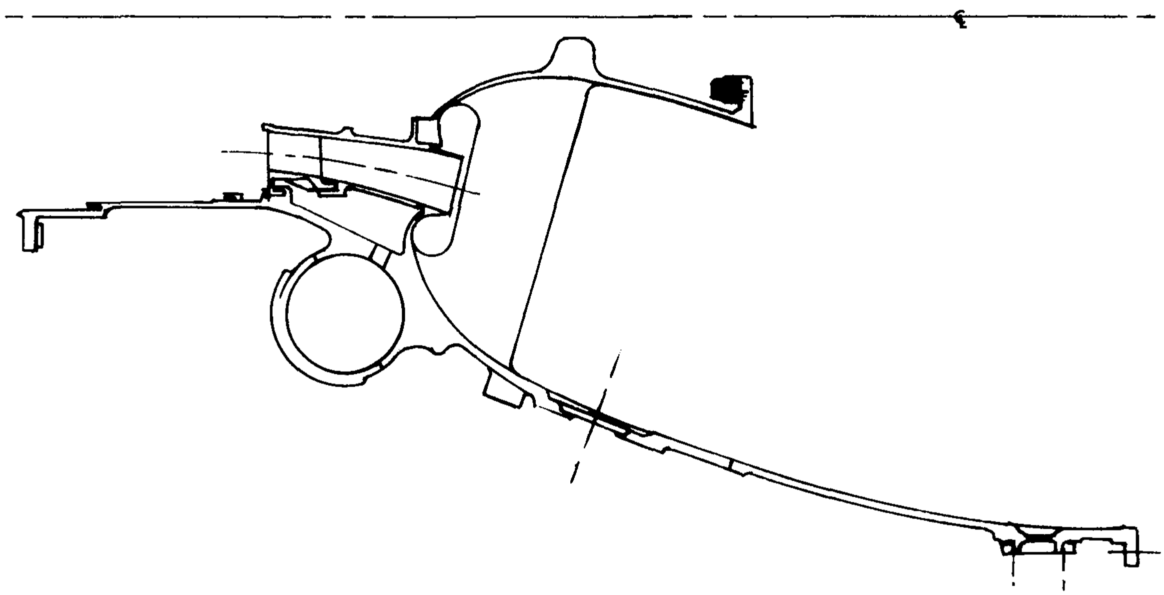

Figure 10 High Strength, Low Expansion Cast Cases - Energy Efficient Engine Diffuser Case

The full goal level property target for this technology is to attain a 40% reduction in the product of the modulus of elasticity and the coefficient of thermal expansion. A material with this characteristic creates reduced tip clearances in the Energy Efficient Engine high pressure compressor rear stages and in all stages of the JT9D-7A low pressure turbine. The extent of the clearance benefits to performance, however, was small. The sensitivity goal level, relying on only 20% reduction, of course, produced even smaller performance benefits.

The diffuser case, being of cast Inconel 718 in the current Energy Efficient Engine, experienced a modest weight decrease due to increased strength in all case elements. An equally modest cost increase accompanied the corresponding raw material cost increase. The JT9D-7A turbine exhaust case is welded and mechanically assembled of AMS 5616. The weight increase of the proposed case came exclusively from casting the mounting flanges. The raw material cost increase, the penalty that must be accepted to gain stiffness and thermal vs. mechanical stress compatibility, overshadowed the casting cost decrease.

(6) Silicon Carbide Reinforced Glass Ceramic -- (Figure 11)

The high specific strength fiber reinforced, glass ceramic technology represents an alternative approach to the fabrication of Energy Efficient Engine critical parts. The use of this 1800°F temperature capability material to replace nickel-base alloys created not only a measurable weight reduction but, if it is assumed that combustor segments are the limiting area of the engine, it also introduced the option to increase the cycle pressure ratio. Increasing the cycle pressure ratio to 45:1 produced results similar to those noted for the dual property disk technology. As airfoil coolant flow increased, a high pressure turbine efficiency penalty was imposed and the increased cooling air dilution resulted in a decrease of high pressure turbine exit temperature. These effects were counteracted, however, by the cycle pressure ratio benefit.

As indicated above, a substantial weight reduction occurred with the substitution of the fiber reinforced glass matrix composites; the density of the composite is one-third that of the critical materials it replaced. The density effect on weight combined with the offsetting effects of cycle pressure ratio weight increase and constant cruise thrust scaling weight decrease resulted in a beneficial net weight reduction.

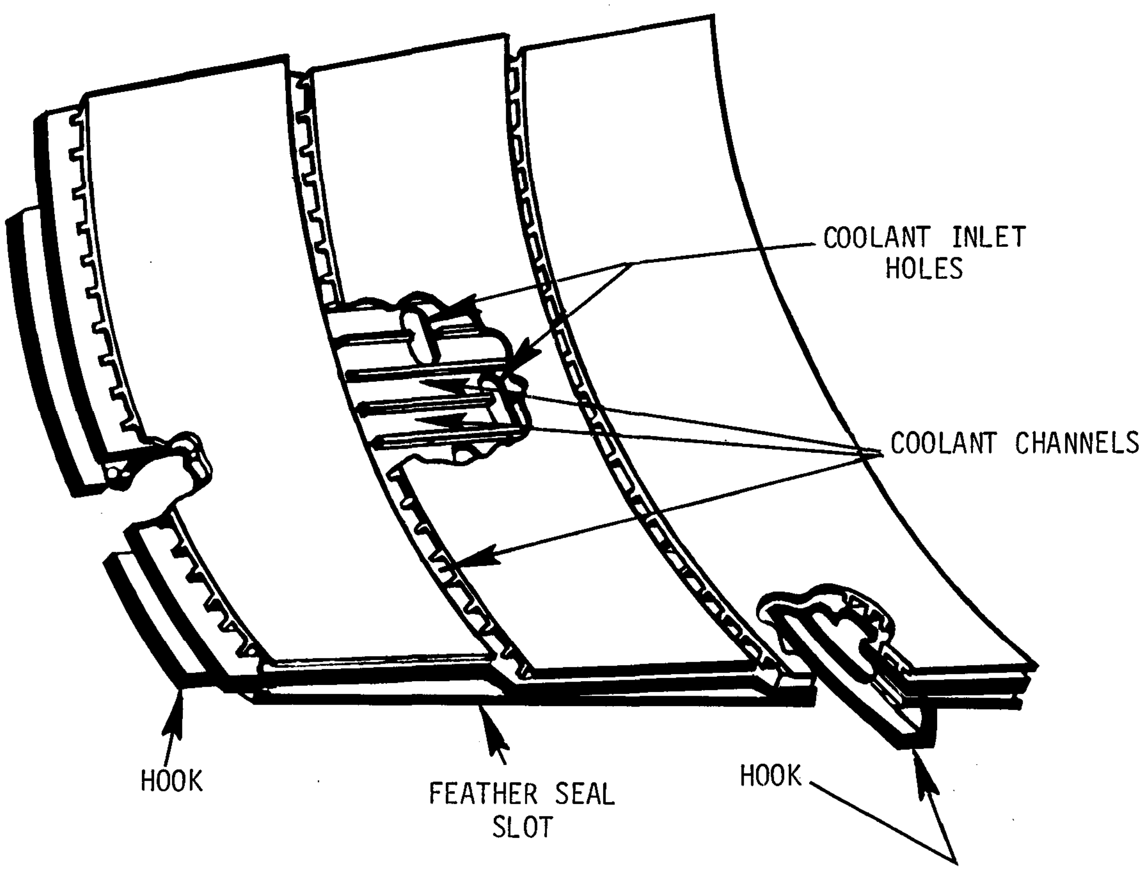

Figure 11 *Silicon Carbide-Reinforced Glass Ceramic-Energy Efficient Engine Combuster Segment*

The early development status of fiber-reinforced glass ceramic technology makes estimating costs difficult. Because of this uncertainty the goal level criterion must be based on costs, hence engine price. The magnitude of the full goal level price reflected the projected minimum cost of fabricating the selected hot section elements plus the cost increase of cycle pressure ratio balanced against the cost decrease derived from scaling to constant cruise thrust. The sensitivity goal level price differed only in the estimate of a more conservative ceramic fabrication cost. Maintenance cost trends followed the engine price trends and for the same reason.

The following comments are made to highlight the similarities in component and engine impacts that resulted from the greatly diverse technologies studied:

Three of six technologies resulted in substantial reductions in fuel consumption due in large part to increased cycle pressure ratio. The higher temperature capabilities of these advanced materials make possible the increased cycle pressure ratio. Of the three, the thermal barrier coated airfoils afforded the largest improvement because of the insulative capability of the coating and the accompanying impacts on high pressure turbine efficiency and cooling airflow dilution discussed earlier. The fuel consumption benefits of the other two technologies were somewhat less; the dual property disk and silicon carbide-reinforced glass ceramic were debited due to the increased coolant airflow required by the airfoils having only an oxidation-resistant coating. The small fuel consumption advantage credited to the fabricated high pressure turbine vane cluster, the engine/nacelle low temperature composites, and the high strength, cast case technologies were due to reduced leakages and/or decreased rotor tip clearances.

Engine weight changes due to technology incorporation were most pronounced where fuel consumption savings were attained. The weight increase associated with increased cycle pressure ratio was balanced against the weight decrease effect of scaling to constant cruise thrust. The silicon carbide-reinforced glass ceramic has, in addition to the above weight change effect, a clear weight reduction due to its low density. The potential use of low temperature composite in the core cowl application provides opportunity for asignificant weight reduction.

Engine prices associated with the technologies studied were higher than for current technology engines either because the advanced technology components have a greater initial cost or because there were cost penalties associated with increased cycle pressure ratio. Also, technologies with sensitivity cost goals that were much higher than the cost of current technology resulted in significant engine price penalties, e.g., the silicon carbide reinforced glass ceramic, and the fabricated high pressure turbine vane cluster.

In general, engine maintenance cost trends followed engine price trends and for the same reasons. The fabricated vane technology was the exception. Greatly reduced maintenance cost resulted from the individual replacement of airfoil or platform, the platform increased scrap life, and the ease of strip and recoat.

Table 13 shows that there are engine length increases associated with those technologies that use cycle pressure ratio increases as the major performance improvement method. The lengths were increased to accommodate the added low pressure compressor stage, the longer inter-turbine transition duct and the longer, larger diameter low pressure turbine. The lengths were decreased in proportion to the smaller engine diametral scaling.

AIRCRAFT BENEFIT ANALYSIS RESULTS

The impact of these overall engine effects on the operation of the domestic trijet base airplane was established and the results are presented in Table 14 for the full materials technology goals, with the sensitivity results shown in parentheses.

The following comments pertain to these results:

The thermal barrier coated airfoils technology showed the best economic benefit of the technologies studied. This was true for both the full goal and sensitivity goal levels. The best economic benefits occurred because this technology had the largest performance and maintenance cost benefits due to engine size down scaling which also resulted in a significant weight benefit. The small price increase incurred does little to detract from the otherwise superior economic picture.

The silicon carbide reinforced glass ceramic technology generally showed the next largest benefit primarily because of significant performance and weight reduction benefits due to down scaling. Full goal and sensitivity goal level price increases, though the largest encountered with any technology, were not so large as to overshadow the benefit factors.

TABLE 14

COST/BENEFIT ANALYSIS RESULTS FOR ADVANCED MATERIALS TECHNOLOGY IN EEE/TRIJET AND JT9D/TRIJET AIRPLANES

Application	Materials Technology	ΔROI - points	ΔDOC -%	ΔLCC -$ X 10^3/ engine	ΔPW -$ X 10^3/ engine
A	Dual Property Advanced Disk	+0.20 (+0.18)‡	-0.56 (-0.53)	- 99 (- 94)	+183 (+170)
A	Thermal Barrier Coated Airfoils	+0.65 (+0.52)	-1.73 (-1.40)	-309 (-256)	+633 (+500)
B	Advanced Fabricated High Pressure Turbine Vane Cluster	+0.05 (-0.015)	-0.15 (+0.05)	- 26 (+ 7)	+ 47 (- 23)
A	Engine/Nacelle Low Temperature Composites	+0.17 (+0.17)	-0.44 (-0.43)	- 82 (- 81)	+168 (+164)
A	High Strength, Low α Cast Diffuser Case	+0.04 (+0.03)	-0.10 (-0.08)	- 18 (- 15)	+ 33 (+ 30)
B	High Strength, Low α Cast Turbine Exhaust Case	+0.02 (-0.01)	-0.08 (0)	- 14 (+ 1)	+ 7 (+ 22)
A	Silicon Carbide-Reinforced Glass Ceramic	+0.29 (+0.24)	-0.79 (-0.64)	-147 (-123)	+273 (+203)

NOTES ‡ *Sensitivity study goal results are shown in parentheses following full materials technology goal results*

- o An increase in ΔROI and ΔPW is a benefit, while a decrease in ΔDOC and ΔLCC is a benefit.
- A Energy Efficient Engine
- B JT9D-7A

The dual property high turbine disk and the engine/nacelle low temperature composites were the next most beneficial technologies, but for somewhat different reasons. The significant performance improvement displayed by the disk technology more than offsets weight and price increases. A measureable performance improvement combined with a weight reduction due to engine down scaling overshadowed even a sensitivity goal price increase to account for the composite technology benefit.

All other materials technologies studied had limited economic benefits. The modest performance improvements that accompanied these technologies were not sufficient to overcome the economic penalties of price increases, however small.

It is apparent from Table 14 and from comments above that for most of the technologies studied the sensitivity goals detracted little from the full goal economic benefits. Of the two exceptions, the fabricated high pressure turbine vane cluster and the silicon carbide reinforced glass ceramic technologies, only the failure to provide an acceptable soft braze, which was the key to a maintenance cost advantage for the fabricated vane concept, was severe enough to lower the ranking of that candidate.

RELATIVE VALUE

The economic results discussed above were difficult to compare on a realistic basis in that they did not consider the relative costs to develop the technologies or the risk associated with achieving the projected goals. In an attempt to temper the economic results, a "Relative Value" parameter was introduced. It is the change in an economic parameter (Δ ROI was used here because it is considered to be the most complete economic parameter) multiplied by the probability of success, divided by the development cost. Probability of success was the result of the risk analysis that was conducted for each study technology. Development cost was the sum of all costs required to take a technology from its present status through rig test and one engine demonstration test. The probability of success and development cost factors were the same for both full and sensitivity analysis results, since both the cost and risk analyses effectively address mean values of the levels of property projections and goals.

Relative Value analysis results are summarized in Table 15 for the full materials technology goals, with the sensitivity analysis results presented in parentheses.

TABLE 15

RELATIVE VALUE OF ADVANCED MATERIALS TECHNOLOGIES IN EEE OR JT9D ENGINES FOR DEVELOPMENT COSTS AND PROBABILITY OF SUCCESS FACTORS SHOWN

Applications	Materials Technology	Relative Value 10^{-5}	ΔROI points	Development Cost $ X 10^6	Probability of Success, percent	Comments
A	Dual Property Advanced Disk	+0.63 (+0.56)‡	+0.20 (+0.18)	1.60	50	Requires a decrease in core diameter and an increase in length to achieve maximum benefits
A	Thermal Barrier Coated Airfoils	+2.25 (+1.73)	+0.65 (+0.52)	1.50	50	Requires a decrease in core diameter and an increase in length to achieve maximum benefits
B	Advanced Fabricated High Pressure Turbine Vane Cluster	+0.12 (-0.04)	+0.05 (-0.015)	2.00	50	
A	Engine/Nacelle Low Temperature Composites	+0.42 (+0.42)	+0.17 (+0.17)	2.00	50	
A	High Strength, Low α Cast Diffuser Case	+0.10 (+0.08)	+0.04 (+0.03)	2.00	50	
B	High Strength, Low α Cast Turbine Exhaust Case	+0.05 (+0.05)	+0.02 (+0.02)	2.00	50	
A	Silicon Carbide-Reinforced Glass Ceramic	+0.21 (+0.17)	+0.29 (+0.24)	3.50	25	Requires a decrease in core diameter and an increase in length to achieve maximum benefits

NOTES ‡ Sensitivity study goal results are shown in parentheses following full materials technology goal results
o An increase in Relative Value and ΔROI is a benefit.
A. Energy Efficient Engine
B. JT9D-7A

The conversion from ΔROI to Relative Value severely reduced the benefit of the silicon carbide reinforced glass ceramic technology because of the high development cost and low probability of success of this technology during its early stage of development. Further advances in this technology will not only increase its probability of success but introduce other applications thus enhancing Relative Value in more than one way. No other technology was affected by the conversion from ΔROI to Relative Value.

RANKING SUMMARY

Table 16 summarizes the position of each technology item for each of the economic parameters considered. Full goal positions are presented first with sensitivity analysis positions shown in parentheses.

A final ranking was determined by considering the Relative Value, ΔROI, ΔDOC, ΔLCC, and ΔPW parameter positions for each technology. In this procedure, Relative Value position was weighed more heavily than the other economic factors, since it is the primary cost/benefit parameter in this study. The full and sensitivity goal positions were however, treated equally. The final recommended ranking of the material technologies (based on their current state of development) evaluated in this study is given below:

(1) Thermal Barrier Coated Airfoils
(2) Dual Property Advanced Disk
(3) Engine/Nacelle Low Temperature Composites
(4) Silicon Carbide Reinforced Glass Ceramic
(5) Advanced Fabricated High Pressure Turbine Vane Cluster
(6) High Strength, Low Expansion, Cast Diffuser Case
(7) High Strength, Low Expansion, Cast Turbine Exhaust Case

A summation of the position results in Table 15, weighing the Relative Value position, led to this final ranking. Contrary to earlier studies where the Relative Value ranking for most technologies was very different from the ranking due to the economic parameters, the current study produced only one ranking change. The silicon carbide reinforced glass ceramic technology was reduced from a second place to a fourth place rank mainly due to the risk associated with its early development status.

TABLE 16

BENEFIT PARAMETER RANKING - POSITION SUMMARY

Materials Technology	Δ ROI	Δ DOC	Δ LCC	Δ PW	Relative Value
Dual property advanced disk	3 (3)	3 (3)	3 (3)	3 (3)	2 (2)
Thermal barrier coated airfoils	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)
Adv. fabricated high pressure turbine vane cluster	5 (6)	5 (6)	5 (6)	5 (7)	5 (7)
Engine/nacelle low temperature composites	4 (4)	4 (4)	4 (4)	4 (4)	3 (3)
High strength, low α cast diffuser case	6 (5)	6 (5)	6 (5)	6 (5)	6 (5)
High strength, low α cast turbine exhaust case	7 (7)	7 (7)	7 (7)	7 (6)	7 (6)
Silicon carbide reinforced glass ceramic	2 (2)	2 (2)	2 (2)	2 (2)	4 (4)

CONCLUSIONS

(1) Four of six material technologies included in this study showed significant benefits for the specific engine/airplane combinations selected.

(2) Technologies resulting in the most significant cost/benefits in terms of Relative Value were thermal barrier coated airfoils, dual property advanced disk and engine/nacelle low temperature composites (Energy Efficient Engine).

(3) Sensitivity analyses indicated that, with the exception of the advanced fabricated high pressure turbine vane cluster technology (JT9D engine), benefit levels were quite insensitive to reduced goals.

(4) Fuel price emerged as the dominant economic factor in the cost/benefit analysis of the material technologies studied.

LIST OF SYMBOLS

DOC	Direct Operating Cost
EEE	Energy Efficient Engine
HIP	Hot Isostatic Pressed
HPT	High Pressure Turbine
IOC	Indirect Operating Cost
LCC	Life Cycle Cost
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MATE	Materials for Advanced Turbine Engine
PW	Present Worth
ROI	Return on Investment
STF	Study Turbofan
TSFC	Thrust Specific Fuel Consumption
Δ	Change in a Value

MATERIALS

PWA 647	Mar-M-509
PWA 655	Inconel 713C
PWA 1455	B1900 + Hf
MERL 80	Nickel-based powder metal
MERL 220	Specially heat treatable nickel alloy

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