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

by
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16. Abstract

Cost/benefit studies were conducted on six advanced materials technologies applicable to future commercial aircraft gas turbine engines in the 1985 start-of-development time frame. The new materials technologies are intended to provide improved burner liners and turbine blades, disks and airseals. The cost/benefit of each technology is given 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 is given based primarily on consideration of "Relative Values" with secondary consideration given to changes in other economic parameters. Technologies showing the most promising cost/benefits are single crystal turbine blades and high strength, hot isostatic pressed turbine disks. In addition, very promising economic benefits (Return on Investment) are also indicated for two other technologies that currently are less well developed – advanced turbine blade alloys and an oxide dispersion strengthened sheet alloy for burner liners.

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FOREWORD

The cost/benefit studies of advanced aircraft gas turbine materials technologies described herein were performed by the Pratt & Whitney Aircraft Division of United Technologies Corporation under the technical direction of Neal T. Saunders, Materials and Structures Division, NASA-Lewis Research Center. This report was prepared by John W. Bisset, the Pratt & Whitney Aircraft Project O Manager. Materials information was prepared and reviewed by M. J. Donachie, S. S. Blecherman, R. A. Sprague, and H. A. Hauser of Pratt & Whitney Aircraft. Overall direction of the contractor's effort was provided by J. G. Giddings, the Pratt & Whitney Aircraft Materials for Advanced Turbine Engine (MATE) 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 relative rankings of the materials technologies under investigation (based on the current states of these technologies) are:

(1) Single Crystal Turbine Blades (highest ranking)
(2) High Strength Hot Isostatic Pressed Turbine Disk
(3) Advanced Oxide Dispersion Strengthened Burner Liner
(4) Bore Entry Cooled Hot Isostatic Pressed Turbine Disk
(5) Turbine Blade Tip - Outer Airseal System
(6) Advanced Turbine Blade Alloys (lowest ranking)

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 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 prioritization, are not included in the Relative Value equation.

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

- Single Crystal Turbine Blades
- High Strength Hot Isostatic Pressed Turbine Disk

Projected economic benefits independent of the probability of success and development cost also should be noted as significant for two additional materials technologies that are not yet as well developed as the other technologies. Economic benefits (here expressed in terms of "Return on Investment") are compared in Figure 2. The additional materials technologies with high potential benefits based on the full-technology goal for this criterion are:

- Advanced Turbine Blade Alloys
- Advanced Oxide Dispersion Strengthened Burner Liner

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

$$\frac{\Delta \text{ Return on Investment}}{\text{Development Cost}} \times \text{Probability of Success.}$$

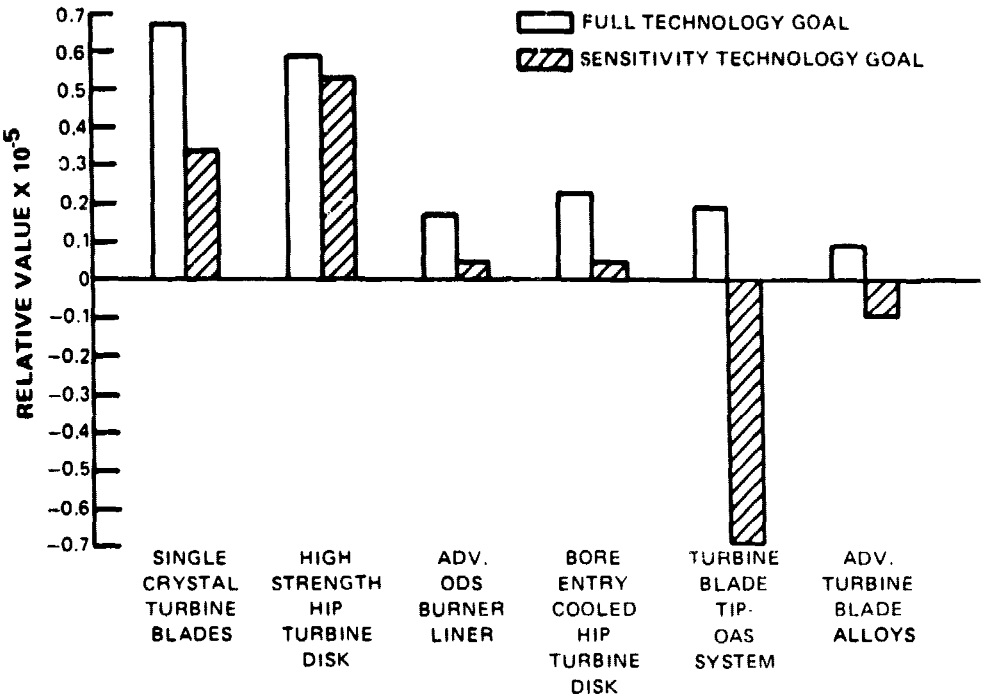

Figure 1 Comparison of Advanced Materials Technologies on the Basis of "Relative Value" Parameter

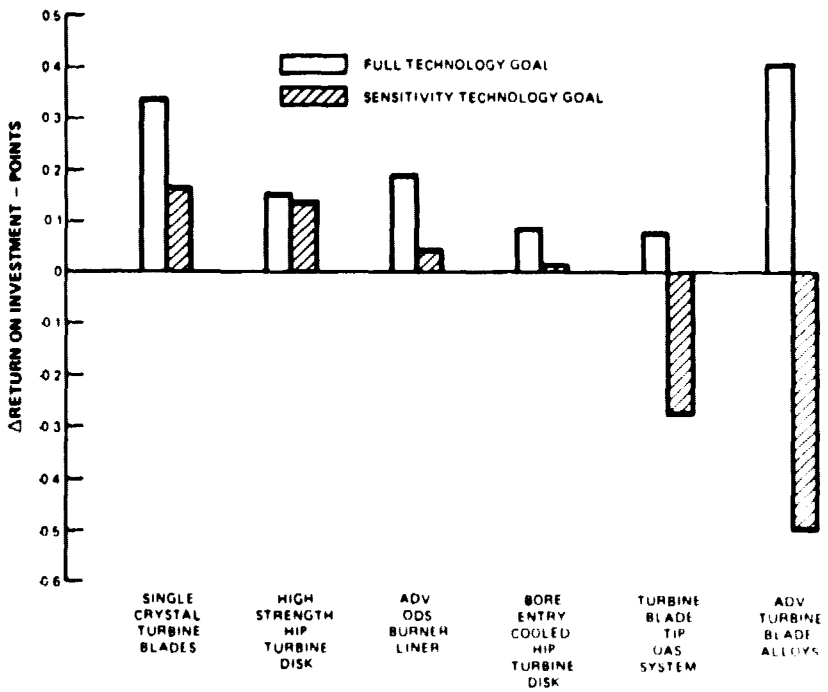

Figure 2 Comparison of Advanced Materials Technologies on the Basis of "Return on Investment" Parameter

INTRODUCTION

NASA and industry have recognized the need to investigate and evaluate advanced component and materials technologies for the improved commercial transport engines of the 1980's. Because of concern for the efficient use of our petroleum resources, high priority has been given to applications which will make the propulsion system more energy efficient. 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 as applied to fan blades and cases, compressor and turbine disks, burner liners, and turbine blades and vanes in engines for aircraft of the 1980's. These results provided inputs to help select the technologies to be developed 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 a typical mid 1980's technology turbofan engine used in a representative advanced commercial transport aircraft.

STUDY APPROACH

Advanced materials technologies selected for this study are shown in Table 1. 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 receive additional research and development funding support and will also be considered for incorporation in the NASA MATE effort.

TABLE I – SELECTED ADVANCED MATERIALS TECHNOLOGIES

- SINGLE CRYSTAL TURBINE BLADES
- ADVANCED TURBINE BLADE ALLOYS
- ADVANCED OXIDE DISPERSION STRENGTHENED (ODS) BURNER LINER
- BORE ENTRY COOLED HOT ISOSTATIC PRESSED (HIP) TURBINE DISK
- HIGH STRENGTH HOT ISOSTATIC PRESSED (HIP) TURBINE DISK
- TURBINE BLADE TIP-OUTER AIRSEAL SYSTEM (OAS)

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 permit 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 derived program plans and represent the funding, in 1976 dollars, estimated to be required 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 done 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 2.

TABLE 2 – 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

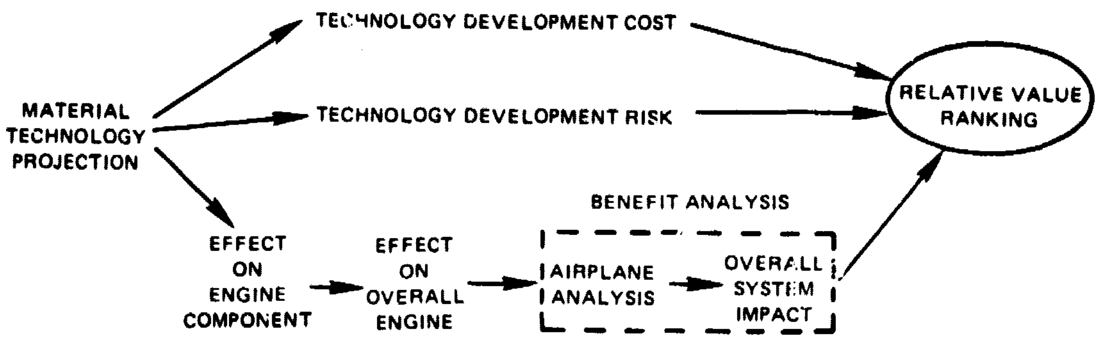

Figure 3 Approach Followed in Cost/Benefit Analyses

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 (Δ ROI), Direct Operating Cost (Δ DOC), Life Cycle Cost (Δ LCC), and Present Worth (Δ PW). The Δ ROI 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:

Δ ROI: 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).

Δ DOC: 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).

Δ LCC: 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 Δ ROI times probability of success divided by development cost.

NOTES: (1) Other abbreviations and symbols used in this report are defined on page 29.
(2) More details on the methodology used in this study are given in NASA CR-134701, Reference 1.

BASE ENGINE/AIRPLANE

The base engine for the study is a 1985 start-of-development STF 477 study engine. This engine was defined by Pratt & Whitney Aircraft in the NASA sponsored "Study of Turbofan Engines Designed for Low Energy Consumption" contract (Reference 2). It consists of a high speed, single-stage 1.7 pressure ratio fan, a three-stage, low pressure compressor of 1.53 pressure ratio, and an 18.2 pressure ratio high pressure compressor in 10 stages. A low emissions, two stage Vorbix combustor with aerating pilot nozzles is utilized to provide a 1427°C (2600°F) maximum average combustor exit temperature. The compression system is powered by a two-stage, high pressure turbine and a five-stage, low pressure turbine. The STF 477 engine parameters are summarized in Table 3 and a cross section of its configuration is presented in Figure 4.

TABLE 3 – STF 477 TURBOFAN ENGINE PARAMETERS

BASE SIZE	
Thrust – N (lb)*	118,100 (26500)
Inlet Airflow (Corrected) - kg/sec (lb/sec)	472 (1040)
NOMINAL CYCLE	
Fan Pressure Ratio	1.70
Bypass Ratio	8.0
Overall Pressure Ratio	45
Max. Combustor Exit Temperature °C (°F)	1427 (2600)
MAX. CRUISE TSFC – (kg/hr/n (lb/hr/lb)**	0.0586 (0.575)
WEIGHT AND DIMENSIONS	
Base Engine Weight - kg (lb)	1787 (3940)
Max. Diameter - m (in.)	1.92 (75.6)
Overall Length - m (in.)	2.88 (113.2)
ACOUSTICS (ENGINE PLUS NACELLE)	FAR36 - 10EPNdB

*Sea level take-off, 28.9°C (84°F) ambient temperature.
**9.1 km (30,000 ft), 0.8 Mn, standard day with customer airbleed and power extraction.

An advanced international quadjet was selected as the base airplane for the study. This airplane was also utilized in the "Study of Turbofan Engines Designed for Low Energy Consumption" contract. Aircraft characteristics include 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 4.

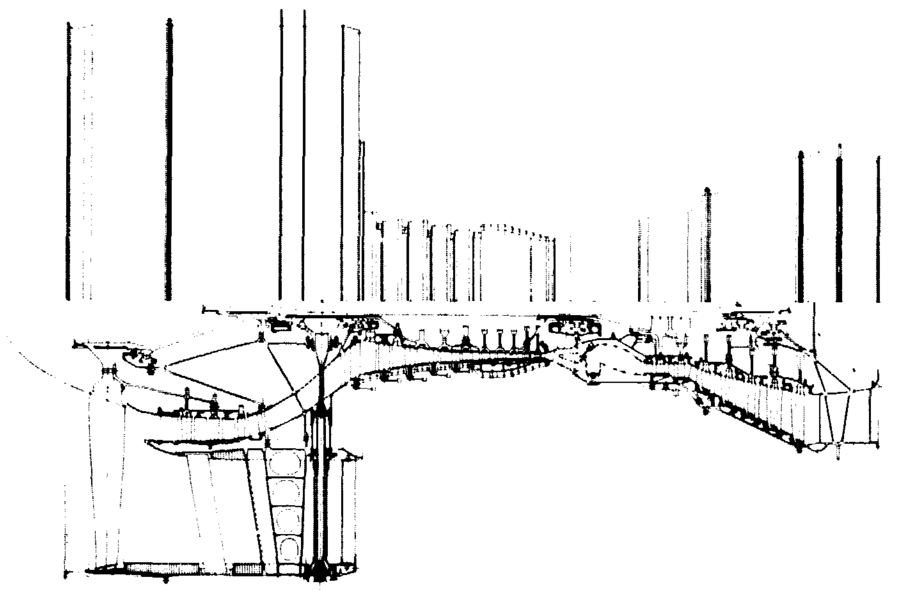

Figure 4 1985 Start of Development Turbofan Engine (STF 477)

TABLE 4 – AIRCRAFT/ECONOMIC PARAMETERS FOR STF 477 TURBOFAN EVALUATION

Design Cruise Mach Number	0.8
Design Range - km (n.mi)	10200 (5500)
Average Range - km (n.mi)	3700 (2000)
Number of Passengers	200
Number of Engines	4
Take-Off Gross Weight-kg (lb)	132000 (288,000)
Load Factor - %	55
Economic Life - Years	15
Operation Hours Per Year - Hrs.	4000
Hours Per Average Flight - Hrs	4.6
Base Return on Investment - %	14.6
Fuel Cost - ¢ /liter (¢ /gal)	12 (45)
Debt Factor	0
Inflation Rate - %	0
Discounting Rate - %	15.0
Discounting Period - Years	15

ADVANCED MATERIALS TECHNOLOGIES

Six advanced materials technologies were evaluated by assessing the impact of each one, individually, on the base STF 477 engine in an international quadjet operating in accordance with the ground rules listed in the preceding section. As previously stated, the advanced technologies considered were:

- Single crystal Turbine Blades
- Advanced Turbine Blade Alloys
- Advanced Oxide Dispersion Strengthened (ODS) Burner Liner
- Bore Entry Cooled Hot Isostatic Pressed (HIP) Turbine Disk
- High Strength Hot Isostatic Pressed (HIP) Turbine Disk
- Turbine Blade Tip-Outer Airseal System (OAS)

A brief description of these advanced technologies follows:

Single Crystal Turbine Blades - A mono-crystal superalloy blade obtained via directional solidification casting processes. Single crystal alloys demonstrating a 23°C - - - 40°F advantage in creep strength relative to the highest strength directionally solidified columinar-grained alloy have been produced using existing facilities. Further advances projected for single crystals are based upon demonstrated alloy concepts applicable to conventionally cast superalloys in combination with compositional modifications made possible through the elimination of grain boundaries.

Advanced Turbine Blade Alloys - A general category of materials, for future turbine blade application, that are in their early stages of development. This technology encompasses an advanced directionally solidified eutectic; a wire reinforced, corrosion resistant sheet matrix composite system; and a γ' strengthened ODS alloy. Considerable development efforts are required to identify ultimate design and manufacturing procedures compatible with the property advantages and limitations of these alloys.

Advanced ODS Burner Liner - An oxidation resistant ODS sheet alloy for burner liner application. ODS sheet alloys with limited oxidation resistance have been available for several years, and component fabrication and joining processes have been developed for them. Burner liner application consequently relies on alloy and process development that has been applied to the identification of more oxidation resistant materials. Goals for advanced ODS burner liner application have been established based on selection and extensive development of one of these oxidation resistant alloys in conjunction with additional joining technology development.

Bore Entry Cooled HIP Turbine Disk - A high strength superalloy high pressure turbine disk concept containing a plurality of radial cooling airflow passages that is fabricated via hot isostatic pressing of powder metal. This concept has been demonstrated on a subscale basis using the "soft can" technique. Continued development of this technology primarily relates to the formation of these complex internal passages during the densification of prealloyed powder, with the precision of core location relative to the container external surfaces and the substantiation of internal passage integrity critical to success.

High Strength HIP Turbine Disk - A high strength superalloy high pressure turbine disk concept with solid construction that is fabricated via hot isostatic pressing of powder metal. This technology represents an alternate approach for advanced turbine disks relative to the bore entry cooling air feed. Both approaches utilize the same advanced material, but differ in construction because of the two methods of feeding cooling airflow to the blades. As for the bore entry cooled disk technology, continued development will make extensive use of the prior HIP processing efforts performed on lower strength superalloys.

Turbine Blade Tip-Outer Airseal System - A high pressure turbine outer gaspath sealing system which accounts for the critical nature of the blade tip-airseal rub interaction. The static outer airseal consists of 0.254 cm --- 0.100 in. multilayer ceramics in conjunction with metallic substrates. The blade tip incorporates a bonded, corrosion resistant Tipaloy™ insert with abrasive particles (grits) imbedded at the rub surface. Extensive prior technology efforts and limited component testing of non-optimized candidate systems form the basis for continued development of this technology.

The baseline used for comparing these advanced technologies was assumed to be current technology as exemplified by the Pratt & Whitney Aircraft JT9D-70, a 236,300N (53,000 lb.) thrust engine currently used on civil transport aircraft such as the B-747 and DC-10. Therefore, the single crystal and advanced alloy turbine blades were compared to PWA 1422 (DS Mar-M-200+Hf) blades; the advanced blade tip-outer airseal system, to the plasma sprayed PWA 1422 blade tip-PWA 647 (Mar-M-509) outer airseal; the advanced ODS liner, to the PWA 1038 (Hastelloy X) liner; and the bore entry cooled and solid high strength HIP turbine disks, to solid forged PWA 1057 (Super WASPALOY®) disks.

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 historical developmental experience and projections of current state-of-the-art. Projected goals for each technology are summarized in Tables 5 through 10. The percentages and numbers given first are full target goals; the sensitivity (less optimistic) goals are shown in parentheses. In some cases two sets of sensitivity goals were used to cover a broader range of possibilities. (The numbers after the dashes are their equivalent in English units.)

TABLE 5 – SINGLE CRYSTAL TURBINE BLADE TECHNOLOGY

PROJECTED GOALS:

- Creep strength 40% (20%) >PWA 1422 at 982°C --- 1800°F.
- Alloy capability 56°C (28°C) --- 100°F (50°F) > PWA 1422 in creep, thermal fatigue and coated oxidation resistance.
- Casting cost 20% (0%) <PWA 1422 casting cost.

ESTIMATED DEVELOPMENT COST:

- $2,500,000

PROBABILITY OF SUCCESS:

- 50%

TABLE 6 – ADVANCED TURBINE BLADE ALLOYS TECHNOLOGY

PROJECTED GOALS:

- Coated alloy capability 111°C (83°C) and (56°C) – – – 200°F (150°F) and (100°F) >PWA 1422 in creep, thermal fatigue and oxidation resistance at same blade weight.
- Finished casting cost 1 x (2x) and (3x) >PWA 1422 finished casting cost.

ESTIMATED DEVELOPMENT COST:	PROBABILITY OF SUCCESS:
• $5,000,000	• 10%

TABLE 7 – ADVANCED OXIDE DISPERSION STRENGTHENED BURNER LINER TECHNOLOGY

PROJECTED GOALS:

- Alloy creep strength capability 111°C (83°C) – – – 200°F (150°F) >PWA 1038; 0.1% creep limit for ODS alloy vs. 0.5% creep limit for PWA 1038. (Property improvements used to increase liner life by estimated factors of 4.0 and 2.7 at the two goal levels.)
- Component cost 1.5x (2x) and (3x) >same component in PWA 1038.

ESTIMATED DEVLEOPMENT COST:	PROBABILITY OF SUCCESS:
• $3,000,000	• 25%

TABLE 8 – BORE ENTRY COOLED HOT ISOSTATIC PRESSED TURBINE DISK TECHNOLOGY

PROJECTED GOALS:

- Mechanical properties of PWA 1073 – IN100
- Improved 2x disk cyclic life, smooth and notched, vs. PWA 1073
- Finished part cost 1.5x (2.5x) >solid High Strength HIP Turbine Disk finished part cost based on full goal level.

ESTIMATED DEVELOPMENT COST:	PROBABILITY OF SUCCESS:
• $1,900,000	• 50%

TABLE 9 – HIGH STRENGTH HOT ISOSTATIC PRESSED TURBINE DISK TECHNOLOGY

PROJECTED GOALS:

- Mechanical properties of PWA 1073.
- Improved 2x disk cyclic life, smooth and notched, vs. PWA 1073.
- Finished part cost reduction of 60% (40%) by HIP to net shape vs. same material Gatorized™.

ESTIMATED DEVELOPMENT COST:	PROBABILITY OF SUCCESS:
• $1,300,000	• 50%

TABLE 10 – TURBINE BLADE TIP - OUTER AIRSEAL TECHNOLOGY

PROJECTED GOALS:

- 1593°C (1482°C) – – – 2900°F (2700°F) temperature capability.
- 0.031 cm (0.0254 cm) – – – 0.015 in. (0.010 in.) clearance reduction relative to Plasma sprayed tip – PWA 647 seal
- Component cost 1.5x (4x) and (6x) > Plasma sprayed tip – PWA 647 seal component cost.

ESTIMATED DEVELOPMENT COST:	PROBABILITY OF SUCCESS:
• $2,000,000	• 50%

TECHNOLOGY DEVELOPMENT COST AND RISK ASSESSMENT

Based on the established goals, development costs and probabilities 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, but costs chargeable to a technology, for example, burner liner construction, and post-test materials analysis were included. 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. These development cost and the 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 5 through 10.

Risk assessment methodology details are described in NASA CR-134701, Reference 1. Risk assessment results for the current study are detailed in Table 11.

TABLE 11 - TECHNOLOGY DEVELOPMENT RISK ASSESSMENT SUMMARY

MATERIAL TECHNOLOGY	RISK FACTORS (as defined in Table 2)						PROB. OF SUCCESS
	1	2	3	4	5	6	-%
Single Crystal Turbine Blade	B	B	C	A	B	C	50
Advanced Turbine Blade	C	C	C	B	A	C	10
ODS Burner Liner	B	C	C	A	A	B	25
Bore Entry Cooled HIP Turbine Disk	B	B	C	B	B	C	50
High Strength HIP Turbine Disk	B	A	C	B	B	C	50
Turbine Blade Tip-Outer Airseal	C	B	B	B	B	A	50

TECHNOLOGY COMPARISON STUDY APPROACH

The base engine for this study, the STF477, is a 1985 start-of-development advanced technology study engine that was defined during the NASA sponsored "Study of Turbofan Engines Designed for Low Energy Consumption" program. This engine has been reconfigured, as necessary, with the advanced materials technologies being considered in the current study. These newly reconfigured engines were then used as the baselines for comparison. To evaluate their benefits, the advanced material technologies' full goals were individually reduced to the corresponding levels of the current materials technologies. The effects on the engine components were then determined. Overall engine effects were subsequently established based on these component changes and these were the inputs to the benefit analysis.

An identical approach was used for the sensitivity analysis goals with the result that they were compared to the full goals for each materials technology.

The base engine, therefore, is the advanced technology engine with the full technology goals. However, to clarify the presentation of results, the signs of the results have been changed as if the substituted current technology material were the base technology for each case. The remainder of this discussion adopts this revised base approach, i.e., benefits are presented relative to a current technology material base.

TECHNOLOGY IMPACT ON COMPONENTS/ENGINE

Following the approach outlined above, the impact of each advanced technology item on its component and the engine was established. Table 12 summarizes these impacts for the full materials technology goals, with sensitivity analysis results presented in parentheses. For technologies where more than one level of sensitivity goal was studied, the sensitivity results shown in the table reflect the most conservative combination of levels. Specific details for the effects of each of these technologies are described in the following paragraphs.

TABLE 12 – IMPACT OF ADVANCED MATERIAL TECHNOLOGY ON STF 477 ENGINE PERFORMANCE, WEIGHT, COST AND DIMENSIONS

% Δ PERFORMANCE (TSFC)	% Δ ENGINE WEIGHT	% Δ ENGINE PRICE	Δ MAINTENANCE COST –$/OP. HR.	% Δ ENGINE DIAM/LENGTH
SINGLE CRYSTAL TURBINE BLADES				
−1.9 (−1.1)	−0.9 (−0.7)	−0.4 (+0.1)	−1.65 (−0.60)	+0.5 (+0.2)/ −0.3 (−0.4)
ADVANCED TURBINE BLADE ALLOYS				
−2.9 (−1.9)	−1.4 (−0.9)	−0.1 (+5.7)	−0.86 (+9.99)	+0.8 (+0.5)/ −0.7 (−0.3)
ADVANCED ODS BURNER LINER				
0 (0)	0 (0)	−0.2 (+0.9)	−3.81 (−1.85)	0 (0)
BORE ENTRY COOLED HIP TURBINE DISK				
−1.6 (−1.6)	+0.5 (+0.5)	+1.6 (+2.7)	+0.62 (+1.06)	−0.2 (−0.2)/ −0.3 (−0.3)
HIGH STRENGTH HIP TURBINE DISK				
−1.5 (−1.5)	−0.6 (−0.6)	+0.3 (+0.5)	+0.40 (+0.50)	−0.2 (−0.2)/ −0.3 (−0.3)
TURBINE BLADE TIP – OUTER AIRSEAL SYSTEM				
−1.2 (−1.0)	−0.5 (−0.4)	+0.3 (+2.9)	+1.35 (+5.65)	+0.3 (+0.3)/ −0.4 (−0.3)

NOTES

- Sensitivity study goal results are shown in parentheses. For technologies where more than one level of sensitivity goal was studied, the above sensitivity results reflect the most conservative levels.
- A decrease in any parameter is a benefit.

(1) Single Crystal Turbine Blades – When single crystal turbine blades replace the current technology PWA 1422 blades in the two-stage high pressure turbine (HPT) – with both blades utilizing the same advanced cooling technology – blade cooling airflow is reduced because of the increased metal temperature capability of the single crystal blades. As a result of this reduced cooling requirement, HPT efficiency is improved. Since the HPT rotor inlet temperature was held constant when the single crystal material was substituted for PWA 1422, the reduced cooling flow requirement results in a decrease in the blade cooling dilution effect and an increase in HPT exit temperature.

The improvement in efficiency and decrease in dilution effect result in more energy being available in the engine primary gas stream. If the engine cycle were to remain unchanged, the increase in primary stream energy would produce an increase in the jet velocity increasing jet noise and changing the performance characteristics of the engine. To maintain the primary jet velocity at its original level, the bypass ratio has to be increased. The higher bypass ratio increases the work requirement of the low pressure turbine (LPT), uses up the increase in energy available, and brings the noise characteristics of the engine with the advanced technology back to the levels of the engine with the current materials technology. However, the increased bypass ratio causes an increase in engine total airflow which would cause a thrust increase at cruise. Therefore, the entire engine was scaled down in size to maintain constant cruise thrust, since, to maintain aircraft systems consistency, the engine must be sized to the same cruise thrust.

As indicated above, fuel consumption was reduced because of the change in blade cooling airflow and the resulting HPT efficiency improvement, while the engine weight was reduced because a smaller engine is needed to provide the same thrust. At the full goal condition, the reduction in casting expense in combination with the use of a smaller engine resulted in an engine price reduction. However, at the sensitivity goal level, a small price penalty was exacted because blade finishing costs after casting were estimated to be higher for the single crystal material than for PWA 1422, and this difference essentially offsets the effect on price of the smaller engine. Engine maintenance costs were reduced by the smaller engine offsetting even the finished blade price penalties at the sensitivity goal. Maintenance costs reflect service life analysis results which indicate that blade repair and scrap lives are the same for the single crystal and the PWA 1422 material.

(2) Advanced Turbine Blade Alloys – Substituting advanced alloy turbine blades for PWA 1422 blades in the two-stage HPT of the STF-477 engine produces results similar to those noted for the single crystal blades. Cooling airflow is reduced because of the advanced alloys' increased metal temperature capability, efficiency is improved because of the cooling airflow reduction, and better fuel consumption and a smaller engine result from the efficiency improvement and cooling airflow reduction. The smaller engine also will weigh less. At the full technology goal level, engine price and maintenance costs are reduced because the impact of the smaller engine predominates. However, at the sensitivity goal levels, higher finished casting costs for the advanced blades overcome smaller engine effects and impose price and maintenance cost penalties. Maintenance costs reflect the result that blade repair and scrap lives were estimated to be the same for the advanced alloys and PWA 1422.

(3) Advanced Oxide Dispersion Strengthened Burner Liner – The advanced ODS burner liner material was utilized in the STF-477 to improve liner life and simplify the liner cooling configuration relative to PWA 1038. Analyses indicated that a PWA 1038 liner in the high (45:1) pressure ratio cycle environment of the STF-477 requires a very advanced cooling scheme such as transpiration or impingement cooling to achieve a cooling airflow level compatible with good combustion. Even then, liner life was estimated to be relatively low. If the advanced ODS material is used, however, the analyses determined that a simple louver cooling configuration should provide a design life of 2.7 to 4.0 times that of the PWA 1038 liner at the sensitivity and full goal levels, respectively. The advanced ODS alloy was directly substituted for the PWA 1038 in these analyses, i.e. both alloys were operated at the same temperature levels.

Because the use of the advanced ODS material permits a simpler cooling scheme, the engine price is reduced for the full cost goal relative to the engine with the PWA 1038 liner. However, for the higher sensitivity cost goals, engine price is penalized by the higher cost of the advanced material. Maintenance cost is reduced at all goal levels because of the improved durability of the advanced ODS material. These maintainance costs reflect estimates that the overall liner life is the same for the advanced ODS and the PWA 1038 liners, whereas repair lives at the full and sensitivity goal levels for the advanced ODS liner were estimated to be 3 and 2 times respectively longer than those for PWA 1038 liners. Engine performance (TSFC), weight and size are not affected by substitution of this new material in the burner.

(4) Bore Entry Cooled Hot Isostatic Pressed Turbine Disk – The high strength HIP disk technology with bore entry cooling air feed was applied to both HPT stages. Current technology disks in these stages are solid non-bore entry, conventionally forged PWA 1057. Analyses were made for both the advanced and current disk materials in the context of the STF-477 engine to establish burst and stress-rupture limits as functions of rotor speed and rim temperature. The analyses indicated that the advanced material allowed a higher rotor speed and cycle pressure ratio because of its increased stress-temperature capability, i.e., to make the current technology PWA 1057 material disk viable, the STF-4777 rotor speed had to be reduced 4% and the cycle pressure ratio had to be reduced from 45 to about 38 in order to satisfy rim temperatures limitations (50°C - - -90°F less than the advanced material). Design cyclic lives for both technology disks were calculated to be similar and commercially acceptable.

As a result, the high strength HIP disk technology with bore entry cooling air feed offers better fuel consumption and a smaller engine because of the increased overall pressure ratio and mid-compressor bleed source for the cooling airflow. However, engine weight for this advanced concept is increased, despite the smaller engine and higher rotor speed weight advantages, because of an additional low pressure compressor (LPC) stage required by the higher cycle pressure ratio and the details associated with the cooling system. For the same reasons and the added factor of increased finished disk cost, both price and maintenance cost are increased for the advanced technology engine. Maintenance costs reflect similar estimated repair and scrap lives for both technologies.

(5) High Strength, Hot Isostatic Pressed Turbine Disk – The high strength HIP turbine disk technology with solid construction represents an alternate approach for advanced HPT's relative to the bore entry cooling air feed. i.e. both approaches studied here utilize the same

advanced material, but differ in construction because of the two cooling concepts. The current technology PWA 1057 disks in this comparison are the same as those defined for the bore entry disk technology comparison, and structural analysis results are the same. Therefore, the solid, high strength HIP disk technology offers better fuel consumption and a smaller engine because of the increased overall pressure ratio. With this cooling approach, engine weight is decreased as the smaller engine and increased rotor speed weight effects offset the weight of the additional LPC stage. However, the added cost of the LPC stage and the higher finished disk cost (relative to PWA 1057) overshadow the smaller engine and increased rotor speed cost effects to increase engine price and maintenance cost. Maintenance cost analyses indicated that advanced and current disk technologies both have the same repair and scrap service lives.

(6) Turbine Blade Tip – Outer Airseal System – Substituting the TIPALOY™/ grits blade-ceramic outer airseal system for the current technology plasma sprayed tip - PWA 647 seal system in the STF-477's two stage HPT reduces cooling airflow because of increased material temperature capability. The cooling airflow reduction in conjunction with the projected tip clearance reduction capability of the advanced system results in an HPT efficiency improvement. Better fuel consumption and a smaller engine are possible because of the improvements in efficiency and cooling airflow. Engine weight is reduced because of the smaller engine, but the higher projected component cost goals overshadow smaller engine cost effects and lead to an engine price and maintenance cost increase. Maintenance costs are impacted by estimates that while the advanced and current technology blade tips have the same repair and scrap lives, the advanced airseal must be scrapped at the same interval in which the current technology airseal is being repaired because as a ceramic, it is considered to be non-repairable.

The following comments apply to all the above results:

All technologies except the advanced ODS burner liner, where the benefit was taken in life, result in substantial reductions in fuel consumption. The advanced turbine blade alloys result in the largest improvement because of their significant increase in metal temperature capability and the accompanying impacts on HPT efficiency and cooling airflow dilution discussed earlier. Average results indicate that the single crystal turbine blades and the two turbine disk technologies generally offer the second largest improvements in fuel consumption – the single crystal blades via the same mechanism as the advanced turbine blade alloys, but with less projected metal temperature capability, and the disks primarily via the ability to allow higher cycle pressure ratios. The small fuel consumption advantage shown by the bore entry cooled disk relative to the solid disk represents the advantage estimated for the mid-compressor air bleed source. The significant fuel consumption benefit shown by the turbine blade tip-outer airseal system is, as discussed earlier, a result of reduced cooling airflow and reduced tip clearance.

Engine weight reductions generally follow the trends displayed by fuel consumption, with the cause being the effect of scaling back down to the constant cruise thrust size. The performance oriented technology running counter to these trends is the bore entry cooled HIP disk where the cooling system details peculiar to this configuration outweigh the benefit provided by the smaller engine size.

Engine prices associated with the technologies studied are at best only slightly less than for current technology engines primarily because the advanced technology components generally are relatively more expensive to the extent that smaller size effects are nullified. Also, technologies with sensitivity cost goals that are much higher than the current technology result in significant engine price penalties, e.g., the advanced turbine blade alloy, the turbine blade tip-outer airseal system, and the bore entry cooled HIP turbine disk.

In general, engine maintenance cost trends follow engine price trends for the same reasons. The exception to this trend is the large maintenance cost reduction shown by the advanced ODS burner liner technology as a result of its longer expected life.

Table 11 shows that engine diameter and length effects are small. For the turbine blade and blade-outer airseal technologies, diameters are increased because bypass ratio effects overshadow smaller engine effects, and lengths are decreased because of the smaller engine scaling. The increased overall pressure ratio effect on size scaling for the disk technologies results in reduced diameter and length – even with the addition of an LPC stage.

AIRCRAFT BENEFIT ANALYSIS RESULTS

The impact of these overall engine effects on the operation of the international quadjet base airplane was established and the results are presented in Table 13 for the full materials technology goals, with the sensitivity results shown in parentheses. For technologies where more than one level of sensitivity goal was studied, the sensitivity results shown in the table reflect the most conservative combination of levels.

The following comments pertain to these results:

The advanced turbine blade alloys technology shows the best and the worst economic benefits of the technologies studied depending on goal level. The best economic benefits result because this technology has the largest performance and weight improvements at both the full and sensitivity goal levels. The large benefits are supplemented at the full goal level by reasonable price and maintenance cost improvements. However, at the most conservative sensitivity goal level, this technology has the worst price and maintenance cost penalties, a result which completely overshadows the performance and weight advantages.

Best overall benefits result for the single crystal turbine blades since this technology shows the second largest performance and weight benefits of the technologies studied in conjunction with reasonable price effects and reasonably large maintenance cost benefits at both goal levels.

The advanced ODS burner liner and high strength HIP turbine disk technologies generally show the next largest benefits. The large maintenance cost improvements displayed by the ODS material account for its benefits. Significant performance and weight advantages for the solid high strength HIP disk technology led to the economic benefit results by overshadowing the reasonably small price and maintenance cost penalties.

Reasonably large economic benefits are also shown for the bore entry cooled HIP turbine technology. However, since it is an alternate technology to the solid high strength disk as discussed earlier, and since, as currently envisioned, it offers substantially lower benefits than the solid disk technology, it would not appear to be the best approach to pursue at this time.

TABLE 13 – COST/BENEFIT ANALYSIS RESULTS FOR ADVANCED MATERIALS TECHNOLOGY IN QUADJET AIRPLANE

ΔROI -POINTS	ΔDOC -%	ΔLCC -$ x 10^3/ENGINE	ΔPW -$ x 10^3/ENGINE
SINGLE CRYSTAL TURBINE BLADES			
+0.333 (+0.164)	−1.348 (−0.673)	−314.4 (−157.3)	+144.1 (+70.5)
ADVANCED TURBINE BLADE ALLOYS			
+0.404 (−0.501)	−1.564 (+2.207)	−365.8 (+507.2)	+170.4 (−239.1)
ADVANCED ODS BURNER LINER			
+0.190 (+0.043)	−1.025 (−0.416)	−236.8 (−95.9)	+94.8 (+27.9)
BORE ENTRY COOLED HIP TURBINE DISK			
+0.085 (+0.013)	−0.431 (−0.228)	−101.9 (−55.0)	+36.2 (+6.7)
HIGH STRENGTH HIP TURBINE DISK			
+0.151 (+0.137)	−0.553 (−0.511)	−130.2 (−120.4)	+61.1 (+55.2)
TURBINE BLADE TIP – OUTER AIRSEAL SYSTEM			
+0.073 (−0.279)	−0.179 (+1.268)	−43.1 (+291.5)	+24.7 (−134.3)

NOTES:
- Sensitivity study goal results are shown in parentheses. For technologies where more than one level of sensitivity goal was studied, the above sensitivity results reflect the most conservative levels.
- An increase in ΔROI and ΔPW is a benefit, while a decrease in ΔDOC and ΔLCC is a benefit.

The turbine blade tip-outer airseal system shows relatively small benefits at the full goal level and large penalties at the sensitivity goal level. This technology has reasonably large performance and weight advantages at both goal levels. However, these advantages are partially offset at the full goal level and are overshadowed at the most conservative sensitivity goal level by engine price and maintenance cost increases.

For technologies where more than one level of sensitivity goal was studied, benefit analysis results were determined parametrically. These results for the advanced turbine blade technology are presented in Figures 5 through 8; for the advanced ODS burner liner technology, in Figures 9 through 12; and for the turbine blade tip - outer airseal technology in Figures 13 through 16.

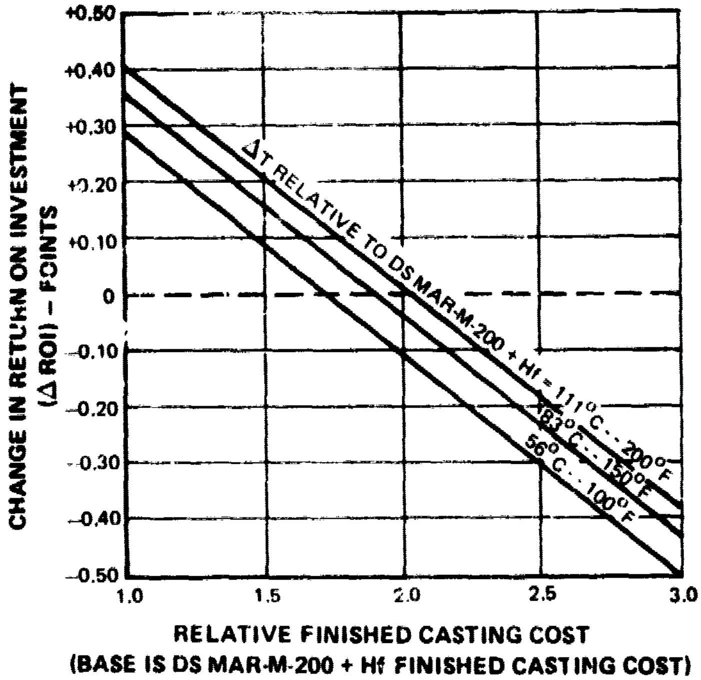

Figure 5 Aircraft Benefit Analysis Results for Advanced Turbine Blade Alloys Technology Showing ΔROI vs. Finished Casting Cost

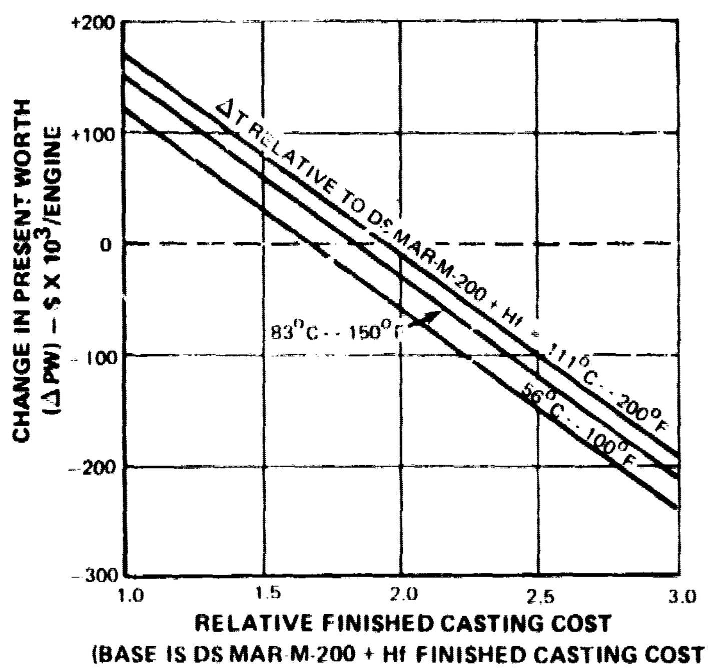

Figure 6 Aircraft Benefit Analysis Results for Advanced Turbine Blade Alloys Technology Showing ΔPW vs. Finished Casting Cost

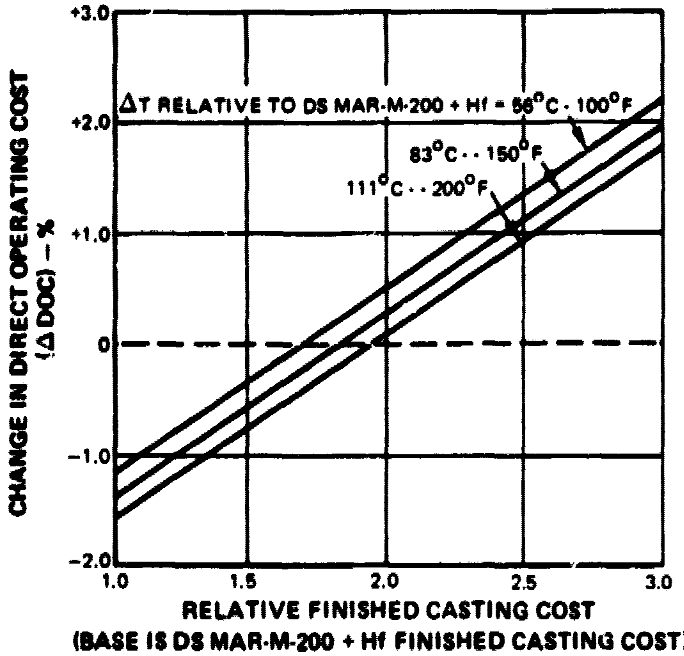

Figure 7 Aircraft Benefit Analysis Results for Advanced Turbine Blade Alloys Technology Showing ΔDOC vs. Finished Casting Cost

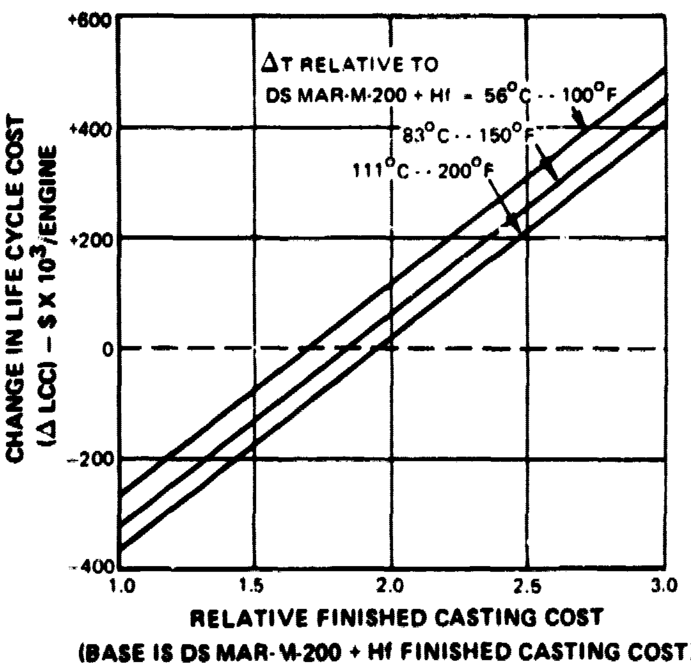

Figure 8 Aircraft Benefit Analysis Results for Advanced Turbine Blade Alloys Technology Showing ΔLCC vs. Finished Casting Cost

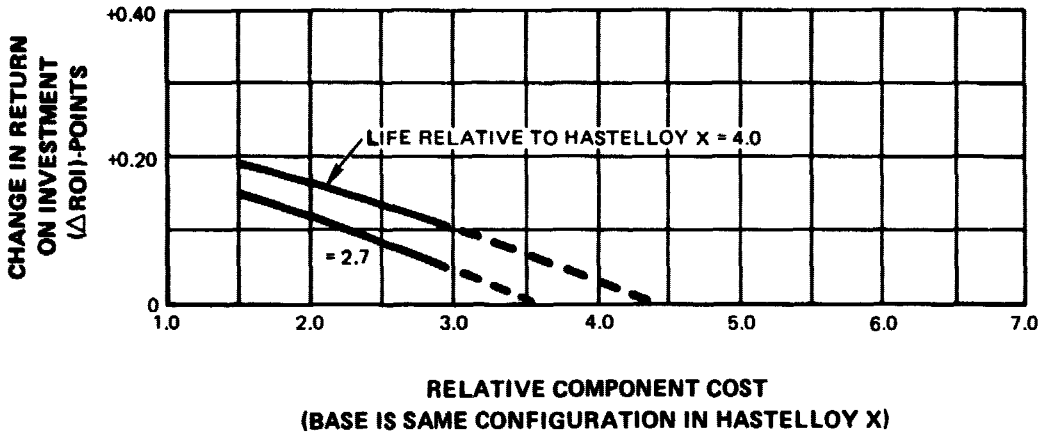

Figure 9 Aircraft Benefit Analysis Results for Advanced ODS Burner Liner Technology Showing ΔROI vs. Component Cost

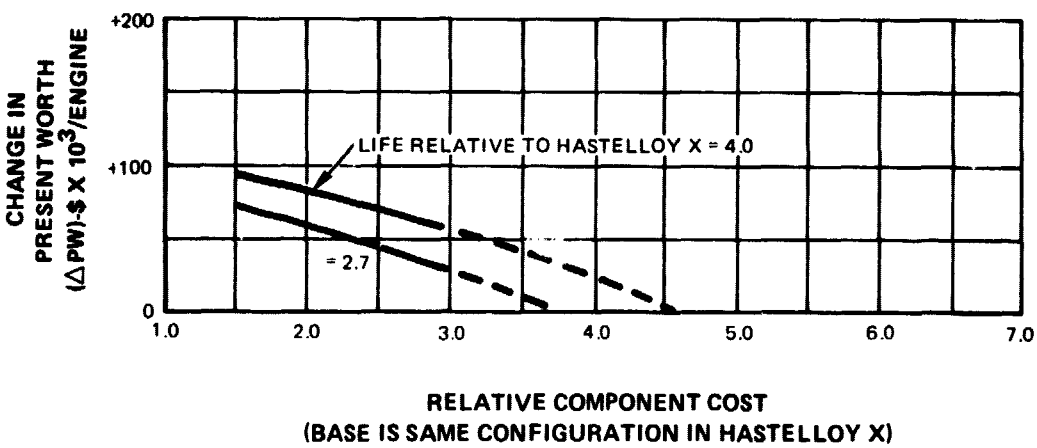

Figure 10 Aircraft Benefit Analysis Results for Advanced ODS Burner Liner Technology Showing ΔPW vs. Component Cost

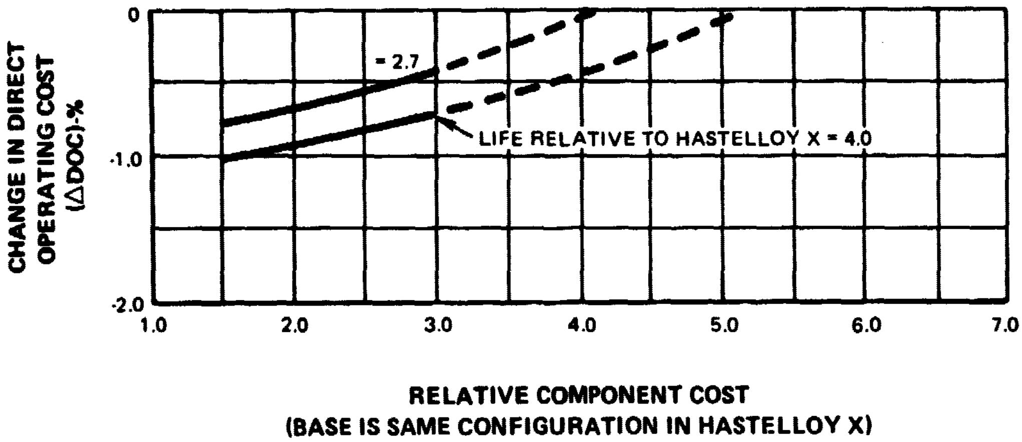

Figure 11 Aircraft Benefit Analysis Results for Advanced ODS Burner Liner Technology Showing ΔDOC vs. Component Cost

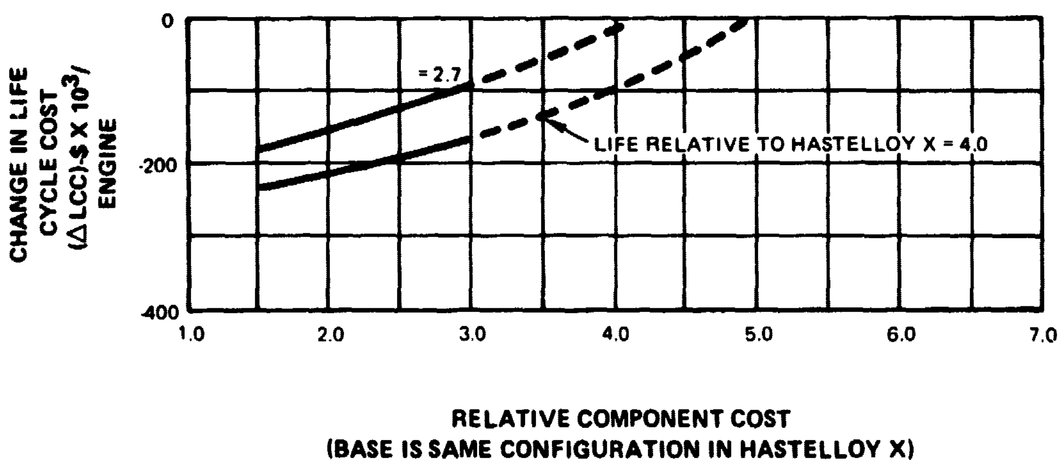

Figure 12 Aircraft Benefit Analysis Results for Advanced ODS Burner Liner Technology Showing ΔLCC vs. Component Cost

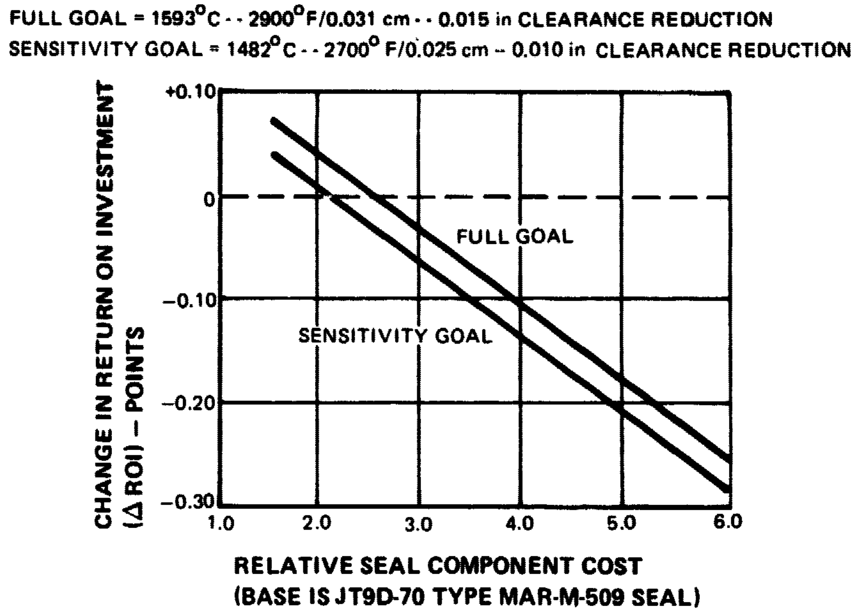

Figure 13 Aircraft Benefit Analysis Results for Turbine Blade Tip-Ceramic Outer Airseal System Showing ΔROI vs. Component Cost

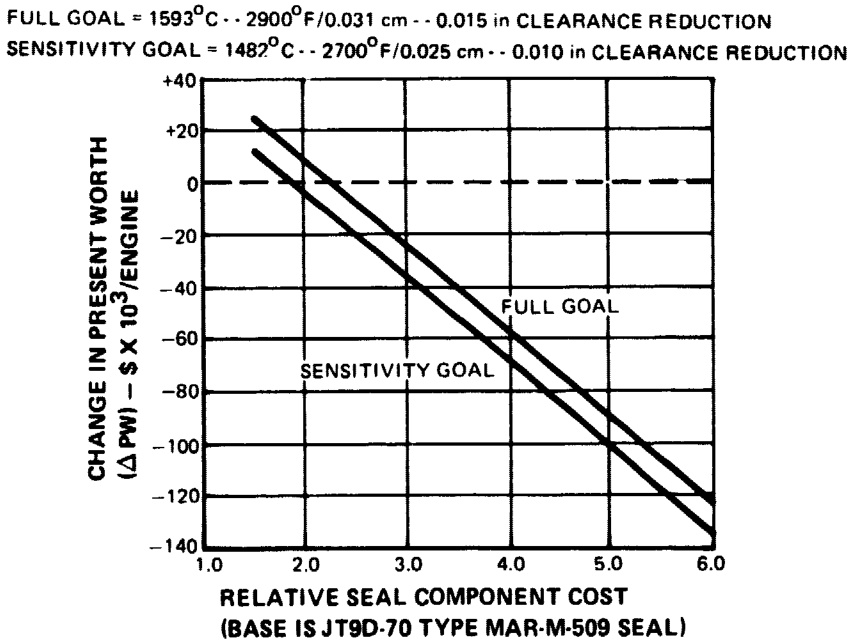

Figure 14 Aircraft Benefit Analysis Results for Turbine Blade Tip-Ceramic Outer Airseal System Showing ΔPW vs. Component Cost

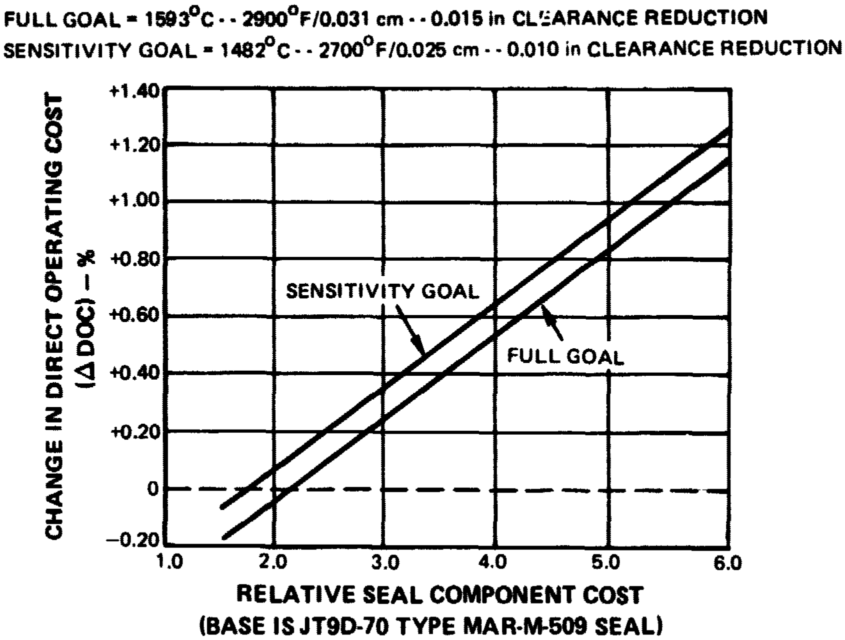

Figure 15 Aircraft Benefit Analysis Results for Turbine Blade Tip-Ceramic Outer Airseal System Showing ΔDOC vs. Component Cost

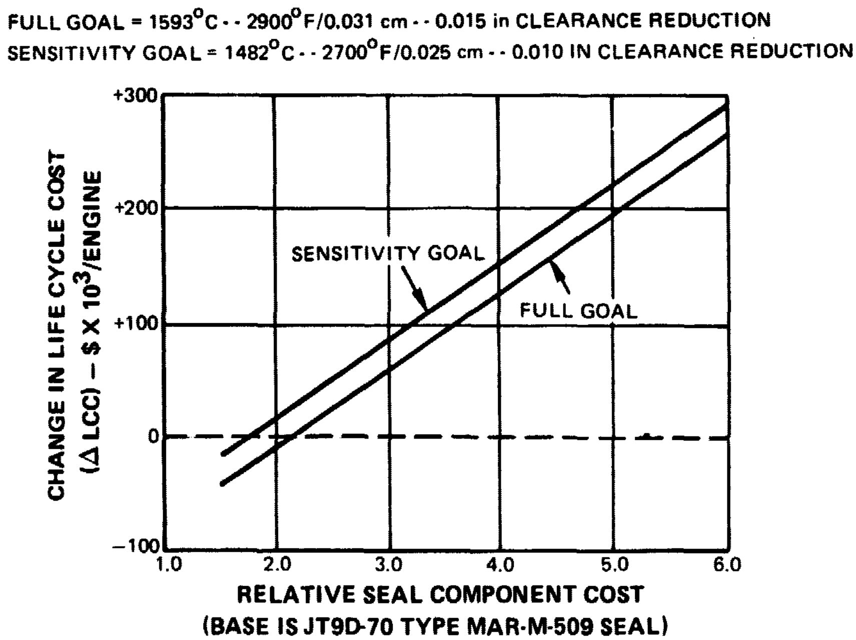

Figure 16 Aircraft Benefit Analysis Results for Turbine Blade-Ceramic Outer Airseal System Showing ΔLCC vs. Component Cost

The independent variables perturbed parametrically for the advanced turbine blade alloy were temperature capability and finished casting cost. The figures show that economics break even for this technology at a cost factor relative to PWA 1422 (DS Mar-M-200 + Hf) of 1.7 to 2.0 depending on the degree of temperature capability improvement. Economic trade factors utilized in this study indicate that the magnitude of economic worth for a temperature capability improvement of 111°C - - - 200°F versus 56°C - - - 100°F is equivalent to a change in TSFC of about 1%.

Relative component cost and life capability were the independent variables for the advanced ODS burner liner technology. The parametric plots show this technology to provide small economic benefits at all levels of goals studied. Obviously, the lower cost, longer life capability goals give the greater benefits. The economic advantages shown for a life capability improvement of 4.0 versus 2.7 represent an equivalent change in TSFC of about 0.5%.

Relative seal component cost and a combined temperature-clearance reduction capability were the parametric variables for the turbine blade tip-outer airseal technology study. Plotted results show that economics break even at costs relative to current technology of 1.7 to 2.5 depending on goal level and the benefit parameter. The economic differences shown between full and sensitivity goal combinations of temperature and clearance are equivalent to a change in TSFC of about 0.3%.

RELATIVE VALUE

The economic results discussed above are difficult to compare on a realistic basis in that they do 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 (ΔROI was used here because it is considered to the most complete economic parameter) multiplied by the probability of success, divided by the development cost. Probability of success is the result of the risk analysis that was conducted for each study technology. Development cost is 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 are 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 14 for the full materials technology goals, with the sensitivity analysis results presented in parentheses. For technologies where more than one level of sensitivity goal was studied, the sensitivity results shown in the table reflect the most conservative combination of levels.

TABLE 14 – RELATIVE VALUE OF ADVANCED MATERIALS TECHNOLOGIES IN STF 477 ENGINE FOR DEVELOPMENT COSTS AND PROBABILITY OF SUCCESS FACTORS SHOWN

RELATIVE VALUE $\times 10^{-5}$	Δ ROI –POINTS	DEVELOPMENT COST –\$ $\times 10^6$	PROBABILITY OF SUCCESS –%
SINGLE CRYSTAL TURBINE BLADES			
+0.67 (+0.33)	+0.333 (+0.164)	2.5	50
ADVANCED TURBINE BLADE ALLOYS			
+0.08 (–0.10)	+0.404 (–0.501)	5.0	10
ADVANCED ODS BURNER LINER			
+0.16 (+0.04)	+0.190 (+0.043)	3.0	25
BORE ENTRY COOLED HIP TURBINE DISK			
+0.22 (+0.03)	+0.085(+0.013)	1.9	50
HIGH STRENGTH HIP TURBINE DISK			
+0.58 (+0.52)	+0.151 (+0.137)	1.3	50
TURBINE BLADE TIP – OUTER AIRSEAL SYSTEM			
+0.18 (–0.70)	+0.073 (–0.279)	2.0	50

NOTES:
- Sensitivity Study Goal Results Are Shown in Parentheses. For Technologies Where More Than One Level of Sensitivity Goal Was Studied, The Above Sensitivity Results Reflect The Most Conservative Levels.
- An Increase in Relative Value and ΔROI is a Benefit.

The conversion from ΔROI to Relative Value severely reduces the impact of the advanced turbine blade alloys because of the high development cost and low probability of success for this technology in this early stage of its development. (Obviously, further advances in this technology could significantly increase the probability of success and thus the Relative Value.) Conversely, the relatively high probabilities of success and relatively low development costs for the solid and bore entry cooled HIP disk technologies significantly enhance their Relative Values. Similarly, the impacts of the single crystal turbine blade and the turbine blade tip-outer airseal technologies have been improved, but to a lesser extent than the disk technologies. The worth of the advanced ODS burner liner technology is basically unchanged when put in terms of Relative Value.

For technologies where more than one level of sensitivity goal was studied, Relative Value results were determined parametrically. These results for the advanced turbine blade, advanced ODS burner liner, and turbine blade tip-outer airseal technologies are shown in Figures 17, 18, and 19 respectively.

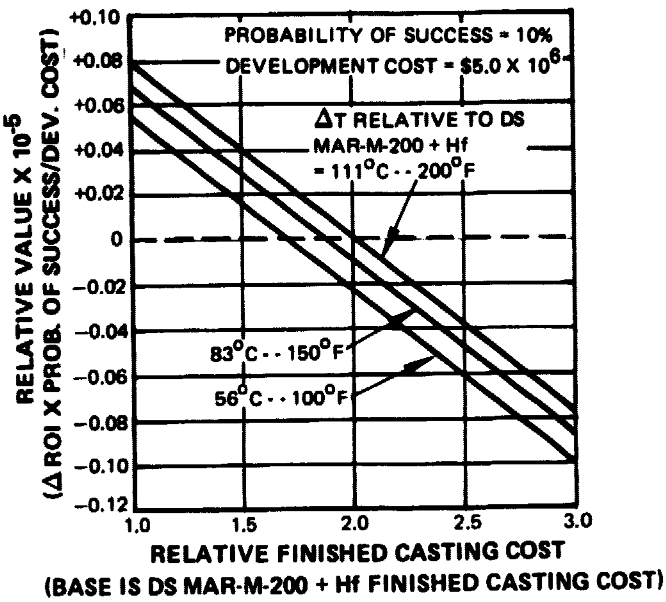

Figure 17 Relative Value Analysis Results for Advanced Turbine Blade Alloy Technology

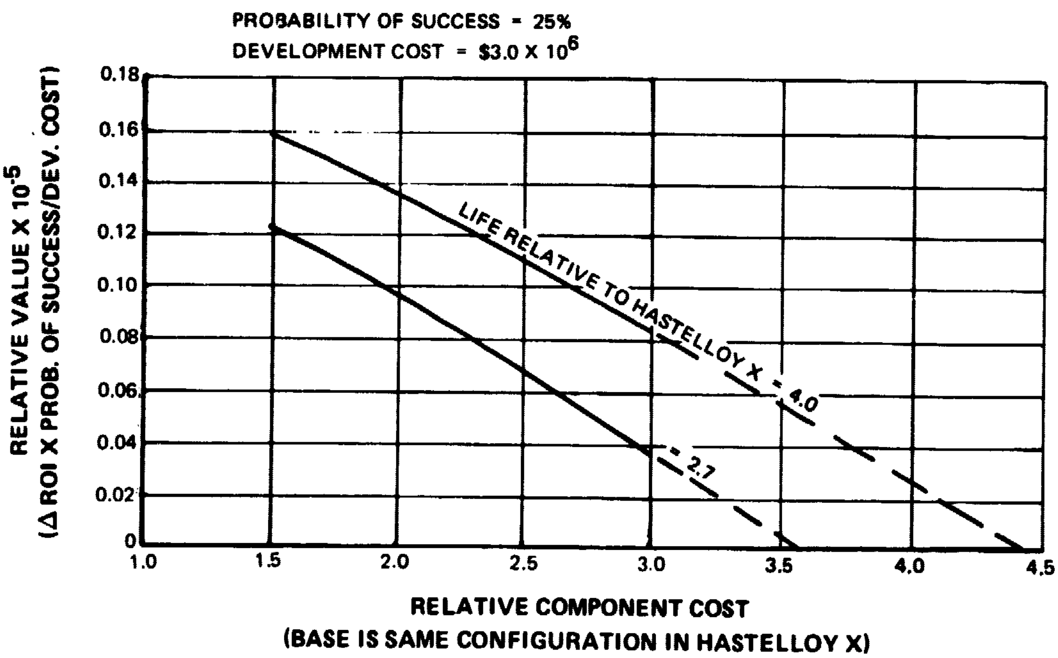

Figure 18 Relative Value Analysis Results foı Advanced ODS Burner Liner Technology

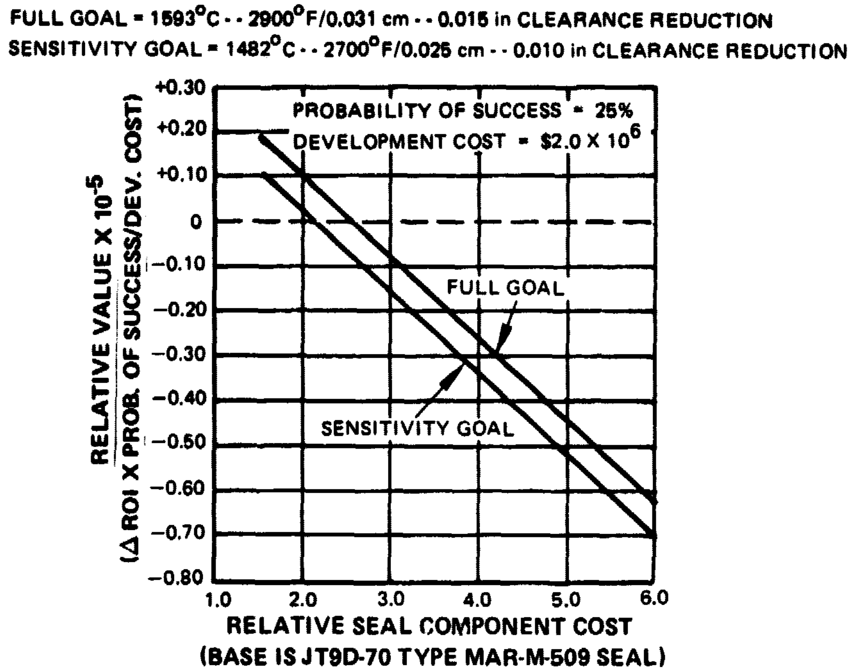

Figure 19 Relative Value Analysis Results for Turbine Blade Tip-Ceramic Outer Airseal System

The parametric Relative Value results for each of these three technologies reflect their respective parametric ΔROI results presented and discussed previously, since ΔROI is the only independent variable in the Relative Value equation. Figure 17 shows that Relative Value breaks even for the advanced turbine blade technology at a finished casting cost factor relative to PWA 1422 of 1.7 to 2.0 depending on the degree of temperature capability improvement. The advanced ODS burner liner technology is seen in Figure 18 to offer Relative Value benefits at all goal levels studied. For the turbine blade tip-outer airseal technology, Figure 19 shows a Relative Value break even at a relative seal component cost of 2.1 to 2.5 depending on the goal level considered.

RANKING SUMMARY

Table 15 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. Again, for technologies where more than one level of sensitivity goal was studied, the sensitivity positions shown in the table reflect results for the most conservative combination of levels.

TABLE 15 – BENEFIT PARAMETER RANKING – POSITION SUMMARY

MATERIALS TECHNOLOGY	ΔROI	ΔDOC	ΔLCC	ΔPW	RELATIVE VALUE
Single Crystal Turbine Blades	2 (1)	2 (1)	2 (1)	2 (1)	1 (2)
Advanced Turbine Blade Alloys	1 (6)	1 (6)	1 (6)	1 (6)	6 (5)
Advanced ODS Burner Liner	3 (3)	3 (3)	3 (3)	3 (3)	5 (3)
Bore Entry Cooled HIP Turbine Disk	5 (4)	5 (4)	5 (4)	5 (4)	3 (4)
High Strength HIP Turbine Disk	4 (2)	4 (2)	4 (2)	4 (2)	2 (1)
Turbine Blade Tip-Outer Airseal	6 (5)	6 (5)	6 (5)	6 (5)	4 (6)

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:

(1) Single crystal turbine blades
(2) High strength HIP turbine disk
(3) Advanced ODS burner liner
(4) Bore entry cooled HIP turbine disk
(5) Turbine blade tip-outer airseal system
(6) Advanced turbine blade alloys

A summation of the position results in Table 15, weighting the Relative Value position, led to this final ranking. Ranks 1, 2, 5, and 6 result directly from this procedure. A tie for third place was broken based on the questionable applicability of the bore entry cooled HIP turbine disk technology when the alternate solid high strength HIP turbine disk technology has larger benefits and a more traditional type of application to the engine component.

The following comments pertain to these ranking results: The first place ranking of the single crystal turbine blades technology is apparent based on its 1(2) Relative Value positions and 2(1) positions for the other benefit parameters. Similarly, second place ranking for the high strength HIP turbine disk technology results because of its 2(1) Relative Value positions combined with its strong 4(2) positions for the other benefit parameters. The ranking procedure resulted in a tie for third place between the advanced ODS burner liner and bore entry cooled HIP turbine disk technologies (tie broken as discussed above) because the small Relative Value position advantage, 3(4) versus 5(3), for the disk technology was exactly offset by the 3(3) versus 5(4) position advantage shown by the burner liner technology for the other benefit parameters. Fifth and sixth place rankings resulted for the turbine blade tip-outer airseal system and advanced turbine blade alloys, respectively, because the small Relative Value position advantage of 4(6) versus 6(5) for the blade tip-airseal system, when weighted, slightly offsets the rather large position advantage shown by the advanced blade alloys in the other benefit parameters, 1(6) versus 6(5). It should be noted that the Relative Value position, and consequently the rank, of the advanced turbine blade alloys technology was severely impacted because the technology is in its early stage of development. Further advances in this technology could significantly increase its probability of success and thus its Relative Value and rank.

CONCLUSIONS

1) All of the material technologies included in this study showed potentially attractive benefits for the specific engine/airplane combination selected.

2) Technologies resulting in the most significant cost/benefits in terms of Relative Value were single crystal turbine blades and high strength hot isostatic pressed turbine disks.

3) Based on economic benefits independent of development cost and risk, additional material technologies showing significant potential benefit were advanced oxide dispersion strengthened burner liners and the advanced turbine blade alloys.

4) Sensitivity analyses indicated that benefit levels for the advanced oxide dispersion strengthened burner liner and bore entry cooled hot isostatic pressed turbine disks technologies are quite sensitive to reduced goals, with engine component cost having the largest impact.

5) Sensitivity results also showed that significant penalties in economic benefits could exist for the turbine blade tip-outer airseal system and advanced turbine blade alloys technologies, with engine component cost again having the largest impact.

6) Since the bore entry cooled hot isostatic pressed turbine disk technology is an alternate to the high strength hot isostatic pressed turbine disk technology, and since it offered substantially lower benefits as currently envisioned, it would not appear to be the disk technology to pursue at this time, at least for the engine configuration/airplane system studied.

LIST OF SYMBOLS

DOC	Direct Operating Cost
DS	Directionally Solidified
EPNdB	Effective Perceived Noise Decibels
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

ODS	Oxide Dispersion Strengthened
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 1038	Hastelloy X
PWA 1057	Super WASPALOY
PWA 1073	IN 100
PWA 1422	DS Mar-M-200+Hf

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