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

MATERIALS FOR ADVANCED TURBINE ENGINES PROJECT COMPLETION REPORT

by

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16 Abstract

Cost/benefit studies were conducted on six advanced materials and processes technologies applicable to commercial engines planned for production in the 1985-1990 time frame. These technologies consisted of·

1. Thermal Barrier Coatings for Combustor and High Pressure Turbine Airfoils
2. Directionally Solidified (DS) Eutectic High Pressure Turbine Blades, Both Cast and Fabricated
3. Titanium Aluminide Mixer, Tail Cone, and Piping
4. Fabricated Titanium Fan Blisk
5. Advanced Turbine Disk Alloy with Improved Low Cycle Fatigue Life
6 Long-Life High Pressure Turbine Blade Abrasive Tip and Ceramic Shroud System

Technologies showing considerable promise as to benefits, low development costs, and high probability of success were thermal barrier coating, DS eutectic turbine blades, and abrasive-tip blades/ceramic-shroud turbine systems

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FOREWORD

The cost/benefit studies of selected advanced gas turbine material and processes technologies discussed herein were evaluated under the technical direction of Salvatore J. Grisaffe, Materials and Structures Division, NASA Lewis Research Center. This effort was conducted by Marshall Stearns of the Aircraft Engine Business Group of General Electric under the overall direction of L.G. Wilbers, the Materials for Advanced Turbine Engines (MATE) Technical Program Manager. The resources of the Materials and Process Technology Laboratories, the Design team of the Energy Efficient Engine (E^3) Operation, and Advanced Process Value Engineering organizations were utilized in this study. This project was conducted as part of Project "0" of General Electric's MATE Program under contract to the NASA-Lewis Research Center.

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1.0 SUMMARY

In this program, the cost/benefits of six advanced-materials technologies were evaluated in an Energy Efficient Engine (E^3) for a typical aircraft mission. The study was based on technologies applicable for introduction in the 1985-1990 time frame into commercial engines. Working with an engine design already geared for high energy efficiency would, on the surface, make large improvements seem improbable. However, working from an extensive list of advanced technologies, a group of six technologies was selected for detailed analysis, four of which showed significant payoffs for the engine/mission combination studied. These technologies and their relative ranking based on present worth, probability of success, and development costs were:

1. Thermal Barrier Coatings (TBC) for Combustor and High Pressure Turbine Airfoils

2. Abrasive-Tip Blades and Ceramic Shroud System

3. Directionally Solidified (DS) Eutectic High Pressure Turbine (HPT) Blading

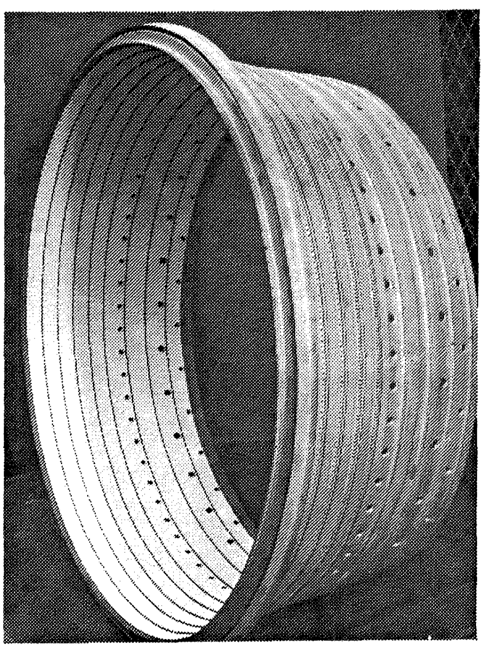
4. Titanium-Aluminide Exhaust Section Components

Since the engine type, size, and planned mission significantly dictate the cost/benefit results, the reader should be cautious before accepting a low mark for a given technology. Cost/benefit studies on a variety of engine types, missions, etc., would substantially improve the credibility of the ranking sequence but were beyond the scope of this study. Furthermore, the rankings might well change in different engine types. In addition, the risk factor (probability of success) is an uncertain, subjective judgement, but it has strong influence on the ranking formula used. This risk factor will change significantly as successes/failures are encountered in the development cycle and will dictate changes in emphasis on development direction and timing.

With due consideration for all these influences, the thermal barrier coatting for combustor and turbine airfoils, the abrasive-tip blade with ceramic shroud system, and DS eutectic HPT blades (assuming significant increases in fuel cost) represent solid technologies for continued development. A tabular summary comparing development cost, probability of success, effect on direct operating costs (DOC) and present worth (PW) is shown in the following tabulation. The ranking parameter attempts to relate value (PW) and probability of success versus development cost. The greater the parameter value, the more attractive the payoff of the technology. All the selected technologies have attractive value versus development cost.

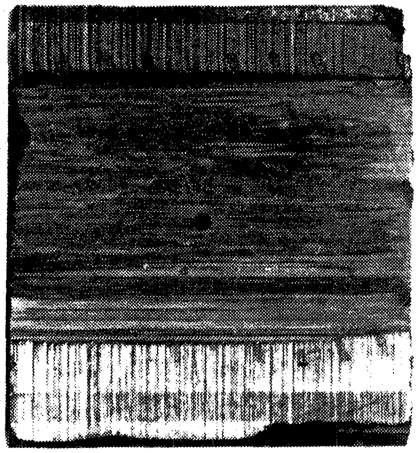
	Initial Develop. Cost, \$ Million	Prob. of Success, %	\$1/gal Fuel ΔDOC, %	\$1/gal Fuel PW, \$ Million	\$2/gal Fuel ΔDOC, %	\$2/gal Fuel PW, \$ Million	Relative Ranking Parameter (\$2/gal Fuel) Present Worth x Prob. of Success / Initial Development Cost
Thermal Barrier Coating							
Combustor			-0.11	4.0	-0.15	8.1	
HP Turbine			-0.30	11.0	-0.43	22.5	
Total	1.55	65	-0.41	15.0	-0.58	30.6	13
DS Eutectic HPT Blading	5.85	70	-0.28	10.4	-0.53	28.0	3
Titanium Aluminide							
Mixer and Tail Cone	1.4	60	-0.70	2.5	-0.11	6.0	3
Abrasive-Tip Blade Shroud System	1.4	50	-0.15	5.4	-0.22	11.4	4

Thermal barrier coatings (TBC's), that is, surface layers of low thermal conductivity materials applied to the hot side of a cooled metal structure to lower the temperature of the metal, are projected to have extensive impact on the continuing effort to increase the overall performance of aircraft gas turbine engines by increasing the turbine inlet gas temperature and/or allowing significant reductions in cooling air. The use of TBC's for application on HPT components also has a potential for savings in compressor bleed air requirements, reductions in complexity of cooling systems, and increases in parts durability due to lower metal wall temperatures and thermal gradients. On this analysis, for both combustor and turbine nozzle bands and blades, part lives were held constant, and all the improvements were taken as a reduction in cooling air. The TBC coating for the combustor is shown below on the inner diameter. A successful TBC can provide a viable alternative and/or a complementary effort to several generations of costly and time-consuming alloy developments.



CF6 Combustor Outer Liner Coated with Ni5%Al/MgO-ZrO_2 Triplex Barrier Coating.

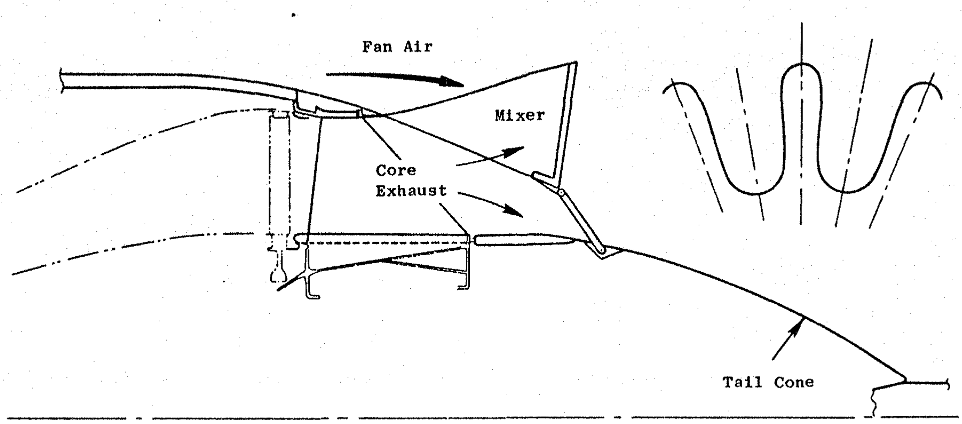
Abrasive tip treatment of turbine blades combined with ceramic stator shrouds (particularly in HPT's) constitute an application of materials to components where significant improvements can be made to performance by reduced cooling air requirements, improved shroud life, weight reduction, and control of blade tip/shroud clearance. Engine testing has shown that lower cooling air requirements and higher gas stream temperature, with improved life and low cost at the same time, can be achieved with shrouds having integrally bonded



Shroud Wear

ceramic flowpath surfaces. However, the better ceramic candidates are relatively abrasive and can accentuate the blade tip/shroud clearance control problem with attendant loss of turbine efficiency. Shroud wear (as shown) with minimized blade tip wear is the basis of the performance improvement of this technology and should be achievable by use of abrasive-tipped turbine blades.

DS eutectic turbine blading has the potential to operate at 53 K (100° F) higher temperature than DS René 150 alloy. Payoffs were determined by substitution of DS eutectic in the current E^3 design and found to be attractive only at higher fuel cost prices. Manufacturing and development costs were strong factors in yielding less attractive PW values. A new engine design, predicated on the capabilities of this alloy system in which second and third tier payoffs are realized, would have yielded even more attractive sfc improvements, plus a substantially reduced weight, than a straight alloy substitution.



Titanium Aluminide Sheet Mixer and Tail Cone.

Titanium aluminide was considered for static components due to its strength-to-weight ratio. In this study, Ti_3Al was substituted for IN 718 in the mixer and for IN 625 in the tail cone with 50% and 42% weight savings, respectively. These weight reductions were then converted to ΔDOC effects.

2.0 INTRODUCTION

Advanced materials technologies have historically made substantial contributions to the evolution of aircraft gas turbine engines and must continue to meet demands for engines with improved performance and cost effectiveness. 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. Concern is for the earliest possible use of promising technologies so as to maintain U.S. preeminence in world gas turbine markets. Improved performance and durability, as well as attractive life cycle costs, are major factors of interest.

To help fulfill these needs in the area of materials technology, NASA and industry have a cooperative effort, the MATE (Materials for Advanced Turbine Engine) Program, to accelerate the introduction of new materials technologies into advanced aircraft turbine engines. Part of this overall program has involved a periodic assessment of the costs and potential benefits of selected advances in materials technology applied in turbofan-powered, commercial transports. The results of these studies provide input that helps in the selection of technologies to be developed in the MATE effort. The study program summarized in this report has established costs and benefits for several advanced materials technologies as applied to specific components of a commercial-aircraft, energy-efficient engine.

Materials technologies selected for this study included high-temperature turbine blades, vanes, and shrouds; combustor liners; fan and turbine disks; and structural components.

The methodology used to assess the benefits, costs, and risks of the advanced materials technologies, as applied to future conventional takeoff and landing (CTOL) propulsion systems, is described in this report. The overall study was based on a time frame of commercial-engine use of the advanced materials technologies by 1985-2015.

Results generated under this program are expected to aid in the selection and subsequent development of those materials technologies offering the greatest potential for use in future aircraft turbine engines. It should be recognized, however, that the ranking of the materials technologies as defined by this study does not represent the sole basis for engineering development and engine application decisions. Other significant factors, which require engineering judgment and may play a major role in ultimate program selection and technology development, are not necessarily included in this cost/benefit study. These include such factors as:

- Conservation of critical materials
- Impact on marketability of engine product lines
- New technology base or technology extension
- Facilitation, both internally and industrywide.

3.0 METHOD FOR COST/BENEFIT ANALYSIS

Economic analyses were conducted to ascertain the concepts most worth pursuing for the selected engine/airframe system. This section describes the analytical procedure and the factors that were considered to arrive at a judgmental ranking of the technologies studied. In general, an engine preliminary design was executed in sufficient depth to establish the effects of each material advancement. This established payoffs, penalties, and hardware costs. The fuel savings and economic benefit were evaluated for such engines powering a modern air transport. Costs to develop the technologies were estimated along with the risks of successfully introducing the technologies. A comparison of the payoffs, risks, and development cost identified which technologies are worth pursuing. A judgmental ranking of the technologies is possible within the confines of the engine/aircraft system studied.

3.1 STUDY ENGINE

In this study, the NASA/GE Energy Efficient Engine was selected as the vehicle in which materials improvements would be analyzed. The E^3 is an advanced-technology, high-bypass-ratio, commercial-transport engine. It is scheduled for performance demonstration in 1982 and 1983 and is representative of "next generation" engine technology to enter service in the 1985 to 1990 time period.

The E^3 cross section is shown in Figure 1 with planned technologies noted. The cycle parameters are compared to those of the CF6, a current-production engine (see Table I). As noted, the E^3 is characterized by higher bypass ratio, higher cycle pressure ratio, hotter turbine inlet temperature, better component efficiency, and a shorter, more rugged structure. Fuel consumption of the E^3 will be about 14% better than current-production engines without incorporation of any of the technologies studied in this program.

Table I. Comparison of E^3 to CF6.

Cycle Parameter	E3	CF6-50C
Cycle Pressure Ratio at Maximum Climb	38	32
Bypass Ratio at Maximum Climb	6.8	4.2
Fan Pressure Ratio at Maximum Climb	1.65	1.76
Turbine Rotor Inlet Temperature, K (° F) at Sea Level Static, 309 K (86° F) Day	1617 (2450)	1614 (2445)
Δsfc, % at 10.7 km (35,000 ft) Mach 0.8 Maximum Cruise	-14.2	Base

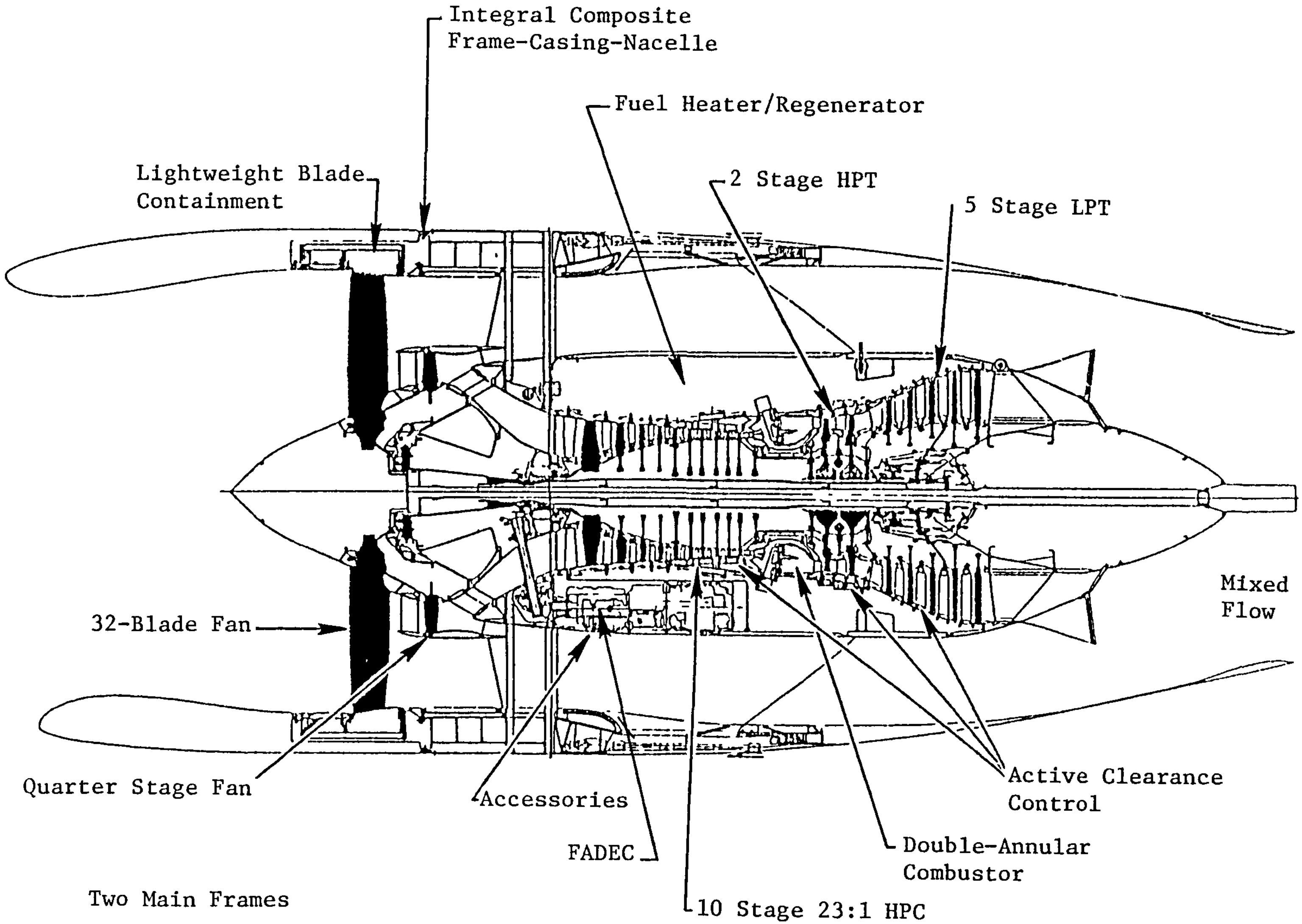


Figure 1. NASA/GE Energy Efficient Engine.

3.2 STUDY AIRCRAFT

The aircraft used to assess payoffs is a typical "next generation" commercial transport. It is a twin-engine airliner flying a domestic route. The aircraft is assumed to fly 3452 hours per year which gives 14.65 megaliters (3,870,000 gallons) of fuel used per year per aircraft.

Aircraft Design

5.6 Mm (3000 nmi) Range
10.7 km (35,000 ft) Cruise Altitude
0.8 Cruise Mach No.
225 Passengers (100% Payload)
128.22 Mg (282,670 lbm) Takeoff Gross Weight
180.54 kN (40,590 lbf) Thrust Per Engine, Sea Level Static, Uninstalled

Aircraft Mission for Analysis

1.3 Mm (700 nmi) Flight
10.7 and 11.9 km (35,000 and 39,000 ft) (Stepped) Cruise Altitude
0.8 Cruise Mach No.
55% Load Factor
6.46 Mg (14,242 lbm) fuel Burned Per Flight
1.895 Hours Per Flight

3.3 TECHNOLOGIES SELECTED FOR EVALUATION

A very broad group of materials technologies was considered for cost/benefit evaluation in 1979. A "shopping list" of 50 was screened to select technologies to undergo detailed cost/benefit analysis. Initial screening was by judgment based on potential payoff need for the technology, feasibility, and risk. Next, a preliminary cost/benefit analysis further screened the technologies. The preliminary analysis included preliminary designs (where needed) and also included an evaluation of specific fuel consumption (sfc) and weight effects on direct operating cost and fuel burned. Based on this analysis, six high-potential technology areas were selected for detailed cost/benefit analysis:

1. Thermal Barrier Coatings for Combustor and HPT Airfoils

2. DS Eutectic HPT Blades, Both Cast and Fabricated

3. Titanium Aluminide Mixer, Tail Cone, and Piping

4. Fabricated Titanium Fan Blisk (Integral Combination Blade and Disk)

5. Advanced Turbine Disk Alloy with Improved Low Cycle Fatigue (LCF) Life

6. Long-Life HPT Abrasive-Tip Blade and Ceramic Shroud System

Each of these technologies is presented in detail in the following sections. The technologies are discussed, material goal properties are projected, and the benefits and costs are quantified on a consistent basis so that comparisons can be made between them.

The cost to develop each technology was estimated in 1980 dollars. These total costs included the cost for each of the following steps:

1. Laboratory Development- Developing the material/process, scaling up to production, and developing the required design data

2. Manufacturing Process Development - Demonstration of adaptability of standard joining, fabrication, and coating technology - process development of new and novel process if necessary to accommodate unique characteristic of a material

3. Transition to Manufacturing - Establish new processes or process modifications in the manufacturing area to achieve engineering requirements

4. Trial Hardware - Produce trial hardware for property evaluation and component tests

5. Engine Test - Proof of concept, evaluation in test engine.

Costs for certification hardware or production facilities were not included in this assessment.

3.4 DESIGN STUDY

The impact of each technology on the engine was ascertained by a design study of the changes in engine weight, maintenance cost, selling price, and performance. Performance-related improvements, such as component efficiency or decreased cooling air requirements, were converted into changes in sfc. The study aircraft requires engines larger than the E^3; therefore, costs and weights were scaled from the 162.35 kN (36,500 lbf) thrust E^3 to the 180.54 kN (40,590 lbf) required for the domestic, twin-engine aircraft. The following scaling factors were used:

- Base Engine Cost/Base E^3 Cost = (Thrust/E^3 Thrust)$^{0.55}$
- Nacelle Cost/E^3 Nacelle Cost = (Thrust/E^3 Thrust)$^{0.8}$
- Base Engine Weight/Base E^3 Weight = (Thrust/E^3 Thrust)$^{1.35}$
- Core Engine Weight/E^3 Core Weight = (Thrust/E^3 Thrust)$^{1.4}$

- LP System Weight/E^3 LP System Weight = (Thrust/E^3 Thrust)$^{1.3}$
- Nacelle Weight/E^3 Nacelle Weight = (Thrust/E^3 Thrust)$^{1.1}$

The improved engine was assumed to be installed in an aircraft optimized for that engine, rather than in an existing aircraft. This means that if fuel consumption or weight is reduced, the fuel required by the aircraft is reduced. Wing area is then reduced, and this further reduces fuel load, aircraft weight, and engine size for the same payload. If the improved engine were installed in existing (fixed) aircraft, the compounding effects would not be realized, and the benefits would be less rewarding.

3.5 ECONOMIC BENEFITS

Production part-cost differences were estimated considering the projected cost of the material and/or process involved to produce the finished part, including finishing processes such as machining and coating. Costs were estimated for a 250-th production engine; this represents an average of the first 1000 engines. The cost difference estimates are relative to the E^3. Early in the E^3 program, a comprehensive economic model was developed for making trade studies. This model provided the basis for evaluating economic effects. The model originally used 35¢/gallon fuel price and 1977 dollars. For the purpose of this study, it was inflated to 1980 dollars. Since fuel price projections are very uncertain, benefits were evaluated for $1/gallon and $2/gallon fuel, in 1980 dollars. This range was expected to cover most fuel price projections over the next decade.

Economic benefits from advanced material technologies were evaluated in terms of changes in direct operating cost (DOC) and present worth (PW).

The DOC incurred by an airline operator is made up of the cost of crew, fuel, airframe maintenance, engine maintenance, depreciation, and insurance. The effects of changes in engine weight, selling price, maintenance cost, and fuel consumption on DOC had been established as follows:

	$1/gal Fuel	$2/gal Fuel
Base DOC, $/Flight-Hour/Aircraft	2700	3840
% ΔDOC for		
Δ Weight, 192 kg (423 lbm)	0.91	1.28
Δ Selling Price, $245,000	0.55	0.55
Δ Maintenance Cost, $6.70/Engine Flight-Hour	0.55	0.55
Δsfc, 1%	0.91	1.28

Payoffs from technical innovations must be compared to investment costs and risks. PW was used to represent the payoff versus investment cost. Present worth is an "equivalent initial value of the discounted future savings to be accumulated over the life of a fleet of airplanes." It recognizes the value of money over time and, therefore, provides a means for comparing payoffs with initial investment. For instance, a \$1 savings 10 years from now is really only worth an investment of 26¢ now if an annual return of, say, 14.6% is expected from the investment.

To calculate present worth, first the dollar savings due to technology for each year is calculated based on the number of aircraft, hours utilization, and ΔDOC.

Savings in One Year = ΔDOC (Flight-Hours/Year)(Number of Aircraft)

For each year a calculation is made of an "equivalent investment" at year zero which, if returning 14.6%, would equal the dollar savings.

Equivalent Investment = (Savings in N-th Year)(1 + Discount Rate)^N

where Discount Rate = 14.6%

The sum of the "equivalent investments" for all N years is the present worth.

Selection of the discount rate is arbitrary. A value of 14.6% is typical and was used in the E^3 program.

For the present worth calculation, a fleet of aircraft was assumed to enter service eight years after investment in the technology being evaluated. Seven years later, the fleet was assumed to reach a full size of 300 aircraft. Fleet size was held steady and then was gradually retired as shown in Figure 2.

A sample calculation of present worth is shown in Table II. A 1% saving in DOC produces \$37,000,000 PW if fuel costs \$1/gallon and \$52,600,000 PW if fuel costs \$2/gallon.

Return on investment (ROI) can be a key economic measure. However, it must be keyed to the assumptions made in the economic model, such as the amount of investment captial which is borrowed and fuel price. Return on investment is a more complex analysis than direct operating cost and could not be simply adjusted for fuel costs. The E^3 ROI calculation was made for the technologies studied. When adjusted to use 1980 dollars, it gave a fuel price of 47¢ per gallon. Because this is below fuel price projections, ROI was retained only as a secondary measure of benefit.

3.6 RISK ANALYSIS

The probability of achieving success was estimated for the following areas:

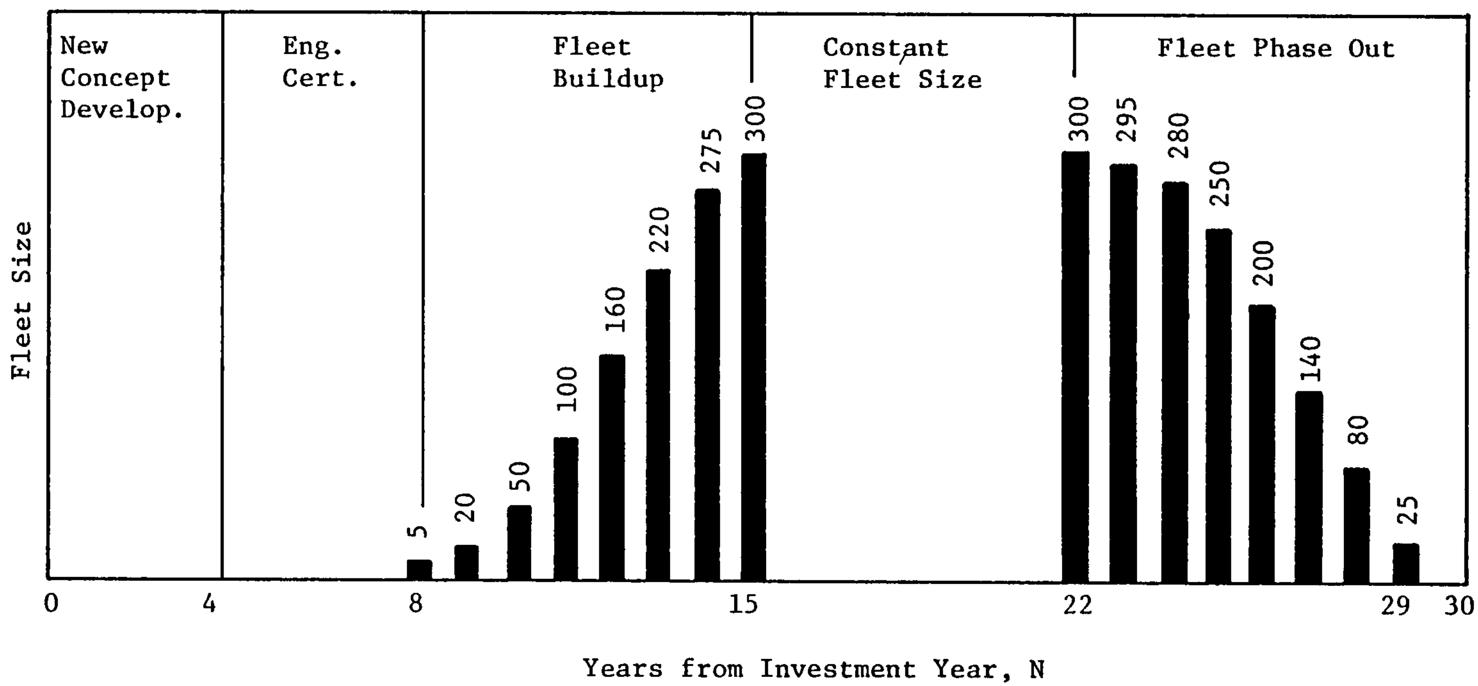


Figure 2. Aircraft Fleet Definition.

Table II. Present-Worth Example Calculation.

For 1% ΔDOC and DOC=$3840/Flight-Hour/Aircraft ($2/gal Fuel)

Year, N	No. of Aircraft	Savings in N-th Year, $ Millions	Present Worth, $ Millions
0	0	0	0
7	0	0	0
8	5	0.66	0.22
9	20	2.65	0.78
10	50	6.62	1.70
15	300	39.75	5.15
22	300	39.75	1.98
22	300	39.75	1.98
22	300	39.75	1.98
22	300	39.75	1.98
26	200	26.50	0.77
27	140	18.55	0.47
28	80	10.60	0.23
29	25	3.31	0.06
30	0	0	0
		TOTAL	52.60

1. Materials - Probability of success in meeting the property goals which are critical to the success of the technology

2. Design - Probability of success in applying the technology, including the acceptance of the technologies in a production engine

3. Manufacturing - Probability of success in producing the parts and at least closely approaching the parts cost goals

The lowest of these probabilities of success was taken as the "overall probability of success" for each technology studied. It may be argued that selection of the lowest of these probabilities as the overall "probability of success" may be overoptimistic. But, since these probability selections are so judgmental in value, it is felt that a combined probability ($P_{mat} \cdot P_{design} \cdot P_{manu}$) would have been too conservative. Instead, some conservatism was built into each probability factor and the lowest value of the three was selected.

3.7 CONCEPT RANKING

A parameter was established to compare the payoff of the technology, considering risk, to the cost to develop the technology:

$$\frac{\text{Present Worth X Probability of Success}}{\text{Initial Development Cost}}$$

If this parameter is greater than unity, and using the assumptions presented, then investment in the technology should be worthwhile.

Because of the many assumptions, the real intent of the parameter was to provide a relative ranking of the pay-back potential of the concepts studied.

4.0 TECHNOLOGY ANALYSES

The technologies selected for the final detailed analyses in the cost/benefit study, after a preliminary judgmental screening and after a preliminary cost/analysis of selected technologies, are:

1. Thermal Barrier Coatings for Combustor and HPT Airfoils
2. DS Eutectic HPT Blades, Both Cast and Fabricated
3. Titanium Aluminide Mixer, Tail Cone, and Piping
4. Fabricated Titanium Fan Blisk
5. Advanced Turbine Disk Alloy with Improved LCF Life
6. Long-Life HPT Abrasive-Tip Blade and Ceramic Shroud System.

Each technology is described and compared to the technology goals in the following paragraphs. The results of design and economic analyses are then presented.

4.1 THERMAL-BARRIER COATINGS

4.1.1 TBC in Combustor

The combustor liner, shown in Figure 3, is cooled by air impingement and air film. It currently does not utilize thermal-barrier coatings. Incorporation of thermal-barrier coating on the hot side of the liner and dome will permit an increase in parts life and/or a reduction in cooling air. In this analysis, parts life was kept constant, and all the improvement was taken as a reduction in cooling air. Since all combustor air must pass through the dome and liner, it might be assumed that there is very little penalty associated with cooling the liner. Even so, the analysis gave a somewhat surprising result because the reduced liner cooling yielded a flatter temperature profile into the turbine; this flat profile, in turn, reduced turbine cooling requirements. Fuel consumption was significantly reduced, because of the lower turbine cooling, for a very small weight and cost penalty.

Addition of TBC increases the weight of the scaled-up engine by 1.6 kg (3.5 lbm) and adds $1,100 to the selling price. Maintenance costs are uncertain, so the basic analysis was done with no increase in maintenance cost. A sensitivity study was performed to determine if maintenance could have a significant impact.

Combustor cooling flows were reduced so that, with TBC, the maximum metal temperatures were unchanged. Liner cooling flow was reduced from 17% to 14%. The reduced cooling flow was supplied as aft-panel trim dilution.

• Thermal-Barrier Coated Surfaces Indicated by Arrows

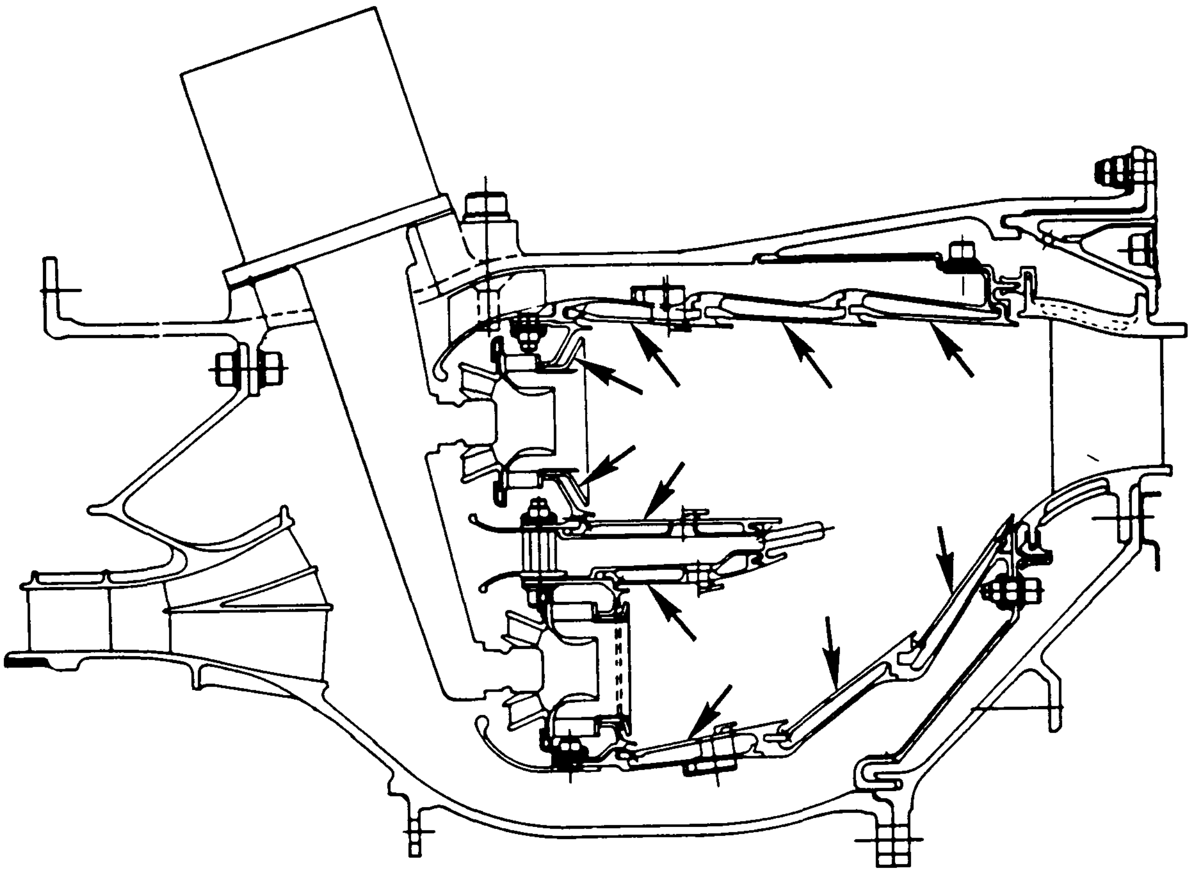


Figure 3. Thermal-Barrier Coated Surfaces in Combustor.

This dropped the pattern factor into the turbine from 1.25 to 1.21 and the profile factor from 1.125 to 1.105. In the HPT, cooling flow could subsequently be reduced in all four airfoil rows. The resulting sfc changes were as follows:

	Δsfc, %
Stage 1 Vane	- 0.0225
Stage 1 Blade	- 0.0428
Stage 2 Vane	- 0.0117
Stage 2 Blade	- 0.0520
Total sfc Improvement	- 0.13%

The economic payoffs are shown in Table III, along with a summary of the design results.

Table III. Economic Payoffs of Thermal Barrier Coating in Combustor.

Design Results

+1.6 kg (3.5 lbm) ΔWeight

+$1,100 ΔCost

Same Life

Reduced Liner Cooling

Reduced Pattern Factor and Profile Factor

Reduced Turbine Cooling Air

-0.13% Δsfc

Economic Results

$1/gal		$2/gal	
ΔDOC, %	PW, $	ΔDOC, %	PW, $
-0.11	4,000,000	-0.15	8,100,000

The effect of maintenance cost was investigated in a sensitivity analysis. The cost of stripping and recoating the combustor at 9,000 hours service was taken at $1,500 and was intended to be a high estimate. The effect on DOC and PW was determined for a range of fuel prices. This is shown in Figure 4. Maintenance cost is significant but does not substantially change the benefit due to TBC.

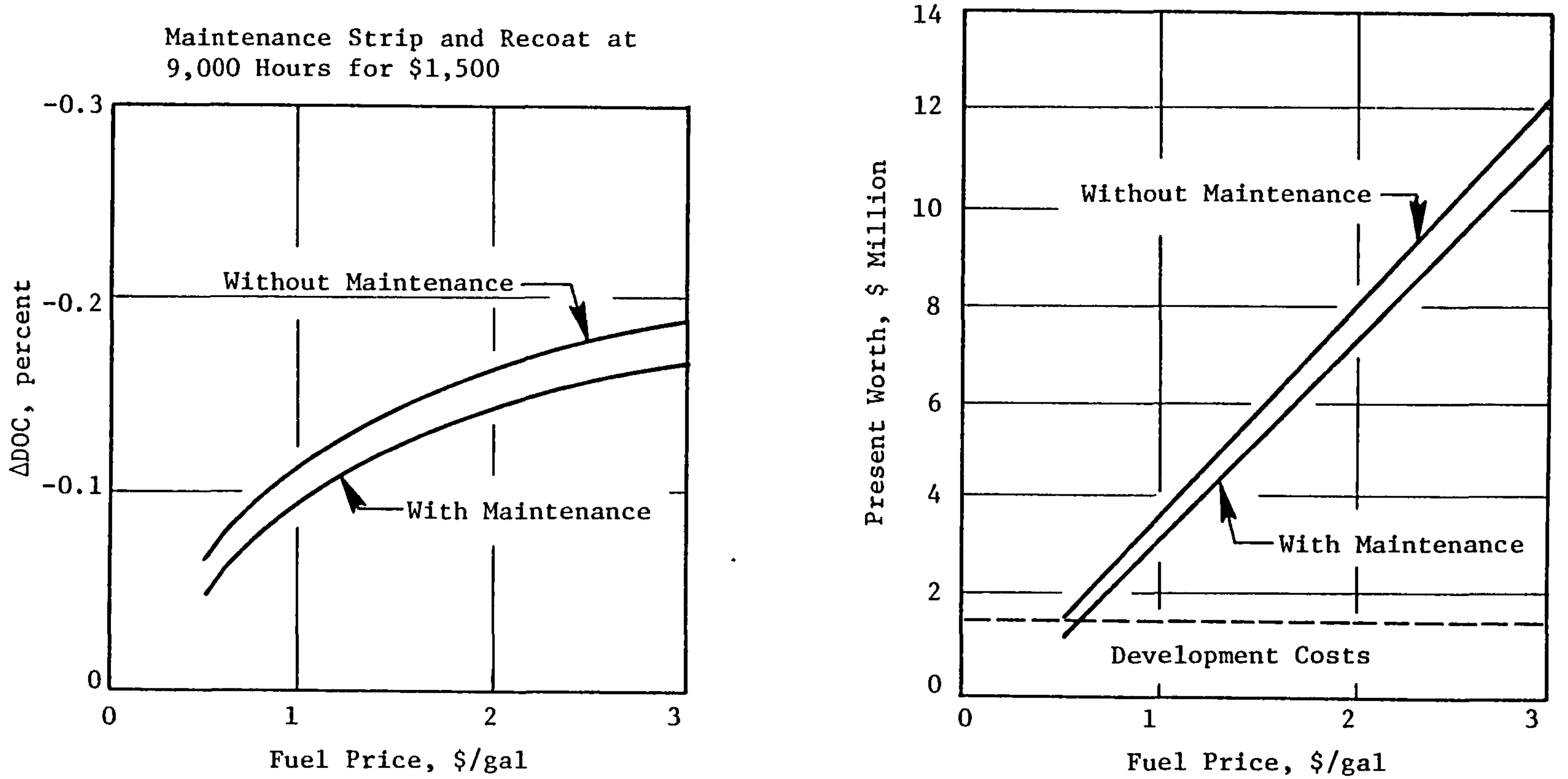


Figure 4. Effect of Thermal-Barrier Coating in Combustor on Maintenance Cost.

Material goals and the probability of meeting these goals are given in Table IV. The key goal is coating life. Where TBC is currently used in aircraft engines, design approaches do not rely upon the coating to stay intact for the life of the part to which it is applied. Therefore, the part must be cooled so it will survive if the TBC fails; this greatly reduces the performance benefit due to TBC. However, in this technology study, the TBC life is equal to or greater than the basic part life, and the full benefits due to TBC are utilized. A 65% probability of success is assessed for meeting the life goal, and this sets the probability of success for the technology. The cost to develop TBC technology is taken to be $1,550,000.

Table IV. Technical Goals for Thermal Barrier Coatings.

	% Probability of Success
Critical	
• Coating life $\geq$ 10,000 Hours	65
• Thermal Conductivity of $\leq$ 2.6 W/m-K (1.5 Btu/hr-Ft-° F) at 1367 K (2000° F)	90
• No Detrimental Loss of Fatigue Strength of Substrate	80
• TBC Part Life 2X Normal Part Life	75
• Bond-Coat Capability $\geq$ 1367 K (2000° F)	75
• Ability to Coat Over or Around Cooling Holes	80
• Surface Finish $\leq$ 0.81 μm (32 μin.) rms	80
• Ability to Strip and Recoat	80
Other	
• Ability to Spot Repair	
• Good Ballistic Impact Resistance	
Development Cost	
• $1,550,000 Shared Between Combustor and Turbine	

4.1.2 TBC In High Pressure Turbine

HPT blading in the E^3 is air-cooled by a combination of convection, impingement, and film cooling. It currently uses TBC, but (as discussed previously) the blading is cooled so that it can survive even if the TBC fails. In this study a significant reduction in cooling flow was taken, assuming the TBC lasts for the life of the part.

The HPT is shown in Figure 5. A detailed analysis was carried out for incorporation of long-life TBC on the Stage 1 vane inner and outer bands and on the Stage 1 blades. Payoffs were then extrapolated to represent the gains that would be realized if long-life TBC were applied to all vanes, bands, blades, and blade hub platforms in the HPT.

Use of TBC allowed the elimination of some film holes on the Stage 1 vane bands. The aft-overhang cooling was changed for TBC by the addition of a small amount of aft cooling through the band. Designs were executed for a range of TBC thicknesses and bond-coat temperature levels. The payoffs in terms of savings in cooling flow and the resultant reductions in sfc are given in Table V. The economic payoffs are given in Table VI. Current

Table V. Design Results for HPT Thermal-Barrier Coating.

	ΔWc, %	Δsfc, %	ΔWeight, kg (lbm)	ΔCost $
Stage 1 Nozzle Bands				
0.25-mm (0.010-in.) Thick, 1256 K (1800° F) Bond	-0.67	-0.044	+0.54 (1.2)	+1,800
0.41-mm (0.016-in.) Thick, 1256 K (1800° F) Bond	-1.00	-0.066	+0.68 (1.5)	+1,800
0.41-mm (0.016-in.) Thick, 1311 K (1900° F) Bond	-1.36	-0.090	+0.68 (1.5)	+1,800
0.41-mm (0.016-in.) Thick, 1367 K (2000° F) Bond	-1.58	-0.104	+0.68 (1.5)	+1,800
Stage 1 Blade				
Base E^3, 1256 K (1800° F) Bond	-0.35	-0.094	+5.9 (13.0)	+3,000
Inc. Film, 1256 K (1800° F) Bond	-0.55	-1.47	+5.9 (13.0)	+3,000
Base E^3, 1311 K (1900° F) Bond	-0.60	-0.161	+5.9 (13.0)	+3,000

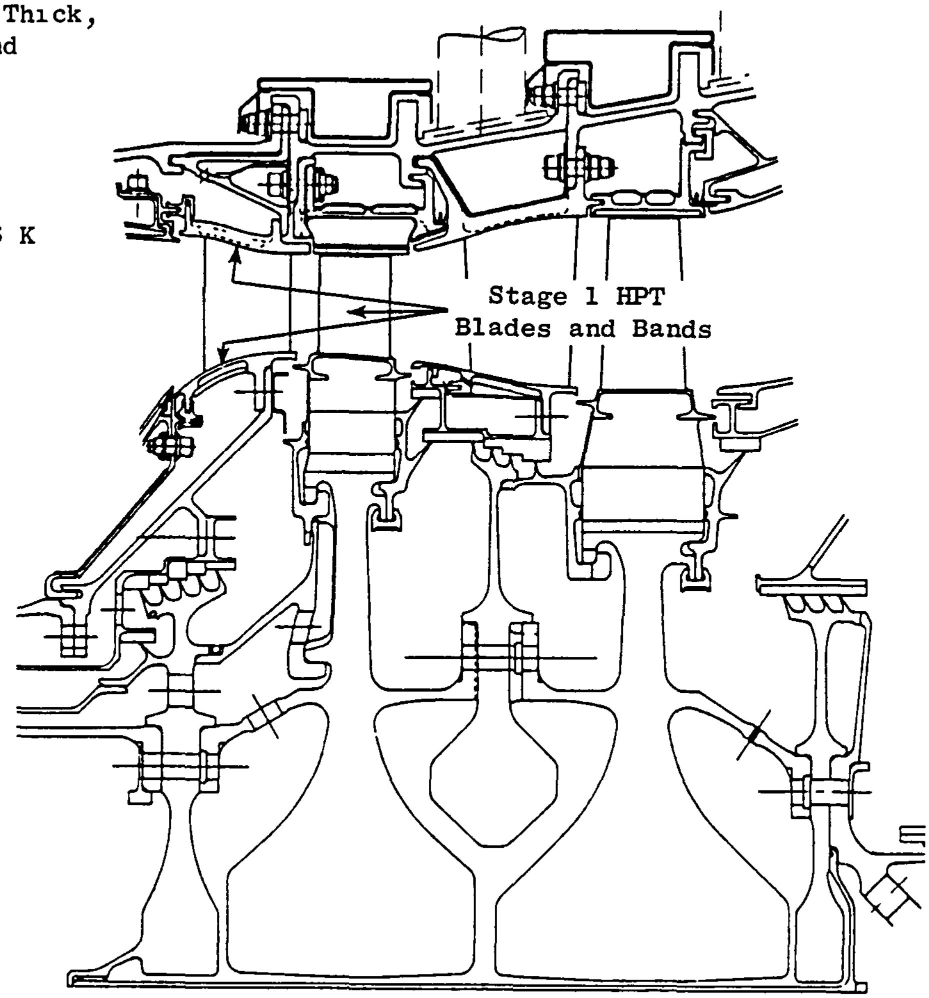


Figure 5. HPT Thermal Barrier Coating.

Table VI. Economic Results for HPT.

	$1/gal Fuel		$2/gal Fuel	
	Δ DOC, %	PW, $ Million	Δ DOC, %	PW, $ Million
Stage 1 Nozzle Bands				
0.25-mm (0.010-in.) Thick, 1256 K (1800° F) Bond	-0.03	1.3	-0.05	2.7
0.41-mm (0.016-in.) Thick, 1256 K (1800° F) Bond	-0.05	2.0	-0.08	4.1
0.41-mm (0.016-in.) Thick, 1311 K (1900° F) Bond	-0.08	2.8	-0.11	5.7
0.41-mm (0.016-in.) Thick, 1367 K (2000° F) Bond	-0.09	3.2	-0.13	6.6
Stage 1 Blade				
Base E^3, 1256 K (1800° F) Bond	-0.05	1.8	-0.07	3.9
Inc. Film, 1256 K (1800° F) Bond	-0.10	3.6	-0.14	7.5
Base E^3, 1311 K (1900° F) Bond	-0.11	4.1	-0.16	8.4

bond-coat temperature capabilities are limited to about 1311 K (1900° F); therefore, the 0.41-mm (0.016-in.) thick TBC with a 1311 K (1900° F) bond coat was selected to represent the payoffs.

Three combinations of blade cooling designs and bond-coat temperatures were studied for the Stage 1 blade. The TBC thickness was 0.41 mm (0.016 in.), and the coating thickness was 0.1 mm (0.004 in.). When these were applied all the way to the trailing edge, a substantial penalty was incurred due to trailing edge blockage. Better overall performance was obtained when TBC was terminated at the aft cooling cavity. The design using the base E^3 cooling system with a 1311 K (1900° F) bond-coat temperature limit gave best results and therefore was selected. This gave a 0.16% reduction in sfc as shown in Table V. The payoff for applying TBC to the entire HPT was taken to be the vane band payoff plus double the Stage 1 blade payoff.

4.1.3 Combustor Plus HPT TBC Payoff

The combined savings for long-life TBC in the combustor and HPT are:

	%Δ sfc	%Δ DOC $2/gal Fuel	$ Million Worth at $2/gal Fuel
Combustor	- 0.13	- 0.15	8.1
HP Turbine	-(0.09 + 2 x 0.16)	-(0.11 + 2 x 0.16)	5.7 + 2 x 8.4
Total	- 0.54	- 0.58	3.6

This gives a ranking parameter of:

$$\frac{\text{Present Worth x Probability of Success}}{\text{Development Cost}} = \frac{30.6 \times 0.65}{1.55} = 13$$

4.2 DS EUTECTIC HPT BLADING

DS eutectic blading has the potential to operate at about 55.6 K (100° F) higher metal temperatures than the René 150 HPT blading currently used in the E^3. Payoffs were determined for substituting DS eutectic blading in the current engine design. Turbine inlet temperature was not changed, and blade life was held constant. Cooling air was reduced, and this gave better fuel consumption.

Material property goals, probabilities of success, and projected development costs are given in Table VII. An alternative approach would be to design an entirely new engine for the material. A newly optimized engine would have a higher turbine inlet temperature, higher cycle pressure ratio, and a smaller core. Such an approach would yield even more attractive sfc plus substantially reduced weight compared to the study carried out here.

DS eutectic materials are expected to be very expensive and have a high payoff when fuel is expensive, but a poor payoff if fuel prices are low.

4.2.1 Stage 1 Blade

Four different designs were investigated for the Stage 1 rotating blade (Figure 6). The airfoil cross sections are shown in Figure 7, along with schematic side views of cooling-flow circuits. The first one is the current E^3 cooling design executed for the better material. Next, the two-piece-fabricated design allows a better cooling configuration but has higher production costs. It provides easy access to treat surface carbides inside the blade if this is necessary. The increased film design explored the payback of using a more advanced cooling design with the better material. A comparison between this design and the present E^3 design gives the effect of a cooling-technology difference and a material difference. Therefore, it is not a candidate for representing the benefits of DS eutectic materials. A

Table VII. Technical Goals For DS Eutectic Turbine Blades (Ni84XB).

	% Probability of Success
Critical	
• Rupture Strength, Coated: 141 K (225° F) > René 80, Coated	75
• Strain Cycle LCF Life at 0.5% for 922-1256 K (1200°-1800° F) Nf $\geq$ 100X René 80	90
• Coating: 500 Hours Life to 1422 K (2100° F), Recoatable	75
• HCF Strength: $\geq$ 1.5X René 80 at A=1, 1033-1367 K (1400°-2000° F)	70
Others	
• Hot-Corrosion and Oxidation Resistance: = René 125	
• High-Temperature Stability: After Long-Time Stressed Exposure no Phase Formation That Causes Drastic Reductions in Strength and/or Ductility	
Development Cost	
• <u>\$4,200,000 Solid</u> + <u>\$1,650,000 Fabricated</u>	

- Cast or Fabricated, Replace René 150

- Base E^3 Stage 1
- Two-Piece, Fabricated
- Increased Film Cooling
- Base + 1.7 Taper Ratio

- Base E^3 Stage 2
- Uncooled, Hollow
- Radial Hole I
- Radial Hole II

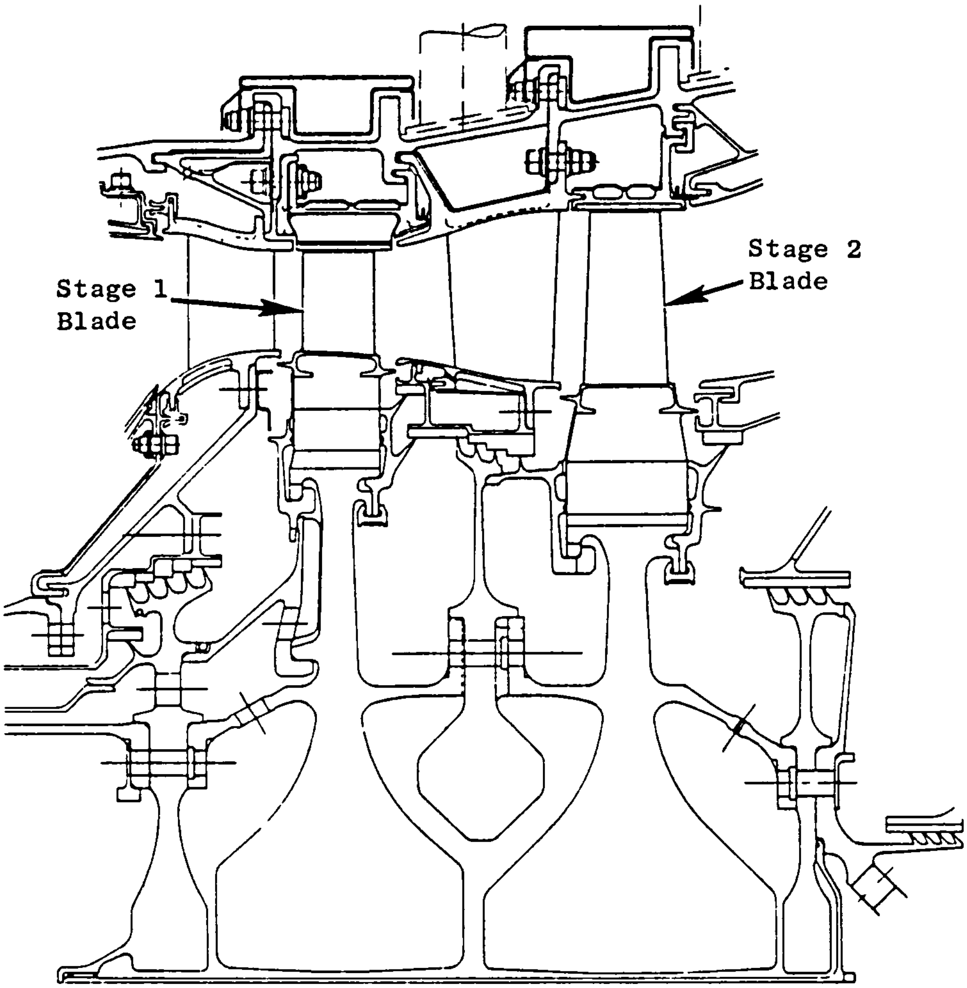


Figure 6. DS Eutectic HPT Blades.

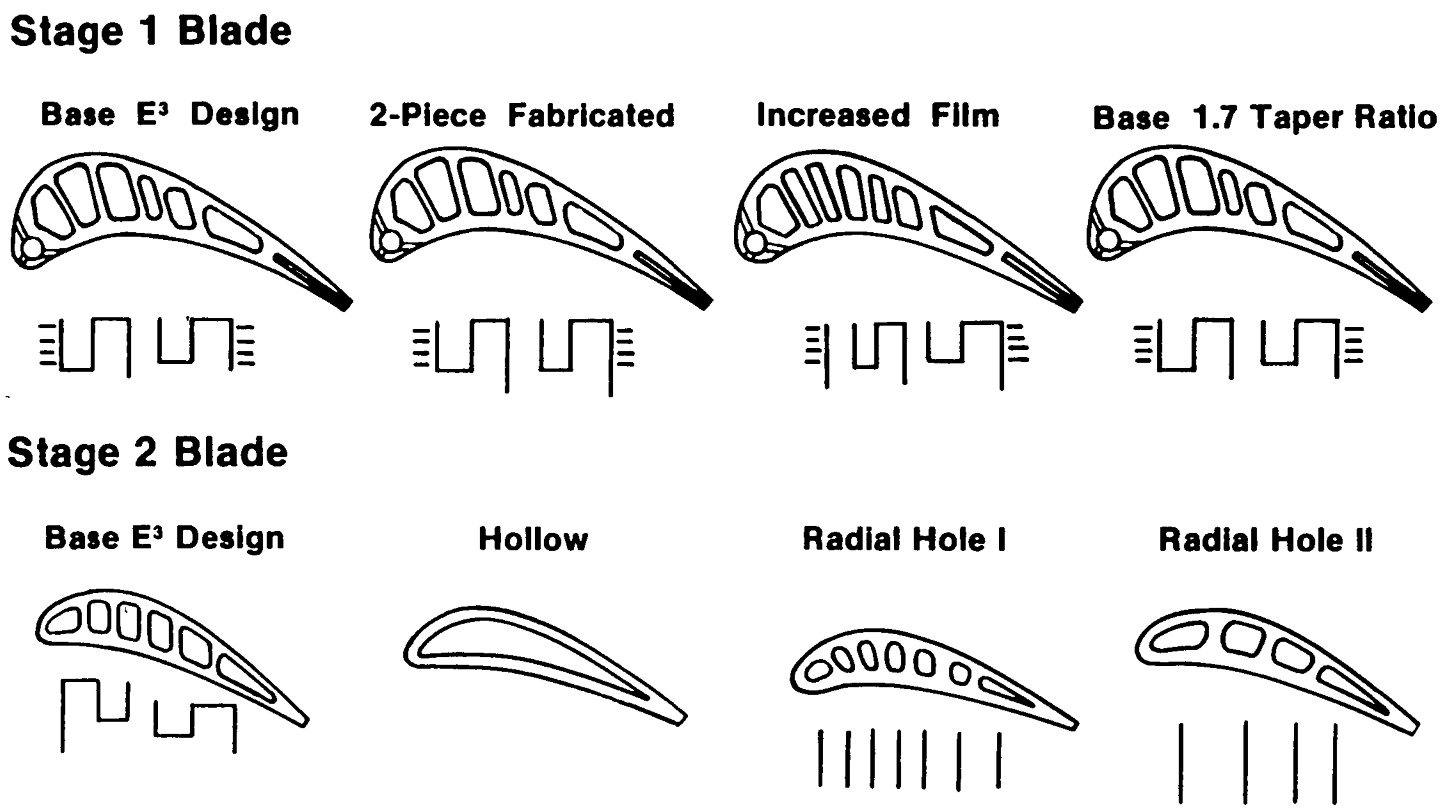


Figure 7. DS Eutectic HPT Blading Cooling Designs.

conventional cooling design with increased hub to tip cross-sectional area taper was also explored. It did not turn out as good as the base DS eutectic design.

Payoffs for the four designs are shown in Tables VIII and IX. For $2/gal fuel, the base design gives the best economic payoff (disregarding the improved-cooling design). The base design, therefore, is taken to represent the application of DS eutectic materials to the Stage 1 blade.

Table VIII. DS Eutectic HPT Stage 1 Blade Design Results.

	ΔW_C, %	Δsfc, %	ΔWeight, kg (lbm)	ΔCost, $
Base E^3 Design	-0.9	-0.24	2.3 (5.1)	52,000
2-Piece-Fabricated Design	-1.2	-0.32	2.3 (5.1)	181,000
Increased-Film Design	-1.4	-0.39	2.3 (5.1)	120,000
1.7 Taper Ratio Design	-0.9	-0.24	4.4 (9.7)	52,000

Table IX. DS Eutectic HPT Stage 1 Blade Economic Results.

	$1/gal Fuel		$2/gal Fuel	
	ΔDOC, %	PW, $ Million	ΔDOC, %	PW, $ Million
Base E^3 Design	-0.12	4.3	-0.23	12.0
2-Piece-Fabricated Design	+0.03	0.	-0.17	9.1
Increased-Film Design	-0.13	5.0	-0.34	17.7
1.7 Taper Ratio Design	-0.11	3.9	-0.21	11.2

4.2.2 Stage 2 Blade

Four cooling designs were investigated for the Stage 2 blade. These are also shown on Figure 7. First, the current E^3 design was executed for the better material. Second, an uncooled blade was attempted. This required a tapered, hollow core to keep stresses within allowable limits. Such a blade was found to be feasible. In addition, designs were explored which used very simple, radial, cooling passages. Two sizes of holes were considered. The uncooled design gave the best payoff, as shown on Tables X and XI.

Table X. DS Eutectic HPT Stage 2 Blade Design Results.

	ΔW_C, %	Δsfc, %	ΔWeight, kg (lbm)	ΔCost $
Base E^3 Design	-0.5	-0.21	+2.2 (4.8)	+60,000
Uncooled, Hollow Design	-0.76	-0.31	+2.8 (6.1)	+60,000
Radial Hole I Design		(No Payoff)		
Radial Hole II Design		(No Payoff)		

Table XI. DS Eutectic HPT Stage 2 Blade Economic Results.

	$1/gal Fuel		$2/gal Fuel	
	ΔDOC, %	PW, $ Million	ΔDOC, %	PW, $ Million
Base E^3 Design	-0.08	2.8	-0.18	9.5
Uncooled, Hollow Design	-0.16	6.1	-0.30	16.0
Radial Hole I Design		(No Payoff)		
Radial Hole II Design		(No Payoff)		

4.2.3 Combined Payoff

A development cost of $4.2 million was used for the basic material technology and an additional $1.65 million for technology to fabricate blades. Because it is not known if the material could be used without fabrication, both were included in the development cost. This technology was given a 70% probability of success.

The ranking parameter, for $2/gal fuel, therefore, turns out to be:

$$\frac{\text{Present Worth x Probability Of Success}}{\text{Development Cost}} = \frac{(12 + 16)\ (0.7)}{(4.2 + 1.65)} = 3$$

4.2.4 Production Cost Sensitivity Study

At the time of the study, the sources of the rhenium used in the DS eutectic materials were undergoing extreme price fluctuations. Prices ranged from $200/lbm to $3000/lbm for some projections. A price of $800/lbm was used for these studies. In addition, a 50% revert recovery and a 60% casting yield were assumed.

Because of the rhenium price uncertainty at the time, and because of the high cost of DS eutectic blading, a sensitivity analysis was made for production costs for the Stage 1 blade. Economic payoffs were evaluated for the base cost increase attributable to DS eutectic materials over the current René 150 materials, for half that cost increase, and for double that cost increase. The results are shown in Figure 8. At lower fuel prices, around $1/gal, an escalation of production costs can cancel the benefits due to the material. At $2/gal, production costs are very important, but there still is a good payback for investment in the technology even if costs escalate substantially. If fuel prices should rise to $3/gal (in 1980 dollars), the payoff for the better material is so large that production costs are no longer a major factor.

4.3 TITANIUM ALUMINIDE

Titanium aluminide is a potentially very attractive material. It has good strength at higher temperature and is very light. However, it is brittle (especially when cold) and, as a subjective consideration, has experienced very little practical application. It potentially has broad applications, including casings, vanes, blades, fasteners, disks, tubing, and sheet. Because of its restricted ductility, only two applications were selected wherein a failure in the material would not be catostrophic to the engine. The sheet metal structures of the mixer and tail cone were one application, and the tubing external to the core was the other.

Material goals, probabilities of success, and estimated development cost are given in Table XII.

4.3.1 Mixer and Tail Cone

The E^3 uses a long fan duct with a mixer to forceably mix the cold fan stream and hot core stream before they expand through the exhaust nozzle. The mixer and tail cone are blocked out in the engine cross section shown in Figure 9. They are shown in more detail in Figure 10.

Ti_3Al was substituted for Inco 718 in the mixer; this saved 50% of the mixer weight. In the tail cone, or centerbody, Ti_3Al was substituted for Inco 625; this saved 42% weight. There is a cost increase for Ti_3Al and no specific fuel consumption change. The effects are shown in Table XIII.

Development cost was taken as $1.4 million at a 60% chance of success. Broader application of the material would, of course, distribute the cost over a wider base. The ranking parameter becomes:

$$\frac{\text{Present Worth x Probability Of Success}}{\text{Development Cost}} = \frac{6.0 \times 0.6}{1.4} = 2.6$$

Titanium aluminide, therefore, is a technology that does not require a massive development investment and provides a good return for the investment.

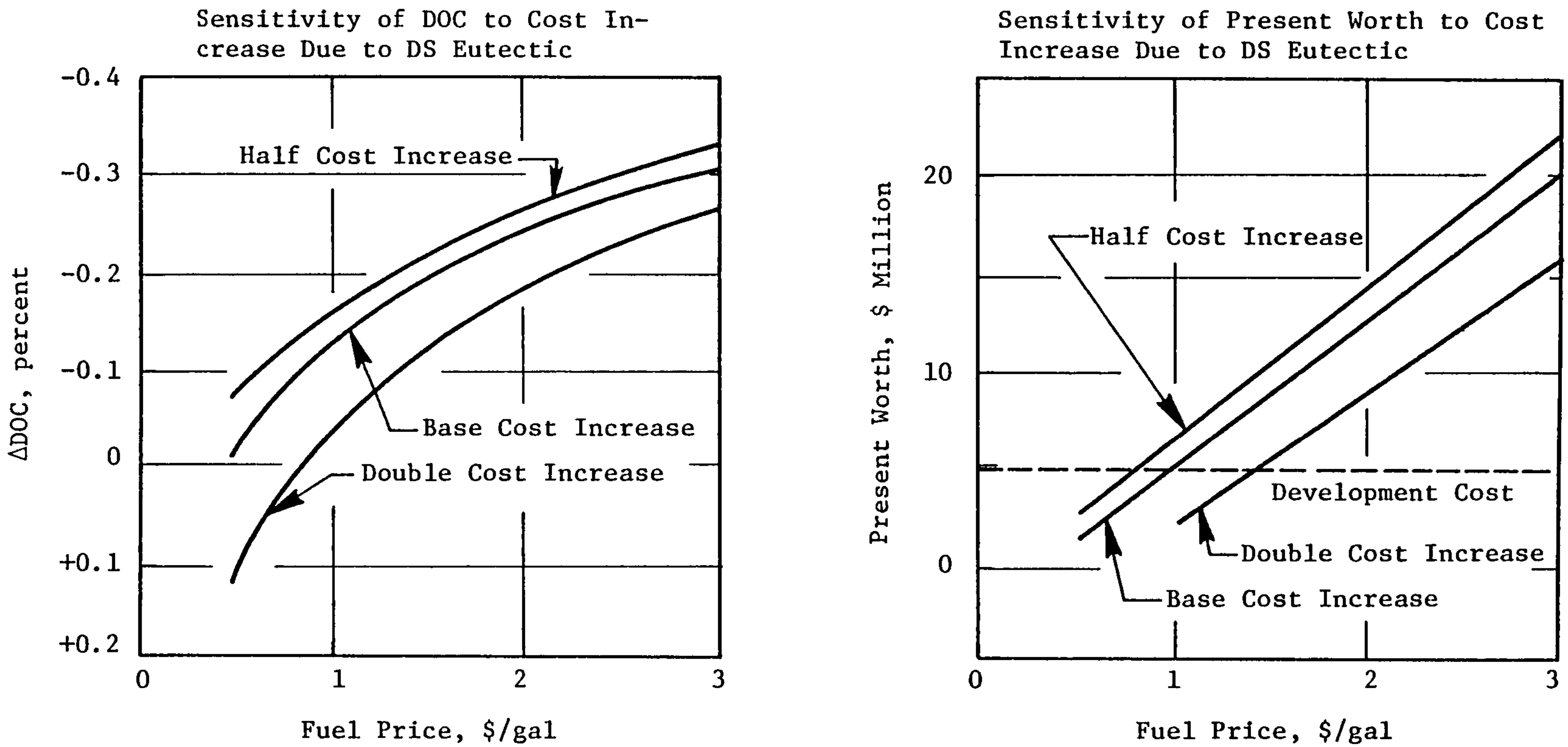


Figure 8. Production Cost Sensitivity for DS Eutectic HPT Blading.

Table XII. Titanium Aluminides (Ti_3Al) Technical Goals.

	% Probability of Success
Critical	
• Mechanical Properties	60
Ultimate Tensile Strength (UTS) $\geq$ 324 MPa (47 ksi) at 1117 K (1550° F)	
Stress Rupture (SR) $\geq$ 207 MPa (30 ksi) at 1117 K (1550° F) for 2000 hours	
Tensile Ductility - Room Temperature to 1117 K (1550° F)	
2% Elongation	
3% Reduction in Area	
• Low and High Cycle Fatigue Comparable to Cast René 77	60
• Usable Without Coating to 978 K (1300° F)	60
Development Cost	
• $1,400,000	

Table XIII. Ti_3Al Mixer and Tail Cone Design and Economic Results.

Design Results

- −20 kg (44 lbm) ΔWeight
- +$14,800 ΔCost
- 0 Δsfc

Economic Results

$1/gal Fuel		$2/gal Fuel	
ΔDOC, %	PW, $ Million	ΔDOC, %	PW, $ Million
−0.07	2.5	−0.11	6.0

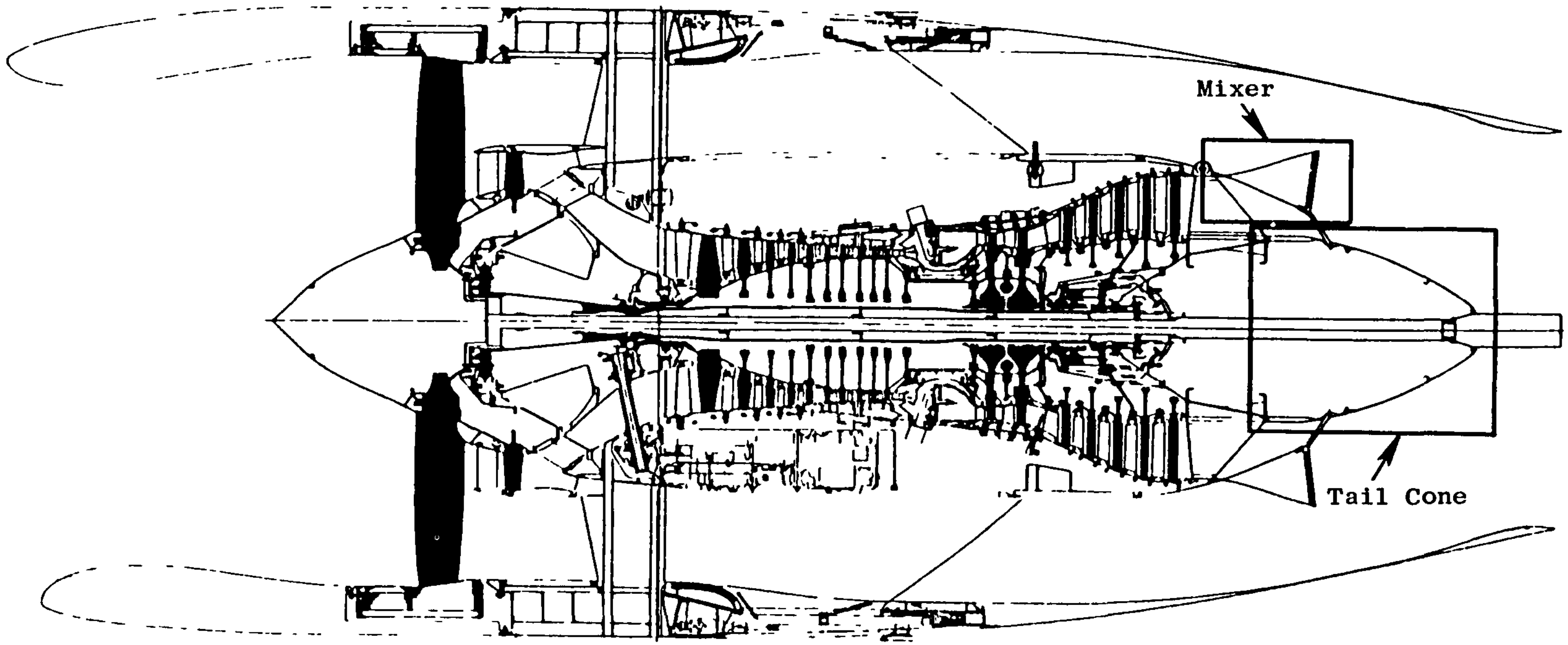


Figure 9. Mixer and Tail Cone.

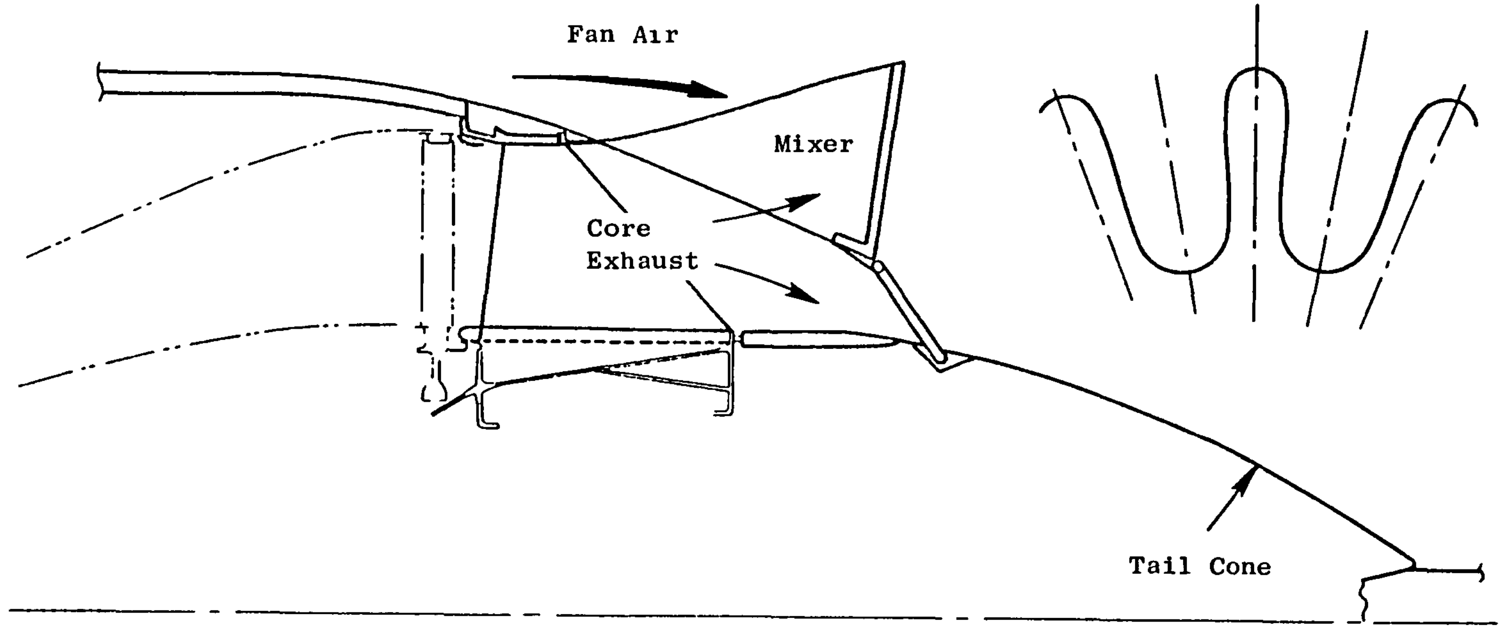


Figure 10. Titanium Aluminide Sheet Mixer and Tail Cone.

4.3.2 Tubing

Titanium aluminide has good strength capabilities at the temperature levels found in engine tubing. Modern, commercial engines have complex tubing systems for multiple-source turbine cooling, active clearance control, customer bleed, and starting bleed. Most of the core-case-mounted tubing for the E^3 is shown in Figure 11. In a large, commercial engine the tubing and manifolding weight can approach 90.7 kg (200 lbm). Titanium aluminide tubing could provide a major weight savings, in the order of 13.6 to 22.7 kg (30 to 50 lbm).

Although it offered desirable strength and weight properties, titanium aluminide was judged not appropriate for use in tubing. Tubing is subjected to stress cycling by alternating pressure, differential thermal growth, and vibration loads. The materials must be selected so that the yield stress is low enough to preclude excessive fatigue stresses. Inco 625 and 321 stainless steel are commonly used. Experience has led to the requirement that the tubing be capable of being flexed practically indefinitely without failing. Titanium aluminide, because of low ductility, does not meet this design requirement.

4.4 FABRICATED FAN BLISK

Integral fan blades and disks, called blisks, have been used successfully in some smaller applications. The payoff for using a fabricated fan blisk in a large, commercial turbofan was determined in this study.

The materials and fabrication technology advancement was aimed at bonding large, hollow, titanium fan blade halves together and then bonding them to a titanium disk. This produces a very large structure, 2 m (7 ft) in diameter. The necessary technology goals are given in Table XIV along with the associated probabilities of success.

To use blisk construction, an alternate fan design was used. This was a Wennerstrom-type fan design. It uses fewer blades (20 compared to 32 in the base E^3 design), much larger chords, and no shroud dampers. The base E^3 design uses one fan stage plus a quarter-stage booster; the Wennerstrom-type fan did not require the booster stage. The two designs are compared on Figure 12. Mechanical details of the base design are shown in Figure 13. The blisk is shown in Figure 14. The Wennerstrom-type fan has better aerodynamic performance than the current fan.

Execution of the blisk design revealed that the fan disk is geometry limited rather than stress limited. Because of this, the material could not be efficiently utilized, and the design was heavy. In the E^3 size, the blisk weight was 688.1 kg (1517 lbm) compared to 458.1 kg (1010 lbm) for the base-design fan and booster. Some additional weight would be added to the blisk blade-containment system to handle the heavier blades. The blisk fan provides a 0.3% sfc advantage that is worth 31.8 kg (70 lbm). The net result was that the fabricated blisk was about 226.8 kg (500 lbm) heavier than the

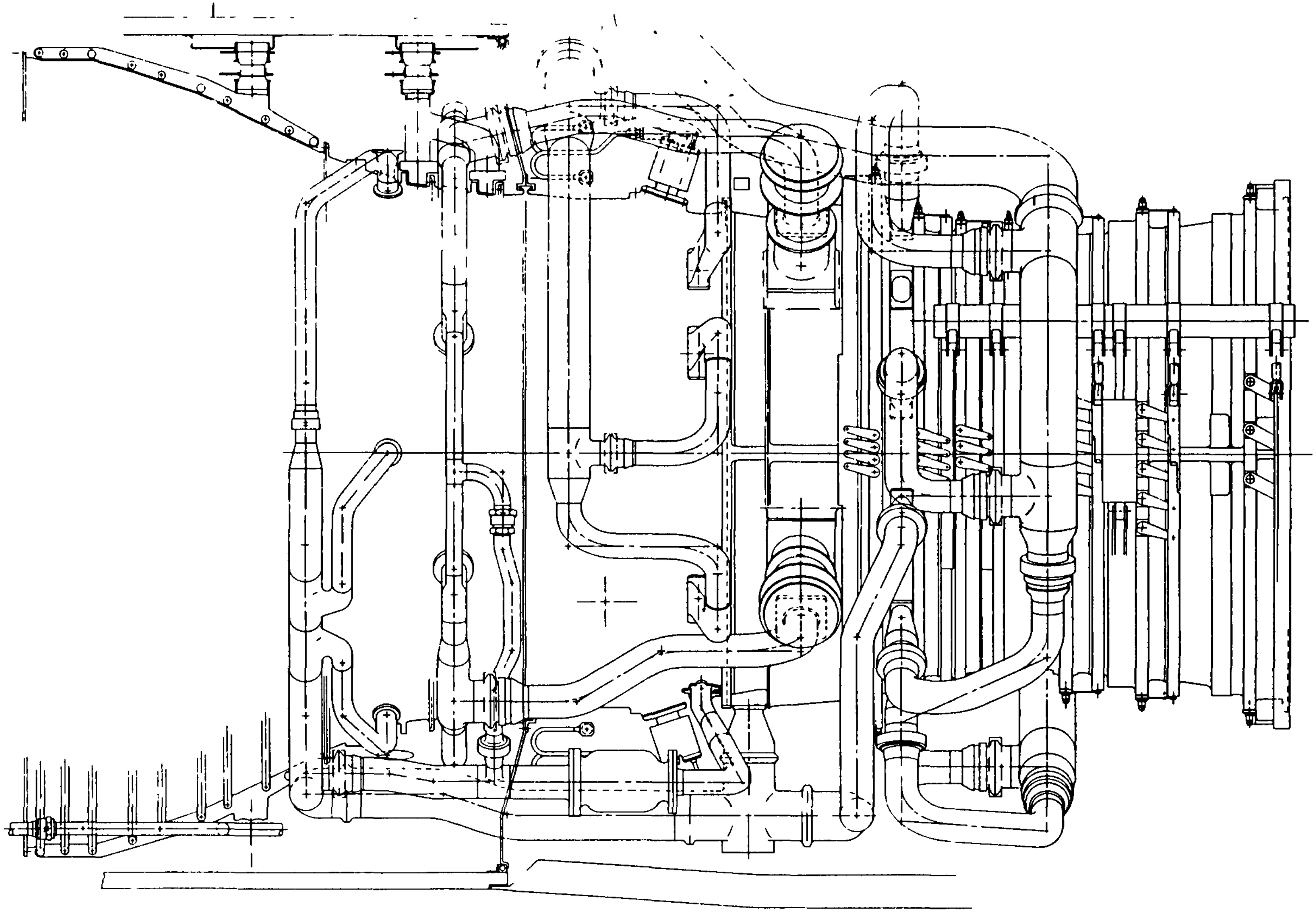


Figure 11. E^3 Core-Case-Mounted Tubing.

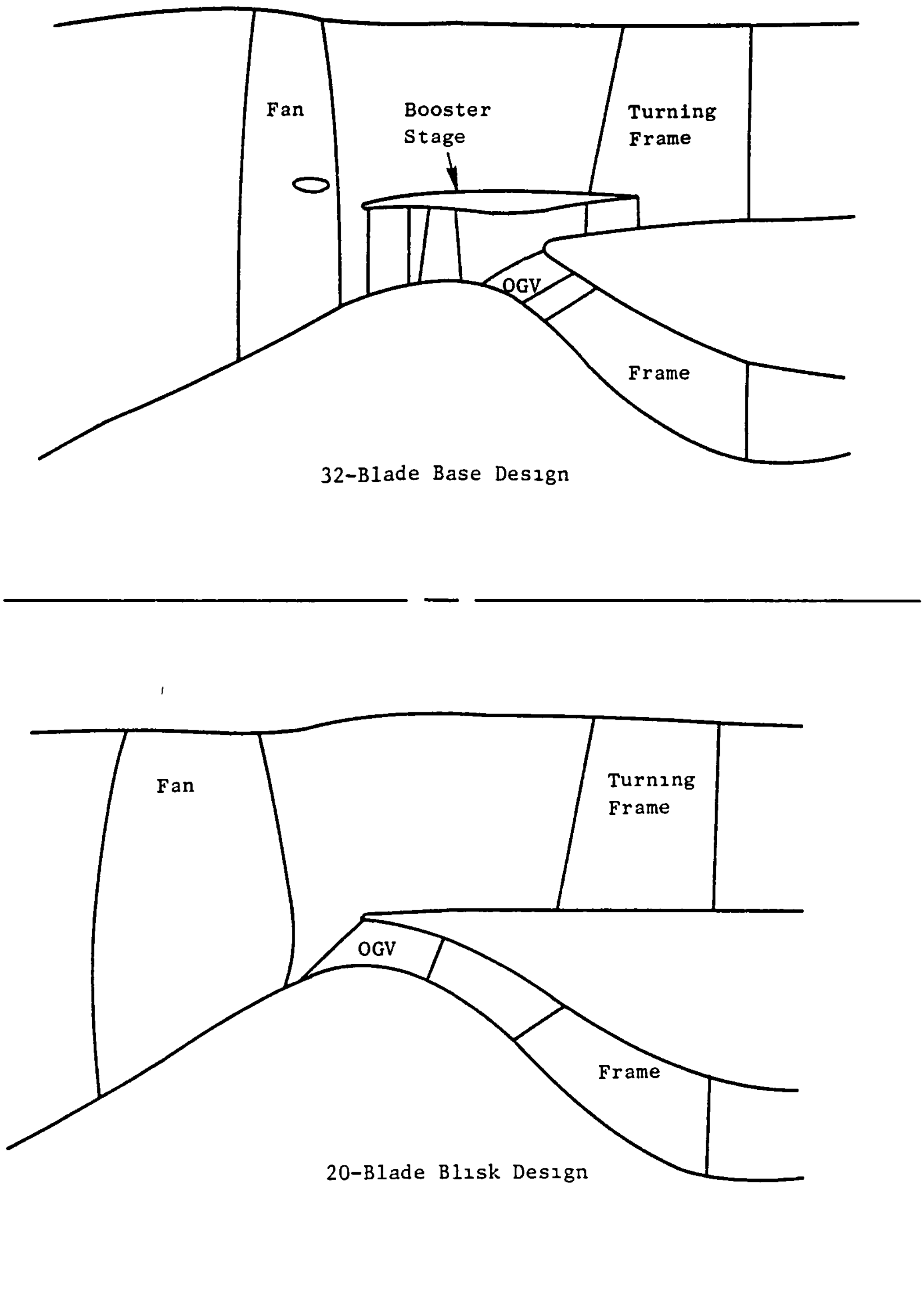


Figure 12. Comparison of Base and Blisk Fans.

	Blisk	Conventional
No. of Blades	20	32
Part-Span Shroud	No	Yes
Booster Stage	No	Yes

Blisk Construction: Two Hollow Blade Halves Bonded Together, Then Bonded to Disk

E^3 Construction: Conventional, Solid Blades and Separate Disk

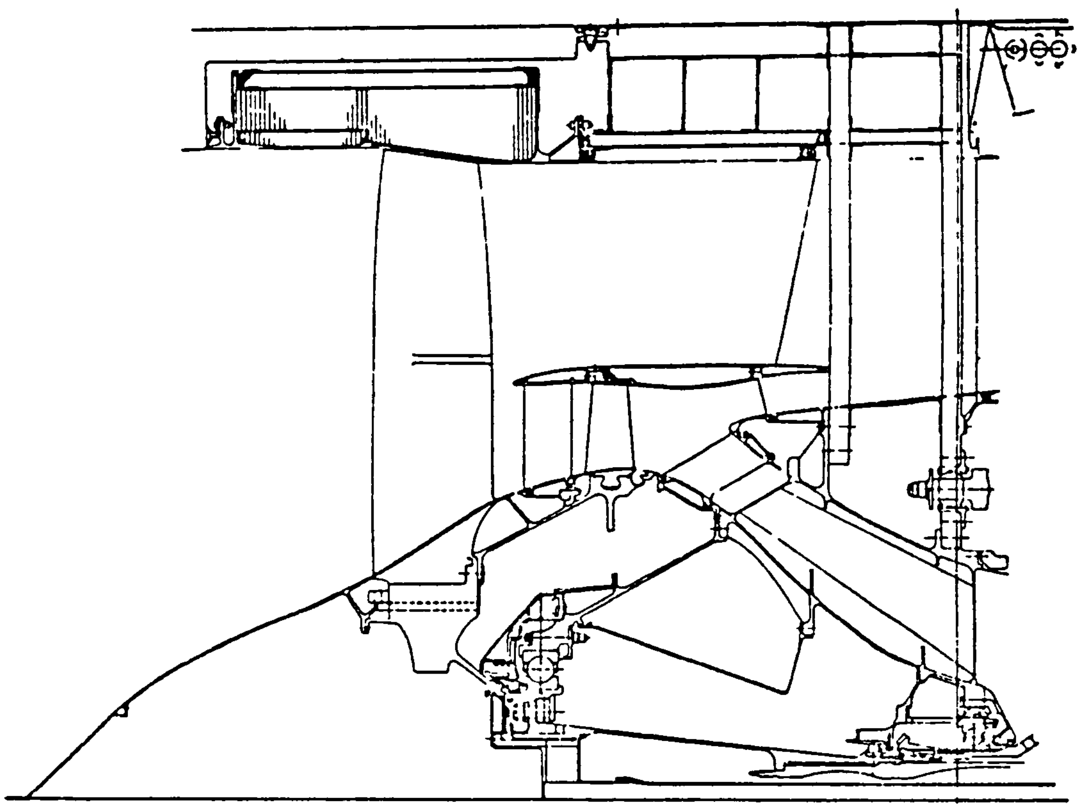


Figure 13. Base Fan Mechanical Design.

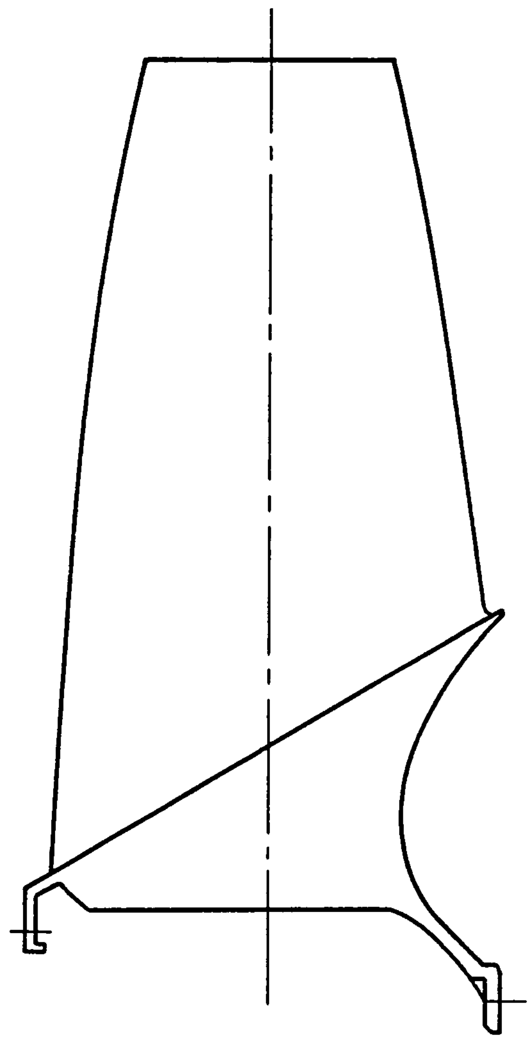


Figure 14. Blisk Mechanical Design.

Table XIV. Pressure-Bonded Titanium Fan Blisk Technical Goals.

	% Probability of Success
Critical	
• Parent Material (Titanium 6 Al-4V) Tensile and High-Cycle Fatigue Strength in Solid-State Joint	80
• Capability to Join Finish Airfoil Blades Except at Joint Area to Disk	70
• Capability to Join 0.0065 m^2 (10 $in.^2$) Area	50
• Develop Nondestructive Inspection Technique to Assure Joint Quality	40
• Control Joint Upset For Accurate Radial Position of Blade With Respect to Disk	95
Other	
• Hollow Blades (to 80% of Blade Length and 33% of Blade Average Thickness) by Diffusion Bonding	
• Solid-State Joint Low Cycle Fatigue Strength $\geq$90% of Parent Material	
• Solid-State Joint Room Temperature Fracture Toughness $\geq$95% of Parent Material	

base design and did not offer an improvement. Further work on the blisk was, therefore, terminated pending new design approaches.

4.5 IMPROVED LCF LIFE HPT DISK ALLOY

Typical turbine disks are highly stressed, heavy, and expensive. Materials technology for disks has been and will continue to be critical to the aircraft engine industry.

The E^3, used as the study vehicle for this program, is characterized by high core speed and very high life, 36,000 cycles. The HPT disks (see Figure 5) are massive, René 95 structures. The disks are LCF-life limited at the bore and are yield limited in the web.

For this study, a disk material was postulated that had the same properties as René 95 except it had double the LCF life. The life curves for René 95 and the advanced alloy are given in Figure 15. Because of the high life

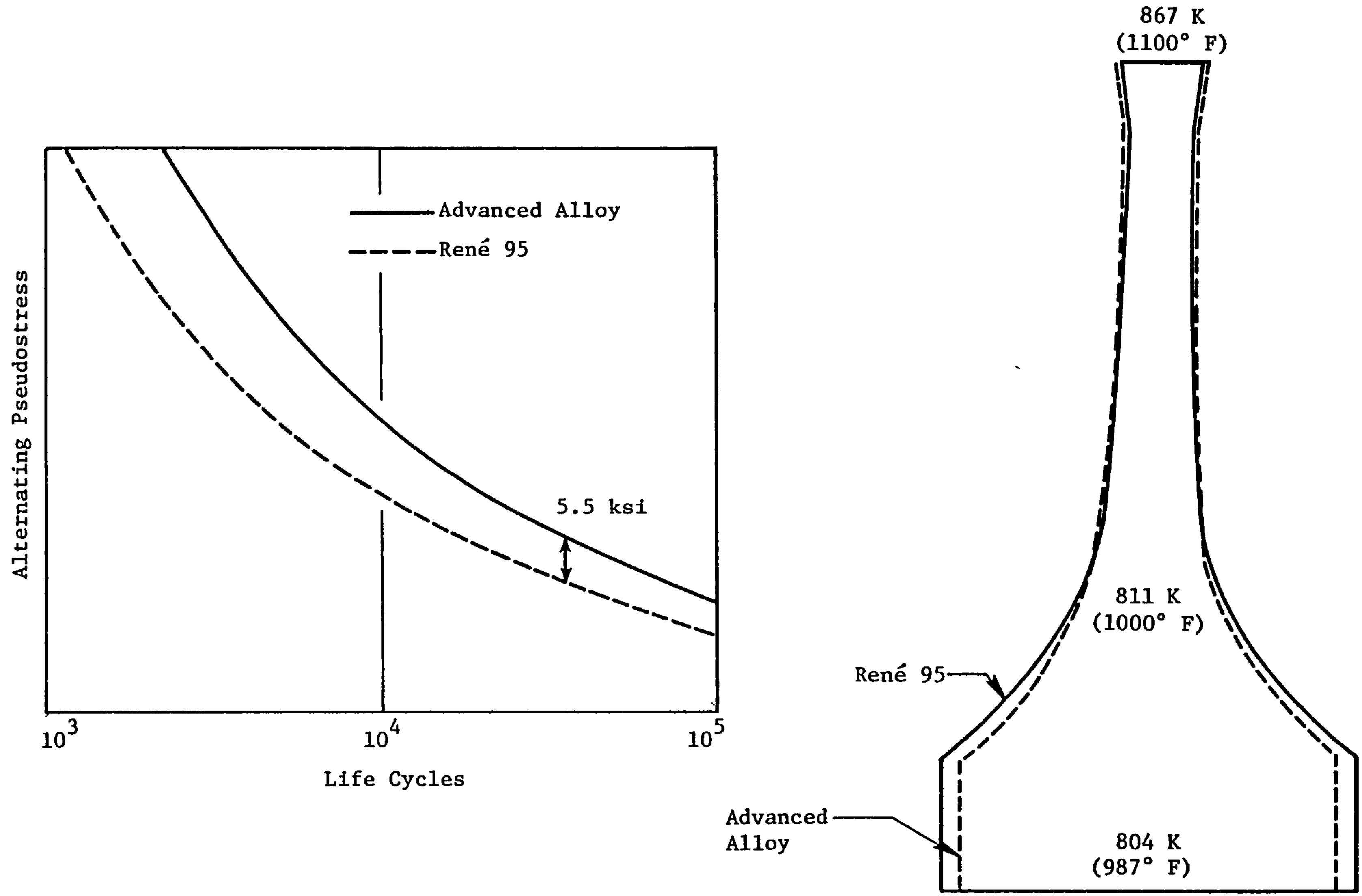


Figure 15. Advanced Disk Material.

levels, doubling LCF life only allows a 38 MPa (5.5 ksi) stress increase. A Stage 1 disk design was executed using the advanced material.

Results of the design analysis were unexpected. The improved material resulted in a very small weight saving, 2.3 kg (5 lbm) or 3.6%. In the bore, where the disk was LCF limited, stress levels could be increased and the bore made narrower. This increased stress levels in the web of the disk. Since the web was yield limited, the web had to be thickened. This nearly cancelled the benefits at the bore. The two disks are superimposed on Figure 15. Since no significant gains were achieved, the advanced disk material study was dropped.

These results should not be assumed to generally apply to all engines. First, the study engine has an exceptionally long-life design, possibly not characteristic of most engines. Next, a different balance of material properties, where some LCF life would be traded for better yield strength, might have produced better results. Also, disks which are more generally LCF limited rather than yield limited would show better payoffs. Then, of course, if an existing disk is LCF deficient, there would be an obvious benefit for better life.

4.6 ABRASIVE-TIP BLADE AND SHROUD SYSTEM

Clearance over the tips of the HPT blades has a very strong impact on fuel consumption. Therefore, if fuel prices are high enough, even extreme measures to keep clearances tight are attractive. For instance, a complex, heating/cooling, active-clearance-control system has been incorporated into the E^3. Mounting and bearing systems are selected to minimize deflections and, therefore, improve tip clearances. An additional means for improving tip clearances is to use abrasive tips on blades so they can wear into the shrouds.

In this study, the benefits were determined for abrasive tips on blades in the HPT. These run against a ceramic zirconium oxide (ZrO_2) shroud in Stage 1 and a solid Genaseal shroud in Stage 2. The blade tips and shrouds can be seen in Figure 5. By wearing the shroud rather than the blade tips, local tight areas can be worn open. In conventional designs, a local tight area would rub down all blade tips and, therefore, open up the clearance around the entire wheel. Local tight areas are caused by shaft-to-casing eccentricity resulting from manufacturing tolerances, by out-of-roundness resulting from manufacturing, and by ovalizations and deflections resulting from operational loads.

The necessary technical goals are listed in Table XV along with the probabilities of success and development cost. Use of abrasive-tip blades improves radial clearance by an average of 0.1 mm (0.004 in.) in both stages. This is worth a 0.19% reduction in sfc. The economic benefits are given in Table XVI.

The resulting ranking parameter is:

$$\frac{\text{Present Worth x Probability Of Success}}{\text{Development Cost}} = \frac{11.4 \times 0.5}{1.4} = 4$$

Table XV. Abrasive-Tip Blades Technical Goals.

	% Probability of Success
Critical	
• Able to Abrade Shroud Material For Life of Blade Tip	50
• Thermal Fatigue Resistance Blade Tip Alloy	50
• Oxidation/Corrosion Resistance 2X of Blade Alloy	80
• Strength Levels $\geq$ Than Tip Requirements	80
• Compatible Shroud Material	60
Other	
• Quality Assurance of Attachment Process	
Development Cost	
• \$1,400,000	

Table XVI. Abrasive-Tip Blade Design and Economic Results.

Design Results

- -0.1 mm (0.004 in.) ΔRadial Clearance - 2 Stages
- +2.4 kg (5.3 lbm) ΔWeight
- +\$8,600 ΔCost
- -0.19% Δsfc

Economic Results

\$1/gal Fuel ΔDOC, %	\$1/gal Fuel PW, \$ Million	\$2/gal Fuel ΔDOC, %	\$2/gal Fuel PW, \$ Million
-0.15	5.4	-0.22	11.4

5.0 DISCUSSION AND RANKING OF TECHNOLOGIES

Potential development technologies can be ranked to establish where development investments are most likely to be productive. The basic ranking parameter is a comparison of the potential payoff to the investment required to develop the technology. In this study, the ranking parameter

$$\frac{\text{Present Worth x Probability of Success}}{\text{Initial Development Cost}}$$

was used. Additional considerations may influence which technologies are selected for development:

- Likelihood of failure and acceptability of failure
- Timing
- Needs of the business
- Magnitude of funding available compared to the funding required
- Tie-in with other programs
- Acceptance by the industry

A summary of the economic payoffs, development costs, risks, and ranking parameters is presented in Table XVII. For the assumptions made, thermal-barrier coating definitely provides the highest return. Thermal-barrier coating requires only a moderate investment and offers a superior payback. It is a key technology. The remaining technologies have roughly comparable paybacks.

DS eutectic payoffs are highly dependent on fuel price. It is a high dollar investment but may be essential if fuel prices escalate.

Titanium aluminide has broad potential applications. Even for the limited applications investigated, a good payback was projected. Assuming that designs are developed to accommodate the lower ductility, titanium aluminide should be considered a high-potential technology.

Abrasive-tip turbine blades were projected to yield a very good payback. Blade and shroud materials are rapidly changing technologies. Development of abrasive tips would provide a key contribution in this area.

Table XVII. Summary of Economic Payoffs.

	Initial Develop. Cost, $ Million	Probab. of Success, %	$1/gal Fuel		$2/gal Fuel		Relative Ranking Parameter
			ΔDOC, %	PW, $ Million	ΔDOC, %	PW, $ Million	Present Worth x Prob. Of Success / Initial Development Cost
Thermal-Barrier Coating							
Combustor			-0.11	4.0	-0.15	8.1	
HP Turbine			-0 30	11.0	-0.43	22.5	
Total	1 55	65	-0.41	15.0	-0.58	30.6	12
DS Eutectic HPT Blading							
	5 85	70	-0 28	10.4	-0.53	28.0	3
Titanium Aluminide							
Mixer and Tail Cone	1 4	60	-0 70	2.5	-0 11	6 0	3
Tubing						---	Dropped
Fabricated Fan Blisk							Dropped
Improved LCF Life HPT Disk							Dropped
Abrasive-Tip Blade Shroud System	1 4	50	-0.15	5.4	-0 22	11.4	4

End of Document