NASA CR-159449

NASA

JT8D AND JT9D JET ENGINE PERFORMANCE IMPROVEMENT PROGRAM– TASK 1, FEASIBILITY ANALYSIS - FINAL REPORT

by
W. O. Gaffin and D. E. Webb

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
Commercial Products Division

Prepared for

National Aeronautics and Space Administration
NASA Lewis Research Center
Contract NAS3-20630

1. Report No	2 Government Accession No	3 Recipient s Catalog No.
CR-159449		

4 Title and Subtitle	5 Report Date
JT8D AND JT9D JET ENGINE PERFORMANCE IMPROVEMENT PROGRAM- TASK1, FEASIBILITY ANALYSIS- FINAL REPORT	April 1979
	6. Performing Organization Code
7. Author(s)	**8 Performing Organization Report No**
W. O. Gaffin and D. E. Webb	P&WA5515-38
	10. Work Unit No
9 Performing Organization Name and Address	**11. Contract or Grant No**
UNITED TECHNOLOGIES CORPORATION Pratt & Whitney Aircraft Group Comercial Products Division	NAS3-20630
12 Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
National Aeronautics and Space Administration Washington, D. C. 20546	Contractor Report February 1977 to December 1977
	14. Sponsoring Agency Code

15 Supplementary Notes

Project Manager, Joseph A. Ziemianski William Prati, Project Engineer
Engine Component Improvement Office
NASA-Lewis Research Center, 21000 Brookpark Rd., Cleveland, Ohio 44135

16. Abstract

JT8D and JT9D component performance improvement concepts which have a high probability of incorporation into production engines have been identified and ranked. A new evaluation method based on airline payback period was developed for the purpose of identifying the most promising concepts. The method used available test data and analytical models along with conceptual/preliminary designs to predict the performance improvements, weight, installation characteristics, cost for new production and retrofit, maintenance cost, and qualitative characteristics of candidate concepts. These results were used to arrive at the concept payback period, which is the time required for an airline to recover the investment cost of concept implementation. The concept payback period was compared to a maximum acceptable payback period, which was defined based on airline financial and operational requirements, to determine the economic acceptability of the concept. The potential cumulative fuel saving with each acceptable concept was projected for all engines produced through the year 1990.

Candidate performance improvement concepts were collected from a wide variety of sources, including engine and airframe manufacturers, airline operators, and Government sponsored programs. These concepts were subjected to preliminary screening which eliminated those candidates having high development risk, small fuel saving potential, or those concepts which were well along in the development cycle. The remaining concepts were subjected to the payback period evaluation process.

17 Key Words (Suggested by Author(s))	18 Distribution Statement
Payback Period Performance Improvement Concept Fuel Saving JT8D, JT9D	

19 Security Classif (of this report)	20 Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	228	

* For sale by the National Technical Information Service, Springfield, Virginia 22151

NASA-C-168 (Rev. 6-71)

FOREWORD

This report prepared for the National Aeronautics and Space Administration, Lewis Research Center under Contract NAS3-20630 presents the results of Task 1, Feasibility Analysis which identifies performance improvement concepts having high probability of being incorporated into JT8D and JT9D engines. Mr. J. A. Ziemianski was the NASA Project Manager for this effort and Mr. W. O. Gaffin was Program Manager for Pratt & Whitney Aircraft. Other participants in the program included representatives from Trans World Airlines, United Airlines, American Airlines, Douglas Aircraft Company and Boeing Commercial Airplane Company.

TABLE OF CONTENTS

Section	Title	Page
1.0	SUMMARY	1/2
2.0	INTRODUCTION	3/4
3.0	ANALYTICAL PROCEDURE	5
	Team Member Role Definition and Analysis Functions	5
	Market Projection	9
	Maintenance Cost and Exhaust Gas Temperature Reductions	10
	Establishment of Economic Figure of Merit	11
	Calculation of Cumulative Fuel Savings	13
	Required Payback Period Derivation	18
4.0	CONCEPT IDENTIFICATION AND CATEGORIZATION	23
	Selection of Component Improvement Concepts	23
5.0	DETAILED SCREENING ASSESSMENT	25
	5.1 Introduction	25
	5.2 Concepts Recommended for ECI Development	26
	5.2.1 JT9D Ceramic Outer Air Seal	36
	5.2.2 JT8D Revised HPT Cooling and Outer Air Seal	42
	5.2.3 JT8D HPT Root Discharge Blade	47
	5.2.4 DC-10 Improved Cabin Air System	53
	5.2.5 DC-9 Nacelle Drag Reduction	55
	5.2.6 JT9D-7 3.8 AR Fan	58
	5.2.7 JT8D Trenched Tip HPC	64
	5.2.8 JT9D Trenched Tip HPC	70
	5.2.9 JT9D 16-Strut Intermediate Case	74
	5.2.10 JT9D Thermal Barrier Coating	79
	5.2.11 JT9D-70/59 4.2 AR Fan	86
	5.2.12 JT9D-70/59 HPT Improved Active Clearance Control	90
	5.2.13 JT9D Structural FEGV	96
	5.3 Concepts Recommended for Further Study	104
	5.3.1 JT9D Mixer	104
	5.3.2 JT9D Electronic Control	114
	5.4 Concepts Not Recommended for Further Consideration	117
	5.4.1 JT8D Fan Aero Refinements	118
	5.4.2 JT8D Fan Tip Abradables	121
	5.4.3 JT8D Revised HPC	122
	5.4.4 JT8D LPT Abradable Seals	124
	5.4.5 JT8D Forced Mixer	125
	5.4.6 727 Installation Weight Reduction	128

TABLE OF CONTENTS (Cont'd)

Section	Title	Page
5.4.7	DC-9 Improved Cabin Air System	130
5.4.8	JT9D-70/59 Increased Fan Diameter	132
5.4.9	JT9D Revised HPC	135
5.4.10	JT9D HPC Active Clearance Control	138
5.4.11	JT9D-70/59 LPT Active Clearance Control	140
5.4.12	JT9D-70/59 CNS Short Aftbody	143
APPENDIX		
A	Boeing Commercial Airplane Company – Final Report	147
B	Douglas Aircraft Company – Final Report	191
C	Long Duct Mixed Flow Nacelle Study – Douglas Aircraft Company	199
SYMBOLS		223
REFERENCES		224

1.0 SUMMARY

A feasibility study was conducted under Task 1 of NASA Contract NAS3-20630 to develop analytical procedures leading to the selection of specific performance improvement concepts which have a high probability of being incorporated into JT8D and JT9D engines. This task is part of a five year program to reduce fuel consumption in these engines during the 1980 time period. The technical effort reported herein covers the period February 1977 to December 1977 and encompasses the following goals:

- Development of an analytical procedure for determining fuel and economic benefits
- Identification of concepts
- Detailed screening and ranking of concepts
- Preparation of technology development plans for the concepts selected by NASA.

A large number of potential improvement concepts were considered for evaluation. The selection was guided by previous work under NASA sponsorship(1),* and from studies conducted by Pratt & Whitney Aircraft and airplane and airline companies participating in this program. A "common sense" approach screened out those concepts showing small fuel savings potential, high development risk, and concepts that were beyond the scope of the program. Further screening based on preliminary evaluations reduced these improvement concepts to those candidates that appeared most promising.

An evaluation procedure was developed by Pratt & Whitney Aircraft, Trans World Airlines, Boeing Commercial Aircraft Company, and Douglas Aircraft Company with consultation by American and United Airlines to determine the acceptability of the selected component improvement concepts. This method uses technical information derived from available test data and analytical models along with conceptual/preliminary designs to establish the predicted performance improvement, weight, installation characteristics, the cost for new production and retrofit, maintenance cost and qualitative characteristics of the performance improvement concepts being evaluated. The results are used to arrive at "payback period", which is the time required for an airline to recover the investment cost of concept implementation, and to predict the amount of fuel saved by the concept. The results of the feasibility analysis were used to rank the selected improvement concepts according to economic acceptability, fuel saved and qualitative considerations.

Based on the findings of the feasibility analysis effort, development program information, and NASA technical and funding considerations, several concepts were selected by NASA for further considerations. Technology development plans were prepared for the selected concepts as the first step in defining the effort required to complete the development of these concepts. The concepts that appear most likely to receive follow-on support under the subject program for the JT8D are the Revised HPT Cooling and Outer Air Seal, HPT Root Discharge Blade, Trenched Tip HPC and DC-9 Nacelle Drag Reduction, and for the JT9D the HPT Improved Active Clearance Control, 3.8 AR Fan, Trenched Tip HPC, Ceramic Outer Air Seal, and Thermal Barrier Coating. If all of these concepts are implemented as estimated in the feasibility study, a total of 12 billion liters (3.2 billion gallons) of fuel will be saved. Of this total 60% would be saved in new production JT9D engines, 17% in retrofit of existing JT9D engines, 7% in new production JT8D engines, and 16% in retrofit of existing JT8D engines.

*References appear after the Appendices.

2.0 INTRODUCTION

National energy demand has outpaced domestic supply, creating an increased U.S. dependence on foreign oil. This increased dependence was dramatized by the OPEC oil embargo in the winter of 1973-74. In addition, the embargo triggered a rapid rise in the cost of fuel which, along with the potential of further increases, brought about a changing economic circumstance with regard to the use of energy. These events, of course, were felt in the air transport industry as well as in other forms of transportation. As a result, the government, with the support of the aviation industry, has initiated programs aimed at both the supply (sources) and demand (consumption) aspects of the problem. The supply problem is being investigated by looking at increasing fuel availability from such sources as coal and oil shale. An approach to the demand aspect of the problem is to evolve new technology for commercial aircraft propulsion systems which will permit development of a more energy efficient turbofan or the use of a different propulsive cycle such as a turboprop. Although studies have indicated large reductions in fuel usage are possible (e.g., 15 to 40 percent), the fuel savings impact of developing and introducing into service a new turbofan or turboprop engine would not be significant for at least ten to fifteen years. In the short term, the only practical propulsion approach is to improve the fuel efficiency of current engines. Examination of this approach has indicated that a five percent fuel reduction goal, starting in the 1980-82 time period, is feasible. Inasmuch as commercial aircraft in the free world are using fuel at a rate in excess of 75 billion liters of fuel per year, even five percent represents significant fuel savings.

Since a major portion of the present commercial aircraft fleet is powered by the JT8D and JT9D engines, NASA is sponsoring a program whose objective is to reduce the fuel consumption of these engines. This program has two main parts, performance improvement and engine diagnostics. The latter part, which is not reported herein, is aimed at identifying the sources and causes of engine deterioration. The performance improvement part is intended to identify and evaluate the concepts which are technically and economically viable for the 1980-82 time period, and then develop and demonstrate these concepts through ground and flight tests.

The initial step to identify and evaluate the JT8D and JT9D performance improvement concepts was conducted under Task 1 of NASA Contract NAS3-20630 and is reported herein. The evaluation procedure which was developed to determine the acceptability of these concepts by the airlines is described in detail. This procedure is a new screening method which predicts airline acceptance of proposed engine and airframe modifications and uses payback period (time required for an airline to recover the investment in a specific concept) to predict economic acceptability. Technical information for the performance improvement concepts is given along with the economic results of the screening process. Based on these results, several performance improvement concepts have been selected by NASA for further development.

3.0 ANALYTICAL PROCEDURE

Team Member Role Definitions and Analysis Functions

In an attempt to establish both realism and credibility in the evaluation of candidate performance improvement concepts, Pratt & Whitney Aircraft established an evaluation team consisting of both manufacturers and operators (sellers and buyers) who simulated, as nearly as possible, the evaluation process that exists on a day-to-day basis in the air transport industry. This team consisted of The Boeing Commercial Aircraft Company, The Douglas Aircraft Company, Trans World Airlines, American Airlines, United Airlines and The Pratt & Whitney Aircraft Group. Each company filled the role that represented their own self interest and area of expertise. Figure 3-1 shows the contributions of the various team members to final evaluation output, payback period and cumulative fuel burned.

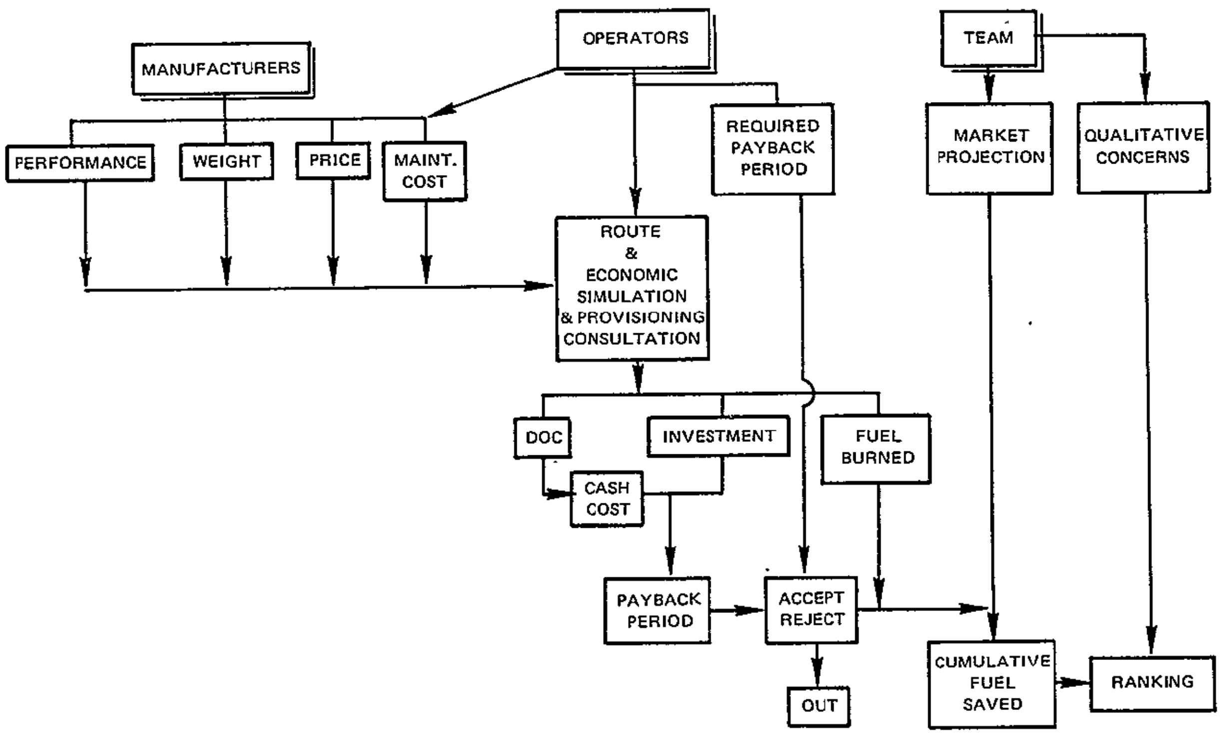


Figure 3-1 ECI-PI Evaluation Procedure

Each applicable engine performance improvement concept was evaluated by both the performance and design groups of the P&WA engineering organization, using established P&WA procedures. Component performance was estimated using analytical methods, experience with similar designs and if possible, test results. Engine performance was calculated based on this component performance; engineering decisions were made on rematching the engine (changing flow areas) to adjust for the effects of the modified component. The flight conditions used for engine performance calculations are shown in Table 3-1 for each of the aircraft studied. The engine performance calculation provided TSFC and stability information plus temperatures, pressures, flows and rotor speeds which were used to estimate noise, emissions and parts life. The design function included both analytical and mechanical design, and provided the basis for estimating weight, cost and maintenance requirements. The design effort also provided a focal point for defining the nature and extent of the program required to develop, certify and initiate production of the modification. This definition was combined with the manufacturing cost estimate and several other factors to determine the concept's impact on the engine price and on the price of the modification kit, when applicable.

Both BCAC and DAC assisted in defining these screening and evaluation processes, conceived performance improvement concepts, critiqued concepts for feasibility, supplied airplane performance, weight, and cost information on selected concepts to TWA, and participated in the qualitative assessment and ranking of the concepts evaluated. In evaluating concepts, both companies relied on established design study organizations and utilized procedures developed from previous analyses, model tests, rig tests, flight tests, and certification tests (see Boeing Final Report, Appendix A and Douglas Final Report, Appendix B for details).

TWA provided the route structure, fleet composition and extensive experience necessary to provide practical viewpoints and real world economic evaluation of ECI concepts. The economic model used by TWA in all aircraft evaluations is called Aircraft Performance and Economic Simulation (APES). This model, developed and improved over the past twelve years, is fully computerized. Each aircraft type is represented by a unique card deck containing aircraft performance (takeoff, climb, cruise, descent and loiter) data, operating cost factors and route applications. Card decks were available at the beginning of the program representing all of the aircraft types in the current TWA system. The TWA aircraft and routes that were of interest to the ECI evaluation are summarized in Table 3-2. With the concurrence of American Airlines and United Airlines, the route structure shown on this table and the APES economic model were deemed representative of most major U.S. carriers. The airplane characteristics in the APES model were changed to correspond to the aircraft/engine combinations listed in Table 3-3.

TABLE 3-1

FLIGHT CONDITIONS FOR ENGINE PERFORMANCE CALCULATIONS

All Conditions Are Std. Day

DC-9	Takeoff	Climb	Avg. Cruise	Hold
Alt. - meters (ft)	0	7925 (26,000)	9145 (30,000)	3050 (10,000)
M_N	0.2	0.7	0.78	0.45
Power Setting ~ %	Max. T/O	Max. Climb	90%	40%
727				
Alt. - meters (ft)	0	7925 (26,000)	9145 (30,000)	3050 (10,000)
M_N	0.2	0.7	0.84	0.45
Power Setting	Max. T/O	Max. Climb	90%	40%
DC-10-40				
Alt. - meters (ft)	0	7925 (26,000)	10,670 (35,000)	3050 (10,000)
M_N	0.2	0.7	0.82	0.45
Power Setting	Max. T/O	Max. Climb	90%	35%
747				
Alt. - meters (ft)	0	7925 (26,000)	10,670 (35,000)	3050 (10,000)
M_N	0.2	0.75	0.84	0.45
Power Setting	Max. T/O	Max. Climb	90%	35%

TABLE 3-2

TWA "APES" FLEET & ROUTE SUMMARY

Aircraft	Fleet Size	Daily Utilization Hrs. ~ Block Hrs/Day	Average Trip Length ~km (St. miles)	Min/Max Trip Length ~km (St. miles)	Weekly Trips	Scheduled City - Pairs
DC9-10	17	7.98	626 (389)	114/1429 (71/ 888)	708	62
727-200	39	8.92	949 (590)	114/2602 (71/1617)	1416	129
L1011-1	29	10.45	2449 (1522)	178/4551 (111/2704)	623	45
747-100	11	13.24	5028 (3125)	365/8782 (227/5458)	162	24

TABLE 3-3

COMPARISON OF TWA ACTUAL AND ECI-PI AIRCRAFT MODELS

Aircraft in TWA Fleet	Aircraft Used in ECI-PI Evaluations
DC9-10	DC9-50/JT8D-17
727-200	727-200/JT8D-15
L1011-1	DC10-40/JT9D-59A
747-100	747-200/JT9D

Concepts for performance improvement were reviewed by TWA's Engineering and Materials Management Department. Provisioning requirements were established and criticisms and suggestions from TWA engineering were taken into account before detailed analysis of economic effects were performed. TWA was also consulted on the establishment of the evaluation figure of merit, payback period. The TWA "APES" model produced the critical output in the evaluation, annual cost and annual fleet fuel burned. Direct operating cost (DOC) was also produced by the APES program.

Both United Airlines and American Airlines served as consultants to P&WA. The combined expertise of these two major carriers was used in establishing the route structure, economic and financial ground rules and the final ranking of the evaluated concepts. Table 3-4 presents the economic and financial ground rules recommended by the team of airline operators.

TABLE 3-4
ECONOMIC & FINANCIAL GROUND RULES

Operating Economics

- 1977 Dollars

- Base Fuel Prices
  Domestic Flights (DC-9, 727, DC-10) – 9.24¢ /liter (35¢ gal.)
  International Flights (747) – 11.89¢ /liter (45¢ gal.)

- Labor Rate 30 $/man hr. (fully allocated)
- Non Revenue Flying 2%
- Insurance Rate 0.5% of Purchase Price (Domestic), 1.0% (International)
- Tax Rate 50% (Total of Federal, State & Local)
- Remaining Operating Costs TWA Internal Model

Financial Ground Rules

- Economic life 15 years
- Debt/Equity = 50/50 (Debt @ 10%, Simple Bond Interest)
- After Tax Cost of Capital = 15%
- Investment Tax Credit = 7%
- Depreciation, Double Declining Balance to Point where Straight Line is Greater, 9.5 Years

Market Projection

All members of the team were consulted on the establishment of a market projection for the JT8D and JT9D engines. The objective was to establish a "reasonable" market projection which would be used to estimate the fuel savings potential in future production engines. The individual team members projections were arithmetically averaged to arrive at the projections shown in Figure 3-2. Pratt & Whitney Aircraft considers these projections as "reasonable" for purposes of a conservative estimate of potential fleet fuel consumption levels. The projections of total sales were divided into sales by engine model in order to evaluate concepts that are not applicable for all models of a given engine (e.g. cooled or uncooled JT8D HP Turbines). The engine population (existing plus projected) by model will be discussed later in light of their role in the cumulative fuel savings estimates.

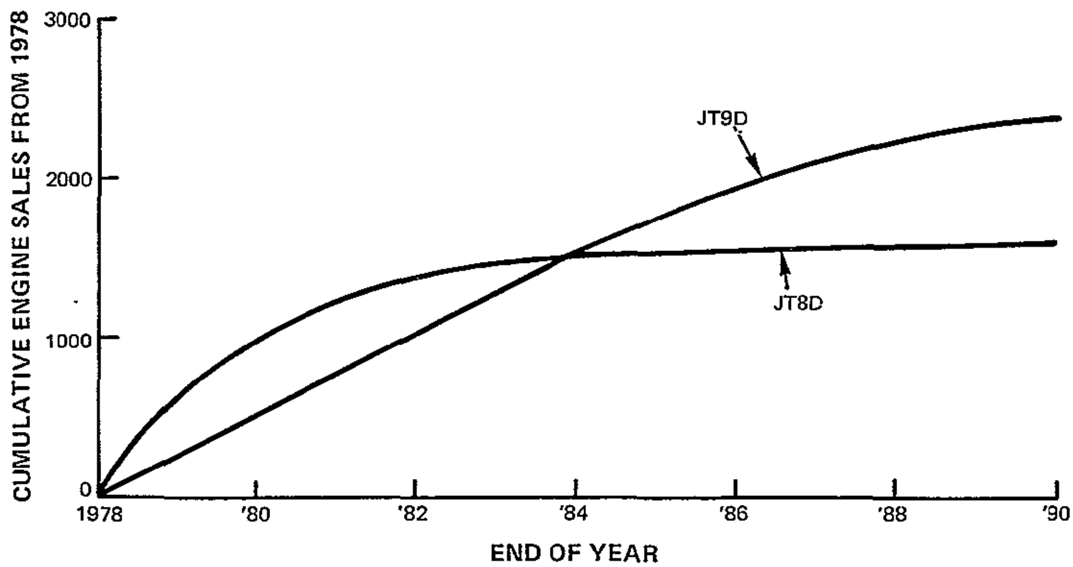


Figure 3-2 JT8D and JT9D Sales Projections (PWA, TWA, AA, BCAC, DACO Consensus)

Maintenance Cost and Exhaust Gas Temperature (EGT) Reductions

The three airlines under contract to P&WA as well as the two under direct contract to NASA (Pan American and Eastern) were consulted on the effect of reductions in EGT resulting from component efficiency gains on the maintenance cost of the engine. A conservative approach was used due to the volatility of the issue. Only savings in shop labor associated with improvements in the frequency of shop visits were claimed even though it is highly probable that significant material cost savings would result from reduced EGT. No improvement in costs due to longer parts life associated with lower EGT were claimed. Table 3-5 shows the results of the survey of the five airlines and the expected improvement in mean time between shop visits (MTBSV) for a 6°C (10°F) reduction in EGT. Significant differences exist in the expected benefit and the "team" was consulted in choosing 200 hours for 6°C (10°F) as a conservative estimate. Since the disassembly, inspection, repair, and reassembly process for each visit was assumed the same, the labor cost savings expressed in Table 3-5 in terms of dollars per engine operating hour merely reflect the percentage change in the engine shop visit rate. The actual relationship for any given operator will depend on the operator's route structure, equipment (type, weight and age), overhaul build standards, operating environment and flight procedures.

TABLE 3-5

SHOP VISIT RATE IMPROVEMENT FOR 6°C (10°F) REDUCTION IN EGT @ T/O AND CLIMB POWER

Airline	Increase in Mean Time Between Shop Visit ~ Hours	
	JT8D	JT9D
A	300	300-500
B	180	150
C	150-200	~
D	> 150	> 200
E	300	1000
"Team"	200	200
Reductions in Engine Shop Labor, $/Engine Operating Hour	1.25	3.67

Establishment of Economic Figure of Merit

One of the most critical decisions was the choice of an economic figure of merit to decide the economic acceptability of a given concept. This figure of merit should be easy to calculate and understand and yet reflect the financial complexities of the "real world". Consequently, traditional air transport approaches were examined. Direct Operating Cost (DOC) was eliminated because it did not reflect the cost of capital. (Cost of capital is the implied obligation to earn an "adequate" rate-of-return on invested capital in order that like funds can be attracted in the future). The cost of capital funds invested directly in flight equipment was established by United Airlines in the NASA RECAT studies[2] at 15% on an after tax basis. This value, which the airline team members agreed was reasonable, results in a very significant cost increase (about 2-1/2 times) over that of the straight depreciation found in DOC. Direct Operating Cost, although eliminated as a prime figure of merit, was calculated for each concept and the results were carried in the evaluation summary.

Return on Investment (ROI), generally considered the most sophisticated approach, was eliminated as a figure of merit for the following reasons:

1. it does not permit direct use of TWA output

2. marginal ROI analysis can yield results that vary to such extremes (e.g., ROI's of 300%) that they are difficult to interpret

3. ROI calculations involve many ground rules, both financial and economic, some of which can be controversal. A figure of merit that allows broad application to all ground rules, but still supplies a realistic screening process would be more desirable.

Payback period (PBP) was selected as the figure of merit because it is subjectively easy to identify with ("How quickly do I get my money back?") and has the capacity for all the sophistication (time value of money, tax rules, etc.) required to be valid in the commercial air transport economic synthesis. PBP is more discriminating as a figure of merit than DOC; it results in the elimination of some concepts that would appear acceptable in a DOC analysis. The traditional criticisms of PBP are that one value is not good for different economic lives and that cash flow discontinuities are not properly evaluated on a present worth (discounted at the rate established by cost of capital) basis. These shortcomings have been eliminated by: 1) calculating a required PBP as a function of remaining life, 2) calculating the present worth of tax implications associated with investment, and 3) assuming that each aircraft operates uniformly for the remaining years of its economic life. The required PBP on a before tax basis, conforming to these constraints, is derived below and shown in Figure 3-3.

Establishing required PBP (maximum acceptable) on a before-tax basis allows direct use of the TWA "APES" program output of cash (out-of-pocket) cost, which is on a before tax basis, and the estimated investment required, to calculate PBP, where

$$\text{PBP} = \frac{\Delta \text{ Investment}}{\Delta \text{ Annual Cash Savings}}$$

Concepts that provide annual cash savings as well as reduced first cost (negative Δ investment) will produce payback periods that are negative. Since such an investment opportunity is acceptable by inspection (costs less to buy and saves cash during its operation) and because negative values of PBP have no fiscal significance, the PBP in these cases is defined as zero. The zero PBP implies instantaneous payback and is therefore acceptable under any criteria for PBP. Concepts that resulted in negative PBP values due to negative annual cash savings (i.e., annual cash costs were increased) were eliminated from further consideration.

Table 3-6 shows that the maximum acceptable PBP for an investment that has a 15 year economic life is 5.97 years. This is called the "new buy" case in ECI-PI evaluations. As shown in Figure 3-3, the maximum acceptable PBP decreases with decreasing economic life (increasing engine age at time of investment). For example, if a PBP of 4.0 years is calculated for the retrofit of a given concept, only engines 8 years old or younger would be considered candidates for the retrofit of that concept.

TABLE 3-6

EFFECT OF LIFE ON PBP REQ'D
FOR USE IN RETROFIT ANALYSIS

Life – Yrs	15	10	5	5 (Expense)
Present Value of Deprec	0.30	0.32	0.37	0.43
Present Value of Interest Paid	0.15	0.13	0.08	0.08
Present Value of ITC	0.06	0.06	0.06	0
Present Value of Taxes Avoided	0.51	0.51	0.51	0.51
Net Investment	0.49	0.49	0.49	0.49
Savings Req'd (A.T.) = Net Inv. x CRF	0.49 x 0.171 = 0.084	0.49 x 0.199 = 0.098	0.49 x 0.298 = 0.146	= 0.146
Savings Req'd (B.T.)	0.168	0.196	0.292	0.292
PBP Yrs.	5.97	5.1	3.4	3.4

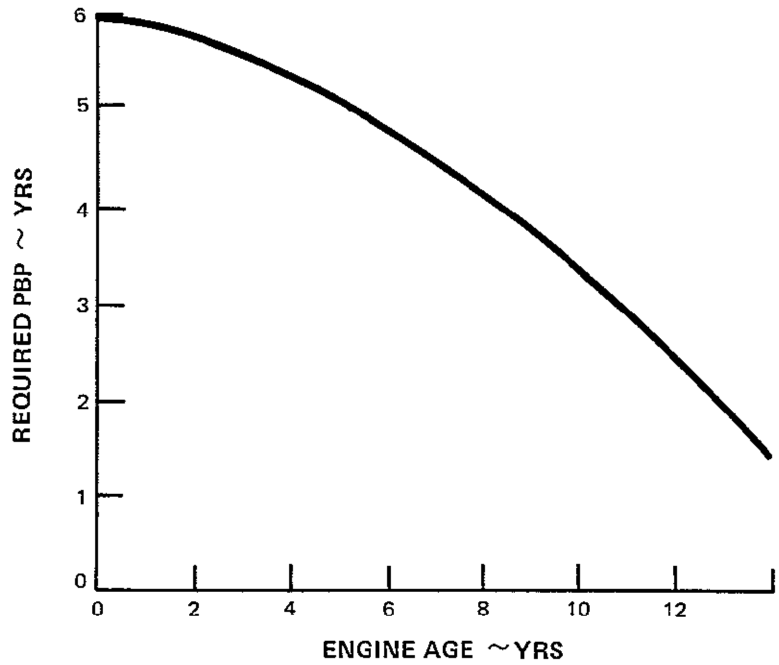


Figure 3-3 Effect of Engine Age on PBP Required

Table 3-6 shows that the required PBP for a short life investment (5 years or less) is not changed by the accounting treatment of the investment (expense or capitalize). This is shown because expensing would probably be common for many of the ECI-PI concepts applied to engine components of relatively short lives (e.g., high pressure turbines). Expensing means the "investment" is claimed as a cost of doing business during the current year and taxes are therefore not paid on the "investment" or cost in this case. Capitalizing (or depreciating) the investment would result in an annual spreading of the investment over a period of years determined by the life of the asset. Generally, expensing reduces tax exposure to the greatest degree and, when possible, is the most economically rational option. There are, however, complications such as tax law, desired posture in the stock market (price to earnings ratio) and absolute earnings level (if there are no earnings there are no taxes and hence no tax savings) that make the choice of accounting treatment unintuitive.

It should also be noted that some airlines might retrofit entire engine fleets with an acceptable concept, and not draw an age limit through the fleet. This would be done to limit shop assembly error, minimize investment in spare parts or for other commonality reasons.

Calculation of Cumulative Fuel Savings

The potential fuel saved through the implementation of an ECI-PI concept is an important figure in the selection of concepts for NASA development participation. Concepts passing the PBP hurdle are judged on their potential for cumulative fuel savings over the life of the engine, the ultimate goal of the program.

The factors considered in calculating the cumulative fuel saved are the mission-averaged change in fuel burned (supplied by the APES program as a percent of total fuel usage), the date the improvement enters service, the number of new production engines with the performance improvement concept, the number of existing engines acceptable for retrofit and the time required to retrofit the existing engine fleet. In the case of a new buy, fuel saved was calculated for all new production if the PBP was equal to or less than 6.0 years. In the case of retrofit, the allowable engine age was determined by the retrofit PBP as shown in Figure 3-3. The allowable engine age and the assumption that the retrofit was accomplished on a convenience basis over a three-year time period determined the number of in-service engines affected. Figures 3-4, 3-5, 3-6, and 3-7 show the JT8D and JT9D engine populations by model as a function of time, used in the cumulative fuel saved calculations. These populations reflect actual engine sales through the year 1977 and the team consensus in the later years. Note that the JT8D refan models (for example, the JT8D-209) are not included in these projections, since none of these models had been committed to production at the time of the study.

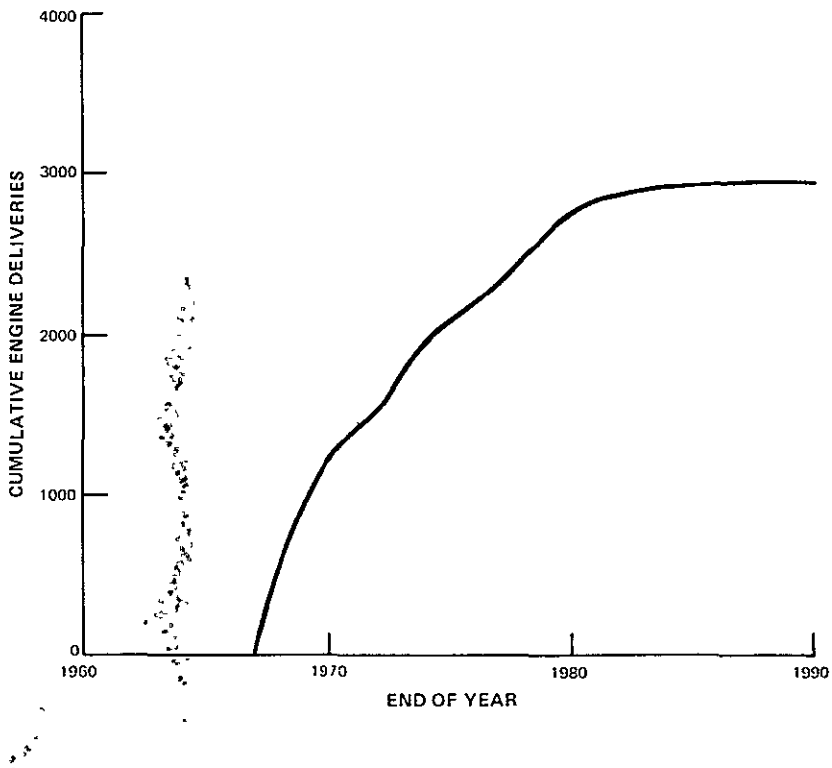


Figure 3-4 JT8D-9 Engine Population

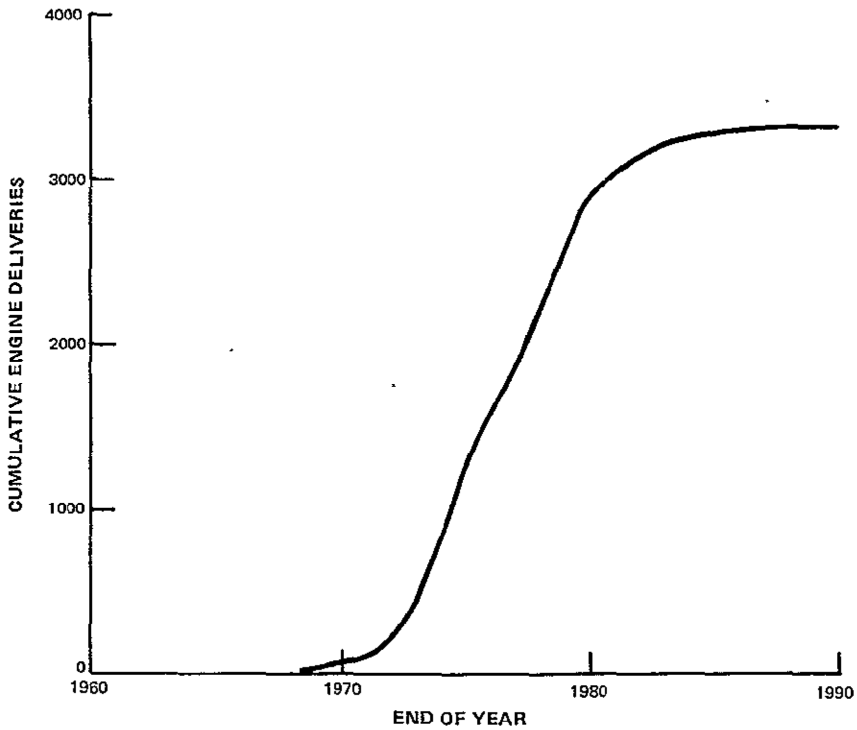


Figure 3-5 JT8D-15/17 Engine Population

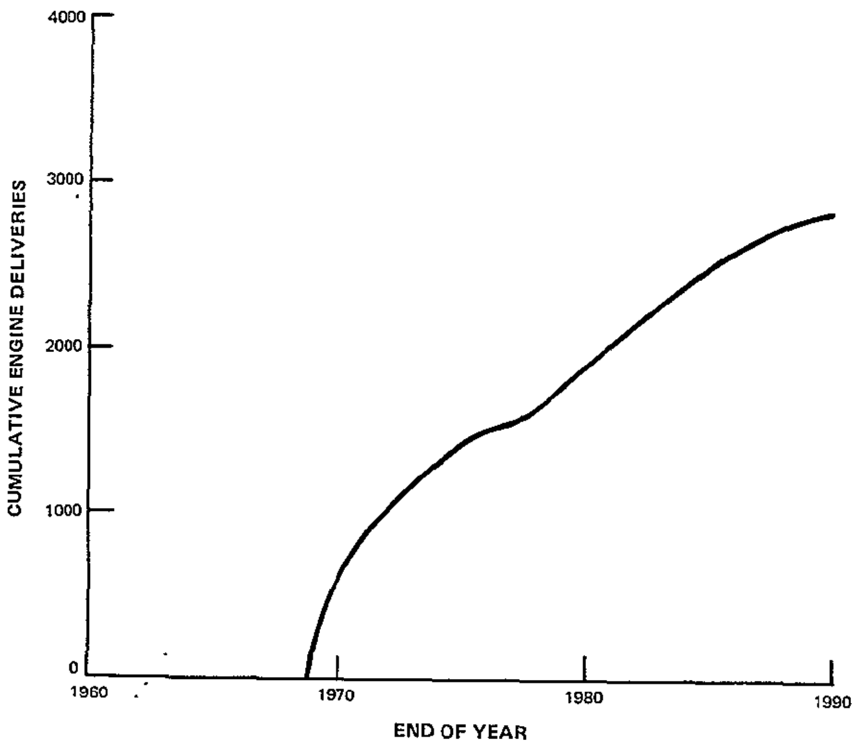


Figure 3-6 JT9D-7 Engine Population

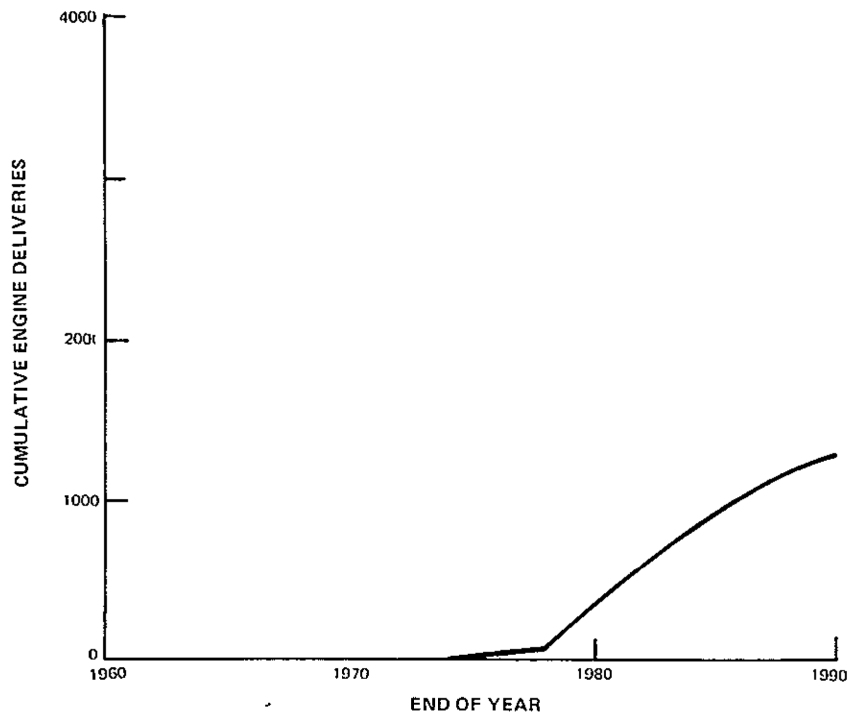


Figure 3-7 JT9D-70/59 Engine Population

Once the number of candidate engines and the percent change in fuel burned is established, only the base level of annual fuel consumption remained to be established.

In order to reflect realistic levels, the baseline annual fuel burned per engine was chosen based on a study of CAB data. The values chosen as typical are shown in Table 3-7 and are considered to be reasonable for purposes of estimating world wide fuel savings potential. (These values may vary somewhat from operator to operator depending on route structure, utilization, build standards, flight procedures, traffic limitations, and age of equipment with annual utilization being perhaps the biggest variant.)

TABLE 3-7
TYPICAL ANNUAL FUEL BURNED

	Annual Fuel Used Per Engine Million Liters (Million Gallons)
JT8D	3.78 (1.0)
JT9D	10.98 (2.9)

The remaining step is to integrate the annual fuel saved by each modified engine from its production or modification date to its economic life limit (15 years from production). Only engines produced through 1990 were considered and the last year of fuel saved is 2005 (engine produced in 1990 serving in its last economic year).

Figure 3-8 is a flow chart of the fuel savings calculation process. Annual fleet fuel burned and the percent change in fuel burned is calculated based on the inputs shown. The engine population simulation is simply a numerical method for integrating the area under the engine population vs. time curve with the constraints defined by the inputs to the simulation.

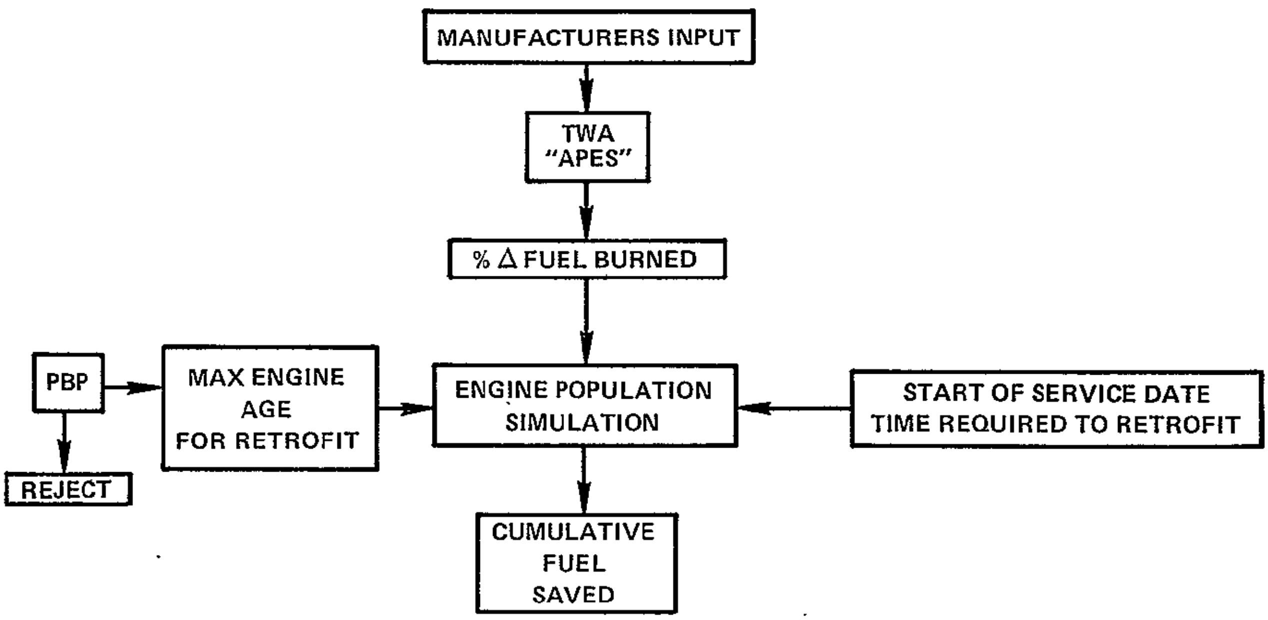


Figure 3-8 Cumulative Fuel Saved

An example of this process, Figure 3-9, shows the engines entering service and being retired after 15 years. A start of service date("S") of 1980 defines the "new engine years" area to be integrated by the simulation. The maximum engine age for retrofit defines "M" (in this case 4 years) and, therefore, the number of engines that are candidates for retrofit.. "C" represents the effect of a 3 year retrofit program. The "retrofit engine years" then is the area to be integrated by the simulation. The total engine years (new plus retrofit) is multiplied by the annual base fuel burned per engine and the percent change in fuel burned determined by the "APES" program to produce the cumulative fuel saved.

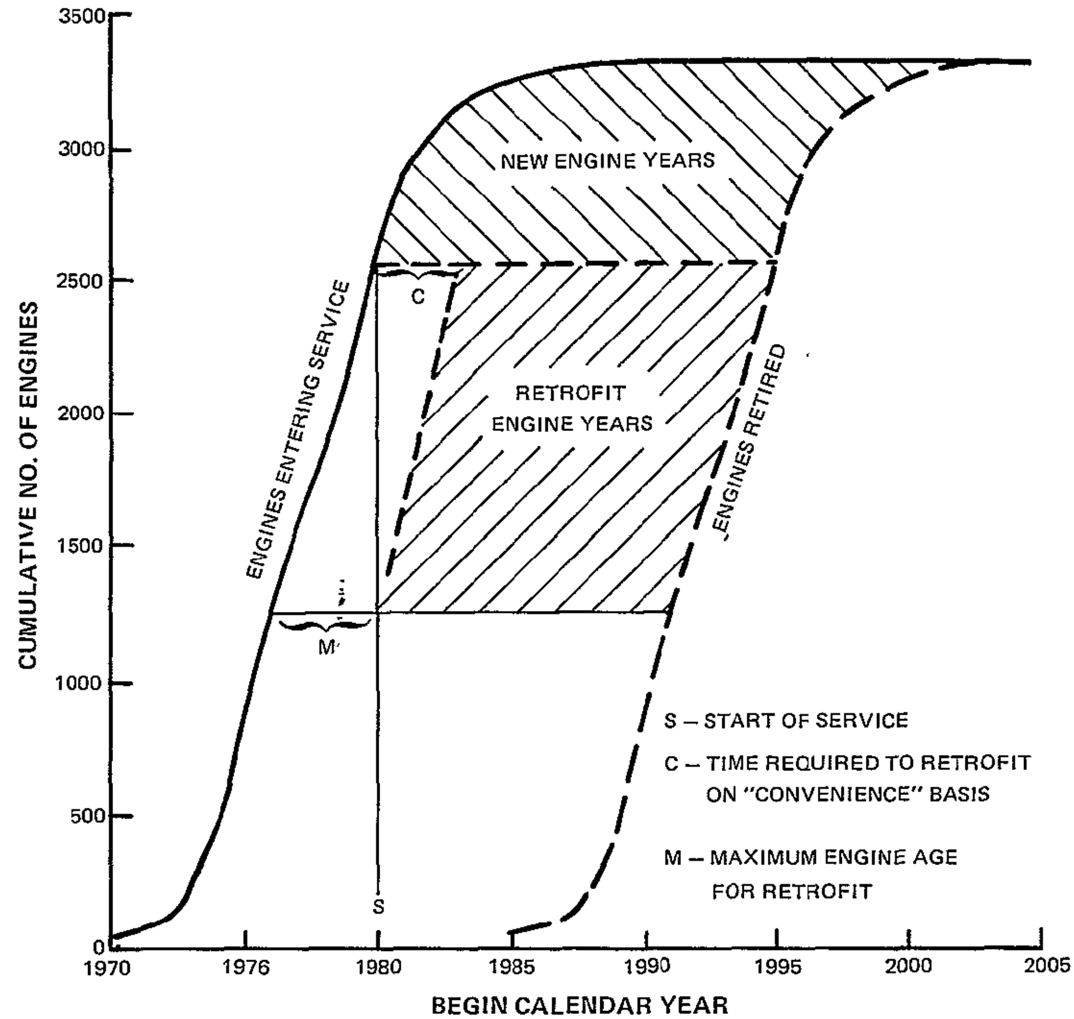


Figure 3-9 Example of Cumulative Fuel Savings Estimate

Required Payback Period Derivation

The before tax payback period required to ensure an adequate after tax return on capital invested (cost of capital) is derived based on a reasonable set of ground rules reflecting an approach for the air transport industry rather than an individual operator. These ground rules and the resultant derivation are discussed in the following paragraphs.

Table 3-8 establishes the financial ground rules for determining the desired maximum acceptable payback period (PBP). These ground rules represent input from United Airlines as well as Trans World Airlines with review and consent from American Airlines, Pan American World Airways, and Eastern Air Lines. The latter two were under direct contract to NASA.

Table 3-9 presents the calculation of the present worth of future tax reductions supplied by depreciation claims for a $1.00 investment with zero salvage value (i.e., no cash market value at the end of its life). The present worth of the depreciation at the 15% discount rate is about 30¢.

Table 3-10 presents the present worth determination for interest paid (a deductible expense) and an assumed 7% investment tax credit (ITC) which is assumed to come 1 year after investment. The present worth of the taxes avoided by interest paid is 14.6¢ and the present worth of taxes avoided by ITC is worth 6.1¢.

Table 3-11 summarizes the present value of the investment after accounting for avoided taxes (reduced tax obligations). The net present value of the $1.00 investment is shown on line 6 to be $0.49. Line 7 establishes the annual savings (after taxes) required on the $0.49 investment to yield a 15% return (capital recovery factor of 0.171). Line 8 establishes the required annual savings on a before tax basis to be 0.168 $/year. Line 9 inverts line 8 to yield a before tax payback period of 5.97 years.

Table 3-6 (shown on page 12) presents the results of this same process for 10 and 5 year economic lives. The 5 year case was done using both depreciation and expensing (1 year write-off) and shows that the required PBP remains the same at 3.4 years. Figure 3-3 (page 12) shows the relationship between required PBP and engine age.

TABLE 3-8

REQUIRED PBP CALCULATION

ASSUMPTIONS

- Economic Life = 15 Years
- Debt/Equity = 50/50 (Debt @ 10%, Simple Bond Interest)
- Total After Tax Cost of Capital = 15%
- Investment Tax Credit (ITC) = 7%
- Depreciation, Double Declining Balance to Point Where Straight Line is Greater, 9.5 Years
- Tax Rate = 50%

TABLE 3-9

PRESENT WORTH OF TAX DEPRECIATION

- Investment = $1.00
- Zero Salvage

Year	Tax Depreciation	Present Worth Factor for 15% Interest	Discounted Value
1	0.2105	0 8696	0 1831
2	0.1662	0.7561	0.1257
3	0.1312	0.6575	0.0863
4	0.1036	0.5718	0.0592
5	0.0818	0.4972	0.0407
6	0.0682	0.4323	0.0295
7	0.0682	0.3759	0.0256
8	0.0681	0.3269	0.0223
9	0.0681	0.2843	0.0194
10	0.0341	0.2472	0.0084
	1.0000		0.6002

Present Worth of Tax Depreciation = (Σ Discounted Values) x (Tax Rate)
= 0.6002 x 0.50
= 0.3001

TABLE 3-10

PRESENT WORTH OF TAXES AVOIDED BY INTEREST AND INVESTMENT TAX CREDIT

- Investment =$1.00

	INTEREST			ITC		
Year	Interest Paid	Present Worth Factor	Discounted Value	INVESTMENT TAX CREDIT	PRESENT WORTH FACTOR	Discounted Value
1	0.05	0.8696	0.0435	0.07	0.8696	0.061
2	0.05	0.7561	0.0378	0		0
3	0.05	0.6575	0.0329	0		0
4	0.05	0.5718	0.0286	0		0
5	0.05	0.4972	0.0249	0		0
6	0.05	0 4323	0.0216	0		0
7	0.05	0.3759	0.0188	0		0
8	0.05	0 3269	0.0163	0		0
9	0.05	0.2843	0.0142	0		0
10	0.05	0.2472	0.0124	0		0
11	0.05	0.2149	0.0107	0		0
12	0.05	0.1869	0.0093	0		0
13	0.05	0.1625	0.0081	0		0
14	0.05	0.1413	0.0071	0		0
15	0 05	0.1229	0.0061	0		0
	Total	0.5847	0.0292	0 07		0.061

Present Worth of Interest Paid = 0.292 x 0.50 = 0.146, Present Worth of ITC = 0.061

TABLE 3-11
REQUIRED PBP CALCULATION

(1)	Investment	\$1.00
(2)	Present Value of Depreciation	0.6 x 0.5 = 0.30
(3)	Present Value of Interest Paid	0.3 x 0.5 = 0.15
(4)	Present Value of ITC	0.07 x 0.87 = 0.06
(5)	Total Present Value of Taxes Avoided by Deprec. + Int + ITC	0.51
(6)	Net Present Value of Investment	1.00 - 0.51 = 0.49
(7)	After Tax Savings Required = Cap. Rec. Factor[(1)] x Net Invest.	0.171[(1)] x 0.49 = 0.084
(8)	Before Tax Savings Required = After Tax Savings ÷ 0.50	= 0.168
(9)	Before Tax PBP = Investment/Savings	1.00/0.168 = 5.97 Years

(1) From Interest Tables @ 15%, 15 Years, Capital Recovery Factor = $i(1+i)^N/(1+i)^N-1$

4.0 CONCEPT IDENTIFICATION AND CATEGORIZATION

Selection of Component Improvement Concepts

In this effort, component performance improvement concepts having the potential of being accepted and incorporated into production JT8D and JT9D engines were selected and screened. An extensive list of candidate concepts was compiled based on previous work under NASA contract[1], on improvement concepts submitted by NASA, airplane and airline companies and on more recent ideas from P&WA. The concepts described in Section 5.0 were selected from this initial list as being the most promising fuel saving ideas for follow-on support under the subject program. The concepts on the initial list that were considered and rejected are listed in Table 4-1 with the reasons for rejection. Some of these concepts might be reconsidered for fuel savings or other benefits in the future as the demand for fuel economy increases or as technology advances.

TABLE 4-1
REJECTED JT8D CANDIDATE CONCEPTS

Concept	Reason for Rejection
Improved fan blade shrouds	Low fuel saving
Abradable LPC tip seals	Low fuel saving
Abradable knife-edge seals in LPC & HPC	Low fuel saving
Blade root sealing in LPC & HPC	Low fuel saving
LPC & HPC airfoil aerodynamic refinements	High development cost
Mini-shrouded stators in LPC & HPC	High development cost
Aerodynamic improvement of intermediate case struts	High development cost
HPC rotor windage covers	Low fuel saving
Reduced case flange leakage	No known practical design
Carbon seal in No. 4 bearing compartment	Development effort nearly completed
Blade root sealing in HPT	Low fuel saving
Closed HPT blade shroud notches	Development effort nearly completed
Sealed HPT vane platforms	Development effort nearly completed
HPT & LPT airfoil aerodynamic refinements	High development cost
Improved HPT airfoil material & coatings	High development cost
Rotor windage covers in HPT	Low fuel saving
Blade root sealing in LPT	Low fuel saving
Case-tied LPT seals	High development cost
Low drag temperature & pressure probes	Low fuel saving
Aerodynamic improvement of turbine exhaust case struts	High development cost
Discharge nozzle area change	Take-off performance penalty
Fan duct loss reduction	High development cost

TABLE 4-1 (Cont'd)
REJECTED JT9D CANDIDATE CONCEPTS

Concept	Reason for Rejection
Improved fan blade manufacturing process	Development effort nearly completed
Improved fan blade rubstrip configuration	Low fuel saving
Aerodynamic improvement of fan exit case struts	Low fuel saving
Improved fan duct acoustic treatment	Low fuel saving
Mini-shrouded stators in LPC	Low fuel saving
Blade root sealing in LPC	Low fuel saving
LPC airfoil aerodynamic refinements	Low fuel saving
Non-adjustable LPC inlet guide vane	Development effort nearly completed
Cruise-optimized HPC stator vane schedule	Low fuel saving
HPC rotor windage covers	Low fuel saving
Reduced case flange leakage	No known practical design
Carbon seal in No. 3 bearing compartment	Development effort nearly completed
Blade root sealing in HPT	Low fuel saving
HPT airfoil cooling refinements	High development cost
Improved HPT airfoil material & coating	High development cost
HPT rotor windage covers	Low fuel saving
HPT & LPT airfoil aerodynamic refinements	High development cost
Clustered vanes in LPT	Development effort nearly completed
Case-tied LPT seals	Development effort nearly completed
Low drag temperature probes	Low fuel saving
Aerodynamic improvement of turbine exhaust case struts	Development effort nearly completed
Fan discharge nozzle area changes	Development effort nearly completed
Remove primary reverser	Development effort nearly completed

5.0 DETAILED SCREENING ASSESSMENT

5.1 INTRODUCTION

The procedure described in Section 3.0 was used to evaluate concepts selected for Detailed Screening Assessment.

The concepts are presented and discussed in this section in three categories:

- those recommended for ECI development and demonstration (Section 5.2)
- those recommended for further study (Section 5.3)
- those not recommended for further consideration (Section 5.4)

The concepts in each category are identified and the evaluation results are summarized in Tables 5-2, 5-56, and 5-65 (pages 27, 104, and 118, respectively). The evaluation parameters presented in these tables are defined in Table 5-1.

Following the summary table in each category are descriptions, performance substantiation discussions, and economic evaluation details for each concept. In addition, a performance and economic risk sensitivity analysis is presented for each concept in the first category.

TABLE 5-1
DEFINITIONS OF EVALUATION PARAMETERS

PBP:	Pay-back period (PBP) is the ratio of the incremental investment to the annual cash savings attributable to the performance improvement concept. The maximum acceptable value of PBP for any concept has been established by the evaluation team to meet an investment hurdle rate of 15 percent. The maximum acceptable PBP, which is a function of engine age, varies as illustrated by Figure 3-3.
Block Speed Effect	The reduction in annual costs resulting from reduced trip time (increased block speed). The trip time reductions are the result of reduced fuel loads throughout any given route structure and schedule pattern.
Δ DOC: (percent)	The percent change in direct operating cost (DOC) on a new buy basis using conventional cost classification and TWA calculation procedures.

TABLE 5-1 (Cont'd)

Percent Fuel Savings:	The percent of mission fuel saved integrated over the entire applicable route structure as calculated by the TWA "APES" program. This value will differ from the internal performance improvement because it includes any weight or aircraft drag effects as well as an integration of engine power settings over the mission profiles for the entire route structure.
Cumulative Fuel Savings:	The world-wide accumulated fuel saved from date of introduction through 15 years total engine life, for engines entering service through 1990, attributable to the performance improvement concept. Both new buy and retrofitted engines which meet or better the payback requirement are included.

5.2 CONCEPTS RECOMMENDED FOR ECI DEVELOPMENT AND DEMONSTRATION

The concepts in this category met the PBP criteria, showed significant fuel savings, and appeared to meet the general funding and schedular requirements of the subject program. These concepts are listed in Table 5-2 in the order ranked by the P&WA evaluation team, according to the criteria previously described in Section 3.0. The ranking considers not only the evaluation results summarized in the table, but qualitative considerations, such as potential for shop assembly error, passenger comfort, and potential for change to flight manuals, which were considered significant by the team. These concepts are discussed in the ranked order, starting on page 36.

Technology development plans were prepared by P&WA for each of the concepts listed in Table 5-2, except for the DC-10 Improved Cabin Air System and the DC-9 Nacelle Drag Reduction concept, which were prepared by DAC.

NASA combined the results of the evaluation and ranking of the Table 5-2 concepts with the information supplied in the technology development plans, and with NASA's own technical and funding considerations to select the concepts to be included in the ECI-PI development and demonstration effort (see Table 5-3).

The concepts listed in Table 5-2, with the exception of the DC-10 Improved Cabin Air System and the DC-9 Nacelle Drag Reduction concepts, were also subjected to an analysis of their sensitivity to technical and economic risk. Technical risk was assessed in terms of the best, most likely, and worst TSFC performance that can be expected with each concept. Economic risk was assessed by arbitrarily assuming a 2.6¢ per liter (10¢ per gallon) increase in the price of fuel.

Table 5-4 presents the performance improvement uncertainty range estimated for each concept.

TABLE 5-2
DETAILED CONCEPT EVALUATION RESULTS

Concept	Airplane	PBP (years) New Buy	PBP (years) Retrofit	ΔDOC (%)	Percent Fuel Savings	Cumulative Fuel Savings - 10^6 liters (gal.) New Buy	Retrofit	Total	Team Rank	Described on Page
JT9D Ceramic Outer Air Seal	747(-7/70)	0.3/0.3	0.4/0.4	-0.3/-0.3					1	36
	DC-10 (-59)	0.4	0.7	-0.2						
	Total				0.4	1120 (296)	833 (220)	1953 (516)		
JT8D Revised HPT Cooling & Outer Air Seal	727	3.9	5.4	-0.1					2	42
	DC-9/737	5.2	7.3	-0.1						
	Total				0.4	189(50)	151(40)	340(90)		
JT8D HPT Root Discharge Blade	727	0	0	-0.3*					3	47
	DC9/737	0	0	-0.3*						
	Total				0.75*	144(38)	836(221)	980(259)		
DC-10 Improved Cabin Air System	DC-10	0.9	0.9	-0.3	0.7	2403(635)	848(224)	3251(859)	4	53
DC-9 Nacelle Drag Reduction	DC-9	0.7	0.7	-0.1	0.5	117(31)	193(51)	322(85)	5	55
JT9D-7 3.8 AR Fan	747	0.9	9.6	-0.8	1.5	2725(720)	0	2725(720)	6	58
JT8D Trenched Tip HPC	727	1.2	5.0	-0.4					7	64
	DC-9	1.4	6.0	-0.4						
	Total				1.0	310(82)	723(191)	1033(273)		
JT9D Trenched Tip HPC	747(-7/70)	0.1/0.1	0.7/0.2	-0.3/-0.3					8	70
	DC-10 (-59)	0.1	0.3	-0.2						
	Total				0.3	1071 (283)	795 (210)	1866 (493)		

*Relative to JT8D Revised HPT Cooling and Outer Air Seal

TABLE 5-2 (Cont'd)
DETAILED CONCEPT EVALUATION RESULTS

Concept	Airplane	PBP (years) New Buy	PBP (years) Retrofit	ΔDOC (%)	Percent Fuel Savings	Cumulative Fuel Savings - 10^6 liters (gal.) New Buy	Retrofit	Total	Team Rank	Described on Page
JT9D 16-Strut Intermediate Case	747(-7/70)	0.3/0.3	6.2/6.1	-1.0/-1.0					9	74
	DC-10 (-59)	0.5	9.2	-0.8						
	Total				1.1	2831 (748)	0/0	2831 (748)		
JT9D Thermal Barrier Coating	747(-7/70)	0/0	0/0	-0.3/-0.3					10	79
	DC-10 (-59)	0		-0.3						
	Total				0.2	560 (148)	420 (111)	980 (259)		
JT9D-70/59 4.2 AR Fan	747	0	7.6	-0.9					11	86
	DC-10	0	11.5	-0.8						
	Total				1.5	1571(415)	0	1571(415)		
JT9D-70/59 HPT Improved Active Clearance Control	747	1.0	6.0	-0.3					12	90
	DC-10	2.1	11.7	-0.3						
	Total				0.9	1771(468)	0	1771(468)		
JT9D-7 Structural FEGV	747	0	12.2	-0.35	0.6	833(220)	0	833(220)	13	96
JT9D 70/59 Structural FEGV	747	0	17.0	-0.3	0.3	439(116)	0	439(116)		
	DC-10	0	28.6	-0.2						

TABLE 5-3

NASA SELECTED CONCEPTS AND ASSOCIATED FUEL SAVINGS

	Fuel Saved ~ 10^6 Liters (Gal.)		
JT8D	**New Engines**	**Retrofit Engines**	**Total**
Revised HPT Cooling and Outer Air Seal	189(50)	151(40)	340(90)
HPT Root Discharge Blade	144(38)	836(221)	980(259)
Trenched Tip HPC	310(82)	723(191)	1033(273)
DC-9 Nacelle Drag Reduction	117(31)	204(54)	310(85)
Total JT8D	760(201)	1911(506)	2663(707)
JT9D			
HPT Improved Active Clearance Control	1771(468)	0	1771(468)
3.8 AR Fan	2725(720)	0	2725(720)
Trenched Tip HPC	1071(282)	794(210)	1865(492)
Ceramic Outer Air Seal	1120(296)	833(220)	1953(516)
Thermal Barrier Coating	560(148)	420(110)	980(258)
Total JT9D	7247(1914)	2047(540)	9294(2454)

TABLE 5-4

RISK ANALYSIS
PERFORMANCE IMPROVEMENT UNCERTAINTY

Rank	Concept	Cruise Performance Improvement - % Worst	Expected	Best
1	JT9D-7 and -70/59 Ceramic Outer Air Seal	0	0.3*	0.6
2	JT8D Revised HPT Cooling and Outer Air Seal	0.3	0.5*	0.7
3	JT8D HPT Root Discharge Blade	0.7	0.95*	1.15
4	DC-10 Improved Cabin Air System			
5	DC-9 Nacelle Drag Reduction			
6	JT9D-7 3.8 AR Fan	1.0	1.3*	1.6
7	JT8D Trenched Tip HPC	0.7	0.9*	1.1
8	JT9D-7 Trenched Tip HPC	0.2	0.3*	0.5
	JT9D-59/70 Trenched Tip HPC	0.1	0.25*	0.4
9	JT9D 16-Strut Intermediate Case**	-0.5	0.0	0.9*
10	JT9D Thermal Barrier Coating	0	0.2*	0.2
11	JT9D-70/59 4.2 AR Fan	1.0	1.4*	1.8
12	JT9D-70/59 HPT Improved Active Clearance Control	0.7	0.9*	1.0
13	JT9D-7 Structural FEGV	-0.1	0.2	0.5*
	JT9D-70/59 Structural FEGV	-0.1	0.1	0.3*

*Used in Detailed Evaluation

**Details on additional risk assessment of this concept are presented in Section 5.2.9, page 74.

Table 5-5 presents the effects of performance uncertainty on PBP. An examination of the case of worst performance shows that the JT9D Ceramic Outer Air Seal, the JT9D 16-Strut Intermediate Case, the JT9D Thermal Barrier Coating, and the JT9D Structural FEGV result in no fuel savings and would therefore be unacceptable. The worst performance in the case of the JT8D Outer Air Seal results in a PBP of 12.4 years for new buy and 17.2 years for retrofit, and would therefore be unacceptable. The remainder of the concepts subjected to the risk analysis remain acceptable even in the case of worst performance. It should be noted that in the case of two concepts, the JT9D 16-Strut Intermediate Case and the JT9D Structural FEGV, the detailed evaluation used a level of performance that was actually the best that could be expected. If the most likely, or expected, value of performance had been used, the 16-Strut Intermediate Case would have shown no fuel savings and would have therefore been eliminated from further consideration. In the case of the Structural FEGV, the expected level of performance would still result in economic acceptability; however, its fuel savings would decrease from 834 million liters to 333 million liters, as shown in Table 5-6.

Table 5-6 presents the impact of performance risk on fuel saved. The fuel saved values represent the combined effect of performance change and the number of candidate engines as affected by any change in economic acceptability due to performance changes.

Table 5-7 shows the impact on PBP of an increase in fuel price of 2.6¢ liter (10¢/gal.). As expected, all concepts have improved economic acceptability at higher fuel prices. Concepts previously not attractive for retrofit but meeting the less than 6.0 year limit at the higher fuel price are the JT9D-70/59 Improved Active Clearance Control and the JT9D 16-Strut Intermediate Case.

TABLE 5-5

RISK ANALYSIS PERFORMANCE/PAYBACK PERIOD

Concept	Performance Uncertainty	PBP - Years			
		747 or 727		DC10 or DC9	
		New Buy	Retrofit	New Buy	Retrofit
JT9D Ceramic Outer Air Seal					
-7	Expected*(E)	0.3	0.4	-	-
	Best (B)	0.2	0.2	-	-
	Worst (W)	No Fuel Saved		-	-
-70/59	E*	0.3	0.3	0.4	0.7
	B	0.2	0.2	0.6	0.9
	W	No Fuel Saved			
JT8D Revised HPT Cooling and Outer Air Seal	E*	3.9	5.4	5.2	7.3
	B	2.4	3.3	2.9	4.1
	W	12.4	17.2	24.6	34.2
JT8D HPT Root Discharge Blade	E*	0	0	0	0
	B	0	0	0	0
	W	0	0	0	0
JT9D-7 3.8 AR Fan	E*	0.9	9.6	-	-
	B	0.7	7.8	-	-
	W	1.1	12.0	-	-
JT8D Trenched Tip HPC	E*	1.2	5.0	1.4	6.0
	B	1.0	4.2	1.2	5.1
	W	1.5	6.3	1.8	7.7
JT9D Trenched Tip HPC					
-7	E*	0.1	0.7	-	-
	B	0.6	0.4	-	-
	W	0.12	1.0	-	-
-70/59	E*	0.1	0.2	0.1	0.3
	B	0.06	0.1	0.08	0.14
	W	0.2	0.4	0.3	0.5
JT9D-7 and 59/70 16-Strut Intermediate Case	E	No Fuel Saved			
	B*	0.3	6.1	0.5	9.2
	W	No Fuel Saved			

*Used in Detailed Evaluation

TABLE 5-5 (Cont'd)

RISK ANALYSIS PERFORMANCE/PAYBACK PERIOD

Concept	Performance Uncertainty	PBP - Years 747 or 727 New Buy	PBP - Years 747 or 727 Retrofit	PBP - Years DC10 or DC9 New Buy	PBP - Years DC10 or DC9 Retrofit
JT9D Thermal Barrier Coating					
	E*	0	0		
	B	0	0		
	W	No Fuel Saved			
JT9D-70/59 4.2 AR Fan	E	0	7.6	0	11.5
	B*	0	6.5	0	10.1
	W	0	9.1	0	13.4
JT9D-70/59 HPT Improved Active Clearance Control	E*	1.0	6.0	2.1	11.7
	B	.9	5.4	1.9	10.4
	W	1.3	7.6	2.8	15.3
JT9D Structural FEGV					
-7	E	0	25.0		
	B*	0	12.2		
	W	No Fuel Saved			
-70/59	E	0	40.0	0	54.0
	B*	0	17.0	0	28.6
	W	No Fuel Saved			

*Used in Detailed Evaluation

TABLE 5-6

RISK ANALYSIS PERFORMANCE/CUMULATIVE FUEL SAVED

Concept	Performance Uncertainty	Cumulative Fuel Saved x 10^6 – liters (gal)		
		New Buy	Retrofit	Total
JT9D-7/70/59 Ceramic Outer Air Seal	(E)*	560 (148)	420 (111)	980 (259)
	(B)	560 (148)	420 (111)	980 (259)
	(W)	0	0	0
JT8D Revised HPT Cooling and Outer Air Seal	(E)*	189 (50)	151 (40)	341 (90)
	(B)	265 (70)	553 (146)	818 (216)
	(W)	0	0	0
JT8D HPT Root Discharge Blade	(E)*	144 (38)	836 (221)	980 (259)
	(B)	174 (46)	1022 (270)	1196 (316)
	(W)	110 (29)	628 (166)	738 (195)
JT9D-7 3.8 AR Fan	(E)*	2725 (720)	0	1033(273)
	(B)	3354 (886)	0	1260(333)
	(W)	2097 (554)	0	242(64)
JT8D Trenched Tip HPC	(E)*	310(82)	723(191)	1033 (273)
	(B)	378(100)	882(233)	1260 (333)
	(W)	242(64)	0	242 (64)
JT9D-7 Trenched Tip HPC	(E)*	541 (143)	519 (137)	1060 (280)
	(B)	897 (237)	859 (227)	1756 (464)
	(W)	363 (96)	348 (92)	712 (188)

*Used in Detailed Evaluation

TABLE 5-6 (Cont'd)

RISK ANALYSIS PERFORMANCE/CUMULATIVE FUEL SAVED

Concept	Performance Uncertainty	Cumulative Fuel Saved x 10^6 liters (gal) New Buy	Retrofit	Total
JT9D-70/59 Trenched Tip HPC	(E)*	530 (140)	276 (73)	806 (213)
	(B)	878 (232)	458 (121)	1336 (353)
	(W)	356 (94)	185 (49)	541 (143)
JT9D-70/59 16-Strut Intermediate Case	(E)	0	0	0
	(B)*	2831 (748)	0	2831 (748)
	(W)	0	0	0
JT9D Thermal Barrier Coating	(E)*	1120 (296)	832 (220)	1952 (516)
	(B)	2240 (592)	1665 (440)	3905 (1032)
	(W)	0	0	0
JT9D-70/59 4.2 AR Fan	(E)*	1571 (415)	0	1571 (415)
	(B)	2021 (534)	0	2021 (534)
	(W)	1120 (296)	0	1120 (296)
JT9D-70/59 HPT Improved Active Clearance Control	(E)*	1771 (468)	0	1771 (468)
	(B)	1968 (520)	189 (50)	2157 (570)
	(W)	1382 (365)	0	1382 (365)
JT9D-7 Structural FEGV	(E)	144 (38)	0	144 (38)
	(B)*	439 (116)	0	439 (116)
	(W)	0	0	0
JT9D-70/59 Structural FEGV	(E)	333 (88)		333 (88)
	(B)*	834 (220)		834 (220)
	(W)	0	0	0

*Used in Detailed Evaluation

TABLE 5-7

RISK ANALYSIS – FUEL PRICE/PAYBACK PERIOD

EFFECT OF 2.6¢ LITER (10¢ /GAL) INCREASE IN FUEL PRICE

	PBP - Years							
	747 or 727				DC10 or DC9			
	New Buy		Retrofit		New Buy		Retrofit	
Fuel Price / Concept	Base	+10¢	Base	+10¢	Base	+10¢	Base	+10¢
JT9D Ceramic Outer Air Seal								
-7	0.3	0.3	0.4	0.4	–	–	–	–
-70/59	0.4	0.3	0.7	0.4	0.4	0.4	0.7	0.6
JT8D Outer Air Seal	3.9	3.3	5.4	4.6	5.2	4.2	7.3	6.1
JT8D HPT Root Discharge Blade	0	0	0	0	0	0	0	0
JT9D-7 3.8 AR Fan	0.9	0.8	9.6	8.2	–	–	–	–
JT8D Trenched HPC	1.2	1.0	5.0	4.4	1.4	1.2	6.0	5.3
JT9D Trenched Tip HPC								
-7	0.1	0.1	0.7	0.6	–	–	–	–
–70/59	0.1	0.1	0.2	0.2	0.1	0.1	0.3	0.2
JT9D 16 Strut Intermediate Case								
-7	0.3	0.3	6.2	5.5	–	–	–	–
–70/59	0.3	0.3	6.1	5.6	0.5	0.4	9.2	8.2
JT9D Thermal Barrier Coating								
-7	0	0	0	0				
–70/59	0	0	0	0	0	0	0	0
JT9D-70/59 4.2 AR Fan	0	0	7.6	6.6	–	–	–	–
JT9D-70/59 HPT Improved Active Clearance Control	1.0	0.8	6.0	4.9	2.1	1.7	11.7	9.2
JT9D Structural FEGV								
-7	0	0	17.0	14.8	0	0	28.6	24.7
–70/59	1.0	0.8	6.0	4.9	2.1	1.7	11.7	9.2

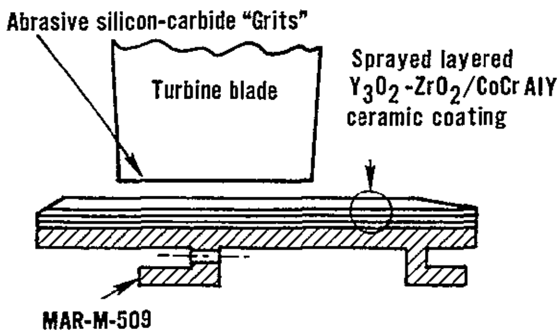
Introduction

The following subsections describe in detail those concepts recommended for further ECI development and demonstration. The discussions appear in the P&WA evaluation team ranked order and include a description of the concept, performance substantiation, and results of the economic evaluation of the concept with respect to engine performance data, airline costs, and fuel savings.

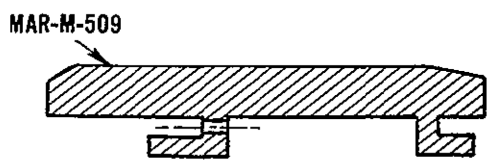
5.2.1 JT9D Ceramic Outer Air Seal

Concept Description

Reduced turbine blade tip clearance can be achieved through the application of an abradable coating to the turbine outer air seal segments as shown in Figure 5-1. Currently, the JT9D high pressure turbine blade tips run against a solid metal seal because available abradable materials have been found to be unacceptable in this environment. The modification applies advanced ceramic coating techniques to obtain an abradable seal surface and an abrasive blade tip treatment.



Abradable ceramic seal segment (reduced number of segments)



Current production seal segment (36 segments in JT9D-7, 56 in JT9D-70)

Figure 5-1 JT9D Turbine Outer Air Seal: Improved version (top) and current production seal (bottom).

The seal system selected is a sprayed yttria stabilized zirconia system, initially investigated under the Ref. 3 contract and continued under the Ref. 4 and 5 contracts. The tips of the turbine blades are treated with abrasive silicon carbide grits so that in the event of a rub, reduction of blade length due to the rub interaction is held to a minimum and the ceramic material is abraded away.

Use of the graded ceramic/metal layer minimizes thermal stresses that would otherwise exist at the interface of a low thermal expansion ceramic material on a high thermal expansion metal. Figure 5-2 is a cross-section showing how the graded layers vary from the metal rich at the metal surface to zirconia rich at the ceramic layer.

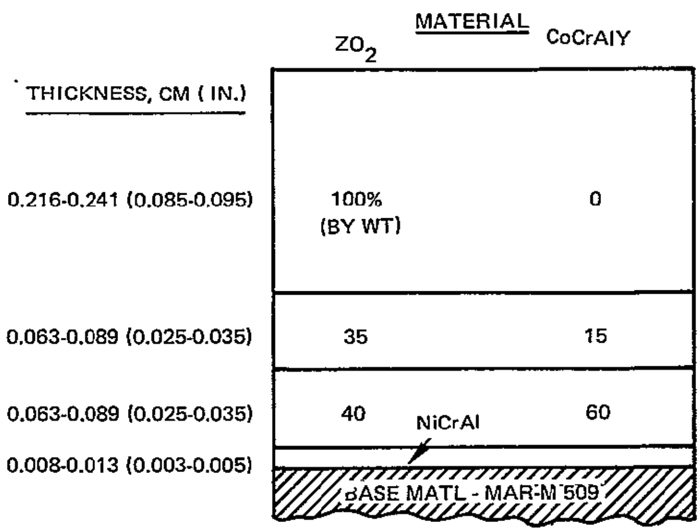


Figure 5-2 Schematic of Sprayed Graded Ceramic/Metal Structure

Yttria (Y_2O_3) is added to the zirconia to act as a stabilizer to prevent a phase transformation of the zirconia, which occurs in the 980 - 1095°C (1800 - 2000°F) temperature range along with a 10% volume change. This volume change can cause destructive internal stresses.

The potential benefits of the ceramic seal are as follows:

- Reduced tip clearance allows higher turbine efficiency and lower fuel consumption.
- Increase in tip clearance resulting from rubs is minimized resulting in less performance loss.
- Insulating qualities of ceramic material reduce temperature of metal seal support.

The turbine efficiency benefit for blade tip clearance reduction for a typical commercial engine is shown in Figure 5-3. Since current turbine seals are generally not abradable, rotor wear and damage results from tip rubs; therefore, a conservative approach is taken in establishing turbine operating clearances.

Rubbing between the blade tips and the static seal shroud can be caused by shroud seal distortions, rotor bending and abnormal engine operation when operating with tight clearances. Since rub interactions usually occur on all blade tips, but only locally on the seal shroud, the rubbing action wears down the blade tips when the conventional metallic seal shroud is used. Figure 5-4 illustrates the advantage of an abradable seal in minimizing the effect of rubs on tip clearance.

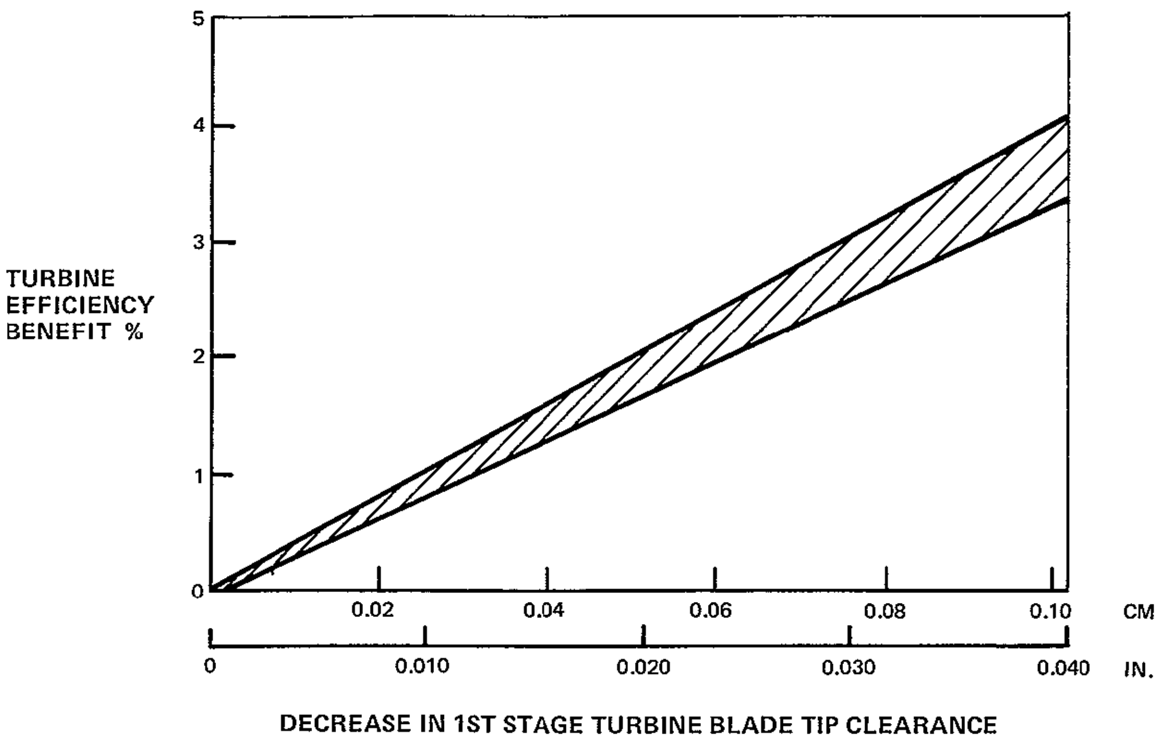


Figure 5-3 Turbine Efficiency and Blade Tip Clearance

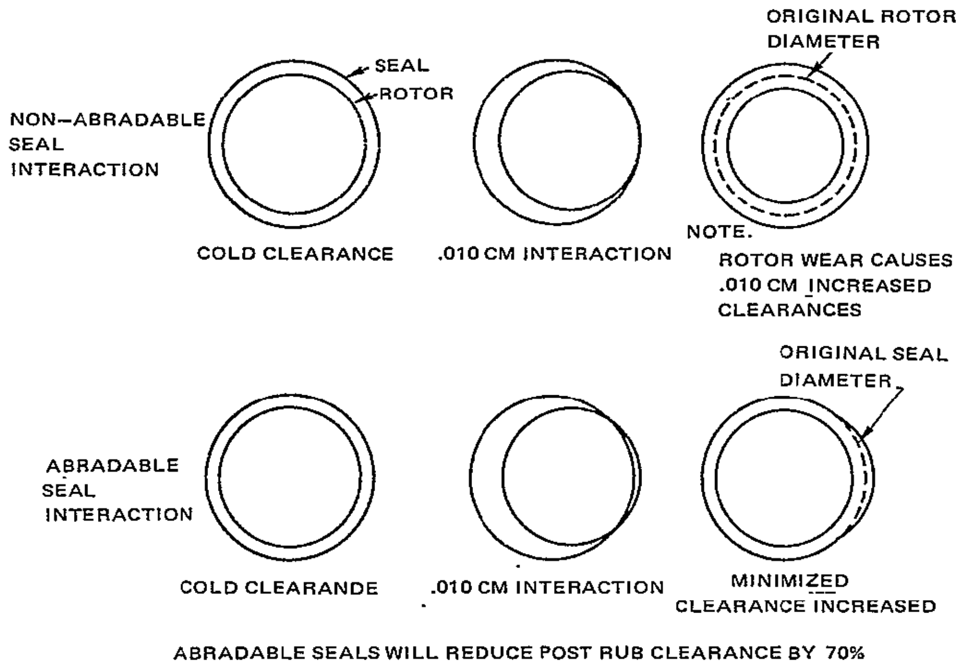


Figure 5-4 Effect of Rubbing on Rotor-To-Seal Clearance

By providing a seal system with a ceramic insulating surface, the temperature of the metal support as well as the thermal stresses will be reduced considerably. As a result it may be possible to:

1) increase the size of the seal segments

2) reduce the amount of required cooling air

3) utilize a less expensive base material

Since current JT9D engines employ 1% or less of engine airflow for outer air seal cooling, a modest reduction in this cooling flow would have an insignificant effect on TSFC.

Advanced engines, however, with higher turbine temperatures will require much greater amounts of cooling air for the seals unless improvements such as a ceramic seal system are developed.

Performance Substantiation

High turbine ceramic outer air seal development work began in 1972 under company funded and government programs. Under Contract N00140-74-C-0586, directed to the development of an advanced turbine high temperature blade tip seal, engine-testing was conducted on the JT9D-7 consisting of 31 hours and 17 thermal cycles. This testing revealed that a graded metallic/ceramic system attached to a metallic substrate was technically feasible for a high turbine seal application.

Through analysis and testing conducted on past JT9D programs, it has been conservatively estimated that a 0.0254 cm (0.010 in.) reduction in tip clearance is possible with an abradable outer air seal. Applying this reduction to both stages of the high pressure turbine results in an estimated turbine efficiency improvement of 0.7%.

Economic Evaluation

The turbine efficiency improvement translates into an engine TSFC improvement of 0.32% at cruise, as shown in Table 5-8. The application of ceramic to the seal shoes results in a price increase, but the increase is small because it was assumed that the number of shoes can be reduced. As a result, the payback period is less than one year in all cases, as shown on Table 5-9. Applying the concept to all JT9D-7 and JT9D-70/59 engines starting in 1982 will result in a fuel savings of nearly 2 billion liters, as shown on Table 5-10.

TABLE 5-8

JT9D CERAMIC OUTER AIR SEAL
ENGINE DATA
Per Engine (-7 and -70/59)

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0.56	6
Climb	0.32	3
Cruise, Avg.	0.32	
Hold	0.7	
Weight Change, Kg (Lb.)	0	
Price Change, $	+3,400	
Kit Price, $	+5,000 (Attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	+0.70	
Labor @ $30 Per Man-Hr.	-2.54	

TABLE 5-9

JT9D CERAMIC OUTER AIR SEAL
AIRLINE COSTS
Per Aircraft

Airplane Model	**747-200**		**DC10-40**	
Operating Costs Changes, $/Year	-7	-70/59	-70/59	
Fuel	-31,830.	-34,100	-13,230	
Maintenance	-33,600.	-33,700	-18,940	
Block Speed Effect	-200.	-200	-500	
Total	-65,630	-68,000	-32,670	
Type of Investment	**New Buy**	**Retrofit**	**New Buy**	**Retrofit**
Required Airline Investment Changes, $	-7&-70/59	-7&-70/59	-70/59	-70/59
Installed Engines	+13,600	+20,000	+10,200	+15,000
Spare Engines	+3,710	+5,450	+2,350	+3,450
Spare Parts	+2,720	+4,000	+2,040	+3,000
Total	+20,030	+29,450	+14,590	+21,450
Payback Period, Years	0.3	0.4	0.4	0.7
DOC Change, %	-0.3		-0.2	

TABLE 5-10

JT9D CERAMIC OUTER AIR SEAL
FUEL SAVINGS

Fleet Fuel Saved, % 0.4

Start of Service Date 1-82

Investment Type		**New Buy**	**Retrofit**	**Total**
No. of Engines Affected	-7	810	2,070	2,880
	-70/59	810	460	1,270
Cum. Fuel Saved, 10^6 liters (gal).	-7	560 (148)	583 (154)	1143 (302)
	-70/59	560 (148)	250 (66)	810 (214)
			Total	1953 (516)

5.2.2 JT8D Revised HPT Cooling and Outer Air Seal

Concept Description

In a JT8D engine, the high-pressure turbine efficiency is inversely proportional to blade tip seal leakage. Many design factors including materials, operating temperatures, and mechanical design requirements determine the operating tip seal leakage.

The current JT8D-15/17 high-pressure turbine blade tip leakage is controlled by a single knife edge on the blade tip running against a nickel-base abradable honey-comb stationary outer strip. Figure 5-5 compares the current outer air seal with the proposed configuration described in the following paragraph.

A significant reduction of seal leakage can be achieved by adding an additional knife edge seal to the blade tip, increasing the width of the honey comb strip, and altering the material of the support ring from Hastelloy C to Hastelloy S to better match the thermal expansion of the disk. The high-pressure turbine blade is aircooled through 11 radial holes discharging out of the tip. Incorporation of an additional shroud knife edge and utilization of the spoiler as a seal to improve outer airseal performance would restrict cooling flow in the first seven holes, resulting in higher metal temperatures and a decrease in airfoil life. In order to maintain the present cooling flow several revisions have been made to the airfoil cooling scheme. The first four leading edge holes have been vented to the convex (suction) side of the foil and the next three holes have been vented to the rear of the spoiler as shown in Figure 5-5. Increased flow restriction due to the new cooling path through the blade is compensated by the decreased exit pressure, so that the flow rate and cooling capacity remain the same. Venting of the cooling air to the suction side does, however, reduce flow to the tip region of the airfoil and consequently increases its temperature. The increased tip metal temperature does not reduce the life of the airfoil since it is still below the life limiting temperature.

Performance Substantiation

The revised seal configuration will provide leakage reduction as a function of radial seal clearance as shown on Figure 5-6. This leakage reduction is achieved by the added sealing surfaces provided by the second knife edge and use of the spoiler as a sealing surface, plus the change of the support ring material. Seal operating clearance is established by adjusting the cold seal clearance so that the knife edges and the honey comb just touch during the critical transient condition. This condition occurs during deceleration from a stabilized sea level take-off power to idle power, as shown on Figure 5-7. Cruise clearance between the knife edges and the honey comb is 0.096 cm (0.038 in.) for the current seal configuration. The substitution of Hastelloy S, with its reduced thermal coefficient of expansion, will permit reduction of cruise clearance to 0.089 cm (0.035 in.).

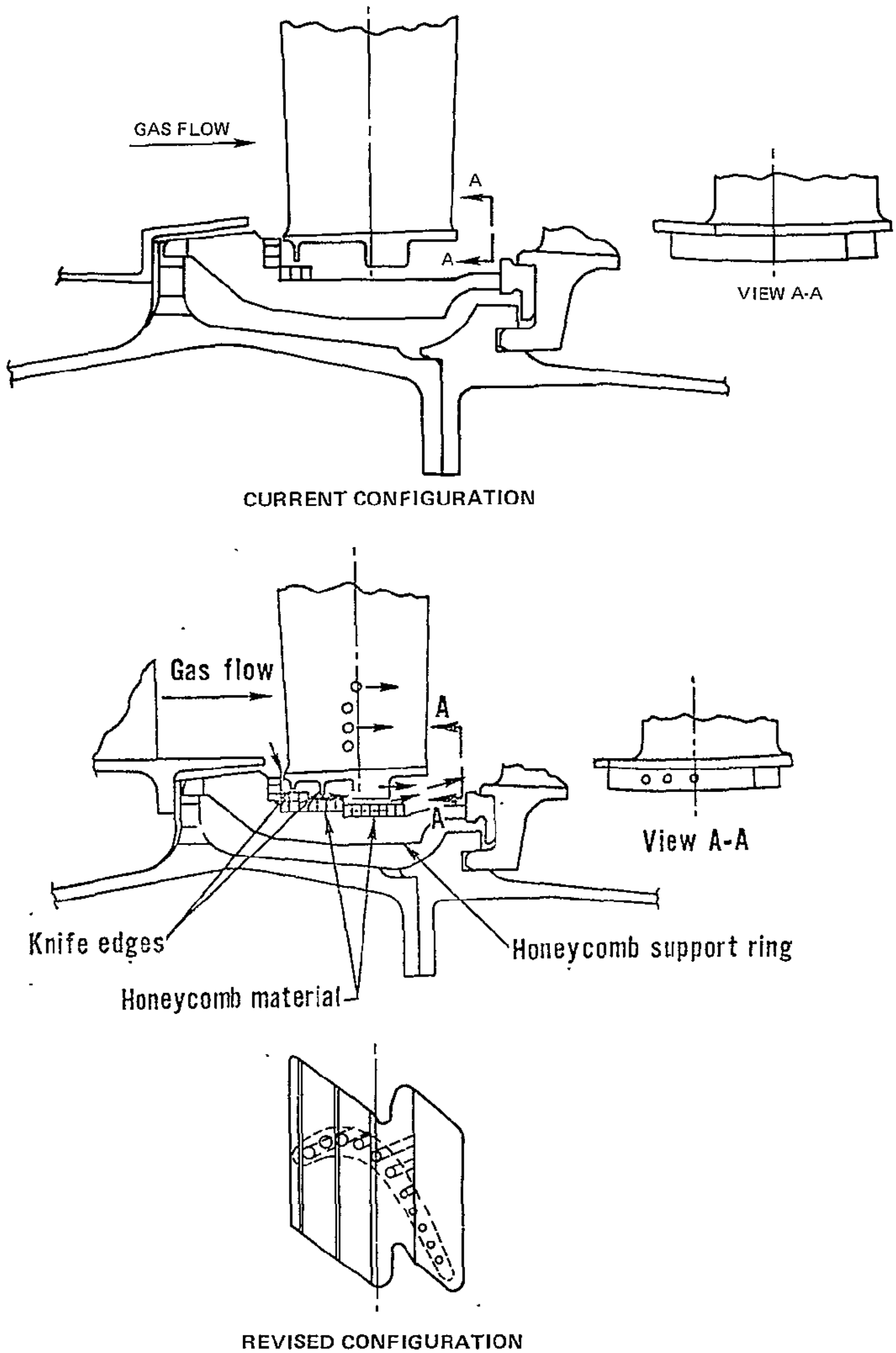


Figure 5-5 Comparison of Current and Revised Outer Air Seal Configuration

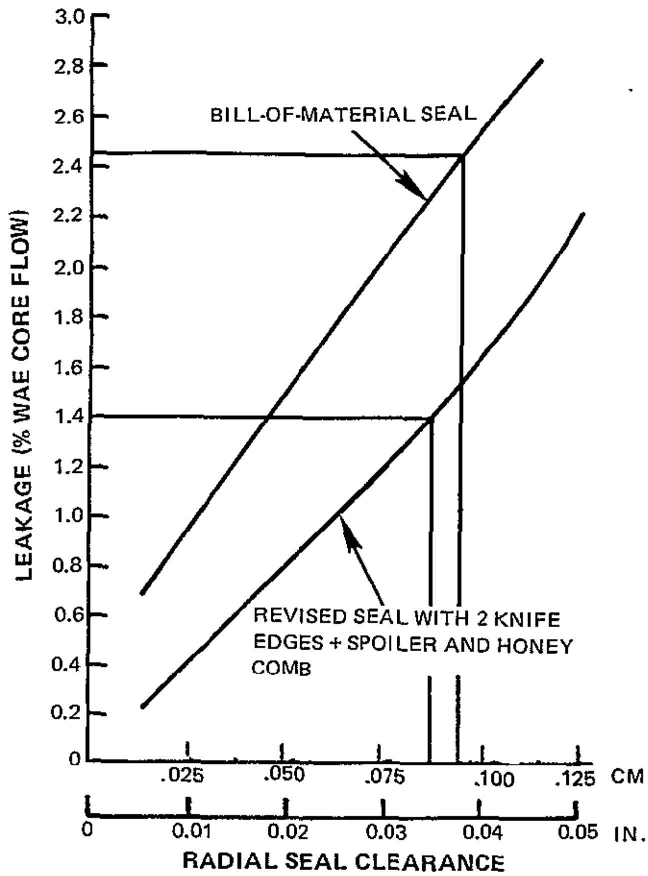


Figure 5-6 *Comparison of First-Stage Turbine Outer Air Seal Leakage as a Function of Clearance for the JT8D-15 Engine*

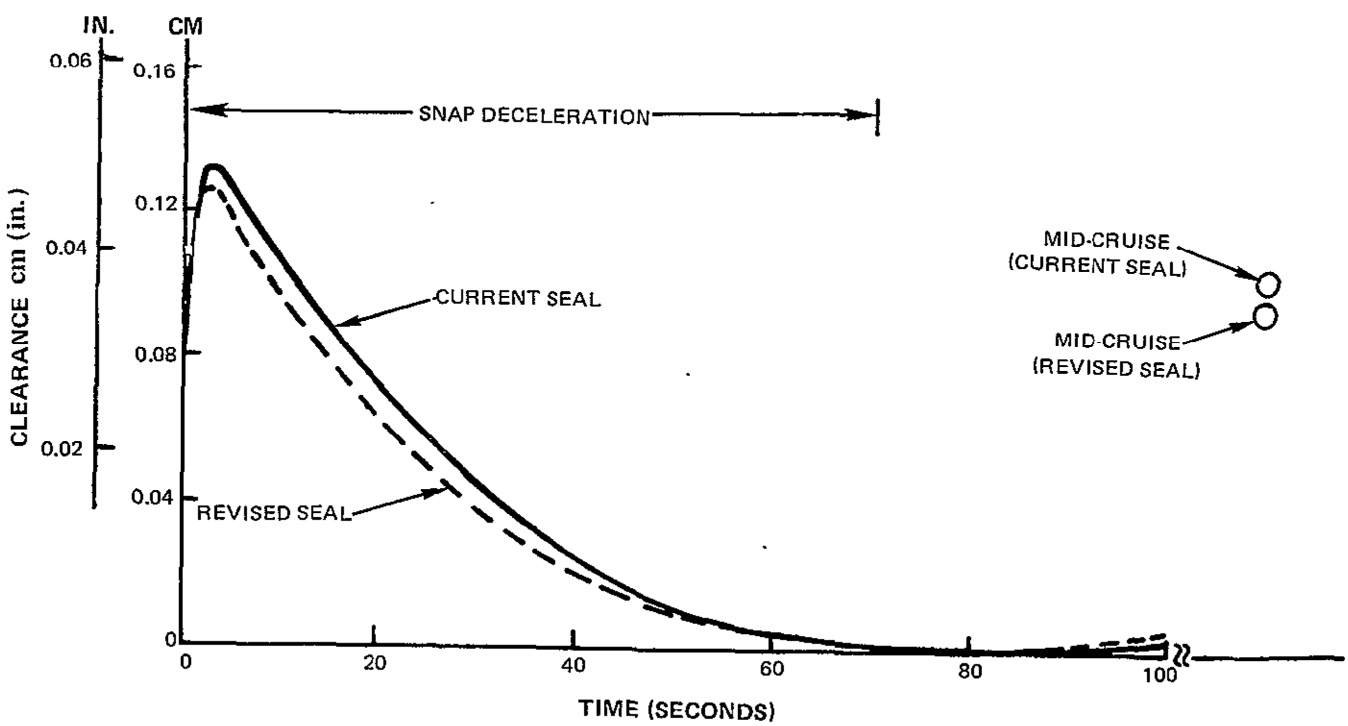


Figure 5-7 *Pinch Curve for the JT8D-15 Engine with Current and Revised Outer Air Seals*

Using these clearances and Figure 5-6, the following cruise clearances and leakages may be tabulated for the current seal and the revised seal:

	Cruise Clearance cm (in.)	Leakage (% WAE)
Bill-of-Materials Seal	0.096(0.038)	2.45
Revised Seal	0.089(0.035)	1.40
Net Reduction in Leakage		1.05

An influence coefficient for leakage past the high-pressure turbine blade tip based on analysis and past experience, may be stated as:

1% leakage reduction = 1% high-pressure turbine efficiency increase

On this basis, the 1.05 percent leakage reduction from Figure 5-6 translates into an efficiency increase of 1.05 percent. However the discharge of about 50% of the blade cooling air on the convex (suction) surface of the turbine blade results in a loss of momentum because of the injection of the low-velocity cooling air into the relatively high-velocity gas stream. This momentum loss is equivalent to a loss in high-pressure turbine efficiency of 0.24 percent.* When these two effects are combined (+1.05 − 0.24), the net resulting improvement in turbine efficiency is 0.81 percent.

An increase in turbine efficiency increases the power available to drive the high-pressure compressor. This increase in power results in an increased high-pressure compressor speed and an accompanying increase in air flow and pressure ratio. These cycle improvements permit a reduction in fuel flow for a given level of thrust. The combined effects were determined by computer analysis, and are summarized in Table 5-11. These data are for standard day cruise conditions at a representative altitude and Mach number for each aircraft type. Improvements in TSFC for other conditions for the two aircraft are also presented in Table 5-11.

* Subsequent investigation indicated that this analysis was pessimistic, since no credit was taken for the favorable momentum effects of reducing the cooling flow discharged from the blade tip.

Another benefit of increased turbine efficiency is a reduction of the exhaust gas temperature required to attain rated thrust. This effect results in an increase of the required shop-visit interval and a slight increase in expected component life.

Economic Evaluation

Tables 5-11, 5-12, and 5-13 present the economic evaluation of the concept in terms of engine performance data, airline costs, and fuel savings, respectively. In Table 5-11, the manufacturing cost of the revised HPT blade and OAS is increased due to the added manufacturing steps for weld-plugging cooling passages and drilling intersecting holes on the blade. The seal cost is increased due to the extension of honeycomb material under the spoiler.

TABLE 5-11
JT8D REVISED HPT COOLING AND OUTER AIR SEAL
ENGINE DATA
Per Engine
JT8D-15/17

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	.20	4
Climb	.23	3
Cruise, Avg.	.50	
Hold	0	
Weight Change, Kg (Lb)	0	
Price Change, $	+7400	
Kit Price, $	10,500 (Attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	+0.90	
Labor @ $30 per Man-Hr.	-0.95	

Table 5-12 shows the concept to have acceptable PBP for new buys of both aircraft models. It is acceptable for retrofit of only the newer (less than 3 years old) 727 models, but not for DC9 models. Application to all acceptable aircraft would result in a cumulative fuel saving of 341 million liters, as shown on Table 5-13.

TABLE 5-12
JT8D REVISED HPT COOLING AND OUTER AIR SEAL
AIRLINE COSTS
Per Aircraft

Airplane Model	727-200		DC9-50	
Operating Cost Changes, $/Year				
Fuel	-7,670		-4,000	
Maintenance	-380		-220	
Block Speed Effect	-1,050		-300	
Total	-9,100		-4,520	
Type of Investment	**New Buy**	**Retrofit**	**New Buy**	**Retrofit**
Required Airline Investment Changes, $				
Installed Engines	22,200	32,500	14,650	21,000
Spare Engines	4,540	6,450	3,200	4,320
Spare Parts	8,700	11,250	5,740	7,480
Total	35,440	49,200	23,600	32,800
Payback Period, Years	3.9	5.4	5.2	7.3
DOC Change, %	-0.1		-0.1	

TABLE 5-13
JT8D REVISED HPT COOLING AND OUTER AIR SEAL
FUEL SAVINGS

Fleet Fuel Saved, % 0.4

Start of Service Date 1-80

Investment Type	New Buy	Retrofit	Total
No. of Engines Affected	720	780	1500
Cum. Fuel Saved, 10^6 liters (gal.)	189 (50)	151 (40)	340 (90)

5.2.3 JT8D HPT Root Discharge Blade

Concept Description

The proposed JT8D high pressure turbine root discharge blade (Figure 5-8) employs a modern improved effectiveness two-pass cooling concept with the cooling flow being discharged from the blade root into the downstream disk rim cavity, a concept which has been demonstrated successfully in a JT9D engine. This blade design replaces the B/M once-through tip discharge multi-holed cooling scheme (described in Section 5.2.2) which is modified in the suction side vent scheme to discharge about 50% of the cooling air from the airfoil suction surface (Figure 5-8). The root discharge blade design maintains acceptable metal temperatures with reduced cooling air flow.

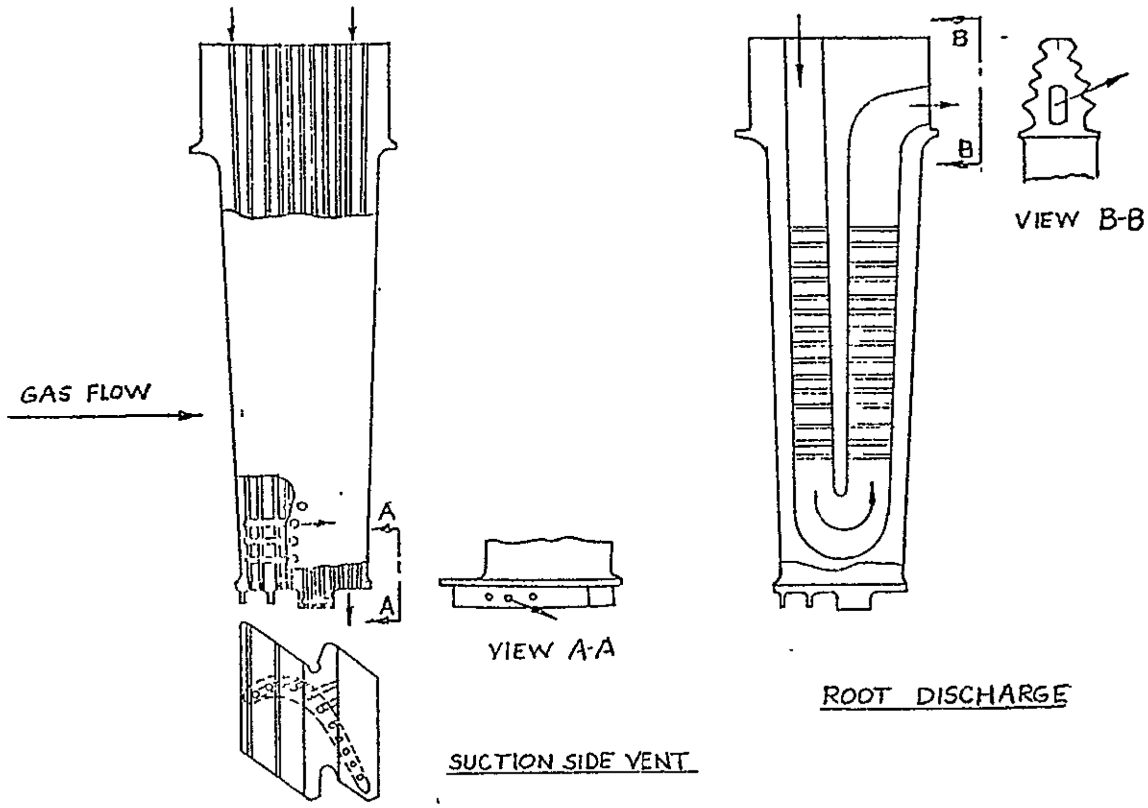


Figure 5-8 Comparison of Suction Side Vent and Root Discharge Configurations for JT8D-15/17 HPT Blade

Because of the different blade internal core configuration, the root discharge blade requires a completely new airfoil casting, which provides an opportunity to use updated materials and casting technology to reduce the airfoil trailing edge (T.E.) thickness. At the same time, some minor improvements in airfoil shape will be incorporated.

The blade tip sealing configuration of the root discharge blade is exactly the same as that described in Section 5.2.2 for the JT8D Revised HPT Cooling and Outer Air Seal, so that no change in seal leakage is expected relative to that configuration.

Performance Substantiation

Table 5-14 summarizes the performance related characteristics of the root discharge relative to the current blade and the suction side vent blade, which is part of the Revised HPT Cooling and Outer Air Seal concept (Section 5.2.2).

TABLE 5-14
JT8D HPT BLADE CHARACTERISTICS SUMMARY

	Current	Suction Side Vent	Root Disch. Blade
Seal Leakage, % Wae	2.45	1.28	1.28
Blade T.E. Thickness, in.	1.372(0.54)	1.372(0.54)	0.76(0.30)
Blade Cooling Disch. Location	100% Tip	50% Tip 50% Suction Side	100% Root
Blade Aero Design	Base	Base	Improved
Blade Cooling Flow, % Wae	1.5	1.5	1.0

Table 5-15 summarizes the turbine efficiency and TSFC improvements of the root discharge blade relative to the suction side vent configuration. The 1.11% turbine efficiency improvement shown converts to a 0.94% TSFC improvement when the cycle effects are included at a typical cruise condition of 90% max cruise power at Mach 0.8 and 10,670 meters (35,000 feet).

TABLE 5-15
JT8D HPT BLADE ROOT DISCHARGE IMPROVEMENTS

	$\Delta\eta$	TSFC
Reduced T.E. Thickness	+0.75	-0.50
Elimination of Suction Side Disch.	+0.24	-0.16
Blade Aero Refinement	+0.12	-0.08
Sub Total	+1.11	-0.74
Cycle Effect of Cooling Flow Reduction		-0.20
Total		-0.94

Reduced T. E. Thickness – A large part of the performance improvement of the root discharge blade is attributable to the reduced T. E. thickness. By redesigning the airfoil and using updated materials and casting technology, the T. E. thickness can be reduced to 0.076 cm (0.030 in.), which is 55% of the B/M thickness. Figure 5-9 shows a correlation of airfoil T. E. loss data with T. E. thickness. For comparison, a line representing 30% of the theoretical sudden expansion loss is superimposed. The data correlation indicates that the T. E. loss of the redesigned JT8D blade will be reduced to about 30% of that of the B/M blade, which is equivalent to a high pressure turbine efficiency improvement of 0.75 percentage points.

TABLE 5-17
JT8D HPT ROOT DISCHARGE BLADE
AIRLINE COSTS
Per Aircraft

Airplane Model	727-200		DC9-50	
Operating Cost Changes, $/Year				
Fuel	-11,400		-7,400.	
Maintenance	-12,700		-7,080.	
Block Speed Effect	-1,050		-300.	
Total	-25,150		-14,780	
Type of Investment	**New Buy**	**Retrofit** (Attrition)	**New Buy**	**Retrofit** (Attrition)
Required Airline Investment Changes, $				
Installed Engines	0	0	0	0
Spare Engines	0	0	0	0
Spare Parts	0	0	0	0
Total	0	0	0	0
Payback Period, Years	0	0	0	0
DOC Change, %	-0.3		-0.3	

TABLE 5-18
JT8D HPT ROOT DISCHARGE BLADE
FUEL SAVINGS

Fleet Fuel Saved, % 0.75

Start of Service Date 6-81

Investment Type	New Buy	Retrofit	Total
No. of Engines Affected	350	2320	2670
Cum. Fuel Saved, 10^6 liters (gal)	144 (38)	836 (221)	980 (259)

5.2.4 DC-10 Improved Cabin Air System

Concept Description

The Environmental Control System in the DC-10 provides conditioned air to the cabin. A comfortable cabin environment requires temperature control and circulation. The temperature controlled air is provided by air-conditioning packs that are driven by engine bleed. Studies indicate that the addition of recirculation loops in the cabin air distribution system will allow a 50% reduction in the quantity of bleed air required from the engine. Reduction in bleed air results in a direct improvement in engine fuel consumption due to the decrease in pneumatic power extraction and a reduction in turbine inlet temperature which decreases engine maintenance costs by prolonging the life of the engine hot section parts. The implementation of this concept provides the additional benefit of decreasing the cabin ozone content and improving the cabin relative humidity. Figure 5-10 is a schematic of the modified system.

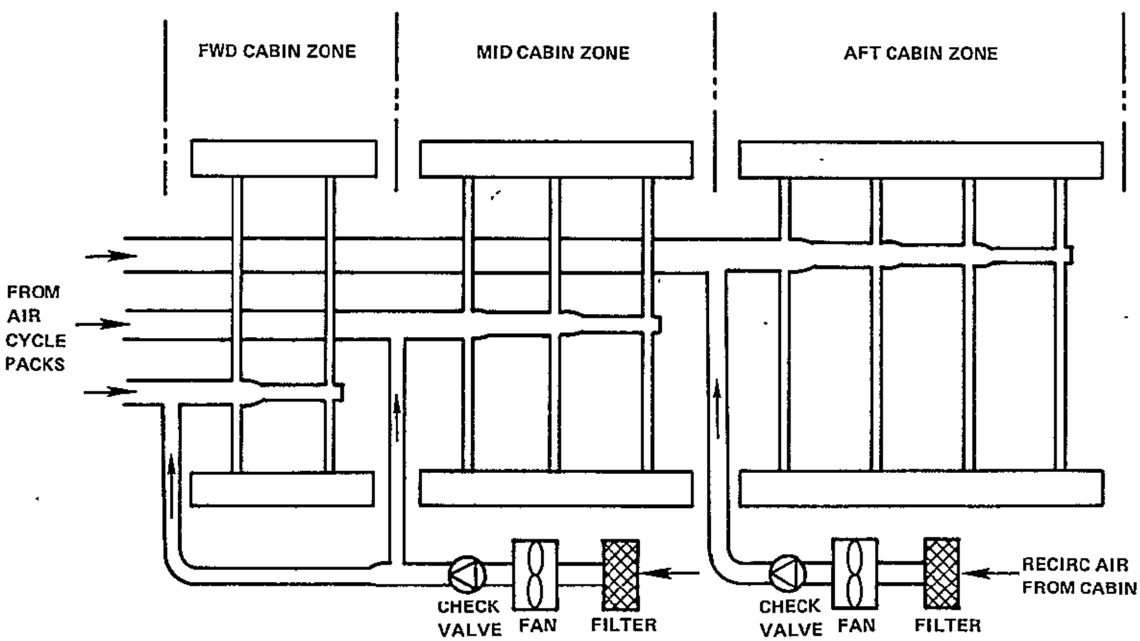


Figure 5-10 *Recirculation System Added to DC10 Environment Control System to Reduce Bleed Air Requirements from JT9D Engines*

Performance Substantiation

The recirculation system was evaluated by DAC under subcontract to P&WA. The evaluation results were very favorable in applications on all DC-10 models powered by JT9D engines.

It was estimated that the recirculation system would increase the airplane operating empty weight 84 Kg (185 lb). Engine cycle computer programs were used to calculate the change in fuel consumption due to reducing bleed flow. It should be noted that the DC-10 cabin air discharge system has a thrust recovery nozzle which minimizes the performance loss from the cabin air conditioning system. This was accounted for in the calculations.

The improved system reduces engine air bleed by 1.47 Kg/sec (3.24 lb/sec), effecting an installed equivalent TSFC improvement of 0.635 percent.

Economic Evaluation

Tables 5-19, 5-20, and 5-21 present the economic evaluation of the concept in terms of engine data, airline costs, and fuel savings, respectively. There is a direct maintenance cost increase due to the addition of the recirculating system, primarily for the cost of changing filters. However, this is more than compensated for by the reduction in engine maintenance cost because there is a decrease in takeoff and climb turbine inlet temperature when the bleed flow is reduced. Retrofit of the modified system is considered economically practical if done on a piecemeal basis.

TABLE 5-19

DC-10 IMPROVED CABIN AIR SYSTEM
ENGINE DATA
Per Engine

Performance:	**TSFC Reduction, %**	**EGT Reduction, °C**
Takeoff	0.51	4
Climb	0.79	4
Cruise, Avg.	0.64	
Hold	0.58	
Weight Change, Kg (lb)/Aircraft	84 (185)	
Price Change, $/Aircraft	+37,000	
Kit Price, $/Aircraft	Same	
Maintenance Cost Change, $/Oper. Hr.		
Materials	+0.3	
Labor @ $30 Per Man-Hr.	-2.39	

TABLE 5-20
DC-10 IMPROVED CABIN AIR SYSTEM
AIRLINE COSTS
Per Aircraft

Airplane Model	**DC10-40**	
Operating Cost Changes, $/Year		
Fuel	-24,670	
Maintenance	-20,500	
Block Speed Effect	- 840	
Total	-46,010	
Type of Investment	**New Buy**	**Retrofit**
Required Airline Investment Changes, $		
Installed Systems	+37,000	
Spares	0	
Spare Parts	+ 3,330	
Total	+40,330	
Payback Period, Years	0.9	
DOC Change, %	-0.3	

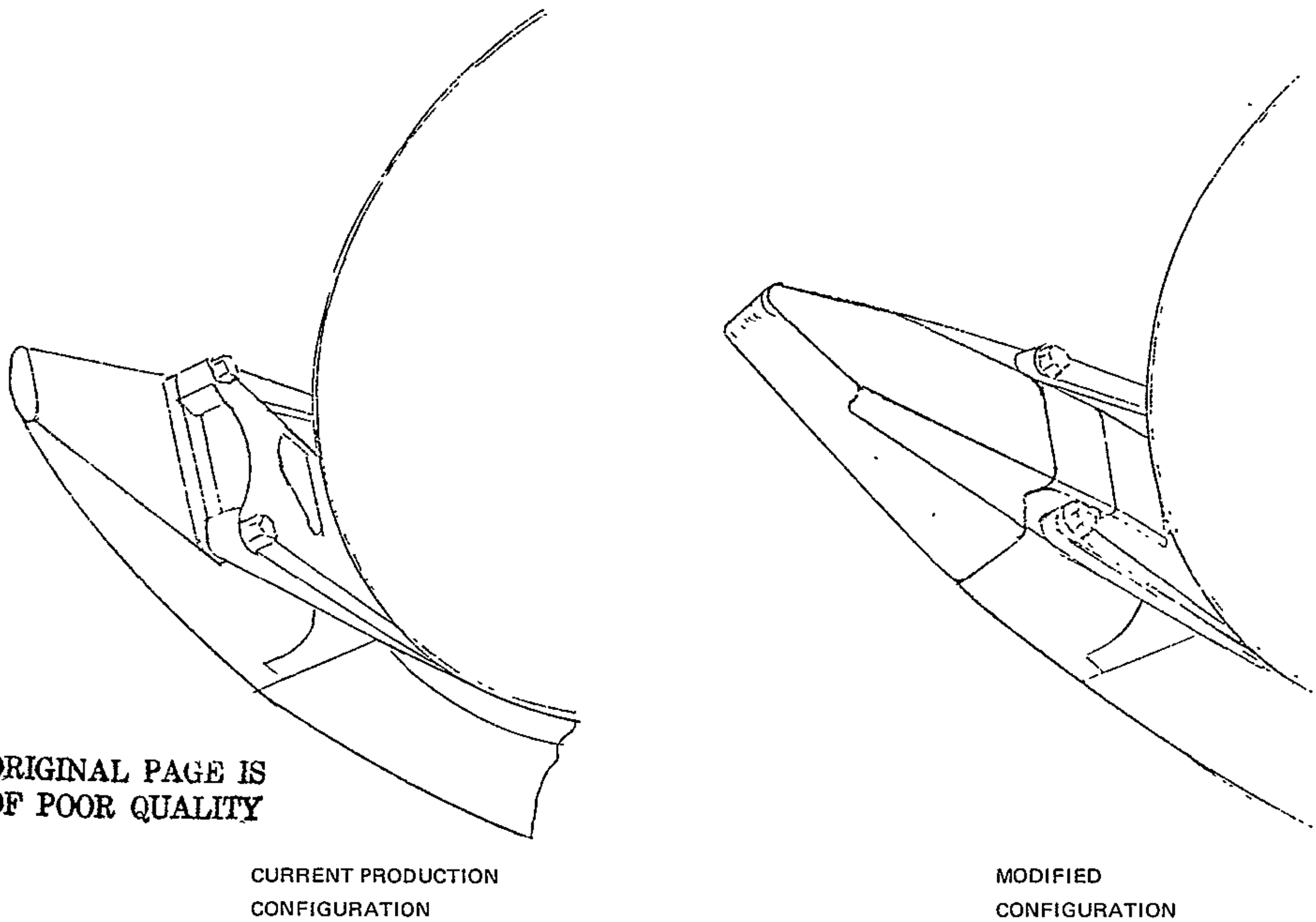
TABLE 5-21
DC-10 IMPROVED CABIN AIR SYSTEM
FUEL SAVINGS

Fleet Fuel Saved, %	0.7			
Start of Service Date	1-80			
Investment Type		New Buy	Retrofit	Total
No. of Aircraft Affected		428	270	698
Cum. Fuel Saved, 10^6 Liters (Gal.)		2403 (635)	848 (224)	3251 (859)

5.2.5 DC-9 Nacelle Drag Reduction

Concept Description

The current and modified design of the aft part of the JT8D installation on the DC-9 is shown in Figure 5-11. The thrust reverser hinge assembly in the current configuration is only partially faired, leaving a significant base area, as shown in the figure. The modified configuration reduces the base area with a more complete fairing. The new fairing is made of advanced composite materials which will tolerate the exhaust temperatures while providing improved fatigue strength and lighter weight than the current aluminum fairing.



ORIGINAL PAGE IS
OF POOR QUALITY

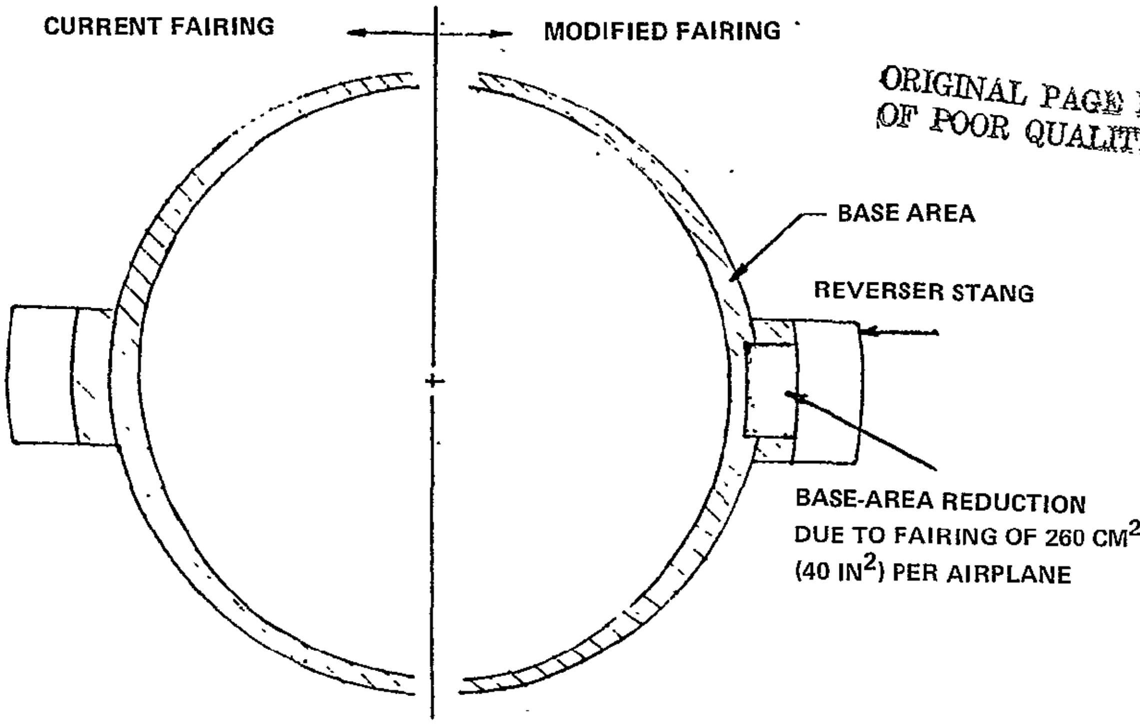
Figure 5-11 Current and Modified Exhaust Nozzle and Reverser Stangs of the Douglas DC-9 Engine Installation

Performance Substantiation

The new reverser stang fairing effects a base area reduction of 260 sq. cm (40 sq. in.) per airplane. Using the classical equation involving dynamic pressure and free stream relationships (see Figure 5-12), an effective base area reduction of 0.012 sq. m. (0.13 sq. ft.) per airplane can be calculated. This base reduction translates to 0.5% of cruise drag, with attendant fuel savings.

Economic Evaluation

Economic evaluations of the concept in terms of engine data, airline costs, and fuel savings are presented in Table 5-22, 5-23, and 5-24 respectively.



BASE-AREA REDUCTION = 260 CM^2 (40 IN^2) PER AIRPLANE

BASE-DRAG COEFFICIENT = 0.25, AND EFFECTIVE $q = \frac{1}{2}(q_{jet} + q_{\infty}) = 1.82\, q_{\infty}$ (CRUISE)

EFFECTIVE BASE AREA REDUCTION OF $\frac{D}{q_{\infty}}$ = 0.012 M^2 (0.13 FT^2) PER AIRPLANE (CRUISE)

= 0.5% OF CRUISE DRAG

Figure 5-12 Schematic Diagram of Nacelle Base

TABLE 5-22
DC-9 NACELLE DRAG REDUCTION
ENGINE DATA
Per Engine

Performance	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0	0
Climb	0.5	0
Cruise, Avg.	0.5	
Hold	0.5	
Weight Change, Kg (lb)	Neg.	
Price Change, $	1350	
Kit Price, $	1350*	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 Per Man-Hr.		

* Subsequent check indicated that the kit price is higher than the nacelle price change.

TABLE 5-22
DC-9 NACELLE DRAG REDUCTION
AIRLINE COSTS
Per Aircraft

Airplane Model	DC9-50	
Operating Cost Changes, $/Year		
Fuel	-4880	
Maintenance	0	
Block Speed Effect	- 210	
Total	-5090	
Type of Investment	**New Buy**	**Retrofit**
Required Airline Investment Changes, $		
Installed Stangs	2700	2700
Spare Engines	0	0
Spare Parts	700	700
Total	3400	3400
Payback Period, Years	0.7	0.7
DOC Change, %	-0.1	

TABLE 5-23
DC-9 NACELLE DRAG REDUCTION
FUEL SAVINGS

Fleet Fuel Saved, %	0.5			
Start of Service Date	1-79			
Investment Type		**New Buy**	**Retrofit**	**Total**
No. of Engines Affected		399	1165	1564
Cum. Fuel Saved, 10^6 Liters (Gal.)		117 (31)	204(54)	322(85)

5.2.6 JT9D-7 3.8 AR Fan

Concept Description

A lightweight single shroud 3.8 aspect ratio (AR) fan blade used with a modified fan exit guide vane has shown significant improvements in engine performance. Currently, the JT9D-7 uses a high aspect ratio, two part span shroud blade. The improved blade is lower in aspect ratio, permitting elimination of one part span shroud. The proposed configuration was based on structural analysis conducted on the JT9D-7 fan blade and an earlier and heavier 3.8 aspect ratio fan blade which provided design information for the lightweight blade.

The primary parts involved in the 3.8 AR fan improvement package include the fan blades, hub, fan exit guide vanes, nose spinner, rubstrip assembly, and fan speed electronic transmitter (see Figure 5-13).

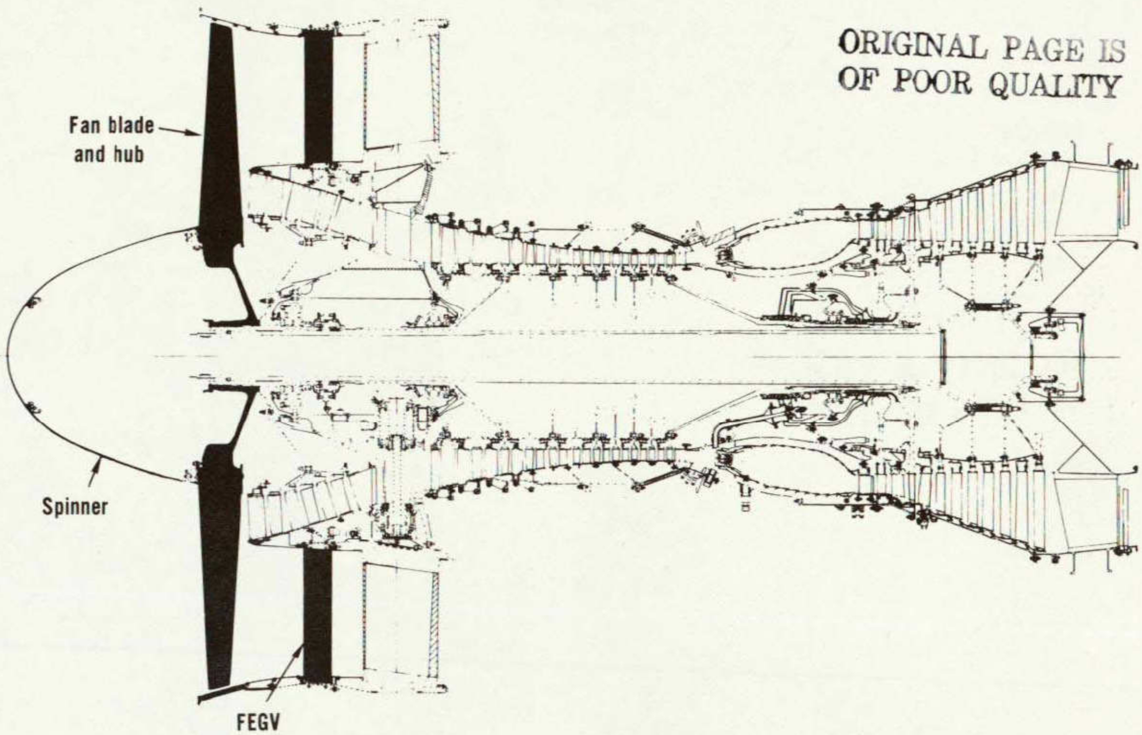


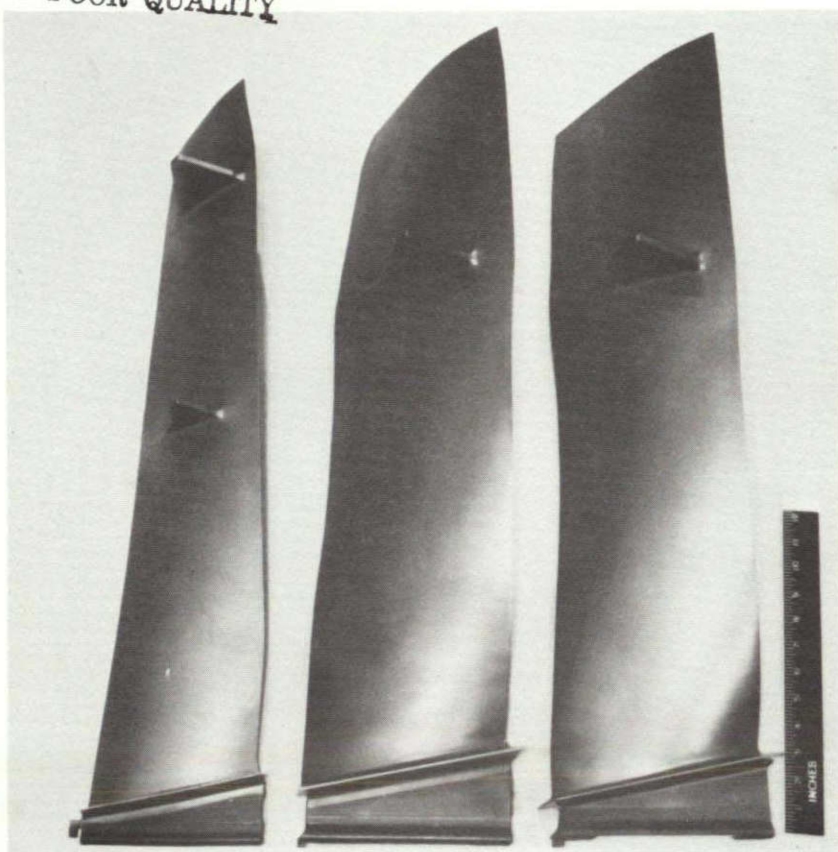
Figure 5-13 Changes in JT9D-7 Turbofan Engine Includes Fan Blades, Fan Exit Guide Vanes and Spinner

Table 5-25 compares the parameters of the 3.8 AR blades with the 4.6 AR blades currently used in the JT9D-7. The 3.8 AR fan blade has a longer chord and only one shroud. The 3.8 AR blades also employ a multiple circular arc airfoil cross section as opposed to the Bill-of-Material J blade airfoil series.

The lightweight 3.8 AR blade benefitted from the structural analysis and test data taken with the heavy 3.8 AR blade. As a result of improved structural analysis, the lightweight 3.8 AR blade is generally thinner and has a shorter chord in the middle of the blade as shown in Figure 5-14. It can also be seen that the two blade root attachments differ slightly. Aerodynamic improvements include optimized blade incidence and choke margins and a revised flow capacity.

TABLE 5-25
SUMMARY OF 4.6 and 3.8 AR FAN BLADE FEATURES

	4.6 AR (Current)	3.8 AR
Blade Material	AMS 4928	AMS 4928
Number of Blades	46	38
Airfoil Series	J	MCA
Root Chord Length, cm (in.)	15.32(6.030)	18.44(7.262)
Tip Chord Length, cm (in.)	19.66(7.740)	25.77(10.148)
Shroud Location	50 & 85% Span	68% Span



4.6 A/R **3.8 A/R HEAVY WT.** **3.8 A/R LIGHT WT.**

Figure 5-14 4.6 Aspect Ratio B/M Blade Shown with 3.8 AR Development Blades

Performance Substantiation

The heavy 3.8 AR fan blade employs a blade and hub combination which is too heavy for practical application. However, tests of the heavy 3.8 AR blade showed increased efficiency and flow capacity over the JT9D-7 blade (Figure 5-15). Based on the work with the heavy 3.8 AR blade, aerodynamic data was developed which contributed to the lightweight 3.8 aspect ratio blades. The lightweight 3.8 AR fan is designed to eliminate the excess flow capacity so that the Bill-of-Material engine match and nozzle areas will not be affected.

The number of fan exit guide vanes (FEGV) must be greater than twice the number of fan blades to minimize the propagation of discreet frequency noise by the blade-vane wake interaction. Since the 3.8 AR fan requires fewer blades than the B/M fan (46 to 38) it can meet the noise requirements with fewer FEGV's (108 to 86). The vane chord and thickness are dictated by vane vibration considerations, so when the number of vanes is reduced, the gap/chord of the vane assembly is increased resulting in reduced aerodynamic blockage, which reduces pressure loss, increases fan stage efficiency, and improves TSFC.

A pressure loss reduction of 0.2% in ΔP/P (Figure 5-16) has been conservatively assumed for the 86 vane configuration which will be used with the lightweight 3.8 AR fan.

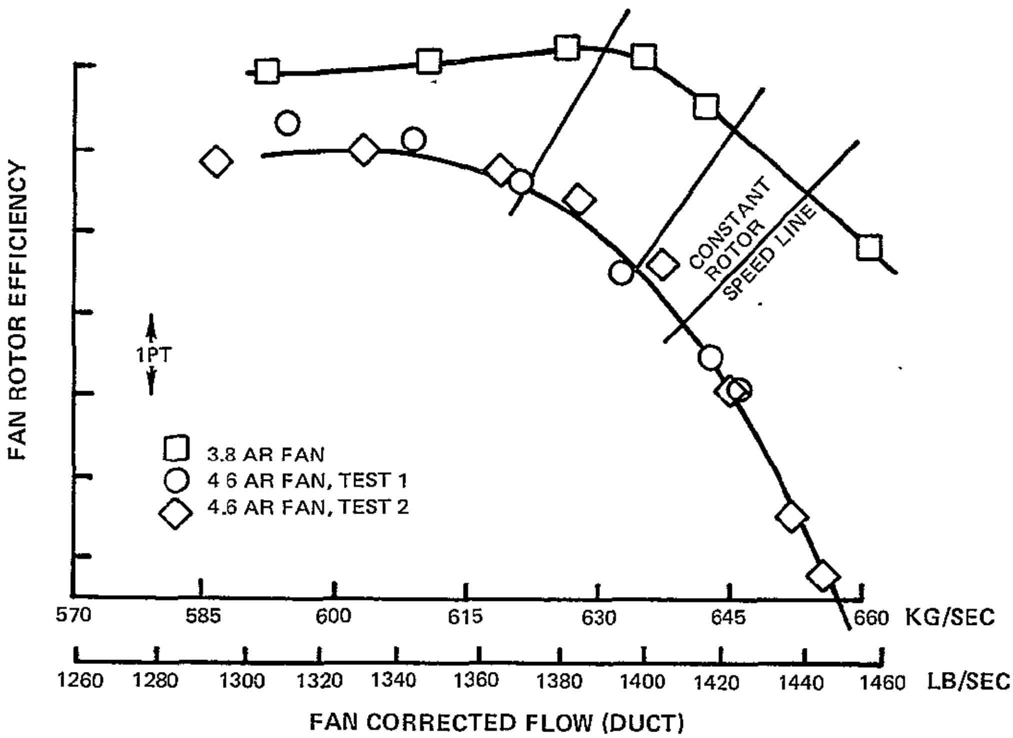


Figure 5-15 JT9D-7 Blade Performance

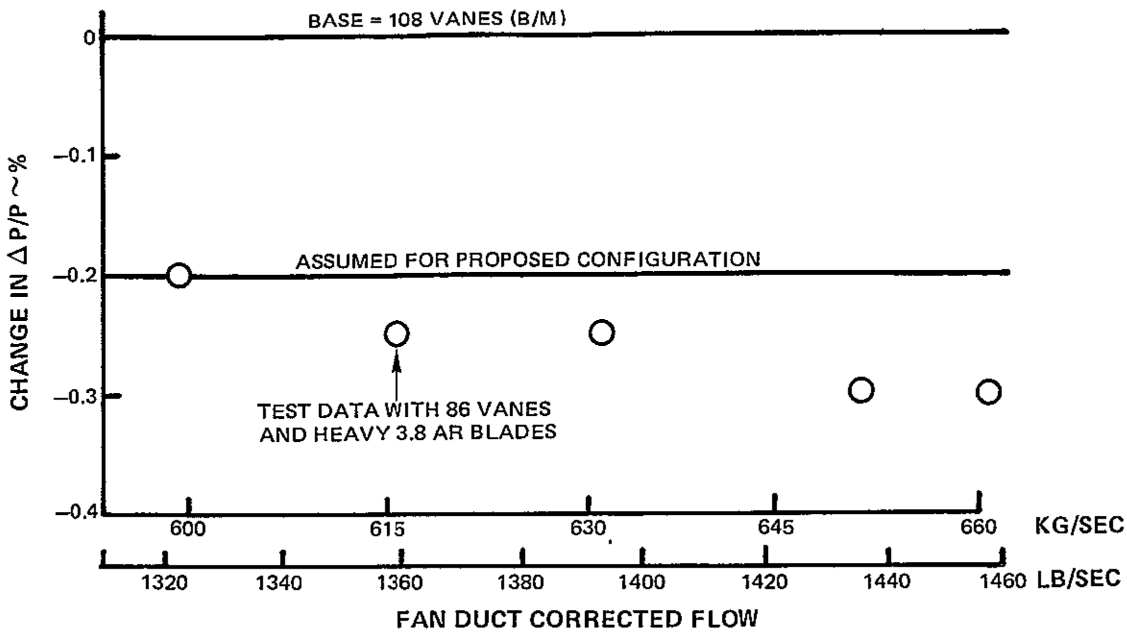


Figure 5-16 Change in Fan Exit Guide Vane Loss

Economic Evaluation

The improved lightweight 3.8 AR fan blade performance is manifested in the overall engine performance through a reduction in TSFC and a reduction in exhaust gas temperature (EGT) as shown in Table 5-26. The reduced EGT leads to an increase in the time between shop visits of about 170 hours which reduces the estimated labor cost per hour of engine operation. The manufacturing cost of the 3.8 AR blade and hub assembly is increased over the Bill-of-Material due to the increased size of the parts and tighter manufacturing tolerances. This cost increase is partially offset by the reduction in the number of blades from 46 to 38. The weight increase is due to the heavier wide chord blades and the increased hub depth.

The investment cost for the 3.8 AR fan in the new buy case is low compared to the annual operating cost saving, resulting in a very favorable payback period of less than one year (Table 5-27). The relatively high investment cost required for the retrofit case results in a payback period which is larger than the maximum acceptable period (6 years), indicating that the airlines would probably not retrofit the 3.8 AR fan to their existing engines.

If the lightweight 3.8 AR fan is applied to the projected deliveries of all JT9D-7 powered airplanes, starting in 1980, a total savings of 2.7 billion liters of fuel will be realized (Table 5-28).

TABLE 5-26
JT9D-7 3.8 AR FAN
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0.6	3
Climb	2.1	7
Cruise, Avg.	1.3	
Hold	0.6	
Weight Change, Kg (Lb)	+20(+45)	
Price Change, $	+25,500	
Kit Price, $	300,600 (Non-Attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	+0.20	
Labor @ $30 Per Man-Hr.	-3.10	

TABLE 5-27
JT9D-7 3.8 AR FAN
AIRLINE COSTS
Per Aircraft

Airplane Model	747-200	
Operating Cost Changes, $/Year		
Fuel	-126,360	
Maintenance	- 53,130	
Block Speed Effect	- 1,630	
Total	-181,120	
Type of Investment	**New Buy**	**Retrofit**
Required Airline Investment Changes, $		
Installed Engines	102,000	1,202,400
Spare Engines	27,800	327,900
Spare Parts	27,500	149,100
Total	157,300	1,722,400
Payback Period, Years	0.9	9.6
DOC Change, %	-0.8	

TABLE 5-28
JT9D-7 3.8 AR FAN
FUEL SAVINGS

Fleet Fuel Saved, %	1.5		
Start of Service Date	1-80		
Investment Type	**New Buy**	**Retrofit**	**Total**
No. of Engines Affected	1050	0	1050
Cum. Fuel Saved, 10^6 Liters (Gal)	2725 (720)	0	2725 (720)

5.2.7 JT8D Trenched Tip HPC

Concept Description

The JT8D engine has relatively large high pressure compressor (HPC) blade tip clearances to minimize the probability of blade tips rubbing the non-abradable shrouds. In-house programs have shown that reduction of these clearances can result in significant potential performance gain, but with some loss in stability margin at high power conditions. These programs also indicate that the stability can be improved through the use of rim seals which isolate the stator inner shroud cavities from the flowpath. A combination of longer blades, trenched abradable tip shrouds, and simple rim seals, applied to all seven stages of the HPC, was selected to obtain a performance improvement while maintaining adequate stability margin and providing for practical retrofit in existing engines. The modifications are shown in Figure 5-17.

The blades are lengthened sufficiently to achieve a line-on-line position with the flowpath outer wall at the average cruise condition. The blade length increase is between 0.051 and 0.221 cm (0.020 and 0.087 in.) depending on the stage. The average increase is 0.114 cm (0.045 in.), and is equivalent to 1 to 2 percent of the blade span.

The blade tip clearances required to accommodate the thermal growth and stress deflection differences between the rotor and shrouds, which are critical during transients, are provided by trenches in the abradable rubstrips, as shown in Figure 5-17. The abradable material could be fibrous metal like that used in current JT9D engines, or an advanced material such as nichrome-polyester for reduced cost and improved erosion resistance.

Previous testing of the JT8D HPC with blade tip clearances reduced by an average of 0.086 cm (0.034 in.) showed an efficiency improvement of 2%, but the high speed stall margin was significantly reduced as shown on Figure 5-18. This rig test was run without trenched or abradable tip shrouds, so special precautions were required to minimize transient effects and avoid blade tip rubs.

The loss of high speed surge margin is believed to result from improved OD pumping capability with the tigher tip clearances, which takes flow away from the airfoil root sections. The reduced root flow leads to a thicker boundary layer, which results in reduced stall tolerance especially in the stators. The root flow can be strengthened and stabilized by isolating the disturbing effects of the stator ID shroud cavities from the flowpath. The selected configuration uses a simple seal ring extension on the front side of each stator ID shroud. These seals mate with the ID surface of the blade platforms, (see Figure 5-17). A similar seal at the rear side of each stator shroud would provide some additional improvement, but not enough to justify the extensive modifications required in the blades, disks, and stator shrouds.

Performance Substantiation

An efficiency improvement of 2% with no loss of surge margin is predicted for the modified HPC design. This prediction is based on the reduced tip clearance test of the JT8D HPC described above, and the results of a 3-stage research rig test program. The rig was run with smooth walls over the blade tips, and with two different trench configurations over the tips, as shown on Figure 5-19. The efficiency variation presented on Figure 5-20 was obtained by changing the tip clearances in this rig, which shows both higher efficiency and reduced sensitivity to clearance with the trenched configuration. Based on these results, it is estimated that the efficiency improvement of 2% shown on Figure 5-18 can be maintained when realistic tip clearances are provided in the JT8D HPC with trenches in abradable rubstrips. It is also predicted that the surge margin loss shown on Figure 5-18 will be recovered by use of rim seals with a minimum requirement for stage rematching.

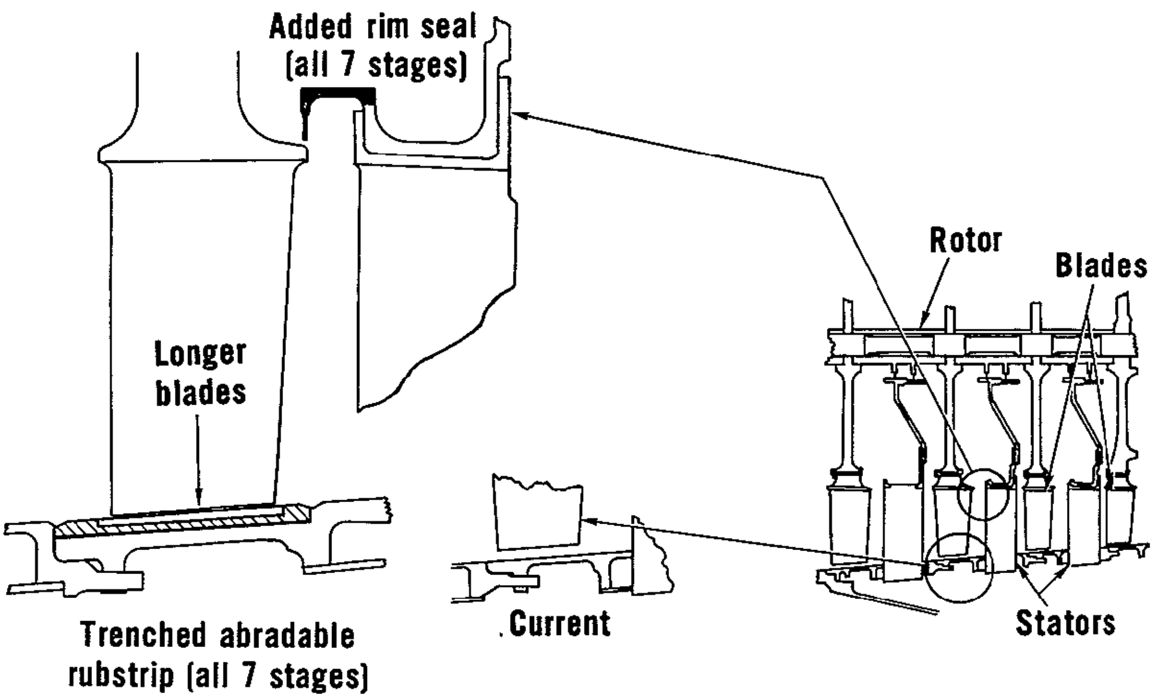


Figure 5-17 Stator and Rotor Modifications

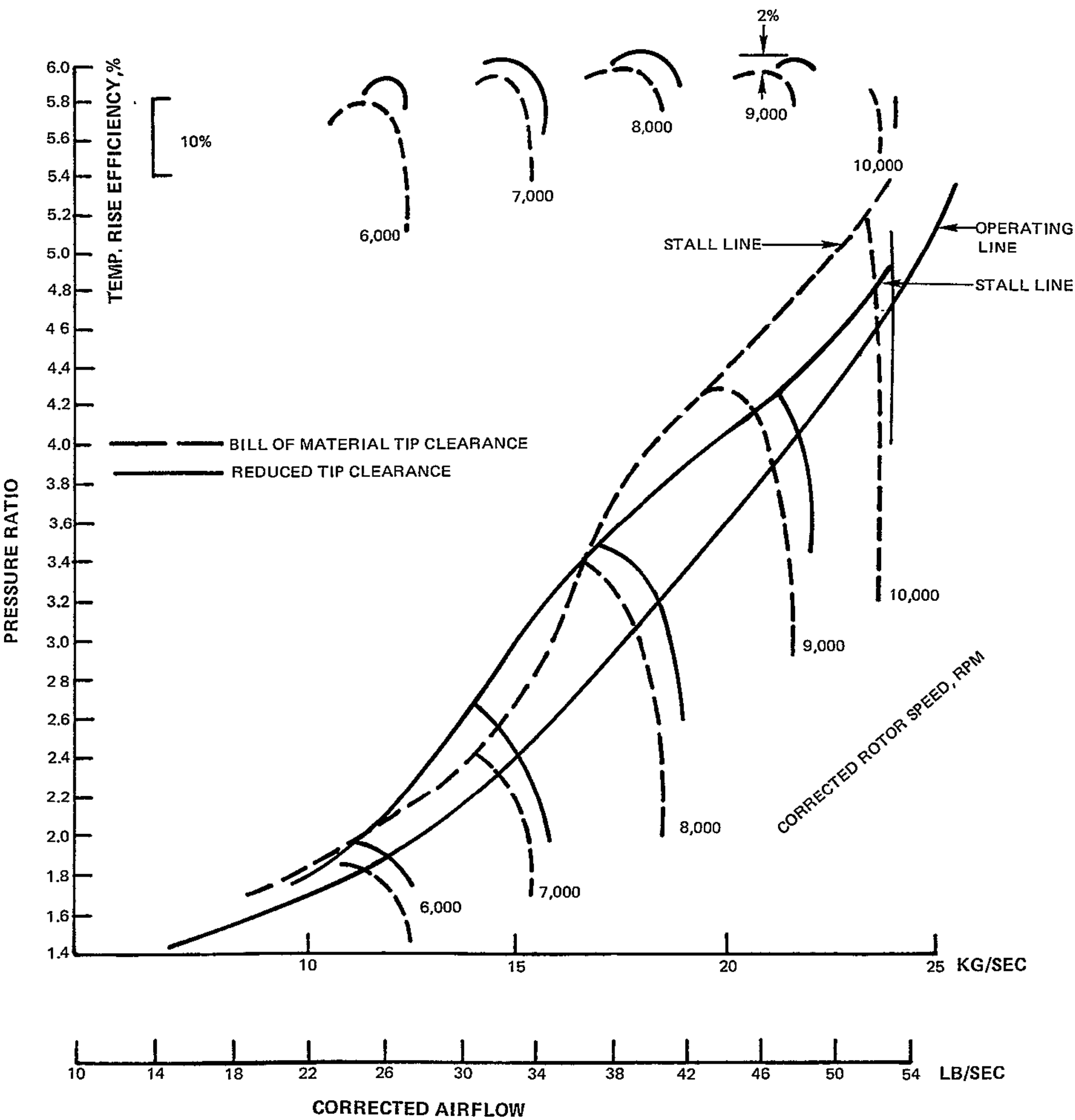


Figure 5-18 Results of HPC Test Rig Results Comparing B/M and Longer Blase Data

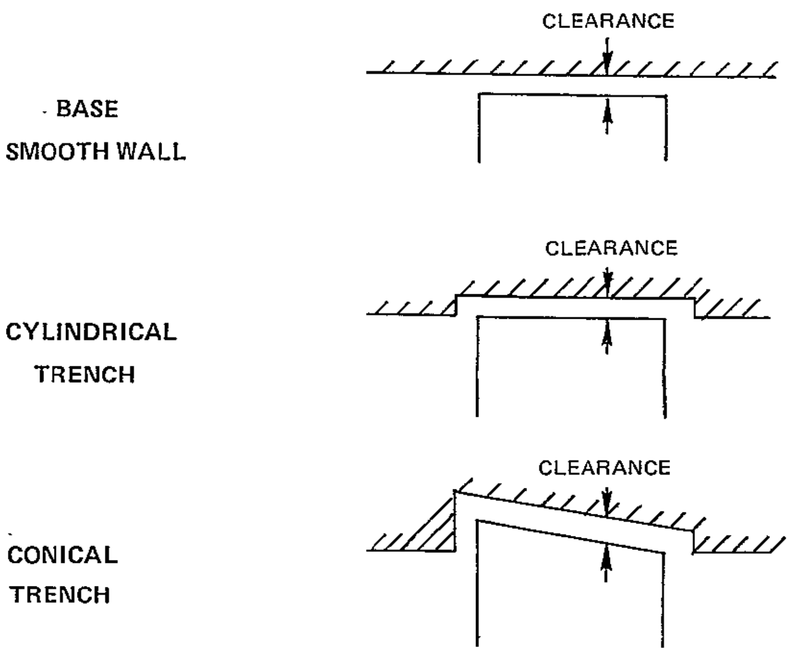


Figure 5-19 Three-Stage Compressor Rotor Tip Configuration

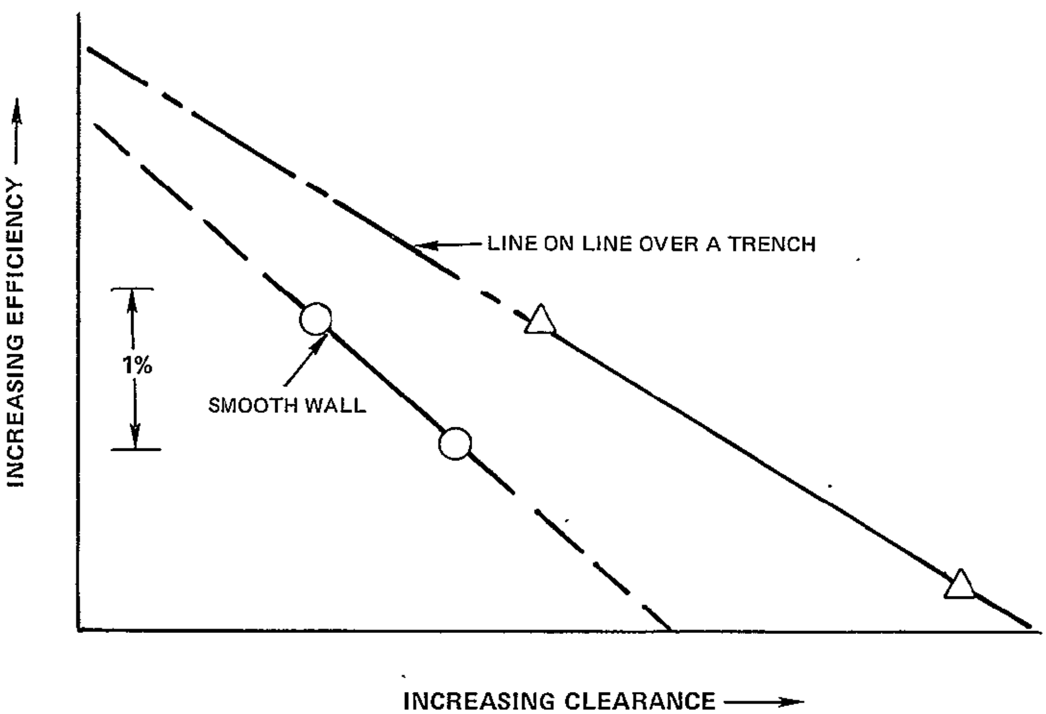


Figure 5-20 Three-Stage Compressor Test Results

Economic Evaluation

The projected HPC efficiency improvement of 2% results in an engine TSFC improvement of 0.9% and an EGT reduction of 8°C, as shown on Table 5-29. The reduced EGT leads to an increase in the time between shop visits of about 280 hours which reduces the estimated labor cost per hours of engine operation. The manufacturing cost of the stator assembly is increased because of the changed shroud, requiring machining of a cavity to accept the abradable material rubstrip. The retrofit cost (kit price) reflects the required purchase of new vane/shroud assembly as well as a set of new (longer) blades.

TABLE 5-29

JT8D TRENCHED TIP HPC
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0.9	8
Climb	0.9	8
Cruise, Avg.	0.9	
Hold	1.4	
Weight Change, Kg (lb)	0	
Price Change, $	10,000	
Kit Price, $	43,000 (Non-attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 per Man-Hr.	-1.90	

Table 5-30 shows the payback period to be acceptable for new buys of both airplanes, marginally acceptable for 727 retrofit, and unacceptable for DC-9 retrofit. If this concept is applied to projected deliveries of JT8D engines beginning in March 1981, and retrofitted in 727 installations that are 6 or less years in age beginning on the same date, a total of 1.0 billion liters of fuel will be saved by the year 1990 (Table 5-31).

TABLE 5-30
JT8D TRENCHED TIP HPC
AIRLINE COSTS
Per Aircraft

Airplane Model	727-200		DC9-50	
Operating Cost Changes, $/Year				
Fuel	-14,650		-9,480	
Maintenance	-14,930		-8,300	
Block Speed Effect	-1,870		-650	
Total	-31,450		-18,430	
Type of Investment	**New Buy**	**Retrofit**	**New Buy**	**Retrofit**
Required Airline Investment Changes, $				
Installed Engines	+30,000	+129,000	+20,000	+86,000
Spare Engines	+6,150	+26,450	+5,300	+22,790
Spare Parts	+900	3,870	+600	+2,580
Total	+37,050	+159,320	+25,900	+111,370
Payback Period, Years	1.2	5.0	1.4	6.0
DOC Change, %	-0.4		-0.4	

TABLE 5-31
JT8D TRENCHED TIP HPC
FUEL SAVINGS

Fleet Fuel Saved, % 1.0

Start of Service Date 3-81

Investment Type	New Buy	Retrofit	Total
No. of Engines Affected	560	1660	2220
Cum. Fuel Saved, 10^6 liters (gal.)	310 (82)	723 (191)	1033 (273)

5.2.8 JT9D Trenched Tip HPC

Concept Description

The JT9D engine is believed to have relatively large blade tip running clearances in the last five stages of the high pressure compressor. The use of a trenched tip configuration employing available abradable outer air seal material and a modification to the criteria for setting blade tip and outer air seal diameters permits the use of tight running clearances, resulting in improvements in efficiency and TSFC.

P&WA's experience with a three-stage research compressor rig (Figure 5-20) was discussed previously under Section 5.2.7, JT8D Trenched Tip HPC, and is the basis for the HPC design. The low speed rig tests have shown a potential compressor efficiency improvement with outer case wall trenches providing the clearance over the rotor tips rather than a gap between a smooth wall and the rotor tip.

Figure 5-21 and 5-22 illustrate the details of the revised blade rub strips. The blade rub strip ID surfaces are recessed slightly into the flowpath outer wall. Longer high pressure compressor blades are used so the rotor tip maintains a line-on-line position with the gas path outer wall at the average cruise condition.

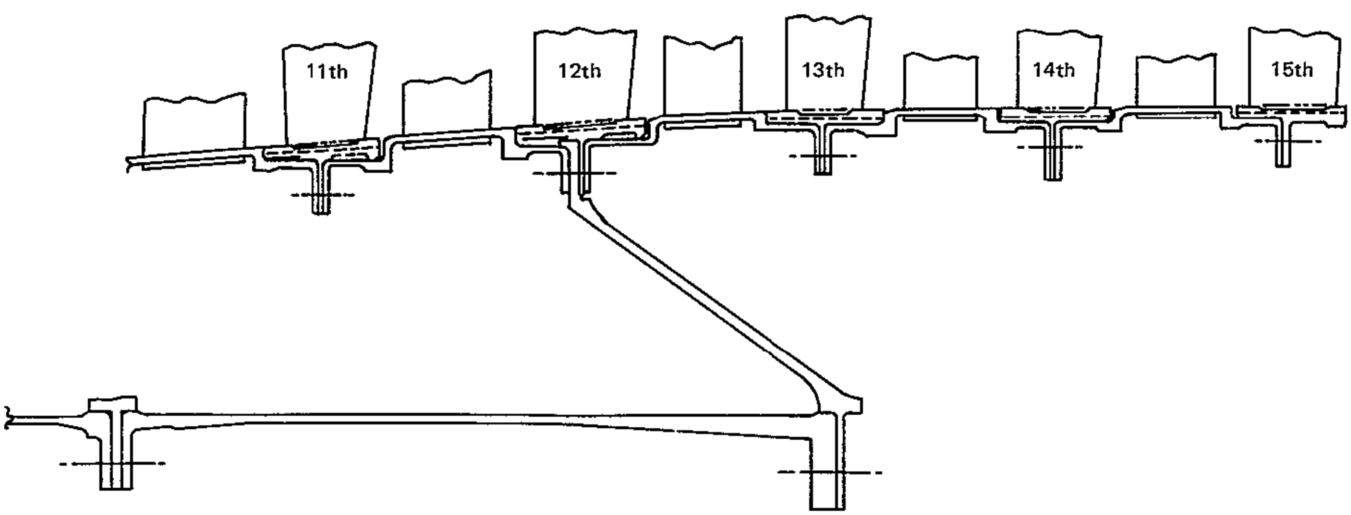


Figure 5-21 Revised Blade Rub Strip Configuration

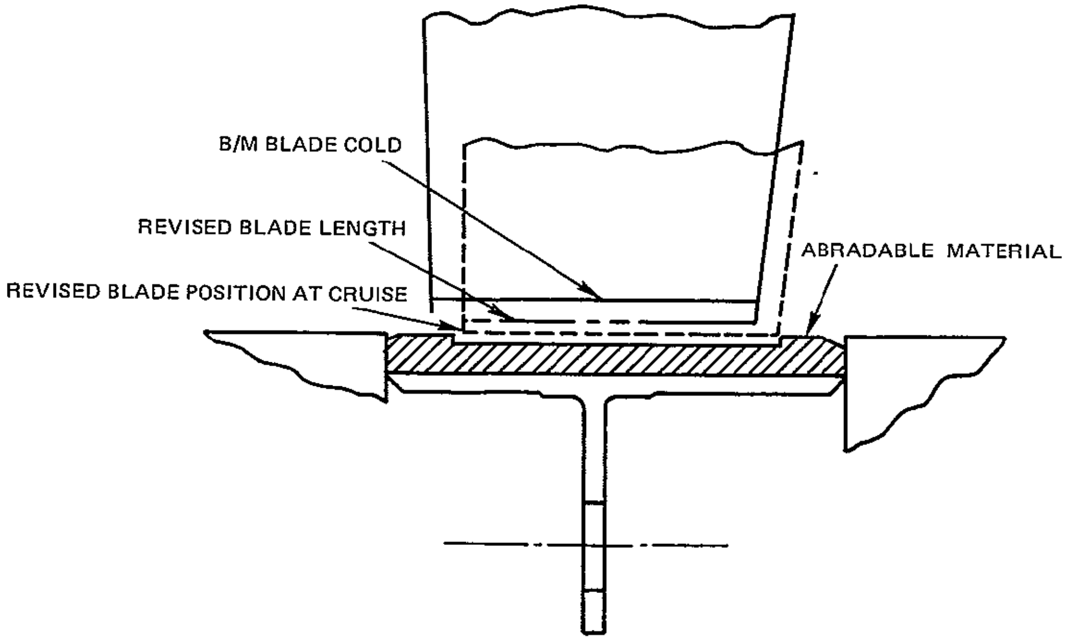


Figure 5-22   Blade and Rubstrip Relationships

Figure 5-23 shows the location of the five stages that will be modified. These stages will respond most effectively to change in rub strip design since they are the shortest and any given tip clearance or change in tip clearance affects a greater percentage of the total flow. In addition, these stages have cylindrical or almost cylindrical endwalls over the blade tip which seem to react more favorably to this endwall design concept.

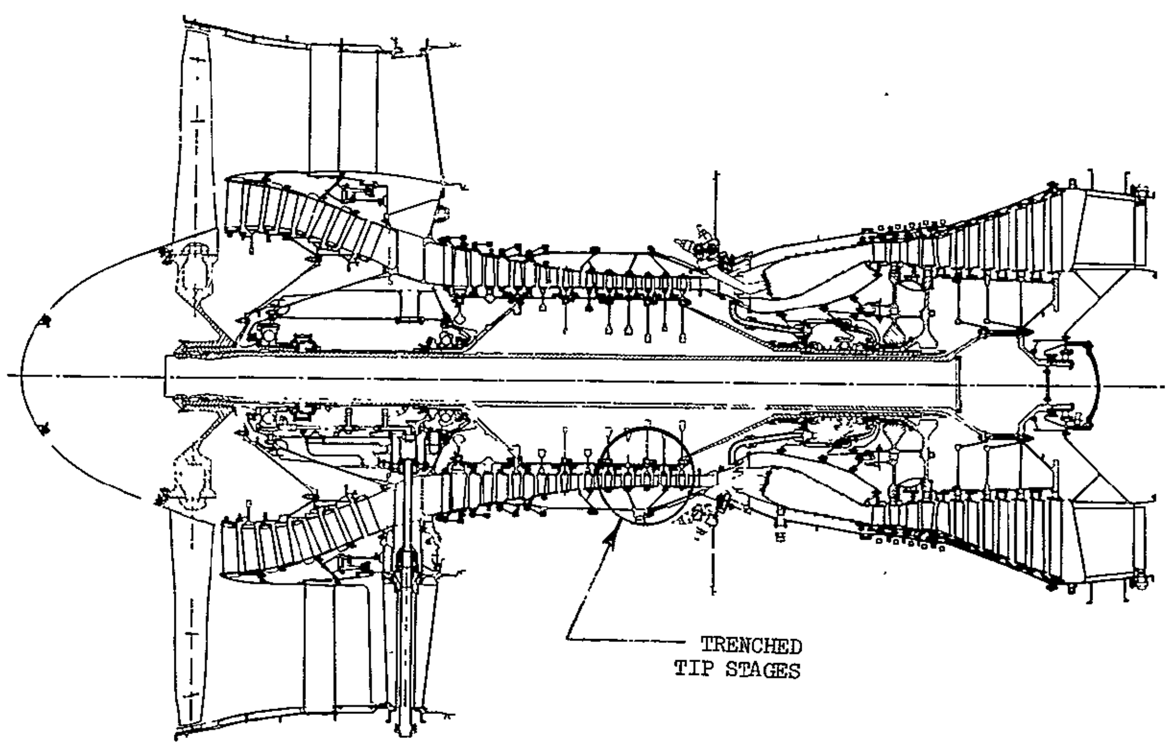


Figure 5-23   JT9D Engine Layout Showing Affected HPC Stages

Performance Substantiation

The internally funded three-stage compressor research rig has been used to investigate a variety of parameters relating to compressor blade tip clearance effects on compressor efficiency as described in Section 5.2.7. Based on this work an optimum configuration and tip clearance has been selected and will be used to improve the JT9D HPC efficiency about 0.7 percentage points.

The following maximum potential benefits for incorporating longer blades and trenched rotors in the rear five stages of the JT9D HPC were estimated analytically.

Model	Δ HPC Flow Capacity	Δ HPC Efficiency	Δ TSFC
D-7	+1.6%	+0.92%	–0.4%
D-70/59	+1.3%	+0.70%	–0.3%

This analysis assumes blade tips are running line on line with the flowpath O.D. wall, and that the shroud trenches are as previously described.

The following trade factors were used in the above analysis:

+1% in HPC efficiency results in –0.5% TSFC
+1% in HPC flow capacity results in +0.05% TSFC

The HPC efficiency trade factor results from cycle studies, whereas the flow capacity factor is derived from experimental engine testing data.

Surge margin or stability is not expected to be affected by the tip trenching. Through past rig and engine testing and analysis it has been determined that blade root sections in the HPC mid stages are critical concerning stall margin. The increased flow required by stages 11 through 15 will pull more flow through these root sections, thereby improving stall margin of the mid stages. Similarily, it has been determined that the rear stages are tip sensitive regarding stall margin so that incorporating the longer blades in these stages will also improve stall margin. The increased flow may require slight changes in the front stage variable vane settings. The predicted overall result of the proposed changes is no change to stall margin or stability.

Economic Evaluation

The maximum potential benefits estimated for the concept were reduced to the TSFC values shown on Table 5-32 to allow for production variations in blade tip diameter and in trench width and position. The cost and weight impact is small because the separate rub-strip arrangement of the JT9D HPC can be modified easily to accommodate the trenches, and the longer blades can be incorporated on an attrition basis in existing engines. As a result, the payback period is less than one year in both new buy and retrofit cases, as shown in Table 5-33. Applying the concept in all engines starting in 1981 will result in a cumulative fuel saving of over 1.8 billion liters, as shown in Table 5-34.

TABLE 5-32

JT9D TRENCHED TIP HPC ENGINE DATA
Per Engine

Performance	TSFC Reduction, %		EGT Reduction, °C
	-7	-70/59	
Takeoff	0.3	0.25	3
Climb	0.3	0.25	3
Cruise, Avg.	0.3	0.25	
Hold	0.3	0.25	
Wt. Change, Kg (lb)	0	0	
Price Change, $	+1,000	+1,000	
Kit Price, $	+8,300	+1,800	(Attrition)
Maintenance Cost, $/Oper. Hr.			
Materials	0	0	
Labor @ $30 per Man-Hr.	-1.94	-1.76	

TABLE 5-33

JT9D TRENCHED TIP HPC AIRLINE COSTS
Per Aircraft

Airplane Model	747-200			DC-10-40	
Operating Cost Changes, $/Yr.:	-7	-59/70		-59/70	
Fuel	-27,300	-24,030		-9,190	
Maintenance	-35,510	-32,220		-18,120	
Block Speed Effect	-175	-80		-215	
Total	-62,985	-56,330		-27,525	
Type of Investment	**New Buy**	**Retrofit**		**New Buy**	**Retrofit**
	-7 & -70/59	-7	-70/59	-70/59	-70/59
Required Airline Investment Changes, $					
Installed Engines	+4,000	+33,180	+7,190	+3,000	+5,400
Spare Engines	+1,090	+9,065	+1,965	+690	+1,235
Spare Parts	+180	+1,500	+325	+135	+240
Total	+5,270	+43,745	+9,480	+3,825	+6,875
Payback Period, Year	0.1	0.7	0.2	0.1	0.3
DOC Change, %	-0.3	–	–	-0.2	–

TABLE 3-34
JT9D TRENCHED TIP HPC
FUEL SAVINGS

Fleet Fuel Saved, %			0.35	
Start of Service Date			3-81 (-7), 6-81 (-70/59)	
Investment Type		New Buy	Retrofit	Total
No. of Engines Affected	-7	910	1940	2855
	-70/59	825	400	1225
Cum. Fuel Saved, 10^6 Liters (Gal.)	-7	541 (143)	518 (137)	1059 (280)
	-70/59	530 (140)	276 (73)	806 (213)
			Total	1865 (493)

5.2.9 JT9D 16-Strut Intermediate Case

Concept Description

The intermediate case is a major structural case in the JT9D engine, located between the low pressure and high pressure compressors. It supports the thrust bearings for both engine rotors and contains the towershaft assembly which provides power to drive the engine and airframe accessories. It has eight structural struts which span the airflow path immediately behind the low pressure compressor (LPC).

In this concept, the number of struts has been increased and the thickness of each strut decreased (as shown in Figure 5-24) to reduce the strength of the flow disturbances propagated upstream into the LPC. The reduced flow disturbances will improve the stability of the LPC, allowing the LPC operating line to be raised while maintaining adequate surge margin. The high pressure turbine nozzle flow area must be increased 7.5 percent and the low pressure turbine nozzle flow area must be decreased 7.5 percent to raise the LPC operating line. These nozzle area changes are large enough to cause significant changes in the incidence angles on the turbine airfoils which will affect the turbine efficiencies.

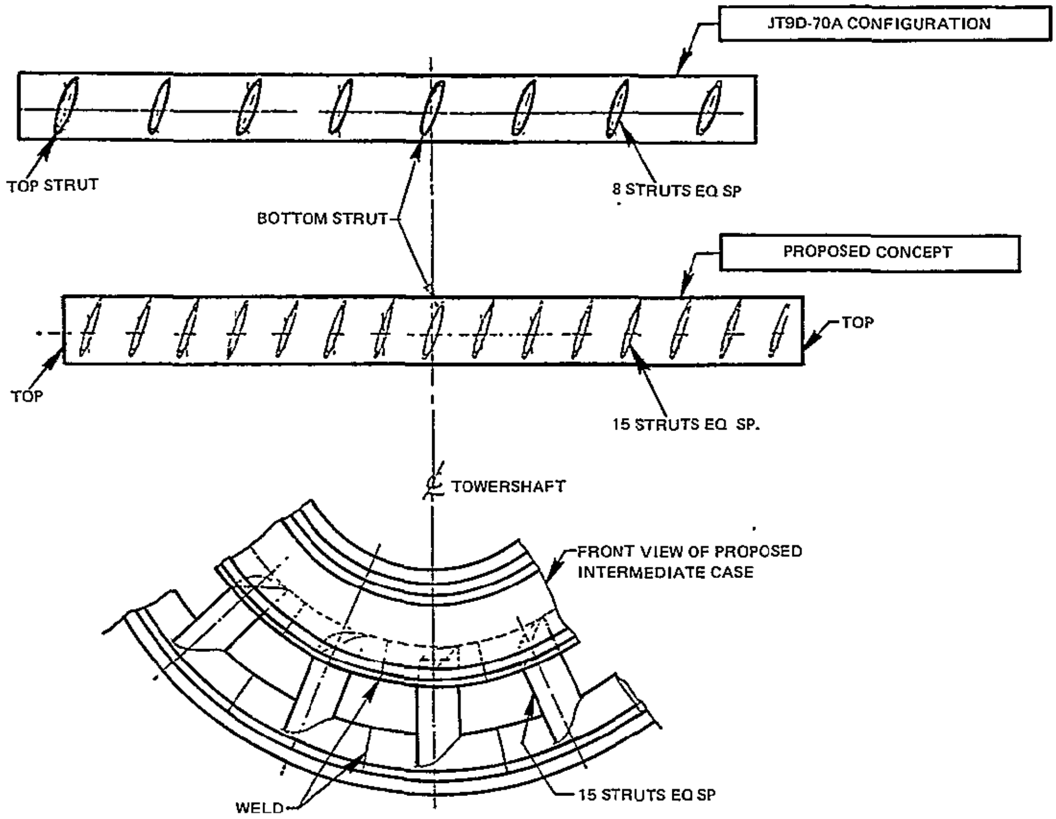


Figure 5-24 Sketch of JT9D-70 B/M Intermediate Case and Proposed Modified Configuration

A prototype intermediate case was fabricated in 1977 to simulate the aerodynamic effects of the proposed design. The prototype has a non-structural "dummy" strut between each of the eight struts in the B/M case, resulting in a total of 16 struts. An analysis of the wake interactions with the compressor blades indicates a resonance vibration with the HPC first stage that falls within the operating speed range of the rotor. This resonance is acceptable in an experimental engine, allowing the prototype case to be used to explore the aerodynamic performance and stability aspects of the concept. Preliminary design work has been done on a 15 strut case design which eliminates the resonance vibration problem, making it structurally acceptable in production engines.

Performance Substantiation

The low pressure compressor (LPC) feels a reduced back-pressure effect from the reduced thickness struts in the 16 strut intermediate case. This improves the stability of the LPC to the extent that the engine operating line for the LPC can be raised about 8 percent. The higher operating line means a higher pressure ratio at a given flow and corrected speed and also moves the LPC into a region of higher efficiency.

The reduced thickness struts of the 16 strut intermediate case do not affect the stability of the high pressure compressor (HPC), therefore no increase in HPC operating line is possible. Since the pressure ratio of the LPC is higher at the same flow, the exit corrected flow from the LPC (inlet corrected flow to the HPC) is smaller, thus creating a downward shift in pressure ratio and corrected speed in the HPC to maintain the same operating line. This may cause a change in efficiency of the HPC depending upon where the HPC was operating relative to its efficiency islands. In most compressors, a downward shift along the operating line at high power output would tend to increase the compressor efficiency, but at low power output it would tend to lower the compressor efficiency.

This rematching of the pressure ratio and corrected flow between the LPC and the HPC is accomplished by changing the inlet nozzle flow areas of the high pressure and the low pressure turbines. In this instance the nozzle area of the high pressure turbine must be increased about 7.5 percent while the inlet nozzle area to the low pressure turbine must be decreased about 7.5 percent.

Engine performance was calculated using an engine simulation performance deck with representative LPC and HPC performance maps. Using the turbine nozzle area changes previously quoted, a significant improvement in LPC efficiency and a somewhat smaller improvement in HPC efficiency were predicted. At lower power levels, these improvements in efficiency were smaller. The net effect of these efficiency changes is an estimated reduction of 0.9 cruise TSFC.

Since the above evaluation was completed, the modified intermediate case has been studied further for possible application to an advanced model of the JT9D. This effort revealed the possibility of a turbine efficiency penalty resulting from the turbine nozzle area changes needed to rematch the low pressure compressor to a higher operating line. When rematching an engine in this manner, the expansion ratio of the high pressure turbine is reduced, in keeping with the lower pressure ratio and reduced work requirements of the HPC. The reduced expansion ratio and the opened up (increased area) nozzle both tend to result in internal mismatching and increased incidences in the high pressure turbine which results in the lower efficiency. This penalty would reduce the engine performance improvement of the concept to near zero, as indicated by the "most likely" entry in the risk assessment summarized in the beginning of Section 5.2.

A redesign of the high pressure turbine might eliminate most, if not all, of the loss in turbine efficiency thus attaining the original ΔTSFC estimate. This estimate is carried as the "best" that could be expected. But a turbine redesign would be very expensive and could add to the cost increase of the concept although this was not done in the economic evaluation.

A "worst" case, which completes a normal distribution with the "best" and "most likely" values, results in increased fuel consumption. Since only the "best" case is economically acceptable based on the new buy payback period criteria, the possibility of achieving a fleet fuel saving with the modified intermediate case appears unlikely, making it a poor candidate for the follow-on ECI-PI program.

Economic Evaluation

Table 5-35 summarizes the effects of the 16 strut intermediate case on the JT9D engine. The performance shown in this table is the "best" case described above, but the other effects are based on the assumption that only the intermediate case is modified. The modified intermediate case is slightly heavier, and it results in an engine price increase because of the increased labor and material cost associated with the increased number of struts. The maintenance material cost does not increase, however, because the intermediate case is not normally replaced during the life of the engine. The maintenance labor cost reduction is a result of the EGT reduction, which improves the time between shop visits.

TABLE 5-35
JT9D 16-STRUT INTERMEDIATE CASE ENGINE DATA
Per Engine

Performance:	TSFC Reduction, % -7, -70/59	EGT Reduction, °C
Takeoff	0.9	9
Climb	0.9	9
Cruise, Avg.	0.9	
Hold		
Weight Change, Kg (lb)	+7 (+15)	
Price Change, $	+11,750	
Kit Price, $	221470 (-7), 227560 (-59/70) (Non Attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 per Man-Hr.	-5.62	

Table 5-36 summarizes the change in costs to the airline operator which would result from incorporating the modified intermediate case. Annual operating cost changes and required airline investment are shown on a per airplane basis for the Douglas DC10 and two models of the Boeing 747 (JT9D-7 and JT9D-70 powered).

The new buy payback period is less than one year in all cases, which means that the concept would be an excellent investment for the airlines. The retrofit payback period is greater than the maximum acceptable value of 6 years in each case, which means that airline operators would probably not retrofit this concept.

Table 5-37 shows the worldwide fleet fuel savings that could be realized if the modified intermediate case were introduced into all applications entering service between mid-1982 (the estimated earliest date that it could be available) and 1990. According to the market projection used in the study, 740 engines of each model will enter service in this time period, and the cumulative fuel saving through the year 1990 would be 2.8 billion liters with the modified case.

TABLE 5-36
JT9D 16-STRUT INTERMEDIATE CASE
AIRLINE COSTS
Per Aircraft

Airplane Model	747-200			DC 10-40	
Operating Cost Changes, $/Year					
	-7		-70/59	-70/59	
Fuel	- 86000		- 91900	-36200	
Maintenance	-102500		-102800	-57800	
Block Speed Effect	- 360		- 500	- 700	
Total	-188860		-195200	-94700	
Type of Investment	New Buy	Retrofit		New Buy	Retrofit
Required Airline Investment Changes, $					
	-7&-70/59	-7	-70/59	-70/59	-70/59
Installed Engines	+47000	+ 885,900	+ 909,800	+35,250	+682,400
Spare Engines	+12800	+ 241,800	+ 248,300	+ 8,100	+156,800
Spare Parts	+ 2100	+ 39,900	+ 41,000	+ 1,600	+ 31,000
Total	+61900	+1167,600	+1199,100	+44,950	+870,200
Payback Period, Years	0.3	6.2	6.1	0.5	9.2
DOC Change, %	-0.9			-0 9	

TABLE 5-37
JT9D 16-STRUT INTERMEDIATE CASE
FUEL SAVINGS

Fleet Fuel Saved, %	1 1			
Start of Service Date	6-82			
Investment Type		New Buy	Retrofit	Total
No. of Engines Affected	-7	740	0	740
	-70/59	740	0	740
Cum. Fuel Saved 10^6 Liters (Gal)	-7	1415 (374)	0	1415 (374)
	-70/59	1415 (374)	0	1415 (374)
				2830 (748)

5.2.10 JT9D Thermal Barrier Coating

Concept Description

To provide adequate cooling of the platform as well as the vane airfoil in JT9D high pressure turbines, cooling air holes are drilled in the surface of the platform to provide a film of cooling air, from an internal cavity source to flow along the platform surface. The drilling of many small surface holes is very expensive and the use of compressor bleed air for cooling increases engine fuel consumption. With the development of improved durability thermal barrier coatings, the insulating property of the coating can be used to reduce the transfer of heat to the vane platform and permit elimination or reduction of the film cooling holes, a reduction in cooling airflow and a reduction in vane fabrication costs (Figure 5-25). Use of this vane will provide savings in fuel at no increase in engine production cost.

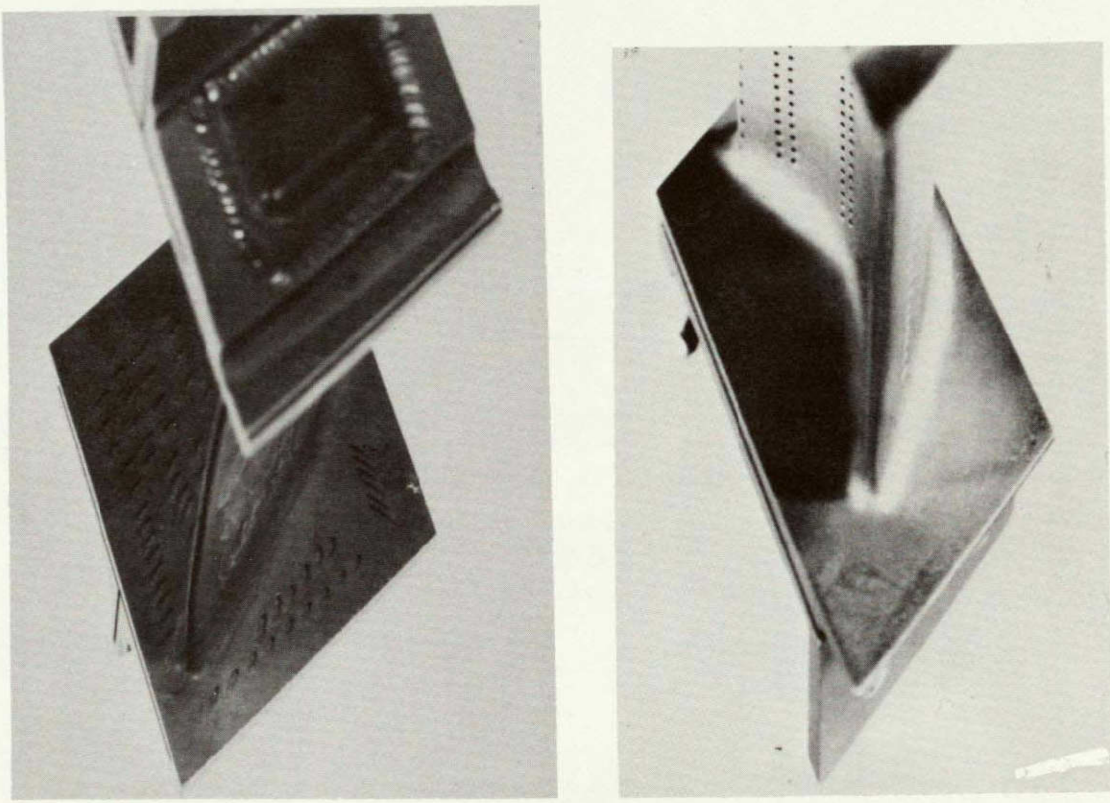


Figure 5-25 *Bill of Materials Turbine Vane (Left) and Thermal Barrier Coated Turbine Vane Platform (Right) – Use of a thermal barrier coating permits elimination of platform cooling holes.*

Thermal Barrier Coating Systems

Current state-of-the-art thermal barrier coating systems of which the microstructure is shown in Figure 5-26, consist of a plasma sprayed insulative ceramic layer applied over an oxidation resistant metallic coating. A second coating system uses electron beam evaporation/physical vapor deposition (EB/PVD) coatings, also applied over an oxidation resistant metallic coating. The metallic sublayer must be capable of providing a protective adherent oxide seal to inhibit oxidation of the superalloy substrate since the ceramic is not a good oxygen barrier. Also, the sublayer adherent oxide scale provides a satisfactory surface for bonding the ceramic layer to the component. The most promising protective sublayers consist of ductile (Ni, Co) CrAlY alloys. Available thermal fatigue data indicate that stabilized zirconia is the best available ceramic for advanced airfoil thermal barrier coating applications.

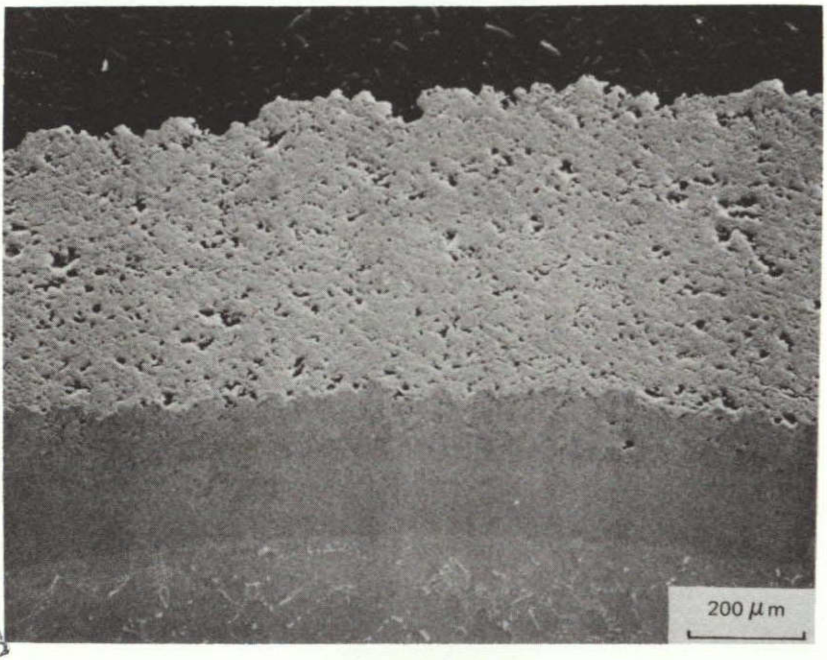


Figure 5-26 *Scanning Electron Microscope Photograph of CoCrAlY Applied by Plasma Spraying plus Yttria-Stabilized Zirconia Thermal Barrier Coating System – This system represents the current state-of-the-art of thermal barrier coatings.*

Performance Substantiation

Thermal barrier coatings of 0.0254 cm (0.010 in.) thickness have been tested on vane platforms in a number of engines over the past few years. Tests have been conducted on first stage vane platforms in a TF30-P-100 engine and a JT9D development engine. In both tests after less than 100 hours, minor coating spallation occurred.

Figure 5-27 shows the thermal barrier coated platforms of the first vane of a JT9D-7F experimental engine after 160 hours (1025 cycles) engine operation. Currently, the vanes with the thermal barrier coated platforms have accumulated 310 hours (2025 cycles) with moderate coating spallation.

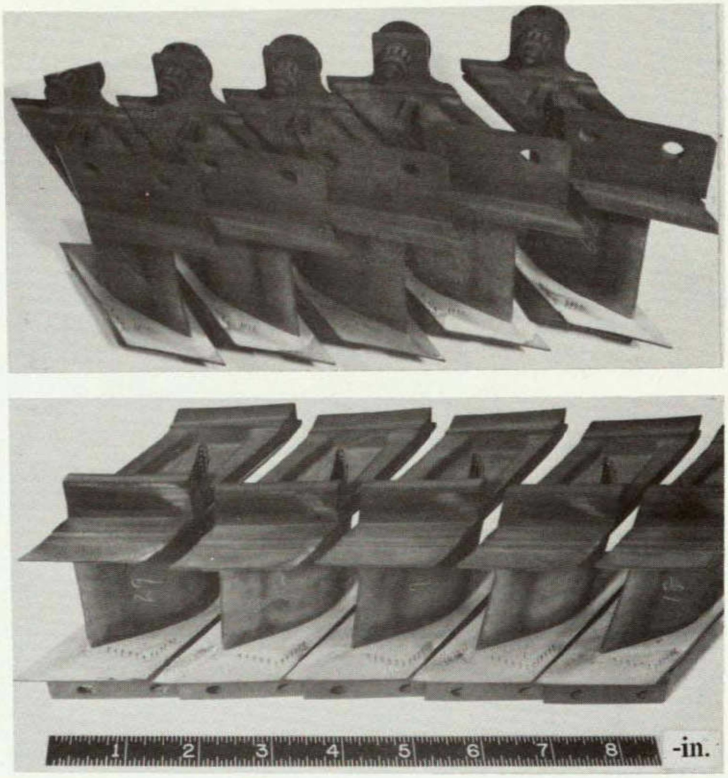


Figure 5-27 *JT9D-7F First-Stage Turbine Vanes With Thermal Barrier Coating – These vanes completed 160 hours and 1025 cycles of engine testing.*

Coated JT9D-70 second stage platforms are also being tested and have exhibited minor spalling after 337 hours (2455 cycles). In both the JT9D-7F and JT9D-70 tests, spalling initiated along the edges of the platforms at the acute-angle corners and at "hot spots" along the edges.

Limited success was demonstrated with NASA and P&WA plasma sprayed thermal barrier coatings on the first stage turbine blades of an experimental JT9D-7E engine during a 264 hour (1424 cycles) endurance test (Figure 5-28). Ceramic layer failures (spalling) were limited to the highest temperature locations; i.e., the leading edge and about one third of the pressure (concave) side of the airfoil. The thermal barrier coatings were intact at other locations on the airfoils and the platforms after the engine testing. The successful performance of the coatings on the blade platforms may be partially attributable to the fact that the ceramic layers were relatively thin (0.0127 cm, or 5 mils).

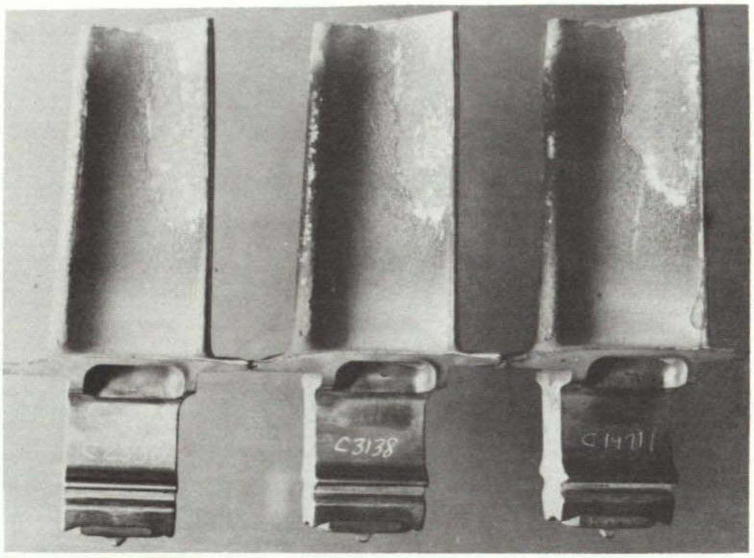
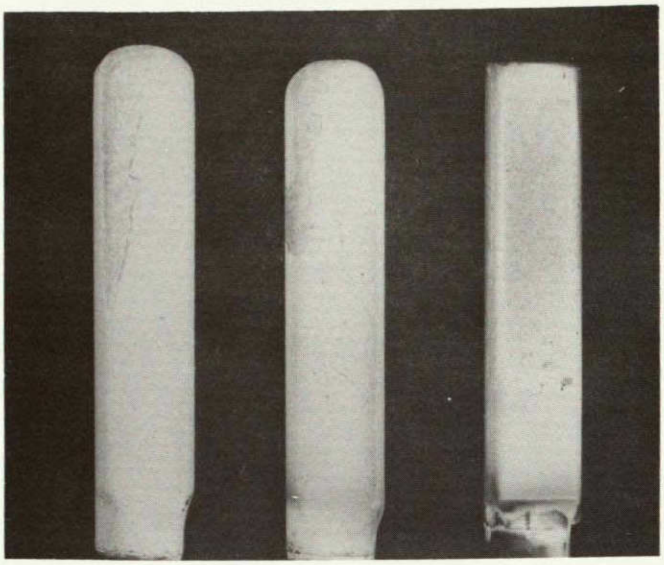


Figure 5-28 JT9D-7E First-Stage Turbine Blades With Thermal Barrier Coating – After 264 hours, 1424 cycle endurance test, spalling occurred in the high-temperature regions of the blades.

The thermal fatigue durability of plasma sprayed and EB/PVD Yttria stabilized Zirconia thermal barrier coating systems are demonstrated by the test specimens in Figure 5-29. The specimens were thermally cycled in an 1010°C (1850°F) hot rig. The thermal cycles consist of four (4) minutes hot and two (2) minutes forced air cooled.

Improved thermal stress durability is sought compared to current plasma sprayed coatings for JT9D-70 turbine vane platform applications. Spallation resistant thermal barrier ceramic layers can be achieved from the development of microcracked or segmented ceramic structures which accommodate ceramic-metal thermal expansion mismatch and thermal strains by free expansion into small gaps between segments. Decreasing the segment diameter also reduces the stress at the ceramic-metal interface (Figure 5-30). EB/PVD coatings may provide further improvement in thermal stress durability.

Thermal barrier coatings on the vane platforms have a small potential for improving turbine efficiency but the reduction in cooling flow has a significant effect on cycle efficiency and TSFC improvement. A much larger potential improvement in turbine efficiency, cycle efficiency and TSFC is possible when thermal barrier coatings applied to vane and blade airfoil surfaces are developed to have durability characteristics that are satisfactory.



SPECIMEN A SPECIMEN B SPECIMEN C SHOWN ACTUAL SIZE

	Specimen A	Specimen B	Specimen C
Coating Process	Plasma Sprayed	Plasma Sprayed	EB/PVD
Ceramic Layer			
Material	Yttria Stabilized Zirconia		
Thickness, cm (in.)	0.0254 (0.010)	0.0127 (0.005)	0.0152 (0.006)
Oxidation Resistant Layer			
Material	NiCoCrAlY	NiCoCrAlY	NiCoCrAlY
Thickness, cm (in.)	0.0127 (0.005)	0.0127 (0.005)	0.0127 (0.005)
Cycles to Initiate Spalling	40	140	>140
Total Cycles Tested	40	1210	>1210

Figure 5-29 *Thermal Fatigue Durability Test Specimens After Test – These specimens demonstrate typical results for plasma sprayed and electron beam physical vapor deposition thermal barrier coatings.*

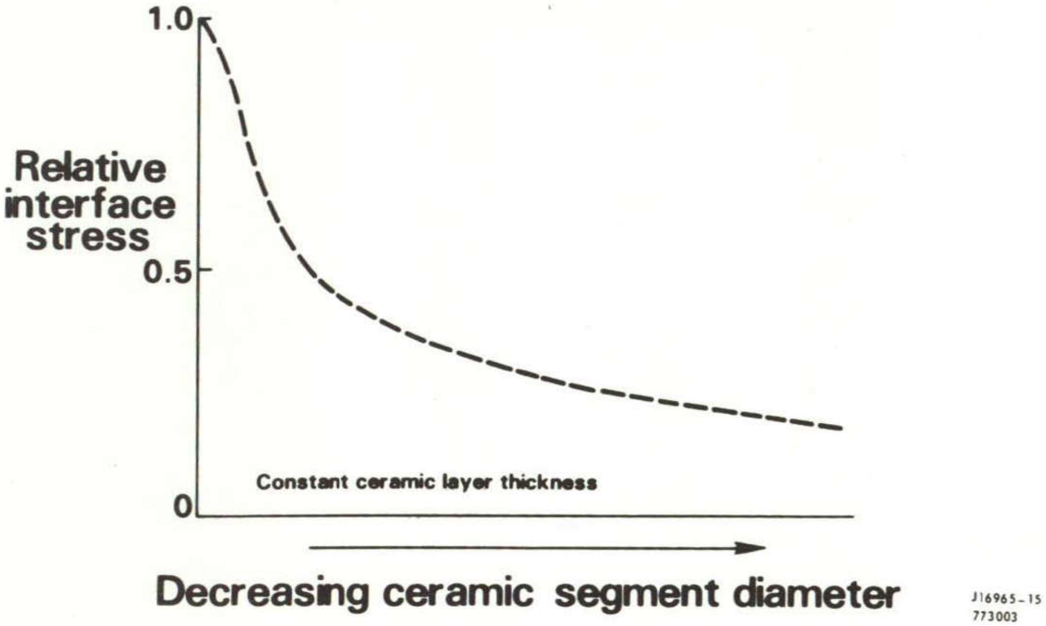


Figure 5-30 Effect of Segment Size on Interface Stress.

The elimination of vane platform film cooling holes is made possible by the insulation properties of thermal barrier coatings which reduce the transfer of heat to the vane platforms. This allows the vane platform cooling configuration to be redesigned for the same metal temperatures with fewer or complete elimination of film cooling holes while requiring less cooling flow. This eliminates or reduces the momentum loss which occurs when the low momentum film cooling air is introduced into the high velocity main gas stream and results in a turbine efficiency improvement of 0.09 percentage points.

A further TSFC improvement results from the engine cycle effect of reducing the vane platform cooling flow by 1.6 percent of the gas generator flow. The estimated effect is based on no change in the turbine nozzle flow areas which results in a small shift in component matching.

Economic Evaluation

Tables 5-38, 5-39 and 5-40 provide the economic evaluation relating to engine data, airline costs, and fuel savings for the JT9D high pressure turbine thermal barrier coatings. The engine data in Table 5-38 shows reduction in cooling flow provides a performance and EGT benefit. The elimination of the cooling holes reduces the cost to manufacture the vanes and hence their price. The price change is greatest in the more complex and expensive -59/70 vanes. Engine maintenance is reduced by the EGT reduction and the reduction in the price of the vanes. Since both the first cost and the annual costs are reduced, PBP becomes instantaneous, indicating a very attractive economic situation, exceeding all criteria for acceptance. The performance improvement would impact over 4,000 engines between 1982 and 1990 and result in a combined fuel saving of 980 million liters.

TABLE 5-38
JT9D THERMAL BARRIER COATING
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0.17	2
Climb	0.17	2
Cruise, Avg.	0.17	
Hold	0.17	
Weight Change, Kg (lb)	0	

	-7	-70/59	
Price Change, $	-5,500	-35,000	
Kit Price, $	-6,300	-32,200	(Attrition)
Maintenance Cost Change, $/Oper. Hr.			
Materials	0	-1.35	
Labor @ $30 Per Man-Hr.	-1.10	-1.10	

TABLE 5-39
JT9D THERMAL BARRIER COATING
AIRLINE COSTS
Per Aircraft

Airline Model	747-200		DC10-40
Operating Cost Changes, $/Year	-7	-70/59	-70/59
Fuel	-16,135	-17,330	-6,990
Maintenance	-20,100	-44,840	-25,220
Block Speed Effect	0	0	0
Total	-36,235	-62,170	-32,210

Type of Investment	New Buy		Retrofit		New Buy	Retrofit
Required Airline Investment Changes, $	-7	-70/59	-7	-70/59	-70/59	-70/59
Installed Engines	-22,000	-140,000	-25,300	-128,800	-105,000	-96,600
Spare Engines	-6,000	-38,220	-6,900	-35,160	-24,150	-22,220
Spare Parts	-4,400	-28,000	-5,000	-25,760	-21,000	-19,320
Total	-32,400	-206,220	-37,200	-189,720	-150,150	-138,140
Payback Period, Years	0	0	0	0	0	0
DOC Change, %	-0.3	-0.3			-0.3	

TABLE 5-40
JT9D THERMAL BARRIER COATING
FUEL SAVINGS

Fleet Fuel Saved, %	0.2			
Start of Service Date	1-82			
Investment Type		**New Buy**	**Retrofit**	**Total**
No. of Engines Affected	-7	810	2,075	2,885
	-70/59	810	460	1,270
Cum. Fuel Saved, 10^6 Liters	-7	280 (74)	295 (78)	575 (152)
(Gal.)	-70/59	280 (74)	125 (33)	405 (107
			Total	980 (259)

5.2.11 JT9D-70/59 4.2 AR Fan

Concept Description

Although it would have been desirable to use the tested 3.8 AR fan blade as the new single shrouded blade for the JT9D-70/59, the weight and resulting gyroscopic loads and unbalance loads in the event of a blade loss introduced by the 3.8 AR blade made its application impractical. As a result the slightly more aggressive 4.2 AR fan blade was selected. However, the same design system and the results from the 3.8 AR fan blade tests were used as the basis to establish the details for the 4.2 AR fan blade, since the 4.2 AR fan also uses a single shroud.

Table 5-41 shows the 4.2 AR fan blade features as compared to the JT9D-70 Bill of Material and the 3.8 AR fan for the JT9D-7.

TABLE 5-41
FAN BLADE FEATURES

Features	JT9D-70 B/M	JT9D-70 Proposed	JT9D-7 3.8 AR
Aspect Ratio	4.6	4.2	3.8
Number of Blades	46	42	38
Root Chord, cm (in)	15.34 (6.04)	17.97 (7.076)	18.41 (7.25)
Tip Chord, cm (in)	21.71 (8.55)	23.70 (9.33)	25.80 (10.16)
Thickness ratio,	0.070	0.078	0.0909
Thickness ratio,	0.024	0.020	0.020
Hub/tip ratio	.4125	.4064	.398
Shroud Location	55 & 85%	70%	68%
Airfoil Series	MCA*	MCA*	MCA*

*Multiple Circular Arc.

As shown in the table the 4.2 AR blade geometry is similar to the successful performing 3.8 AR fan blade tested in the JT9D-7. Development modifications are expected to be minimal to the blade.

Although the 4.2 AR fan design is more aggressive structurally than the 3.8 AR fan, the deviation in the design from the 3.8 AR fan is not felt to be large enough to reduce the confidence in the expected success of the 4.2 AR fan program.

The number of airfoils in the FEGV is primarily set by a noise criteria. In the JT9D-7 with 46 blades the criteria dictated 108 FEGV's. The JT9D-70/59 which was designed after the D-7 employed a slightly more aggressive noise posture and utilized 96 FEGV's with the original 46 fan blades. With the change to 42 blades a correspondingly aggressive posture would result in 88 FEGV's. The gain in performance in going from 96 vanes to 88 was considered too small to warrant the fabrication of new fan exit guide vane assemblies.

The parts involved in the 4.2 AR fan change are shown in Figure 5-31 and include the fan blades, hub, spinner support, and fan blade rup strip. Changes to the fan case and fan exit guide vane case may be necessary depending on results of a blade containment study.

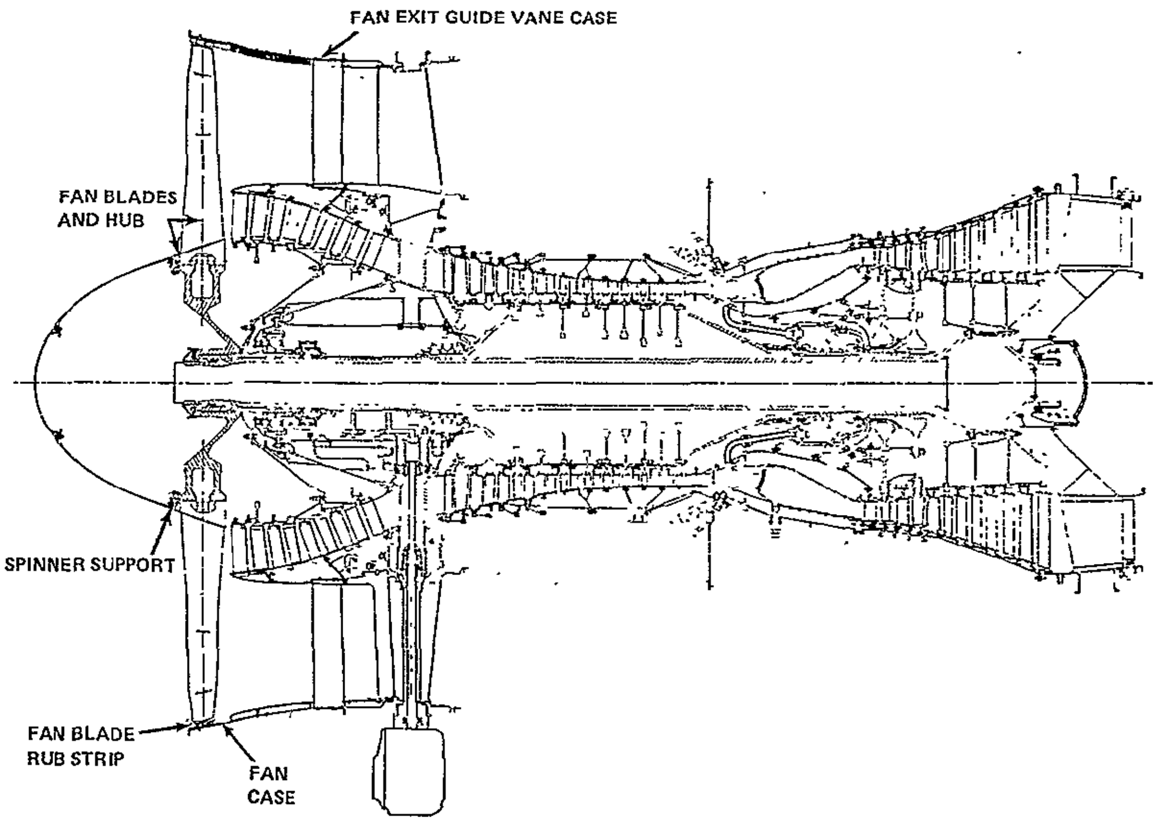


Figure 5-31 JT9D-70/59 Parts Affected by Fan Blade Change

Performance Substantiation

As mentioned earlier, the design system and test results from the 3.8 AR fan blade were used to establish the details for the 4.2 AR fan blade. Figure 5-32 shows that the 4.2 AR fan has a higher estimated efficiency than the B/M 4.6 AR fan, resulting in improved TSFC.

The fan airflow and pressure ratio capabilities at a given speed are slightly higher for the 4.2 AR fan compared to the Bill-of Material 4.6 AR fan. However, both parameters are increased proportionally so the fan operating line (pressure ratio vs airflow) is unchanged.

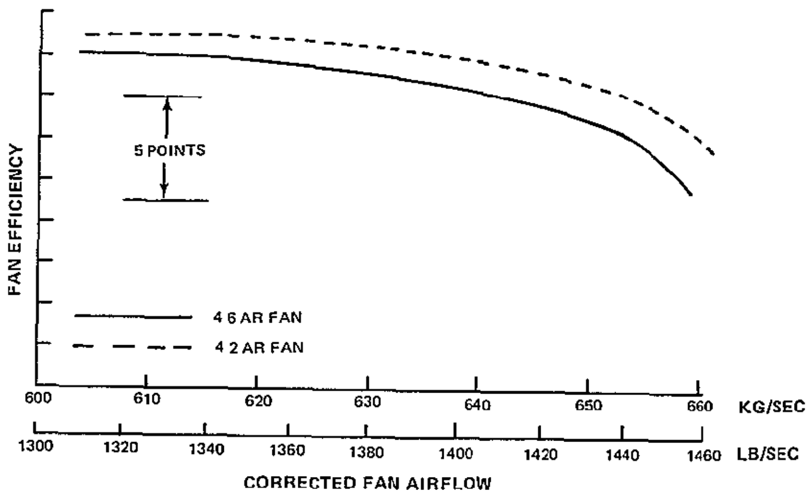


Figure 5-32 Predicted 4.2 AR Fan Blade Performance

Economic Evaluation

The engine data shown in Table 5-42 indicate the effect of improved 4.2 AR fan blade performance on TSFC and EGT. The reduced EGT results in a decrease in the frequency of shop visits of about 260 hours which reduces the estimated labor cost per hour of engine operation. The price of each blade is increased due to the increased cost to manufacture the larger blade, an increase more than offset by the reduction in the number of blades from 46 to 42, resulting in a net decrease in engine price. The increased weight is due to the heavier wide chord blades and the increased hub depth.

Payback periods for new buy cases appear very attractive as shown in Table 5-43. The retrofit case, however, is unattractive due to the large investment required to install the 4.2 AR blades in engines currently having 4.6 AR blades making it unlikely that operators would consider retrofit of this concept. The 910 engines impacted between introduction in 1981 and 1990 will consume 1571 million liters less fuel during their service lives (Table 5-44).

TABLE 5-42
JT9D - 70/59 4.2 AR FAN ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0.7	5
Climb	3.1	9
Cruise, Avg.	1.4	
Hold	0.7	
Weight Change, Kg (lb)	+330 (+150)	
Price Change, $	-3800	
Kit Price, $	284,600 (Non-Attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	-0.20	
Labor @ $30 Per Man-Hr.	-4.77	

TABLE 5-43
JT9D - 70/59 4.2 AR FAN AIRLINE COSTS
Per Aircraft

Airplane Model	747-200		DC10-40	
Operating Cost Changes, $/Year				
Fuel	-122530.		-50555	
Maintenance	- 89300.		-50240	
Block Speed Effect	- 1575		- 1330	
Total	-213405		-102125	
Type of Investment	**New Buy**	**Retrofit**	**New Buy**	**Retrofit**
Required Airline Investment Changes, $				
Installed Engines	-15200	+1,138,400	-11410	+853,800
Spare Engines	- 4145	+ 310,470	- 2620	+196,275
Spare Parts	- 3100	+ 167,930	- 2320	+121,700
Total	-22445	+1,616,800	-16,400	+1,171,775
Payback Period, Years	0	7.6	0	11.5
DOC Change, %	-0.9		-0.8	

TABLE 5-44

JT9D - 70/59 4.2 AR FAN
FUEL SAVINGS

Fleet Fuel Saved, % 1.5

Start of Service Date 3-81

Investment Type	New Buy	Retrofit	Total
No. of Engines Affected	910	0	910
Cum. Fuel Saved, 10^6 Liters (Gal)	1571 (415)	0	1571 (415)

5.2.12 JT9D-70/59 HPT Improved Active Clearance Control

Concept Description

The Bill-of-Materials JT9D-70/59 engine incorporates a high-pressure turbine active clearance control system to obtain reduced blade tip clearances during cruise operating conditions. Clearance reduction is provided by ducting cooling air to the outer flanges of the high-pressure turbine case to reduce the temperature of this component. The reduced temperature level results in limiting the thermal growth of the turbine case which, in relation to the normal thermal growth of the turbine disk and blades, provides a reduction in blade tip clearance and a corresponding reduction in thrust specific fuel consumption (TSFC). Air for cooling the turbine case is provided by a scoop in the nacelle fan-air duct.

Compared to the Bill-of-Materials system, the improved active clearance control system includes: 1) a three-fold increase in the amount of cooling air from the fan, and 2) an improved air delivery and distribution system featuring "square" cooling air pipes which are positioned closer to the turbine case flanges and rails. Cooling air is ducted from the fan air stream in the engine nacelle by two scoops, two elbows, and two air control valves to twin cooling air collectors. A schematic comparison of the Bill-of-Materials and the improved active clearance control systems is shown in Figure 5-33. The improved system uses sets of semicircular cooling air pipes (Figure 5-34), which connect to the air collectors as shown in Figure 5-35. The dual air delivery plumbing in the improved active clearance control system ensures passage of the higher air flow with a reasonable pressure drop.

The utilization of nominally square cooling air pipes in the improved system increases the cooling capability and efficiency by providing for the increased cooling air flow and optimizing the impingement of the cooling air onto critical regions of the turbine case structure while limiting the required spatial envelope by nesting the pipes closely between the turbine case flanges and rails. Figure 5-36 compares the Bill-of-Materials configuration, with its round pipes, with the improved system configuration, with its square pipes. The improved configuration is designed to have an air flow capacity sufficient to reduce the high-pressure turbine case flange and rail temperatures by an additional 90°C (160°F) at cruise conditions pared to the Bill-of-Materials configuration, as illustrated in Figure 5-37.

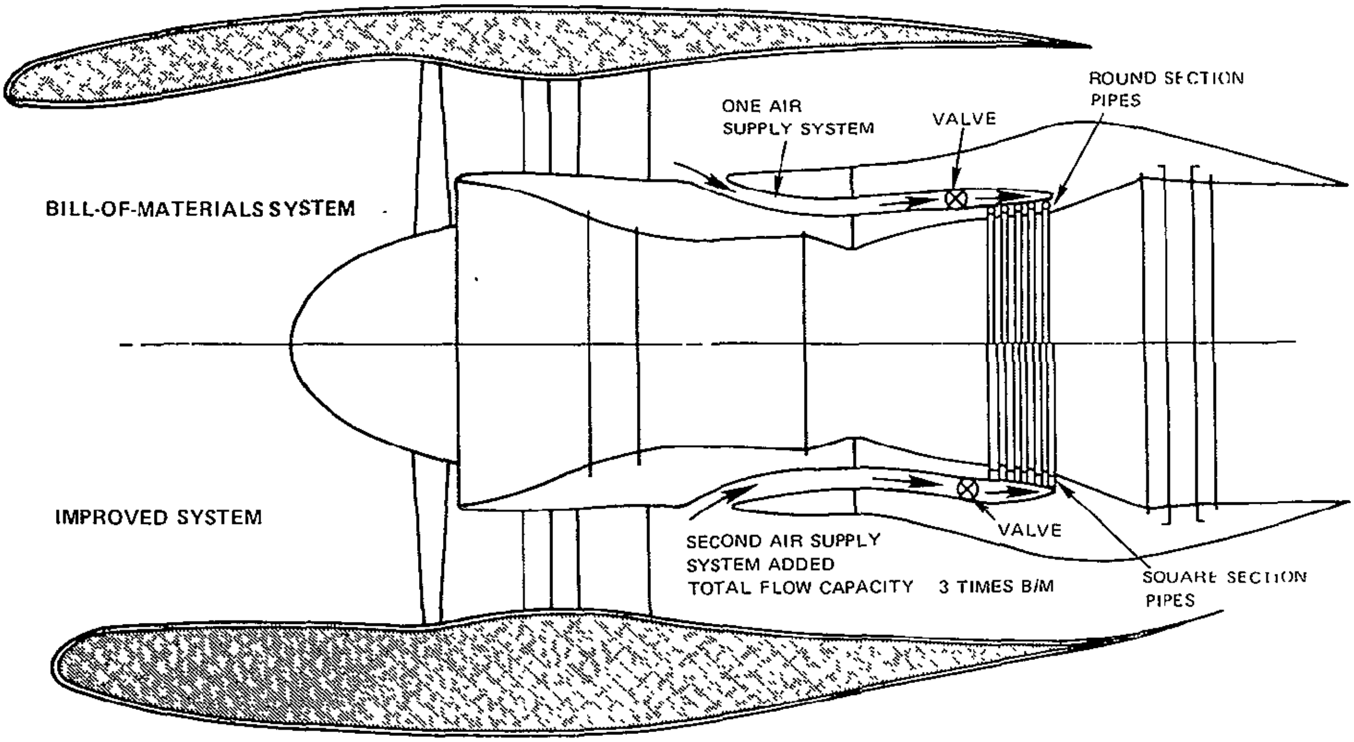


Figure 5-33 Schematic Comparison of Bill-of-Materials and Improved Active Clearance Control Systems

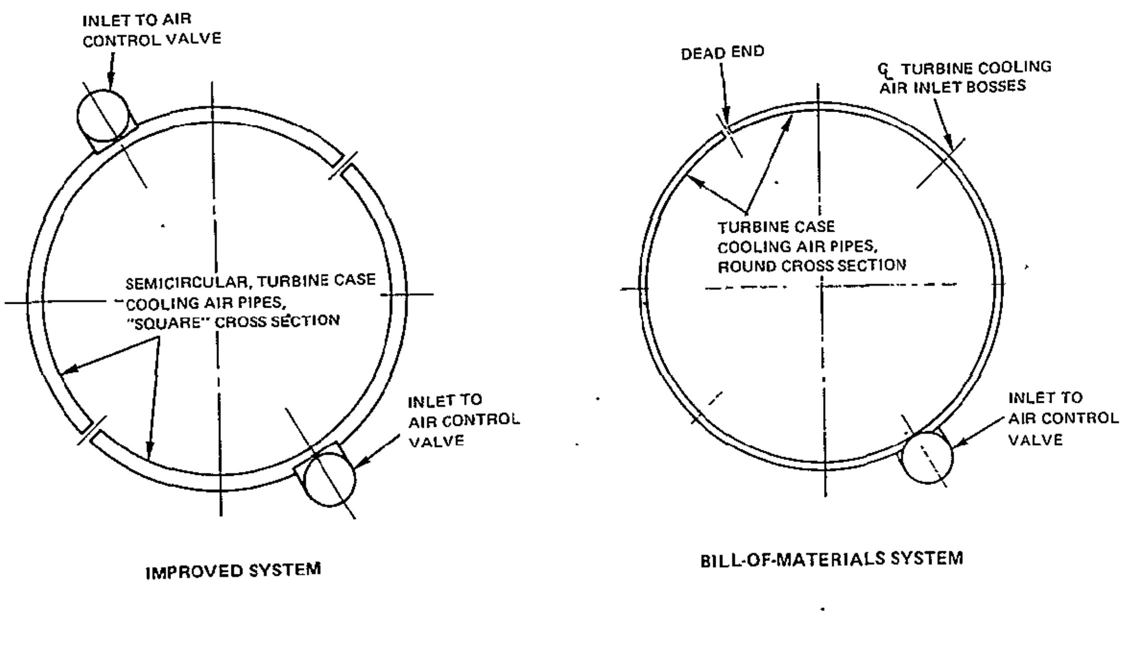


Figure 5-34 Comparison of Turbine Outer Case Cooling Air Pipe Arrangement for Bill-of-Materials and Revised Systems

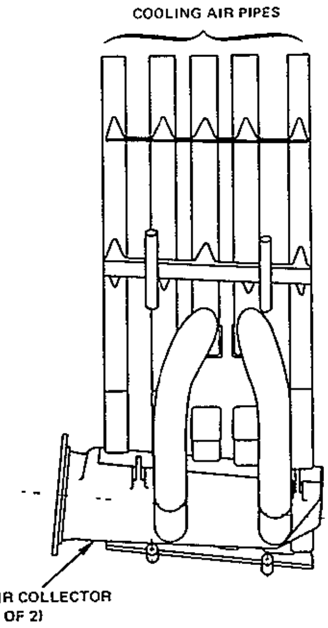


Figure 5-35 "Square" Pipe Attachment to Cooling Air Collector

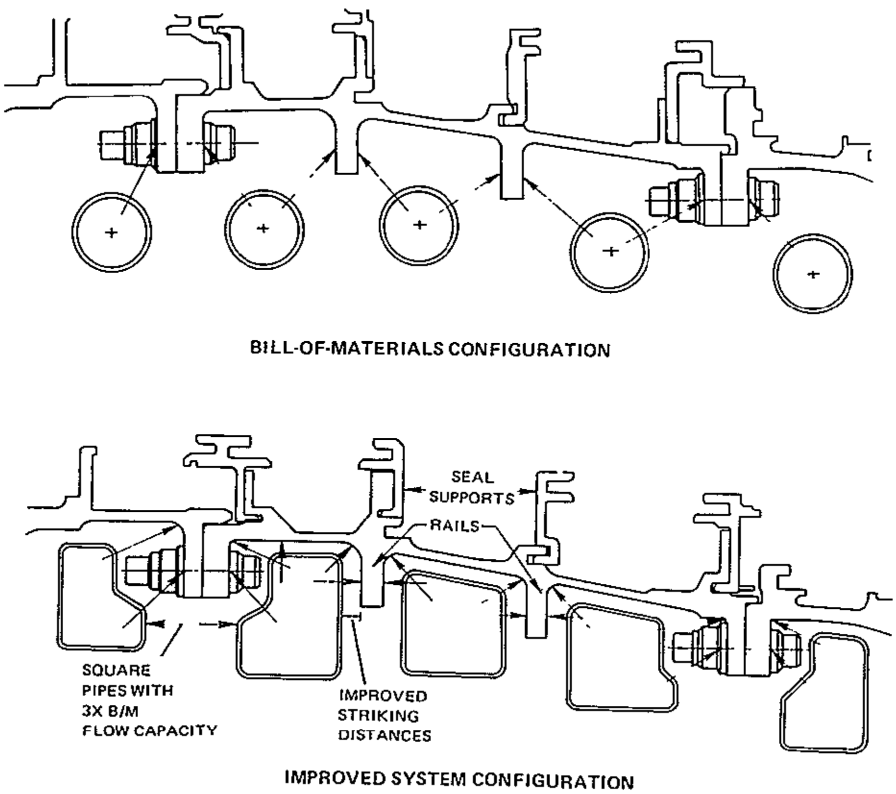


Figure 5-36 Comparison of Bill-of-Materials and Improved System Cooling Pipe Configurations

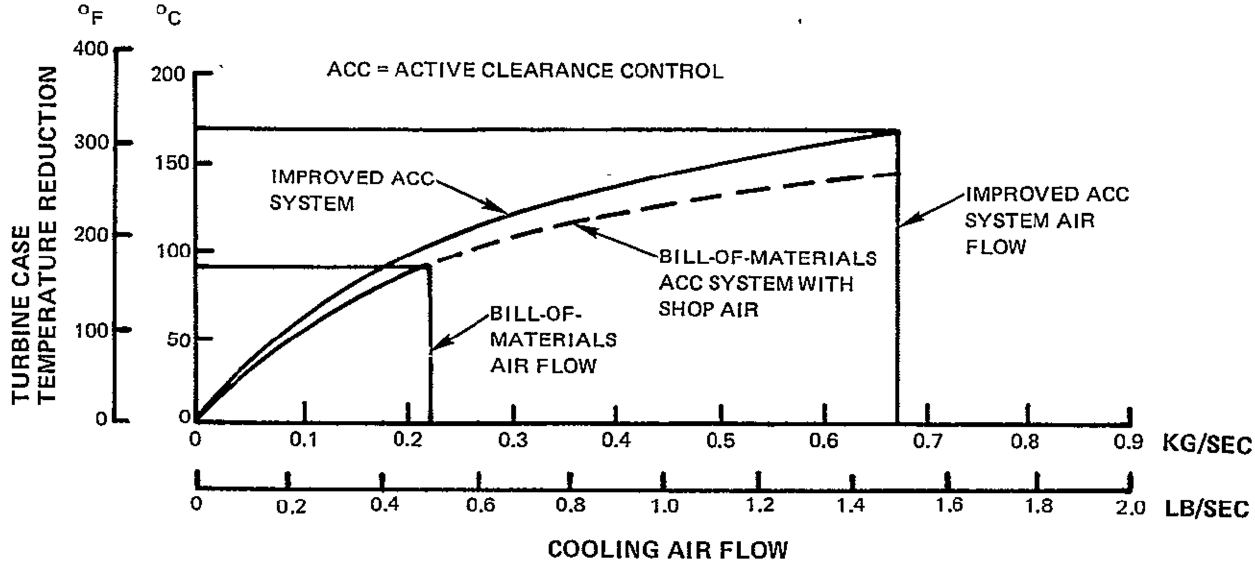


Figure 5-37 High-Pressure Turbine Case Temperature Reduction Potential

Analytical thermal evaluations show that internal engine parts, such as the outer air seal support rings, outer air seals, and second-stage turbine vanes, resist the shrinkage of the turbine outer case. In some regions where this internal resistance exists, because of parts interference and resultant binding, possible damage to internal parts may result. "Shaving" of some internal parts (that is, increasing the clearance between adjacent parts) will reduce the binding condition. Shaving of the outer air seal segments and the second-stage vanes has been considered to relieve the binding condition. Structural modification of the seal supports is also possible to increase the responsiveness of the seal clearance to case diameter changes.

Performance Substantiation

Experimental engine testing has been conducted at sea level static conditions with the Bill-of-Materials active clearance control system using shop air for turbine case cooling. As shown in Figure 5-38, the results of these tests indicate a TSFC improvement of 1.2 percent for the Bill-of-Materials high-pressure turbine case temperature reduction of 85°C (156°F). (This temperature reduction is equal to that expected at altitude cruise conditions.) The indicated sea level TSFC improvement is equivalent to 0.7 percent at altitude cruise conditions. Tests at simulated altitude conditions of another experimental engine incorporating the Bill-of-Materials active clearance control system verified the TSFC reduction of 0.7 percent.

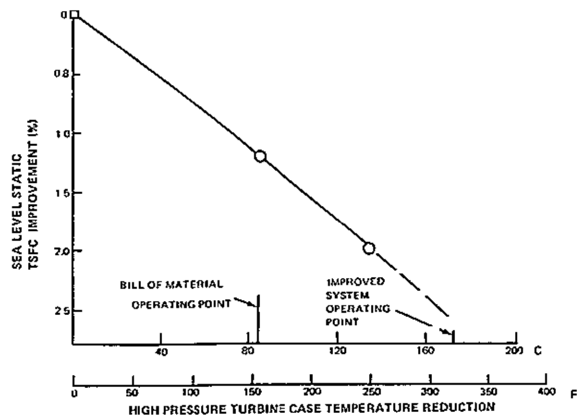


Figure 5-38 Sea Level TSFC Reduction Demonstrated Using Shop Air for Active Clearance Control

To investigate the effect of high-pressure turbine outer case temperature reductions in excess of the initial tests with the B/M system, the high pressure shop air was again used to provide a higher flow capacity. With the higher flow, a high-pressure turbine outer case temperature reduction of nearly 140°C (250°F) with a corresponding TSFC reduction of 2.0% was achieved compared to the initial temperature reduction of 85°C (156°F). If the curve in Figure 38 is extrapolated to about 175°C (320°F), a temperature reduction achieved during an altitude test of an engine with square pipes and fan cooling air, a total potential TSFC reduction of 2.6% is obtained at sea level conditions compared to an uncooled turbine case. This sea level reduction in TSFC is equivalent to 1.4% TSFC improvement at altitude conditions. This demonstrated achievement represents a cruise TSFC improvement of 0.7% over the capability of the B/M active clearance control system.

The tabulation below indicates the conversion of the sea level results to the resultant TSFC improvement at cruise conditions.

	Improvement in Level TSFC (%)		Sea Level-to-Altitude Cruise TSFC Ratio		Fan, Air Cooling Flow TSFC Penalty (%)		Improvement in Altitude Cruise TSFC (%)
Improved System	2.6	x	0.7	–	0.42	=	1.4
Bill-of-Materials System	1.2	x	0.7	–	0.14	=	0.7
Net Improvement over Bill-of-Materials System						=	0.7

Two factors have not been accounted for in the above evaluation. Decreasing the internal resistance to turbine case shrinkage will permit a reduction in cooling air flow to achieve the same degree of clearance reduction. The reduced air flow required from the fan stream will provide a slight additional reduction in TSFC by reducing the fan air penalty. Further, the cooling air flow on the downstream flange of the high-pressure turbine will also influence the case temperature of the first stage of the low-pressure turbine and decrease its clearance. This will provide a still further reduction in TSFC. Both of these effects are expected to be relatively small, but studies have indicated that the total additional TSFC reduction should be about 0.2 percent. On this basis, it is expected that the improved active clearance control system should provide a total TSFC reduction of 0.9 percent, the value used in the economic evaluation.

Economic Evaluation

The price of the engine is increased due to the segmenting of the outer seal support rings and associated changes to the HPT case to accommodate the segmented rings plus a more costly dual control valve and delivery system. The relatively high kit price is due to the requirement to buy a new HPT case, a purchase that would not be done on an attrition basis. Table 5-45 presents the engine data for this concept.

TABLE 5-45
JT9D - 70/59 HPT IMPROVED ACTIVE CLEARANCE CONTROL
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	–	–
Climb	–	–
Cruise, Avg.	0.9	
Hold	–	
Weight Change, Kg (lb)	+34 (+75)	
Price Change, $	+13,400	
Kit Price, $	80,600 (Non-Attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 Per Man-Hr.	0	

An evaluation of the airline costs shows that new buy economics are excellent with payback periods of 1.0 and 2.1 years for the 747 and DC10 respectively (Table 5-46). The retrofit case is not attractive and would probably not be adopted by the airline operators. Installation of the HPT active clearance control systems on 1150 new JT9D-50/70 engines beginning service in 6-79 show that 1771 million liters of fuel would be saved (Table 5-47).

TABLE 5-46
JT9D - 70/59 HPT IMPROVED ACTIVE CLEARANCE CONTROL
AIRLINE COSTS
Per Aircraft

Airplane Model	747-200		DC10-40	
Operating Cost Changes, $/Year				
Fuel	-74,140		-27,100	
Maintenance	0		0	
Block Speed Effect	-1,920		-1,200	
Total	-76,060		-28,300	
Type of Investment	**New Buy**	**Retrofit**	**New Buy**	**Retrofit**
Required Airline Investment Changes, $				
Installed Engines	+53,600	+322,400	+43,500	+241,800
Spare Engines	+14,600	+87,900	+10,000	55,600
Spare Parts	+7,900	+44,000	+6,000	33,350
Total	+76,100	+454,300	+59,500	+330,750
Payback Period, Years	1.0	6.0	2.1	11.7
DOC Change, %	-0.3		-0.3	

TABLE 5-47
JT9D - 70/59 HPT IMPROVED ACTIVE CLEARANCE CONTROL
FUEL SAVINGS

Fleet Fuel Saved, % 0.9

Start of Service Date 6-79

Investment Type	New Buy	Retrofit	Total
No. of Engines Affected	1150	0	1150
Cum. Fuel Saved, 10^6 liters (gal.)	1771 (468)	0	1771 (468)

5.2.1.3 JT9D Structural FEGV

Concept Description

The Structural FEGV concept proposes a change to the fan exhaust case of the JT9D-7 and JT9D-70/59 engines in which the fan aerodynamic exit vanes are moved downstream into the plane of the structural struts and combines the functions of both into one row of airfoils, thereby eliminating one row of loss producing surfaces. The fan exhaust cases of the JT9D-7 and D-70/59 engines are similar in many respects. The major difference between the two is the addition of a second thick structural strut in the bottom of the case of the D-70/59 to accommodate a tower shaft which drives the accessories mounted on the bottom outer diameter of the fan case as shown on Figure 5-39. The D-7 accessories are mounted in the space between the high spool and the fan duct, eliminating the need for a tower shaft penetrating the fan duct. A thick structural strut is common to both engines at the top of the fan case to provide a leading edge fairing for the duct bifurcation which contains the engine support structure and some accessories, airframe bleed and other power requirements. The two models also have different numbers of aerodynamic vanes as shown in Table 5-48. The Structural FEGV concept results in the same spacing of structural vanes in both models, with the only difference being the requirement for a second thick strut in the D-70 to accommodate the tower shaft. This thick strut replaces two of the thin struts in the D-7.

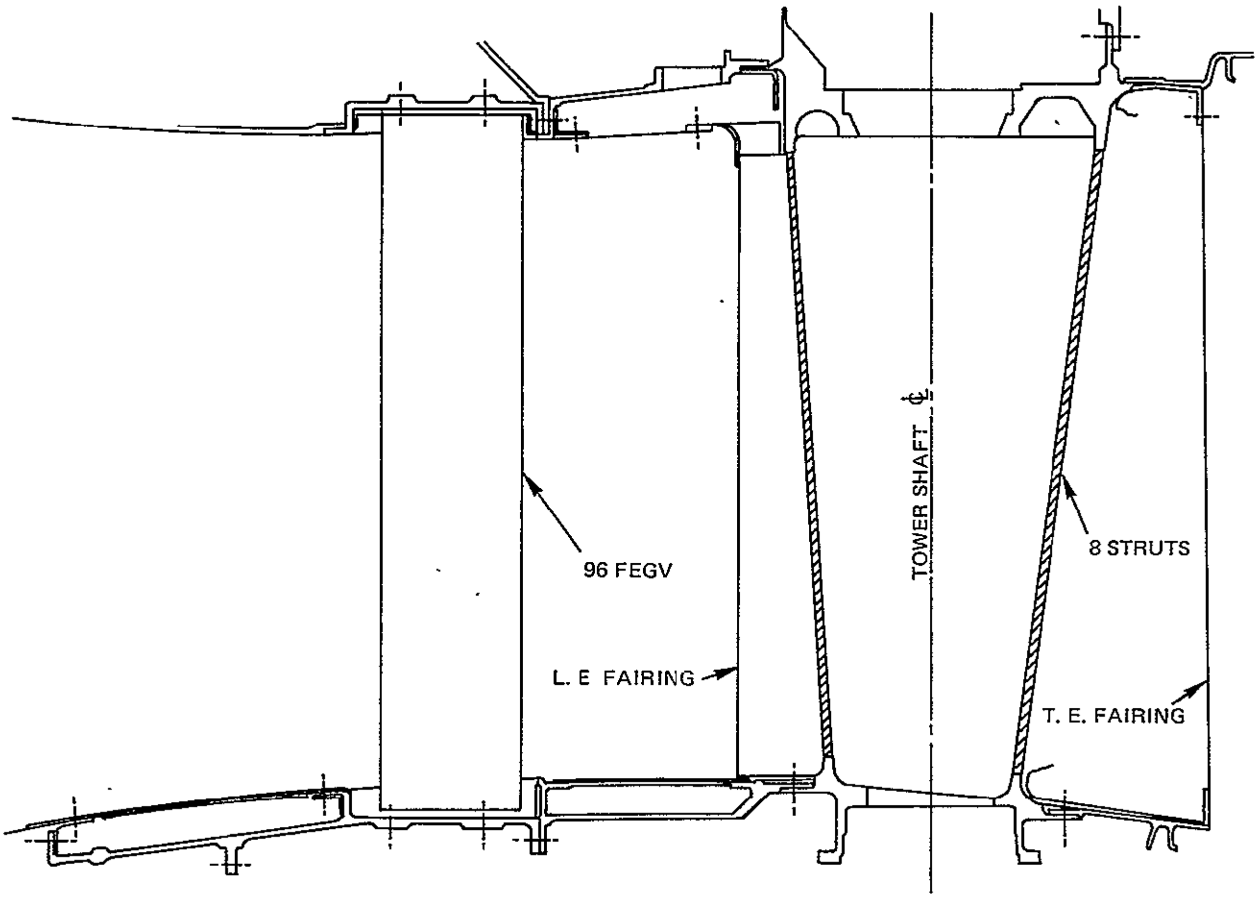


Figure 5-39 JT9D-70 Bill-of-Materials Fan Exhaust Case Showing FEGV's and Structural Struts

TABLE 5-48
SUMMARY OF JT9D FAN EXHAUST CASE GEOMETRY

	B/M		Structural FEGV	
	D-7	D-70/59	D-7	D-70/59
Number of EGV's	108	96	0	0
Number of Struts, thick	1	2	1	2
thin	8	6	58	56

C-2

The structural FEGV concept is shown in Figure 5-40. It can be seen that the leading edge (LE) of the FEGV's have been moved to the same axial plane as the LE of the sheet metal fairing around the thick structural strut at the bottom of the B/M D-70/59 case. Looking up from the bottom of the engine, the JT9D-70/59 B/M fan exhaust case is compared to the structural FEGV configuration in Figure 5-41. The constant speed drive oil cooler for the JT9D-70/59 installation interferes with the structural FEGV arrangement and has been relocated to the side of the bottom bifurcation fairing.

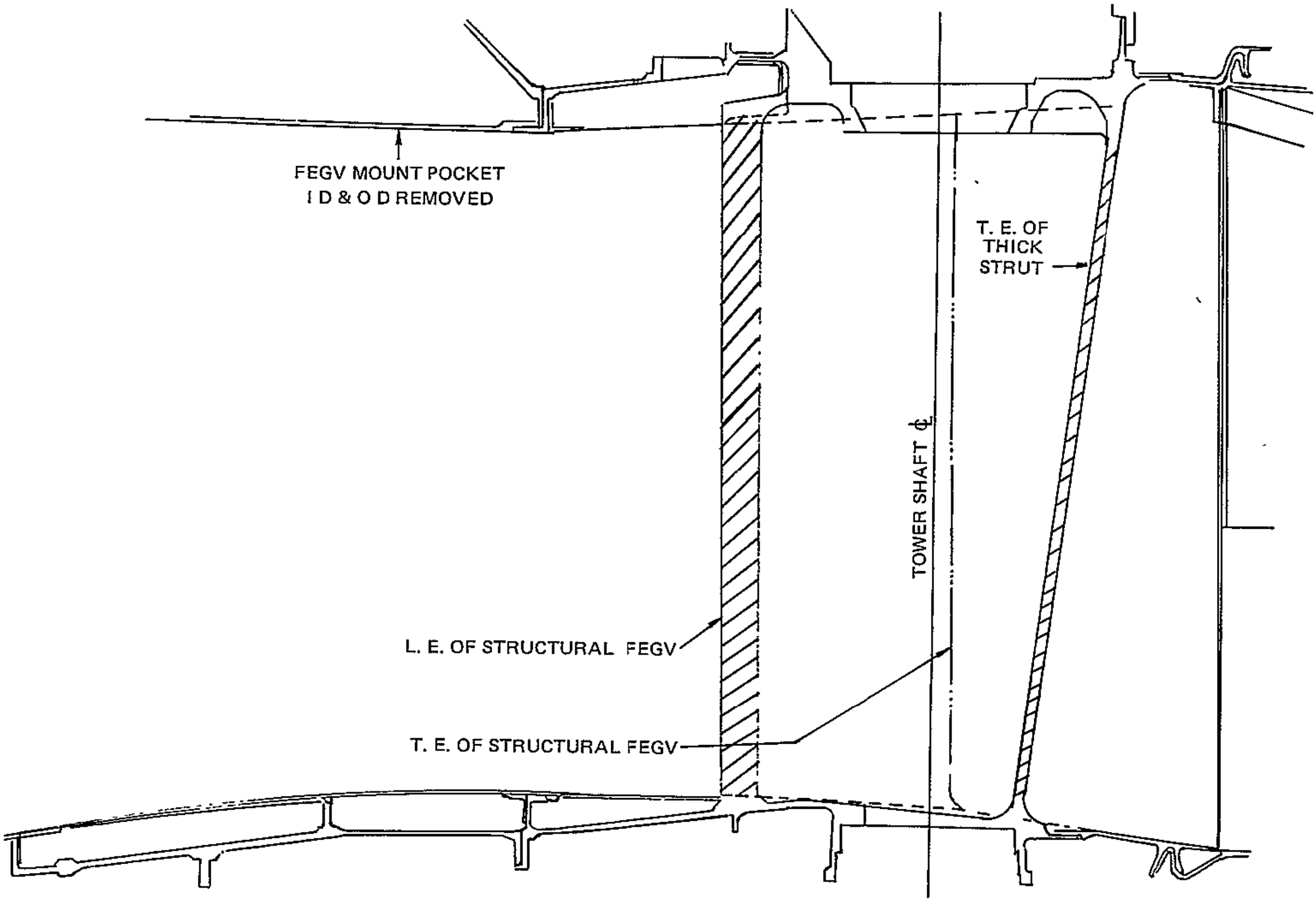
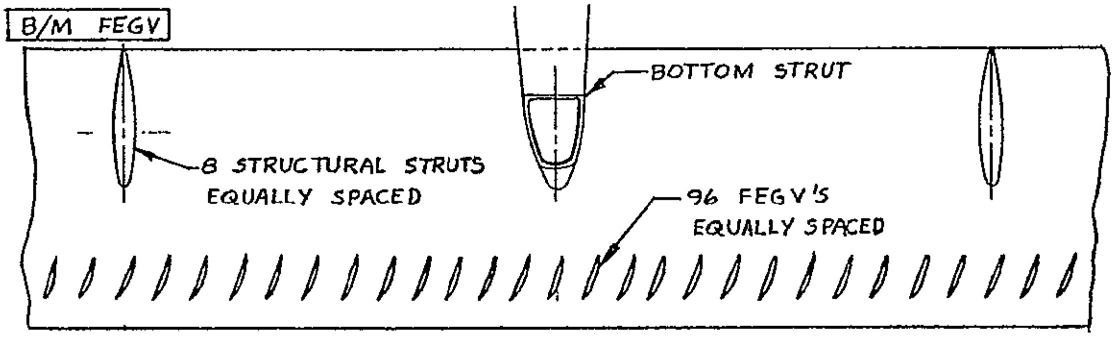
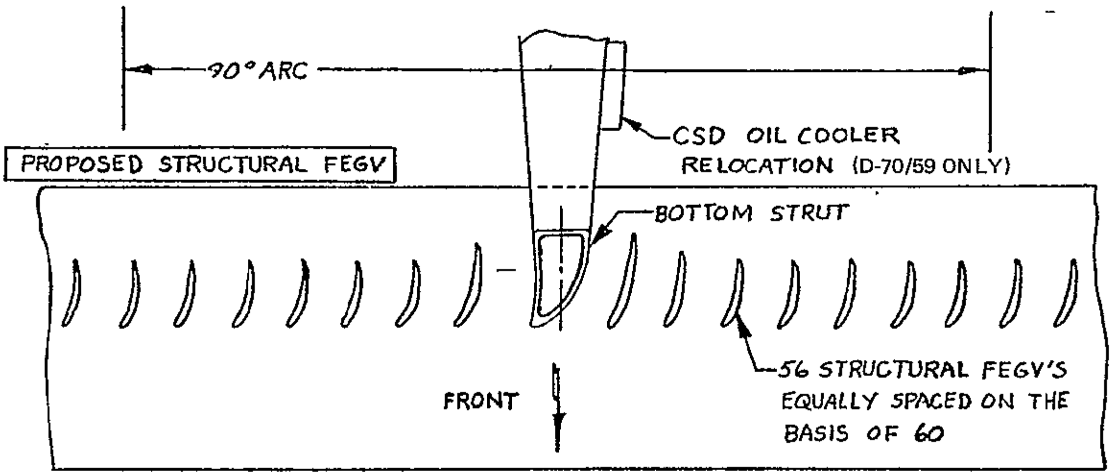


Figure 5-40 Proposed Structural FEGV Concept for the JT9D-7 and JT9D-70/59 Fan Exhaust Case



B/M FEGV



STRUCTURAL FEGV

Figure 5-41 *View of Unwrapped Section of JT9D-70 B/M Fan Exhaust Case and Proposed Structural FEGV Exhaust Case*

Performance Substantiation

The losses in the fan exhaust case are made up from two sources: (1) the FEGV's and (2) the structural struts.

FEGV Losses – The pressure loss in the FEGV of the D-7B/M case is approximately 2% of the duct stream pressure. This FEGV has a gap/chord ratio which is too tight and results in a less than optimum aerodynamic loading on the airfoils. This tight vane spacing was believed to be necessary to monimize fan noise at the time the D-7 was designed. The D-70/59 case has only 96 FEGV's with approximately 1.8% pressure loss.

Strut Losses – The strut losses for the B/M cases are approximately 1%. When the FEGV's are moved to the plane of the struts, now becoming structural FEGV's, the gap/chord ratio of the struts are reduced to approximately the level of the D-70/59 B/M FEGV's to be able to efficiently handle the aerodynamic turning now required of the struts. The losses of the structural FEGV's are increased somewhat above the B/M levels because of the thick struts that are still required to accommodate accessories and airframe services. In addition, the structural loads the new FEGV's are required to carry dictate a small increase in airfoil thickness ratio which also increases the loss level.

A summary of the fan exhaust case losses for the JT9D-7 and D-70/59 with and without the structural FEGV concept is presented in Table 5-49.

TABLE 5-49
SUMMARY OF FAN EXHAUST CASE LOSSES

	B/M Cases		Structural FEGV	
	D-7	D-70/59	D-7	D-70/59
FEGV Loss, ΔP/P	.020	.018	0	0
Strut Loss, ΔP/P	.010	.010	.025	.025
Total Airfoil Loss	.030	.028	.025	.025
Change in loss relative to base, Δ (ΔP/P)	BASE	BASE	– .005	– .003
Reduction in TSFC relative to base, % (Δ TSFC)	BASE	BASE	0.5	0.3

Economic Evaluation

Economic evaluations for the D-7 in terms of engine performance data, airline costs and fuel savings are presented in Tables 5-50, 5-51 and 5-52, respectively, and for the D-70/59 in Tables 5-53, 5-54 and 5-55, respectively.

Table 5-50 shows the engine price decrease due to a reduction in the cost to manufacture the configuration with fewer fan exit guide vanes. The maintenance materials cost reduction corresponds to this price reduction. The maintenance labor cost reduction is a result of the EGT reduction.

Table 5-51 shows the payback period in the new buy case to be very attractive because there is a savings in both annual cash costs and initial investments. The retrofit case is prohibitively expensive due to the fact that cases must be replaced that are not normally replaced. It is unlikely that operators would consider this concept for retrofit.

The resultant fuel saving of 0.6% shown in Table 5-52 would save a total of 834 million liters of fuel if applied to the eligible 850 JT9D-7 engines that will start service after 9-81.

TABLE 5-50
JT9D STRUCTURAL FEGV
ENGINE DATA
JT9D-7 ENGINE
Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0.5	4
Climb	0.5	4
Cruise, Avg.	0.5	
Hold	0.5	
Weight Change, Kg (lb)	+11 (+35)	
Price Change, $	-28,600	
Kit Price, $	157,000 (Non-Attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	-0.45	
Labor @ $30 Per Man-Hr.	-0.73	

TABLE 5-51
JT9D STRUCTURAL FEGV
AIRLINE COSTS
JT9D-7 ENGINE
Per Aircraft

Airplane Model	747-200	
Operating Cost Changes, $/Year		
Fuel	- 45670	
Maintenance	- 21530	
Block Speed Effect	- 900	
Total	- 68100	
Type of Investment	**New Buy**	**Retrofit**
Required Airline Investment Changes, $		
Installed Engines	-114,400	+629,200
Spare Engines	- 31,230	+171,800
Spare Parts	- 5,150	+ 28,300
Total	-150,780	+829,300
Payback Period, Years	0	12.2
DOC Change, %	-0.35	

TABLE 5-52
JT9D STRUCTURAL FEGV
FUEL SAVINGS
JT9D-7 ENGINE
Per Engine

Fleet Fuel Saved, %	0.6		
Start of Service Date	9-81		
Investment Type	**New Buy**	**Retrofit**	**Total**
No. of Engines Affected	850	0	850
Cum. Fuel Saved, 10^6 Liters	834	0	834
(Gal.)	(220)		(220)

TABLE 5-53
JT9D STRUCTURAL FEGV
ENGINE DATA
JT9D-70/59 ENGINE
Per Engine

Performance:	**TSFC Reduction, %**	**EGT Reduction, °C**
Takeoff	0.3	2
Climb	0.3	2
Cruise, Avg.	0.3	
Hold	0.3	
Weight Change, Kg (lb)	+32 (+70)	
Price Change, $	-5,500	
Kit Price, $	136,700	
Maintenance Cost Change, $/Oper. Hr.		
Materials	-0.45	
Labor @ $30 Per Man-Hr.	-0.37	

TABLE 5-54
JT9D STRUCTURAL FEGV
AIRLINE COSTS
JT9D-70/59 ENGINE
Per Aircraft

Airplane Model	747-200		DC10-40	
Operating Cost Changes, $/Year				
Fuel	-26800		-9700	
Maintenance	-15000		-8440	
Block Speed Effect	400		160	
Total	-42200		-18300	
Type of Investment	**New Buy**	**Retrofit**	**New Buy**	**Retrofit**
Required Airline Investment Changes, $				
Installed Engines	-22000	+546,800	-16500	+410,100
Spare Engines	- 6000	+147,600	- 3800	+ 94,300
Spare Parts	- 1000	+ 24,600	- 740	+ 18,500
Total	-29000	+719,000	-21040	+522,900
Payback Period, Years	0	17.0	0	28.6
DOC Change, %	-0.3		-0.2	

TABLE 5-55
JT9D STRUCTURAL FEGV
FUEL SAVINGS
JT9D-70/59 ENGINE

Fleet Fuel Saved, %	0.3			
Start of Service Date	9-81			
Investment Type		**New Buy**	**Retrofit**	**Total**
No. of Engines Affected		850	0	850
Cum. Fuel Saved, 10^6 Liters (Gal)		439 (116)	0	439 (116)

Table 5-53 shows a JT9D - 70/59 engine price reduction due to a reduction in the number of fan exit guide vanes. The maintenance materials cost is reduced in accordance with the number of parts and price. The labor cost is reduced due to the EGT reduction.

As in the case of the 9D-7, the new buy situation is very attractive, while the retrofit case is prohibitively expensive due to the cost of the major parts required for retrofit, as indicated in Table 5-54.

The 0.34 reduction in fuel burned results in a savings of 439 million liters of fuel from 9-81 through the life of the 850 JT9D-70 engines that are candidates for this concept (Table 5-55).

5.3 CONCEPTS RECOMMENDED FOR FURTHER STUDY

The incorporation of the two concepts in this category, the JT9D Mixer and the Electronic Control, depends on substantial airframe integration efforts. The overall benefits from these two concepts can be significant in terms of fuel saved, reduced flight crew workload and improved engine diagnostics but very costly modifications to and investigations of existing systems would be required. Table 5-56 summarizes the results of the evaluation of the two concepts. These results utilize the analyses of both BCAC and DAC which are included as Appendices A and C.

TABLE 5-56
CONCEPT EVALUATION RESULTS

Concept	Airplane	Pay-Back Period ~ PBP (years) New Buy	Retrofit	ΔDOC (%)	Percent Fuel Savings	Cumulative Fuel Savings - 10^6 liters (gal.) New Buy	Retrofit	Total
JT9D Mixer	747	1.9	~	−0.8	2.7	1885 (498)	~	1885 (498)
Nacelle	DC10	2.0	~	−1.6	6.6	1026 (271)	~	1026 (271)
JT9D Electronic Control	747/ DC10	Low fuel saving, evaluation discontinued						

5.3.1 JT9D Mixer

The JT9D mixer concepts were analyzed for technical and economic risks because of their large potential improvement benefit. However, further study is needed to determine the mixer performance characteristics and overall internal engine performance. In addition, further testing is required to determine overall external engine performance in order that uncertainty bands associated with the propulsion system may be reduced. Comparable analysis and test is required on an integrated engine/airframe basis to reduce drag and weight uncertainty. Table 5-57 presents the risk analysis of the JT9D mixer concepts. This analysis shows the large potential benefit for mixing and the areas in which risks exist.

TABLE 5-57

RESULTS OF JT9D-7 AND JT9D-59 MIXER SENSITIVITY EVALUATIONS

	Predicted Values for JT9D-7 in 747's	Predicted Values for JT9D-59 in DC-10's	Estimated Uncertainty Band
Internal Performance, ΔTSFC (%) (cycle, ΔP, leakage, % mixing, Cv)	-4.2	-5.1	-1 to +2
Δ Drag, equivalent ΔTSFC (%) (isolated nacelle, interference)	+1.2	-0.8	-1 to +2
Δ Weight per nacelle, Kg (lb) (mixer, nacelle with advanced materials)	645 (+1425)	0	±130 (±300)
Δ Price per nacelle ($) (mixer, nacelle)	+137,150	+183,300	±50,000
Δ Maintenance Cost per Engine Operating Hour ($)	-7.10	-7.10	±2
Pay-Back Period (years)	+1.9	+2.0	-2 to +4
Fuel Savings (%)	+2.7	+6.6	±3
Cumulative Fuel Savings (10^6 gallons)	+498	+271	±500

Mixer Design

The JT9D mixer design (Figure 5-42) evaluated in the ECI-PI program is based on the P&WA JT8D mixer program experience. Mixer flowpaths for both JT9D-7 and JT9D-70 engines were determined using engine hard points and flows. Temperatures and pressures at the inlet of the mixer were determined through existing engine simulators. The maximum mixer temperature including the effects of expected engine deterioration is predicted to be 650°C (1200°F) at takeoff on a hot day and occurs at the mixer inlet.

The material selected for the mixer is INCO 625. To save weight, titanium was considered; however, titanium alloys that are currently available have not been proven for temperatures above 590°C (1100°F) where alloy instability becomes a concern.

The JT9D mixer wall thickness of 0.198 cm (0.078 in.) is based on calculations of blending stresses in the valley of the lobes in the JT8D program. The JT9D tailplug thickness is estimated to be 0.170 cm (0.067 in.), scaled up from the 0.127 cm (0.050 in.) wall of the JT8D mixer based on the same stresses. More detailed effort in this area is required.

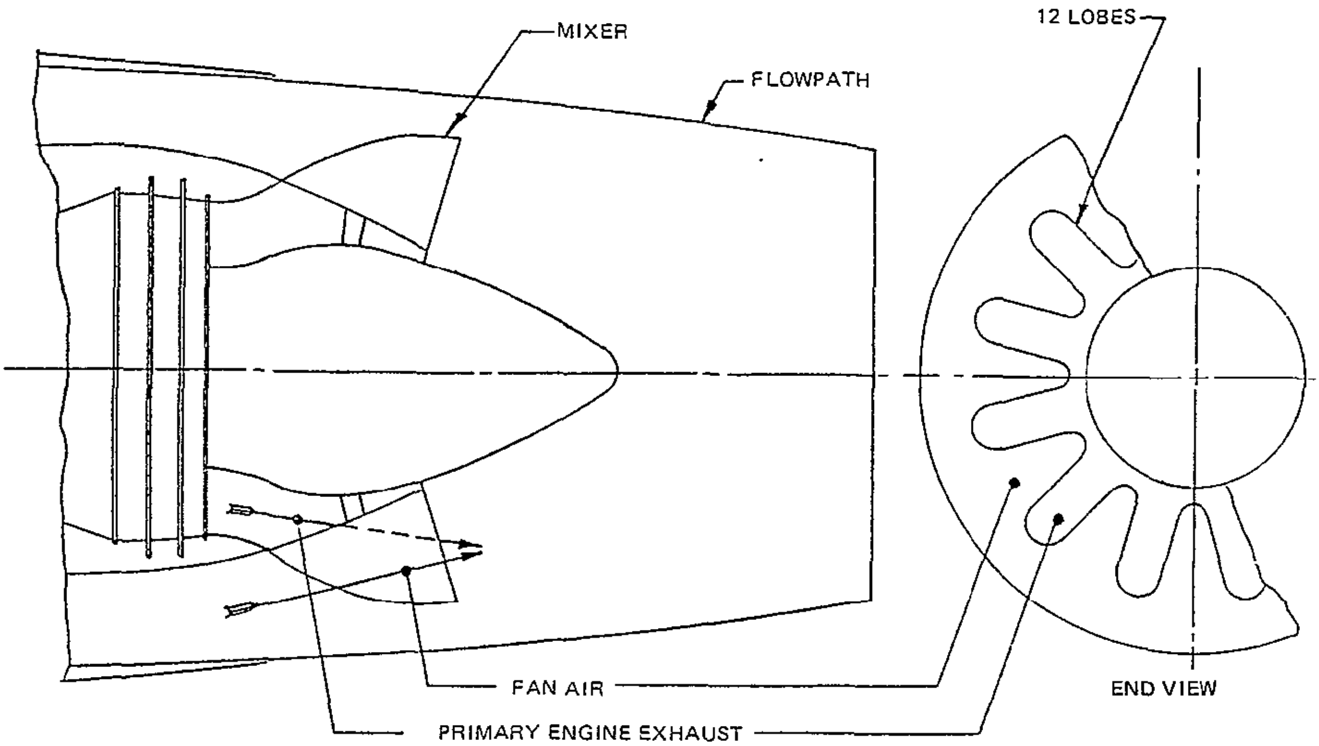


Figure 5-42 JT9D Mixer Design Evaluated In ECI - PI Program

Struts are used on the I.D. of the lobes to support the mixer from the tailplug, providing radial and circumferential restraint. Use of struts at the O.D. of the lobes (as in the 8D program) was unacceptable to Douglas because of the flexible, lightweight composite materials they had selected for the tailpipe in the area of the struts.

The inboard attachment of the struts has the capability of taking radial loads in two directions to restrain the mixer. Since the fan duct static pressure is higher than the primary, and since the tailplug is at a higher temperature than the mixer in normal operation, the struts are in compression. During thrust reverser operation, the direction of the resultant pressure acting on the mixer is reversed, directing the fan air outboard of the engine ahead of the mixer, resulting in heating mixers to the same temperature as the tailplug. Therefore, the effect of thrust reverser operation causes the struts to be in tension. The struts are free to slide in the axial direction to allow for thermal exposure.

A study to investigate potential problems with the inner flange of the turbine exhaust case caused by the new tailplug concluded that no problem existed. Both the weight and location of the C.G. of the new plug relative to the mounting flange are less severe than the baseline.

Mixer Maintenance

Maintainability and reliability studies conducted by P&WA determined the impact of the mixer on engine maintenance cost. Experience of UAL with jet noise suppressors revealed little maintenance cost associated with noise suppressors, and that no materials cost is associated with such a part since it is easily repaired. The frequency of repair was estimated from the UAL experience and is thought to be conservative since suppressors are in a more hostile environment (sonic flow) for vibration and hence cracking that requires repair. The result is a 0.30 $/EOH maintenance labor penalty for the mixer itself. There is, of course, the associated EGT reduction for the mixer which reduces engine shop visit rate.

Mixer Weights and Costs

Mixer weights and costs are determined from the material selection and mixer wall thicknesses. Manufacturing confirmation is obtained for all cost estimates in order to ensure fabrication practicality.

Mixer Performance

The source of the P&WA estimate of the internal engine performance improvement in the mixed flow installations is shown in Figures 5-43 and 5-44. In each case, the performance accounting starts from the basic unmixed engine with separate ideal (no loss) ducts and nozzles for the fan and primary flow. The current short duct 747-200 installation effects are applied to the JT9D-7 and the current 3/4 duct DC10 installation effects are applied to the JT9D-59 to establish baselines for the mixed installations. The thermodynamic effect of mixing is based on 85% mixing in both cases, but the TSFC benefit differs somewhat as shown because of cycle differences between the two engine models. When the pressure losses in the long ducts, mixers, tailpipes and discharge nozzles on the mixed installations are deducted from the mixing benefit, the TSFC of the mixed engines is still somewhat better than the unmixed engines with ideal installations. Compared to the actual current installations of the unmixed engines, the mixed installations show approximately 5.5% TSFC improvement at the average cruise condition. Because of thermodynamic effects, this improvement increases at higher power settings and decreases at lower power settings. It should be noted that the external drag of mixed installations will be different from that of the short and 3/4 duct baseline installations. These differences are discussed by BCAC and DAC in Appendices A and C, and are reflected in the data presented in the Economic Evaluation below.

Figure 5-45 shows the envelope of model test data used by P&WA to establish 85% as a target for the JT9D mixer in the ECI-PI program. Although this goal appears aggressive based on the data, it must be pointed out that no attempt was made in the testing of the various mixers to optimize configuration details nor was scalloping (a successful technique in the JT8D mixer program) included. It is felt that a JT9D program which optimizes the mixer configuration will have high probability of achieving 85% mixing.

Economic Evaluation

The economic evaluations presented in the following tables are based on BCAC and DAC estimates of the effects of installing the JT9D with a mixer in their respective airplanes. These estimates are discussed in Appendices A and C, which were prepared by BCAC and DAC, respectively. The airplane companies elected to use the P&WA estimates of the internal engine effects of the mixer in all cases except for the internal performance effect in the 747 airplane, which are shown on the first section of Table 5-58. These performance effects were estimated by BCAC, based on 70% mixing instead of the 85% assumed by P&WA. This difference results from different interpretations of similar testing results, and represents a major portion of the uncertainty band on mixed engine performance shown in Table 5-57. The second section of Table 5-58 summarizes the BCAC estimates of the effects of installing the JT9D-7 engine with mixer in the 747 airplane instead of the same engine in the standard short duct nacelle. The weight and price effects shown on this table are based on the use of an advanced nacelle design without the use of advanced composite materials as described in Appendix A. Tables 5-59 and 5-60 complete the summary of the economic evaluation of the mixer on the 747 airplane, showing the concept to have an acceptable payback period and a significant fuel saving if it were developed and incorporated in all 747's delivered after January 1985.

Table 5-61 summarizes the effects of installing the JT9D-59 with mixer in the DC10 airplane instead of the same engine in the 3/4-length duct Common Nacelle System. All of the internal engine effects are those estimated by P&WA, while the installation effects were estimated by DAC, as discussed in Appendix C. Table 5-62 shows the payback period in the DC10 to be about the same as in the 747 despite the significantly higher fuel burned improvement predicted for the DC10. This result is due to a combination of factors. The higher (international) fuel price used for the 747 (45¢ /gal vs. 35¢ /gal for the DC-10), the relative sizes of the two aircraft (reflecting absolute levels of fuel flow) and the international route structure of the 747 (yielding higher annual utilization) all place more importance on fuel in the 747 and lead to the nearly equal payback periods. The cumulative fuel saving is less with the DC10 as shown on Table 5-63 because the low sales projection for JT9D powered DC10's overbalances the higher percent fuel saving.

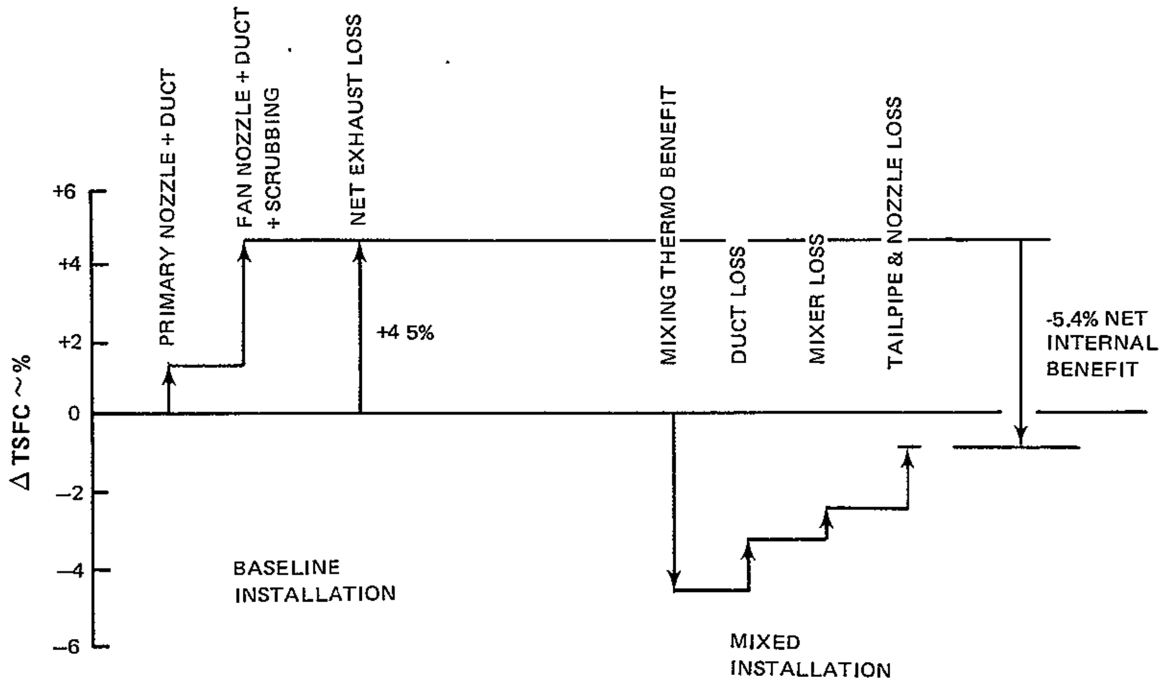


Figure 5-43 *Internal Performance Benefit Due to Mixing JT9D - 7 in 747-200 at Average Cruise Power*

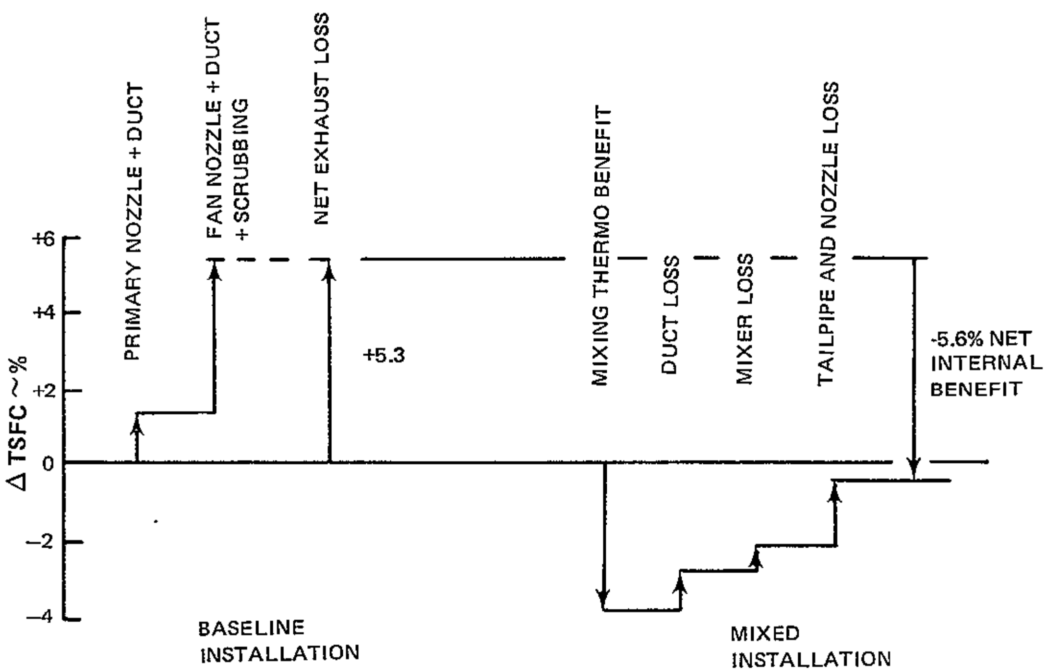


Figure 5-44 *Internal Performance Benefit Due to Mixing JT9D-59 in DC10 at Average Cruise Power*

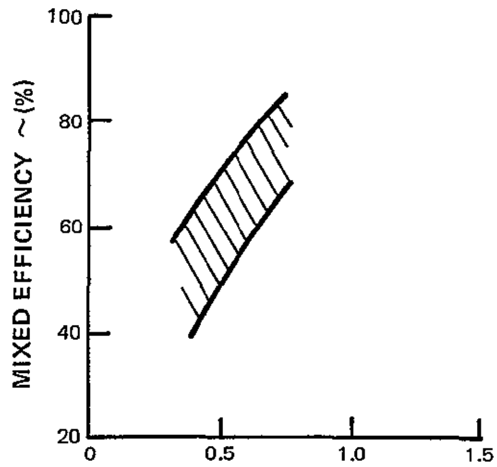


Figure 5-45 Results of P&WA High Bypass Ratio Mixer Model Tests (No Scalloping)

TABLE 5-58
JT9D-7 MIXER ENGINE
ENGINE DATA
Per Engine

Performance: (Internal JT9D-7)	TSFC Reduction, % (Internal)	EGT Reduction, °C
Takeoff	2.0	21°C
Climb	5.2	6°C
Cruise, Avg.	4.2	
Hold	2.5	
Weight Change, Kg (lb)	+188 (+415)	
Price Change, $ per Engine	+28,400	
Kit Price, $ per Engine	+36,900	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 Per Man-Hr.	-7.10	

TABLE 5-58 (Cont'd)

Performance: (Installed on 747)	TSFC Reduction, % (Effective)	EGT Reduction, °C
Takeoff	2.0	21
Climb	4.0	6
Cruise, Avg.	3.0	
Hold	1.6	
Weight Change, Kg (lb), ΔOWE/Engine	645 (+1425)	
Price Change, $ per Nacelle	+137,150	
Kit Price, $ per Nacelle	None Defined	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 Per Man-Hr.	-7.10	

TABLE 5-59
JT9D-7 MIXER
AIRLINE COSTS
Per Airplane

Changes in Annual Cash Cost ~$/Aircraft Year	747-200	
Fuel	-220,160	
Maintenance	-129,930	
Speed Effect	- 1,200	
Total	-351,290	
Required Airline Investment Charges ~$	New Buy	
Installed Systems	+548,600	(435,000 Airframe, 113,600 Engine)
Spares	+117,100	
Total	665,700	
Payback Period	1.89 Years	
DOC Change, %	-0.8	

TABLE 5-60
JT9D-7 MIXER
FUEL SAVINGS

Fleet Fuel Saved, %	2.7	
Start Service Date	1-85	
Investment Type	New Buy	Total
No. of Engines Affected	360	360
Cumulative Fuel Saved		
~10^6 Gallons Liters	1885	1885
(10^6 Gallons)	(498)	(498)

TABLE 5-61
JT9D-59 MIXER
ENGINE DATA
Per Engine

Performance: (Internal JT9D-59)	TSFC Reduction, %	EGT Reduction, °C
Takeoff	3.6	20
Climb	6.5	8
Cruise, Avg.	5.6	
Hold	3.8	
Weight Change, Kg (lb)	+188 (+415)	
Price Change, $	+28,400	
Kit Price, $	36,900	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 Per Man-Hr.	-7.10	
Performance: (Installed on DC10)	TSFC Reduction, % (Effective)	EGT Reduction, °C
Takeoff	3.6	20
Climb	5.6	8
Cruise, Avg.	6.4	
Hold	2.4	
Weight Change, Kg (lb) ΔOWE/Engine	158 (347)	
Price Change, $/Engine	+183,300 (Mixer plus Nacelle)	
Kit Price, $	None Defined	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 Per Man-Hr.	-7.10	

TABLE 5-62
JT9D-59 MIXER
AIRLINE COSTS
Per Airplane

Changes in Annual Cash Cost ~$/Aircraft Year	DC10-40 (JT9D-59)	
Fuel	-208,300	
Maintenance	- 73.000	
Speed Effect	- 17,900	
Total	-299,200	
Required Changes in Airlines Investment ~$		
Installed Engines & Nacelles	550,000	(85,200 Engine, 464,800 Nacelle)
Spares (Engines and Nacelles)	50,600	(19,600 Engine, 31,000 Nacelle)
Total	600,600	
Payback Period	2.0 Years	
DOC Change, %	-1.6	

TABLE 5-63
JT9D-59 MIXER
FUEL SAVINGS

Fleet Fuel Saved, %	6.6	
Start of Service Date	1-85	
Investment Type	New Buy	Total
No. of Engines Affected	90	90
Cumulative Fuel Saved, 10^6 liters (gal.)	1026 (271)	1026 (271)

5.3.2 JT9D Electronic Control

Summary

The fuel saving potential of a full authority electronic control system on the JT9D engine was evaluated. The results, summarized in Table 5-64, show that fuel savings would probably be small relative to the current hydromechanical control system. Based on this finding, the electronic control was not considered under the ECI-PI program. It is recognized that the electronic control may offer significant fuel saving and other benefits when coupled with other modifications of the JT9D engine or with advanced engine designs.

TABLE 5-64

SUMMARY OF ELECTRONIC CONTROL EVALUATION
POTENTIAL FUEL SAVINGS, %

	P&WA	BCAC	DAC
Ground Trim	0 to 0.1	0.1 to 0.2	–
Mission Fuel	0 to 0.1	0	–
Deterioration	0	0.3 to 0.4	–
TOTAL	0 to 0.2	0.4 to 0.7	0

Concept Description

The control system evaluated for the JT9D consists of two identical full authority electronic engine controls which are separately mounted, and one hydromechanical flow body unit.

The electronic units are vibration isolated and fuel cooled 16-bit digital computers mounted on the engine. The isolation and cooling scheme is specifically designed to provide a well defined and controlled internal environment that is completely compatible with the electrical and mechanical design of the circuit boards and components. This approach assures a reliable control with high component life.

The electronic functions of the two separate control units provide full redundancy for fail-safe operation. Either of the electronic sections is capable of performing the following:

1. Schedules engine starting, acceleration, and deceleration fuel flow as a function of burner pressure, high rotor speed, compressor exit temperature and fan inlet temperature.

2. Provides closed loop governing of engine ratings as a function of power lever angle, fan inlet temperature, ambient pressure, and fan inlet pressure.

3. Provides closed loop governing of high rotor speed at idle.

4. Limits maximum burner pressure.

5. Limits low turbine inlet temperature for hot section protection during starting.

6. Limits high and low rotor speeds for structural protection.

7. Schedules the variable compressor stator vanes, and resets for additional transient stability margin.

8. Schedules compression system surge bleeds.

9. Provides digital engine data gathered from control sensors for engine and control condition monitoring, and for flight deck thrust setting displays.

10. Provides switching for two solenoids which: a) operate the engine starting bleeds, and b) operate the turbine case cooling system.

The electronic units incorporate extensive self-test features which enhance system functional integrity by keeping the percentage of undetected failures extremely low.

Failure protection is provided by employing a hierarchy of fault logic as follows:

1. First failure - switch to other (healthy) channel
2. Next failure - obtain data from first channel
3. Next failure - synthesize required data using healthiest channel
4. Shutdown.

Fuel Saving Evaluation

The following potential sources of fuel savings with a full authority electronic control system on the JT9D engine were evaluated by P&WA with assistance from the team members:

- Ground Trim
- Mission Fuel
- Reduced Turbine Deterioration

The results of the evaluation are discussed below. BCAC and DAC also conducted independent evaluations of the electronic control, including its integration with the aircraft control system. These evaluations are discussed in Appendices A and B, respectively.

Ground Trim – Hydromechanical controls must be adjusted or trimmed on the airplane to coordinate the control functions with the engine operating requirements and limits. This trimming has been done by running the engine on the ground while a mechanic makes the necessary adjustments on the fuel control. The electronic control eliminates the need for trimming, since the engine operating requirements and limits are programmed into the control. Data obtained from TWA, UAL, BCAC, and DAC under the study shows that the extent and frequency of ground trimming of JT9D engines by the airlines varies over a wide band. The extremes of this band are shown below.

	Trim Frequency Trim/eng/yr	Fuel Used, liters (gal.) Per Trim	Per Eng.-Yr.
Minimum	3	340 (90)	1020 (270)
Maximum	4.5	2910 (770)	23230(3500)

Since the average JT9D uses about 11 million liters (2.9 million gallons) of fuel per year (see Table 3-7 in Section 3.0), the fuel saving for elimination of ground trimming is about 0.1% maximum.

Information received from current JT9D operators indicates a trend toward reduced use of ground runup for trim with the current control system, which will reduce further the potential saving with the electronic control. The requirement for ground runup is being reduced by adjusting the control based on information supplied by the flight crew from the service operations of the airplane.

Mission Fuel – Derated takeoff and climb are used in practice to save turbine life by reducing the high temperature exposure which can be due in part to overboost. The electronic control would eliminate overboost while holding ratings, thereby allowing a higher rating for the same turbine life. The higher rating would in turn shorten climb distance and allow slightly more of the mission to be flown in the more efficient cruise mode. However, the benefits of eliminating derate are small. Fuel is saved at the rate of 0.02% for each 1% of derate eliminated.

Reduced Turbine Deterioration – The ability of the electronic control to prevent overboost would be expected to reduce damage to the hot section parts and slow the rate of engine performance deterioration that occurs between shop visits. The effect of such damage on fuel consumption depends on the extent of overboost being experienced and the sensitivity of hot section part performance to high temperature damage. Many airlines depend entirely on the flight crew to be aware of the rating limits specified in the flight manual, and to observe the limits. The frequency and extent of overboost under these conditions is difficult to determine, and probably varies depending on the pilot workload. Other airlines use optional on-board computers to indicate the rating limits on the engine gages, depending on the crew to observe the limits, which would be expected to reduce the frequency of overboost.

Studies of JT9D turbine blades and vanes that have been scrapped by the airlines indicate that over temperature damage is one of the lower ranking causes of parts scrappage. Other causes, such as erosion, corrosion, and foreign object damage are much more prevalent. This finding would lead to the conjecture that the overboost which does occur does not lead to airfoil damage that significantly affects the engine performance. However, further study is needed to quantify these observations, and to determine the effect of overboost on turbine seal clearance deterioration.

Evaluation results show that fuel saving with the electronic control on current production models of the JT9D would not be large enough to warrant the investment required. However, the electronic control may offer significant fuel saving and other benefits in combination with advanced engine designs. Some of the potential benefits that should be considered are listed below:

- Reduced flight crew workload
- Improved engine diagnostics
- Fuel savings with optimized engine designs
- Reduced control system cost (initial and maintenance) and weight as control requirements become more complex.

5.4 CONCEPTS NOT RECOMMENDED FOR FURTHER CONSIDERATION

The concepts in this category were not recommended for further consideration by NASA for a variety of reasons, as indicated on Table 5-65. As noted in the table, when a concept was found to be unacceptable in the initial steps of the evaluation process, the evaluation was discontinued so more effort could be devoted to the more promising concepts.

TABLE 5-65

CONCEPTS NOT RECOMMENDED

		Pay-Back Period ~ PBP (years)				Fuel Savings Cumulative 10^6 liters (gal)				
Concept	Airplane	New Buy	Retrofit	Δ DOC (%)	Percent	New Buy	Retrofit	Total	Reasons for Unacceptability	Described on Page
JT8D Fan Aero Refinements	727	0 9	0	-0 3					Performance demonstration effort nearing completion under in house funding	118
	DC-9/737	1 1	0	-0 2						
	Total				0 7	462 (122)	1185 (313)	1646 (435)		
JT8D Fan Tip Abradables									Insufficient performance improvement	121
JT8D Revised HPC (Includes JT8D-209)	727	2 9	11 0	-0 5					High development cost	122
	DC-9/737	3 4	12 9	-0 5						
	Total				1 5	409 (108)	0	409 (108)		
JT8D LPT Abradable Seals									No measurable performance improvement after snap accelerations and decelerations	124
JT8D Forced Mixer	727	11 0	11 0	-0 03					Unacceptable payback period	125
	DC-9/737	11 0	11 0	-0 04						
	Total				0 7					
727 Installation Weight Reduction	727								Fuel improvement too small for development and certification costs	128
DC-9 Improved Cabin Air System	DC-9	22 6	–	0					Unacceptable payback period	130
JT9D-70/59 Increased Fan Diameter	747	3 9	–	–1.3	2 0	1241 (328)	–	1241 (328)	High development cost	132
JT9D Revised HPC	747 (-7/70)	1 2/0 6	3 5/3 3	-0 5/-0 5					High development cost	135
	DC-10	0.9	4 9	-0 4						
	Total				0 7	2146 (567)	1143 (302)	3289 (869)		
JT9D HPC Active Clearance Control	747 (-7/70)	8 8/7 1	None	-0 1/-0 1					Unacceptable payback period	138
	DC-10	22 7	None	0						
	Total									
JT9D-70/59 LPT Active Clearance Control	747	0 4	0 8	– 0 3					Major benefit would be provided by HPT Active Clearance Control System	140
	DC-10	0 9	1.7	– 0 2						
	Total				0 8	1559 (412)	140 (37)	1699 (449)		
JT9D-70/59 CNS Short Aftbody	DC-10	0 1	4 8	–0 7	2 6	1059 (280)	39 (10)	1098 (290)	Development for DC-10 nearly complete, not suitable for 747 application	143

5.4.1 JT8D Fan Aero Refinements

Engine ratings and fan design technology have progressed extensively since the development of the JT8D two-stage fan in the early 1960's. Preliminary investigations have indicated that relatively minor aerodynamic modifications to the fan airfoils would result in significant performance improvements, especially at the high corrected airflow conditions of the higher rated models of the engine.

One modification involves a chamfer cut on the suction side of the leading edge of both rows of fan blades, as shown in Figure 5-46 The chamfer cut effectively reduces the leading edge radius to near the lower limit of the production tolerance band, and also increases the leading edge camber slightly. Chamfer cut leading edges have been applied successfully as a field refurbishment for lower rated models of the JT8D, but had not been applied to production of the newer, high rated engines.

The second modification, also shown on Figure 5-46, involves restaggering and recambering the second stator (located between the first and second fan rotor stages) to improve the stage airflow matching at high flow conditions.

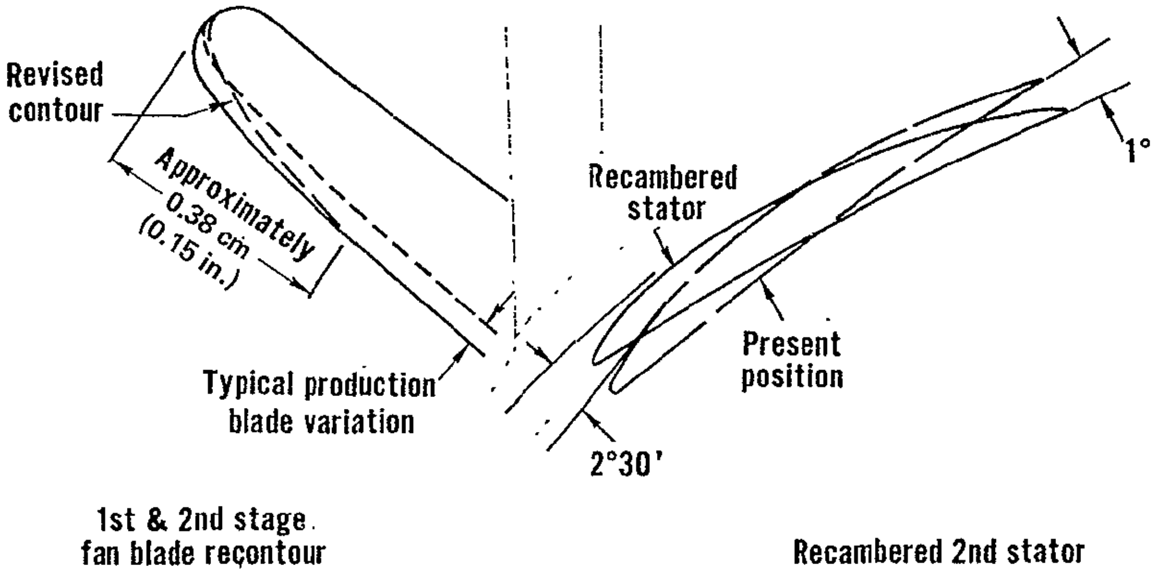


Figure 5-46 *The Chamfer Cut Leading Edge on the Fan Blades and a Recamber/Restagger of the Second Stator (between the second fan blade and the LP compressor) were considered to improve the performance of the JT8D fan.*

The effects of these modifications on fan pressure ratio, airflow, and efficiency were estimated analytically. The results were evaluated in the engine performance simulation to obtain the TSFC and EGT improvement estimates shown on Table 5-66. The chamfer cuts require an additional step in the blade manufacturing process, resulting in the estimated engine price increase and kit price shown in Table 5-66. Since the JT8D fan blades are scrapped very infrequently in service, the higher price of the parts is reflected in a relatively small increase in maintenance material cost. The EGT reductions at the critical take-off and climb out conditions reduces the frequency of engine removals for hot section maintenance, resulting in a significant estimated reduction in maintenance labor cost.

TABLE 5-66
JT8D FAN AERO REFINEMENTS
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0.35	3
Climb	0.50	3
Cruise, Avg.	0.80	
Hold	0.80	
Weight Change, Kg (lb)	0	
Price Change, $	+4,075	
Kit Price, $	+5,200 (Attrition)	
Maintenance Cost Change, $/Oper. Hr.		
Materials	+.04	
Labor @ $30 Per Man-Hr.	-.62	

A review of these modifications by airframe subcontractors has shown that the 727 and DC9 airframe drags, prices, and empty weights are unaffected by these internal engine modifications. One negative qualitative factor was identified during the evaluation: the sharper blade leading edges created by the chamfer cuts may be more prone to erosion and FOD damage.

The concept was judged to be very acceptable as a performance improvement idea, but it was not pursued further under the subject program because the performance demonstration effort was nearing completion under in-house funding.

The effects on airline economics are shown in Table 5-67. Note that the airline investment cost to retrofit the concept to existing engines is shown as zero. This reflects the opinion of the operators in the study that the modifications can be accomplished by reworking the existing parts. This results in the unusual situation of the retrofit case providing a shorter payback period than the new buy.

As shown on Table 5-68, the concept results in a fleet fuel saving of 0.7% and a cumulative fuel saving of over 1.6 million liters, with the major portion of the savings coming from retrofit of existing engines.

TABLE 5-67
JT8D FAN AERO REFINEMENTS
AIRLINE COSTS
Per Aircraft

Airplane Model	727-200		DC9-50	
Operating Cost Changes, $/Year				
Fuel	-10,450		-6,350	
Maintenance	-4,450		-2,530	
Block Speed Effect	-1,250		-450	
Total	-16,150		-9,330	
Type of Investment	**New Buy**	**Retrofit**	**New Buy**	**Retrofit**
Required Airline Investment Changes, $		Rework		Rework
Installed Engines	12,225		8,150	
Spare Engines	2,510		2,160	
Spare Parts	400		300	
Total	15,135	0	10,610	0
Payback Period, Years	0.9	0	1.1	0
DOC Change, %	-.25		-.22	

TABLE 5-68
JT8D FAN AERO REFINEMENTS
FUEL SAVINGS

Fleet Fuel Saved, % 0.7

Start of Service Date 1-80

Investment Type	New Buy	Retrofit	Total
No. of Engines Affected	1,040	4,650	5,690
Cum. Fuel Saved, 10^6 Liters (Gal).	462 (122)	1,185 (313)	1,646 (435)

5.4.2 JT8D Fan Tip Abradables

The JT8D fan blades operate with tip clearances large enough to ensure that the blades will not rub the metal containment case walls under the most severe thermal transient or structural load conditions during normal operation. The clearances could be closed if abradable rubstrips were recessed into the case walls, as shown in Figure 5-47, so that the rub could be tolerated without damage to the blades or case. This abradable rubstrip concept is used successfully on the fan and all compressor stages of the JT9D engine. The amount of clearance closure possible on the two JT8D fan stages was estimated at 0.0125 and 0.025 cm (0.005 and 0.010 in), respectively, based on X-rays of a running engine and on structural analyses. These closures represent clearance-to-span ratios of only 0.04% and 0.1%, respectively. Evaluation showed the effect of these changes on fan efficiency and engine performance to be too small (TSFC improvement is less than 0.1%) to justify the redesign of the fan cases.

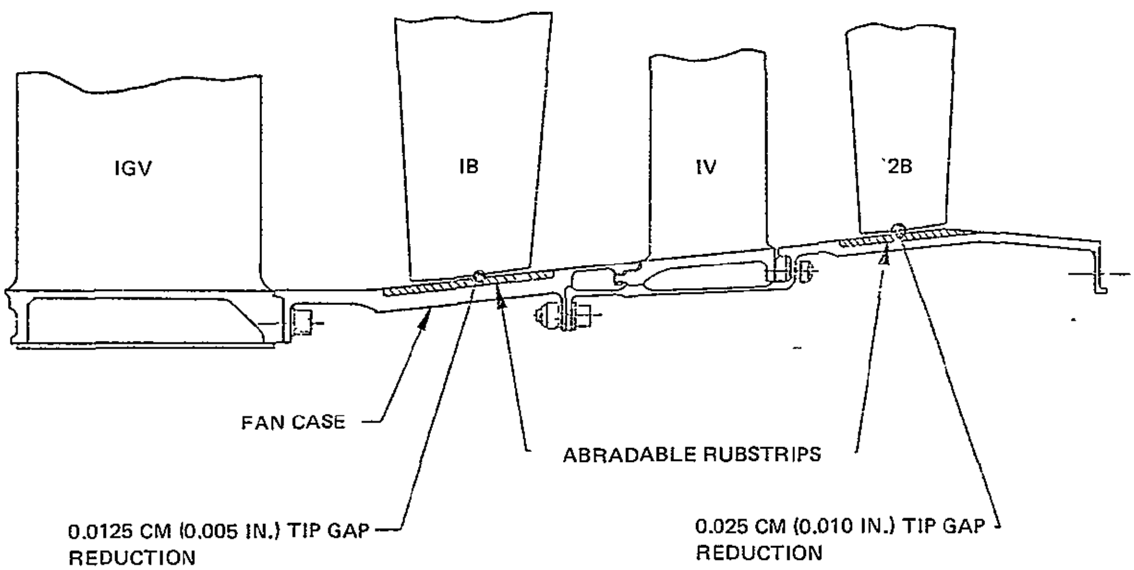


Figure 5-47 The Fan Cases are Modified to Receive an Abradable Material, Which Allows the Tip Clearance to be Reduced Without Danger of Damaging the Blade Tips in a Rub

5.4.3 JT8D Revised HPC

The JT8D high-pressure compressor (HPC) rotor is assembled with long tie-bolts extending through holes in the individual disks, hubs, and spacers, as shown in Figure 5-48. For disk structural reasons, the bolt holes are located at a relatively short radial distance from the rotor centerline. Consequently, the spacers which carry the interstage seal knife edges are small in diameter relative to the flowpath, resulting in deep cavities which communicate aerodynamically with the flowpath. The air in these cavities is pumped radially by the disk faces, creating a windage loss for the rotor and a disturbing perpendicular flow into the main compressor flow.

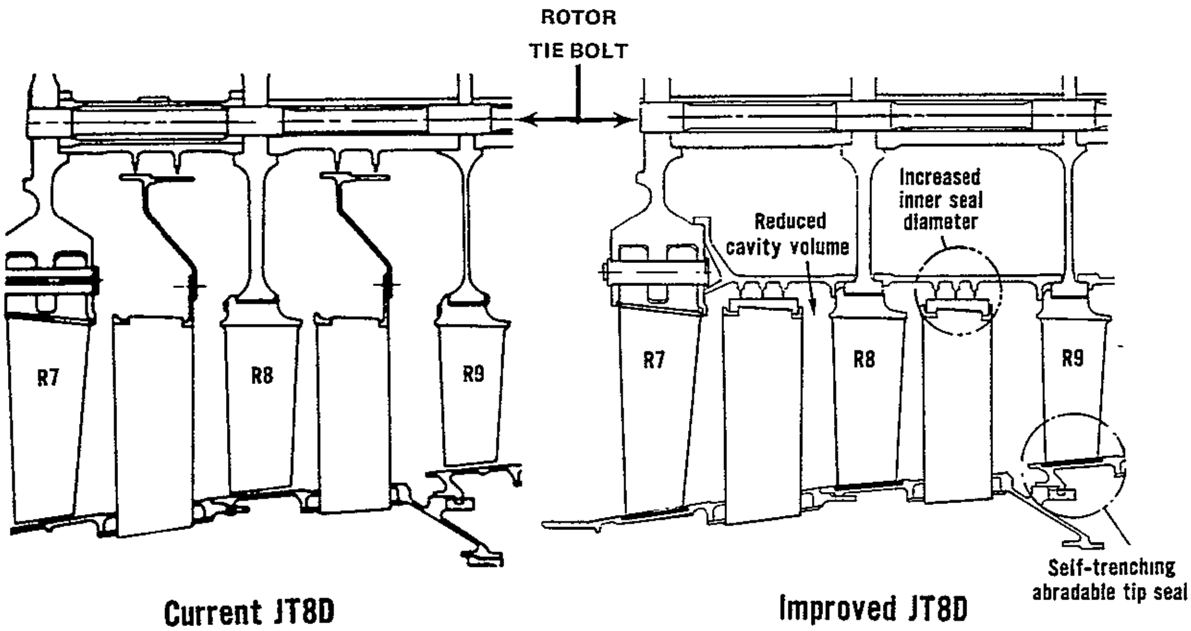


Figure 5-48 The Concept Includes A Major Reduction in the Interstage Seal Cavity Volumes, Trenched Abradable Blade Tip Rubstrips, and Airfoil Refinements.

These undesirable effects could be reduced significantly by adding secondary spacers trapped between the disk rims, as shown in Figure 5-48. The interstage seals are then established at this larger diameter by adding knife edges to the secondary spacer and forming the seal land directly on the stator inner shrouds. The performance effect of this modification was estimated to be 1.1% increase in HPC efficiency, based on experience with a three stage research (see Section 5.2.7). This improvement was combined with the JT8D Trenched Tip HPC concept described in Section 5.2.7 and aerodynamic refinements of the airfoils to form the Revised HPC performance improvement package. The total effect on engine TSFC is a 1.4% improvement at the higher power conditions, as shown in Table 5-69. The weight and price of the engine has increased as shown, primarily due to the addition of the secondary spacers. The retrofit kit price is relatively high because new disks, blades, and stator assemblies are required in addition to the secondary spacers.

TABLE 5-69
JT8D REVISED HPC
ENGINE DATA PER ENGINE

Performance:	TSFC Reduction, %		EGT Reduction, °C
Takeoff	1.4		13
Climb	1.4		13
Cruise, Avg.	1.4		
Hold	2.2		
Weight Change, Kg (lb)	+6.3 (+14)		
Price Change, $	+30,000		
Kit Price, $	113,000	(Non-Attrition)	
Maintenance Cost Change, $/Oper. Hr.			
Materials	+1.00		
Labor @ $30 Per Man-Hr.	-2.68		

The airline cost evaluation, Table 5-70, shows the concept to be acceptable for new engines, but not for retrofit. The cumulative fuel savings is limited by the projected number of engines to be produced after the estimated start of service date of mid-1981, as shown in Table 5-71.

TABLE 5-70
JT8D REVISED HPC
AIRLINE COSTS PER AIRPLANE

Airplane Model	727-200		DC9-50	
Operating Cost Changes, $/Year				
Fuel	-22,200		-14,350	
Maintenance	-13,200		-7,340	
Block Speed Effect	-2,820		-1,000	
Total	-38,220		-22,690	
Type of Investment	New Buy	Retrofit	New Buy	Retrofit
Required Airline Investment Changes, $				
Installed Engines	+90,000	+339,000	+60,000	+226,000
Spare Engines	+18,450	+69,500	+15,900	+59,900
Spare Parts	+2,700	+10,000	+1,800	+6,700
Total	+111,150	+418,500	+77,700	+292,600
Payback Period, Years	2.9	11.0	3.4	12.9
DOC Change, %	-0.5		-0.5	

TABLE 5-71
JT8D REVISED HPC
FUEL SAVINGS

Fleet Fuel Saved, % 1.5			
Start of Service Date 6-81			
Investment Type	New Buy	Retrofit	Total
No. of Engines Affected	500	0	500
Cum. Fuel Saved, 10^6 liters (gal)	409 (108)		409 (108)

The complete package represented by this concept was not recommended for further consideration because the development risk and cost associated with the rotor structural modifications appeared too high for the fuel savings benefit, and because it is applicable to new engines only. However, the trenched tip portion of the package was evaluated as a separate concept, "JT8D Trenched Tip HPC". This concept was recommended for development, and is discussed in Section 5.2.7.

5.4.4 JT8D LPT Abradable Seals

The JT8D low pressure turbine (LPT) flowpath is sealed by knife-edges on the disk spacers and the blade tip shrouds running with close clearances against smooth metal lands on the vane inner shroud rings and against floating rings in the outer case. A major redesign of this LPT has been accomplished to accommodate the higher work and expansion requirements of the JT8D refan models, and this redesign includes abradable honeycomb rubstrips to achieve tighter clearances without destructive knife-edge wear. The abradable honey comb could be incorporated in the standard JT8D LPT as shown in Figure 5-49 with minor redesign of the inner and outer seal land rings. In 1974, a similar configuration was tested. Results of this earlier testing showed an initial measurable performance improvement, but the improvement disappeared after snap accelerations and decelerations were run to simulate engine acceptance test procedures.

While these results cannot be explained analytically using effective abradable rubstrips, the evaluation effort was discontinued because of the risk that no performance improvement could be obtained.

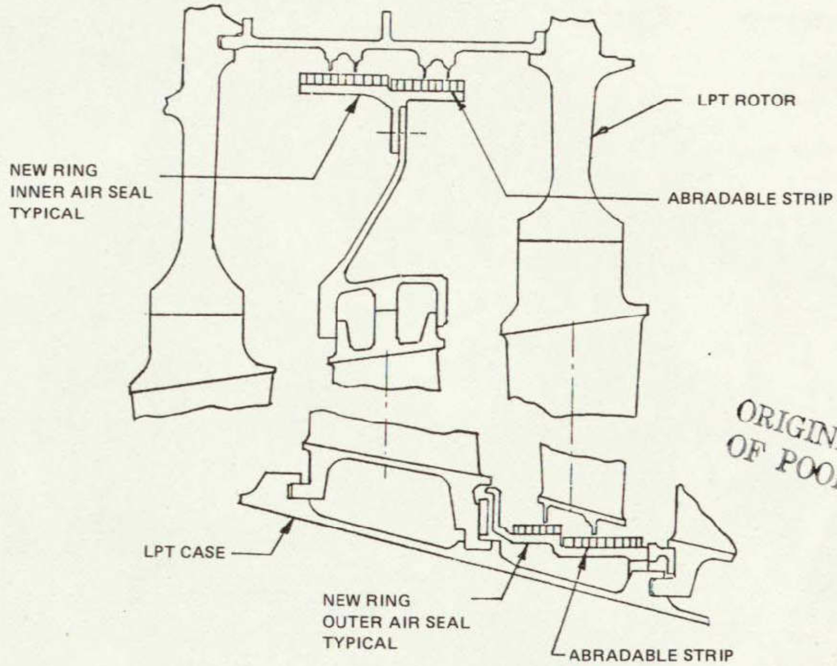


Figure 5-49 Abradable Honeycomb Material is Applied to Both the Inner and Outer Seal Rings of all Stages

5.4.5 JT8D Forced Mixer

The JT8D engine is equipped with a full length fan discharge duct that is integral with the engine case structure. The engine is installed with a common exhaust nozzle, which combines the fan discharge and turbine discharge flows into a single stream. The configuration of the engine cases and the nozzle permits about 30% mixing of fan and turbine discharge before they leave the nozzle.

A forced mixer has been developed for the JT8D-refan models, which are similar to the standard JT8D in duct arrangement, but have a higher fan duct flow. This mixer (see Figure 5-50) was developed primarily for jet noise reduction, but it also provides a small cruise performance improvement.

An FAA-funded effort, which includes model and full-scale engine testing, is being conducted to apply the refan mixer technology to the standard JT8D. A basic objective of this effort is to provide significant noise suppression within existing 727 and DC9 nacelles where space limitations dictate a very short mixer length. A secondary objective is to maintain or improve installed engine performance. Figure 5-51 shows the general configuration and some of the integration details of a typical mixer being evaluated under the program. Model test results indicate that such a mixer will improve TSFC by about 1% at high nozzle expansion ratio conditions such as altitude climb and cruise operations; however, no performance improvement is attained at take-off and climb out conditions, as indicated on Table 5-72.

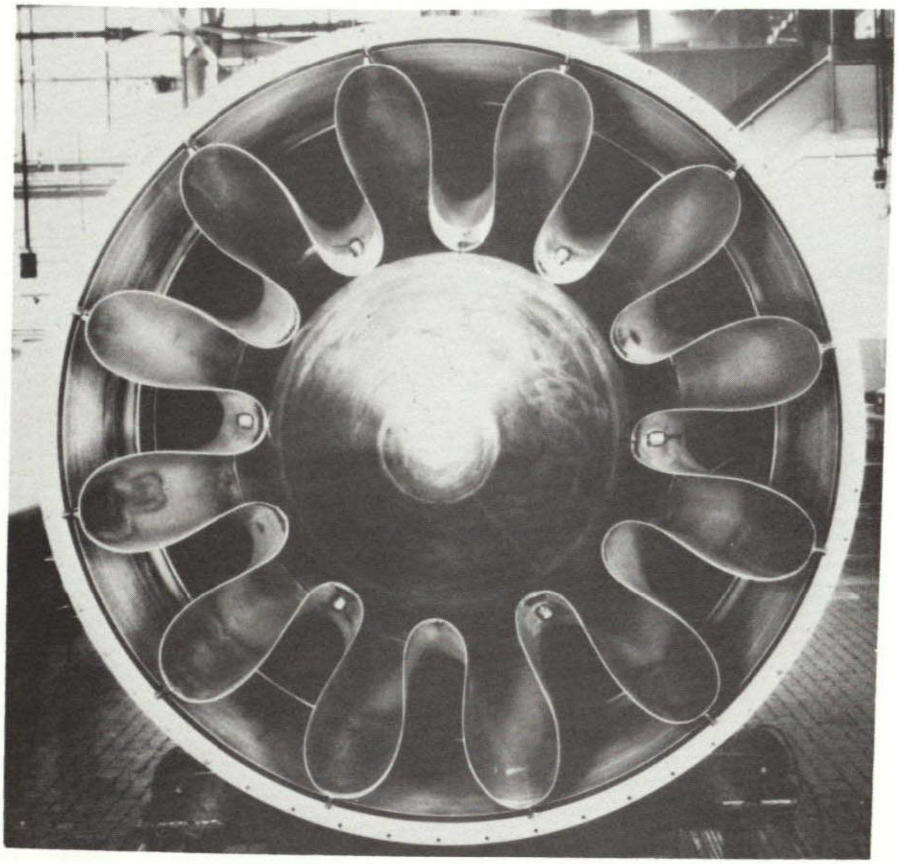


Figure 5-50 JT8D Refan Engine With Full Scale Mixer

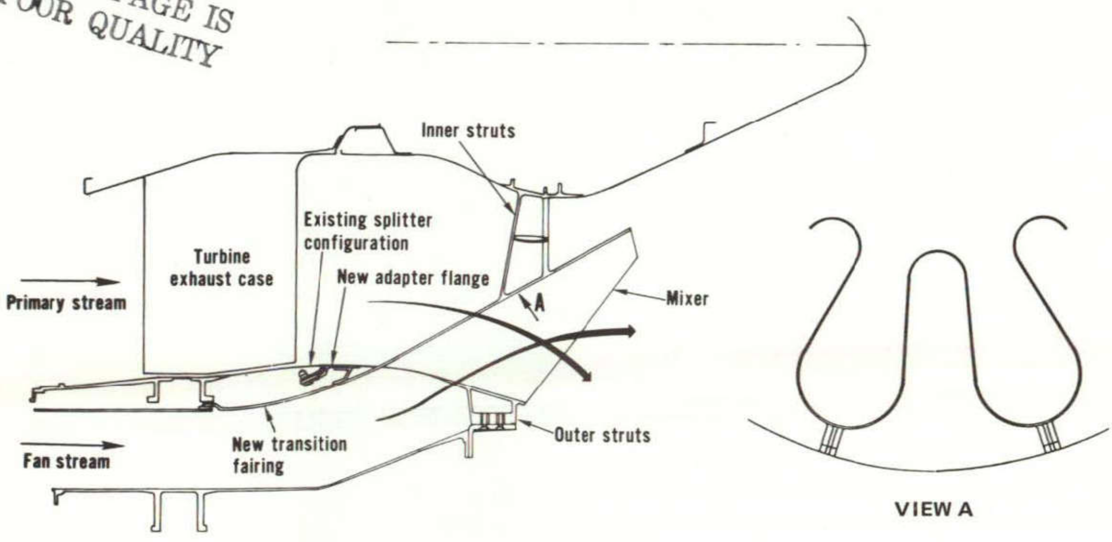


Figure 5-51 Noise Reducing Mixer Which Can be Used Within the Current Nacelle – Model test results indicate that the engine performance may also improve, especially at cruise conditions.

TABLE 5-72
JT8D FORCED MIXER
ENGINE DATA

Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0	0
Climb	1.0	0
Cruise, Avg.	1.0	
Hold	0	
Weight Change, Kg (lb)	+45 (+100)	
Price Change, $	+25,000	
Kit Price, $	+25,000	
Maintenance Cost Change, $/Oper. Hr.		
Materials	0	
Labor @ $30 Per Man-Hr.	+0.30	

The weight of this mixer was estimated at 45 Kg (100 lb). An additional 727 and DC9 airplane weight penalty of about 27 Kg (60 lb) per engine is imposed by ballast which must be carried in the nose to counterbalance the mixer weight on their aft-mounted engines.

The price of the mixer in JT8D Bill-of-Materials production quantities is estimated to be $25,000. This estimate is consistent with the prices of other concepts evaluated for the ECI program. (A higher price for limited quantity production has been discussed with some airlines who are interested in a near term application to meet severe local noise restrictions.) A maintenance labor cost increase of 30¢ per engine operating hour was estimated for repair of the mixer itself, as shown on Table 5-72.

The mixer fails the payback period limit of 6 years, as shown on Table 5-73. This means that it would not be purchased for its fuel saving potential alone, so it was not given credit for a cumulative fuel saving in the subject program. However, the mixer has the potential for a 0.7 percent fleet fuel saving which reduces the penalty that would be suffered if it were required to meet future noise criteria.

TABLE 5-73

JT8D FORCED MIXER
AIRLINE COSTS
Per Aircraft

Airplane Model	727-200	DC9-50
Operating Cost Changes, $/Year		
Fuel	-10470	-7300
Maintenance	+ 2360	+1350
Block Speed Effect	- 125	- 50
Total	- 8235	-6000
Type of Investment	**New Buy & Retrofit**	**New Buy & Retrofit**
Required Airline Investment Changes, $		
Installed Engines	75000	50000
Spare Engines	15373	16000
Spare Parts	0	0
Total	90,373	66,000
Payback Period, Years	11.0	11.0
DOC Change, %	-0.03	-0.04

5.4.6 727 Installation Weight Reduction

Several independent concepts were considered in order to reduce the weight of the JT8D installation in the Boeing 727 as shown in Figures 5-52 and 5-53. Concepts based on current materials technology (Figure 5-57) include: replacing the aluminum center inlet duct and its anti-ice reinforcing patch with a fiberglass duct; shortening the inlet and tailpipe of the side nacelles; and substituting titanium for Hastelloy in the construction of the thrust reverser frames for all three engines. The use of advanced composite materials, which are unproven in aircraft nacelle environments, was considered in selected areas of the two side nacelles, as shown in Figure 5-53. The results of the weight evaluation of these concepts are summarized in Table 5-74. None of the concepts were recommended for further consideration in the subject program because of their small fuel saving potential (0.1% or less in each case). However, several of the concepts are under development by the airframe manufacturer for their weight and/or cost saving potential.

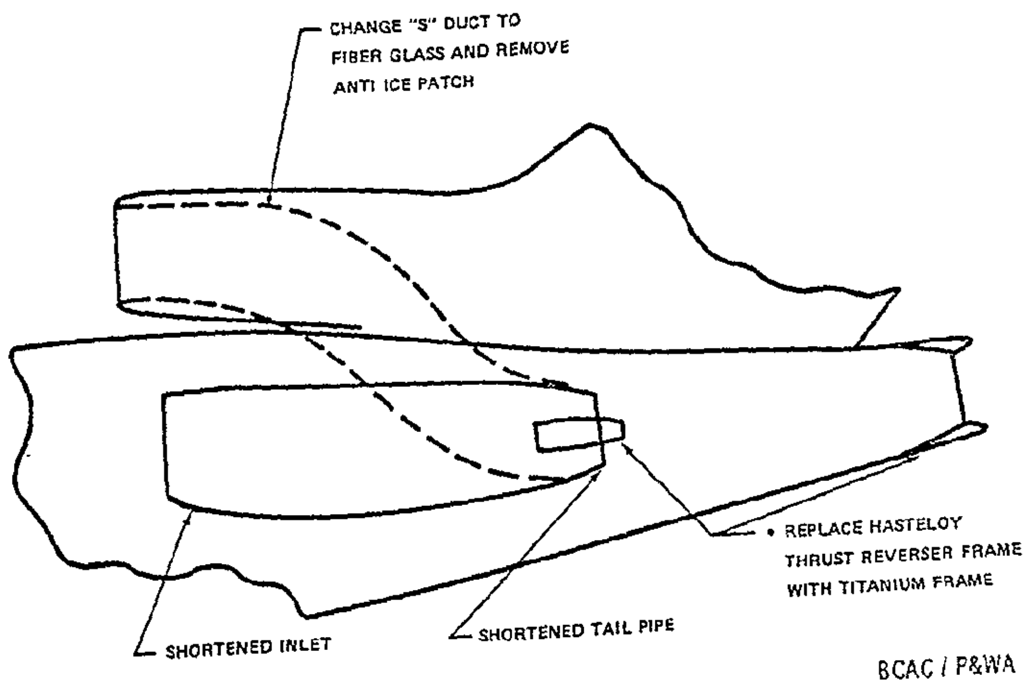


Figure 5-52 Application of Current Technology to Reduce the Engine Installation Weight in the Boeing 727.

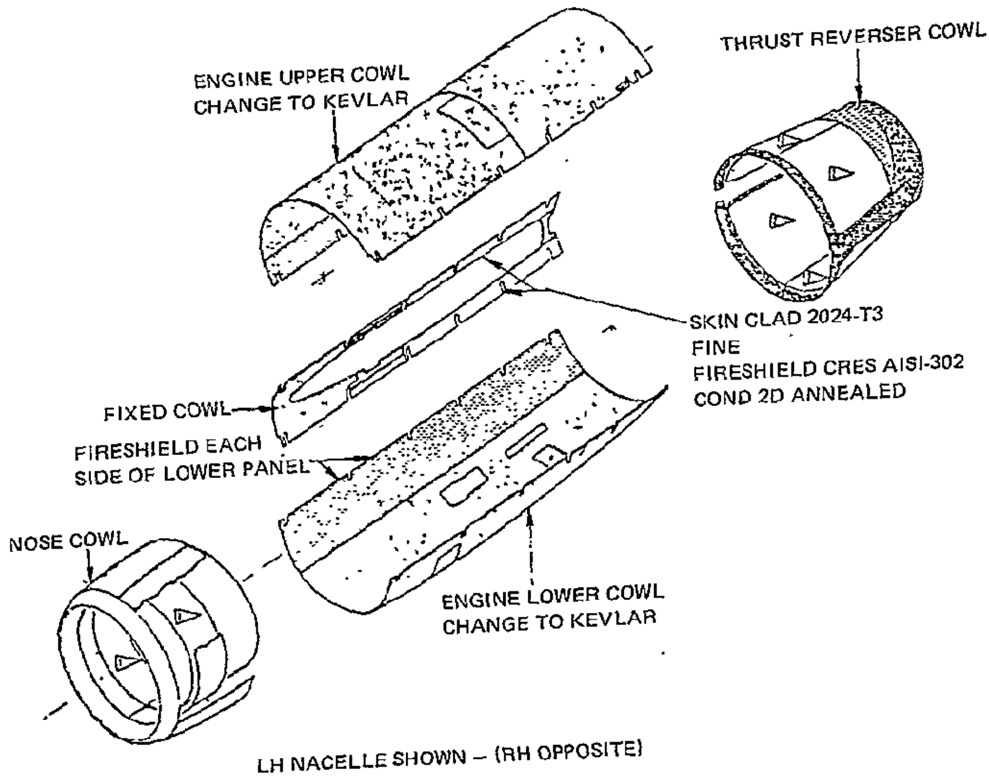


Figure 5-53 Application of Advanced Composite Materials in Selected Areas of the Boeing 727 Nacelles

TABLE 5-74
WEIGHT EVALUATION SUMMARY
727/JT8D INSTALLATION

Concept	Weight Saving, Kg (lb)/aircraft	Equivalent Fuel Saving, %
Fiber glass "S" duct	61 (135)	<0.1
25.5 cm reduction of inlet and tailpipe length	70 (154)	<0.1
Titanium thrust reverser frames	108 (240)	0.1
Advanced composites in nacelles	87 (191)	<0.1

5.4.7 DC-9 Improved Cabin Air System

The addition of a recirculation system to the DC-9 environmental control system, as shown in Figure 5-54, was considered to reduce the quantity of bleed air flow required from the JT8D engines by 50%. This bleed flow reduction will improve the engine thrust specific fuel consumption by 1% at cruise conditions; however, the effective TSFC improvement for the installed propulsion system is reduced to the values shown on Table 5-75 because the thrust recovery at the cabin air outflow nozzle is reduced. The added recirculation system adds weight, price, and maintenance materials cost to the airplane, as shown on Table 5-75.

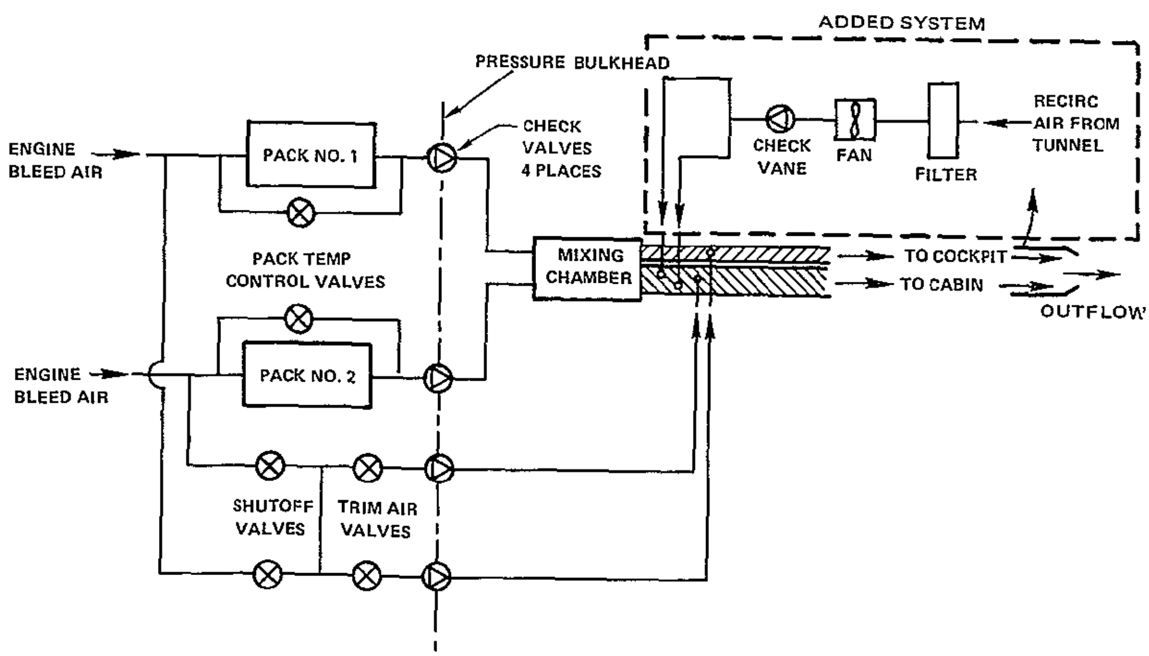


Figure 5-54 Engine Air Bleed Reduced by 50 Percent for Cabin Air Conditioning

The airline cost evaluation showed the payback period to be unacceptably long for the new buy case as shown on Table 5-76. The retrofit case was not evaluated, but it would result in an even longer payback period because of the cost of installing the recirculation system kit.

This concept was not recommended for further consideration because of its unacceptable payback period.

TABLE 5-75
DC-9 IMPROVED CABIN AIR SYSTEM
SYSTEM DATA

Performance	TSFC Reduction, %	EGT Reduction, °C
Takeoff	0	0
Climb	0	0
Cruise, Avg.	0.43	
Hold	0.35	
Weight Change, Kg (lb)/Aircraft	80 (+177)	
Price Change, $/Aircraft	+51,200	
Kit Price, $	+51,200	
Maintenance Cost Change, $/Oper. Hr.		
Materials	+0.26	
Labor @ $30 Per Man-Hr.	0	

TABLE 5-76
DC-9 IMPROVED CABIN AIR SYSTEM
AIRLINE COSTS
Per Aircraft

Airplane Model	DC9-50	
Operating Cost Changes, $/Year		
Fuel	−3325	
Maintenance	+1136	
Block Speed Effect	− 75	
Total	−2264	
Type of Investment	**New Buy**	**Retrofit**
Required Airline Investment Changes, $		Not Evaluated
Installed Systems	+51,200	
Spare Engines	0	
Spare Parts	0	
Total	+51,200	
Payback Period, Years	22.6	
DOC Change, %	Small increase	

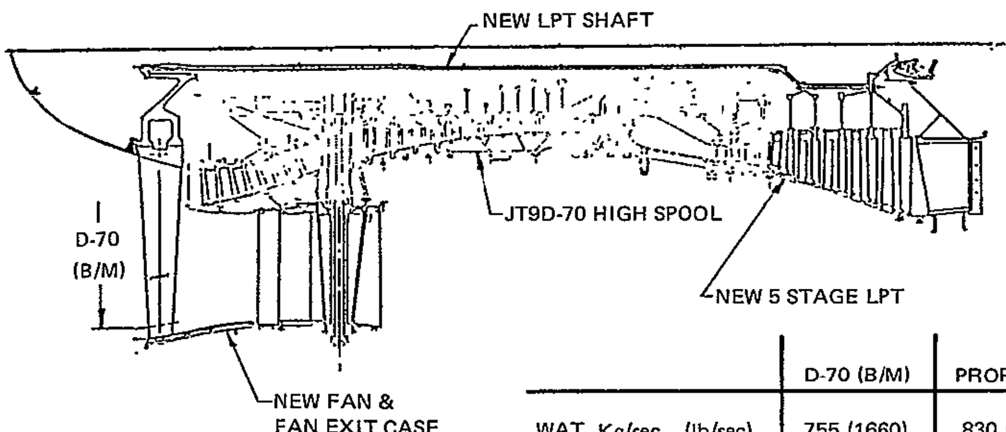
5.4.8 JT9D-70/59 Increased Fan Diameter

If the fan airflow of the JT9D-70/59 were increased, the propulsive efficiency and consequently the TSFC of the engine would be improved, especially at the higher power settings. A study was made of an increased diameter fan to obtain an airflow increase that would provide near-minimum TSFC at the cruise thrust condition of the engine. The fan modification is shown on Figure 5-55, along with the other engine modifications made necessary by the larger fan. One additional stage is needed on the turbine to drive the fan, and a larger turbine exhaust case is needed to match up with the new turbine. A beefed-up shaft is needed to transmit the increased torque from the turbine to the fan. The fan hub, blades, containment case, and exit case must all be increased in size. The estimated performance, weight, price, and maintenance cost effects on the engine are summarized on Table 5-77. No kit price is shown since the concept was judged to be impractical for retrofit.

Evaluation of the modified engine in the Boeing 747 installation showed the need for nacelle and strut modifications as described in Appendix A. The resulting airplane weight, price, and drag increases are summarized on Table 5-78.

The airline cost impact of the concept is summarized on Table 5-79. The new buy payback period is well within the 6 year limit. The cumulative fuel savings that would result if the concept were developed and put into service by 1985 are shown on Table 5-80.

The JT8D-70/59 Increased Fan Diameter concept was deleted from further consideration for the subject program because of its high development cost and time period.



	D-70 (B/M)	PROPOSED
WAT, Kg/sec (lb/sec)	755 (1660)	830 (1825)
BPR	5.0	5.6
FAN DIA., cm (in.)	237.87 (93.65)	247 77 (97.55)
NO. TURB. STAGES	4	5

Figure 5-55 Engine Modifications Required to Incorporate Larger Fan Diameter

TABLE 5-77
JT9D-70/59 INCREASED FAN DIAMETER
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %	EGT Reduction, °C
Takeoff	4.2	25
Climb	3.0	25
Cruise, Avg.	2.4	
Hold	0.6	
Weight Change, Kg (lb)	+374 (+825.)	
Price Change, $	+96,430	
Kit Price, $	No Kit	
Maintenance Cost Change, $/Oper. Hr.		
Materials	+1.20	
Labor @ $30 Per Man-Hr.	-7.40	

TABLE 5-78
JT9D-70/59 INCREASED FAN DIAMETER
AIRPLANE EFFECTS

Airplane Weight, Kg (lb)		+2320 (+5120)
Engines	+1495 (+3300)	
Installations	+ 825 (+1820)	
Airplane Price, $		+ 870,000
Engines	+ 385,700	
Installations	+ 485,000	
Airplane Drag, %		+ 0.12

TABLE 5-79
JT9D-70/59 INCREASED FAN DIAMETER
AIRLINE COSTS
Per Aircraft

Changes in Annual Cash Cost ~$/Aircraft Year	747-200
Fuel	-165,300
Maintenance	-113,460
Speed Effect	- 1,100
Total	-279,860
Required Change in Airline Investment.	
Installed Systems	+870,700 (485,000 Nacelle, 385,700 Engine)
Spares	+229,000 (82,450 Nacelle, 146,550 Engine)
Total	1,099,700
Payback Period	3.9 Years
DOC Change, %	-1.3

TABLE 5-80
JT9D-70/59 INCREASED FAN DIAMETER
FUEL SAVINGS

% Fleet Fuel Saved	2.0%	
Start of Service Date	1-85	
Investment Type	New Buy	**Total**
No. of Engines Affected	360	360
Cumulative Fuel Saved 10^6 Liters (10^6 Gallons)	1241 (328)	1241 (328)

5.4.9 JT9D Revised HPC

The interstage seals of the JT9D high pressure compressor (HPC) are submerged somewhat inside the flowpath boundary, as shown in Figure 5-56. This arrangement creates cavities which communicate aerodynamically with the main flow and create losses due to disk pumping, recirculation, and windage. Experience with a three stage research rig indicates that these losses can be reduced significantly by increasing the seal diameter so that the cavity volumes are reduced as shown in Figure 5-56. This idea was applied to all eleven stages of the HPC and combined with the trenched blade tip rubstrip idea (described under JT9D Trenched Tip HPC in Section 5.2) to make the JT9D Revised HPC concept. The effects of these modifications on compressor efficiency are summarized in Table 5-81.

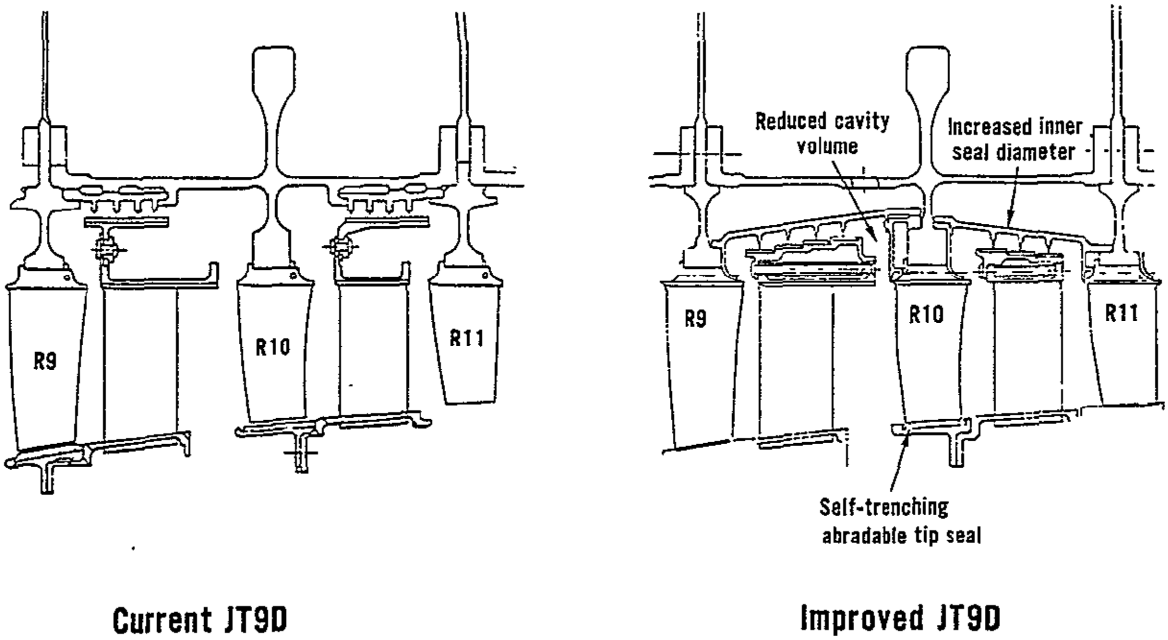


Figure 5-56 The inter-stage seal cavity volume is reduced by moving the knife-edge assembly closer to the flow path.

TABLE 5-81

REVISED HPC EFFICIENCY IMPROVEMENTS

Feature	Stages Affected	$\Delta\eta$ D-7	$\Delta\eta$ D-70
Reduced Cavity Volume	11	0.8%	0.8%
Trenched Tip	5	0.9%	0.7%
Total	–	1.7	1.5

The compressor efficiency improvement translates conservative to 0.6 and 0.55 percent engine TSFC improvement for the two models, as shown in Table 5-82. The engine weight and price are increased primarily by the more complex interstage seal arrangement. Retrofit is assumed to be done on an attrition basis, so that the kit price reflects only the difference in price between the current and improved parts.

The airline cost evaluation shows the payback period to be acceptable in all cases, as shown on Table 5-83. Applying the concept to all applicable engines starting in 1981 would result in a cumulative fuel saving of nearly 3.3 billion liters (Table 5-84). Despite these favorable evaluation results, this concept package was not recommended for further consideration in the ECI program because of the high development risk and cost associated with the structural modifications of the rotor. Instead, the trenched tip portion of the package was evaluated as a separate concept titled, "JT9D Trenched Tip HPC". This concept was recommended for development under the ECI program and is discussed in Section 5.2.

TABLE 5-82
JT9D REVISED HPC
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %		EGT Reduction, °C
	-7	-59/70	
Takeoff	0.60	0.55	6
Climb	0.60	0.55	6
Cruise, Avg.	0.60	0.55	
Hold	0.60	0.55	
Weight Change, Kg (lb)	20 (+45)	20 (+45)	
Price Change, $	+24,900	+13,400	
Kit Price, $	76,000	69.500	(Attrition)
Maintenance Cost Change, $/Oper. Hr.			
Materials	+ 0.65	+ 0.65	
Labor @ $30 per Man-Hr.	- 3.89	- 3.52	

TABLE 5-83
JT9D REVISED HPC
AIRLINE COSTS
Per Airplane

Airplane Model	747-200		DC 10-40
	-7	-70/59	-70/59
Operating Cost Changes, $/Year			
Fuel	- 54,600	- 53.400	-20,420
Maintenance	- 59.100	- 58,000	-32,630
Block Speed Effect	- 350	- 100	- 525
Total	-114,050	-111,500	-53,575

Type of Investment	New Buy		Retrofit		New Buy	Retrofit
	-7	-70/59	-7	-70/59	-70/59	-70/59
Required Airline Investment Changes, $						
Installed Engines	+ 99,600	+53,600	+303,800	+277,700	+40,200	+208,600
Spare Engines	+ 27,200	+14,600	+ 83,000	+ 75,900	+ 9,200	+ 47,750
Spare Parts	+ 4,500	+ 2,420	+ 13,700	+ 12,500	+ 1,800	+ 9,340
Total	+131,300	+70,620	+400,500	+366,100	+51,200	+265,690
Payback Period, Years	1.2	0.6	3.5	3.3	0.9	4.9
DOC Change, %	-0.5	-0.5			-0.4	

TABLE 5-84
JT9D REVISED HPC
FUEL SAVINGS

Fleet Fuel Saved, %	0.7			
Start of Service Date	3-81 (-7), 6-81 (-70/59)			
Investment Type		New Buy	Retrofit	Total
No. of Engines Affected	-7	910	1010	1920
	-70/59	825	400	1225
Cum. Fuel Saved, 10^6 Liters (Gal)	-7	1086 (287)	757 (200)	1843 (487)
	-70/59	1060 (280)	386 (102)	1446 (382)
				3289 (869)

5.4.10 JT9D HPC Active Clearance Control

The principle of active clearance control, which has been applied successfully to the high pressure turbine of the JT9D, was considered for the high pressure compressor (HPC). The blade tip clearances at cruise conditions in the bill-of-materials HPC are dictated by the relative thermal expansions and structural deflections of the case and rotor structures, which are critical at high power, fast transient, and high "g" load conditions. Both thermal and mechanical clearance control systems were considered to reduce the blade tip clearances at cruise. A mechanical system shown in Figure 5-57, was found to be especially compatible with the unique double case structural arrangement of the aft portion of the JT9D HPC. The inner case forms the air flow path wall and carries only nominal pressure loads. The outer case, which is significantly larger in diameter, carries the major structural loads. The annular space between the inner and outer cases is ideal for locating the actuating mechanisms of the mechanical system. Conversely, the double case arrangement makes a thermal clearance control system, which depends on heating or cooling the outer case, very ineffective.

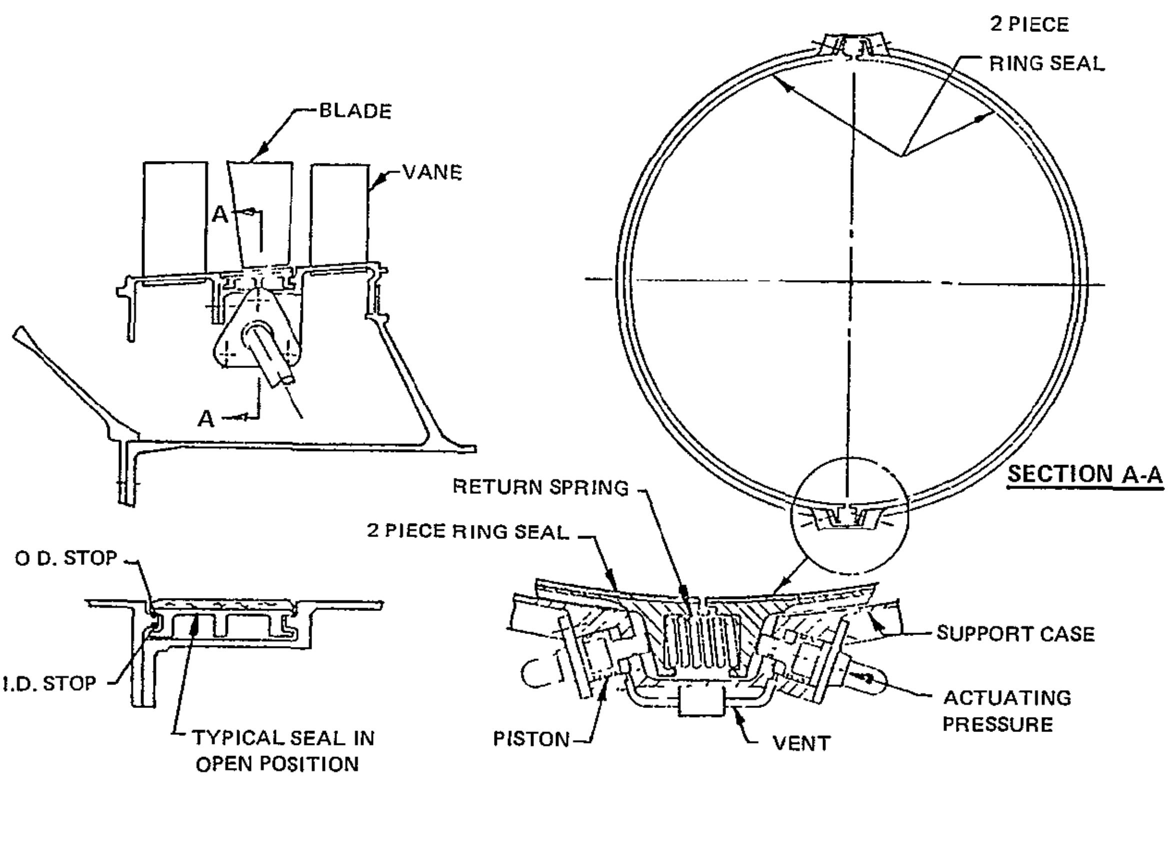


Figure 5-57 Proposed HPC Active Clearance Control System

The selected system shown in the figure was applied to the last 8 stages of the 11 stage HPC. Each stage has a two-piece ring seal trapped in annular grooves in the inner case. The two-pieces are forced outward against O.D. stops by springs during takeoff, climb, and landing, where large clearances are needed. At cruise conditions, valves are opened to apply compressor discharge air to pistons which push the ring halves inward against I.D. stops, reducing the blade tip clearances.

The amount of clearance reduction that could be attained at cruise in each stage was estimated analytically based on x-ray clearance measurements made on an engine running at sea level static conditions. The estimated clearance reductions, which are shown on Table 5-85, will increase compressor efficiency to improve cruise TSFC by 0.5%, as shown in Table 5-86.

TABLE 5-85
JT9D HPC CLEARANCE REDUCTION

Stage No.	Estimated Clearance Reduction, cm (in.)
8	0.020 (0.008)
9	0.015 (0.006)
10	0.012 (0.005)
11	0.036 (0.014)
12	0.043 (0.017)
13	0.053 (0.021)
14	0.025 (0.010)
15	0.074 (0.029)

TABLE 5-86
JT9D HPC ACTIVE CLEARANCE CONTROL
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %		EGT Reduction, °C
Takeoff	0		0
Climb	0		0
Cruise, Avg.	0.5		
Hold	0		
	-7	-70/59	
Weight Change, Kg (lb)	+34 (+75)	+34 (+75)	
Price Change, $	+31,710	+31,150	
Kit Price, $	not estimated		
Maintenance Cost Change, $/Oper. Hr.			
Materials	+0.10	+0.10	
Labor @ $30 Per Man-Hr.	+1.10	+1.10	

Also shown are the engine weight, price, and maintenance cost increases estimated for the system. A kit price was not estimated because the concept was not expected to be acceptable for retrofit. Airline retrofit costs also were not estimated.

The results of the airline cost evaluation are shown on Table 5-87. Because the payback period exceeds the 6 year limit in all cases, the concept was dropped from further consideration in the program.

TABLE 5-87

JT9D HPC ACTIVE CLEARANCE CONTROL
AIRLINE COSTS
Per Aircraft

Airplane Model	747-200		DC10-40
Operating Cost Changes, $/Year			
	-7	-70	-59
Fuel	-39,400	-43,600	-16,430
Maintenance	+21,900	+21,900	+12,350
Block Speed Effect	-1,500	-1,600	1,400
Total	-19,000	-23,300	-5,480
Type of Investment	New Buy	New Buy	New Buy
Required Airline Investment Changes, $			
Installed Engines	+126,800	124,600	+93,450
Spare Engines	+34,600	34,000	+21,500
Spare Parts	+5,700	5,600	+4,200
Total	+167,100	164,200	+119,150
Payback Period, Years	8.8	7.1	22.7
DOC Change, %	-0.1	-0.1	Negligible Increase

5.4.11 JT9D-70/59 LPT Active Clearance Control

An active clearance control system for the low pressure turbine (LPT) of the JT9D-70/59, shown in Figure 5-58, was also considered in addition to the improved active clearance control system for the high pressure turbine. The existing JT9D-70/59 LPT case includes an internal cooling system which utilizes 9th stage compressor bleed air to cool the case structure and protect it from over-temperature during high power operation. The active clearance control system considered makes use of this existing cooling system to minimize the modification impact. A valve is installed in the existing 9th stage bleed air pipe so the air supply can be turned off at takeoff and climb conditions, and turned on at cruise conditions. With this arrangement the LPT clearances can be set tighter at assembly and will run tighter at cruise, improving turbine efficiency at cruise. The increased clearances required to accommodate transients and "g" loads during takeoff, climb, and landing operations are obtained when the case temperature increases with the cooling air turned off. To prevent overtemperaturing of the critical vane support hooks in the case the existing 13th stage cooling system to the HPT is vented to the LPT. The estimated effect is a cruise TSFC improvement of 0.8% as shown on Table 5-88. Engine weight and price are increased only slightly as shown on Table.5-89, resulting in very acceptable payback periods for both new buy and retrofit cases. The estimated cumulative fuel saving, assuming that all JT9D-70/59 engines are equipped with the system after mid-1979, is nearly 1.7 billion liters (see Table 5-90).

Despite the good evaluation results, the LPT active clearance control system was not recommended for further consideration because tests indicated that a major portion of the LPT clearance control benefit is being obtained from cooling of the LPT case by flow from the bill-of-material high pressure turbine active clearance control system. Use of the recommended improved system on the high pressure turbine is expected to reduce even further the improvement of a separate LPT system.

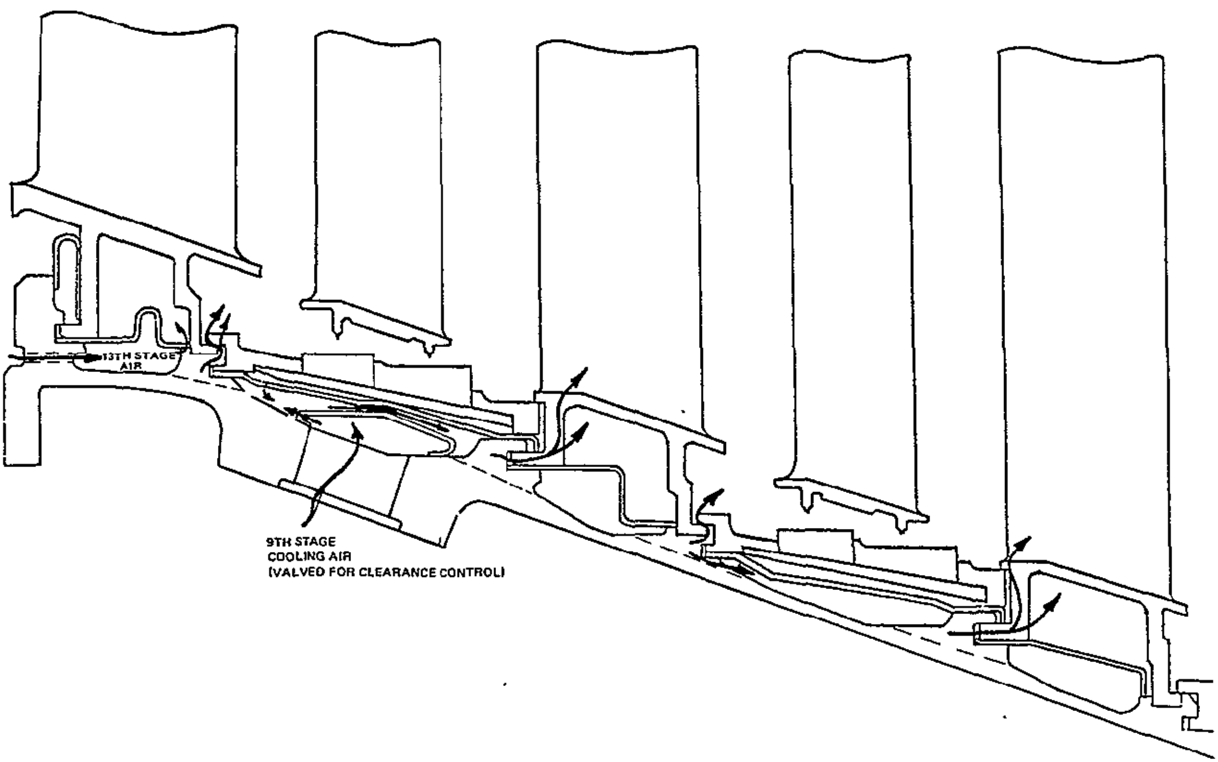


Figure 5-58 LPT Active Clearance Control System Requires Only Plumbing Modifications and Adds a Valve to the Existing 9th Stage Cooling Air Supply

TABLE 5-88
JT9D-70/59 LPT ACTIVE CLEARANCE CONTROL
ENGINE DATA
Per Engine

Performance:	TSFC Reduction, %		EGT Reduction, °C
Takeoff	0		0
Climb	0		0
Cruise, Avg.	0.8		
Hold	0		
Weight Change, Kg (lb)	+2 (+5)		
Price Change, $	+5,200		
Kit Price, $	10,300	(Non-Attrition)	
Maintenance Cost Changes, $/Oper. Hr.	0		
Materials	0		
Labor @ $30 Per Man-Hr.	0		

TABLE 5-89
JT9D-70/59 LPT ACTIVE CLEARANCE CONTROL
AIRLINE COSTS
Per Aircraft

Airplane Model	747-200		DC10-40	
Operating Cost Changes, $/Year				
Fuel	-69,600		-23,800	
Maintenance	0		0	
Block Speed Effect	-1,800		-1,100	
Total	-71,400		-24,900	
Type of Investment	**New Buy**	**Retrofit**	**New Buy**	**Retrofit**
Required Airline Investment Changes, $				
Installed Engines	+20,800	+41,200	+15,600	+30,900
Spare Engines	+5,670	+11,200	+3,600	+7,100
Spare Parts	+3,100	+5,600	+2,300	+4,300
Total	+29,570	+58,000	+21,500	+42,300
Payback Period, Years	0.4	0.8	0.9	1.7
DOC Change, %	-0.3		-0.2	

TABLE 5-90
JT9D-70/59 LPT ACTIVE CLEARANCE CONTROL
FUEL SAVINGS

Fleet Fuel Saved, % 0.8

Start of Service Date 6-79

Investment Type	New Buy	Retrofit	Total
No. of Engines Affected	1150	150	1300
Cum. Fuel Saved, 10^6 liters (gal.)	1559 (412)	140 (37)	1699 (449)

5.4.12 JT9D-70/59 CNS Short Aftbody

Simulated altitude testing indicates that the specific fuel consumption of the JT9D-70/59 engine installed in the Common Nacelle System can be improved by an aerodynamic refinement of the nacelle as shown in Figure 5-59. This refinement shortens and steepens the afterbody of the primary cowl and steepens the trailing edge angle of the aft fan cowl. The performance of the isolated nacelle without free stream flow is improved, as shown by the first column of Table 5-91, because of the reduction in area scrubbed by the fan nozzle discharge flow. EGT is not improved by this modification because it is external to the basic engine.

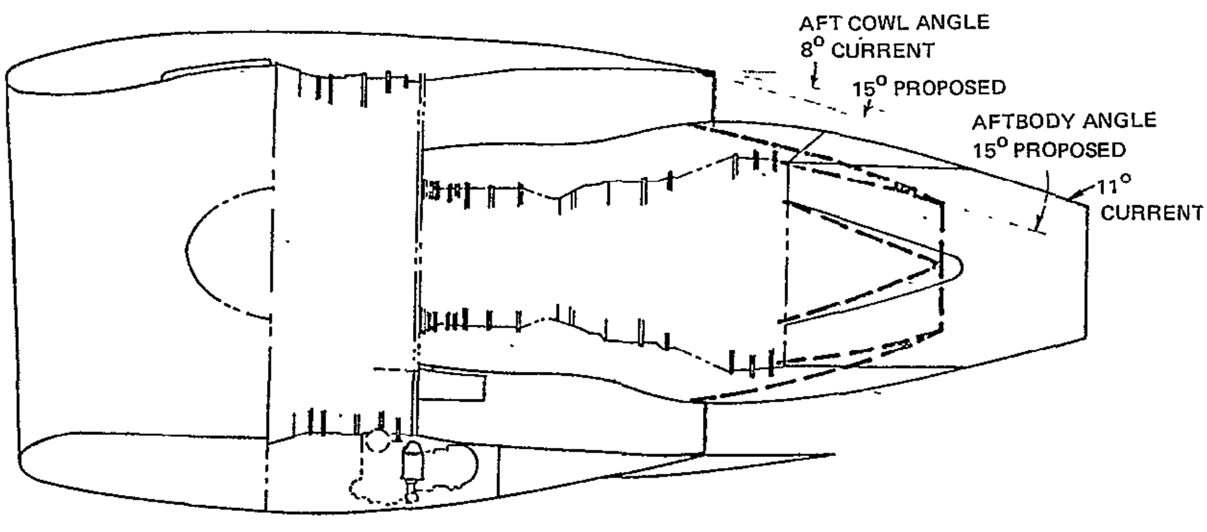


Figure 5-59 Modification of the Primary Nacelle Afterbody Reduces the Area Scrubbed by the Fan Discharge Nozzle Flow

TABLE 5-91
JT9D-70/59 CNS SHORT AFTERBODY
ENGINE DATA
Per Engine

Performance Effects, %	ΔTSFC	ΔDrag DC-10	ΔDrag 747	Net DC-10	Net 747
Takeoff	-0.18	0	–	-0.18	–
Climb	-0.46	0	–	-0.46	–
Cruise	-0.5	-2.0	+1.0	-2.50	+0.5
Hold	-0.22	0	–		
Weight Change, Kg (lb)	-60 (-130)				
Price Change, $	0				
Kit Price, $	120,000				
Maintenance Cost, $/Oper. Hr.					
Materials	0				
Labor	0				

The effects of the modification on free stream drag and interference drag were estimated by the airplane companies based on wind tunnel tests and are shown in the second and third columns of Table 5-91. These effects differ dramatically between the Boeing 747 and Douglas DC-10 installations because of differences in the location and configuration of the pylon, wing, and fuselage relative to the nacelle. As a result of these differences, the net effect of the modification is a substantial performance improvement for the DC-10, but a performance penalty for the 747 (see the last two columns of Table 5-91.

The nacelle modification results in a weight reduction of 60 kg (130 lb) per nacelle, without affecting the price of a new nacelle. However, retrofit of an existing nacelle requires a substantial investment in parts that are not normally replaced by attrition, as indicated by the kit price on Table 5-91.

The airline economics evaluation of the concept in the DC-10 showed payback periods of less than one year for the new buy case and 4.8 years for retrofit, as shown on Table 5-92. The relatively long payback period for the retrofit case implies that engines should be less than 6 years old to economically justify the modification. The economics of the 747 were not evaluated because of the performance penalty resulting from the concept. The cumulative fuel saving possible with the DC-10 application only is approximately 1.1 billion liters, as shown on Table 5-93.

The short aftbody concept was not recommended for further consideration under the subject program because its development for the DC-10 application was nearly completed and because its application to the 747 is undesirable.

TABLE 5-92
JT9D-70/59 CNS SHORT AFTERBODY
AIRLINE COSTS
Per Aircraft

Airplane Model	DC-10-40	
Operating Cost Changes, $/year		
Fuel	-86,800	
Maintenance	0	
Block Speed Effect	- 5,200	
Total	-92,000	
Required Changes in Investments	**New Buy**	**Retrofit**
Installed Engines	+11,000	+371,000
Spares & Spare Parts	+2,000	+71,800
Total	+13,000	+442,800
Payback Period – Years	0.1	4.8
DOC Change, %	-0.7%	

TABLE 5-93
JT9D-70/59 CNS SHORT AFTERBODY
FUEL SAVINGS

Fleet Fuel Saved, % 2.6 (DC-10 Only)

Start of Service Date 1/79

Investment Type	New Buy	Retrofit (6 Yrs.)	Total
No. of Engines Affected	240	20	260
Cumulative Fuel Saved, 10^6 liters	1059	39	1098
(gal.)	(280)	(10)	(290)

APPENDIX A
ENGINE PERFORMANCE IMPROVEMENT PROGRAM

BOEING COMMERCIAL AIRPLANE COMPANY

JT8D and JT9D

ENGINE PERFORMANCE IMPROVEMENT PROGRAM

CONTRACT NO. 20630-1

PREPARED FOR:

PRATT & WHITNEY AIRCRAFT GROUP

COMMERCIAL PRODUCTS DIVISION

EAST HARTFORD, CONNECTICUT

BY:

BOEING COMMERCIAL AIRPLANE COMPANY

P. O. BOX 3707

SEATTLE, WASHINGTON 98124

BOEING COMMERCIAL AIRPLANE COMPANY ANALYSIS OF JT8D AND JT9D PERFORMANCE IMPROVEMENT CONCEPTS

Technical Analysis Procedure

All proposed Performance Improvement Concepts were reviewed by the Boeing Commercial Airplane Company Program Manager and forwarded to the various technical organizations for analysis and evaluation. The evaluating organizations were the same as those evaluating Boeing internal preliminary design studies and utilized procedures based on established Boeing preliminary design evaluation methods. These procedures make maximum use of existing data, much of which is proprietary. Sources of this data include previous analyses, model tests, full scale tests, flight tests and certification tests. These data were used to develop sensitivity factors, where possible, to assess changes from the baseline airplane performance.

The impact of engine design changes on the nacelle configuration were assessed by the Propulsion Design organization. Where necessary, layout studies were made to define required changes to the nacelle and strut. These changes were iterated with the Structures, Weights, Noise and Aerodynamics Staffs to ensure that possible impact on aircraft structure, flutter, weight, noise and aerodynamics were checked. Work statements were also prepared, where necessary, for cost estimates.

The Propulsion Staff organization evaluated the component improvement performance data supplied by Pratt & Whitney relative to baseline engine installed performance. Existing data on similar engine improvements were used to evaluate the impact of performance changes and provide installed performance estimates.

Estimated changes in baseline airplane weight were provided by the Weights Staff for those concepts where the nacelle and strut were impacted. These weight change estimates were based on previous detailed design studies where possible. For those items not covered by past studies, preliminary design weight estimation methods were used. These methods utilize analytical and parametric studies along with geometry, loading, mass flow and noise level information provided by Pratt & Whitney and the Propulsion Design organization. The effects of all weight changes on airplane loadability and balance were then evaluated.

The Structures Staff reviewed each concept for its potential impact on the airplane structure. Those concepts with minor weight increases (less than 45 kg (100 lbs) per nacelle) and engine center of gravity changes were considered to have no effect on existing airplane structure and did not undergo the full structural analysis. Other concepts, such as the Long Duct Mixed Flow Nacelle, underwent a more detailed structural analysis. Where necessary, the airframe structural weight was increased to carry the additional loads. A preliminary design flutter assessment was also made for those concepts where weight increases and engine center of gravity changes were significant.

Each concept was evaluated to quantify its effect on the external drag of the airplane. Incremental changes in weight, thrust specific fuel consumption (TSFC) and thrust of each concept were identified by the Weights and Propulsion Staffs. Improvements in cruise TSFC assessed for the 35585 N (8,000 lbs) to 40034 N (9,000 lbs) thrust level at 10,668 M (35,000 ft), 0.85 Mach number were used for the JT9D-70 Increased Diameter Fan concept at all cruise altitude/Mach number mission conditions. A curve of percent change in TSFC versus percent of maximum cruise thrust was used at cruise conditions for the JT9D-7 mixed flow nacelle. This was based on Boeing's assessment of performance improvements with the mixer. These deltas were applied to the baseline airplane, and new airplane data were estimated for the basic mission. The climb, cruise and holding performance changes were integrated in the mission analysis. The analysis provided the block fuel as a function of range from 926 km (500 NMi) to 8334 km (4500 NMi).

None of the concepts analyzed involved a thrust change; thus, the takeoff field length for the concepts which also had no drag increment remained unchanged from the baseline. Those concepts which involved changes in external drag were evaluated to determine the change in the airplane's performance at takeoff, for enroute climb and at FAR Part 36 conditions for noise. The change in noise performance for the concepts involving a drag change was estimated and transmitted to the noise staff. This information, together with estimated changes to the engine source noise characteristics, was used to calculate changes to the FAR Part 36 certified noise levels when data were available.

The baseline airplane and basic mission profile were reviewed for potential noise impact by the Noise Staff. Those items that showed potentially significant changes were evaluated using preliminary design noise evaluation procedures. The primary items considered with this procedure are the component parameters, mixing rate exit profile, velocity, density and nozzle sizes.

Results of the technical evaluation were forwarded to Trans World Airlines along with aircraft price changes and maintenance cost changes for economic analysis.

Results

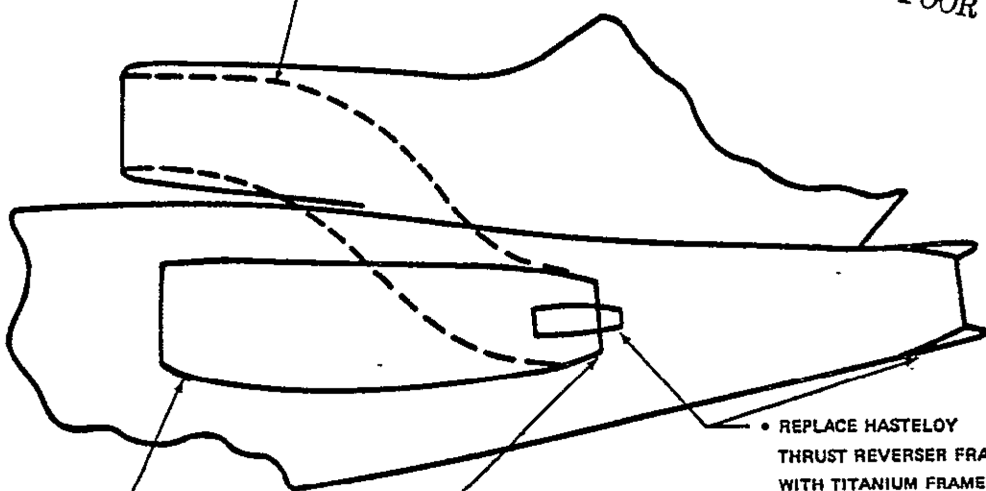
Screening of the following concepts confirmed that there were no performance or economic impacts other than those stated by Pratt & Whitney.

Fan Aero Refinements
Sealed HPT Vane Platforms
Revised HPT Blade Cooling Discharge
Closed HPT Blade Shroud Notches
3.8 AR Fan
4.2 AR Fan
LPT Active Clearance Control
HPT Active Clearance Control

No additional inputs were made by Boeing regarding these concepts.

Concepts that required Boeing input were the 727 Installation Weight Reduction, 727 Composite Nacelle, CNS Short Aft-Body, Increased Diameter Fan (JT9D-70), JT9D-7 Mixer Nacelle, and Electronic Control. Discussion on each of these concepts are presented on the following pages.

727 WEIGHT REDUCTION



BCAC / P&WA

The "S" duct, anti-ice patch, test hardware is complete and a test scheduled to certify the change. Results of the fiber glass "S" duct study shows that when it is combined with the anti-ice patch removal, the total weight reduction of 61 kg (135 lb.) would give less than 0.1% fuel burn reduction.

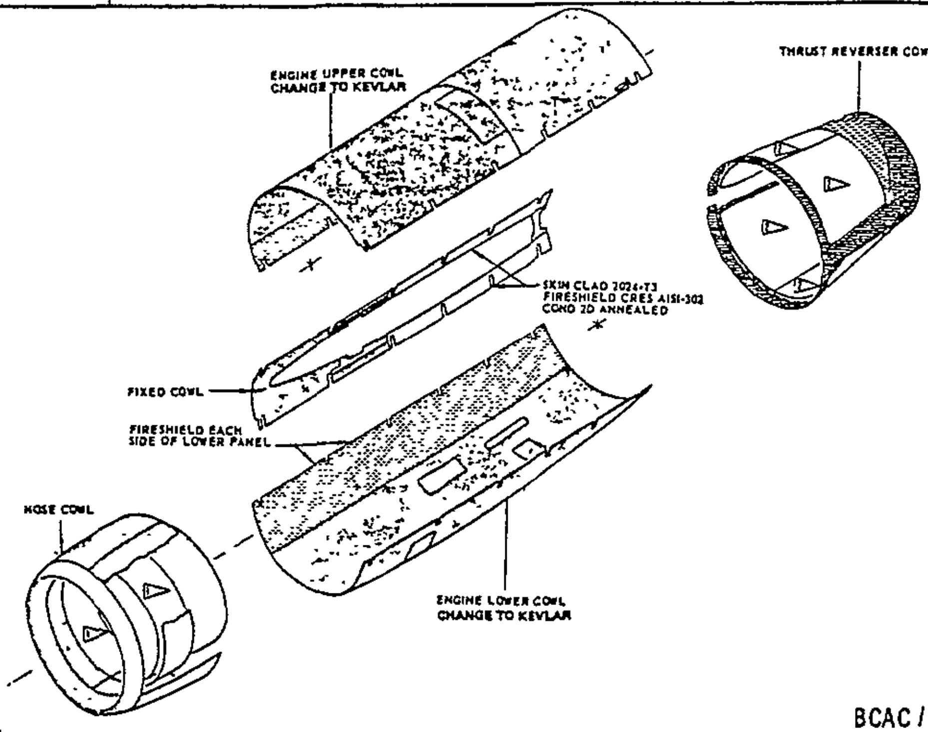
The weight saving gained by an acceptable shortening of the inlet and/or the tailpipe does not save sufficient fuel to justify the costs of accomplishing the change. For instance, a 25.4 cm (10 in.) reduction of both the inlet and exhaust pipe is only 35 kg (77 lbs.), and the fuel saving is below 0.1%.

Changing the thrust reverser frame from hasteloy to titanium saves 0.1% fuel. The high cost of development and certification cannot be justified by the potential fuel saved.

All the above weight saving concepts are suggested for elimination from the ECI-PI program.

NASA
ECI-PI

727 COMPOSITE NACELLE



BCAC / P&WA

LH NACELLE SHOWN – (RH OPPOSITE)

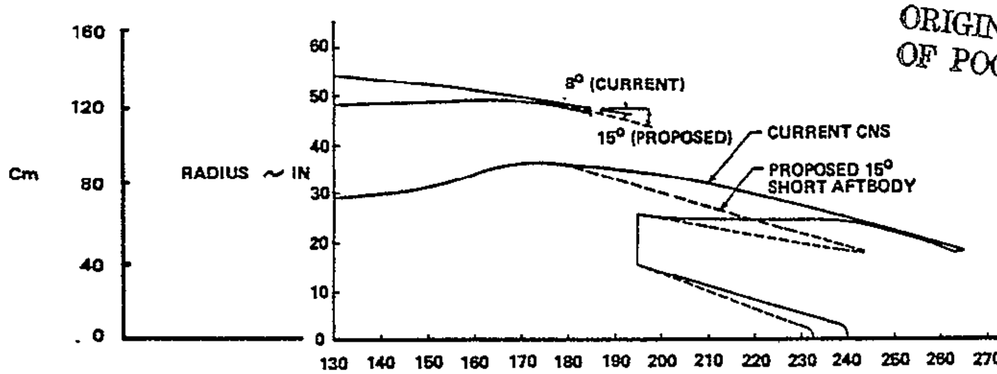
ORIGINAL PAGE
OF POOR QUALITY

Boeing has an existing program for replacing the 727 JT8D nacelle side cowls with composite material. Currently the side cowls are being fabricated and the service evaluation program established.

Secondly, the efficiency of the original structural design is such that the change to Kevlar material saves relatively little weight and the fuel burn reduction is less than 0.1%.

The concept is suggested for deletion.

CONCEPT 3A10 CNS SHORT AFTBODY



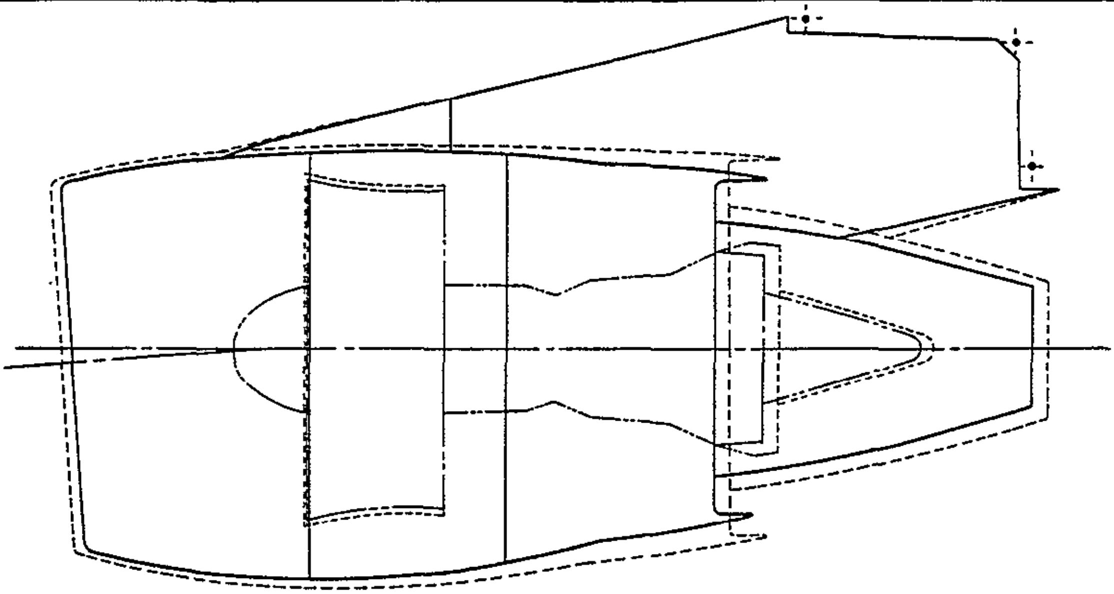
BCAC / P&WA

Wind tunnel tests of a short aftbody nacelle show an aircraft drag increase of 1% over a production 747 3/4 length fan duct nacelle. The estimated thrust specific fuel consumption improvement is 0.5% and the weight reduction is 59 kg (130 lbs.) per nacelle.

The weight saving of 59 kg (130 lbs.) does not include deletion of the primary thrust reverser which is independent of this concept and has already been accomplished.

Sensitivity factors indicated a fuel burn increase of 0.5%. Therefore, the concept is suggested for deletion.

INCREASED DIAMETER FAN



BCAC/P&WA

The major changes to the engine which affect the engine installation are: 1) the fan front flange is moved 1.27 cm (0.5 in.) forward and increased 9.91 cm (3.9 in.) in diameter, 2) the fan duct outer wall flange is increased in diameter, 3) the turbine exhaust flange is moved 14.48 cm (5.7 in.) aft and increased 9.91 cm (3.9 in.) in diameter, 4) the rear mount is moved aft and up, and 5) the engine weight is increased approximately 374 kg (825 lbs.) with an engine center of gravity shift to the rear of approximately 2.54 cm (1 in.).

The above engine changes require the following changes to the nacelle and strut: 1) larger diameter and longer flight inlet, 2) larger diameter fan cowl, 3) larger diameter fan duct cowls and fan reverser, 4) larger diameter and slightly longer primary nozzle, 5) relocate the rear mount 14.48 cm (5.7 in.) aft and approximately 4.70 cm (1.85 in.) up, 6) modify the forward strut fairing to match the larger diameter fan cowl and fan duct cowl, 7) a new rear strut fairing to accommodate the new configuration at the aft end of the engine, 8) relocate the hinge center lines for the fan cowls and fan duct cowls, and 9) a slight increase in the size of the structural members of the strut. Since the engine driven gearbox is moved down approximately 3.81 cm (1.5 in.) to accommodate the larger fan case, slight changes are required to the following: 1) fuel inlet line to the fuel pump, 2) hydraulic pressure and return lines to the hydraulic pump, 3) constant speed drive oil cooler lines, and 4) the pneumatic duct to the starter.

The above changes result in a total airplane weight increase of 2320 kg (5120 lbs.) including the engine weight increase. This weight increase is broken down as follows:

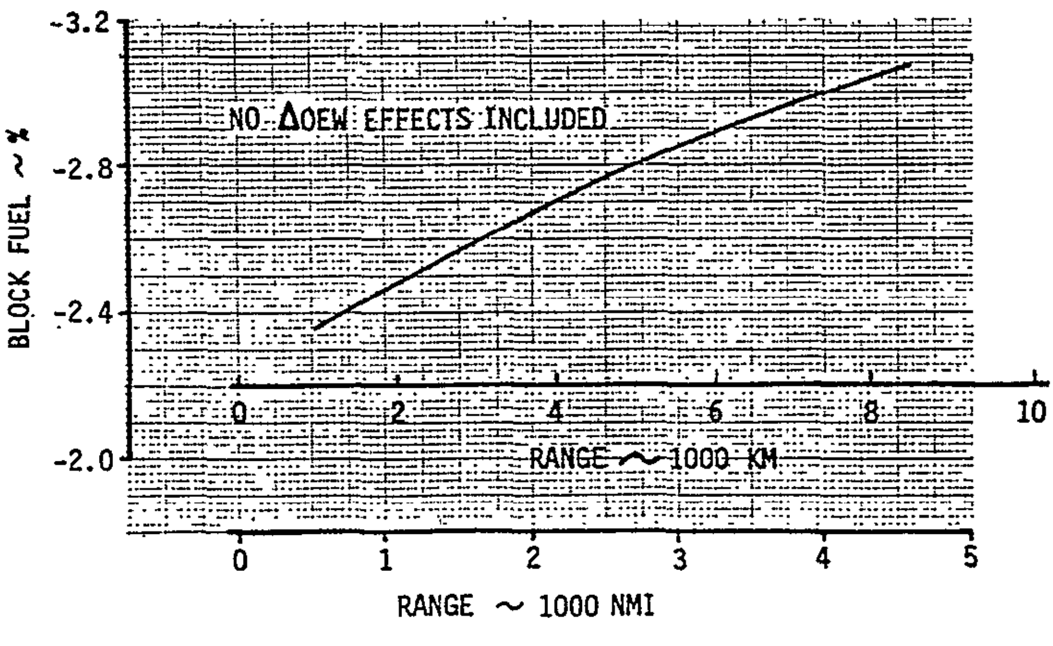
Item	Weight kg/nacelle	Weight lbs/nacelle
Engine	+374	+ 825
Inlet	+ 54	+ 120
Fan Cowl	+ 9	+ 20
Fan Duct and Thrust Reverser	+ 99	+ 218
Nozzle	+ 12	+ 27
Plug	+ 0	0
Strut	+ 32	+ 70
Total	+580	+1280

It has been assumed that no wing weight increase will be required as a result of this increased nacelle weight and the accompanying center of gravity shift. If this concept is pursued further, wing strength and detailed flutter investigations will be required to confirm this.

The drag increment on the 747 for the increased diameter fan was assessed at +0.12% relative to the standard production 747 equipped with JT9D-70A engines. This assumes that the inlet lip geometry and throat diameter of the current JT9D-70 nacelle is not increased. This assumption is based on the growth capability of the current design and on the fact that this evaluation is done at no thrust increase.

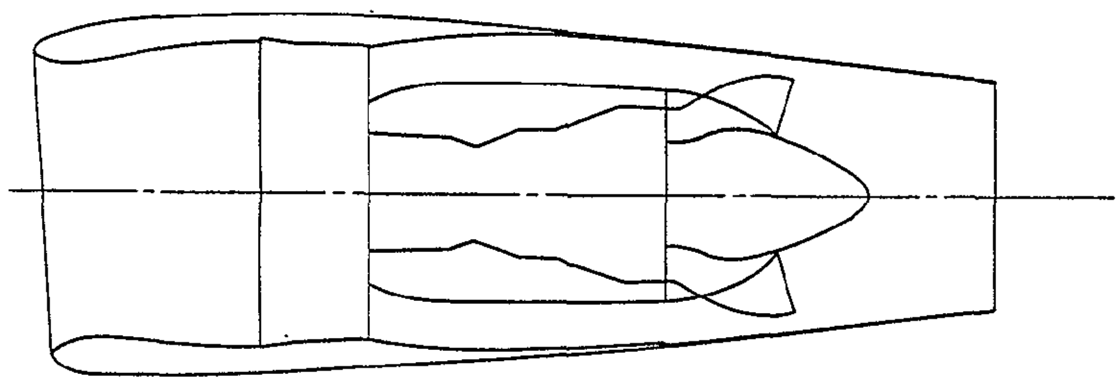
A total airplane price increase of $870,700 was projected. This consists of an engine price increase of $385,700 per shipset as quoted by Pratt & Whitney Aircraft and a nacelle price increase of $485,00 per shipset.

Fuel savings were computed for a baseline 747-200B airplane with JT9D-70A engines, ATA International Reserve Requirements and Operating Empty Weight plus Payload equal to 217,466 kg (479,430 lbs.) utilizing step cruise at Mach 0.85. The effects of the Operating Empty Weight increase and the fuel weight were included in the TWA analyses. Percent reduction in block fuel as a function of range is presented below.



These reductions in block fuel are based on the TSFC reductions provided by Pratt & Whitney Aircraft since installation effects do not penalize these performance gains.

JT9D-7 MIXER NACELLE



BCAC/P&WA

Three JT9D-7 mixer nacelle configurations were analyzed; however, only one basic design was defined with layouts. The configuration defined with layouts was a mixer nacelle of an advanced design structure to reduce weight. For comparison purposes, weight estimates were prepared for a mixer nacelle of conventional design structure and a mixer nacelle of advanced design structure utilizing composites. The performance gains were assumed to be the same for all three configurations.

Installation of a forced mixer on the JT9D-7 will require extensive modifications to the existing installation. The inlet and fan cowl forward of nacelle station 100 are unchanged from the current JT9D-7 installation. The nacelle lines are unchanged forward of nacelle station 135. The changes defined below represent an advanced design structure without composites.

A completely new thrust reverser design will be required, and for the purpose of this study, it was assumed to be designed by Boeing. The fan duct between the fan frame and turbine frame would consist of two "D" sections hinged to the strut. The primary structure would be an aluminum-brazed titanium inner wall and bifurcation and a bonded aluminum outer wall. The axial loads in the nacelle would be carried from the exhaust nozzle to the fan frame through the fan duct by the use of vee-groove flanges.

The strut structure would be revised to carry the additional nacelle weight, and the fairings would be revised to match the nacelle contour. The core cowl would be eliminated since the inner wall of the fan duct will perform this function.

A new exhaust nozzle sized for the combined flow would be required. The nozzle would be constructed of aluminum brazed titanium honeycomb. This will require the mixer to be designed to avoid hot gas impingement on the nozzle such that the normal operating temperature is less than 427°C (800°F), and the reverse thrust operating temperature is less than 538°C (1000°F).

The estimated weight increase for the three configurations and the associated price increases are listed below in Table I.

TABLE I
WEIGHT AND PRICE INCREASES

	*Weight kg/Airplane	lbs/Airplane	Nacelle Cost $/Airplane	Engine Cost $/Airplane
Conventional Design Mixer Nacelle	+4935	+10,880	+435,000	+113,600
Advanced Design Mixer Nacelle	+2585	+ 5,700	+435,000	+113,600
Advanced Design Mixer Nacelle with Composites	+1972	+ 4,348	+450,000	+113,600

*Weight increases include the increased engine weight.

Engine performance changes were based on Boeing's assessment of duct pressure losses, nozzle coefficients and mixing effectiveness which are defined in Figure 1.

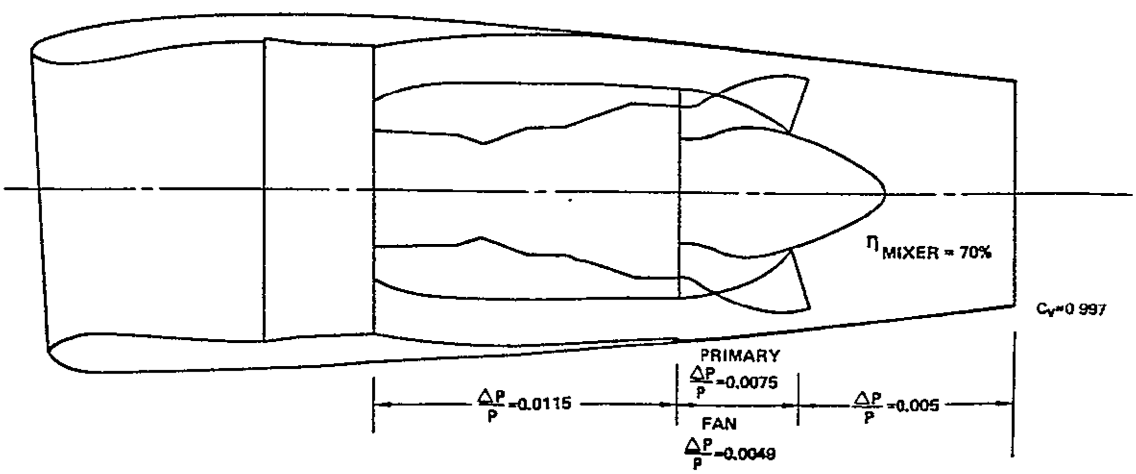


FIGURE 1 PRESSURE LOSS ASSESSMENT

No thrust increment was assumed, and all performance gains were taken as TSFC improvements. The TSFC improvement was assessed as a 2% reduction at takeoff, a 5.2% reduction during climb and a 2.5% reduction during hold. Performance gains during cruise conditions are shown in Figure 2.

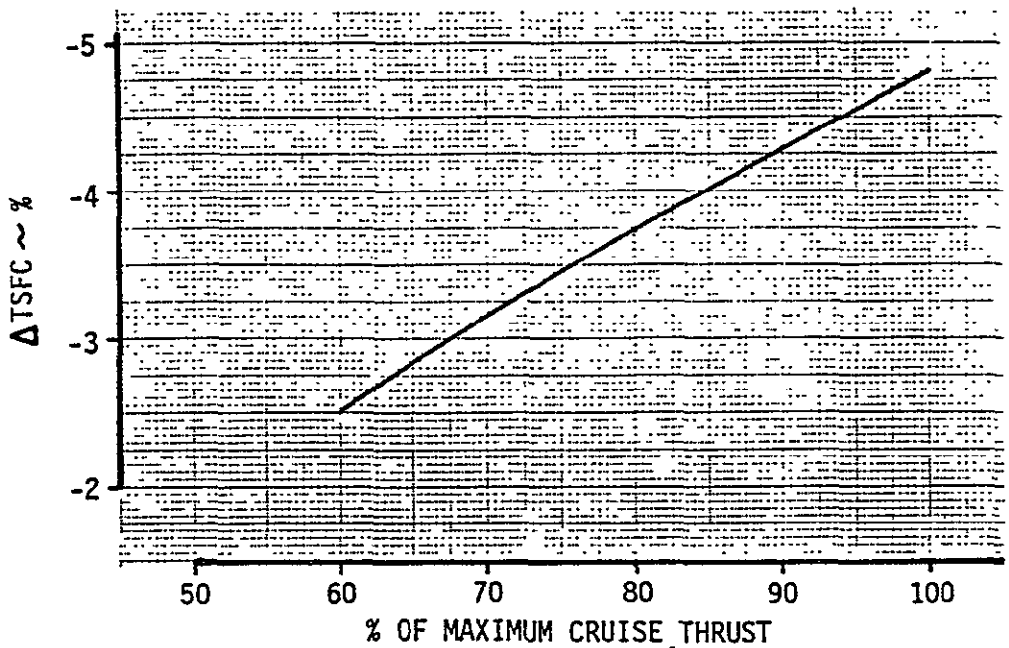


FIGURE 2 TSFC IMPROVEMENT

The change in airplane performance was defined as a reduction in block fuel versus range for a 747-200B airplane with JT9D-7AW engines, ATA International Fuel Reserves, and an Operating Empty Weight plus Payload equal to 213,792 kg (471,330 lbs.). The changes in block fuel are shown in Figure 3 and do not include the increased Operating Empty Weight effects.

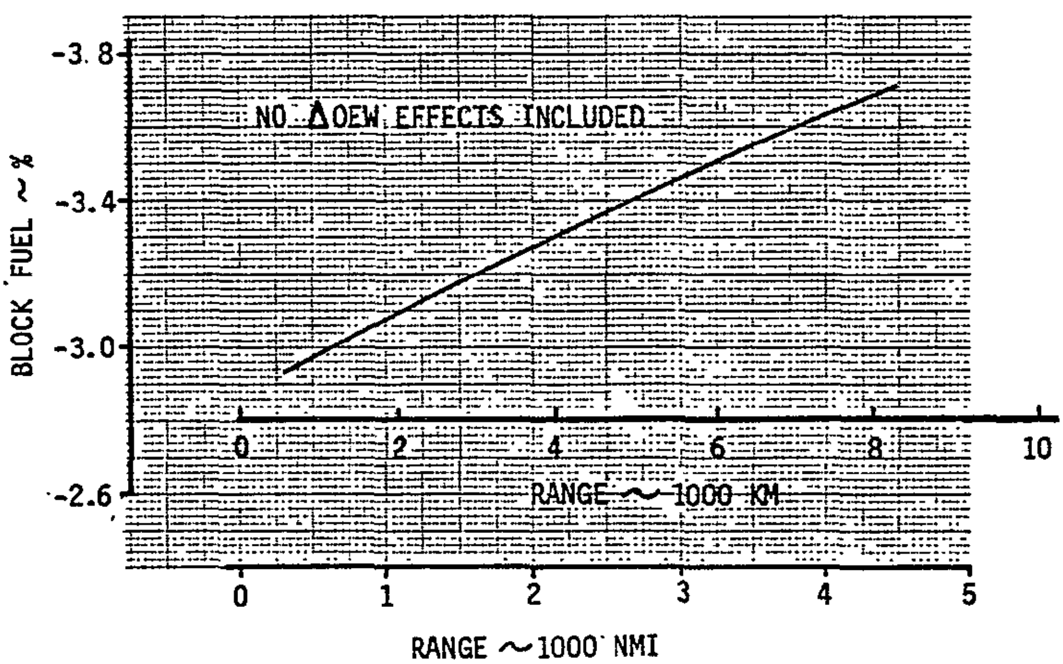


FIGURE 3 CHANGE IN BLOCK FUEL

JT9D-7 MIXED FLOW NACELLE (JT9D-7)

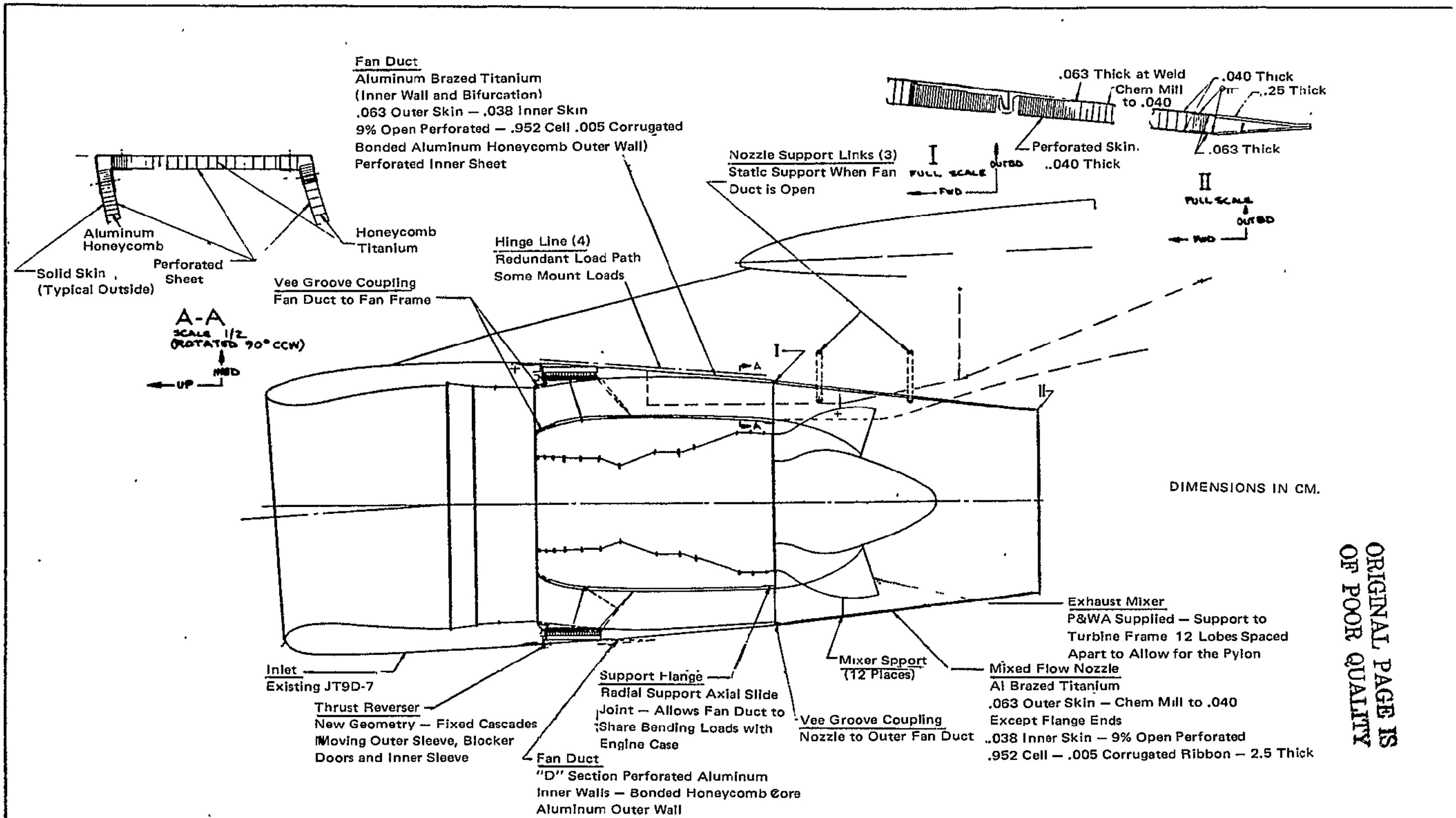
The mixed flow long duct nacelle concept requires extensive modifications to existing hardware. However, in order to best understand the comparison of the mixed flow long-duct nacelle configuration relative to the baseline configuration, only the changes necessary to incorporate the forced mixer were evaluated. The engine is modified by the replacement of the primary exhaust nozzle with a forced mixer and the modification of the flanges, bulkheads and seals that interface with the fan duct. Changes to the Boeing supplied hardware would consist of a new fan thrust reverser, a new fan duct, and a new exhaust nozzle. The strut would be modified to carry the additional weight and fair to the long-duct contour. The existing core engine cowl would be replaced by the inner wall of the fan duct. An aircraft certification test with the new nacelle would be required.

The attached drawing, Figure I-1, provides the basic layout of a long-duct nacelle with improved TSFC obtained by forced mixing of the primary and fan exhaust streams. The base nacelle for comparison is the current JT9D-7 installation on the 747 airplane without the turbine thrust reverser. The nacelle external lines were established by utilizing the existing inlet and fan cowls and providing an acceptable aerodynamic contour to an exhaust nozzle with a 10° boat tail angle. The external lines were also influenced by the requirements of the fan thrust reverser. The inner duct wall was placed with minimum desired clearance to the engine. The resulting duct area was judged to be satisfactory at this time. If future detail design shows the duct area to be overexpanded, the inner wall can be moved outward with little effect on the mechanical design.

Loading - To prevent an unacceptable increase in the engine mount loads in the long nacelle, it is necessary to carry the exhaust nozzle axial forces back to the fan frame. This is accomplished by coupling the fan duct between the exhaust nozzle and fan frame with "V" groove flanges. The fan duct is attached to the strut with hinges which must carry hoop loads. At the same time the hinges will provide a redundant load path along with the engine mounts for nacelle loads in the vertical and transverse directions. By providing a flange at the turbine rear frame to transfer radial loads between the fan duct and engine, the fan duct can be used to help support the core engine case in bending.

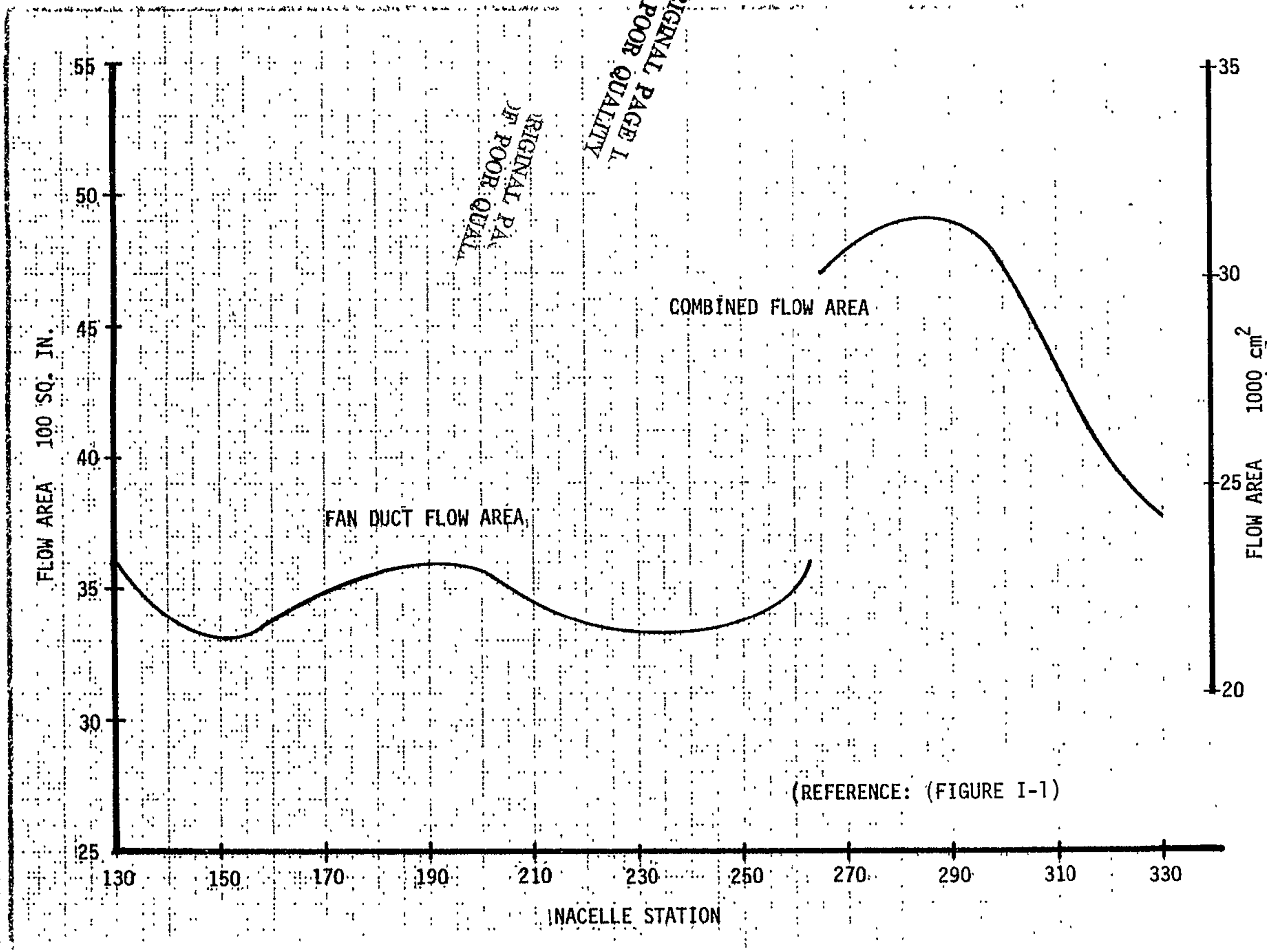
Fan Duct - The fan duct is made of two "D" sections hinged to the strut at the top and latched together at the bottom. The complete fan duct and thrust reverser assembly is opened by an installed drive motor to provide access to the core engine for maintenance or inspection. A manual system is also provided for those instances where power is not available for the drive motor or the drive motor malfunctions.

The inner wall of the "D" duct replaces existing core cowls. The upper and lower duct bifurcations are formed by end walls of the "D" duct. The duct walls are made of bonded-aluminum honeycomb sandwich structure to provide a lightweight stiff structure and maximum duct flow area. The walls adjacent to the fan flow area are perforated to absorb noise. The fan duct flow area progression is shown in Figure 1-2.



ORIGINAL PAGE IS OF POOR QUALITY

FIGURE I-1 LONG DUCT MIXED FLOW NACELLE 747 INBOARD INSTALLATION



ORIGINAL PAGE IS OF POOR QUALITY

FIGURE I-2 FAN DUCT FLOW AREA
JT9D-7 MIXER NACELLE

Fan Thrust Reverser - The thrust reverser is located at the forward end of the fan duct and is made in two halves that swing open with the fan duct. Although the operating principle of blocker doors and cascades are the same as the existing design, a completely new design is required to satisfy the geometry of the long-duct nacelle. The thrust reverser actuators move an outer sleeve that has slides in the upper and lower bifurcations. An inner sleeve containing the blocker doors is attached to the outer sleeve by struts that pass through slots in the cascades and moves together with the outer sleeve. The remainder of the fan duct containing the inner wall, bifurcation and cascades does not move during actuation of the thrust reverser. The axial nozzle load and duct loads are transmitted to the fan frame through this stationary structure.

Exhaust Nozzle - The exhaust nozzle is fabricated of aluminum-brazed titanium honeycomb. The use of this material places a requirement on the mixer to prevent impingement of hot gas during normal operation. The allowable temperature for forward thrust operation is 427°C (800°F). In the reverse thrust mode, when the fan air is not being mixed with the exhaust gas, the allowable temperature is 538°C (1000°F) for 36,000 cycles of 30 seconds duration each. If these temperature limitations cannot be met, the nozzle will have to be made of inconel instead of titanium which would result in an additional weight penalty.

Flutter - A "preliminary design" flutter assessment of the advanced structure design defined in Figure I-1 indicates the installation on the nominal 747-200B airplane would exhibit adequate and acceptable damping characteristics. Therefore, flutter required design changes to the baseline airplane would not be required. Two 747-200B configurations were analyzed. These were the two nominal flutter critical conditions revealed through previous experience and analyses. The nacelles were assumed to be located with the inlets the same distance ahead of the wing leading edge as current 747-200B installations, and the current strut stiffness was assumed to be applicable.

Weights - Weight estimates are provided for three mixed flow nacelle designs. The first is a lightweight design utilizing advanced structure that was developed for this contract and discussed above. The second is a "conventional" design which is provided to show the amount of weight reduction achieved by the advanced structure design. The third is an advanced structure design utilizing composites where possible. The advanced structure design reduces the weight penalty for incorporating a forced mixer from 4935 kg (10,880 lbs.) per airplane to 2585 kg (5700 lbs.) per airplane. The design utilizing composites reduces the weight penalty to 1972 kg (4348 lbs.) per airplane.

The weight shown for the advanced structure design is based on the incorporation of several design features involving a high technical risk. These features need to be investigated in more detail before a great deal of confidence can be placed in this weight estimate. The following is a partial list of the items that need to be looked at in greater detail to substantiate the weight shown for the advanced structure nacelle.

- The advanced structure nacelle uses titanium sandwich construction for the mixed flow nozzle. The metal temperature aft of the mixer and during reverse thrust operation may be too high to allow use of this material. Further analysis and testing are required to substantiate the use of this material.

- The mixed flow nozzle and aft portion of the fan duct do not have an outer cowling (i.e., they are constructed from a single, 1/2" thick, titanium sandwich panel). This severely limits the structural depth available for frames and for the nozzle to fan duct joint.

- The thrust reverser design presents unique problems on the mixed flow nacelle because the fan duct cannot be translated aft to expose the cascades. The thrust reverser design developed to overcome this problem needs to be investigated in more detail to confirm that it is feasible and can be built for the weight allowed.

- It has been assumed in developing the weight estimates that the engine can be placed in the same position relative to the wing as the current JT9D-7/747 engines. Analysis and testing are required to confirm this.

- It was also assumed that no wing weight increase will be required as a result of the increased weight, revised geometry, and center of gravity shift caused by the mixed flow nacelle.

Until these investigations are completed, the weight increase for the mixed flow nacelle should be considered as being within the range defined by the advanced structure nacelle with composites (+1972 kg (4348 lbs.) per airplane) and the conventional nacelle (+4935 kg (10,880 lbs.) per airplane).

Propulsion System Performance - Propulsion system performance improvements were assessed by Boeing based on the information supplied by Pratt & Whitney Aircraft. The estimated duct pressure losses and nozzle coefficients used in the analysis are shown in Figure I-3. The 70% mixing effectiveness used is considered optimistic since it is on the high side of Boeing's model test experience. These cycle assumptions were then used to calculate the cruise TSFC improvements shown in Figure I-4. This curve was used along with the specified percent change in TSFC for the takeoff, climb, and hold conditions to calculate block fuel savings.

Aerodynamics - The increase in wetted area and its associated roughness due to the nacelle extension to accommodate the mixer results in 1.2% increase in friction and excrescence drag. Interference drag was assumed to be the same as the current JT9D-7 installation.

JT9D-7 MIXER NACELLE

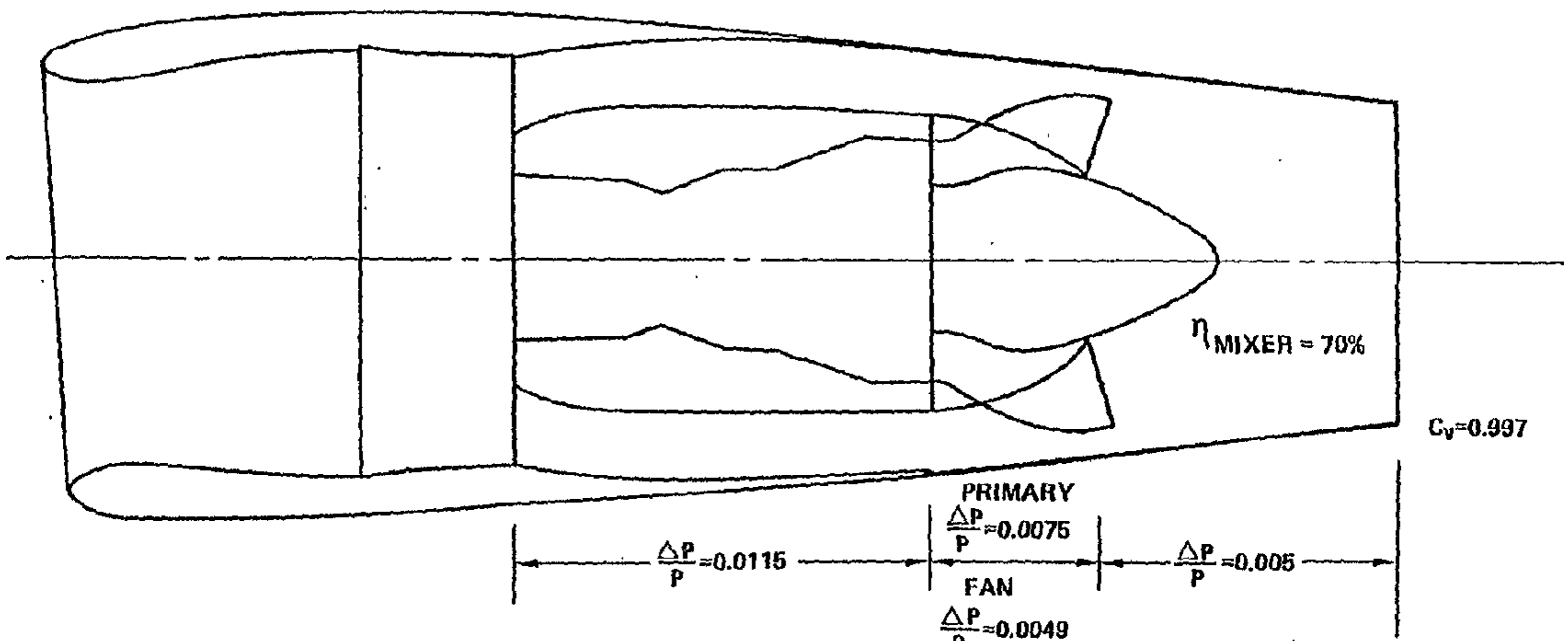
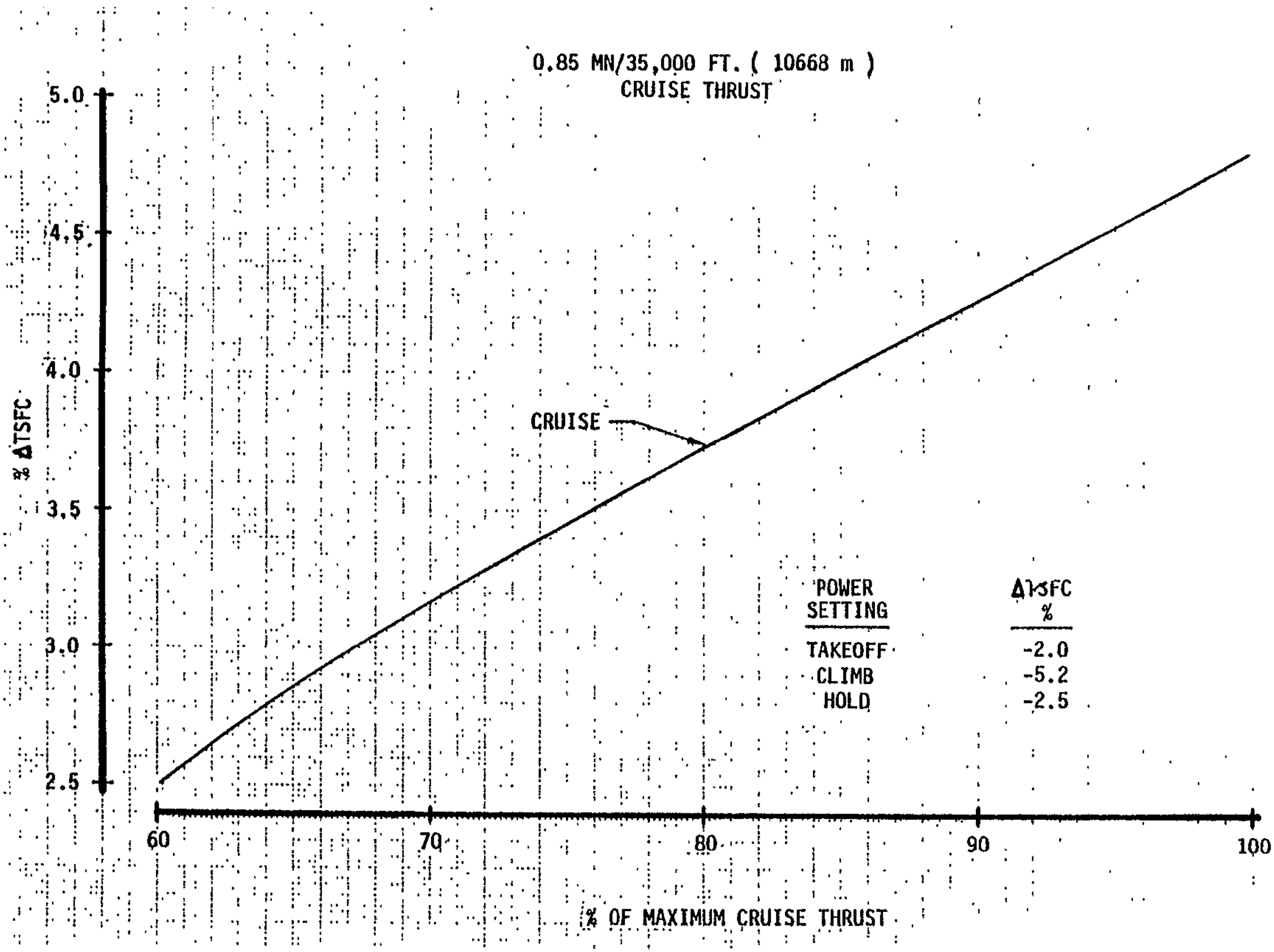


FIGURE I-3 MIXED FLOW CYCLE ASSUMPTIONS



POWER SETTING	ΔTSFC %
TAKEOFF	-2.0
CLIMB	-5.2
HOLD	-2.5

FIGURE I-4 TSFC IMPROVEMENT WITH JT9D-7 MIXER NACELLE

Results - The incremental changes in drag and TSFC were applied to the baseline airplane and analyzed over the mission profile.

The mission analysis provided the block fuel changes shown in Figure 1-5. The airplane performance analysis was made for a 747-200B airplane equipped with JT9D-7AW engines. This combination was selected, in conjunction with TWA, to be the most representative of the anticipated 747 fleet over the next five years. This performance information was forwarded to Trans World Airlines along with the Operating Empty Weight Changes for use in their analysis.

The successful application of a forced mixer on the JT9D-7/747-200B will require significant development efforts in three specific areas.

1. A considerable amount of development testing of the mixer itself should be conducted to develop an efficient, lightweight mixer design for a high-bypass ratio engine. To date, most mixer development testing has been accomplished with low-bypass ratio designs. Achievement of a 70% or better mixer effectiveness with a high-bypass ratio engine will require a significant amount of development. Boeing data for low-bypass ratio mixer designs indicate that a 70% mixer effectiveness is on the high side of the confidence band of what could reasonably be achieved. In order to get the penetration and mixing required to achieve a 70% effectiveness with a high-bypass design, the lobes will have to be long and relatively narrow in addition to preventing the hot gas from impinging on the outer walls. This will not only increase the pressure loss in the mixer, it will cause structural and durability problems that must be overcome. Therefore, in addition to the aerodynamic/thermodynamic testing required, a considerable amount of hardware development will be required to produce a lightweight mixer with the durability and repairability required for commercial service.

2. Success of the mixer will also be dependent upon the development of a lightweight nacelle. As with the mixer, considerable development work must be done on the nacelle itself. The advanced structure design is dependent upon the use of aluminum-brazed titanium honeycomb which has some temperature limitations. In addition, the thickness limits the structural depth available for frames and the nozzle-to-fan duct joint.

3. One of the assumptions made in this evaluation was that the mixed flow long-duct nacelle could be incorporated with no change in interference drag. This is dependent upon correct placement/location of the strut and nacelle on the wing. Additional analysis and testing is required to validate this assumption. If changes in placement are required, additional investigations of wing strength and flutter will also be required.

747-200B W/JT9D-7AW ENGINES
ATA INTERNATIONAL RESERVES
OEW + P/L = 213,792 kg (471,330 LB)
STEP CRUISE, M=.85

NO ΔOEW EFFECTS INCLUDED

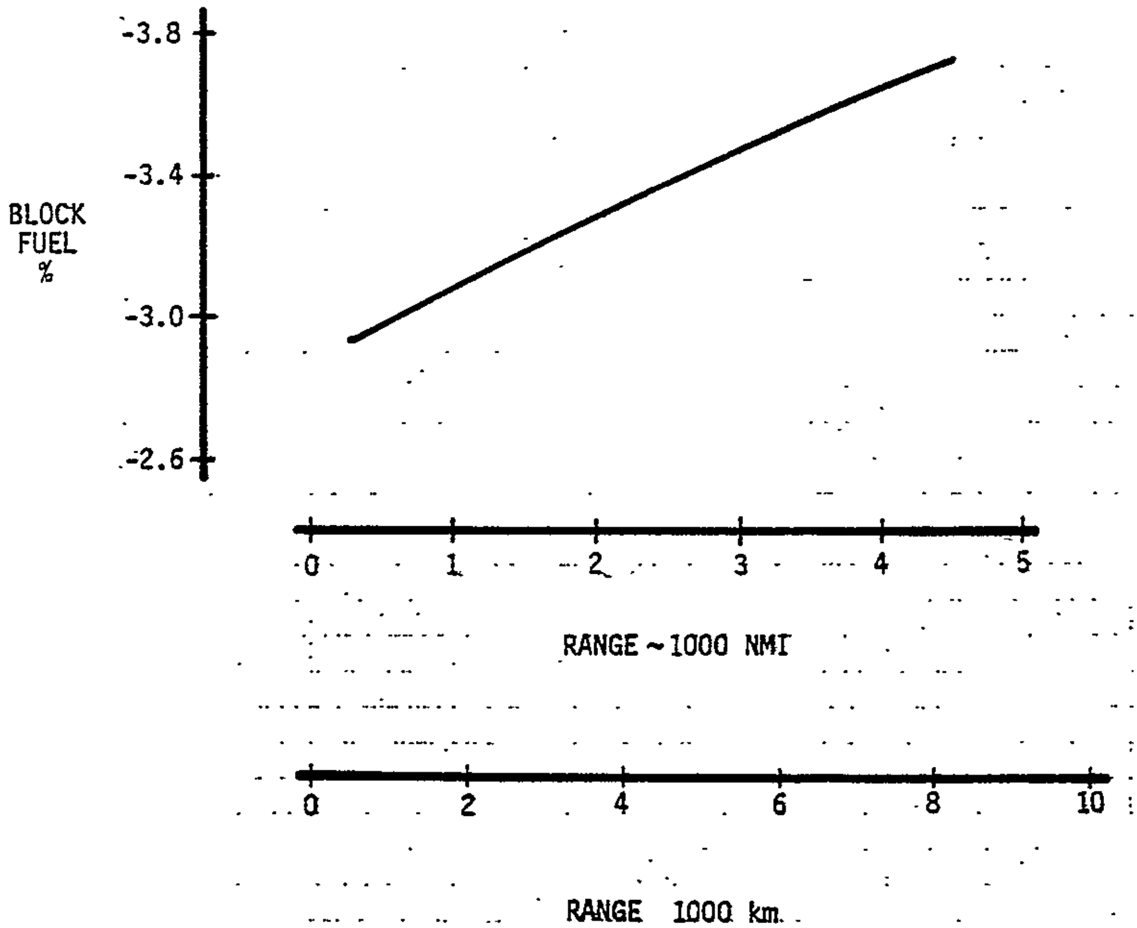


FIGURE I-5 BLOCK FUEL IMPROVEMENT
WITH
JT9D-7 MIXER NACELLE

ELECTRONIC CONTROL

I. SUMMARY

This discussion supports the effort within the NASA ECI-PI Program to analyze the expected economic impact of digital electronics on engine performance improvement. It would be a mistake to view the results of this effort as a useful justification for introduction into service of such controls; however, many share the belief that electronic engine controls are inevitable. The basic forcing function is the perceived need for further control sophistication (beyond the limitations of hydro-mechanical controls and simple electronic augmentation) to make advanced engines work properly in the hands of pilots, whose primary task is to fly airplanes rather than worry about the stability, response and life cycle costs of power plants.

Thus, the question must be raised: what should these "inevitable systems" be used for and what are the best modes of utilization in terms of economics, safety, human factors, engine performance and other such concerns? Also, one must acknowledge the fact that there will be great variety among digital electronic systems and unlimited growth in sophistication. Therefore, this report is based on an imagined electronic control system that could be implemented using contemporary state-of-the-art. In order to add realism to the study, we have assumed that the control system is similar to the EPCS (Electronic Propulsion Control System) that was recently tested in a cooperative program between Boeing and United Aircraft.

This system, although it serves as baseline for this study, is not merely a translation of a contemporary hydromechanical control system into the domain of digital electronics. EPCS was tailored for a good pilot interface ("rating command control"), included many advanced monitoring and self-healing features, and utilized control laws superior to those obtainable in mechanical implementations (Ref. 1).

This report identifies fuel savings and other economic benefits from such an EPCS-like baseline system. The savings fall in the "1% fuel" category; i.e., they are not negligible. However, other aspects of the EPCS type system are not attractive. For instance, the use of electrical wires for control links induces a significant weight penalty and, at least in the eyes of some, carries the threat from lightning induced transients. Fibre-optics should, therefore, be considered for the follow-on generation of digital electronic controls. Fibre-optics are light, reliable and immune from induced transients. A follow-on study is suggested to address the benefits from and installation problems with fibre-optics for data links and compatible sensors and equipments.

In the preparation for the advent of electronic engine controls, serious consideration should be given to the best utilization of the inherent potential of advanced electronics. Two more follow-on study items are, therefore, suggested that should address the use of electronics for advanced control laws (using currently available variable geometries) and new control loops (e.g., variable nozzle area, active clearance control, etc.) that were never seriously considered because of the inherent limitations of available controllers.

II. BENEFITS OF DIGITAL ELECTRONIC CONTROL (EPCS TYPE)

The potential benefits of digital electronic controls on engine performance improvement are considered. The subject headings are Direct Fuel Savings, Engine Maintenance and Control System Maintenance. Also included are references and bibliography.

A. Direct Fuel Savings

1. Engine Trim

Fuel usage and cost for an engine trim on the 747 airplane using the current hydromechanical control system trim procedure is as follows:

a. Fuel usage during a full engine ground trim is on the order of 2271 liters (600 gal.) to 3785 liters (1000 gal.) per engine.

b. Airlines using this trim procedure averages 3-4 trims per engine per year.

c. The labor cost for such a trim procedure is $100 - $125 per trim.

Several airlines use a "fuel economy" trim procedure when an engine is squawked by the crew. This procedure consists of adjusting the fuel control slightly (with little or no ground running) and then checking engine operation during the next in-service flight.

The major expense for this simplified trim procedure is labor (approx. $50/trim). The frequency of trim is as needed to resolve the problem.

For airlines using the full engine control system trim, a fuel saving of about 0.2% is expected by changing from hydromechanical to electronic controls. For those airlines using the "fuel economy" trim, a fuel saving of about 0.1% is expected.

2. Elimination of Overboost

Engine overboost during climb is primarily an engine life problem. However, in order to minimize maintenance cost, most operators use derated takeoff and climb procedures. The end result is thus a longer time to climb to the desired cruise altitude and additional climb fuel usage. For example, the 747 with JT9D-7 engines operated at 10% climb derate burns about 91 kg (200 lbs.) to 227 kg (500 lbs.) more fuel to optimum altitudes than at the full climb rating. Similar penalties would be incurred by the other engines certified for use on the 747.

With the autothrottle and TAT/EPRL* computer operating, the lead engine will operate at climb rating and the others will track through the autothrottle. Due to engine differences across the wing, there may still be a slight fuel burn penalty (say 45 kg (100 lbs.) - 68 kg (150 lbs.) compared to all engines operated at climb rating (as would occur with individual electronic engine controls).

3. Accurate Setting and Maintaining of Required Engine Thrust

The electronic control, in conjunction with "fly-by-wire" links from cockpit to engine and appropriate flight deck instrumentation, offers the opportunity for:

a. Rapid and accurate setting of desired thrust (N_1).
b. Maintaining climb rating (or a percentage thereof) at a fixed throttle position. This permits engine operation at climb rating without engine overboost, thereby minimizing climb fuel with no attendant maintenance penalty.

---

*"TAT/EPRL" is a digital electronic computer on the 747 airplane that computes total air temperature and stores, for display to the pilot or use by other systems, the engine ratings (in terms of engine pressure ratio) contained in the flight manual.

In addition, the use of a "command" control system (i.e., thrust setting display responds directly to throttle position with engine response following) provides the means for rapid setting of the required thrust and thrust equilization across the wing.

The ability to implement such an advanced control procedure is beyond the capabilities of a hydromechanical control system. It is virtually impossible to allocate an economic benefit to this capability of an electronic control system; however, ease of engine operation is likely to be the single most important step forward. Those who were privileged to operate the EPCS system in a simulated go-around engine acceleration were convinced that the rapidity of commanding and obtaining rated go-around power without over-boost (merely pushing all throttle levers to the forward stop) represented a very significant improvement toward increased aircraft safety. During periods of high stress, such as those leading up to and during go-around maneuvers, the pilot's flying task should not be burdened with concerns for engine stability, acceleration and performance.

B. Engine Maintenance

1. Effects of Benign Engine Operation

Derated engine operation in climb will directly result in some fuel inefficiency. This is economically offset by the parallel reduction in engine maintenance costs from derating. Further reductions in maintenance cost can be obtained from more accurate control and the elimination of overboost episodes by using "smarter" (e.g., eléctronic) controls. It is not known,at this time, what the best derating strategy should be for a given fuel price that would result in overall optimal economy.

Perhaps more importantly, there are indirect fuel economy benefits to be gained from benign engine operation, i.e., from extension of overhaul periods. The premise for this is the fact that overhauls are often not performed to the degree that would fully restore TSFC to the initial values. Over the years of operation, there is a gradual decrease in fuel efficiency, underlying the shorter term deterioration and restoration functions. It can be shown that this underlying fuel efficiency curve can be influenced by benign engine control to yield fuel savings, particularly in the later years of an engine's useful life. Assuming that electronic controls can extend the time by 10% for an engine to deteriorate to an overhaul condition, we estimate fuel savings on the order of 0.3 - 0.5%.

2. Degree of Performance Restoration at Overhaul

The degree of performance restoration at each overhaul is a critical item; past efforts have tended to minimize total maintenance cost. Sallee, et.al., (Ref. 2) pointed out the benefit of doing compressor maintenance more frequently when the engine is already in the shop for hot section maintenance. Epstein (Ref. 3) also noted the benefit of refurbishing the low pressure system in addition to the core when the engine is overhauled. This philosophy will result in more of the engine performance loss being restored at each overhaul, thus reducing the net performance loss over the long term. The airlines are tending toward this type of maintenance philosophy as engine removal and repair costs (as well as fuel costs) increase.

3. Engine Performance Monitor

Boeing has done extensive studies on engine performance monitoring. These studies show that a performance monitor is compatible with a digital electronic control concept and should be included as a part of each engine controller. It would be useful in tracking and predicting performance trends, thereby indicating when certain engine maintenance actions should be taken.

C. Control System Maintenance

Fuel and engine maintenance savings, brought about by advanced controls, could possibly be negated by adverse operating costs of these devices. The following examines failure rates and control system maintenance.

Electronic controls are expected to meet the high operational reliability levels of current conventional controls (in terms of In-Flight Shut-Downs, IFSD) and to substantially reduce the number of delays arising from control failures prior to takeoff. While electronic controls will cause more frequent maintenance actions, they lend themselves to definitive fault identification and, being compatible with automatic electronic test equipment, should ultimately realize an overall saving in maintenance costs.

From an overall view, it is concluded that advanced propulsion controls will realize savings in the fuel and maintenance areas to a degree that is not offset by the operational costs of the advanced controls themselves. This picture could be affected, particularly in the introductory phase, by higher initial costs for electronic controls. Over the long term, however, the price of electronics (particularly digital electronics) is expected to decrease; thus, operational costs for a mature system should not be excessive.

The following comments compare control system maintenance features of hydromechanical and electronic systems.

1. Failure rates

   a. Hydromechanical Controls

      The delay and cancellation rate chargeable to the JT9D controls and accessories is $\approx$ 1.2 per 1000 departures for the 747 installation. Of these, the fuel and stator vane control account for $\approx$ 0.3 per 1000 departures.

The number of in-flight shutdowns (IFSD) chargeable to the JT9D controls and accessories is $\approx$7 per million engine hours. Of these, the fuel and stator vane control account for 2 to 3 per million engine hours. Similar numbers apply to the other engines certified for use on the 747.

b. Digital Avionics

When electronic propulsion control systems are used, they will be required to meet or better current hydromechanical control system failure rates with regard to in-flight shut-downs and dispatch delays. Based on available failure rates for contemporary aircraft electronics, a Mean Time Between Failure (MTBF) of $\approx$ 3000 hours (mature value) is feasible for each channel of an engine-mounted digital control computer. Thus, the need for parallel redundant electronic computers (primary $\pm$ secondary) operating in conjunction with hydromechanical flow valves and variable geometry actuators is apparent.

In a dual-redundant control system (with identical parallel electronic lanes) the currently achievable electronic reliability levels are more than adequate to meet or better the current IFSD rate chargeable to controls. As a matter of fact, the case can be made for allowing the occasional dispatch with one of the two redundant systems inoperative and still meet (when viewed over a sufficiently long time span) the current IFSD rates. The capability to dispatch occasionally with one system lane out is economically attractive, since it would reduce dispatch delays chargeable to controls practically to zero and permit repair at the first opportune time following failure rather than prior to next dispatch.

Reliability of electronics during the first 3 to 5 years of introduction into airline operation is expected to be poorer than "mature" electronics, just as new engine reliability has characteristically been low during the first years, reaching a stable mature level after 3 or more years. Thus, initial MTBF of each controller channel may be $\approx$ 1000 hours. This will still be satisfactory for early service with parallel redundant channels.

c. Self-test for Digital System

Reference 4 presented data for electronic flight controls, showing the effect of built-in test equipment (BITE) on premature removal rate. The mature value for the DC-10 system (with BITE) is approximately half that of the DC-8 system (without BITE).

In addition, the primary electronic engine control requires a high level of failure detection with switching to the backup control prior to any significant thrust change. With proper attention to design, we can be assured that no failures will be allowed to drive an engine beyond structural limits and in addition, that most of the failures of the primary control that can have any unacceptable effect on thrust can be detected and reacted prior to such a thrust change.

2. Removal Times

Reference 5 (p.28) gives typical power plant accessory replacement times for the JT9D engines. The time given for removal of the JT9D fuel control and pump is 240 minutes.

Replacement times for digital electronic controls are expected to be on the order of 30-45 minutes (assuming a clean installation with good access). This is compatible with most airplane turn-arounds and will not impact airplane departure.

A significant opportunity obtained from the use of redundant electronic control systems is that the airplane may be dispatchable for a given number of flight hours after failure of the "primary" control system. Assuming such a concept is compatible with certification rules, control removal can be deferred until the airplane is available at a depot equipped with digital checkout equipment.

3. Failure Confirmation

A bench check of a hydromechanical control to confirm failure could be on the order of 4-6 hours. Checkout of a digital electronic control using a pre-programmed test could be accomplished in minutes, on wing or bench, without requiring the engine to run.

4. Repair, Test and Return to Service

Bench time required to repair and checkout a current technology digital air data computer is about two hours. Since the electronic engine control computer would be of about the same complexity, it is expected the repair and checkout time would be of the same magnitude as for the digital air data computer.

The current hydromechanical control is a complex piece of equipment. It is expected that a complete teardown, repair and re-assembly of the control could easily consume 25-30 man hours. Thus, the time required is an order of magnitude greater than that required for repair and checkout of a digital electronic control. This does not represent the total cost to an airline, since installation on the engine and engine trim requires additional time.

III. AREAS NEEDING FUTURE INVESTIGATION

The benefits of electronic propulsion controls over current hydro-mechanical controls have been discussed in the material supporting the current NASA ECI-PI program.

Table I lists the broad potential for fuel conservation through the use of electronic propulsion control systems (EPCS). The areas requiring additional investigation to further utilize the capability of electronic controls to improve the performance of current high bypass engine and airplane systems are:

A. Use of fiber-optics to reduce electronic propulsion control system weight and provide improved signal integrity with respect to induced electromagnetic interference (e.g., lightning strike).

B. TSFC improvement and retention by means of new control loops (e.g., variable nozzle area, active clearance control).

C. Improved engine control laws to provide better airplane speed stability at cruise (reduce throttle motion during cruise auto-throttle operation, thereby decreasing fuel burn).

These items are beyond the scope of the current ECI-PI program; thus, additional investigations are required to study the impact of these features on current engine/airplane systems. A short discussion for each study item is given below.

A. USE OF FIBER-OPTICS

Discussion

Electronic propulsion control systems being studied will adequately perform the necessary tasks; however, they do not take full advantage of the emerging fiber-optic technology. Thus, we believe an improvement in engine performance can be accomplished through the use of these new concepts.

An electronic propulsion control system using fiber-optic data links that will provide high-integrity data transmission and yields an engine performance improvement by means of reduced system weight should be configured and studied. The system should be evaluated with regard to initial and maintenance costs, reliability and performance. Assuming these factors are satisfactory, the system weight should be determined and compared to an electronic system utilizing wiring for data transmission.

Fiber-optic data links offer several potential advantages over wires for critical communication systems, such as the flight deck to engine link. Large signal bandwidth and immunity to electromagnetic interference are well known properties of fiber-optic cables. Other important attributes are freedom from disabling short circuits and intermittent connections, complete electrical isolation of interconnected redundant systems, no ground loops, safe in explosive environments, light weight and potentially low in cost.

Electronic engine control introduction may be impeded (if not stunted) if mechanical control links between cockpit and engines are not replaced by methods directly compatible with the digital data domain. Also, sensors and instruments directly compatible with the digital data format are being developed and should be used with the optical data link to minimize the need for analog/digital and digital/analog converters.

B. TSFC IMPROVEMENT AND RETENTION

Discussion

Decreasing the fuel usage of current high bypass ratio engines is of extreme importance and is one of the primary objectives of the NASA ECI-PI program. Variable geometry features that were discarded in the initial engine design process may now have sufficient potential for mission fuel saving that they should be reconsidered. In addition, methods for maintaining blade tip/case clearances are important to engine performance retention. Both of these features may be accommodated with the flexibility of digital electronic controls.

The net fuel saving that could be obtained by incorporating additional variable geometry components on current high bypass ratio engines should be defined. In addition, the effect of clearance control schemes on fuel burn by means of improved performance retention should be estimated.

A high bypass ratio engine design incorporating selected variable geometry should be configured and studied over a typical airplane mission. The configuration should be evaluated with regard to mission fuel burn, weight, reliability and cost. Also, advanced concepts for blade tip clearance control should be developed and evaluated for fuel savings over an extended time period (e.g., 4000 engine hours).

With the flexibility of digital electronic controls, it is possible to easily incorporate the algorithms for new control loops if these features can be shown to reduce mission fuel flow (either directly or by means of performance retention).

C. IMPROVED AIRPLANE SPEED STABILITY AT CRUISE

Discussion

Figure II-1 illustrates the typical relationship of thrust available (Power Lever Angle (PLA) = constant) and thrust required (airplane gross weight = constant). Two features are apparent:

a) A gradual decrease in PLA is needed to maintain constant Mach number as fuel is burned off during cruise.

b) The desired cruise Mach number for maximum range is near the bucket of he "thrust required" curve. Since the "thrust available" curve is also quite flat, the natural restoring force on the airplane following a slight Mach number change is small.

Both of these features can contribute to an airplane speed instability condition following a disturbance, especially on current aircraft using hydromechanical fuel controls and long cable runs from flight deck to engine with the attendant inaccuracies.

A cruise control law for engine operation that would provide more stable airplane/engine operation should be defined. An evaluation of the fuel saving that could result (compared to current airplane/engine systems) should be made.

Using the flexibility of electronic engine controls, a cruise control law may be possible to provide "thrust available" curves having a steeper negative slope. This would improve the inherent airplane/engine speed stability, since a larger restoring force would be provided when a small change in Mach number occurs (e.g., due to air turbulence). Such an improvement in inherent speed stability would greatly reduce the autothrottle activity, thereby resulting in lower cruise fuel usage. The magnitude of this saving should be estimated.

Electronic controllers offer the potential for implementation of improved control laws as well as elimination of input cable hysteresis and lag through use of electrical or fiber-optic data links. Thus, improved airplane stability and reduced fuel usage during cruise is attainable using electronic controls. Progress to date in this area has only been through development of improved autothrottle control laws. These efforts can only be partially successful since they still must contend with the inherent and seemingly unsurmountable inaccuracies of cable links.

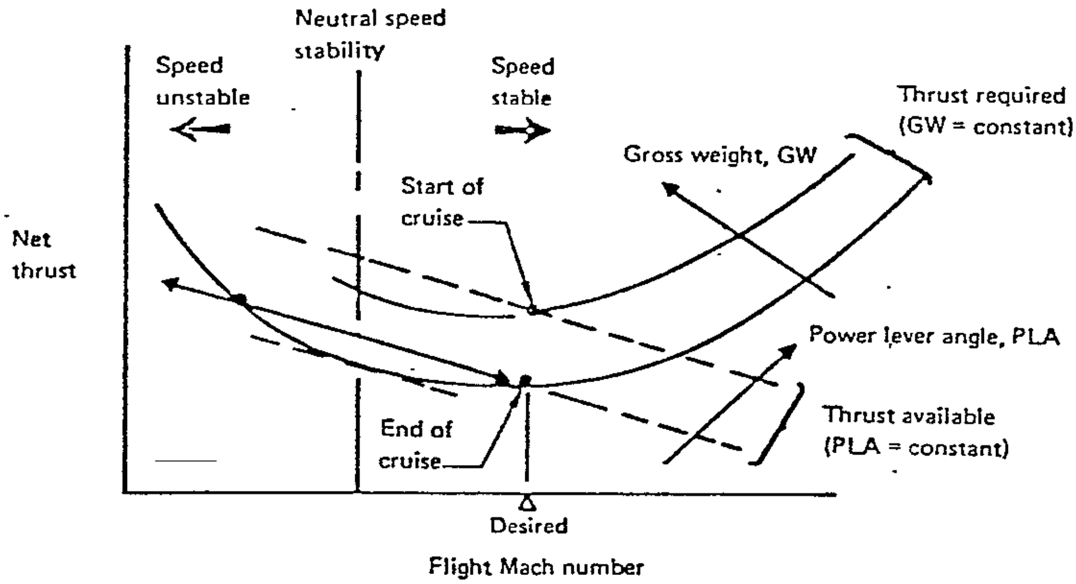
NASA ECI-PI

TABLE I

FUEL CONSERVATION POTENTIAL - ELECTRONIC PROPULSION CONTROLS

• * TSFC PRESERVATION IN SERVICE	-- ENGINE PROTECTION, BENIGN CONTROL, REDUCED DETERIORATION RATE
• * REDUCED OR ELIMINATED GROUND ENGINE TRIM REQUIREMENT	-- IMPROVED CONTROL LINKS AND INTERFACES, RATING COMMAND CONTROL
• * AIRPLANE MINIMUM FUEL BURN LOGIC IN PROPULSION SYSTEM MANAGEMENT	-- AUTOMATED THRUST MANAGEMENT, AIR CONDITIONING·BLEED LOADS OPTIMIZED, IMPROVED LOAD DISTRIBUTIONS
• MINIMUM FUEL BURN PROVIDED BY AUTOMATED FLIGHT PATH CONTROL	-- EASE OF INTERFACING WITH AUTOMATED FLIGHT CONTROL SYSTEMS (ALTITUDE VS. SPEED)
• * ENGINE CONTROL SYSTEM WEIGHT REDUCED	-- ELECTRONIC VS. MECHANICAL COMPONENTS
• * MORE SOPHISTICATED CONTROL MODES PROVIDED	-- COORDINATED CONTROL OF MANY ENGINE VARIABLES TO SAVE FUEL DIRECTLY OR INDIRECTLY, INCLUDING VARIABLES NOT CURRENTLY CONTROLLED

* ASSOCIATED MAINTENANCE COST REDUCTION BENEFITS



THRUST/MACH STABILITY DURING CRUISE

FIGURE II-1

D. References

1. Kamber, P. W., Zimmerman, W. H., Ransom, R. D. and Sullivan, J. T., "Progress in Electronic Propulsion Control for Commercial Aircraft," AIAA Paper 76-655, July 1976.

2. Sallee, G. P., Kruckenberg, H. D. and Toomey, E. H., "Analysis of Turbofan Engine Performance Deterioration and Proposed Follow-On Tests," NASA CR 134769, 1975.

3. Epstein, Norman and Hess, Paul J., "Improving Performance Retention of High Bypass Engines," SAE Paper 750620, May 1975.

4. Brecht, Marlowe W., "Factors to be Considered in Applying New Technology to the Airline Environment," SAE Paper 760510, May 1976.

5. Sallee, G. Phillip, "An Airline Study of Advanced Technology Requirements for Advanced High Speed Commercial Transport Engines II - Engine Preliminary Design Assessment," NASA CR-121133 under NASA Contract NAS3-15572, March 1973.

E. Bibliography

1. Sallee, G. Phillip, "An Airline Study of Advanced Technology Requirements for Advanced High Speed Commercial Transport Engines," Parts I and III, NASA CR 121132 and 121134 under NASA Contract NAS3-15572, March 1973.

2. Sallee, G. P., "Aircraft Economics and its Effects on Propulsion System Design," AIAA Paper 73-808, August 1973.

3. Flanders, T. A., "The Architecture of a Turbine Engine Control," Presented at the Royal Aeronautical/IEE Symposium on the Application of Electrical Control to Aircraft Propulsion System, London, February 1974.

4. Sallee, G. P., "Performance Versus Cost Tradeoffs - Initial look at Alternatives," SAE Paper 740494, May 1974.

5. Sallee, G. Phillip, "Economic Effects of Propulsion System Technology on Existing and Future Aircraft," NASA CR 134645 under NASA Contract NAS3-17326, July 1974.

6. Kamber, P. W., "An Airframe Manufacturer's Requirements for Future Propulsion Controls," Presented at the 44th Meeting, Propulsion and Energetics Panel (AGARD) on Power Plant Controls for Aero-Gas Turbine Engines, September 1974.

7. Epstein, Norman, "Powerplant Energy Management," AIAA Paper 74-1066, October 1974.

8. Sevich, G. J., and Newirth, D. M., "Economic Benefits of Digital Electronic Propulsion Controls for Advanced Commercial Aircraft," SAE Paper 760508, May 1976.

9. Beyerly, W. R. and Sweeney, J. G., "Life Cycle Fuel Consumption of Commercial Turbofan Engines," AIAA Paper 76-645, July 1976.

APPENDIX B
ENGINE PERFORMANCE IMPROVEMENT PROGRAM

DOUGLAS AIRCRAFT COMPANY

JT8D and JT9D

ENGINE PERFORMANCE IMPROVEMENT PROGRAM

CONTRACT NO. 20630-2

PREPARED FOR:

PRATT & WHITNEY AIRCRAFT GROUP

COMMERCIAL PRODUCTS DIVISION

EAST HARTFORD, CONNECTICUT

BY:

DOUGLAS AIRCRAFT COMPANY

3855 LAKEWOOD BOULEVARD

LONG BEACH, CALIFORNIA 90846

INTRODUCTION

The Douglas Aircraft Company participated in the NASA Engine Component Improvement Program, Performance Improvement Studies as a subcontractor to Pratt & Whitney Aircraft. This participation was done from February through December 1977 under P&W Purchase Order 20630-2.

The Douglas participation used numerous technical specialists in the engineering department for technical evaluations and studies as well as manufacturing and pricing personnel for cost estimation.

The basic Douglas activities were:

- Conceived Performance Improvement Concepts
- Assisted in Establishing Screening Procedure
- Critiqued Concepts for Feasability
- Determined Airplane Performance, Weights and Costs on Selected Concepts

CONCEPTS STUDIED

In addition to participating in qualitiative assessments of the various concepts, detailed studies were made on concepts that required airframe changes. The study activities conducted on these concepts are summarized on Table 1.

The DC-9 Nacelle Drag Reduction is a new fairing covering the reverser stangs. There is no temperature measurement data on the current fairing but there is limited data on the thrust reverser arm during reverse thrust. These data show the temperature on the fairing will probably reach 230°C (450°F) during reverse. A polyimide resin system would therefore be used in an advanced composite fairing.

The DC-9 Improved Cabin Air concept, unlike that for the DC-10 had unfavorable economics. The DC-9 concept is more complex than required in the DC-10 resulting in a higher cost but lower fuel savings.

The CNS with mixer appears to be very promising. An in-depth study was made and is reported in a separate document.

The Short A/B is very-promising and considerable activity has been underway by Douglas and P&W.

The DC-10 Cabin Air Concept would reduce the engine bleed flow required up to 50% and is actually expected to improve the cabin environmental quality by improving humidity and reducing the ozone content.

Electronic controls appear to be evolving although significant direct fuel savings were not quantifiable. Electronic controls can simplify functions that save fuel but can be done without electronic controls. Recent evaluation of using electronic engine controls to reduce fuel consumption on current commerical jet transport aircraft have resulted in the general conclusion that such a benefit is not likely before 1982. Studies have been made, utilizing the experience gained from adapting partial off-engine electronic propulsion

TABLE 1

CONCEPTS STUDIED

DC-9 NAC DRAG REDUCTION

o Preliminary Design
o Airplane Performance and Weight
o Retrofit Kit Costs
o Technology Planning

DC-9 IMP CABIN AIR

o Preliminary Design
o Airplane Performance and Weight
o Effect on Airplane Selling Price

CNS WITH MIXER AND COMPOSITES

o Preliminary Design Including Incorporation of Additional Features
o Airplane Performance and Weights
o Noise at FAR 39 Measuring Points
o Effect on Airplane Selling Price
o Study Report

SHORT A/B

o Airplane Performance and Weights
o Effect on Airplane Selling Price

DC-10 IMP. CABIN AIR

o Preliminary Design
o Airplane Performance and Weights
o Effect on Airplane Selling Price
o Technology Planning

ELECTRONIC CONTROLS

o Evaluated use of Electronic Controls for Direct Fuel Savings

o Evaluated use of Electronic Controls to Improve Propulsion Control System controls in the YC-15 aircraft. Discussions also have been held with the engine companies and electronic component manufacturers.

Some of the current Douglas conclusions are:

- The widespread use of reduced takeoff thrust largely negates benefits from ability to prevent overboost at rated thrust.
- Significant fuel savings have not yet been quantifiable.
- Electronic engine controls are expected on future engines, particularily to accomodate additional control functions required by the engine.
- Proper integration of engine and airframe controls will reduce pilot work load.
- Electronic controls will provide system benefits such as reduced engine maintenance cost, but requires increased engine/airframe system integration.

RECOMENDATIONS

The Douglas Aircraft Company recommendations are summarized below:

- o Proceed with Technology Development of Promising Concepts
- o Proceed with Several Concepts that include Airframe and Airline Companies Participation
    - oo DC-9 Drag Reduction
    - oo DC-10 Imp. Cabin Air
- o Pursue Technology Development of Concepts that may not specifically fall within current P1 Program
    - oo Long Duct Mixed Flow with Composites
    - oo Electronic Propulsion Controls

A number of concepts should undergo technology development. Since Pratt & Whitney is the manufacturer of the JT8D and JT9D engines, concepts that Pratt & Whitney recommends be developed for these engines should be given priority consideration.

In addition several concepts that do not require Pratt & Whitney involvement have shown a high probability of helping achieve NASA's goal of reducing fuel consumption by 5% by 1982. In addition to the fuel savings, they directly benefit the engines because of the effective de-rate that results. These are the DC-9 Drag Reduction and DC-10 Imp. Cabin Air.

The drag reduction concept will not only result in fuel savings, but because of the advanced composite construction, will help maintain technological leadership in nacelle composites in the U.S. There is little data and no service experience using the polyimide resin matrix in a high noise level environment. A technology program would provide this.

The Cabin Air concept results in a major reduction in engine bleed flow at take-off and climb out and will result in significant improvements in engine hot section life.

Two concepts the long duct mixed flow and electronic propulsion controls may not fit within current NASA PI program funding and goals. They should, however, be pursued by NASA because of their overall long term payoff.

APPENDIX C

ENGINE PERFORMANCE IMPROVEMENT PROGRAM
LONG DUCT MIXED FLOW NACELLE STUDY

DOUGLAS AIRCRAFT COMAPNY

JT8D and JT9D

ENGINE PERFORMANCE IMPROVEMENT PROGRAM

LONG DUCT MIXED FLOW NACELLE STUDY

CONTRACT NO. 20630-2

PREPARED FOR:

PRATT & WHITNEY AIRCRAFT GROUP

COMMERCIAL PRODUCTS DIVISION

EAST HARTFORD, CONNECTICUT

BY:

DOUGLAS AIRCRAFT COMPANY

3855 LAKEWOOD BOULEVARD

LONG BEACH, CALIFORNIA 90846

TABLE OF CONTENTS

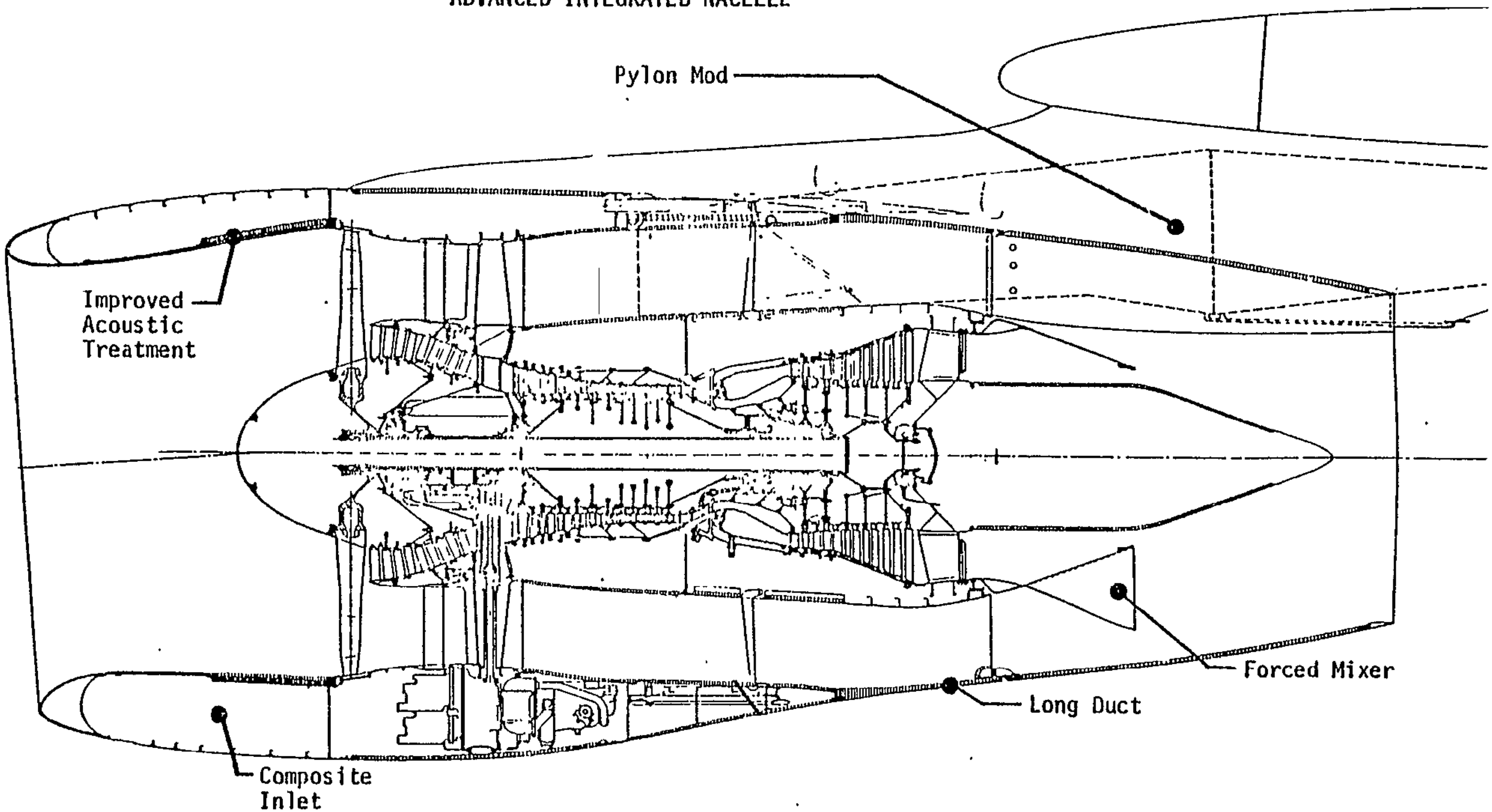
	Pages
1.0 Introduction	202
2.0 Long Duct Mixed Flow Description	204
2.1 Performance	204
2.2 Noise	204
2.2.1 Inlet Noise	204
2.2.2 Fan Discharge Noise	204
2.2.3 Turbine Noise	205
2.3 Weights	208
2.4 Long Duct Mixed Flow Installation Design	210
2.4.1 Materials	210
2.4.2 Construction	211
2.4.2.1 Nose Cowl	211
2.4.2.2 Fan Cowl Door	214
2.4.2.3 Fan Reverser	219
2.4.2.4 Mixed Nozzle	219

1.0 INTRODUCTION

The results of design studies on the Common Nacelle System (CNS) mixer and composites is presented. The long duct mixed flow nacelle was evaluated using the Pratt & Whitney JT9D-59 engine. Incorporation of this concept would require a major development program. This effort would require substantial non-recurring expenditures for retooling and recertification. Since the cost associated with adding other design features is nominal, they were included in this study. Primary emphasis placed on these additional features was directed toward the reduction of engine deterioration. The features of the CNS concept and the additional design concepts are depicted in Figure 1.

FIGURE 1

ADVANCED INTEGRATED NACELLE



FEATURES

- o Composite long duct reduces drag & accomodates additional acoustic treatment
- o Pylon modification minimizes interference drag
- o Forced mixer improves propulsive efficiency and reduces jet noise
- o Load sharing composite core cowl reduces engine deterioration
- o Composite inlet reduces weight
- o Improved acoustic treatment reduces noise

2.0 LONG DUCT MIXED FLOW DESCRIPTION

2.1 PERFORMANCE

The long duct mixed flow nacelle improves the performance of the aircraft by reducing fuel consumption. The increased performance is accomplished by: the reduction of high mach number scrubbing drag due to fan flow discharging on the core cowling, internal thermal mixing of the primary flow with the fan flow; and reduced interference drag. The additional area of the exterior surfaces on the nacelle has increased external skin friction and drag. The performance gains and losses in each phase of flight is shown in Table 1. A 2% interference drag improvement was assumed in these calculations based on the estimated potential improvement possible by elimination of shock induced flow separation that data shows currently exists.

2.2 NOISE

Jet noise is reduced below that of the short duct nacelle by reducing the maximum exhaust velocities. This is accomplished by the mixing of fan and turbine flows. The resultant achievable level reduction estimates are shown in Table 2. To accomplish these noise reductions, improved and/or additional acoustic treatment was needed in the inlet, fan discharge and turbine discharge areas. The following paragraphs explain what steps were taken to accomplish these noise reductions.

2.2.1 INLET NOISE. For inlet radiated fan noise, improved acoustic material is used in the nose cowl because of its superior ability to absorb high frequency noise.

2.2.2 FAN DISCHARGE NOISE. From the fan discharge ducts, there is a reduction in radiated noise. This is accomplished by using acoustical treatment in the additional available area. The most appropriate lining design for this increased area is a perforated face sheet, made from advanced fibers, bonded to a composite, but impervious, honeycomb core.

2.2.3 TURBINE NOISE - For turbine noise reduction, essentially all of the nozzle wall is treated, and additional treatment is installed on the wall of the centerbody. The current corrugated core design, would be changed to a honeycomb core design to gain additional treated area. This requires that high temperature titanium be milled to foil thicknesses.

TABLE 1

LONG DUCT MIXED FLOW NACELLE: PERFORMANCE IMPROVEMENTS
JT9D-59A ENGINE INSTALLED

	$\left(\frac{\Delta SFC}{SFC}\right)$ Internal %	$\left(\frac{\Delta SFC}{SFC}\right)$ External Scrubbing %	$\left(\frac{\Delta D}{D}\right)$ Interference %	$\left(\frac{\Delta SFC}{SFC}\right)$ TOTAL %
TAKEOFF	-3.6	NIL	NIL	-3.6
CLIMB	-6.5	0.9	NIL	-5.6
HOLD	-3.7	1.3	NIL	-2.4
CRUISE				
70%	-4.6	1.2	-2.0	-5.4
80%	-5.1	1.2	-2.0	-5.9
90%	-5.6	1.2	-2.0	-6.4
100%	-6.1	1.2	-2.0	-6.9
DESCENT	NIL	NIL	NIL	NIL

TABLE 2

ESTIMATED NOISE REDUCTION (ΔEPNdB)

FOR

LONG DUCT NACELLE WITH MIXER NOZZLE AND BULK TREATMENT

IN THE INLET AT MAXIMUM CERTIFIED GROSS WEIGHT

TOGW = 267,619 Kg LGW = 197,766 Kg

AIRPLANE CONFIG.	TAKEOFF	SIDELINE	APPROACH @ MAX FLAPS
DC-10-40/JT9D-59A	3-4	3-4	2-3

2.3 WEIGHTS

A weight estimate was made for the long duct mixed flow nacelle. The weight estimate is broken down into the major nacelle components. (Fan cowl door, Fan Reverser etc.) A separate weight estimate is made for the tail nacelle due to a slight variation in dimensions. These estimated weights along with the current pod weights are compared in Table 3. The purpose for comparing these weights is to see if it is necessary to add structural strength to the pylon. As shown in the Tables, the long duct mixed flow nacelle with composites is approximately two percent lighter than current pods. This leaves a 90 kg (200 lb) cushion which will absorb any changes between preliminary and final design.

TABLE 3

NACELLE WEIGHT COMPARISON

JT9D-59, EBU of 478 kg and engine not included

	CURRENT PODS		LONG DUCT MIXED FLOW WITH COMPOSITES		
	kg	(lbs)	kg	(lbs)	% CHANGE[1]
WING	1571	(3463)	1539	(3394)	-1.99
TAIL	1487	(3279)	1457	(3213)	-2.01
TOTAL A/C	4629	(10205)	4536	(10001)	-2.00

1. Percent change with respect to current pods

2.4 LONG DUCT MIXED FLOW INSTALLATION DESIGN

2.4.1 MATERIALS:

To be able to incorporate the long duct mixed flow with minimum effect on airframe support structures, composite materials are used to keep the weight of the long duct design to a minimum. The basic long duct nacelle construction is a thin walled design concept using composite face skins bonded to a honeycomb core.

The material chosen for a majority of the face skins is a Graphite/Kevlar 50/50 hybrid fabric. The material is comprised of fifty percent Graphite (Thornel 300, Fibrite) and fifty percent Kevlar (Kevlar 49, E.I. DuPont). The weave is an eight harness satin and the thread count is 24 X 24. The fabric style is W-107 and has a density of .329 Kg/m^2. The reason for choosing this material is for its diversified characteristics. The Graphite in the face skins enables the conduction of current due to secondary lightning strikes. The Graphite has good tensile and compressive strength to weight ratios which reduces the number of plies. The Graphite alone has poor impact characteristics. This leads to the use of a second material, Kevlar, which is chosen for its impact characteristics. The Kevlar also has good tensile strength to weight ratio but has a poor compressive strength to weight ratio. This weakness is compensated by the characteristics of Graphite. Combining the Kevlar and Graphite in a bi-woven hybrid the weak characteristics of one material is compensated for by the strength of the other material.

The material is chosen in a fabric form over the conventional tape form due to the dimensions of the nacelle. With the large shapes of the nacelle components, the use of fabrics reduces lay-up time and labor costs. This cost savings outweights the weight increase caused by using the heavier fabric.

A polyimide resin (matrix) system is used to fabricate the composite face skins. The polyimide resin has not had as an extensive testing program in industry as epoxy resins, but shows several advantages which make it worth developing. An increase in impact resistance is accomplished when a polyimide resin is substituted for an epoxy resin in the use of composite panels. A polyimide resin has higher service temperature (232°C) than that of an epoxy (177°C). The polyimide resin also has more resistance to fire than an epoxy resin.

The core material chosen is a nylon phenolic or Nomex* honeycomb. The cell size and core thickness varies in different areas of the nacelle. In areas where acoustic treatment is needed the cell size is 9 mm and is between 19 mm to 25 mm deep. A similar aluminum core was considered but rejected because of the possibility of Galvanic corrosion with Graphite fibers and the vulnerability to secondary lightning strikes.

A proprietary approach was used in the protection of composite panels located in fire zones. The fire zones of the nacelle are shown in Figure 1A. The Federal Aviation Administration (FAA) requires that any material in a fire zone be able to withstand 1094°C for fifteen minutes. To meet this requirement, tests conducted by Douglas show proper selection of materials and construction will provide the necessary fire resistance.

2.4.2 CONSTRUCTION

The basic construction for the long duct mixed flow nacelle is shown below. The wing and tail designs have similar construction.

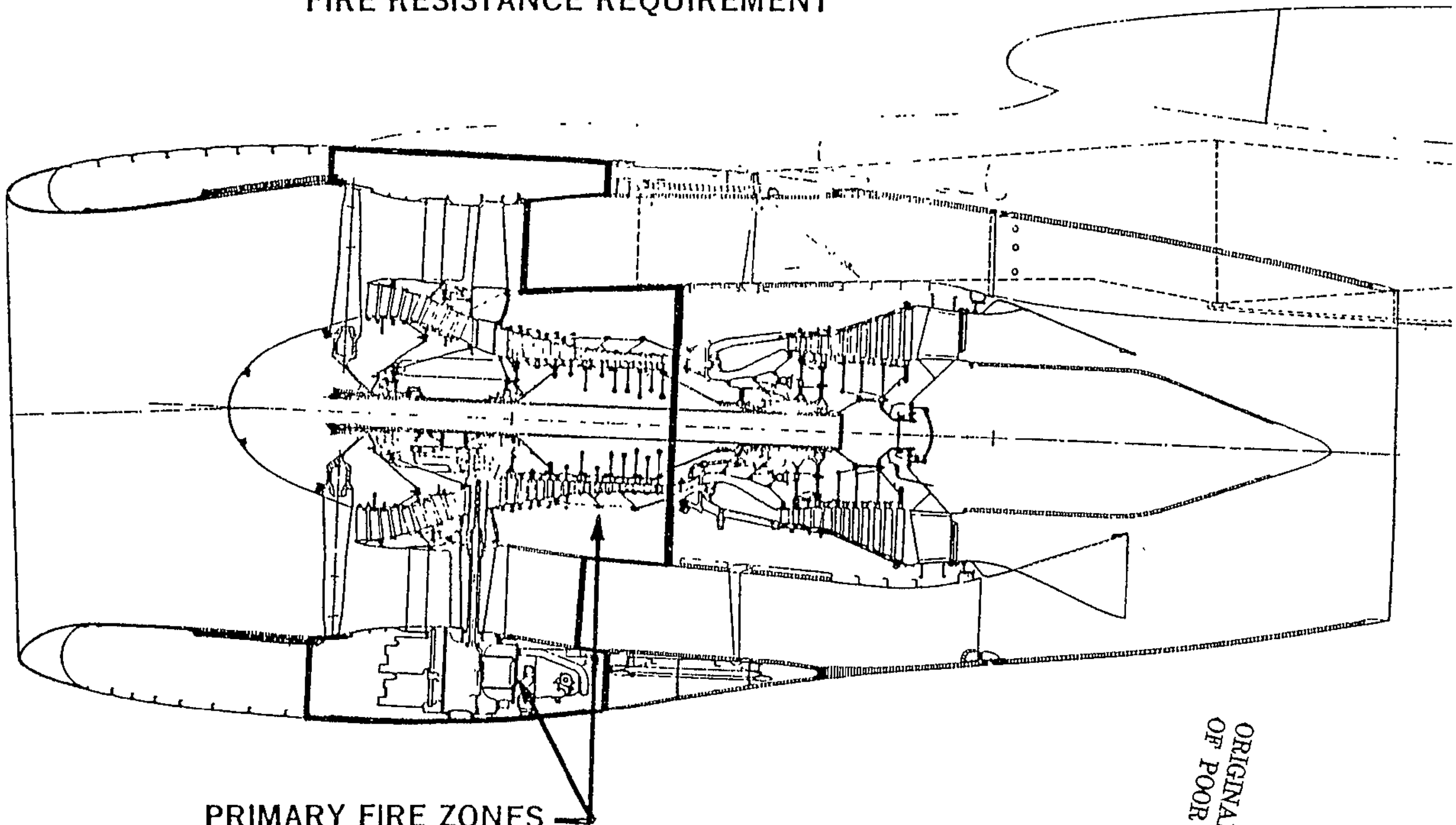
2.4.2.1 Nose Cowl - The nose cowl is designed to provide smooth airflow into the engine as shown in Figure 2. The current baseline design has three inlet panels which are acoustically treated aluminum honeycomb. The exterior skin is comprised of aluminum skin and stringer. There are two titanium bulkheads stationed forward and aft in the nose cowl assembly.

In an effort to reduce weight several sections of the nose cowl were changed to composites. The anti-icing lip assembly and the titanium bulkheads were not changed due to the high temperature environment in this area. The inlet

*Nomex is Du Pont's trademark for nylon phenolic honeycomb.

NACELLE ADVANCED COMPOSITES

FIRE RESISTANCE REQUIREMENT



- FIRE ZONES REQUIRE 194°C, 15-MINUTE FIRE CONTAINMENT CAPABILITY

FIGURE 1-A

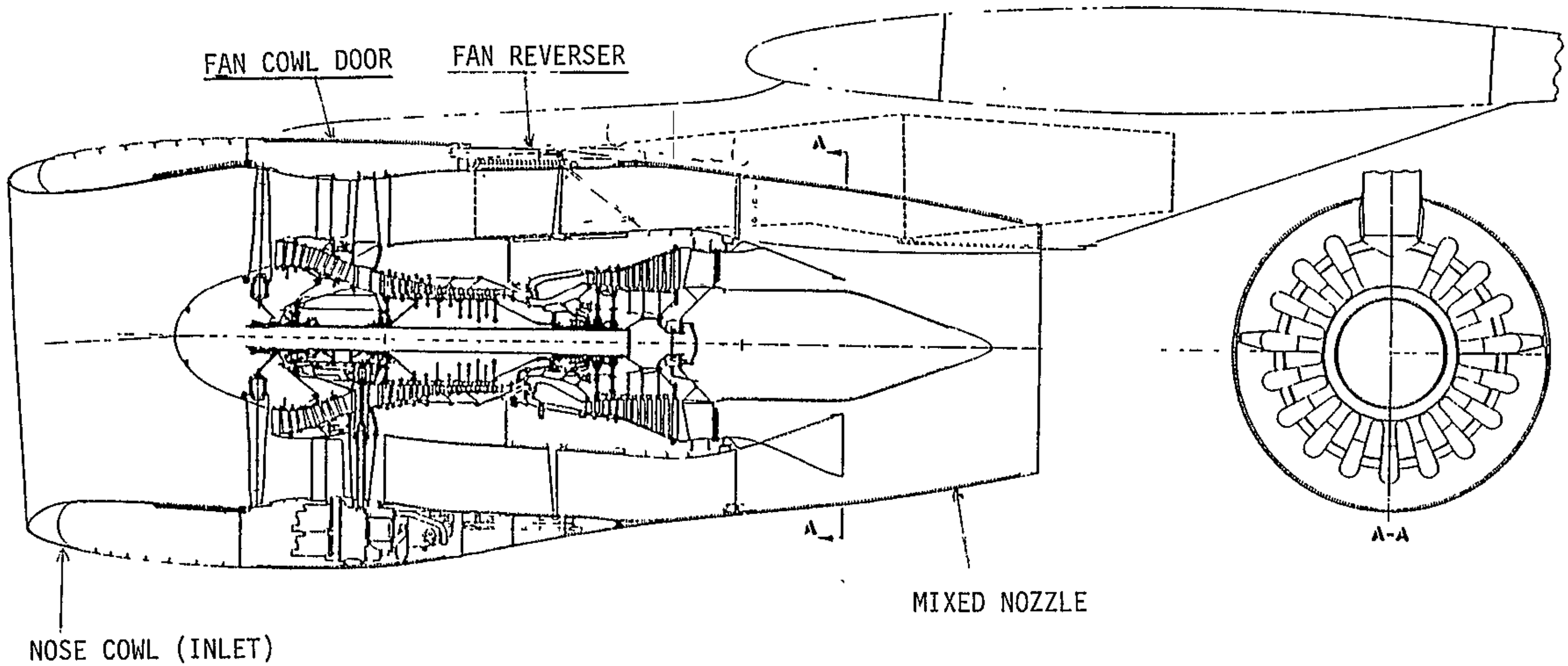

FAN COWL DOOR
FAN REVERSER
A
A
A-A
MIXED NOZZLE
NOSE COWL (INLET)

FIGURE 2

barrel was changed to a composite design. The outer skin was changed from aluminum skin and stringer design to a similar composite design.

The construction of the inner barrel is shown in Figure 3. The inlet barrel is divided into three panels. Each panel is similar in design but not identical. The panels are designed in two parts. The aft end of the inner barrel is a double honeycomb design. This is designed to absorb the buzz saw noise emitted by the engine. The inner face skin is four plies of porous Kevlar fabric. The high impact resistance of Kevlar meets the requirement that maintenance personnel be able to walk in the inlet. The inner and outer core is a Nomex honeycomb with 9 mm cells. The septum skin is five plies of porous Graphite fabric. This intermediate face skin is designed to carry a majority of the nose cowl loads. The outer face skin is two plies of Graphite fabric.

The outer aerodynamic surface or outer barrel of the nose cowl is made of seven plies of Graphite-Kevlar hybrid fabric strengthed by graphite stringers. The structure is broken down into three similar but not identical panels. This construction can be seen in Figure 4. The fabrication process takes the outer face skin fabric and lays it up against a mold to create a smooth aerodynamic surface. The stringers are fit to this double contour panel by using B-staged unidirectional Graphite and rubber mandrels. The face skins and stringers are then cocured together.

An alternative design is Graphite/Kevlar outer face skins with stiffeners designed into hat sections. The hat sections are composed of a honeycomb core with unidirectional Graphite fabric on three sides. The fourth side is cocured to the face skins. This concept adds to the cost of the manufacturing process by requiring the honeycomb to be machined to the double contour of the panel.

2.4.2.2 Fan Cowl Door - The fan cowl door, shown in Figure 2, is designed to provide access to the engine accessories. There are two doors per nacelle. The doors are similar but not identical. The door's current design is made

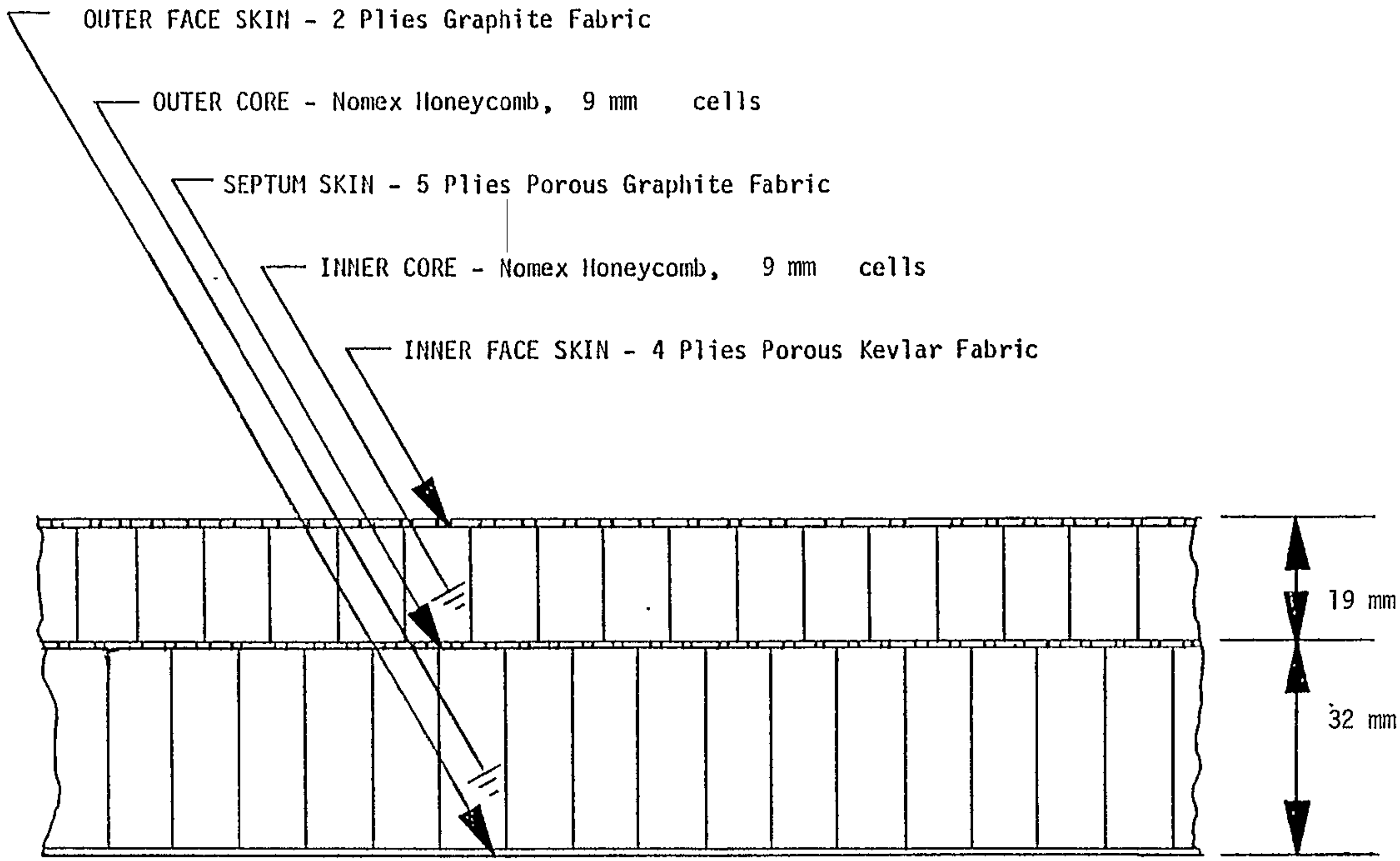


FIGURE 3. NOSE COWL, INNER BARREL CONSTRUCTION

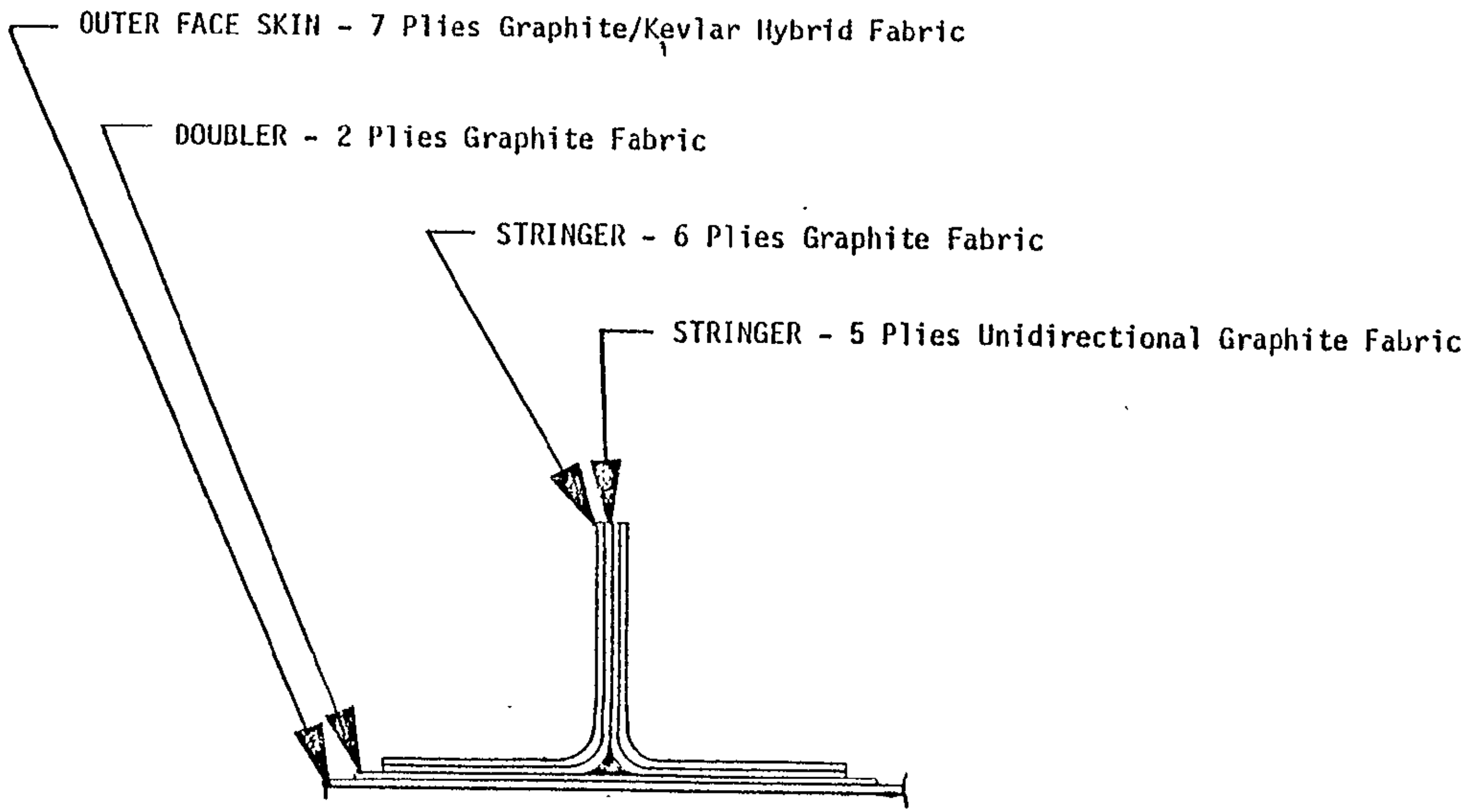


FIGURE 4. NOSE COWL, OUTER BARREL CONSTRUCTION

of aluminum honeycomb. Three hinges attach each fan cowl door to the side of the pylon. The doors are connected by a series of three latches along the bottom centerline of the engine. The right hand door has two small access doors, a pressure relief door, and two duct installations. The left hand door has three duct installations and an access door. Each door has incorporated two hold open rods to support the door during maintenance opertions.

In order to reduce the weight of the fan cowl door, composite materials were chosen to replace the aluminum honeycomb panel in the baseline design. To help keep the cost of the composite door down, existing latches, hinges, rubstrips and hold open rods were retained in the new design. By converting to the composite honeycomb design, a weight savings was accomplished of approximately fifteen percent. The outer face skin, made of Kevlar/Graphite hybrid was chosen because of its ability to improve impact resistance. The core was changed from an aluminum honeycomb to a Nomex honeycomb to eliminate corrosion and the possibility of an explosive reaction due to a secondary lightning strike. A special thermal barrier was added to the inner skin enabling the door to resist fire penetration. The basic construction of the composite fan cowl door is shown in Figure 5. This construction is similar for both right and left handed doors. The outer face skin of the door is composed of two plies of Kevlar/Graphite hybrid fabric. The core consists of a Nomex honeycomb material. The core is approximately 25.4 mm thick and has a cell size of 4.8 mm. The core was made this thick in order to provide sufficient rigidity to handle torsional loads. The inner face skin is two plies of unidirectional Graphite fabric. An additional ply of unidirectional Graphite fabric was added in 15 cm strips from the hinges at the top of the door to the latches at the bottom.

A titanium edge frame was incorporated in the perimeter of the fan cowl door. Its purpose was to help reduce maintenance cost, increase rigidity and conduct currents from secondary lightning strikes. The material selection eliminated those materials which were lighter than titanium because of their incompatibility with composites so far as thermal expansion in a cocured process.

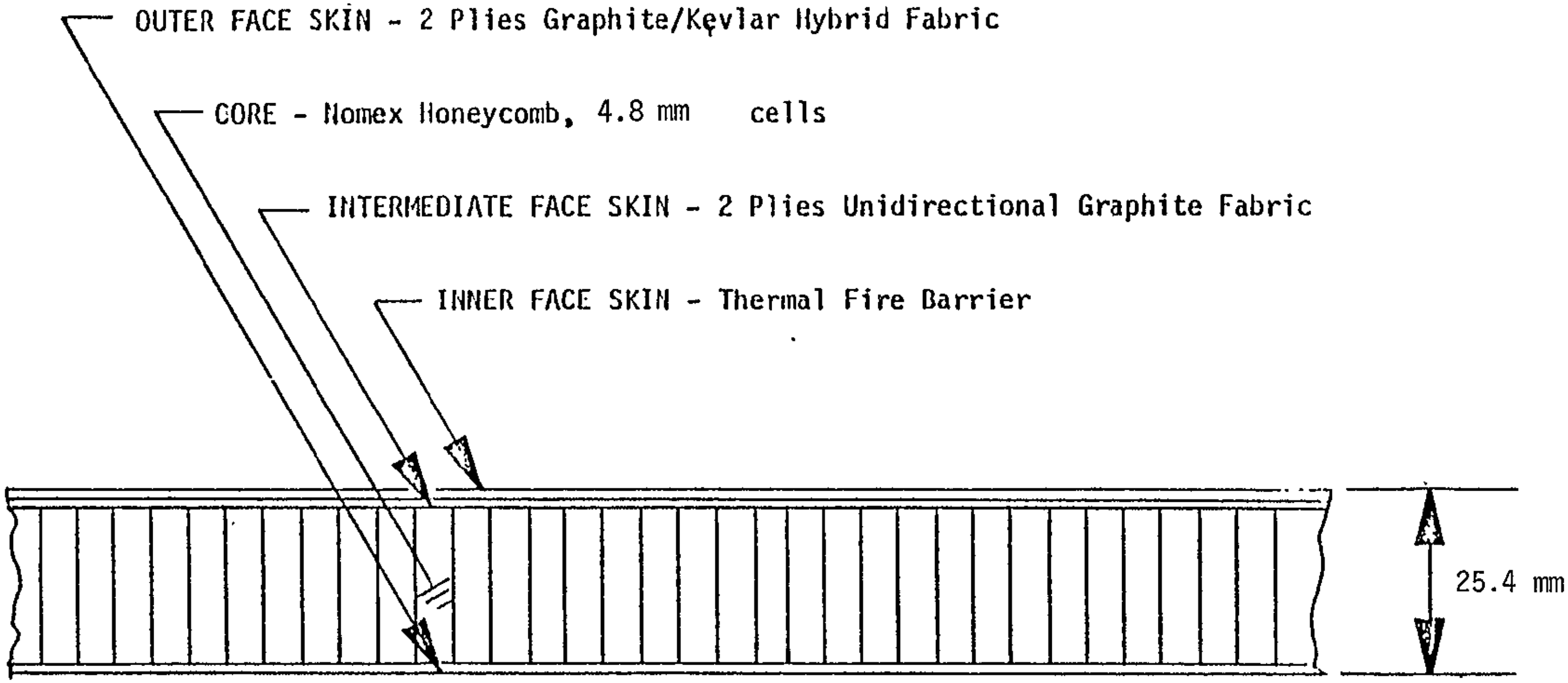


Figure 5. Fan Cowl Door Construction

2.4.2.3 Fan Reverser - The reverser, shown in Figure 2, is designed to provide reverse thrust during the landing roll. The cascades and blocker doors are designed to direct the reverse flow primarily forward and upward. The use of composite materials is to minimize the weight of the fan reverser.

The basic construction of the reverser inner barrel wall is shown in Figure 6. The outer face skin is a Graphite/Kevlar hybrid fabric. The outer core is composed of a Nomex honeycomb. The intermediate impervious face sheet is Graphite fabric. The inner core is comprised of high temperature phenolic honeycomb. The inner face sheet is made of a special thermal barrier. The inner barrel of the fan reverser is in a fire zone (Figure 1A). The inner core provides some spacing between the fire and the pressurized acoustic panel.

The construction of the outer barrel and blocker doors in the fan reverser is shown in Figure 7. The outer and inner face skins are of a Graphite/Kevlar hybrid fabric. The core is Nomex honeycomb. Since this is not a fire zone there is no need for additional protection as in the inner barrel. The frames between outer barrel panels are made of unidirectional Graphite fabric.

2.4.2.4 Mixed Nozzle - The mixed nozzle contains the flow from the mixing of fan and turbine gases as shown in Figure 2. The nozzle is manufactured into two half panels which are bolted to the pylon. The panel has a perforated inner face skin to provide for acoustic treatment. The trailing edge is a formed converging diverging nozzle.

A high temperature titanium is required in this area because of the existence of adverse environmental conditions. In mixing fan and turbine air, hot streaks appear on the face skins. Hot streaks occur when turbine air (538°C) is not thoroughly mixed with fan air. The titanium used to withstand this type of condition is Ti-6AL-2sn-4zr-2mo. This material is a near alpha and

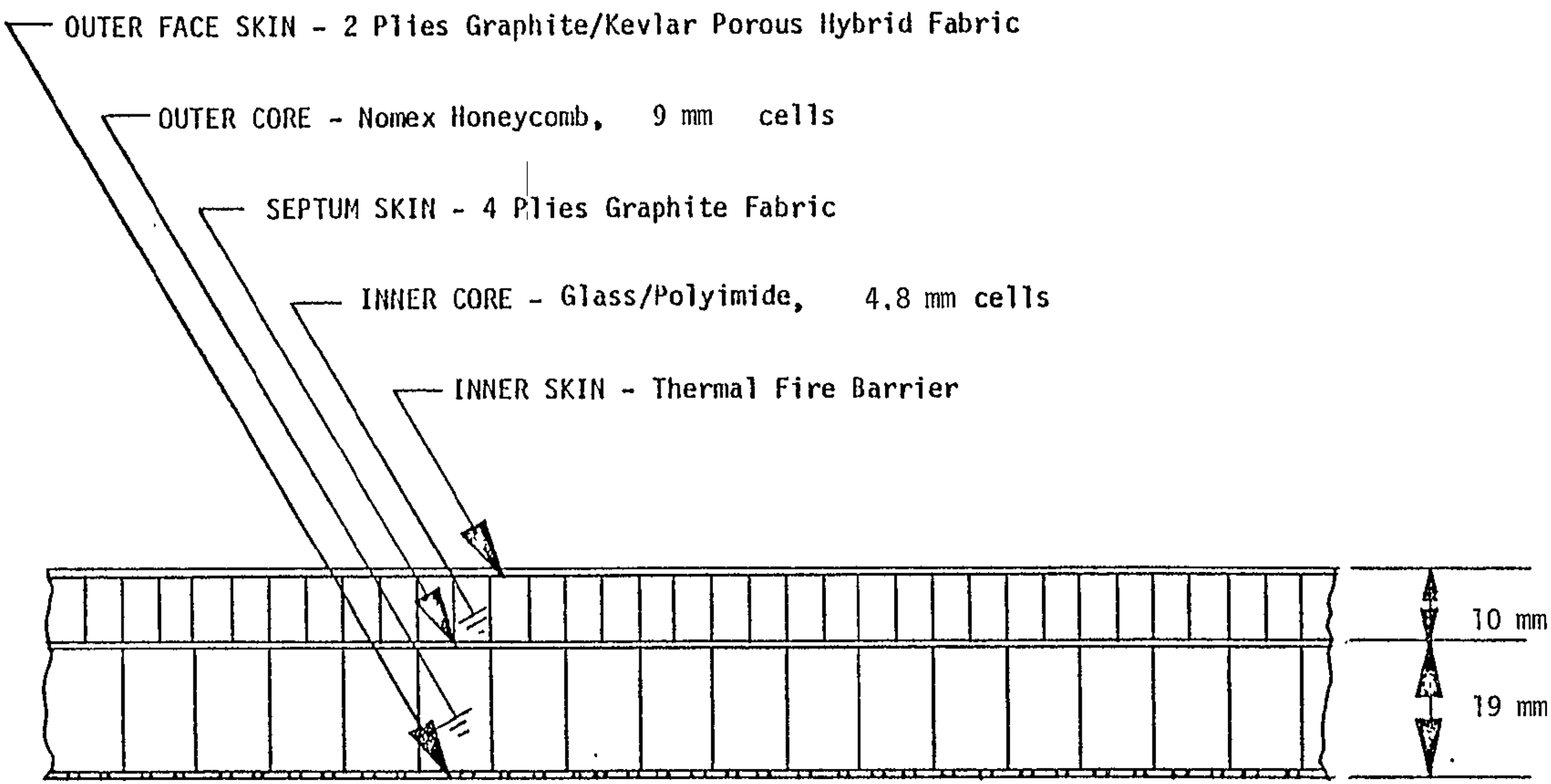


Figure 6. Fan Reverser, Inner Barrel Construction

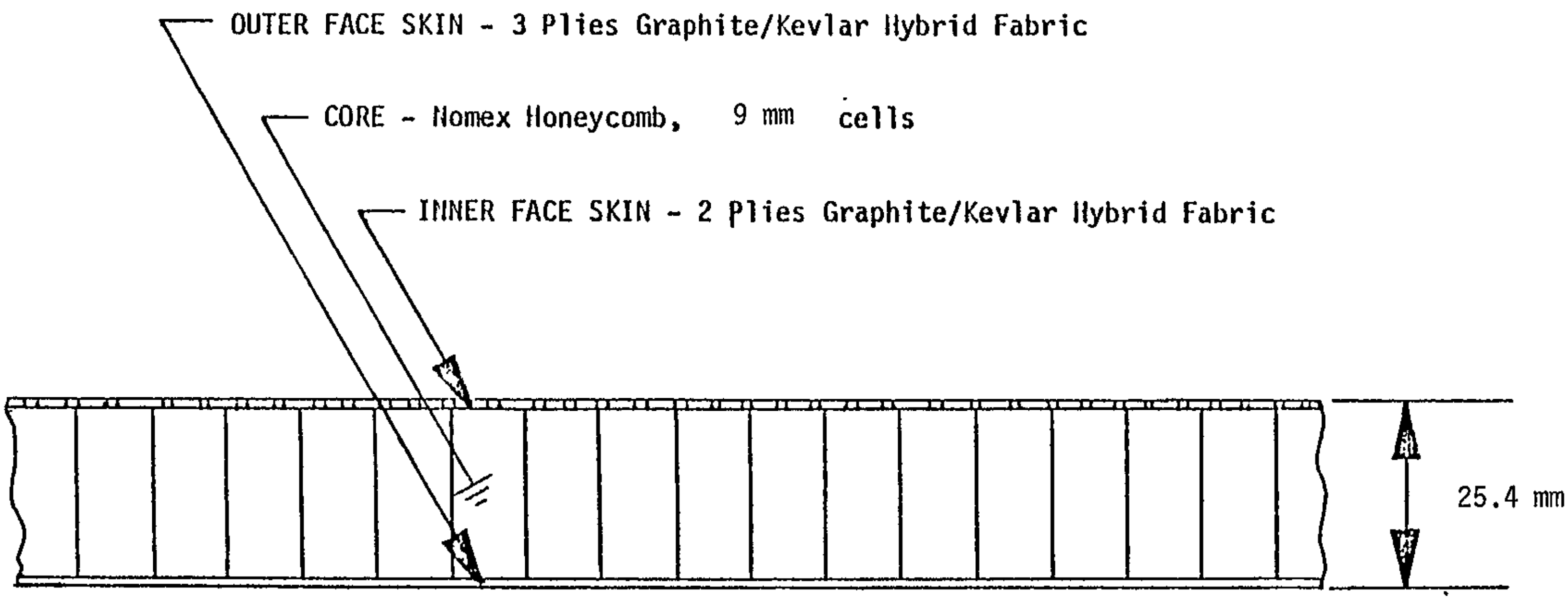


Figure 7. Fan Reverser, Outer Barrel and Blocker Door Construction

has a maximum service temperature of 583°C.

Several alternative constructions were considered. Plastic forming was considered for its ability to provide a uniform structure. Plastic forming is in the experimental stages and would require further development. If the high temperature titanium is unable to withstand the environment, a stainless steel material will be used in the panel. Actual environmental conditions will not be known until full scale tests are conducted.

The basic construction of the mixed nozzle is shown in Figure 8. The inner perforated titanium face skin has a thickness of .4 mm. The outer impervious titanium face skin has a thickness of .3 mm. The core was developed to provide maximum acoustic treatment within the constraints of the high temperature titanium. Titanium 6-2-4-2 can be rolled into sheet form of a minimum thickness of .3 mm. This eliminates the possibility of using a honeycomb design because of its nominal gauge thickness of .08 mm. The design developed was a continuous trapezoidal hat section. The wall thickness is .3 mm. The skins and the core will be brazed together in the sandwich construction.

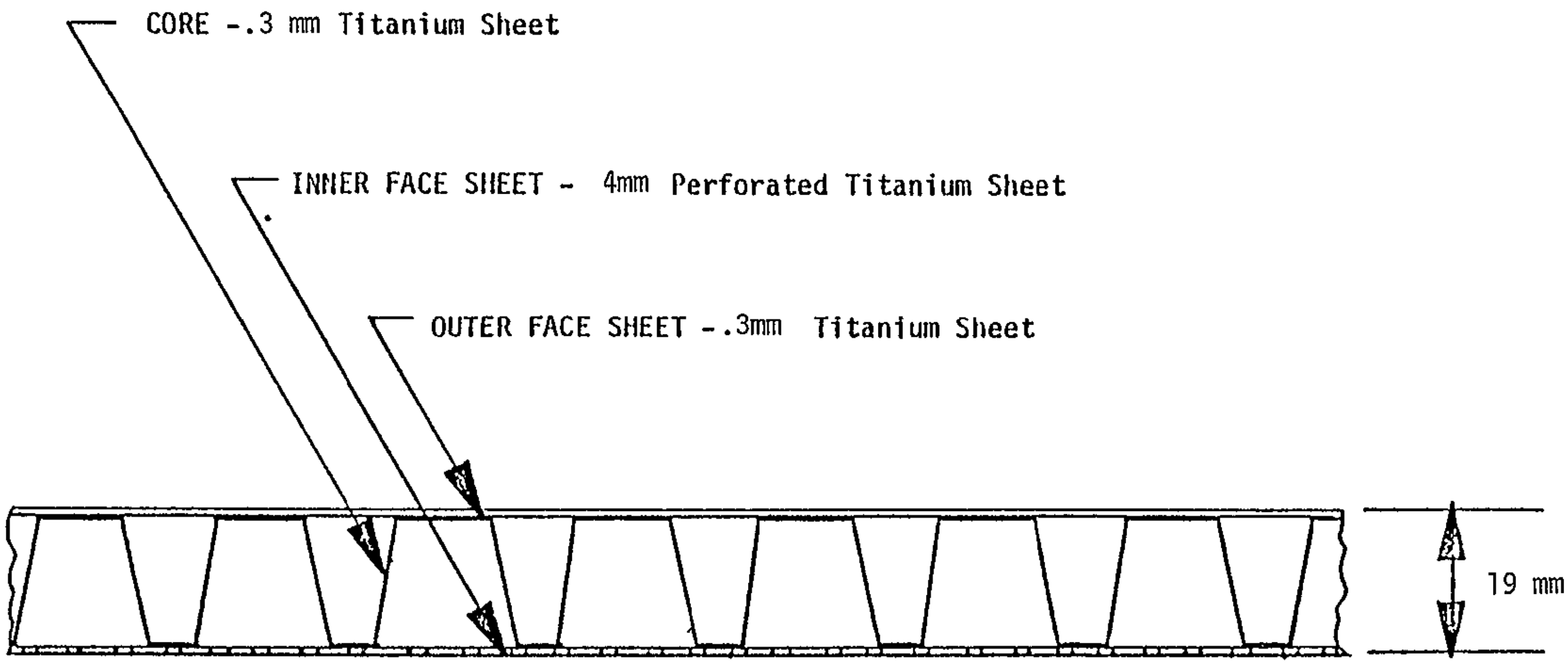


Figure 8. Mixed Nozzle Construction

LIST OF SYMBOLS

AA	American Airlines
A/B	Aftbody
APES	Aircraft Performance and Economic Simulation
AR	Aspect Ratio
ATA	Air Transport Association
BCAC	Boeing Commercial Aircraft Company
B/M	Bill of Material
CAB	Civil Aeronautics Board
CNS	Common Nacelle System
CRF	Capital Recovery Factor
DAC	Douglas Aircraft Company
DOC	Direct Operating Cost
ECI	Engine Component Improvement
EGT	Exhaust Gas Temperature
EOH	Engine Operating Hour
EPCS	Electronic Propulsion Control System
EPRL	Engine Pressure Ratio Limiter
FAA	Federal Aviation Administration
FEGV	Fan Exit Guide Vane
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IFSD	In-Flight Shutdown
IGV	Inlet Guide Vane
ITC	Investment Tax Credit
LE	Leading Edge (of Airfoil)
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
M	Mach
M_N	Mach Number
MCA	Multiple Circular Arc
MTBSV	Mean Time Between Shop Visits
NASA	National Aeronautics and Space Administration
OAS	Outer Air Seal
OEW	Operating Empty Weight
OWE	Operating Weight Empty
PBP	Payback Period
PI	Performance Improvement
PLA	Power Lever Angle
P&WA	Pratt & Whitney Aircraft
ROI	Return on Investment
TE	Trailing Edge (of Airfoil)
T/O	Takeoff
TRC	Thrust Rating Computer
TSFC	Thrust Specific Fuel Consumption
TWA	Trans World Airlines
UA	United Airlines
W_{AE}	Gas Generator Airflow
W_{AT}	Total Engine Airflow

REFERENCES

1. Contract NAS3-19132, "Study of Turbofan Engines Designed for Low Energy Consumption", NASA CR-135002, April 1976.

2. "Study of Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System," (United Airlines), NASA CR-137891, June 1977.

3. Contract NAS3-18565, "Continued Development of Abradable Gas Path Seals," NASA CR-134879, November 1975.

4. Contract NAS3-19759, "Development of Plasma Sprayed Ceramic Gas Path Seals for High Pressure Turbine Applications," NASA CR-135183, April 1977.

5. Contract NAS3-20590, "Development of Improved High Pressure Turbine Outer Gas Path Seal Component, " in progress.

DISTRIBUTION LIST

COMPANY/PERSONNEL

National Aeronautics & Space Adm.
Washington, DC 20546
Frederick Povinelli/RJP-9 (3)

Dr. James Kramer/R-1

Dr. John Klineberg/RJB-9

Harry Johnson/RL-5

George Deutsch/RW-3

G. G. Kayten/RX-4

F. E. Penaranda/RM-2

L. P. Shomo/RMP-2

E. L. Sanchez/RMR-2

NASA Scientific and Technical
Information Facility
Attn: Accessioning Department
P. O. Box 8757
Balt/Wash. International Airport
MD 21240 (30 copies)

National Aeronautics & Space Adm.
Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135
Warner L. Stewart/MS 3-5
Director of Aeronautics

Richard A. Rudey/MS 60-4
Chief, Airbreathing Engines Div.

Milton A. Beheim/MS 86-1
Chief, Wind Tunnel & Flight Div.

Donald L. Nored/MS 301-2
Chief, Energy Conserv. Engines Office

Joseph A. Ziemianski/MS 301-4
Manager, Engine Component Improvement
(3 copies)

COMPANY/PERSONNEL

John E. McAulay/MS 301-4
(13 copies)

Robert W. Schroeder/MS 500-207
Chief, V/STOL & Noise Div.

Ambrose Ginsburg/MS 5-3
Chief, Fluid Systems Div.

William J. Anderson/MS 23-2
Chief, Mechanical Components Branch

Lawrence Ludwig/MS 23-2

Melvin J. Hartmann/MS 5-9
Chief, Fan & Compressor Branch

Harold E. Rohlik/MS 77-2
Chief, Turbine Branch

Robert W. Hall/MS 49-1
Chief, Materials & Structures Div.

Tito T. Serafini/MS 49-1

Salvatore J. Grisaffe/MS 49-3
Chief, Surface Protection

Kenneth E. Skeels/MS 500-313
Contracting Officer

Lewis Library/MS 60-3 (2 copies)

Report Control Office/MS 5-5

Naval Air Propuslion Center
1440 Parkway Avenue
Trenton, NJ 08628
W. L. Pasela (PE 63)
Project Engineer-Test & Evaluation

National Aeronautics & Space Adm.
Langley Research Center
Hampton, VA 23665
Dr. Robert Leonard

W. J. Alford

COMPANY/PERSONNEL

National Aeronautics & Space Adm.
Hugh L. Dryden Flight Research Center
PO Box 273
Edwards, CA 93523
Dr. James Albers

National Aeronautics & Space Adm.
Ames Research Center
Moffett Field, CA 94035
L. J. Williams

Arnold Engineering & Development Center
AEDC/XRFX
Arnold AFS, TN 39389
R. Roepke

Dr. James G. Mitchell
Director of Facility Plans & Programs

Wright-Patterson Air Force Base
Dayton, OH 45433
E. Bailey, AFAPL/TBD

Major C. L. Klinger, ASD/YZET

E. C. Simpson, AFAPL/TB

Lt. Col. D. S. Dickson, ASD/YZI

C. M. High, ASD/YZE

Department of Transportation
21000 Second St., SW
Washington, DC 20591
Harold Ture

R. S. Zuckerman ARD 550
Aircraft Noise Project Manager

Federal Aviation Administration
DOT/FAA/NAFEC
ANA-410, Bldg. 211
Atlantic City, NJ 08405
Gary Frings
Project Engineer

COMPANY/PERSONNEL

Civil Aeronautics Board
Washington, DC 20428
J. E. Constantz
Chief, Economic Analysis
Division, B-68

Air Transport Association
1709 New York Avenue, NW
Washington, DC 20056
E. L. Thomas, Asst. V. P. Engineering

Pan American World Airways, Inc.
John F. Kennedy International Airport
Jamaica, NY 10430
John G. Borger
Vice-President & Chief Engineer

Niels Andersen
Project Engineer

Angus MacLarty
Director Powerplant Engineering

Robert E. Clinton, Jr.

Piedmont Airlines
Smith Reynolds Airport
Winston-Salem, NC 27102
H. M. Cartwright, Vice-President
Maintenance & Engineering

Paul M. Rehder, Supervisor
Power Plant Engineering

Allegheny Airlines, Inc.
Greater Pittsburgh International
Pittsburgh, PA 15231
William G. Peppler
Director of Engineering

Braniff International
Braniff Tower
P O Box 35001
Exchange Park
Dallas, TX 75235
Hank Nelson
Director, Powerplant Engineering

COMPANY/PERSONNEL

Continental Airlines, Inc.
Los Angeles International Airport
Los Angeles, CA 90009
Frank Forster
Director, Powerplant Engineering

Eastern Air Lines, Inc.
Miami International Airport
Miami, FL 33148
Arthur Fishbein, Sr. Engineer
Power Plant Engineering-MIAEW
Bldg. 21

Max Dow, Director, Powerplant
Engineering-MIAEW, Bldg. 21

P. M. Johnstone
Vice-President, Engineering

The Flying Tiger Line, Inc.
7401 World Way West
Los Angles International Airport
Los Angeles, CA 90009
J. M. Dimin
Manager, Powerplant Engineering

B. Lewandowski

National Airlines, Inc.
PO Box 592055
Airport Mail Facility
Miami, FL 33159
R. A. Starner, Director-Engineering

Northwest Airlines, Inc.
Minneapolis-St. Paul Int'l. Airport
St. Paul, MN 55111
A. Radosta - MS 838, Ass't Director,
Powerplant Maintenance

United Airlines, Inc.
San Francisco International Airport
San Francisco, CA 94128
John Curry

James Uhl

COMPANY/PERSONNEL

Trans World Airlines
Kansas City International Airport
PO Box 20126
Kansas City, MO 64195
W. D. Sherwood

Ken Izumikawa
2-280 MCI

Delta Air Lines, Inc.
Hartsfield-Atlanta Int'l Airport
Altanta, GA 30320
Jim Goodrum

Seaboard World Airlines, Inc.
Seaboard World Bldg.
John F. Kennedy Int'l Airport
Jamaica, NY 11430
Jere T. Farrah
VP Maintenance and Engineering

Ralph J. Barba
MGR, Powerplant Engineering

Western Air Lines, Inc.
6060 Avion Dr. Box 92,005
World Way Postal Center
Los Angeles, CA 90009
Walter Holtz

American Airlines, Inc.
Tulsa Maintenance & Engineering Center
N. Mingo Road
Keith Grayson

AVCO Lycoming Division
550 South Main Street
Stratford, CN 06497
A. Bright
Engine Performance

Air Research Manufacturing
Company of Arizona
Department 93-010/503-4B
PO Box 5217
Phoenix, AZ 85010
Dr. M. C. Steele

COMPANY/PERSONNEL

Air Research Manufacturing
Company of Arizona
Department 93-200/503-3S
402 South 36th Street
Phoenix, AZ 85010
Karl R. Fledderjohn
Chief of Fan and Jet Engines

Detroit Diesel Allison Div.
General Motors Corp.
PO Box 894
Indianapolis, IN 46206
R. A. Sulkoske
Dept. 8896 MS: V19

McDonnell Douglas
3855 Lakewood Blvd.
Long Beach, CA 90846
Ronald Kawai MC 36-41
Powerplant Engineering
(213) 593-1998

Frank L. Junkermann MC 36-41

Technical Library ADTL 246-75

The Boeing Company
PO Box 3707
Seattle, WA 98124
Richard Martin MS: 73-07 (2 copies)

Lockheed-California Co.
PO Box 551
Burbank, CA 91520
T. F. Laughlin, Jr.
Director, Aircraft Operations-Technology

Pacific Airmotive Corporation
2940 N. Hollywood Way
Burbank, CA 91503
Oddvar Bendikson
Director, Project Engineering

J. R. Gast
Sr. Director Engineering

COMPANY/PERSONNEL

Cooper Airmotive, Inc.
4312 Putman Street
Dallas, TX 75235
Terry Harrison

Hamilton Standard Div., UTC
Windsor Locks, CN 06096
Louis A. Urban
Sr. Design Project Engineer
MS: 3-2-36

United Technologies Corp.
Pratt and Whitney Aircraft Group
Commercial Products Division
400 Main Street
East Hartford, CT 05108
Mr. W. O. Gaffin (10 copies)

General Electric Company
Aircraft Engine Group
One Neumann Way
Evendale, OH 45215
Mr. A. J. Albright (10 copies)