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CF6 JET ENGINE PERFORMANCE IMPROVEMENT PROGRAM

TASK 1

FEASIBILITY ANALYSIS

FINAL REPORT

MARCH 1979

W.A. Fasching

General Electric Company
Aircraft Engine Group
Cincinnati, Ohio 45215

For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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16. Abstract

A Feasibility Analysis of performance improvement and retention concepts for the CF6-6 and CF6-50 engines, consisting of technical and economic studies, has been conducted and the most viable concepts have been identified.

Seven engine improvement concepts were selected for subsequent development.

- Fan Improvement
- Short Core Exhaust
- HP Turbine Aerodynamic Improvement
- HP Turbine Roundness Control
- HP Turbine Active Clearance Control
- HP Turbine Active Clearance Control

The only engine related aircraft performance improvement concept selected for development:

- Cabin Air Recirculation

The estimated fuel savings from the selected engine modification concepts for the CF6 fleet for an assumed production through 1990 amounts to 7-1/2 to 10-1/2 billion liters (2 to 2 3/4 billion gallons).

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FOREWORD

The study was conducted by the CF6 Engineering Department of General Electric's Aircraft Engine Group, Aircraft Engine Engineering Division, Cincinnati, Ohio, in cooperation with the Boeing Commercial Airplane Company, Seattle, Washington and the Douglas Aircraft Company, Long Beach, California. The program was conducted for the National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, as Task I of the CF6 Jet Engine Performance Improvement Program, Contract Number NAS3-20629. The NASA Project Engineer for this program was R.J. Antl. The Boeing subcontract was directed by R.L. Martin and the Douglas subcontract was managed by R.T. Kawai. The program was initiated on February 10, 1977 and was completed on April 21, 1978.

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

1.0 SUMMARY

A feasibility analysis of performance improvement and retention concepts for the CF6-6 and CF6-50 engines consisting of technical and economic studies has been conducted, and the most viable concepts have been identified. This task was part of an overall program to reduce the fuel consumption in these engines during the 1980 time period. The study was carried out in cooperation with the Boeing and Douglas aircraft companies and American and United airlines.

Included in the feasibility analysis was the identification of concepts, technical and economic assessment of the viable concepts, the selection of the most promising concepts, and the preparation of Technology Development Plans for development of these concepts.

A total of 62 component improvements was identified. An initial review was conducted with some concepts being eliminated and others grouped together. Reasons for eliminating concepts included low payoff (high cost for low performance gain), development time exceeding 1980 to 1982 time period, and high development risk. This initial screening resulted in 24 concepts remaining for further detailed technical and economic assessment.

Based on the results of this assessment, which included specific fuel consumption reduction (sfc), projected fuel savings, payback period, airline acceptability, and probability of introduction on new engines as well as retrofit, the following engine modifications were selected for development consideration:

Fan Improvement - Improved aerodynamic performance, lower operating line, and reduced clearances with sfc reductions of 1.6 to 1.8 percent.

Short Core Exhaust - Reduced weight and nozzle scrubbing drag yielding 1 percent sfc reduction; potential for 1 to 2 percent additional sfc reduction from reduced interference drag.

High Pressure Turbine (HPT) Aerodynamics - New blade design with optimized cooling and improved clearance and swirl matching; sfc reductions of 1.3 percent for new engines and 1.6 percent at 3000 hours.

Front Mount - Improved load distribution providing for compressor case roundness and reduced clearances; sfc reduction of 0.3 percent.

High Pressure Turbine (HPT) Roundness Control - Passive rotor/stator thermal matching with improved materials, design, and cooling techniques, and reduced clearances; sfc reductions of 0.4% for new engines and 0.8 percent at 3000 hours.

High Pressure Turbine (HPT) Active Clearance Control - Active rotor/stator thermal matching with a variable cooling air source to yield reduced cruise clearances and a 0.6 percent sfc reduction.

Low Pressure Turbine (LPT) Active Clearance Control - Active rotor/stator thermal matching with variance cooling air to provide reduced cruise clearances and sfc reductions from 0.1 to 0.3 percent.

The only airplane modification studied was also judged attractive for development, namely:

Cabin Air Recirculation - Recirculation of cabin air-conditioning air yielding reduced compressor bleed and a 0.7 percent sfc reduction.

The total estimated fuel savings to be realized with implementation of the selected engine modifications was determined for the CF6 fleet (CF6-6 and CF6-50 engines). This estimate was based on an assumed new engine production and attrition retrofit through 1990 and amounted to 7½ to 10½ billion liters (2 to 2-3/4 billion gallons).

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 to 1974. 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 other forms of transportation. As a result of these experiences, the Government, with the support of the aviation industry, has initiated programs aimed at both the supply and demand aspects of the problem. The supply problem is being investigated by looking at increasing fuel availability from such sources as coal and oil shale. Efforts are currently underway to develop engine combustor and fuel systems that will accept fuels with broader specifications.

Reduced fuel consumption is the other approach to deal with the overall problem. A long-range effort to reduce consumption is to evolve new technology 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 impact of this approach in any significant way would be 15 or more years away. 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 5 percent fuel reduction goal starting in the 1980 to 1982 time period is feasible for the CF6 engine. This engine is, and will continue to be, a significant fuel user for the next 15 to 20 years.

Accordingly, NASA is sponsoring an overall program to reduce the CF6 fuel consumption. This program consists of two parts: engine diagnostics and performance improvement. The engine diagnostics effort (not reported herein) is to provide information to identify the sources and causes of engine deterioration. The performance improvement effort is directed at developing engine performance improvement and retention components for new production and retrofit engines. The initial effort consisted of a feasibility analysis which was conducted in cooperation with the Boeing and Douglas aircraft companies and American and United airlines. The study consisted of:

- The identification of engine and component modifications which exhibited a fuel savings potential over current practice in CF6 engines.
- The technical and economic assessment of the modifications, including the impact on airline acceptability and the probability of production introduction of the concepts by the 1980 to 1982 time period as well as their retrofit potential.

- The assessment of fuel savings for the DC-10-10, DC-10-30, and the B-747-200 aircraft.

- The selection of the most promising concepts and the preparation of Technology Development Plans for their development and evaluation in ground test facilities.

The analytical procedure used for the feasibility analysis is described and the results of the technical and economic evaluation is given for each of the concepts selected for detailed screening. These results are summarized in terms of specific fuel consumption (sfc), projected fuel savings, payback period, airline acceptability, and probability of introduction on new engines as well as retrofit. The concepts selected for development consideration are delineated herein.

3.0 ANALYTICAL PROCEDURE

3.1 OVERVIEW

The purpose of the feasibility analysis was to identify engine/aircraft modification concepts which provide reductions in fuel consumption commensurate with risk, customer acceptance and the airline economic guidelines.

The feasibility analysis was conducted in cooperation with the Boeing Commercial Airplane Company and the Douglas Aircraft Company as subcontractors. American Airlines and United Airlines reviewed the results of both airframe companies, while Eastern Air Lines and Pan American World Airways served as consultants to NASA to provide an overall assessment (Figure 1).

The flow of the improvement items through the various organizations and the key steps are presented in Figure 2. Concepts were initially identified by the contractors, and an initial review with a qualitative assessment was performed. On the basis of this assessment, an initial screening was performed by General Electric Engineering management; and a recommended disposition was submitted to NASA, the aircraft manufacturers, and the airlines for review. Following NASA approval, a more comprehensive screening process was initiated on a reduced number of performance improvement concepts.

Preliminary design studies were conducted as appropriate to define the desired evaluation parameters. Appropriate definition was provided to the General Electric Commercial Engine Programs Division to obtain pricing and maintenance data as well as production impact assessment. The required information was then submitted to the aircraft companies for economic analysis and an assessment of risk, aircraft impact and customer acceptance. The screening/ranking was then accomplished jointly and presented to NASA for review. Following NASA review and selection, technology development plans and proposals were then submitted for the selected improvement concepts.

3.2 TECHNICAL ASSESSMENT PROCEDURE

3.2.1 General Electric

The three key General Electric contributors to the NASA performance improvement program were the Aircraft Engine Engineering, Aircraft Engine Manufacturing and Commercial Engine Programs Divisions of the Aircraft Engine Group. Engineering had prime responsibility for implementation of the contract; however, inputs for the screening studies were provided by Commercial Engine which has program management responsibility for the CF6 engine family and Manufacturing which manufactures the engines.

The Aircraft Engine Engineering organizational structure has an inherent capability for providing most of the major inputs to the screening assessment. The Engine Systems Manager has complete engineering responsibility for the

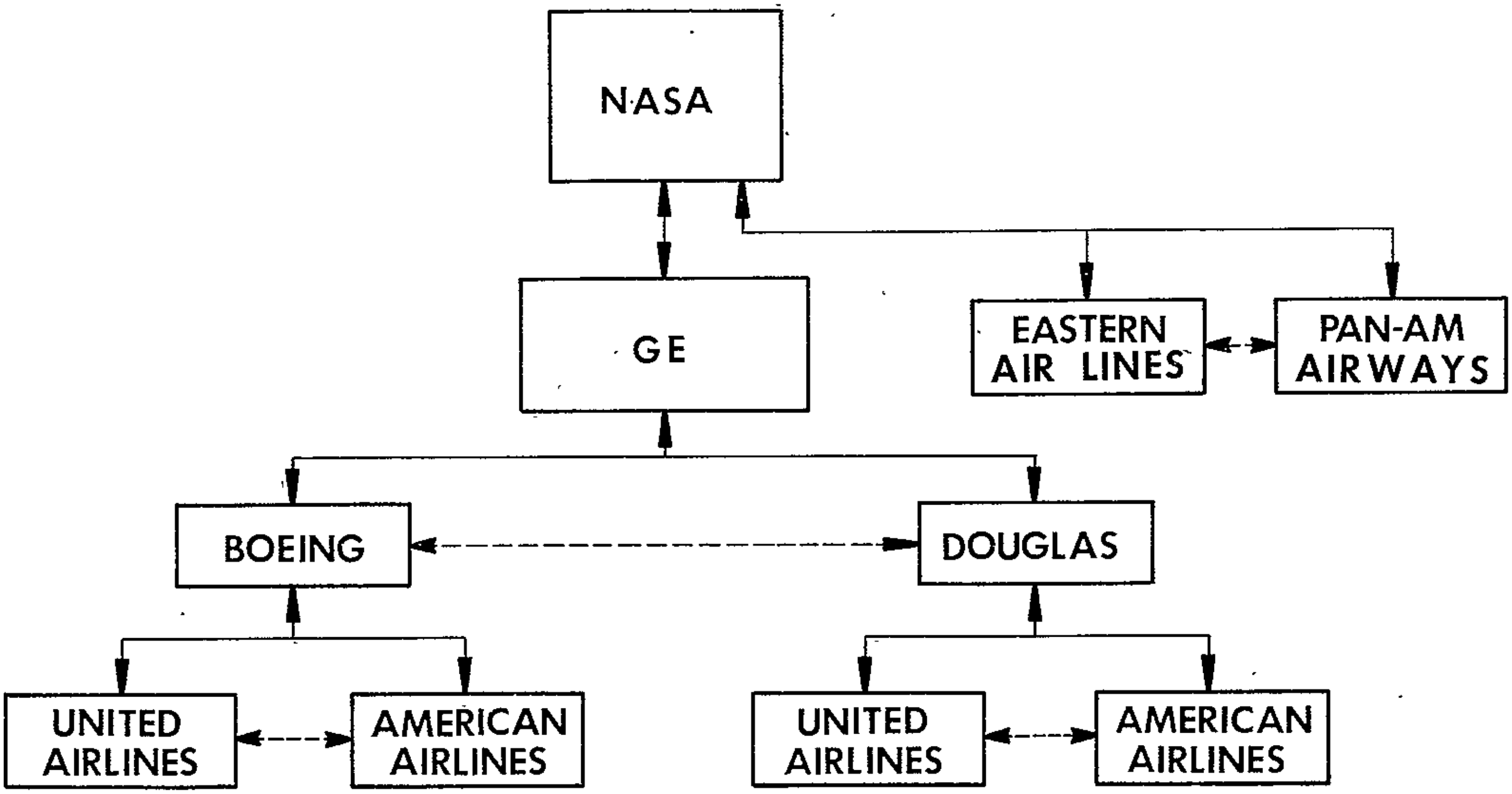

Figure 1. CF6 Jet Engine Performance Improvement Program Channels of Interface.

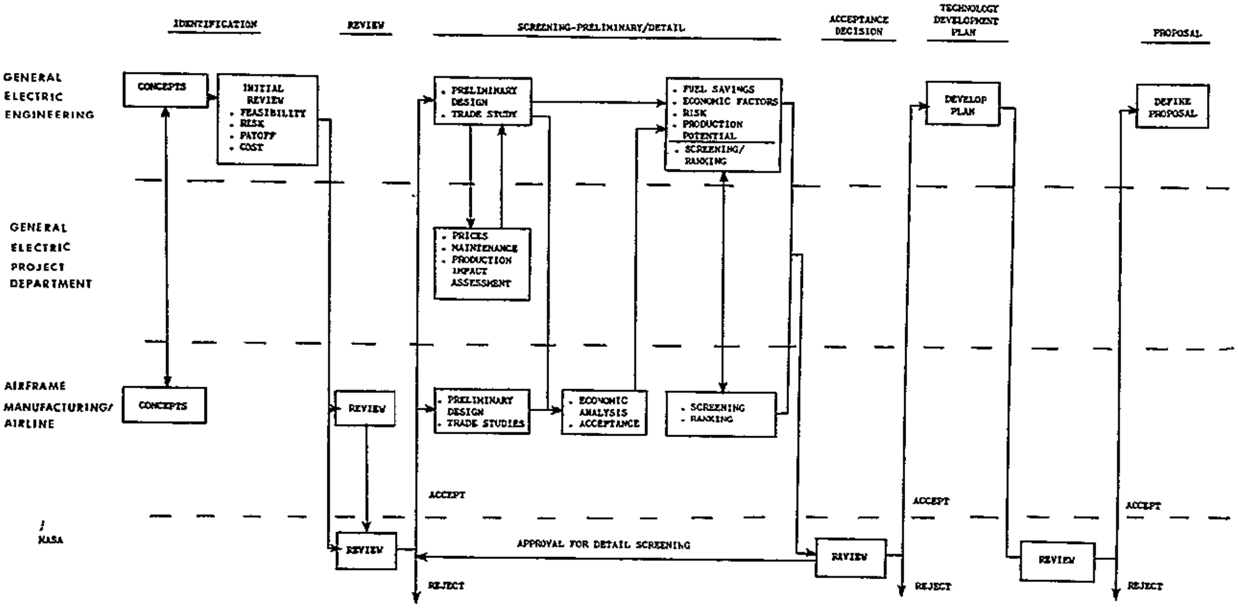

Figure 2. Improvement Item Flow Chart.

engine. He, in turn, directs design managers who have total "cradle-to-grave" responsibility for their respective components. They receive technical support in special areas, including aerodynamics, thermodynamics, materials and acoustics; but they have the final responsibility for the total design. Also contained within the organization are systems, performance, installation and configuration management functions. The Performance Improvement Program Manager also reports to the Engine Systems Manager, thus facilitating a highly responsive and thorough evaluation of improvement items.

Preliminary design trade studies were conducted by CF6 Engineering to define the design and to calculate the performance improvements and weight changes. Also studied were the impact of the improvement concept on the installation, changes in life and reliability, engine system impact, environmental impact, preliminary assessment of aircraft systems impact, risk and development requirements.

Commercial-type parts price and maintenance data were established by the Commercial Engine Programs Division following a program control board review. This board contains representatives of all key functions of the total commercial engine business. They reviewed the details of the concept as provided by Engineering and then defined all significant elements such as manufacturing cost, retrofit considerations, and other data needed for maintenance and price data.

Maintenance material costs were calculated by the General Electric method and compared to the results of a method developed by American Airlines. The American Airlines method utilizes a set of mathematical formulas containing geometric and cycle parameters. The General Electric method considers each performance improvement item as an effective derate in turbine inlet temperature and exhaust gas temperature and utilizes severity ratio curves versus derate and flight length derived from the Operational Severity Analysis Program. This program predicts the relative effect of various engine operating profiles on the failure rates of the major engine components. In addition, the General Electric method uses actual CF6 maintenance cost data plus combined Engineering and Airline Support Engineering predictions of the effect of specific design changes. Reductions in turbine inlet temperature were evaluated analogous to a derate thereby providing reductions in maintenance costs for hot parts due to increase in time between overhaul and increased parts life.

In general, the two methods provided similar results. In cases where agreement was lacking, the differences were analyzed and explained.

The General Electric inputs were summarized in Screening Assessment Sheets for each concept and forwarded to the airframe companies. The Screening Assessment Sheet contains performance data for the flight conditions of the various mission legs, weight and center of gravity data and, economic data as well as definitions of the retrofit capability and other impacts of the concept. A Fan Improvement Screening Assessment Sheet is shown in Figure 3 as an example.

TITLE Fan Improvement (Blades, Operating Line and Stiffener) CF6-50

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION	Δ% SFC
	ALT, m (ft)/M	
T/O	SLS	-2.4
T/O	0 (0)/0.25	-2.0
CLIMB	7620 (25000)/0.80	-0.5
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-1.8
MAX CRUISE	10668 (35000)/0.85/+10°C	-0.3
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-2.4
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-31 (-69) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +13 (+29 lb)

ΔCG, cm (in) - 0.8 cm (0.3 in) fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $19,000 Increase

RETROFIT - ATTRITION - $19,000 Increase

INSTALLATION COST - $12,000 - $20,000 Retrofit (Includes QEC Mods) Negligible cost for new engine installation.

MAINTENANCE

MATERIAL - $1.60/Engine Flight Hour (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - Fan Blades - 6% spares

RETROFIT CAPABILITY Improvement package is retrofittable as total package - Aircraft power management change and piping changes (QEC mods) in vicinity of fan case stiffener are required.

OTHER IMPACTS Fan speed vs. airflow/thrust changed. Fan nozzle area increased ≈ 2.5%. Noise predicted to be same as current engine.

Figure 3. Example of Screening Assessment Input.

3.2.2 Douglas Aircraft Company

The overall assessment procedure of Douglas is shown in Figure 4. Concept definitions were received from General Electric as well as some being conceived by Douglas. Initially, a qualitative assessment was made. This was done to determine the practicality of the concept before engineering studies were conducted. For those items which continued to have merit, technical evaluations were made. The technical evaluations were followed by airline economic evaluations to assess the cost effectiveness of improvement concepts.

The technical evaluation was composed of conducting preliminary design studies in the normal way concepts are evaluated in production programs. Sketches and drawings were made which formed the bases for performance, weight and cost estimating. Airplane performance estimates based on installed performance were then made using production airplane computer programs with the engine performance and weights adjusted to reflect the effect of the concepts evaluated.

The assessments were conducted using the same technical specialists as the production programs. A large number of specialists was involved who worked part time on the evaluations. The use of production specialists provided a more realistic evaluation. The fuel burned analyses were conducted on the DC-10-10 (CF6-6 Engines) and DC-10-30 (CF6-50 Engines) at typical ranges that are representative of average stage lengths. Flight Mach numbers and altitudes were for minimum direct operating cost (DOC) and minimum fuel burned. The payloads represented typical passenger plus cargo loads and were based on a 100 percent passenger load factor with no cargo (Figure 5).

The airline subcontractor specified the flight profiles for both the minimum DOC and the minimum fuel burn conditions. The mission profile used is shown in Figure 6. The difference between the DC-10-10 and DC-10-30 mission profile is in the reserves. The domestic reserve used on the DC-10-10 was 1 hour while 10 percent cruise time was used in the international DC-10-30.

An example of the fuel burned results is shown in Figure 7 for the fan improvement concept on the DC-10-30 (CF6-50 engines) for the minimum fuel case. The fuel burned and fuel burned savings are shown by flight segment. The results are for the three stage lengths evaluated. Similar results were determined for each concept studied on the DC-10-10 and/or DC-10-30, as applicable, for both minimum fuel burned and minimum DOC Cruise Conditions.

3.2.3 Boeing Commercial Airplane Company

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

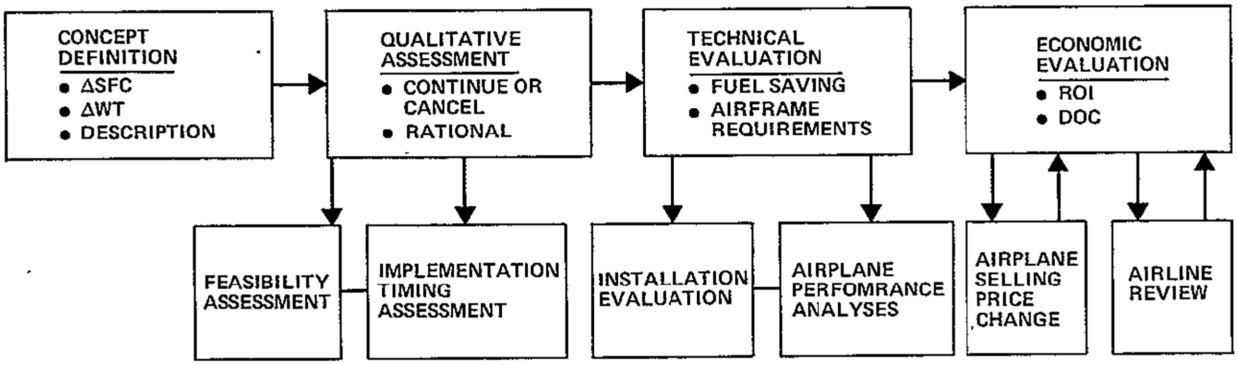

Figure 4. Douglas Assessment Procedure.

DC-10-10

Range: 645, 1690, 3700 km
(400, 1050, 2300 mi)

Mach No. and Altitude: Minimum Fuel and Minimum DOC

Payload: 25, 758 kg
(56, 785 lb)

DC-10-30

Range: 805, 2735, 6275 km
(500, 1700, 3900 mi)

Mach No. and Altitude: Minimum Fuel and Minimum DOC

Payload: 23, 433 kg
(51, 660 lb)

Figure 5. Douglas Fuel Burned Analyses Assumptions.

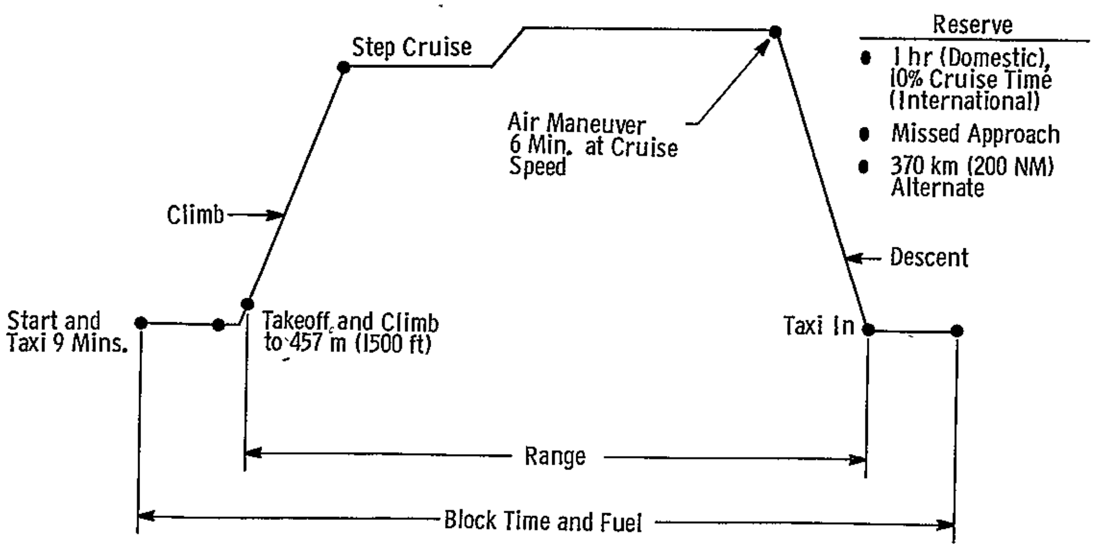

Figure 6. Mission Profile.

MTOGW = 251,748 kg (555,000 lb)
OEW = 121,565 kg (268,000 lb)
△OEW = +40 kg (+87 lb)
Payload = 23,436 kg (51,660 lb)
(252 passengers at 93 kg (205 lb/passenger)

- International Reserves, 370 km (200 n miles) alternate
- Mach 0.82
- Std Day

Range/Profile	805 km/11,890 m (500 mi/39,000 ft)			2735 km/10,670-11,890 m (1700 mi/35/39,000 ft)			6275 km/9450/10,670-11,890 m (3900 mi/31/35/39,000 ft)		
Segment	Current Fan Fuel kg (lb)/ Time (hr)	New Fan Package Fuel kg (lb)/ Time (hr)	△ Fuel (%)	Current Fan Fuel, kg (lb)/ Time (hr)	New Fan Package Fuel, kg (lb)/ Time (hr)	△ Fuel (%)	Current Fan Fuel, kg (lb)/ Time (hr)	New Fan Package Fuel, kg (lb)/ Time (hr)	△ Fuel (%)
Engine Start & Taxi Out	327 (720 lb)/ 0.150	327 (720 lb)/ 0.150	0.0	345 (760 lb)/ 0.150	345 (760 lb)/ 0.150	0.0	381 (840 lb)/ 0.150	381 (840 lb)/ 0.150	0.0
Takeoff & Accelerate to 610 m (2,000 ft)	612 (1,350 lb)/ 0.023	600 (1,323 lb)/ 0.023	2.0	680 (1,500 lb)/ 0.026	667 (1,470 lb)/ 0.026	2.0	862 (1,900 lb)/ 0.033	845 (1,862 lb)/ 0.033	2.0
Long Range Climb	3,536 (7,795 lb)/ 0.243	3,513 (7,745 lb)/ 0.243	0.6	3,572 7,874 lb)/ 0.227	3,540 (7,804 lb)/ 0.226	0.9	4,208 (9,276 lb)/ 0.255	4,144 (9, 35 lb)/ 0.252	1.5
Cruise	3,865 (8,521 lb)/ 0.619	3,796 (8,368 lb)/ 0.620	1.8	19,390 (42,747 lb)/ 2.897	19,022 (41,935 lb)/ 2.898	1.9	51,783 (114,159 lb)/ 6.989	50,706 (111,786 lb)/ 6.994	2.1
Long Range Descent	660 (1,454 lb)/ 0.307	660 (1,454 lb)/ 0.307	0 0	661 (1,458 lb)/ 0.308	661 (1,458 lb)/ 0.308	0.0	665 (1.465 lb)/ 0.310	665 (1.465 lb)/ 0.310	0.0
Approach & Landing	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0
Taxi In	227 (500 lb)/	227 (500 lb)/	0.0	227 (500 lb)/	227 (500 lb)/	0.0	227 (500 lb)/	227 (500 lb)/	0.0
Block Fuel/Time	9907 (21,840 lb)/ 1.509	9803 (21,610 lb)/ 1.510	1.1	25,555 (56,339 lb)/ 3.775	25,142 (55,427 lb)/ 3.775	1.6	58,806 (129,640 lb)/ 7 904	57,648 (127,088 lb)/ 7.906	2.0
Reserves	8,118 (17,896 lb)	8,031 (17,705 lb)	1.1	9,521 (20,989 lb)	9,408 (20.740 lb)	1.2	12,109 (26,696 lb)	11,950 (26,344 lb)	1.3

Figure 7. Douglas Example of Fuel Usage for Minimum Fuel Cost Case for Fan Improvement Package for the DC-10-30 with GE CF6-50C Engines.

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 results of the design and technical staff analyses were integrated in a mission analysis to determine airplane performance changes. Aircraft performance definitions were combined with pricing and maintenance cost changes provided by General Electric, nacelle price change and airframe maintenance cost change estimate provided by the finance organization, and were forwarded to marketing for economic analysis. The Boeing marketing organization performed the economic analysis utilizing a procedure established in conjunction with the participating airlines. Results of the economic analyses were then provided to United Airlines and American Airlines for their comments. The data flow through the analyses procedure is illustrated in Figure 8.

The impact of engine design changes on the nacelle configuration was assessed by the propulsion design organization. Where necessary, layout studies were made to define changes to the nacelle and strut. These changes were iterated with the Structures, Weights, Noise and Aerodynamic Staffs to ensure that possible impact on aircraft structure, flutter, weight, noise and aerodynamics was checked. Work Statements were also prepared, where necessary, for cost estimates. Figure 9 illustrates the data flow through propulsion design.

The Propulsion Staff organization evaluated the component improvement performance data supplied by General Electric relative to baseline engine installed performance. Existing data on similar engine improvements were used to evaluate the impact of performance changes and provide installed engine performance estimates as illustrated in Figure 10. These were utilized in the mission cycle.

Estimated changes in baseline airplane weight were provided by the Weights Staff. 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 General Electric and the propulsion design organization. The effects of all weight changes on airplane loadability and balance were then evaluated. This procedure is diagrammed in Figure 11.

The BCAC Structures Staff reviewed each concept for its potential impact on the airplane structure. Those concepts with minor weight increases (less than 50 kg per nacelle) and center of gravity changes were considered to have no effect on existing airplane structure and did not undergo the full structural analysis. The Long Duct Mixed Flow Nacelle concept underwent the structural analysis diagrammed in Figure 12. Where necessary, the airframe

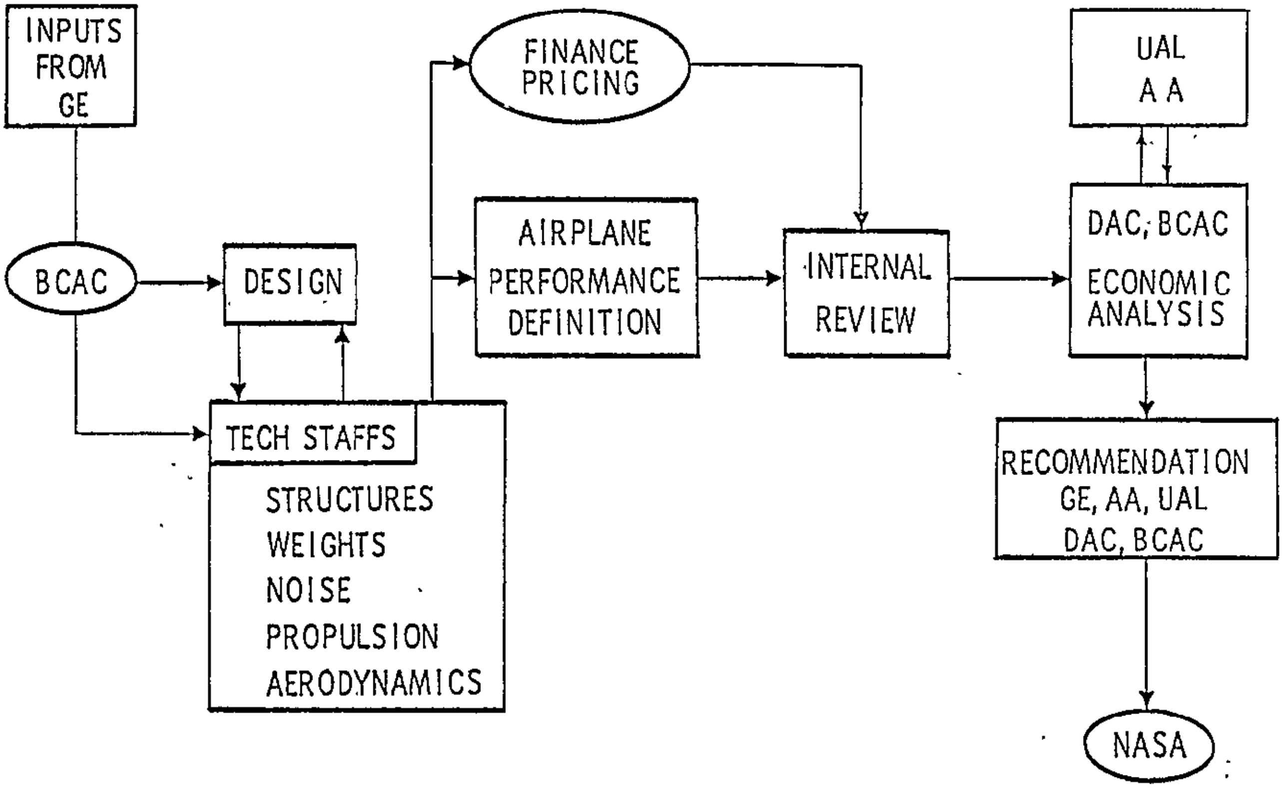

Figure 8. Boeing Data Flow.

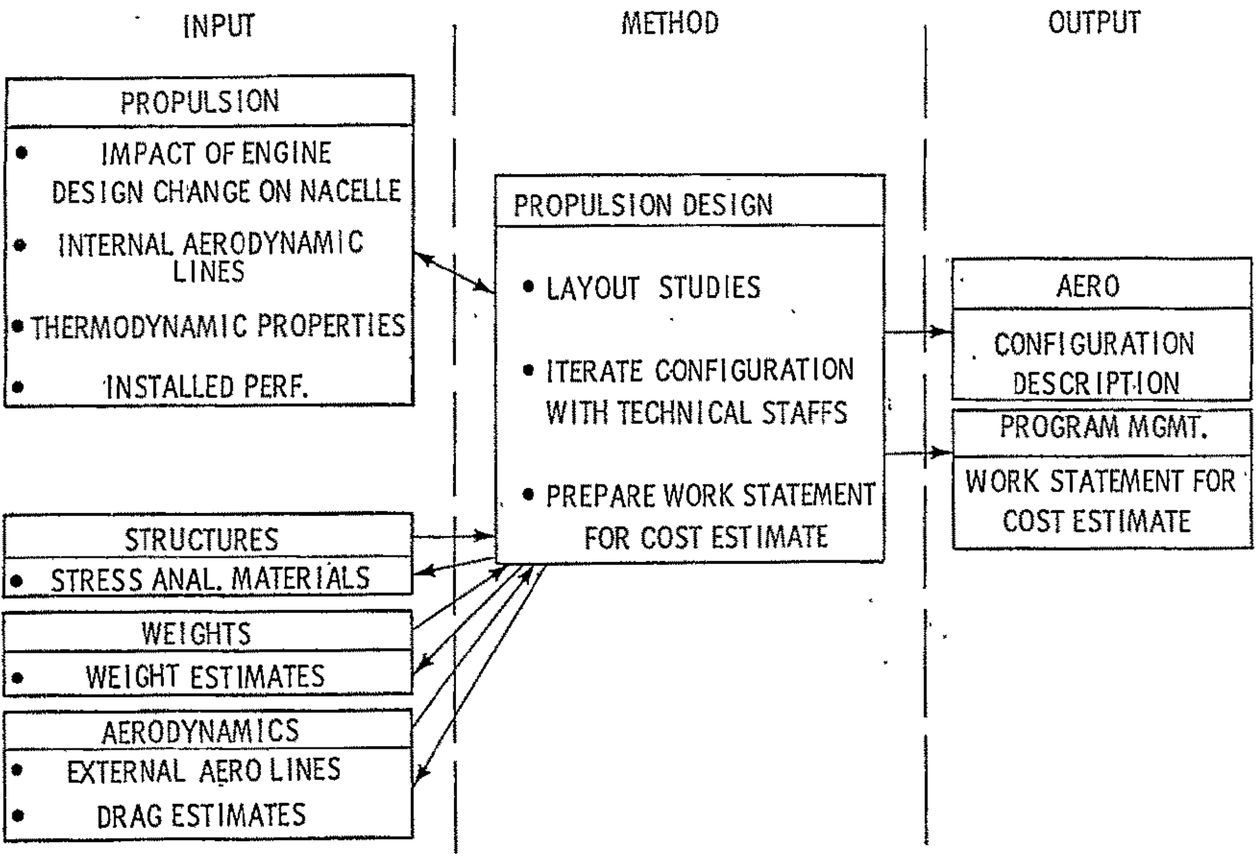

Figure 9. Boeing Data Flow Through Propulsion Design.

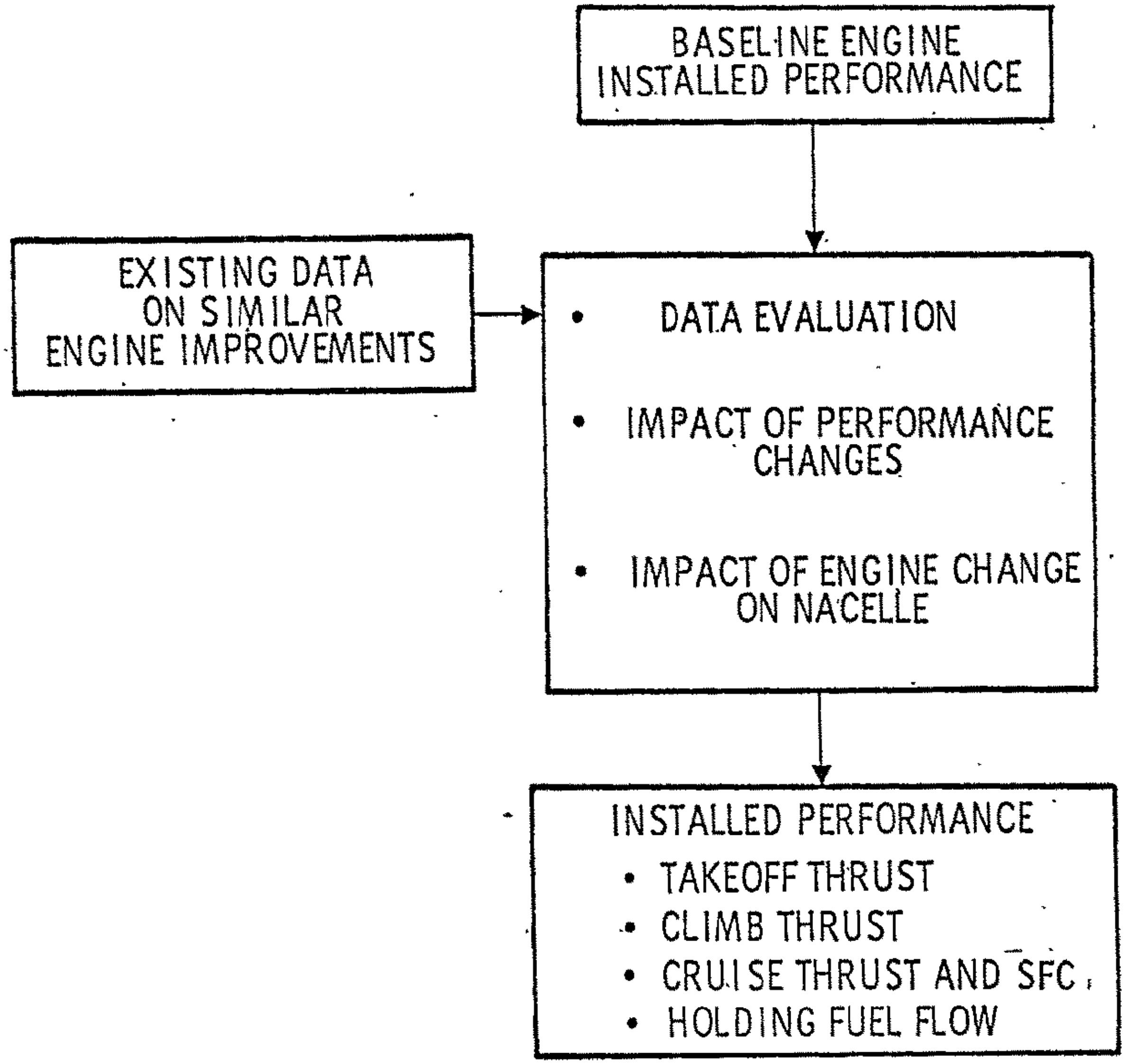

Figure 10. Boeing Propulsion Analysis Method.

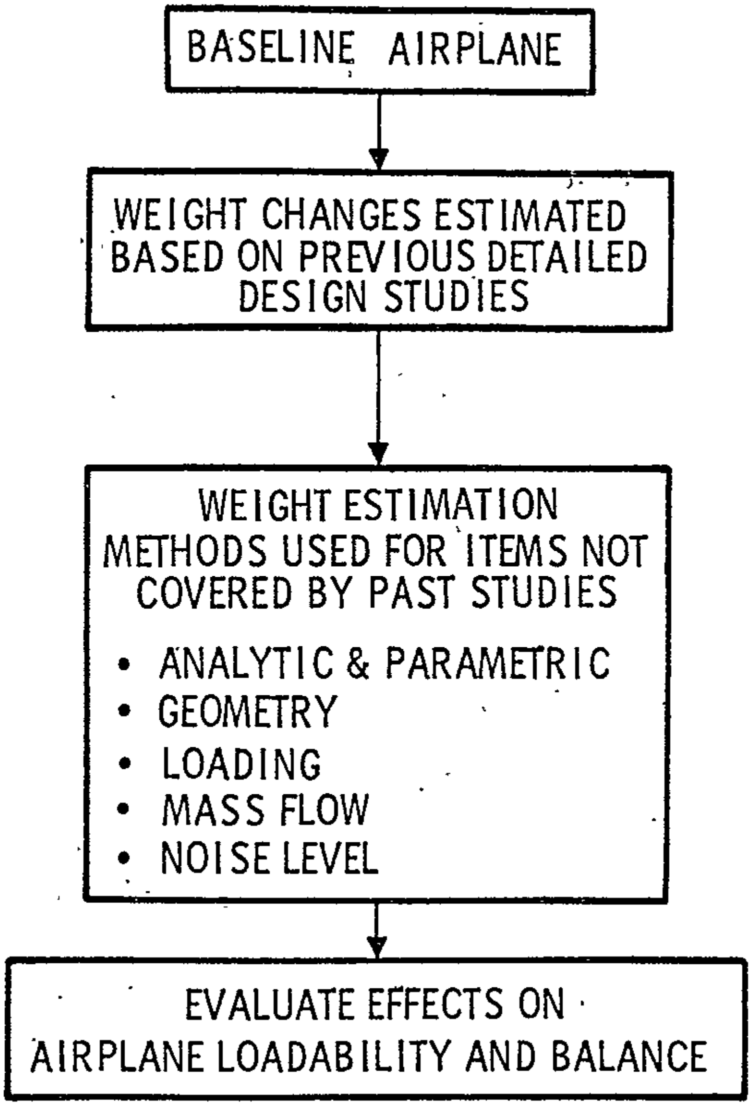

Figure 11. Boeing Weights Analysis Method.

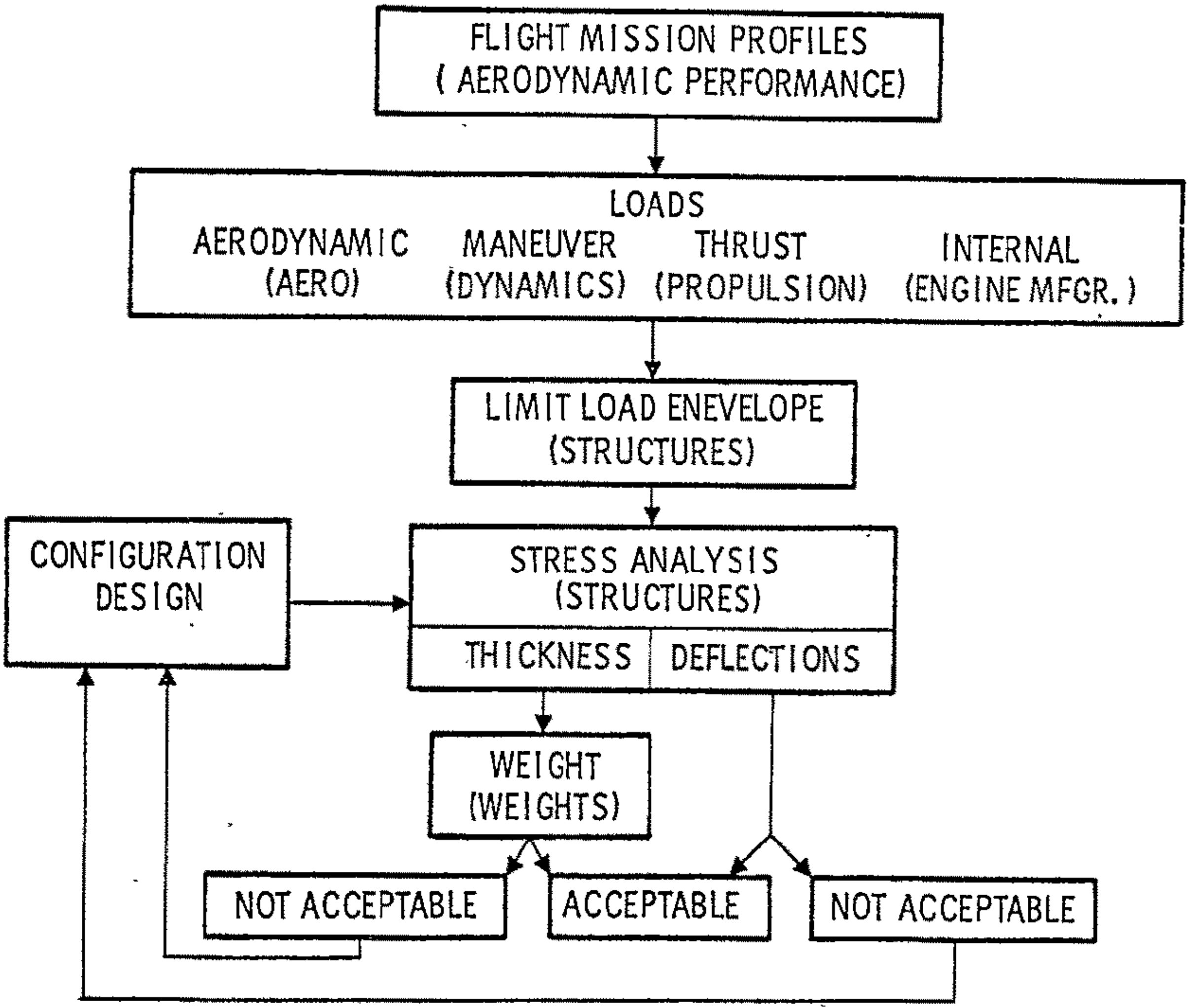

Figure 12. Boeing Structural Analysis Method.

structure was strengthened to carry the additional loads resulting in additional weight. A preliminary design flutter assessment was also made for those concepts where weight increases and center of gravity changes were significant.

The Aerodynamics Staff determined the effect of each concept on the capability limits of the airplane and on the mission fuel consumption or block fuel. The baseline airplane and basic mission profile were defined by aerodynamics and marketing analysis with concurrence of the airline subcontractors. The baseline airplane is defined in Table I and the conditions for the basic mission analysis are identified in Table II. The aerodynamic analysis method is diagrammed in Figure 13.

Table I. Boeing 747/CF6-50 Baseline Airplane.

Aircraft Model	747-200B
Engine	CF6-50E
Passengers	426
Max. BRGW - kg (lb)	362,880 (800,000)
Fuel Capacity - liters (gal)	193,894 (51,227)
OEW - kg (lb)	170,508 (375,900)
Payload - kg (lb) (426 Pass. @ 95.7 (211) each)	40,772 (89,886)

Table II. Boeing 747/CF6-50 Mission Conditions.

Still Air Range km (mi)	770 (480)	3460 (2150)	6195 (3850)
Cruise Conditions			
• Altitudes m (ft)	11,278 (37,000)	11,887 (39,000)	10,668-11,887 (35-39,000)
• Mach No.	0.82	0.83	0.83
Climb/Descent	Normal	Normal	Normal
Reserves	ATA International	ATA International	ATA International

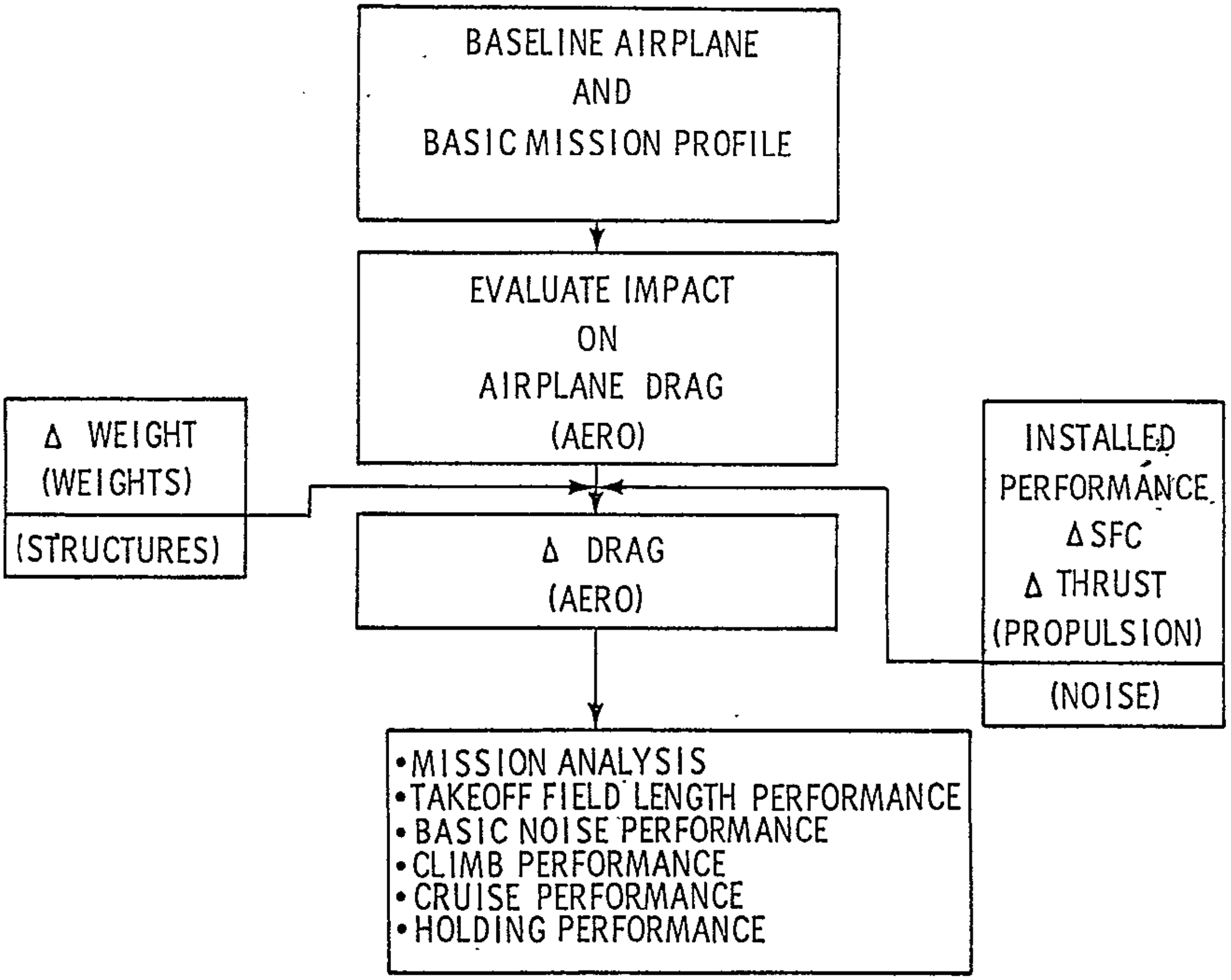

Figure 13. Boeing Aerodynamic Analysis Method.

Each concept was evaluated to quantify its effect on the external drag of the airplane. Incremental changes in weight, specific fuel consumption (sfc) and thrust of each concept were identified by the Weights and Propulsion Staffs. Improvements in cruise sfc assessed for the 35,600 to 40,000 N (8000/9000 lb) thrust level at 10,668 m (35,000 ft), 0.85 Mach number were used for the three cruise altitude/Mach number mission conditions shown in Table II. These deltas were applied to the baseline airplane and analyzed for the mission diagrammed in Figure 6. Performance changes for all mission segments were integrated in this mission analysis. The analysis provided the block fuel for three ranges, 770 km (480 mi), 3460 km (2150 mi) and 6195 km (3850 mi) in addition to the maximum range and payload capacity of the airplane for each concept.

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 performance at takeoff for enroute climb and at FAR Part 36 conditions for noise. The takeoff performance was evaluated as a change in brake release gross weight from a field for which the airplane was either acceleration or climb limited. The enroute climb performance was evaluated as a change in gross weight capability at a given altitude for the airplane with one or two engines out. 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.

The change in source noise and height at the measuring point was 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 the marketing organization along with aircraft price changes and maintenance cost changes. The economic analysis was performed and the results were forwarded to United Airlines and American Airlines for their analysis.

3.3 ECONOMIC ANALYSIS PROCEDURE

The objective of the economic analyses was to identify and select those engine component improvement items economically feasible for incorporation in current and future CF6-6 and CF6-50 engines. In carrying out this objective, data were needed from the engine manufacturer, the technical analyses of the airframe manufacturers, as well as the airlines. The generation of these data and their flow into the economic applying analyses are shown in Figure 14. The participation of the airlines included approving

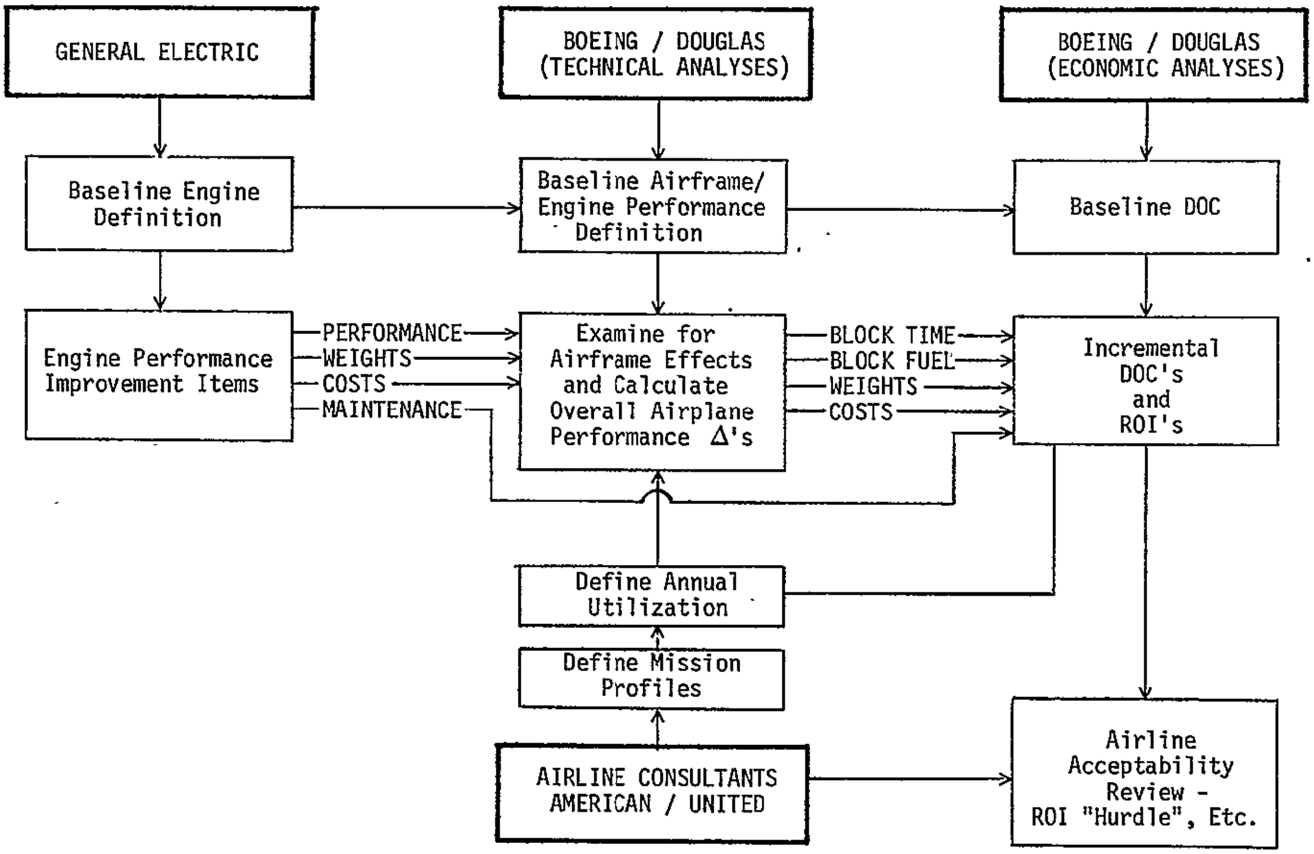

Figure 14. Economic Analysis - Data Flow.

the DOC and ROI (return on investment) methods, including data inputs to the methods, approving the results, and assessing airline acceptability and usability of each engine improvement concept.

The overall approach which Boeing and Douglas agreed to use began with the determination of the current range usages of the airplanes under study, the DC-10-10, DC-10-30, and B-747. Throughout the study, the DC-10-10 and the B-747 were simulated in the U.S. domestic operations, while the DC-10-30 was operated in international service. Three study fuel prices were used for each type of operation. Domestic fuel prices were 7.93 cents (30 cents), 11.89 cents (45 cents), and 15.85 cents (60 cents) per liter (gal) and international fuel prices were 10.57 cents (40 cents), 14.53 cents (55 cents), and 18.49 cents (70 cents) per liter (gal). Rounded values of the fuel price per liter are shown for simplification.

In lieu of a complete route analysis, three representative missions were selected for each aircraft to determine potential airline fuel savings achieved with each engine improvement. Current airline usage for the study aircraft was determined from the August 1976 Official Airline Guide. Departures for each airplane were distributed by stage length. This distribution of total departures was then divided into three equally weighted groups, and the average stage lengths of each group were selected as the three representative missions. An example of this procedure is given for the DC-10-10 in Figure 15. The selected stage lengths are tabulated below:

Representative Missions Selected

Stage Length, km (mi)

B-747	DC-10-10	DC-10-30
770 (480)	645 (400)	805 (500)
3,460 (2,150)	1,690 (1,050)	2,735 (1,700)
6,195 (3,850)	3,700 (2,300)	6,275 (3,900)

The airline subcontractors specified the flight profiles to be used for each aircraft, assuming both minimum DOC and minimum fuel cruise conditions. These flight profiles were needed to determine the block fuels at each range for the baseline airplanes and the same airplanes incorporating the various engine improvement concepts. These data, along with the estimated initial investment costs for the engine modifications, were used to determine the incremental operating cost savings and improved ROI of each improvement concept. The concepts were evaluated and ranked by operating cost savings and improved ROI's. The airline subcontractors then reviewed the acceptability of each concept.

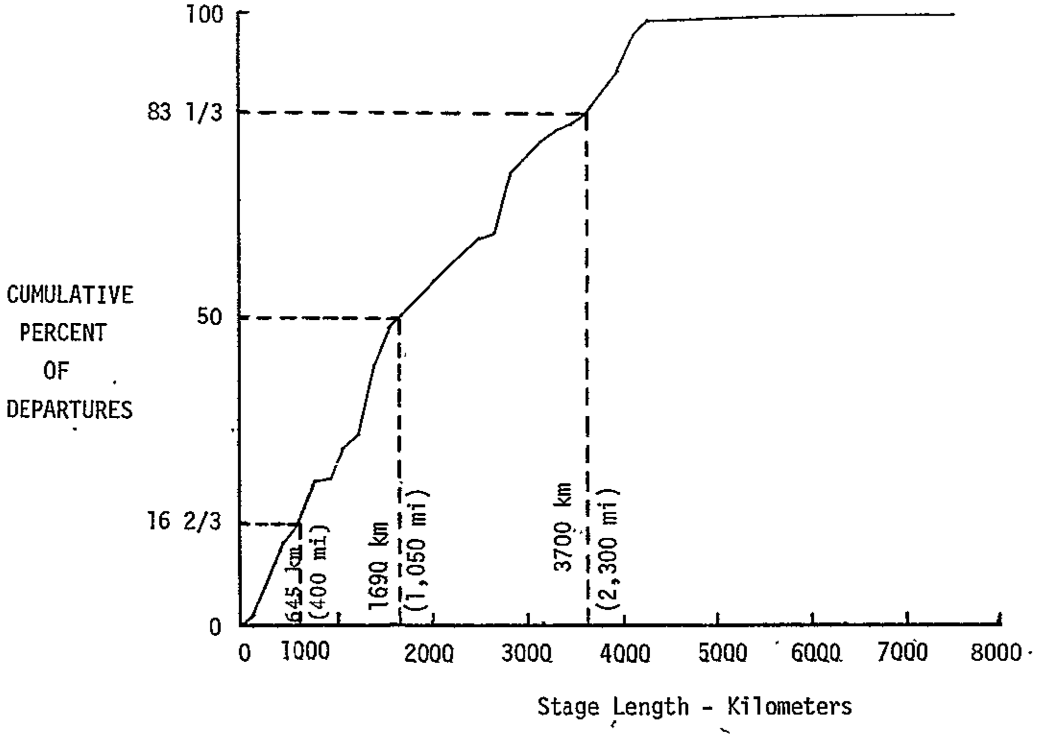

Figure 15. World Scheduled DC-10-10 Departures - August 1976 Official Airline Guide.

The generalized mission profile shown in Figure 6 was used for both minimum DOC and minimum fuel cruise conditions. Minimum DOC operations included a step cruise from 9,449 m (31,000 ft) to 10,668 m (35,000 ft) to 11,887 m (39,000 ft) and a Mach number of 0.85. Minimum fuel operations included the same step cruise but a Mach number of 0.82. Since the DC-10-10 and B-747 were operated domestically and the DC-10-10 internationally, reserves are given for either domestic (1 hour) or international operations (10 percent cruise time). These flight profiles, along with manufacturer specification performance data for each aircraft and its engines, were used to generate block times and block fuel consumptions at the three ranges for each baseline aircraft and these same airplanes incorporating the engine improvement concepts. Fuel consumption was based on the study ground rule of 100 percent passenger payload and no cargo.

A realistic airline utilization that could be achieved at each selected stage length was specified by American and United airlines for each study aircraft. Based upon these specified utilizations and the block times determined from the mission profiles for each aircraft, the annual number of trips was calculated for both minimum DOC and minimum fuel operations. The block times, utilization, and the number of annual trips are given in Table III. The annual trips were used in determining the annual operating cost savings generated by each engine improvement component under study.

In order to select those engine component improvement concepts that were economically and realistically feasible in airline operations, economic acceptability criteria were established by the airline subcontractors. The primary acceptance measure for a component was the achievement of an after-tax ROI of 15 percent. Both airlines agreed that a 15 percent after-tax ROI was the threshold rate at which a component would begin to look attractive to an airline. Other considerations that were weighed in determining an airline's acceptance or rejection of a concept with a marginal ROI are as follows:

- Fuel savings
- Risk of achieving estimated savings
- Standardization between engine model/module types both now and in the future
- Potential interaction on other engine component improvements
- Product service life remaining

An incremental return on investment method was used to determine the relative economic acceptability of each component improvement. The incremental ROI was defined as the discount rate at which the net present value of future cash-in flows (cost savings) is equal to the initial cash outlay (investment):

Table III. Mission Utilizations, Minimum DOC Flight Profile.

Aircraft	Stage Length (km/mi)	Block Time Hours	Utilization Hours		Annual Trips
			Daily	Annual	
DC-10-10	645/400	1.30	8.0	2,920	2,246
	1,690/1,050	2.48	10.0	3,650	1,472
	3,700/2,300	4.67	10.0	3,650	782
DC-10-30	805/500	1.47	8.5	3,100	2,109
	2,735/1,700	3.65	10.0	3,650	1,000
	6,275/3,900	7.60	15.0	5,475	720
B-747-200	770/480	1.05	6.9	2,521	2,401
	3,460/2,150	4.10	8.5	3,116	760
	6,195/3,850	7.20	14.6	5,320	739

$$\text{Net Present Value (NPV)} = \text{Cash}_{\text{Out}} + \sum_{n=1}^{\substack{\text{Useful}\\ \text{Life}}} \frac{\text{Cash}_{\text{In}}}{(1+R)^n}$$

when the net present value is zero, the discount rate equals the return on investment:

$$\text{NPV} = 0,\ R = \text{ROI} = \text{Discount Rate}$$

The cash in-flows were those operating cost savings directly attributable to the incorporation of the proposed components on the study aircraft. Cost savings were achieved from potential fuel and maintenance expense reductions less any additional insurance costs. The initial cash outlay for a component represented the total investment required in engine and airframe modifications, necessary additional spare parts and possible installation costs.

The features of the ROI method are as follows:

- Based on cash flow of engine modification and annual savings.
- Recognizes time value of money.
- Can be related to any airline's cost of capital to show how much a modification is above or below the "hurdle rate".
- Cash flow in constant (1977) dollars to assure consistent comparison of different modifications.
- Effect of inflation is contained within the airline ROI hurdle rate.

A sample calculation using the incremental ROI method is shown in Table IV for the high pressure turbine aerodynamic improvement on the DC-10-10 at a stage length of 1690 km (1050 mi). The total initial investment cost per airplane was $34,347. Annual operating cost savings were determined for the three study fuel prices. A very small increase in insurance expense was incurred with this concept. Depreciation tax effects and any potential investment tax credits during the life of the modification were not considered, since before tax ROI's were calculated in this study.

The discount rate at which the net present value of the future annual cost savings ($193,980 over the 15 year life of the modification) was equal to the initial cash investment ($34,347) was 565 percent with fuel costs at 8 cents per liter (30 cents/gal). An additional economic assessment of the engine improvements was the determination of the length of the payback period for each modification. The payback period is the number of years it takes to pay back the initial cash investment with annual cost savings and is equal to:

Table IV. Example of Incremental Rate of Return on Engine Improvement Investment.

Cash Outlay	HP Turbine Aerodynamic Improvement @ 1690 km (1050 mi)		
Incremental Engine Mod Cost	$32,100	($10,700 each)	
Incremental Airframe Mod Cost	0		
Additional Spares Inventory	2,247		
Installation Cost	0		
	$34,347		

Annual Cash Savings Discounted Over Life of Modification	Fuel Price, ¢/Liter (¢/gal)		
	8(30)	12(45)	16(60)
Cash Operating Cost Savings			
Fuel	34,018	51,020	68,036
Engine Maintenance	160,124	160,124	160,124
Airframe Maintenance	0	0	0
Insurance	- 162	- 162	- 162
Total	193,980	210,982	227,998
Depreciation Tax Effects	0	0	0
Investment Tax Credit	0	0	0

$$\text{PAYBACK PERIOD} = \frac{\text{CASH OUTLAY}}{\text{ANNUAL CASH SAVINGS}}$$

For the example (Table IV), the initial investment would be recovered in 0.18 year with fuel at 8 cents per liter.

In competing with other enterprises to obtain necessary capital financing, United applies a hurdle rate concept to ensure financially strong investment decisions. United's after-tax hurdle rate of 15 percent is predicted upon a desirable 50/50 debt-to-equity ratio, the need to meet an after-tax payback of 10 percent to 12 percent, and the need to maintain adequate coverage for necessary nonfinancial advantage projects.

In establishing the hurdle rate, a factor of 1.35 was applied to the cost of capital to cover nonpaying capital expenditures, such as legislated aircraft noise retrofits. This factor will vary considerably and was not intended to be representative of the airline industry nor United's system. An average after-tax payback requirement of 11 percent multiplied by this factor, 1.35, yielded an approximate capital investment hurdle rate of 15 percent.

Since Boeing and Douglas agreed to generate before-tax rather than after-tax ROI's, it was necessary to determine a before-tax ROI hurdle rate equivalent to the airline 15 percent after-tax rate. To accomplish this, before-tax and after-tax ROI's were calculated for several of the engine modifications. The resulting before-tax and after-tax ROI equivalents were plotted as shown in Figure 16. The assumptions used in determining this equivalence are listed and were approved by the airline subcontractors. New production concepts were assumed to have a 15 year useful life while retrofits were given a maximum useful life of 7 years.

In calculating the after-tax ROI's, two conditions were examined i.e., one in which a 10 percent investment tax credit (ITC) was allowed, and one in which no ITC was included. With a 10 percent investment tax credit, the before-tax ROI equivalent to the 15 percent after-tax rate varied from 18-20 percent, depending on whether the component was new production or retrofit. Assuming no ITC, the equivalent before-tax hurdle was 23 percent for both new production and retrofit concepts. Therefore, the before-tax ROI hurdle rate established for the economic evaluation of the engine improvements was 23 percent.

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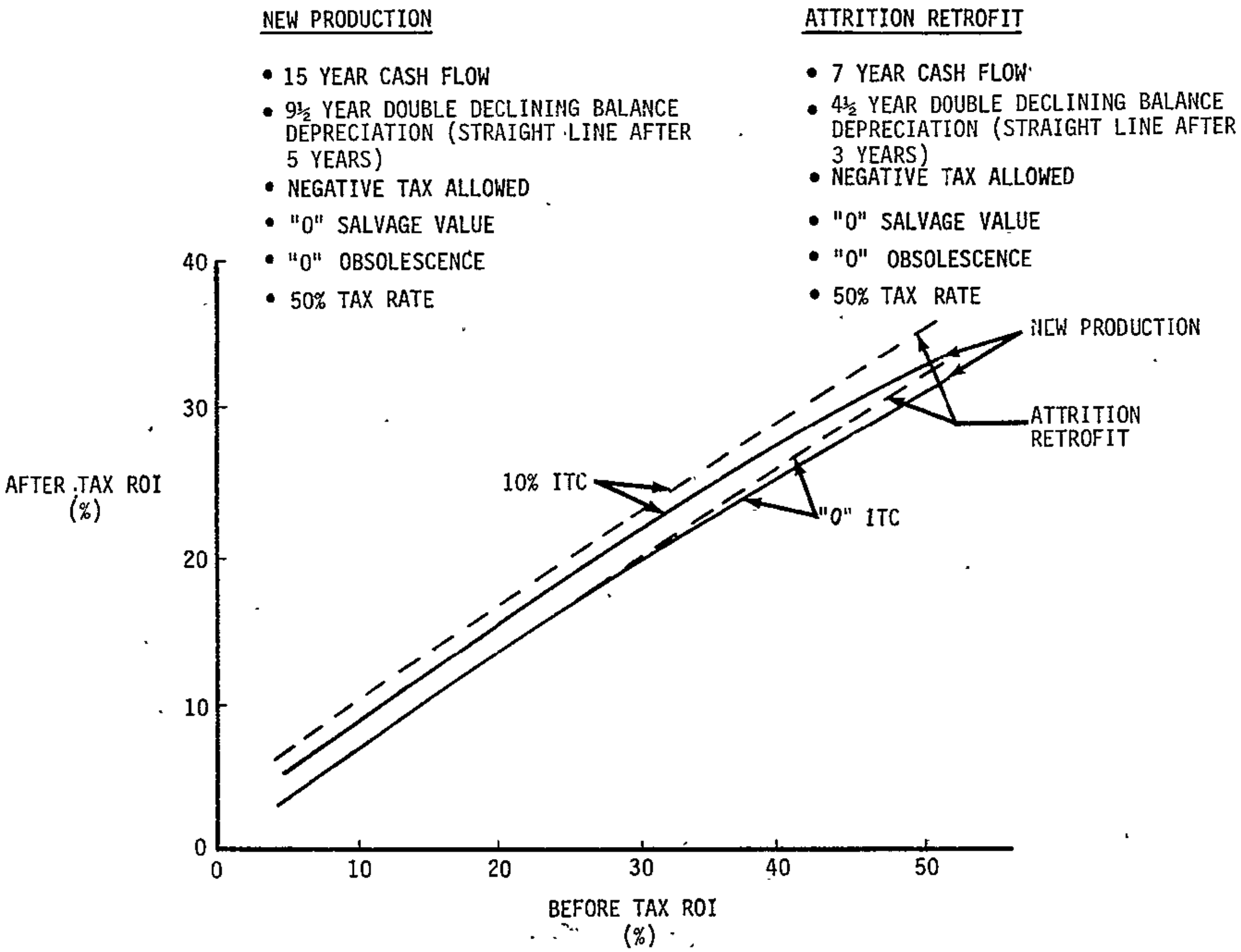


Figure 16. Before Tax/After Tax ROI Equivalence.

4.0 IDENTIFICATION OF CONCEPTS

A total of 62 component improvements was identified for consideration in the feasibility analysis. An initial review was conducted with some concepts being eliminated for one or more of the following reasons:

- Payoff - The cost of the component improvement is too high for the estimated performance gain.
- Program Timing - The time to develop the concept goes beyond the 1980 to 1982 fleet introduction date.
- Risk - The risk for developing the improvement concept for the 1980 to 1982 fleet introduction is too high.

Table V shows the 62 initially proposed improvement concepts categorized for the respective engine components and their disposition after the initial screening.

Of the concepts that remained, several offered improvements which were within calculation or test accuracy. These concepts were logically grouped together by engine component. The concepts or groups of concepts remaining for detailed screening are presented in Table VI. This table also indicates the category of the improvement, such as performance improvement "I" or performance retention "R", the engine model studied, the retrofit potential, and the estimated sfc reduction. The screening of these 24 concepts (or groups of concepts) is described in Section 5.

Table V. Initially Proposed Performance Improvement Concepts.

Item	Disposition
Fan	
Blade Aero Redesign	Retain
Lower Operating Line	Retain
Reduced Clearance	Retain
OGV Aero Redesign	Retain
Flowpath Steps	Delete - Payoff
Vane Base Steps	Delete - Payoff
Increased Fan Diameter	Retain
Booster	
Smooth Shrouds	Delete - Program Timing
Clearance Optimization	Delete - Payoff
ID Flowpath Steps	Delete - Payoff
Reduced Seal Cell Size	Delete - Payoff
Stage 3 Clearances	Delete - Payoff
Fan Frame Flowpath Steps	Delete - Payoff
Vane Base Steps	Delete - Payoff
Compressor	
Vane Rigging Tolerances	Delete - Payoff
Reduced Flange Leakage	Delete - Payoff
Reduced Case Distortion (Front Mount)	Retain
"Hard" Blade Tips	Delete - Payoff - Risk
Improved CDP Seal	Delete - Payoff - Risk
Improved S1 & S2 Shroud Seals	Delete - Payoff
Rotor/Stator Thermal Match	Retain
Reduced Stator Bushing Leakage	Retain
Improved Stage 1 Blade	Retain
Improved Rub Coatings	Delete - Program Timing
Dovetail Seals	Retain
Blade Coatings	Retain

Table V. Initially Proposed Performance Improvement Concepts (Continued).

Item	Disposition
High Pressure Turbine	
Frame Roundness Control	Retain
Stage 2 Nozzle Support Isolation	Retain
R150 Blades	Retain
CF6 Stage 2 Blade	Retain
Reduced Exit Swirl	Retain
Improved Segment Seals	Retain
NiCrAlY Shrouds	Delete - Program Timing, Risk
Variable Cooling Air	Delete - Risk
Cooled Cooling Air	Retain
Rotor Leakage Reduction	Delete - Payoff
Reduced Vane Cooling	Delete - Payoff
Reduced Band Cooling	Delete - Payoff
Pressure Side Bleed Blade	Delete - Payoff
Flowpath Match	Delete - Payoff
Erosion Prevention Coating	Delete - Payoff
Active Clearance Control	Retain
"Hard" Blade Tips	Retain
R125 Stage 2 Blade	Delete - Payoff, Risk
Low Pressure Turbine	
Improved Thermal Match	Retain
Improved Temperature Distribution	Retain
Stage 1 Incidence	Retain
Reduced Leakage Interstage Seals	Retain
Airfoil Finish	Delete - Payoff
Nacelle/Exhaust Systems	
Long Duct Mixed Flow Nacelle	Retain
Core Cowl Gap	Delete
Short Core Exhaust	Retain

Table V. Initially Proposed Performance Improvement Concepts (Concluded).

Item	Disposition
Nacelle/Exhaust Systems	
Vortaway - Vortex Suppressor	Retain
Improved Nacelle Aero	Retain
Fire Shield Deletion	Retain
Optimized Nacelle Cooling	Retain
Reduced Leakage	Retain
Controls	
Optimized Stator Schedule	Delete - Program Timing
Stall Prevention	Delete - Payof
Stator Cruise Flat	Delete - Payoff
N_1/EGT Control Logic (Modified Controls)	Retain
FADEC	Retain

Table VI. Selected Concepts for Detail Screening.

Component	Concept	Performance Category	Engine Model Studied	Retrofit Potential	Estimated % sfc Reduction
Fan	Fan Improvement	I (1)	-6, -50	Moderate	1.6, 1.8
	Blade Aero Design				
	Lower Operating Line				
	Reduced Clearances				
	Fan OGV Redesign	I	-6, -50	Moderate	0.3
	Increased Fan Diameter	I	-50	Low	3.5
Compressor	Front Mount – Case Distortion	I/R (2)	-6, -50	Moderate	0.3
	Rotor/Stator Thermal Match	I/R	-50	Low	0.2
	Reduced Stator Bushing Leakage	R	-50	Low	0.1
	Improved Stage 1 Blade	I	-6, -50	High	0.1
	Dovetail Seals	I	-50	Moderate	0.1
	Blade Coatings	R	-6, -50	High	---
High Pressure Turbine	Roundness Control	I/R	-50	Moderate	0.4/0.8 (3)
	Frame/Nozzle Support				
	R150 Turbine Blades	I	-50	Moderate	0.7
	Aerodynamic Improvements	I/R	-6	Moderate	1.3/1.6 (3)
	CF6 Blades				
	Improved Seals				
	Reduced Exit Swirl				
	Cooled Cooling Air	I	-6	Low	0.6
	Active Clearance Control	I/R	-6, -50	Low	0.6
	"Hard" Blade Tips	I/R	-6, -50	High	---
Low Pressure Turbine	Active Clearance Control	I/R	-6, -50	Moderate	0.1, 0.3
	Improved Thermal Match				
	Temperature Distribution				
	Stage 1 Incidence	I	-50	High	0.1
	Reduced Leakage Interstage Seals	I	-50	Moderate	0.1
Nacelle	Long Duct Mixed Flow Nacelle	I	-50	Low	1.6
	Short Core Exhaust	I	-50	Moderate	1.0
	Vortaway – Vortex Suppressor	R	-6, -50	Moderate	0.2, 0.3 (3)
	Improved Nacelle System	I/R	-6, -50	Low	---
	Improved Aero				
	Reduced Leakage				
	Fire Shield Deletion				
	Optimized Cooling				
Controls	Modified Controls	R	-6, -50	Moderate	0.2/0.4 (3)
	FADEC	I/R	-6, -50	Moderate	0.3/0.5 (3)
Airframe	Cabin Air Recirculation (4)	I	-6, -50	---	0.7

NOTE. (1) I = Improvement
(2) R = Retention
(3) At 3000 hours
(4) Concept identified by Douglas and added to original concept list.

5.0 SCREENING STUDY

5.1 TECHNICAL ANALYSIS

This section discusses the technical analysis of the selected component improvements for detail screening as shown in Table VI. The concepts are discussed in the order shown and the analysis of the concepts consists of three points: 1) A description of the concepts and its technical analysis by General Electric, 2) the technical analysis by Boeing, and 3) the analysis of the concept by Douglas.

Some concepts were analyzed for both the CF6-6 and CF6-50 engines while others were studied for one selected engine only; however, with the exception of the HPT Aerodynamic Improvements, the LPT Stage 1 Incidence Angle, and the Short Core Exhaust, all concepts are applicable to both engine models.

5.1.1 Fan Performance Improvement (CF6-6, -50)

5.1.1.1 General Electric

The proposed fan performance improvement package consists of three parts, namely:

- Improved performance fan blade
- Increased fan reverser nozzle area (lower operating line)
- Fan case stiffener ring (reduced tip clearances)

The new fan blade design (Figure 17) incorporates the following changes relative to the current production design for improved adiabatic efficiency:

- The part-span shroud is moved aft on the airfoil chord to reduce the aerodynamic blockage through the passage. The current design has higher blockage because the shroud is very near the throat of the passage which results in greater aerodynamic losses.
- The airfoil camber is increased by a small amount and the distribution of camber is modified to move the throat of the passage forward.

The thickness distribution of the new fan blade is the same as the current production design in a chordwise and spanwise direction. The platform and shank of the new blade are very similar to the production blade. The dovetail is identical so that the two designs are completely interchangeable in the same fan disk in sets. Both fan blades are common to both CF6-6 and CF6-50 engines. The new fan blade has the same maintainability features as the current production blade, such as individual replacement on wing. A change in the fan disk platform is required becasue of a small change in the hub flowpath. Otherwise, all interfaces are unchanged.

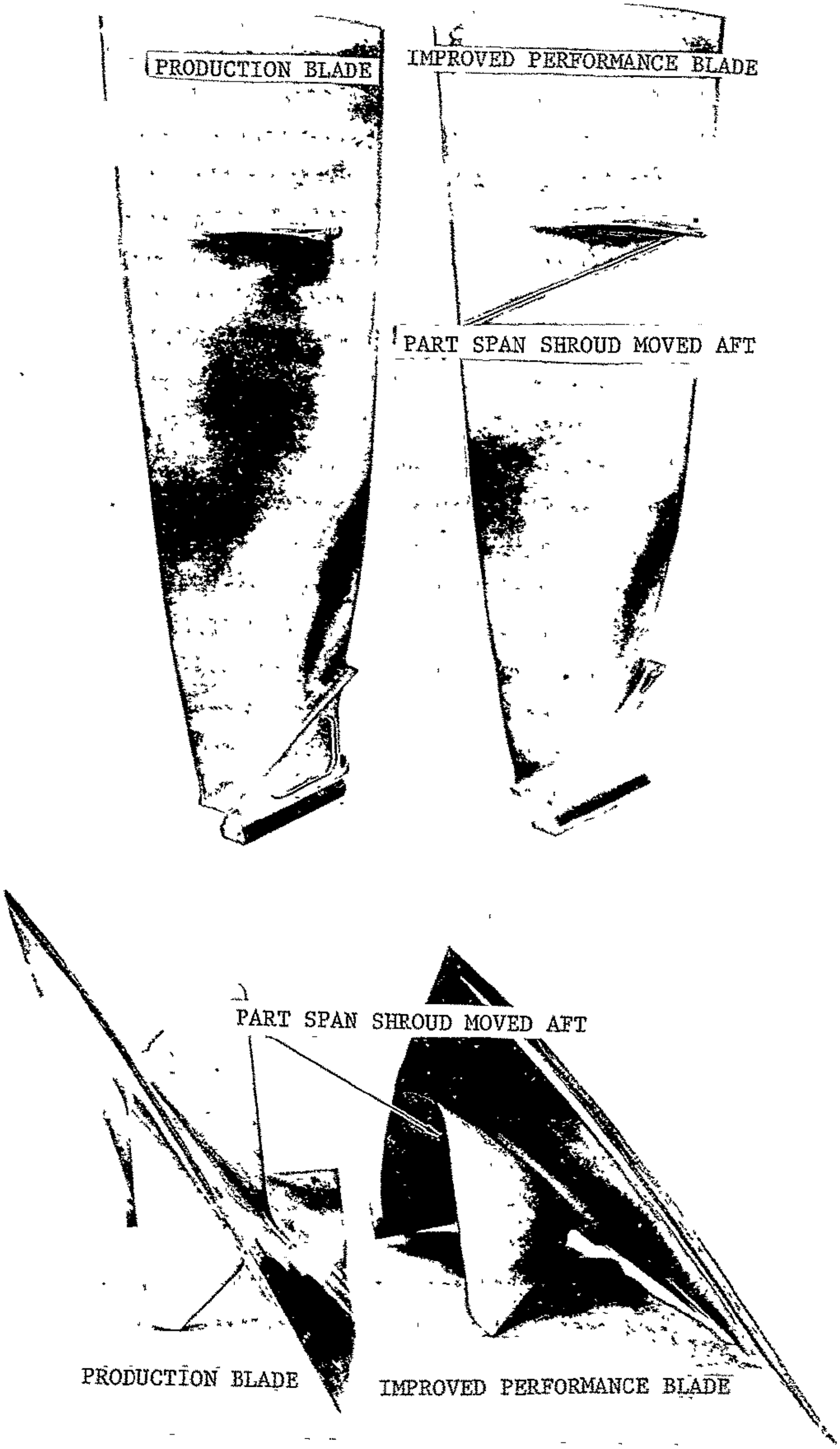


Figure 17. Comparison of Production Blade to Improve Performance Blade.

The new high pressure fan was tested in a CF6-50 development engine in 1976 and installed and tested in a CF6-6 and CF6-50 production engine for overall engine performance demonstrations early in 1977. The performance test on the development engine consisted of the new fan without the stiffener and no decrease in tip clearance. The improved fan blade provided efficiency improvements at all airflows up to 680 kg/sec corrected flow. The overall low pressure system (fan, booster, and LP turbine) performance improvements, as evidenced by efficiency calculations and overall engine performance measurements, were determined to be equivalent to approximately 2.3 points in fan efficiency along the peak efficiency island. The cruise operating line is close to the peak operating line. Figure 18 shows the estimated peak efficiency improvement for the improved blade.

The improved blade has higher airflow for the same speed compared to the current blade. The comparison of the flow-speed and the thrust-speed relationship of the two blades is shown in Figures 19 and 20. Because of the difference in these characteristics, a revision in the engine power management would be required and all engines of an aircraft must be equipped with the new fan blades.

Fan performance can be improved by repositioning the fan operating line in relation to the peak efficiency island of the fan map. It is proposed to increase the fan reverser nozzle area by trimming back the closeout extrusion on the translating cowl of the fan reverser (Figure 21). The required area increase is estimated at about 2 percent for the CF6-50 and at about 4 percent for the CF6-6.

An additional improvement in fan performance is possible from a reduction in fan tip clearance. This can be accomplished by stiffening the fan casing in order to raise the critical interaction frequencies of the fan and the fan case above the maximum operating fan speed. The proposed fan case stiffener is an extruded aluminum, chem-milled structure which is mechanically attached to the fan case (Figure 22). The addition of the stiffener will require minor configuration changes in the area of the fan casing.

The fan performance improvement was assessed for the total package of fan blade, operating line and stiffener, and for the fan blade and operating line adjustment only. These improvements for the CF6-50 and CF6-6 engines are shown in Figures 23 through 26 together with the weight, price and maintenance cost changes.

The CF6-50 total fan improvement package improves the cruise sfc by 1.8 percent. It should be noted that at maximum cruise the Δ sfc improvement decreases to 0.3%, which indicates the sensitivity of engine performance to slight shifts in fan operation. The predicted Δ EGT improvement at takeoff is about 6° C. This fan concept increases the engine weight by 13 kg (29 lb) and increases the engine price by $19,000. The installation costs in the case of retrofit are estimated to be from $12,000 to $10,000. Maintenance material costs are reduced by $1.60 per engine flight hour with no change in maintenance labor. The concept is retrofittable but requires aircraft power management and piping configuration changes in the vicinity of the fan case stiffener.

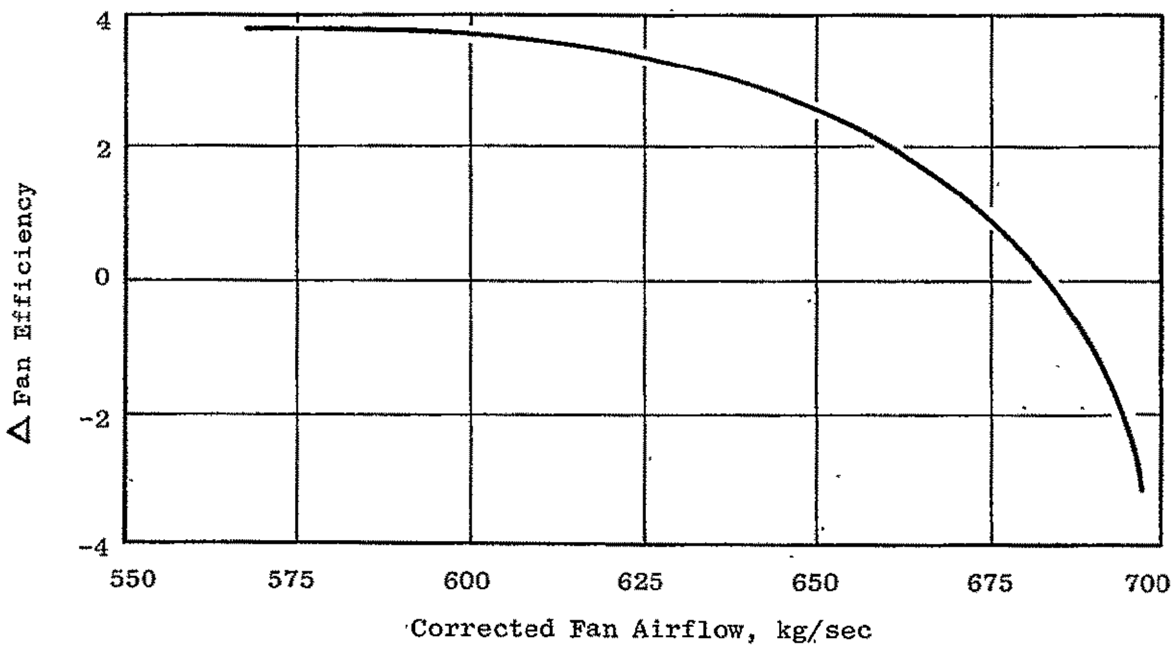


Figure 18. CF6-50 Improved Fan Blade, Efficiency Improvement Relative to Original Blade.

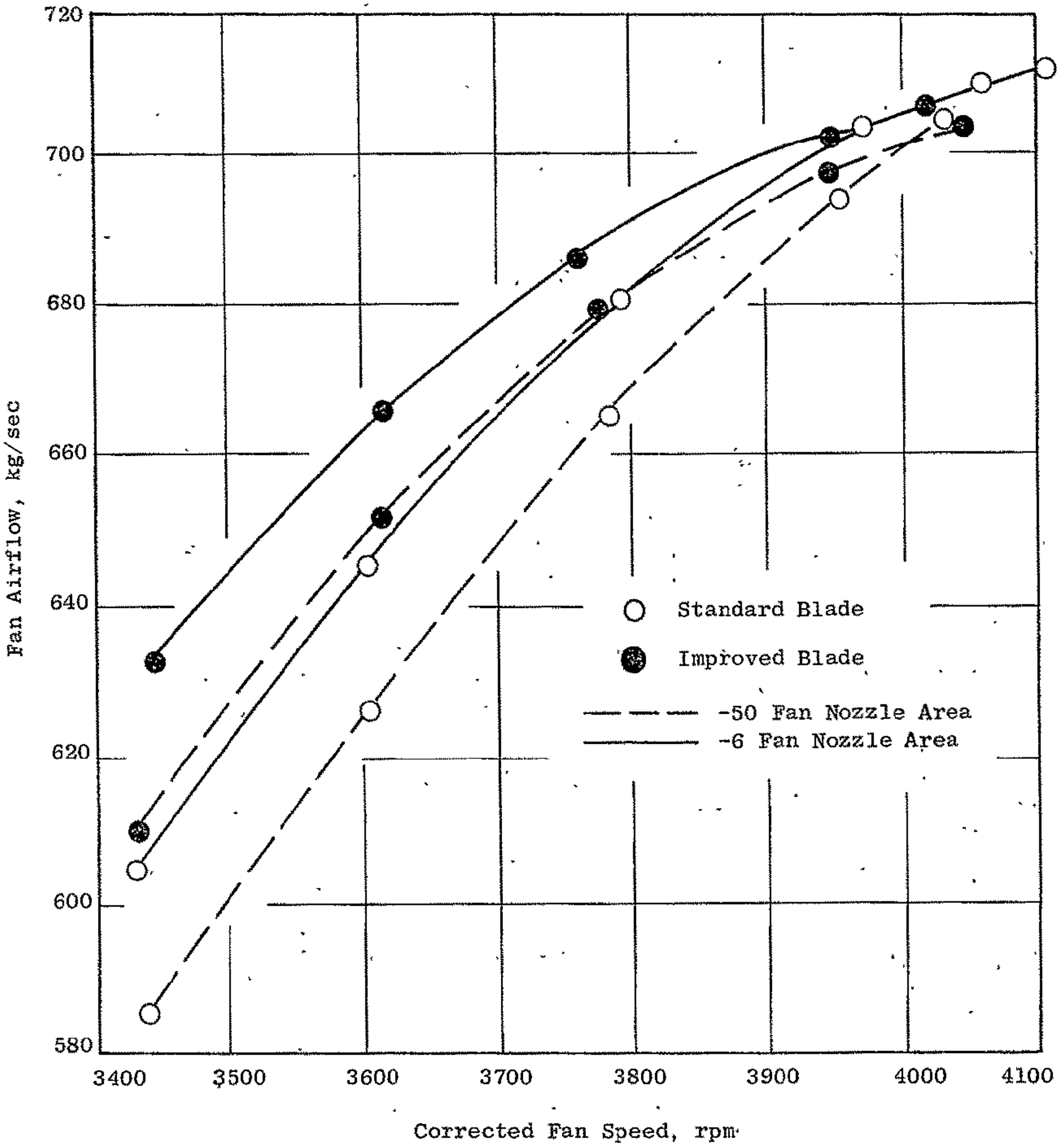


Figure 19. Engine 455-105/6 Fan Airflow Versus Fan Speed.

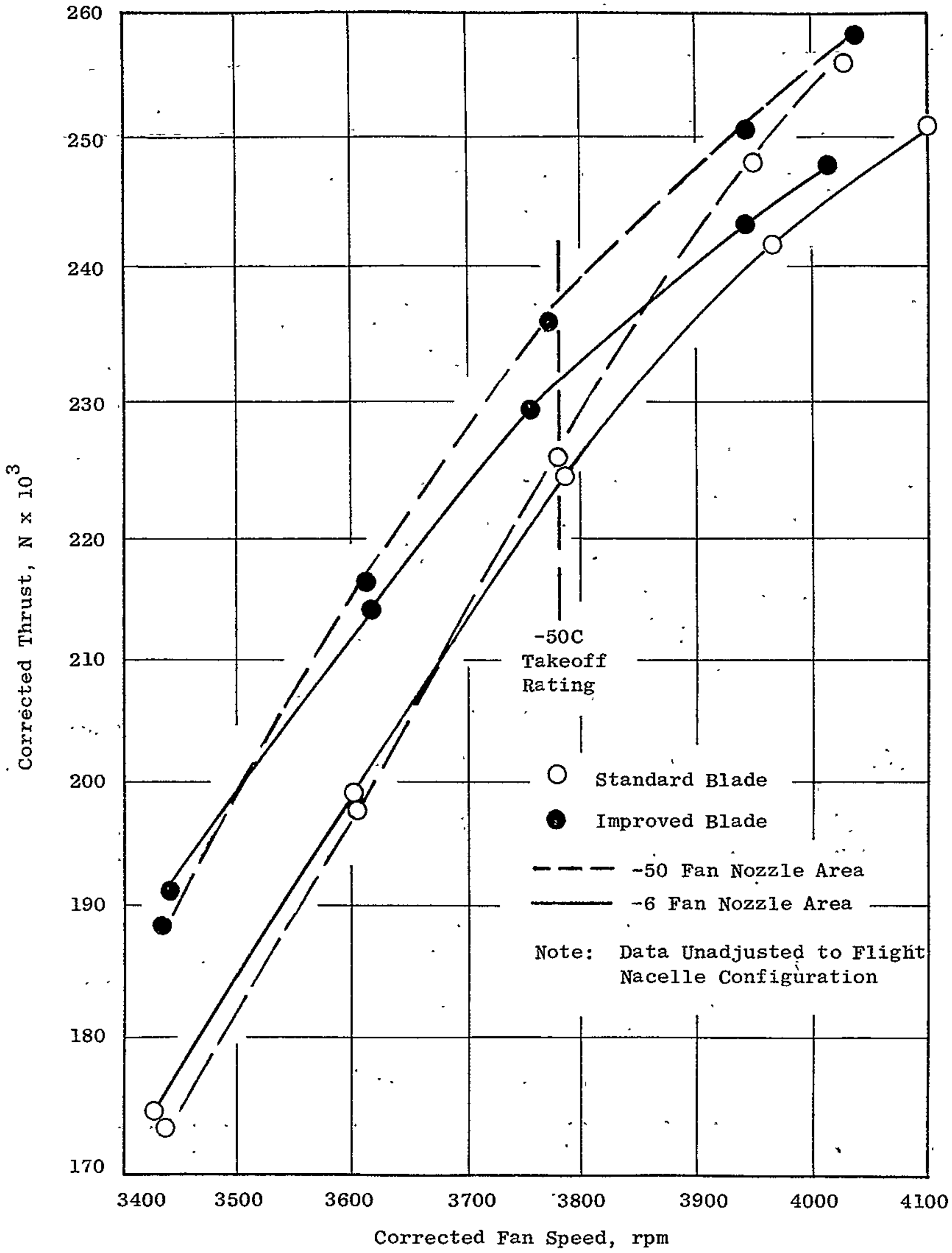


Figure 20. Engine 455-105/6 Thrust Versus Fan Speed.

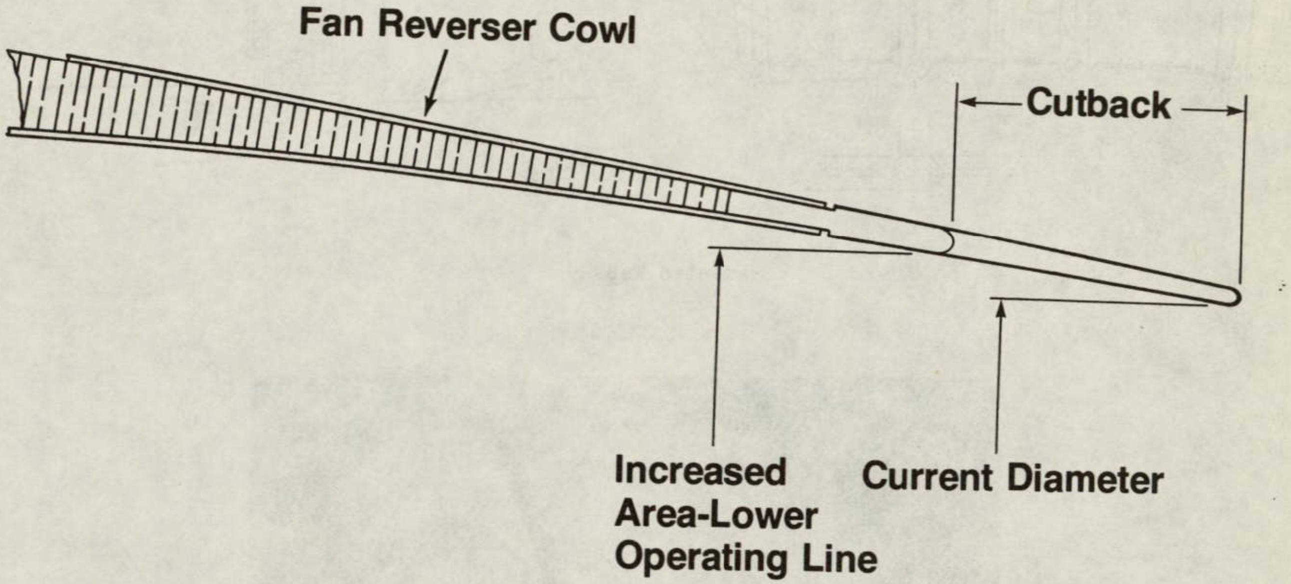
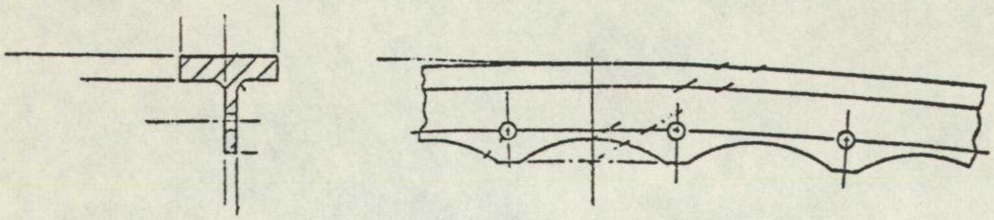
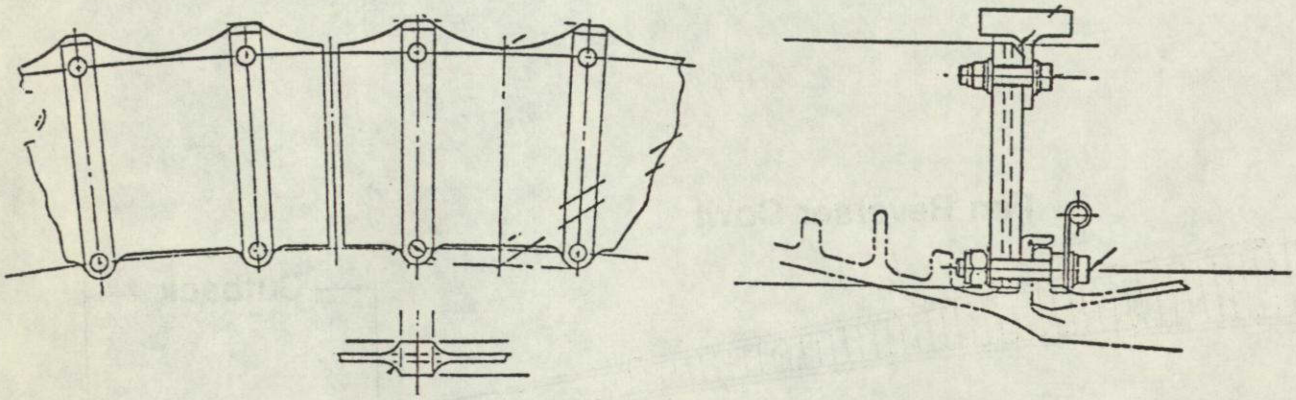


Figure 21. Fan Reverser Nozzle Area Increase.



360° Ring



Segmented Web

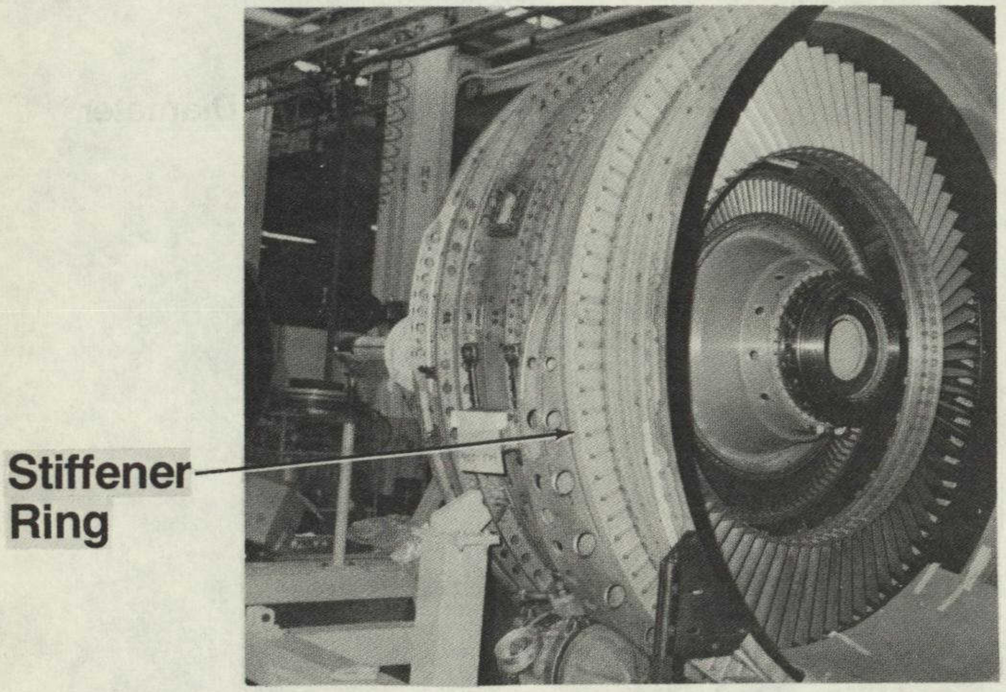


Figure 22. Fan Case Stiffener.

TITLE Fan Improvement (Blades, Operating Line and Stiffener) CF6-50

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-2.4
T/O	0 (0)/0.25	-2.0
CLIMB	7620 (25000)/0.80	-0.5
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-1.8
MAX CRUISE	10668 (35000)/0.85/+10°C	-0.3
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-2.4
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-31 (-69) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +13 kg (+29 lbs.)

ΔCG, cm (in) - 0.8 cm (0.3 in) fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $19,000 Increase

RETROFIT - ATTRITION - $19,000 Increase

INSTALLATION COST - $12,000 - $20,000 Retrofit (Includes QEC mods) Negligible cost for new engine installation.

MAINTENANCE

MATERIAL - -$1.60/Engine Flight Hour (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - Fan Blades - 6% spares

RETROFIT CAPABILITY Improvement package is retrofittable as total package - Aircraft power management change and piping changes (QEC mods) in vicinity of fan case stiffener are required.

OTHER IMPACTS Fan speed vs. airflow/thrust changed. Fan nozzle area increased ≈ 2.5%. Noise predicted to be same as current engine.

Figure 23. CF6-50 Fan Improvement (Blades, Operating Line and Stiffener) Screening Assessment.

TITLE Fan Improvement (Blades, Operating Line & Stiffener) CF6-6

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION	Δ% SFC
	ALT, m (ft)/M	
T/O	SLS	-4.5
T/O	0 (0)/0.25	-3.5
CLIMB	7620 (25000)/0.80	-1.6
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-1.6
MAX CRUISE	10668 (35000)/0.85/+10°C	-1.6
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-2.0
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-40 (-89) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +13 kg (+29 lb.)

ΔCG, cm (in) - 0.8 cm (0.3 in.) fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $19,000 increase

RETROFIT - ATTRITION - $19,000 increase

INSTALLATION COST - $12,000 - $20,000 retrofit (includes QEC mods). Negligible cost for new engine installations.

MAINTENANCE

MATERIAL - -$1.60/Engine Flight Hour (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - Fan Blades - 6% spares

RETROFIT CAPABILITY Improvement package is retrofittable as package - Aircraft power management change and piping changes (QEC Mods) in vicinity of fan case stiffener are required.

OTHER IMPACTS Fan speed vs. airflow/thrust changed. Fan nozzle area increased ≈4.0%. Noise predicted to be same as current engine.

Figure 24. CF6-6 Fan Improvement (Blades, Operating Line and Stiffener) Screening Assessment.

TITLE Fan Improvement (Blades and Operating Line) CF6-50

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-1.6
T/O	0 (0)/0.25	-1.3
CLIMB	7620 (25000)/0.80	0
CRUISE, Fn, N (1b)=37800 (8500)	10668 (35000)/0.85	-1.2
MAX CRUISE	10668 (35000)/0.85/+10°C	+0.1
CRUISE, Fn, N(1b)=31100 (7000)	7620 (25000)/0.70	-1.8
HOLD, Fn, N(1b)=28900 (6500)	457 (1500)/0.325	-19 (-41)(1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (1b) - -4.5 kg (-10 1b)

ΔCG, cm (in) - 0

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $13,000 increase

RETROFIT - ATTRITION - $13,000 increase

INSTALLATION COST - Negligible

MAINTENANCE

MATERIAL - - $0.80/Engine Flight Hour (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - Fan Blades - 6% Spares

RETROFIT CAPABILITY Fan blades retrofittable, aircraft power management change required.

OTHER IMPACTS Fan speed vs. airflow/thrust changed. Fan nozzle area increased ≈ 2.5%. Noise predicted to be same as current engine.

Figure 25. CF6-50 Fan Improvement (Blades and Operating Line) Screening Assessment.

TITLE Fan Improvement (Blades and Operating Line) CF6-6

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION	Δ% SFC
	ALT, m (ft)/M	
T/O	SLS	-4.0
T/O	0 (0)/0.25	-3.1
CLIMB	7620 (25000)/0.80	-1.3
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-1.3
MAX CRUISE	10668 (35000)/0.85/+10°C	-1.3
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-1.6
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-35 kg(-78) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - -4.5 kg (-10 lb).

ΔCG, cm (in) - 0

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $13,000 increase

RETROFIT - ATTRITION - $13,000 increase

INSTALLATION COST - Negligible

MAINTENANCE

MATERIAL - -$0.80/Engine Flight Hour (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - Fan Blades - 6% spares

RETROFIT CAPABILITY Fan blades retrofittable, aircraft power management change required.

OTHER IMPACTS Fan speed vs. airflow/thrust changed. Fan nozzle area increased ≈ 4.0%. Noise predicted to be same as current engine.

Figure 26. CF6-6 Fan Improvement (Blades and Operating Line) Screening Assessment.

5.1.1.2 Boeing

Fan Blades, Operating Line and Stiffener

The following nacelle changes would be required to accommodate the fan stiffener modifications:

- The fire detector wire installation will have to be moved forward approximately 4 centimeters on the left-hand side of engine and lowered approximately 4 centimeters at the bottom of the engine. These changes require a longer detector run. The two support brackets at 6:00 and 7:30 o'clock will have to be changed.

- Three hydraulic lines (supply, return, and case bleed return) on the left-hand side of fan case will have to be moved outboard approximately 2.5 centimeters. This will require an increase of approximately 2.5 to 5 centimeters in the length of the three lines.

- The leg to the three support brackets which straddle the flange will have to be lengthened approximately 2.5 centimeters. The other parts of the support bracket will not require changes.

- The fan speed sensor electrical connector will have to be rotated to clear the T-angle on the flange. The wire bundle will also have to be moved to clear the T-angle. The above changes clear the fan cowl by a minimum of 5 centimeters.

In addition to the changes required to accommodate the stiffeners, the increase in fan airflow necessitates an increase in fan nozzle area. This fan nozzle area increase would be obtained by cutting back the fan reverser cowl.

The above changes would not produce an additional aircraft weight increase over the 13 kg per engine resulting from the engine modifications. The additional engine weight and center of gravity change would not require an increase in aircraft structural weight or result in weight and balance restrictions.

The only changes in aircraft maintenance cost or price are those produced by the engine maintenance cost reduction and engine price increase.

General Electric's estimates of specific fuel consumption improvements for this concept would not be affected by installation in the nacelle and were used in the aircraft performance analysis. The block fuel savings are presented in Table VII for the total fan package for both Boeing and Douglas aircraft. In addition to providing a 1 to 2 percent block fuel savings for the B-747, a range increase of 177 km (110 mi) at maximum takeoff gross weight is realized along with an increased payload capability of 2053 kg or 21 passengers on limited routes.

Table VII. Fan Improvement (Blades, Operating Line and Stiffener) Block Fuel Savings (Min. Fuel Analysis).

Δ0EW = +39 kg

	RANGE	ΔFUEL	
	km	kg	%
DC-10-10 (CF6-6)			
	645	-119.3	-1.5
	1690	-261.3	-1.6
	3700	-561.6	-1.8
DC-10-30 (CF6-50)			
	805	-104.3	-1.1
	2735	-412.8	-1.6
	6275	-1157.6	-2.0
B-747-200 (CF6-50)			
	770	-123	-1.1
	3460	-712	-1.7
	6195	-1497	-2.0

Fan Blades and Operating Line

Since no external engine changes are included in this concept, the only nacelle change required would be an increase in fan nozzle area to accommodate the increased fan airflow which would be accomplished by cutting back the fan reverser cowl. The 4.5 kg per engine weight reduction is not sufficient to cause any change in aircraft structural weight or balance.

Since this concept does not require any changes to the airframe, there would be no airplane price increase beyond the engine price increase. In addition, there would be no change in maintenance cost beyond the reduction resulting from the engine changes.

The uninstalled sfc improvement estimates provided by General Electric for this concept were considered to be representative of the levels of installed performance improvement and were used in the aircraft performance analysis. The technical analysis results for the fan blade and operating line adjustment are presented in Table VIII for both Boeing and Douglas aircraft. In addition to providing a 0.7 to 1.3 percent block fuel savings for the B-747, a range increase of 121 km (75 mi) at maximum takeoff gross weight is realized along with an increase payload capability of 1361 kg or 14 passengers.

5.1.1.3 Douglas

The new fan results in a power management change which in turn requires a revision to the thrust rating computer and recertification. The stiffening ring requires a minor replumbing of the hydraulic system on the bottom of the fan case. Otherwise, some rerouting or moving of wires will accommodate the fan case stiffener.

The fuel burned savings are summarized in Table VII for the total fan package, namely, fan blades, operating line, and stiffener and in Table VIII for the fan blades and operating line adjustment only. Detailed fuel burned results for the total fan improvement package were presented in Section 3.2.2 and Figure 7. The results of the minimum fuel analysis and the minimum DOC analysis are very similar. Therefore, for the sake of clarity, only minimum fuel analysis results are being shown.

5.1.2 Fan OGV Redesign (CF6-6, -50)

This concept consists of the redesign of the fan outlet guide vane to better match the new fan. The initial study indicated no payoff, but a subsequent review indicated that there is a potential of 0.5 percent improvement in fan efficiency equivalent to 0.25 percent in sfc. It is, therefore, recommended that this concept be considered in any future studies.

Table VIII. Fan Improvement (Blades and Operating Line) Block Fuel Savings (Min. Fuel Analysis).

ΔOEW = -13.5 kg

	RANGE	ΔFUEL	
	km	kg	%
DC-10-10 (CF6-6)			
	645	-106.6	-1.3
	1690	-219.5	-1.4
	3700	-483.0	-1.5
DC-10-30 (CF6-50)			
	805	-59.0	-0.6
	2735	-271.3	-1.1
	6275	-768.4	-1.3
B-747-200 (CF6-50)			
	770	-77	-0.7
	3460	-463	-1.1
	6195	-984	-1.3

5.1.3 Increased Fan Diameter (CF6-50)

5.1.3.1 General Electric

An increase in bypass ratio for the CF6-50 engines can directly improve fuel consumption from the cycle effects and indirectly allow further improvements resulting from reduced deterioration. The latter effect is a reflection of lower core operating presssures and temperatures attained by increasing the mass flow. Although an inlet larger than those used on current CF6-50 engines is required resulting in a slight drag increase, the reduction of fan stream jet velocity and somewhat smaller diameter core cowling required to match nozzle area requirements should yield scrubbing drag reductions in excess of the increase in inlet drag. The overall installed performance is expected to be improved slightly beyond the increment defined for the uninstalled case.

The higher bypass ratio is obtained through the use of a large diameter fan based on the improved aerodynamic fan design of 2195 mm diameter (see Fan Performance Improvement). The larger fan is projected to be 2311 mm in diameter with a small increase in inlet hub diameter which would necessitate modification of Stage 1 of the booster. The fan will operate at speeds which yield thrust levels comparable to the CF6-50 at a physical high pressure compressor speed no greater than that currently used. This results in slightly reduced fan speeds and will require aerodynamic redesign of the low pressure turbine to retain its aerodynamic efficiency.

The larger fan requires modification of flowpath parts bounding the fan case and fan frame. The diameter increase results in longer fan outlet guide vanes and extension of the frame struts. However, it should be noted that the outer flowpath converges slightly through the fan case and frame to match the fan reverser transcowl diameter and no change is required to the transcowl wall (Figure 27).

Because of the higher loading of the low pressure turbine brought about by both the higher work extraction required to drive the larger fan and the reduction in speed, redesign of the low pressure turbine is desired to avoid efficiency loss. Improved aerodynamic design techniques can be used to design blading which will yield very high efficiency at the higher loading level. Further, it is envisioned that the turbine module will be of "stacked" construction, thereby eliminating the current horizontal split lines. This approach will provide the opportunity to design improved vane/blade overlaps, reduced leakage, and superior roundness control.

The higher bypass fan has a major aircraft system impact such as a larger inlet, modifications of the flowpath bounding fan case and frame, a smaller core cowl, and a revision in the power management.

The following assumptions were used to calculate performance for the increased diameter fan:

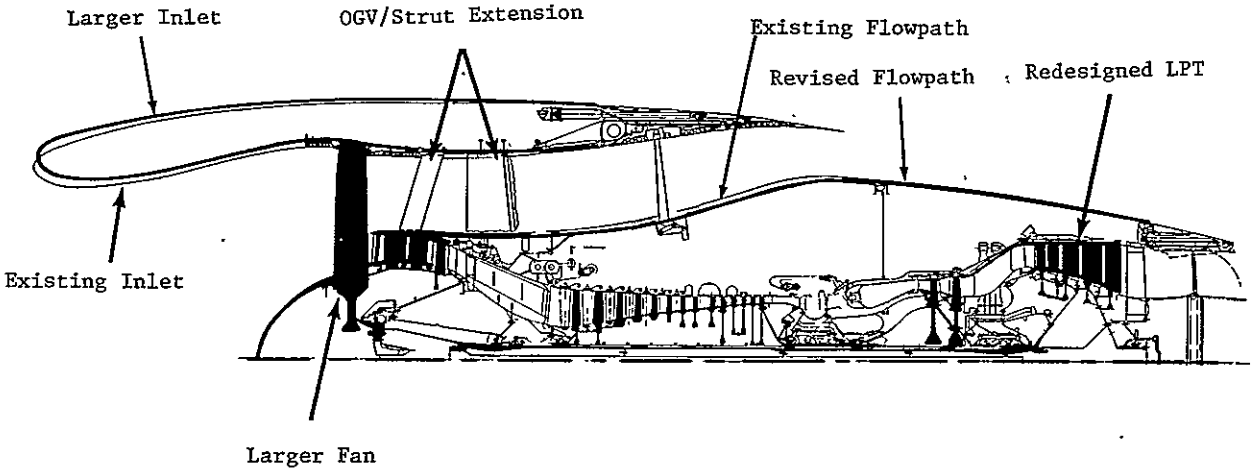


Figure 27. Increased Fan Diameter/Flow Compared to Existing CF6-50.

- Improved performance fan blade, repositioned operating line and reduced tip clearance
- Fan flow increased 12.4 percent
- Bypass duct effective inlet area increased 7.2 percent
- Fan exhaust nozzle area increased 16.1 percent
- Core exhaust nozzle area increased 6.8 percent
- Low pressure turbine rebladed to hold efficiency at the higher loading

The technical assessment for the higher bypass fan concept is shown in Figure 28. The predicted cruise sfc reduction for this concept was 3.5 percent.

TITLE Higher Bypass Fan (CF6-50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-9.6
T/O	0 (0)/0.25	-6.4
CLIMB	7620 (25000)/0.80	-3.0
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-3.5
MAX CRUISE	10668 (35000)/0.85/+10°C	-3.5
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-3.5
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-9 kg (-20.0 lb)(1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - 227 kg (500 Lb.)

ΔCG, cm (in) - 5 cm (2 in) Forward

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $200,000 (Increase)

RETROFIT - Not Evaluated

INSTALLATION COST - Included in new engines

MAINTENANCE

MATERIAL - -$3.00/engine flight hour (reduction)(3)

DIRECT LABOR - -0.1 man hours/engine flight hour (reduction)

INVESTMENT SPARES RATIO - Fan blades 6%

RETROFIT CAPABILITY Increased fan diameter of 91" (86.4" Base) requires increase in inlet size and modification of flow path parts bounding fan case and frame. Flow path matches fan reverser transcowl; no change required to transcowl wall. Requires smaller core cowling to match increase in fan nozzle area.

OTHER IMPACTS

(3) Based on constant thrust

Figure 28. CF6-50 Higher Bypass Fan Screening Assessment.

5.1.3.2 Boeing

The fan diameter increase from 2195 mm to 2311 mm requires an increase in inlet size, in addition to changes in the fan cowl, side cowl and strut. The inlet would be scaled up to maintain the length to diameter ratio of the existing CF6-50 engine inlet with the outside contour being modified to produce the same radial space at the fan frame. The fan cowl would require recontouring to match the new inlet at the forward end and would have the same diameter as the existing cowl at the aft end. The side cowl would be recontoured to fair from the fan nozzle to the turbine nozzle. The strut forward fairing would be recontoured to match the new inlet. The fairing between the nacelle and the engine must be revised to match the nacelle contour. The support hinges for the side cowl would be modified to suit the new contour.

The structure of the strut would be changed as necessary to support the additional engine weight. The engine mount locations would be the same with the only changes required being those necessary to carry the additional engine weight.

The above changes impact weight on several components. The weight changes would be as follows:

Engine		+227.0 kg per engine
Inlet		+ 79.8 kg per inlet
Fan Cowl		+ 5.0 kg per nacelle
Aft Core Cowl		- 5.9 kg per nacelle
Fan Duct		+ 10.4 kg per nacelle
Strut and Wing		+ 36.3 kg per nacelle
	Total	+352.6 kg

The changes to the inlet, nacelle and strut, coupled with the certification test requirements of this concept, would result in an airframe price increase of $560,000. When the engine price increase of $800,000 per shipset is included, the total airplane price would increase by $1,360,000. There would be no change in inlet or nacelle maintenance cost.

The installed sfc improvements used were the same as the uninstalled sfc improvement estimates provided by General Electric. The results of the technical analysis of this concept are summarized in Table IX. In addition to the fuel savings of 2.2 to 2.3 percent, the aircraft range increases by 225 km (140 mi) and the payload increases by 2495 kg (5500 lb).

5.1.3.3 Douglas

This concept has merit as a way to increase thrust for growth aircraft but does not appear to be practical for the DC-10 fuel savings applications before 1982.

Table IX. Increased Fan Diameter (CF6-50) Block Fuel Savings (Min. Fuel Analysis).

	Range	ΔFuel	
	km	kg	%
B-747-200	770	-249.5	-2.2
	3460	-1193	-2.9
	6195	-2468	-3.3

The improvement with the higher bypass ratio fan needs to be compared to the improved fan. Compared to this improved fan, the higher bypass engine improvement is 1.7 percent. The weight effect needs to be subtracted from this, which results in an equivalent fuel savings of approximately 1 percent.

The concept requires increasing the inner diameter of the last vertical tail banjo spar or moving the engine aft to prevent excessive flow diffusion angles in the inlet just ahead of the fan on the tail engine. These are major changes to the DC-10 and would require more in-depth studies and analyses to determine costs.

The concept requires major changes to the nacelle and pylon hardware and will require recertification because of changes in noise, power management, and performance. Because there are changes in the fan that supercharges the gas generator and in the low pressure turbine, for all practical purposes from the airframe aspects, it is close to being a new engine.

The $600,000 price increase for engines in a trijet plus an estimate of a $200,000 or more increase in airframe cost indicates the payback period will exceed 10 years, since it will be more than 14 times that of the fan improvement concept when the fan improvement concept is used as the base.

5.1.4 Front Mount (CF6-6, -50)

5.1.4.1 General Electric

The present CF6 engine forward mount system shown in Figure 29 is a rigid link connection of the mount to the fan frame 12 o'clock midstrut casting. Fan frame analysis and component testing have shown that the clevis support beams which connect the clevis to the high pressure case flange transmit large radial and axial point loads. These point loadings result in localized compressor case distortions which, when coupled with the engine system "backbone" bending modes, require larger than desired compressor blade-to-case clearances in order to eliminate heavy rotor rubs (Figures 30 and 31). Further, aircraft certification of the higher thrust CF6-50 engine configurations has indicated more extensive high pressure rotor rubs through Stage 11 than previously observed. The present mount system at these higher rated thrust loads will require even greater increases in blade clearances in order to eliminate heavy rotor rubs with attendant losses in performance and stall margin.

A finite element structural analytical model of the engine which includes the engine core structure between the engine mounting frames has been correlated with component test results. Using the correlation of the structural analytical model to the baseline component tests, a series of tests was conducted in concert with analysis in order to minimize the local effects of point loadings on the high pressure case. Based on this effort,

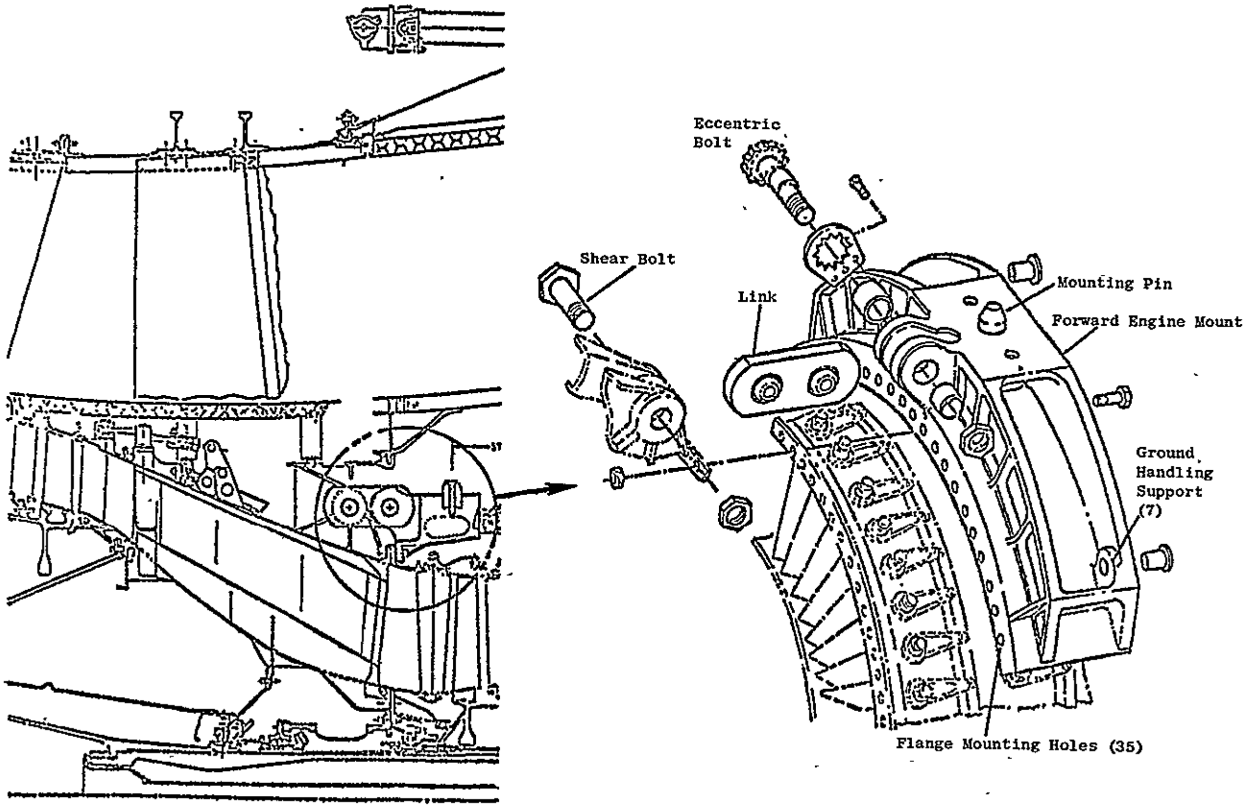


Figure 29. Current CF6 Forward Mount System.

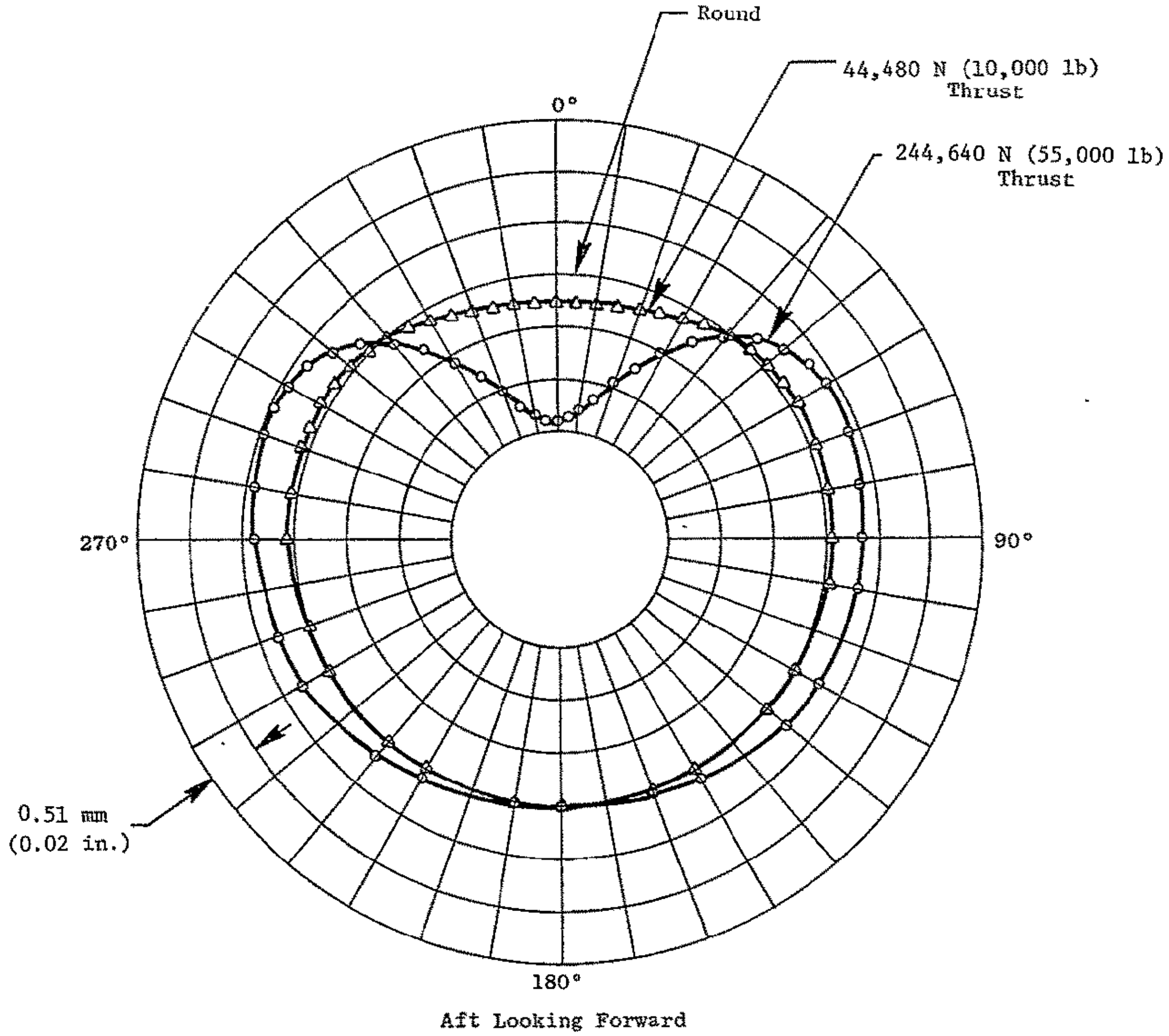


Figure 30. Typical Compressor Case Circumferential Distortion (Stage 3 Test Data Shown).

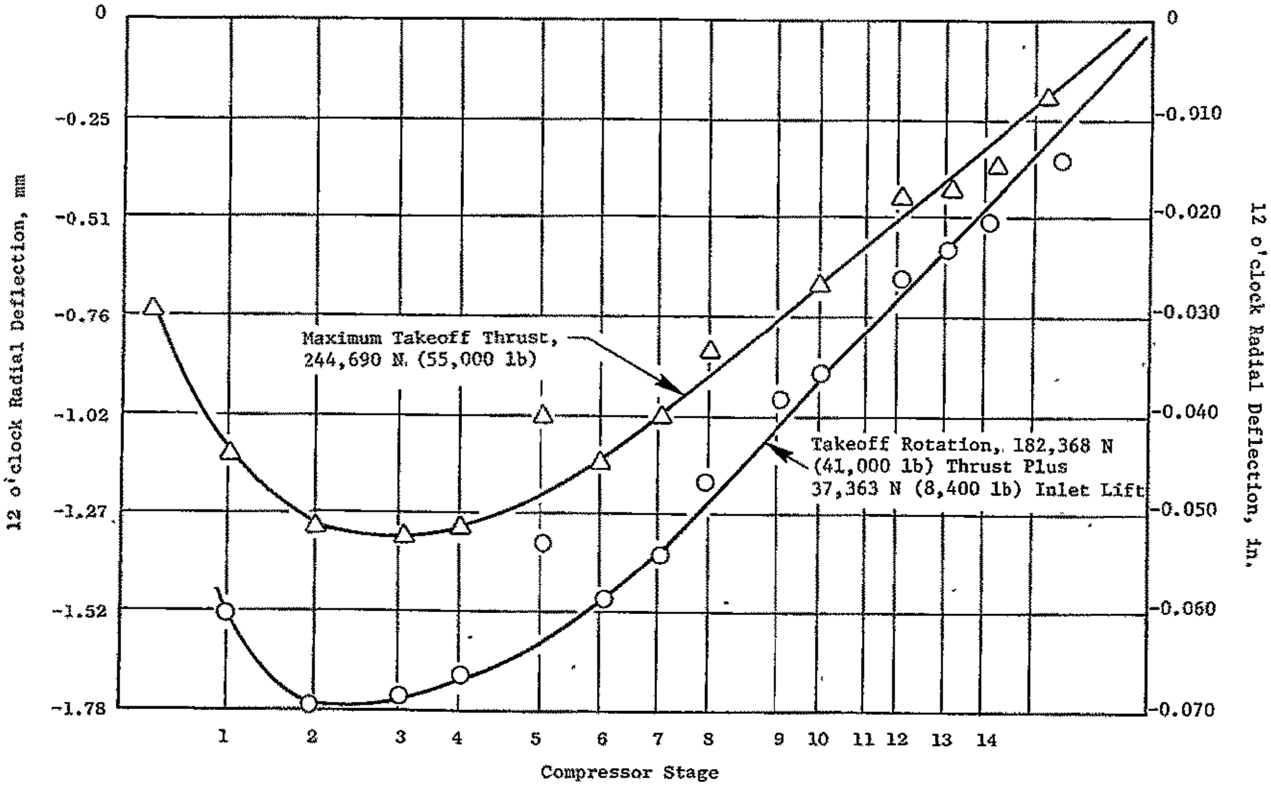


Figure 31. Compressor Case Radial Deflection as a Function of Compressor Stage.

a mount system was conceived that minimizes the local effects. This mount applies the engine thrust reaction at two points $\pm 30^\circ$ from the top vertical centerline and reacts engine vertical and side forces with a series of links (Figure 32).

A prototype mount with this approach was component tested and showed a sizeable reduction in high pressure core deflection. Figure 33 presents the predicted improvement in compressor deflection with the new front mount versus the present production mount for the takeoff rotation condition. Also presented for comparison is the predicted core engine beam bending which is the minimum distortion possible without major stiffening of the compressor case.

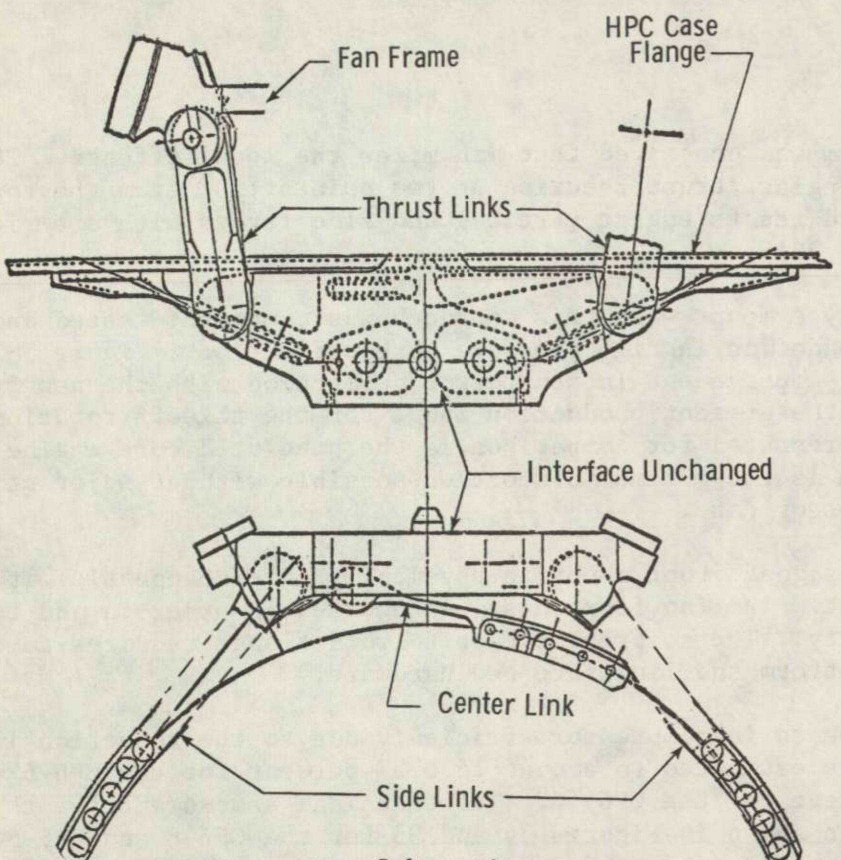
The redesigned front mount is physically interchangeable with the original mount. The fan frame must be reworked in order to add the thrust link capability. The compressor case forward flange requires some rework. The mount platform and links are new hardware.

Improvements in compressor efficiency due to the reduction in running clearance were estimated to amount to 0.57 percent for the CF6-6 engine and 0.43 percent for the CF6-50. The technical assessment for the new front mount is shown in Figures 34 and 35 for the CF6-6 and CF6-50 engines. The new front mount predicted cruise sfc improvement is about 0.3 percent, and the predicted ΔEGT improvement at takeoff is about 3.5° C. This concept increases engine weight by 4.5 kg (10 lb) and increases the engine price by $3000.00.

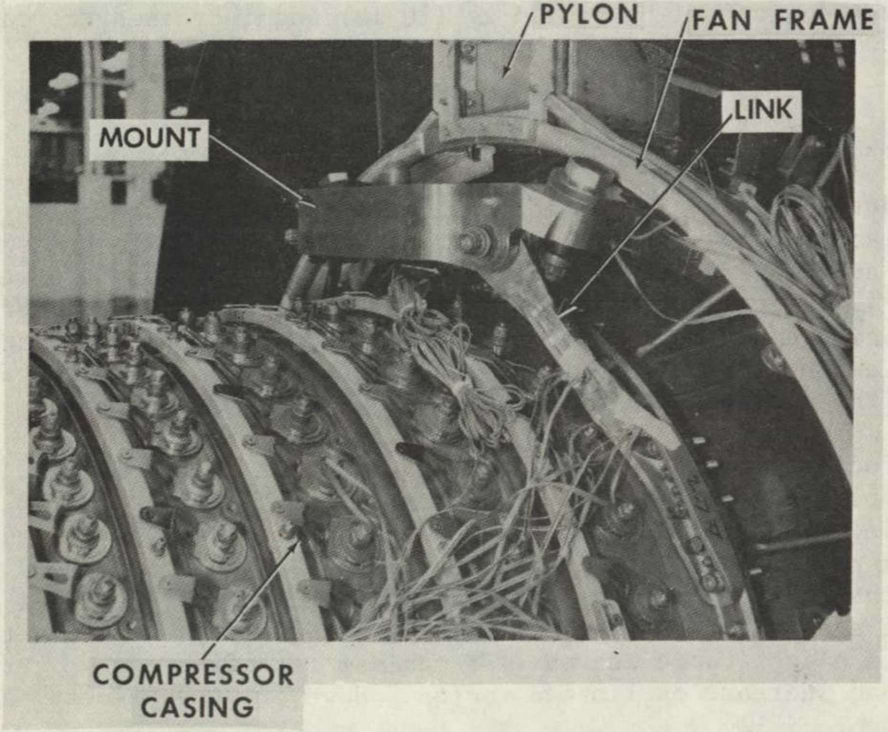
5.1.4.2 Boeing

The redesigned front mount is physically interchangeable with the present mount, and the rework of the fan frame and forward high pressure case flange does not require nacelle modifications. In addition, the weight increase of 4.5 kg per engine and slight center of gravity movement do not require airframe structural changes. As a result, the only changes in aircraft weight, price, and maintenance cost are those attributable directly to the engine.

Block fuel savings for the front mount concept are summarized in Table X for both Boeing and Douglas aircraft. The sfc improvement estimates supplied by General Electric were used directly and, when coupled with the weight increase, result in a savings of approximately 0.2 percent to 0.3 percent in block fuel depending on flight length. The fuel burn savings were sufficient to overcome the operating empty weight increase and provide a slight range increase at maximum takeoff gross weight or a slight payload increase on limited routes. However, these increases were negligible.



a. Schematic



b. Photograph

Figure 32. New Front Mount.

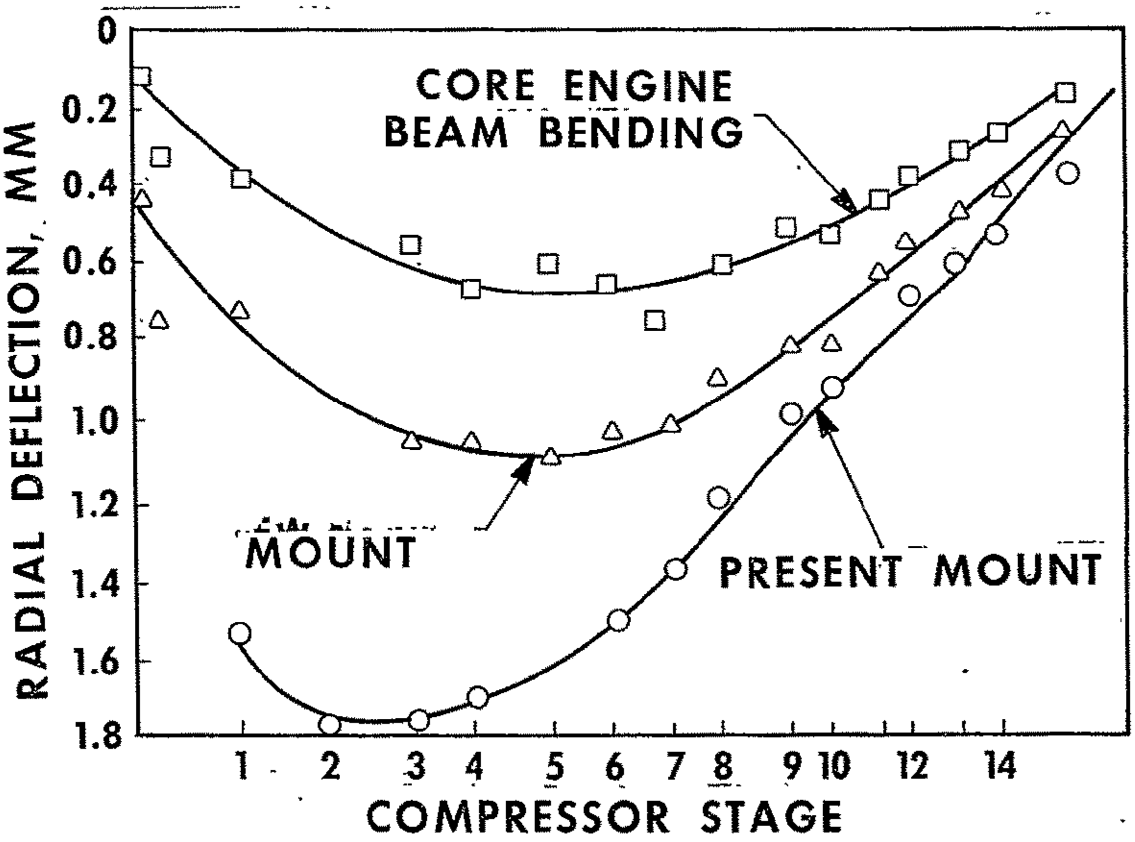


Figure 33. Calculated Front Mount Radial Deflection Comparison 12 O'Clock Position Takeoff/Rotation.

TITLE Front Mount (CF6-6)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-.5
T/O	0 (0)/0.25	-.5
CLIMB	7620 (25000)/0.80	-.3
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.3
MAX CRUISE	10668 (35000)/0.85/+10°C	-.3
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.4
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-9 kg. (-20lb) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +4.5 kg (+10 Lb.)

ΔCG, cm (in) - 0.08 cm (0.03 in) Fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $3000 increase

RETROFIT - Not Evaluated

INSTALLATION COST - 'Negligible for new engine.

MAINTENANCE

MATERIAL - $0.50 reduction/engine flight hour

DIRECT LABOR - negligible

INVESTMENT SPARES RATIO - ≈ 0% spares

RETROFIT CAPABILITY The redesigned mount is physically interchangeable with the present mount. The fan frame and the fwd. HP case flange must be reworked.

OTHER IMPACTS Needs new compressor with tighter clearances.

Figure 34. CF6-6 Front Mount Screening Assessment.

TITLE Front Mount (CF6-50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-.3
T/O	0 (0)/0.25	-.3
CLIMB	7620 (25000)/0.80	-.2
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.3
MAX CRUISE	10668 (35000)/0.85/+10°C	-.2
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.3
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-7.7 kg (-17 lb) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +4.5 kg (+10 Lb.)

ΔCG, cm (in) - 0.08 cm (0.03 in) Fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $3000 increase

RETROFIT - Not Evaluated

INSTALLATION COST - Negligible for new engine

MAINTENANCE

MATERIAL - $0.50 reduction/engine flight hour

DIRECT LABOR - negligible

INVESTMENT SPARES RATIO - ≈ 0% spares

RETROFIT CAPABILITY The redesigned mount is physically interchangeable with the present mount. The fan frame and the fwd. HP case flange must be reworked.

OTHER IMPACTS

Figure 35. CF6-50 Front Mount Screening Assessment.

Table X. Front Mount Block Fuel Savings (Min. Fuel Analysis).

	RANGE	ΔFUEL	
	km	kg	%
DC-10-10 (CF6-6)			
	645	-20.9	-0.3
	1690	-47.2	-0.3
	3700	-101.2	-0.3
DC-10-30 (CF6-50)			
	805	-21.3	-0.2
	2735	-73.5	-0.3
	6275	-199.6	-0.3
B-747-200 (CF6-50)			
	770	-22	-0.2
	3460	-123	-0.3
	6195	-254	-0.3

5.1.4.3 Douglas

The new front mount is designed to attach to current airframe mount points and, therefore, has no effect on the airframe. The operating empty weight of the airplane increases by 14 kilograms. Block fuel savings are tabulated in Table X for the minimum fuel analysis.

5.1.5 Compressor Rotor/Stator Thermal Match (CF6-50)

5.1.5.1 General Electric

Improved transient thermal matching of the compressor rotor and stator was proposed by incorporating separate flowpath liners in the compressor casing structure from the flowpath gas stream, thereby slightly reducing the casing steady-state temperature and increasing the transient response time during transient conditions to more closely match the thermal response of the compressor.

The linered casing construction consists of a slightly increased diameter of the casing structure with individual liner segments installed in circumferential tracks machined in the casing inner wall (Figure 36). The liners subsequently have circumferential tracks machined to position the Stages 6-11 fixed stator vanes. The proposed stator construction offers the potential for further insulating the stator structure from the flowpath by incorporating an insulation material in the cavity between casing and liners to further retard heat transfer.

The redesigned casing is interchangeable with the original configuration as a stator assembly. Modification or redesign of some actuation rings and levers will be required to be compatible with the redesigned casing. The stator vanes are totally interchangeable.

The proposed compressor casing offers significant improvement in durability by protecting the primary structure from flowpath damage and heavy blade rub. The linered casing would permit replacement of damaged liners without requiring casing repair, thereby providing a long range maintainability advantage.

An improvement in compressor efficiency of 0.48 percent has been estimated. This amounts to a 0.2 percent reduction in cruise sfc. The technical assessment of this concept is shown in Figure 37.

5.1.5.2 Boeing

This concept does not require changes to the nacelle or airframe; therefore, the only impact on airplane price and maintenance cost would be that resulting from the engine modification. The modest weight increase of 31.8 kg per engine will not result in an increase in aircraft structure or require weight and balance restrictions. The estimates of sfc improvements

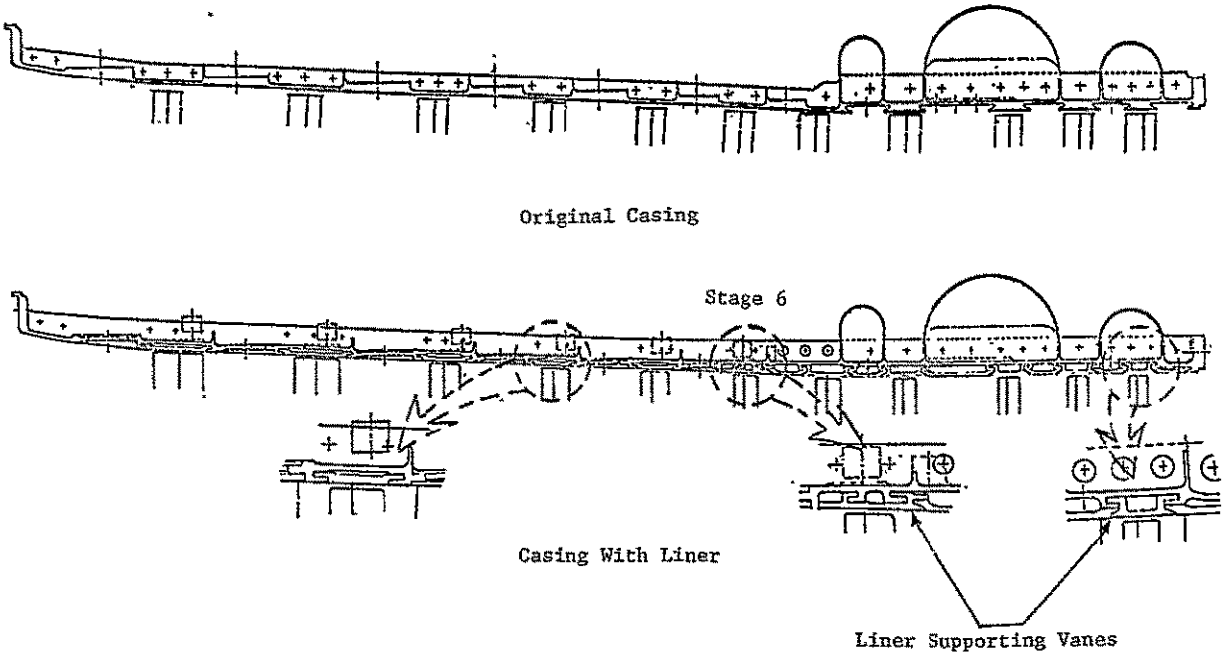


Figure 36. Compressor Rotor/Stator Thermal Match.

TITLE Compressor Rotor/Stator Thermal Match (CF6-50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-.3
T/O	0 (0)/0.25	-.3
CLIMB	7620 (25000)/0.80	-.2
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.2
MAX CRUISE	10668 (35000)/0.85/+10°C	-.2
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.3
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-7.7 (-17 lb)(1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +31.8 (+70 lb)

ΔCG, cm (in) - 0.15 cm (0.06 in.) fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $25,000 Increase

RETROFIT - Not Evaluated

INSTALLATION COST - Included in new engines.

MAINTENANCE

MATERIAL - $0.30/engine flight hr. (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY The redesigned casing is interchangeable as a stator assembly, modification of some actuation rings and levers will be required.

OTHER IMPACTS

Figure 37. CF6-50 Compressor Rotor/Stator Thermal Match Screening Assessment.

provided by General Electric would not suffer from installation effects and were, therefore, used in the airplane performance analysis. The block fuel savings are shown in Table XI. The savings resulting from the sfc reduction and operating empty weight increase vary from 0.1 percent to 0.2 percent depending on flight length. While the operating empty weight increase is compensated for by the sfc improvement and a block fuel savings is realized, there is a negligible gain in range and payload capabilities.

5.1.5.3 Douglas

The changes are internal to the engine and there is no effect on the airframe. The aircraft OEW is increased by 95 kg. Block fuel savings, calculated for the DC-10-30, are shown in Table XI.

5.1.6 Reduced Stator Bushing Leakage (CF6-50)

5.1.6.1 General Electric

It was proposed to reduce the variable stator vane (VSV) bushing leakage on Stages 3-5 of the CF6-50 compressor by changing vane configuration from low boss to high boss configuration as shown in Figure 38. This would be accomplished by redesigning both the stator casing and vanes to reduce the bushing wear and breakage by reacting the airfoil gas moment through an increased wheel base journal reaction, rather than the current low boss washer face reaction.

The proposed design will include a common bushing design on Stages 3-5 and reduce the total number of bushing and spacer parts provisioned from 42 to 3. The high boss stator system would be functionally interchangeable with the current stator system but would require replacement of casing, vanes, bushings, and levers. The life of the proposed bushing system is expected to be significantly greater than the current design due to lower bearing stresses and elimination of the dependency on selective fit to establish the correct bearing fit. The maintainability of the redesigned VSV system will be improved by eliminating the need for selective fitting spacers to achieve the proper radial stackup of the vane. Assembly is as currently required for the low boss system.

The proposed change would improve performance by reducing the bushing bearing stress and providing a close journal fit in nonwearing areas to reduce the bushing leakage. The technical assessment, shown in Figure 39, indicates a 0.1 percent improvement in sfc.

5.1.6.2 Boeing

The high boss stator system which reduces stator bushing leakage does not require inlet or nacelle modifications, and the 9 kg per engine weight increase will not impact the airframe structural weight or impose weight

Table XI. Compressor Rotor/Stator Thermal Match Block Fuel Savings (Min. Fuel Analysis) (CF6-50).

	RANGE	ΔFUEL	
	km	kg	%
DC-10-30			
	805	-13.6	-0.1
	2735	-38.6	-0.2
	6275	-105.2	-0.2
B-747-200			
	770	-13.6	-0.1
	3460	-68.0	-0.2
	6195	-140.6	-0.2

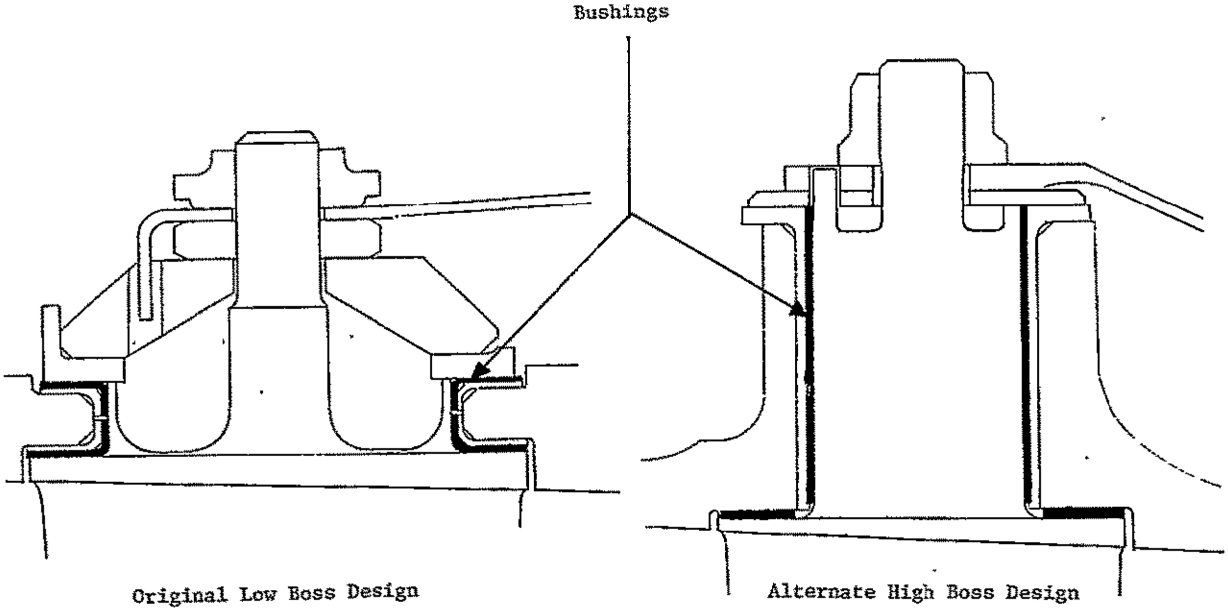


Figure 38. Stator Boss Configuration.

TITLE Reduced Stator Bushing Leakage (CF6-50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION	Δ% SFC
	ALT, m (ft)/M	
T/O	SLS	-.1
T/O	0 (0)/0.25	-.1
CLIMB	7620 (25000)/0.80	-.1
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.1
MAX CRUISE	10668 (35000)/0.85/+10°C	-.1
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.1
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-1.8 (-4 lb) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +9 (+20 lb)

ΔCG, cm (in) - 0.08 cm (0.03 in) fwd

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $13,000 (Increase)

RETROFIT - Not Evaluated

INSTALLATION COST - Included in new engine price.

MAINTENANCE

MATERIAL - -$0.15 (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY The high boss stator system is functionally interchangeable and provides replacement of casing, vanes, bushings and levers.

OTHER IMPACTS

Figure 39. CF6-50 Reduced Stator Bushing Leakage Screening Assessment.

and balance restrictions. Since no airframe modifications are required, there would not be any impact on airplane price other than the engine price increase.

The installed sfc improvement was considered to be the same as the uninstalled sfc improvement provided by General Electric and was, therefore, used in the airplane performance analysis. The fuel savings produced by this concept are approximately 0.1 percent for the flight lengths analyzed (Table XII). This fuel savings coupled with the 36 kg increase in operating empty weight result in negligible increases in range and payload.

5.1.6.3 Douglas

This concept is internal to the engine and does not affect the airframe. The aircraft OEW is increased by 27 kg. Block fuel savings for the minimum fuel case were calculated for the DC-10-30 as shown in Table XII.

5.1.7 Improved Compressor Stage 1 Blade (CF6-6 and CF6-50)

5.1.7.1 General Electric

Aerodynamic design analyses of the exit flow field indicate that the Stage 1 efficiency could be potentially improved by about 2 percent with an overall compressor efficiency improvement of about 0.2 percent through redesign. If this improvement were achieved, cruise sfc reductions of approximately 0.08 percent and 0.11 percent would result for the CF6-50 and -6 engines, respectively. However, the development cost of the new blade is estimated to be in excess of $600,000, including extensive testing and, particularly, a telemetry stress engine. Further, the improvement is well within the overall measurement accuracy band; thus, it will be nearly impossible to determine if the gain achieved is other than any gain implied by measured changes in blade exit profiles.

The concept has been deleted because of the high cost for the small (0.1 percent sfc) payoff.

5.1.8 Compressor Dovetail Seals (CF6-50)

5.1.8.1 General Electric

It was proposed to improve performance by reducing compressor recirculation leakage through improved sealing of the radial gap between the rotor spool and the underside of the blade platforms. This improvement would be obtained by machining a shallow 360° groove in the spool under the blade platform near the leading edge on Stages 3-14 circumferential dovetail blades. A closely fitting wire seal would be installed in the groove prior to assembling the rotor blades (Figure 40). During engine operation, centrifugal loading would seat the wire against the underside of the blade

Table XII. Reduced Stator Bushing Leakage Block Fuel Savings (Min. Fuel Analysis) (CF6-50).

	RANGE	ΔFUEL	
	km	kg	%
DC-10-30			
	805	-6.8	-0.1
	2735	-21.8	-0.1
	6275	-57.6	-0.1
B-747-200			
	770	-9.1	-0.1
	3460	-36.3	-0.1
	6195	-77.1	-0.1

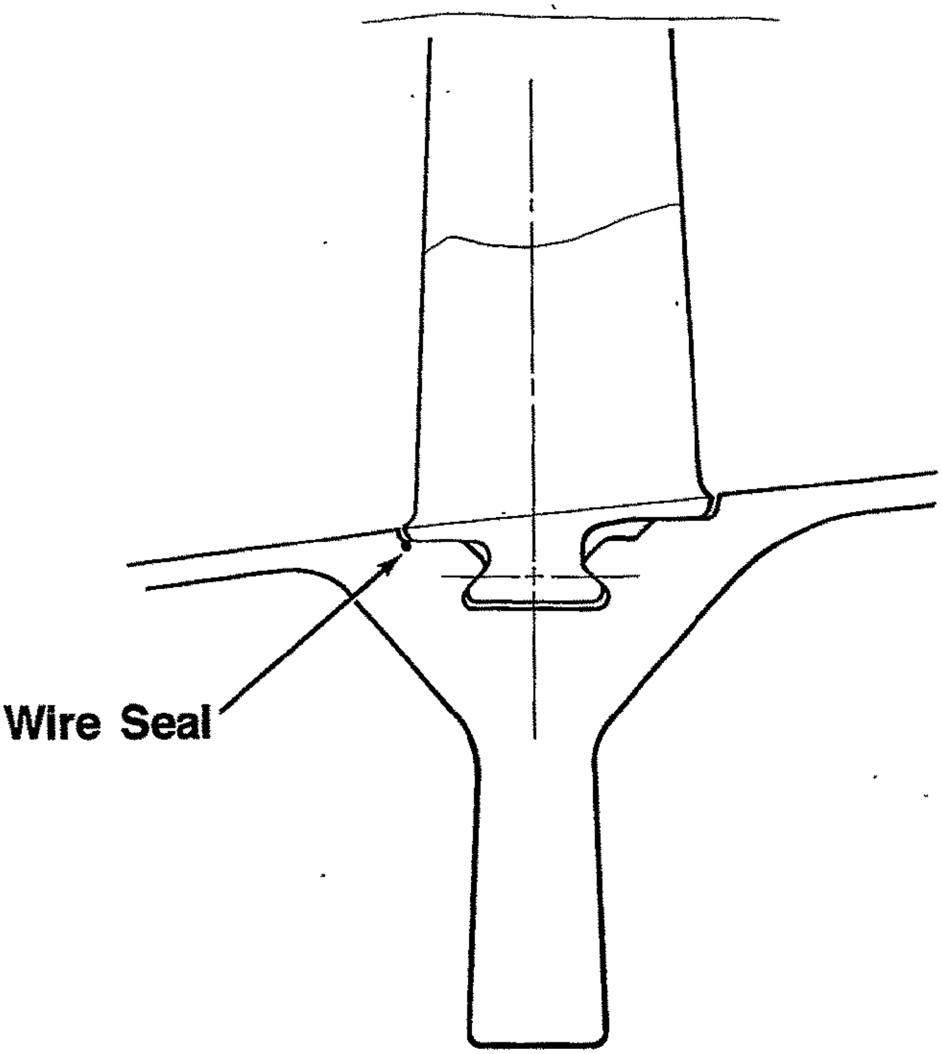


Figure 40. Dovetail Seal.

platform, restricting the flow area between blade and spool. The proposed configuration is interchangeable with and reworkable from the existing compressor rotor.

Total compressor efficiency loss due to rotor platform leakage has been calculated at 0.25 percent. The proposed platform seal is expected to reduce the leakage flow approximately 50 percent. Blade-to-blade platform variation and centrifugal deflection of the convex platform corner will prevent total area blockage. Thus, the expected improvement is estimated to increase compressor efficiency by 0.12 percent and provide a 0.1 percent reduction in sfc. The technical assessment is shown in Figure 41.

5.1.8.2 Boeing

This concept does not require changes to the airframe itself. The estimated sfc improvements would not suffer from installation effects. This concept is unique, however, in that it does not produce any change in operating empty weight. The results are shown in Table XIII. Improvements in range and payload are negligible.

5.1.8.3 Douglas

This concept is internal to the engine and does not increase the airplane OEW. The minimum fuel analysis block fuel savings are summarized in Table XIII.

5.1.9 Compressor Blade Coatings (CF6-6, -50)

5.1.9.1 General Electric

The subject concept offered the potential for performance improvement/retention through prevention/retardation of compressor blade erosion. The evaluation of this concept covered a review of a field survey, a review of a coating study, a cost study and a review of other programs aimed at reducing compressor blade erosion and increasing blade erosion life.

From a recent survey of field engines at three different customer locations, the following conclusions were reached regarding blade erosion:

- Erosion is essentially uniform on Stages 3-16 blades.
- Leading edge chord wears at a rate of 0.25 millimeter per 1000 flight cycles (equivalent to about 2400 hours).
- Trailing edge thinning occurs on the concave side of the airfoil tip at a rate of 0.06 millimeter per 1000 flight cycles.

TITLE Compressor Dovetail Seals (CF6-50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION	Δ% SFC
	ALT, m (ft)/M	
T/O	SLS	-.1
T/O	0 (0)/0.25	-.1
CLIMB	7620 (25000)/0.80	-.1
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.1
MAX CRUISE	10668 (35000)/0.85/+10°C	-.1
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.1
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-1.8 (-4 lb) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - 0

ΔCG, cm (in) - 0

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $900 Increase

RETROFIT - ATTRITION - $900.

INSTALLATION COST - No cost at core engine overhaul.

MAINTENANCE

MATERIAL - $0.15/engine flight hour (reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY Sealing configuration is interchangeable with and reworkable from the existing compressor rotor.

OTHER IMPACTS

Figure 41. CF6-50 Compressor Dovetail Seals Screening Assessment.

Table XIII. Compressor Dovetail Seals Block Fuel Savings (Min. Fuel Analysis) (CF6-50).

	RANGE	ΔFUEL	
	km	kg	%
DC-10-30			
	805	-8.2	-0.1
	2735	-25.4	-0.1
	6275	-68.0	-0.1
B-747-200			
	770	-9	-0.1
	3460	-45	-0.1
	6195	-86	-0.1

- Blade erosion life is controlled by trailing edge thickness.
- Average blade life is 5600 cycles or about 13,000 hours.
- Properly timed rework may add as much as 2000 cycles additional life.

From a study of erosion resistant coatings conducted by General Electric on various substrate materials, the following conclusions can be reached:

- Most coatings investigated offered negligible increases in erosivity.
- The only coatings which increased erosivity significantly are the carbide coatings.
- All the coatings reduced the fatigue strength of the titanium parent metal.
- Most coatings increased the surface roughness which would result in a decrease in performance.
- Increased coating thickness would be required at the leading edge and the trailing edge tip of the blade; this is difficult to achieve.

Blade coating costs are quite high and amount to about one-third of new parts costs. Based on an average blade erosion life of 5600 cycles, the break-even life requirements of blade coatings are, therefore, about 1900 cycles. Consideration must also be given to the potential of foreign object damage (FOD). As the cycles/hours increase on blades, so does the random probability of FOD which would keep blades from attaining their full life potential.

Programs released or proposed by General Electric would add an average of 0.15 to 0.20 millimeter additional material at the tip trailing edge for the middle stages (4-10). Blade erosion life for these stages is estimated to increase to 8400 cycles, an additional 2800 cycles over the average blade erosion life.

Blade erosion life would also be increased by the vortex suppressor concept (Vortaway). FOD and airfoil erosion are reduced proportionally to the reduction in ingested materials.

In summary, it is concluded from the above reviews that there is more payoff in ruggedizing blade tips and to reduce ingestion by vortex suppression. Further, there is ample supporting work on compressor blade coatings in progress outside the Performance Improvement Program. Accordingly, it was recommended that this concept not be studied any further.

5.1.10 High Pressure Turbine Roundness Control (CF6-50)

5.1.10.1 General Electric

The objective of this concept was to develop passive rotor/stator thermal matching schemes to provide roundness and allow for reduced blade tip clearances for the CF6-50 high pressure turbine (HPT). The modifications proposed fall into two categories:

1. Modifications to engine structural components such as low pressure turbine (LPT) casing, turbine midframe (TMF), compressor rear frame (CRF), etc., to improve the overall level of engine roundness (see Figure 42).
2. Modification of the high pressure turbine supporting structures to reduce the deteriorating effects of cavity recirculation of hot gases and to provide a more suitable transient response match between the static and rotating structures to permit a reduction in running clearances.

These two endeavors are intimately related. The design of a high pressure turbine support structure can provide running clearance reductions only in proportion to the ability of the engine to stay round. If engines do not stay round, running clearances must be increased directly with out-of-roundness to avoid contact between the rotating and stationary structures. This contact will cause deterioration both in engine performance levels, as well as in the actual hardware; and it is, therefore, desirable to minimize this condition.

Since the frames and casings comprise the primary engine structure, they are inherently stiff, rugged components. Any distortions which they experience will be directly transmitted throughout the engine. The Category 1 effort, which is to improve the overall roundness, will provide several changes to components and include:

- Eliminating circumferential thermal gradients with improved liner purge cavity seals.
- Equalizing the thermal growth of TMF struts by providing symmetrical strut temperatures.
- Modifying the engine mount design to spread the points where loads are reacted.
- Providing better sealing, shielding and cooling at casing split lines.

A typical HPT shroud support deflection is shown in Figure 43 as an example of component out-of-roundness. These shroud distortions occur during the thermal transients following the engine acceleration from idle to maximum power.

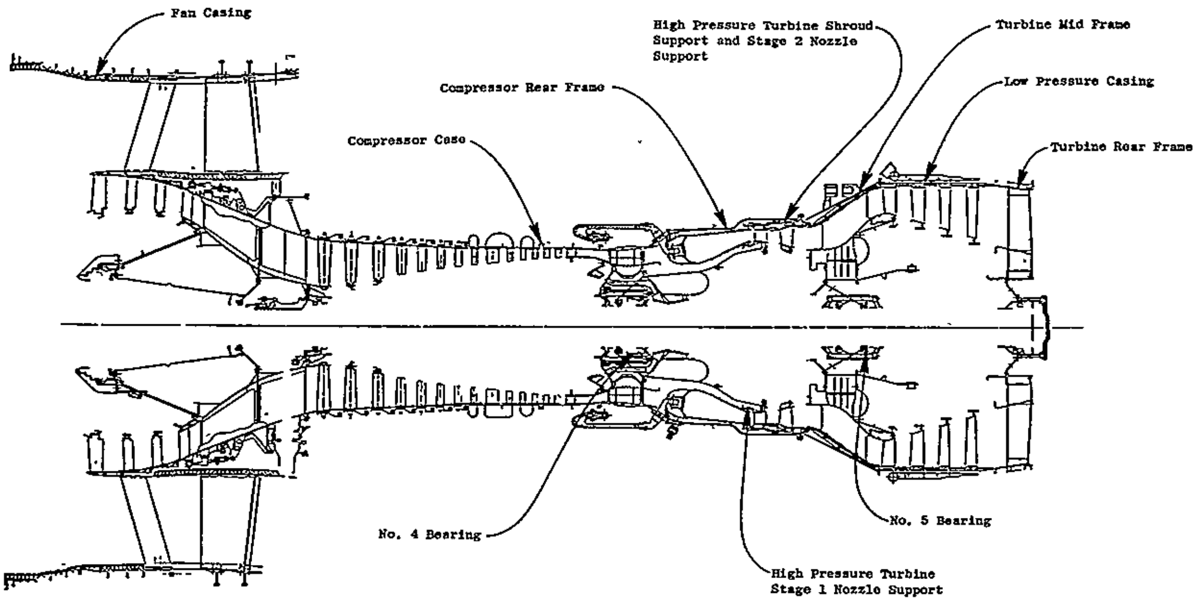


Figure 42. CF6-50 Major Cases and Frames.

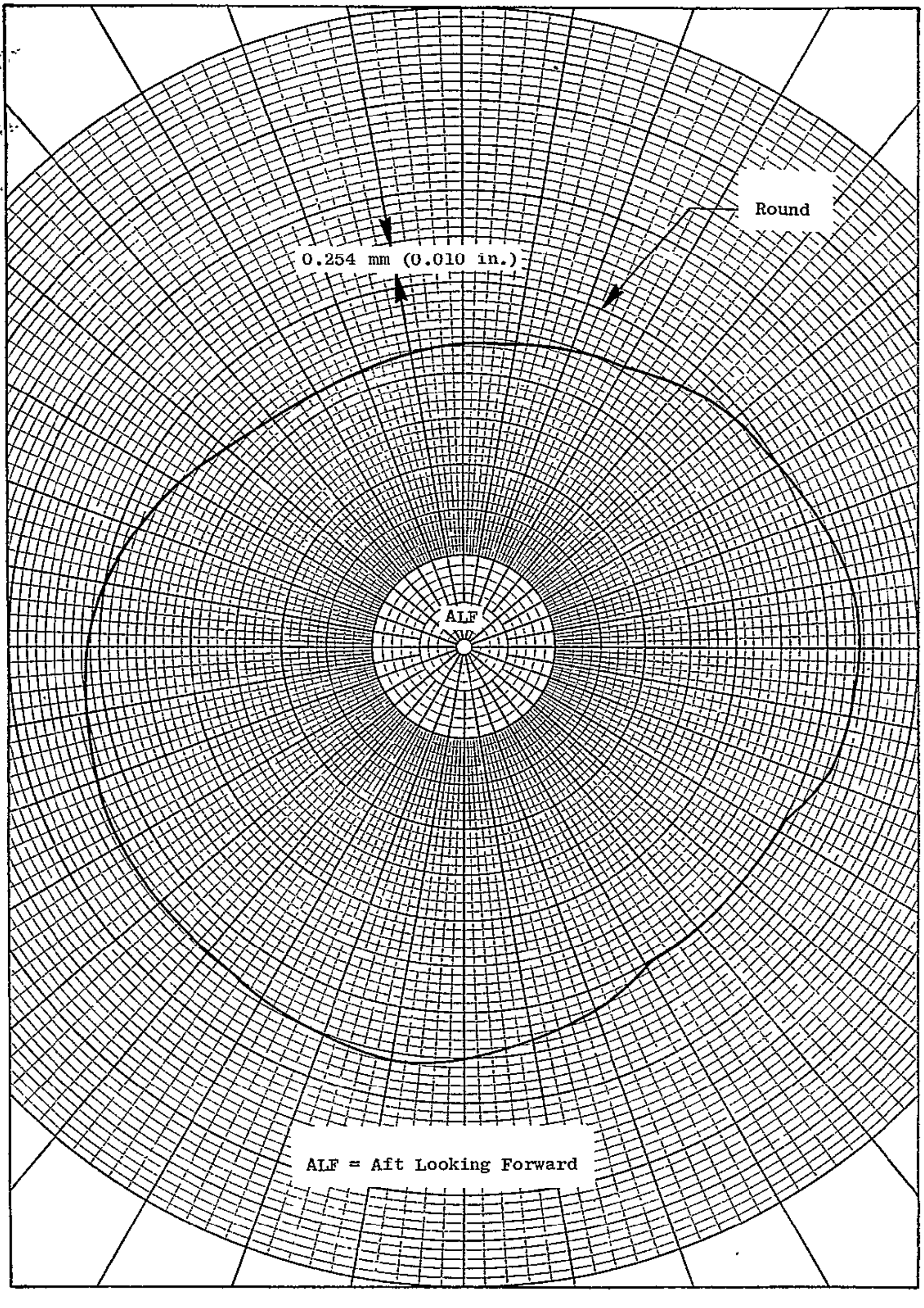


Figure 43. Typical HPT Shroud Support Deflection Relative to TMF Hub Centerline.

The Category 2 activity will address the modification of both the supporting structures as well as flowpath components as indicated in Figure 44. Cavities between flowpath components will be reduced in size as will the passages which permit hot gas to communicate with these cavities from the flowpath. This will reduce the probability of local component circumferential hot spots which generate out-of-round distortions and make cavities easier to purge.

Supporting structures themselves will be modified so as to provide a transient response characteristic which more closely approximates that of the blade tip than is currently available. This may be accomplished by modifying the environment in which the part exists and by altering the thermal inertia of the structure. Material changes in the supporting structure to select thermal expansion coefficients which permit a better response match with the turbine rotor will be included in this category. Materials under consideration include Inconel 903 and CTX2 which have low coefficients of expansion (COE). The effect of these materials on the HPT operating clearances is shown schematically in Figure 45.

In addition, studies of concepts to isolate the HPT shroud support will be conducted. This isolation will be accomplished by a design in which the radial stiffness of the shroud tie to the compressor rear frame-turbine midframe flange is softened sufficiently to permit the frames to distort without affecting the roundness or location of the shroud support ring.

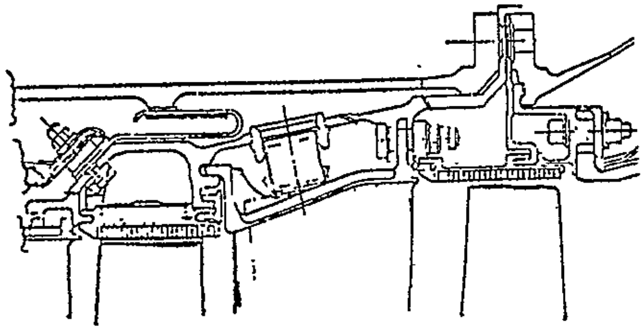
The clearance/roundness control package may be offered as an option or a kit to substitute for conventional hardware. No modifications to airframe or cowls are required.

Performance improvements must be assessed in two categories:

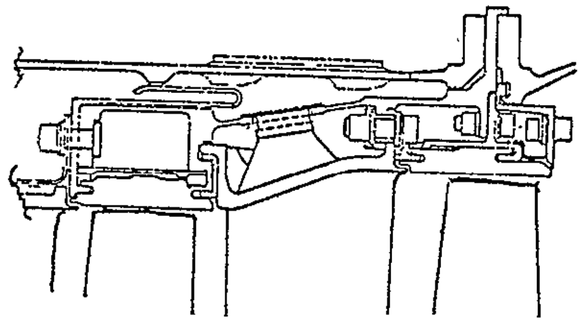
- New engine performance
- Reduction in engine deterioration

New engine performance, defined here in terms of Stage 1 blade tip clearance, may be improved by 0.38 mm which is equivalent to about 0.7 percent in turbine efficiency.

Current field engines generally experience rubs in the range of 0.5 to 0.8 mm in depth. This indicates an out-of-round and reburst problem of 0.9 to 1.2 mm from the various causes previously discussed. Reduction in out-of-roundness to 0.25 mm would eliminate rubs generally experienced in the field which would be worth about 1 percent in turbine efficiency due to reduced engine deterioration. In a "most severe" engine operating condition, rubs with improved roundness and improved support design and material selection would be limited to less than 0.25 mm versus a possible 1.1 mm average in the current design. In conclusion, a cumulative 1.7 percent in turbine efficiency improvement will result from the above



Current Design



New Design

- Reduced Cavity Hot Gas Recirculation
- Added Mass and Support Shielding to Improve Support Transient Response
- Segmented Shroud Hangers to Isolate Support from Flowpath Thermal Gradients
- Select New Material with Improved Thermal Growth Characteristics
- Reduce Support Sensitivity to Applied Pressure Loads
- Revised Stage 2 Shroud Attachment to Reduce Shroud Tilt

Figure 44. Improved Shroud Support Design Features.

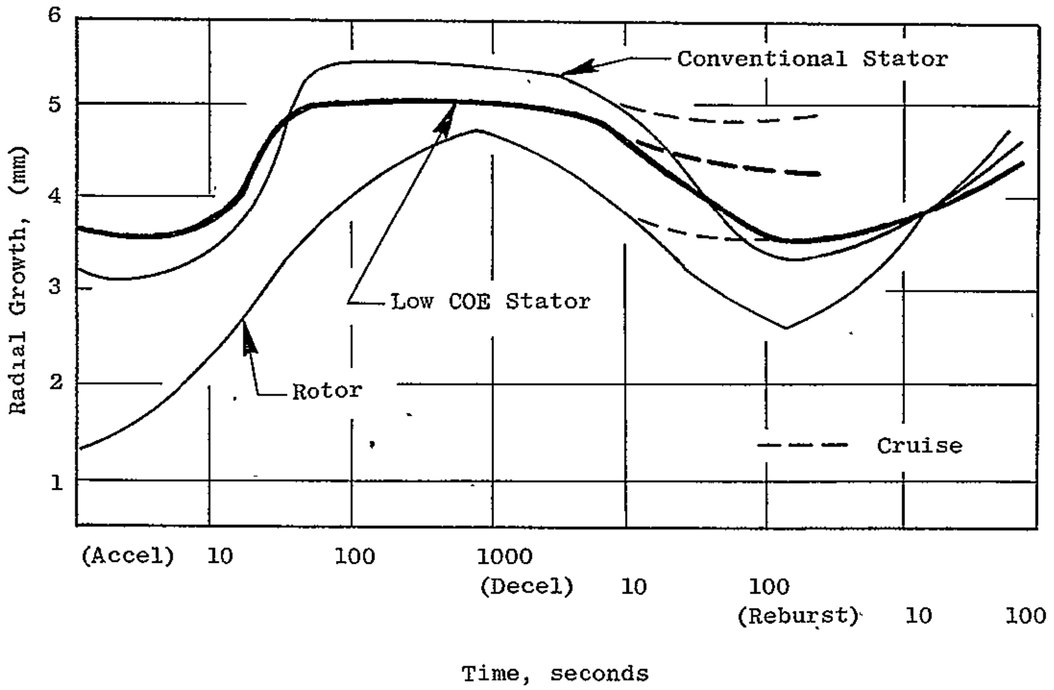


Figure 45. HPT Clearance/Roundness - Alloy Clearance Comparison.

changes. This improvement yields cruise sfc reductions of 0.4 percent for a new engine and 0.8 percent for an engine at 3000 hours.

The technical assessment for this concept is shown in Figure 46.

5.1.10.2 Boeing

The engine hardware changes proposed with this concept do not impact the inlet or nacelle. No changes in airplane price or maintenance cost beyond those produced by the engine would be required. In addition, the engine weight change is minor and would not result in structural weight changes to the airframe or impose weight and balance restrictions on the airplane.

Since this concept would reduce sfc deterioration, the benefits would increase with engine age relative to current engines of comparable ages. Therefore, this concept was analyzed to determine potential fuel savings as a new engine and as an engine with 3000 hours since last high pressure turbine heavy maintenance. The results of the analysis at 3000 hours are shown in Table XIV. The installed sfc improvement levels used in the analyses were the same as those provided by General Electric for the uninstalled case. On a new engine basis, this concept shows a 0.3-0.4 percent savings in block fuel with a slight gain in range at maximum takeoff gross weight and a 476 kg payload increase on limited routes. As a 3000 hour engine, the block fuel savings would be 0.4-0.9 percent.

5.1.10.3 Douglas

This concept is internal to the engine and does not affect the airframe. It increases the aircraft OEW by 16 kg, and it was evaluated for the 3000 hour engine on the DC-10-30 aircraft as shown in Table XIV.

5.1.11 Rene' 150 High Pressure Turbine Blades (CF6-50)

5.1.11.1 General Electric

Rene' 150 (R150) is a directionally solidified superalloy HPT blade material which has approximately 55° C increased temperature capability over the current Rene' 80 material. The use of R150 would permit a reduction in blade cooling air with a resulting increase in turbine efficiency.

The current and redesign configurations of the CF6-50 HPT Stage 1 and 2 blades are shown in Figure 47. The current Stage 1 blade is cooled by air which enters the blades through the base of the dovetails. The cooling air circulates through radial passages in the blade and is discharged through external airfoil cooling holes in such a manner as to provide:

TITLE HPT Roundness Control (CF6-50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC	Δ% SFC (2)
T/O	SLS	-.4	-.8
T/O	0 (0)/0.25	-.5	-.8
CLIMB	7620 (25000)/0.80	-.3	-.7
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.4	-.8
MAX CRUISE	10668 (35000)/0.85/+10°C	-.2	-.9
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.5	-.7
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-12 kg (-27 lb) (1)	-25 (-55 lb)

(1) ΔWf, kg/hr (lb/hr) (2) At 3000 Hours

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +5.4 (+12 lb)

ΔCG, cm (in) - 0.18 cm (0.07 in) aft

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $10,000 increase

RETROFIT - ATTRITION - Not Evaluated

INSTALLATION COST - Negligible for new engine

MAINTENANCE

MATERIAL - $0.90 reduction/engine flight hour

DIRECT LABOR - negligible

INVESTMENT SPARES RATIO - 5% spares

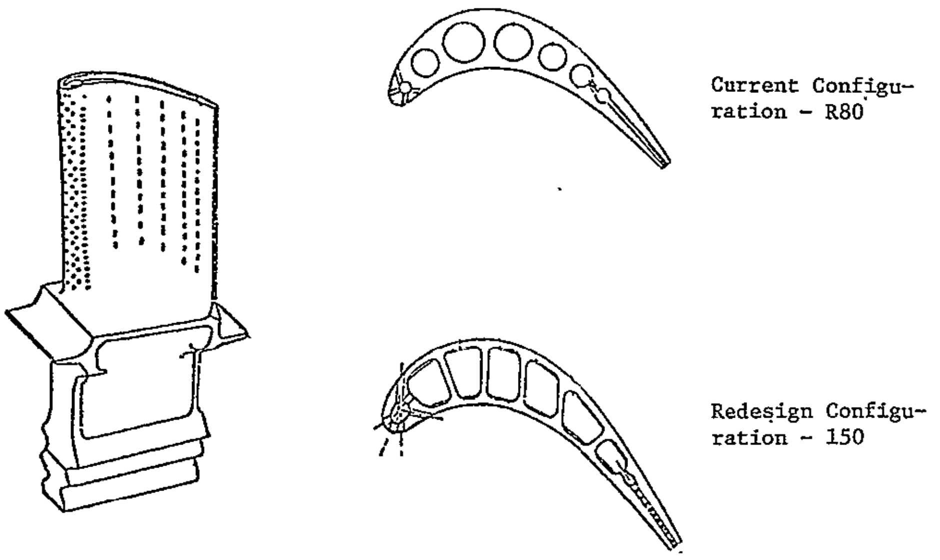
RETROFIT CAPABILITY The HPT nozzles are interchangeable, Stage 1 shroud, Stage 2 vanes and interstage seal are not interchangeable. It is contemplated that, with rework to the Stage 1 vane segment, the Stage 2 nozzle assembly may be installed as a kit, along with the Stage 1 support.

OTHER IMPACTS

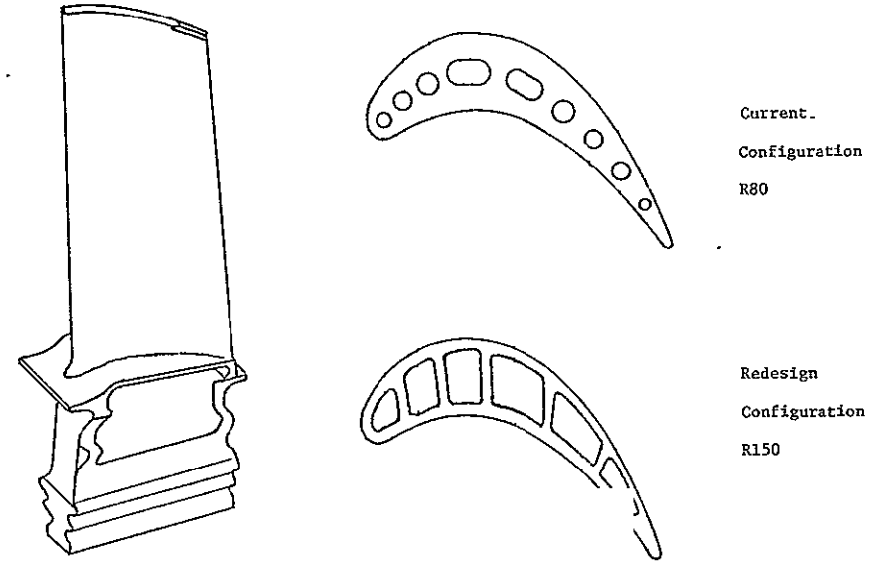
Figure 46. CF6-50 HPT Roundness Control Screening Assessment.

Table XIV. HPT Roundness Control Block Fuel Savings at 3000 Hours (Min. Fuel Analysis) (CF6-50).

	RANGE	ΔFUEL	
	km	kg	%
DC-10-30			
	805	-64	-0.7
	2735	-205	-0.8
	6275	-546	-0.9
B-747-200			
	770	-36	-0.4
	3460	-168	-0.8
	6195	-345	-0.9



Stage 1



Stage 2

Figure 47. CF6-50 HPT Stage 1 and 2 Blades.

- Leading edge impingement cooling for the nose of the airfoil.
- Airfoil film cooling for the airfoil leading edge and for the airfoil pressure and suction surfaces.
- Trailing edge cooling through convection holes.

The current CF6-50 Stage 2 HPT blade is also cooled by air which enters the blades through the base of the dovetails. The blade is cooled entirely by convection as the cooling air circulates through radial passages and is discharged at the tip.

These cooling methods permit the cooling air to be distributed to all parts of the airfoil surface in a manner needed to maintain acceptable blade metal temperatures. The cooling airflow and cooling effectiveness can be controlled by selection of the number and diameter of the airfoil cooling holes, the size and shape of the radial cooling passages and by the use of turbulence promoters inside the radial passages. This allows cooling air usage to be adjusted to use the maximum blade material capability.

The Stage 1 HPT blade will be cast with the current production external configuration and the new three-circuit core configuration. A direct Rene' 150 material substitution coupled with modifications to the blade external cooling hole patterns would allow the blade metal temperature to increase approximately 55° C which would result in a reduction in cooling air.

The current Stage 2 HPT blade cannot be produced with a direct material substitution. This blade is cast in Rene' 80 by using quartz rods to form the radial passages. These quartz rods become too soft during the directional solidification casting process used with the R150 alloy. Therefore, the Stage 2 blade would need to be redesigned using ceramic cored radial passages somewhat like those already used in the Stage 1 HPT blade. The cored passages could also incorporate turbulence promoters like those used in the Stage 1 blade to increase the cooling effectiveness. Again, the blade metal temperatures would be increased approximately 55° C over the current design to allow the cooling air reduction.

The Stages 1 and 2 blades would be interchangeable in sets. Any mixing of current blades with the R150 blades would result in less of a performance improvement.

The reduction in cooling air for changing to R150 material is 0.7 percent for Stage 1 and 0.45 percent for Stage 2. This would result in a cruise sfc reduction of 0.7 percent. The technical assessment for this concept is shown in Figure 48.

TITLE R150 HPT Blades (CF6-50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-.7
T/O	0 (0)/0.25	-.7
CLIMB	7620 (25000)/0.80	-.9
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.7
MAX CRUISE	10668 (35000)/0.85/$+10^{\circ}$C	-.7
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.9
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-20 kg (-44 lb) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +3.2 kg (+7 lb)

ΔCG, cm (in) - 0.08 cm (0.03 in.) aft

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $40,000 Increase

RETROFIT - $40,000 attrition, $156,000 Campaign

INSTALLATION COST - Included in new engine, no cost at core engine overhaul.

MAINTENANCE

MATERIAL - 0

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY Stage 1 and 2 blades interchangeable as sets.

OTHER IMPACTS

Figure 48. R150 HPT Blades (CF6-50) Screening Assessment.

5.1.11.2 Boeing

The engine changes identified for this concept are internal and are of such a nature as not to require changes to the inlet, nacelle, or airframe. The engine weight increase of 3 kg would not require an increase in airframe structural weight. In addition, no changes in airplane price or maintenance cost beyond those resulting from the engine itself are anticipated.

The block fuel savings for this concept are presented in Table XV. In addition to the savings in block fuel, a range increase of 72 km is realized at maximum take-off gross weight, and a payload increase of 862 kg would be available on limited routes.

5.1.11.3 Douglas

This concept does not affect the airframe and increases the OEW by 9 kg. Block fuel savings for the DC-10-30 for the minimum fuel analysis are shown in Table XV.

5.1.12 High Pressure Turbine Aerodynamic Improvement (CF6-6)

5.1.12.1 General Electric

General Electric has initiated a program for the aerodynamic and mechanical improvement of the marine and industrial LM2500 high pressure turbine (A CF6-6 derivative) which is aimed at improved ruggedness and longer life in addition to significant reductions in specific fuel consumption and reduced deterioration in service. Thus far, the program has concentrated on:

- Improving the life of the Stage 1 turbine nozzle by way of an improved cooling design.
- Improving the life of Stage 1 and 2 turbine blades by adoption of the single shank concept utilized on the CF6-50 engine rather than the twin shank concept employed on the CF6-6 (Figures 49 through 52).
- Improvement in clearance control to reduce blade tip rubs and thereby improve life and durability.

While the foregoing improvements have been primarily LM2500 oriented, it has been decided that taking them a step further would be of significant benefit to the CF6-6 as well. Accordingly, in addition to the mechanical integrity improvements above, aerodynamic improvements have been incorporated in the design in concert with these mechanical design innovations. The resulting turbine has fewer, more rugged blades and longer chord Stage 2 nozzle vanes, both of which provide improved aerodynamic efficiency and

C-2

Table XV. R150 HPT Blades Block Fuel Savings (Min. Fuel Analysis) (CF6-50).

	RANGE	ΔFUEL	
	km	kg	%
DC-10-30			
	805	-66.6	-0.7
	2735	-192.3	-0.8
	6274	-493.5	-0.8
B-747-200			
	770	-77	-0.7
	3460	-322	-0.8
	6195	-635	-0.8

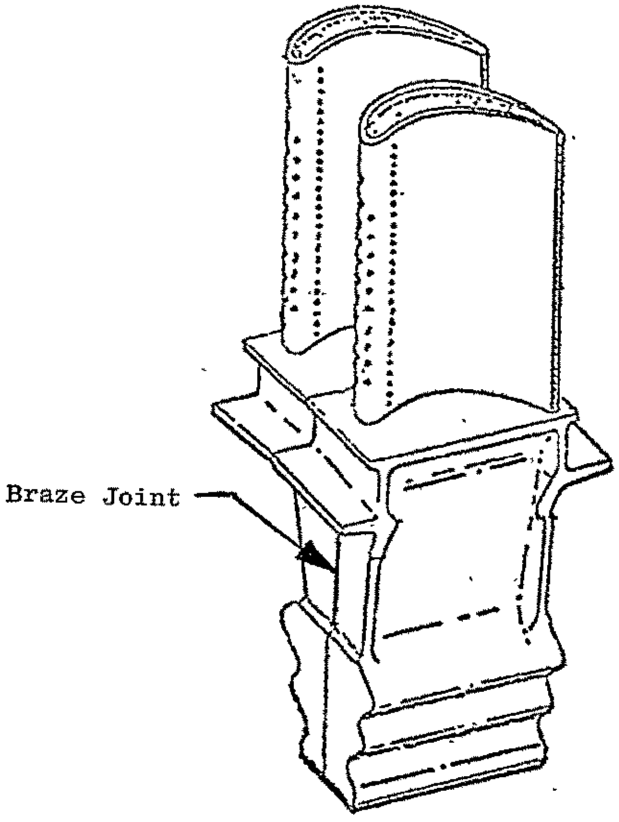


Figure 49. Current CF6-6 Stage 1 HPT Blade Pair.

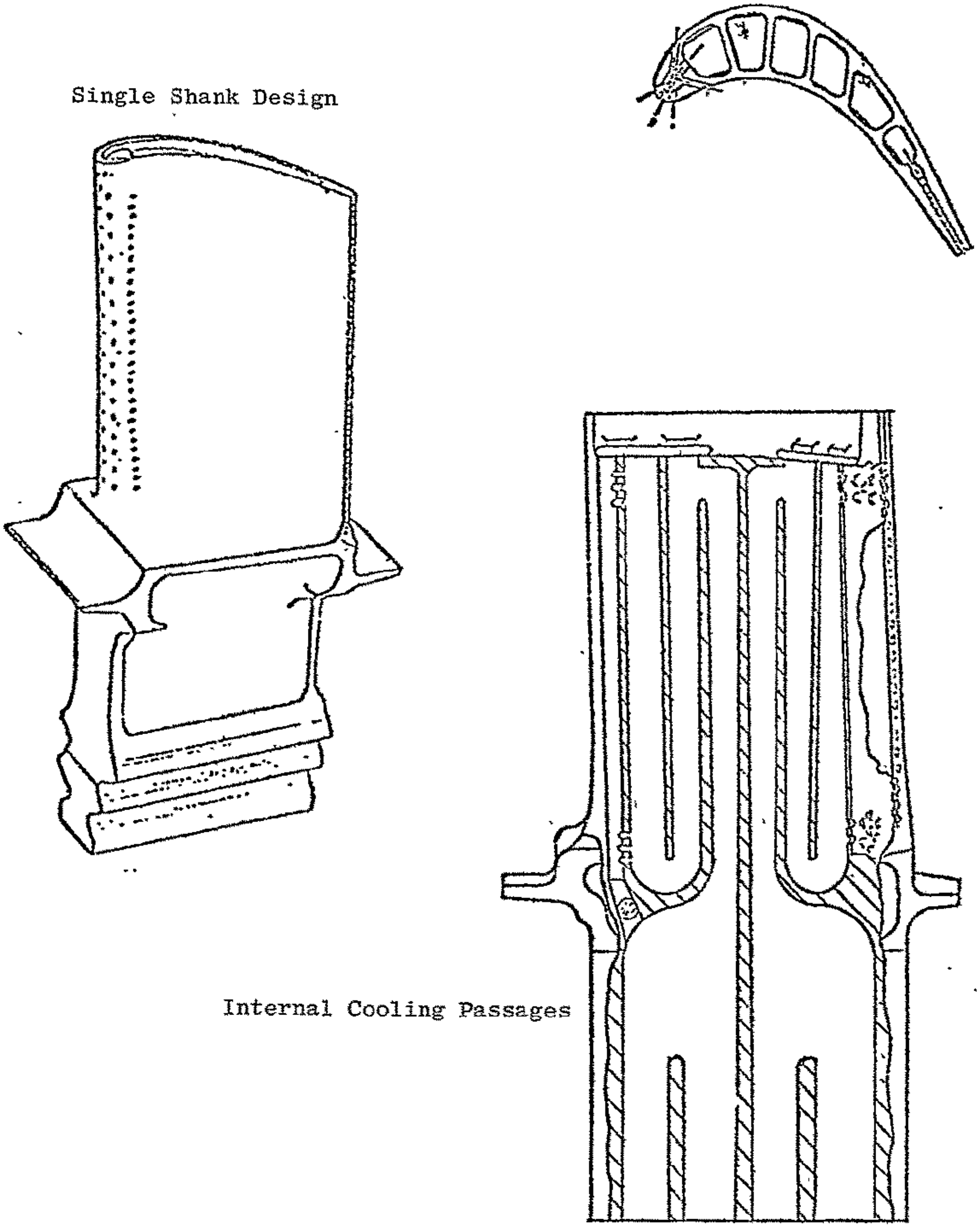


Figure 50. New HPT Single Shank Blade.

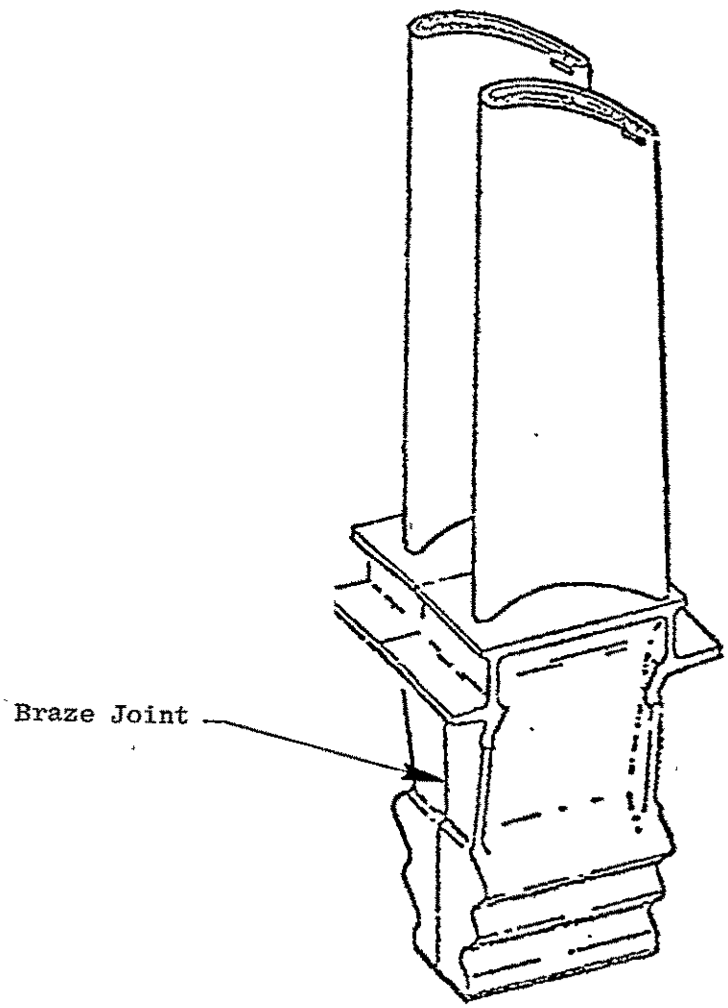


Figure 51. Current CF6-6 Stage 2 HPT Blade Pair.

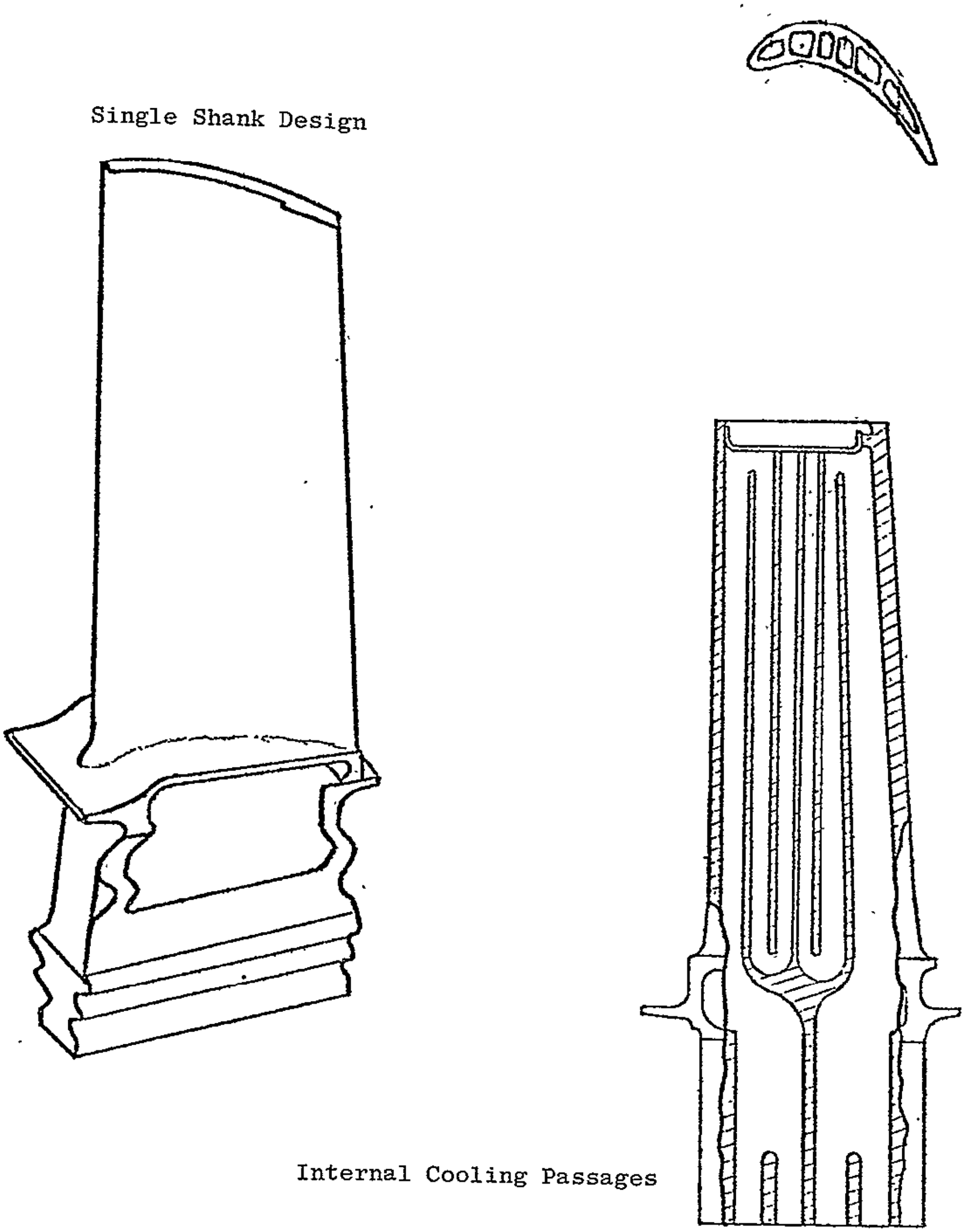


Figure 52. New CF6-6 Stage HPT Stage 2 Blade.

reduced turbine exit losses. A comparison of the current and new single-shank turbines with the specific performance improvements indicated is shown in Figure 53. The improvements are discussed below:

Reduced Exit Swirl - The increased flow area in the new Stage 2 blade results in a 9° reduction in the discharge swirl entering the turbine mid-frame.

Increased Solidity Stage 2 Vane - The redesigned vane solidity was increased by increasing chord length while maintaining the same number of vanes.

Reduced Stage 2 Blade Cooling Flow - Modern casting technology allows more flexibility in the design of internal cooling passages. Larger cooling surfaces and heat transfer enhancement (turbolators) reduce cooling flow requirements with no increase in metal temperatures.

Improved Cavity Seals - An improved baffling system between the stator and rotor parts near the hot flowpath coupled with reduced disk cross-stage leakage with the single shank design allows a reduction in the purge flow required to control the wheel space cavity temperatures.

Improved Airfoil Surface Finish - The blade and vane surface finish requirements for the CF6-50 HPT are presently more stringent than those for the CF6-6 twin shank design. Surface finish requirements for the single shank design will be brought in line with those for the CF6-50.

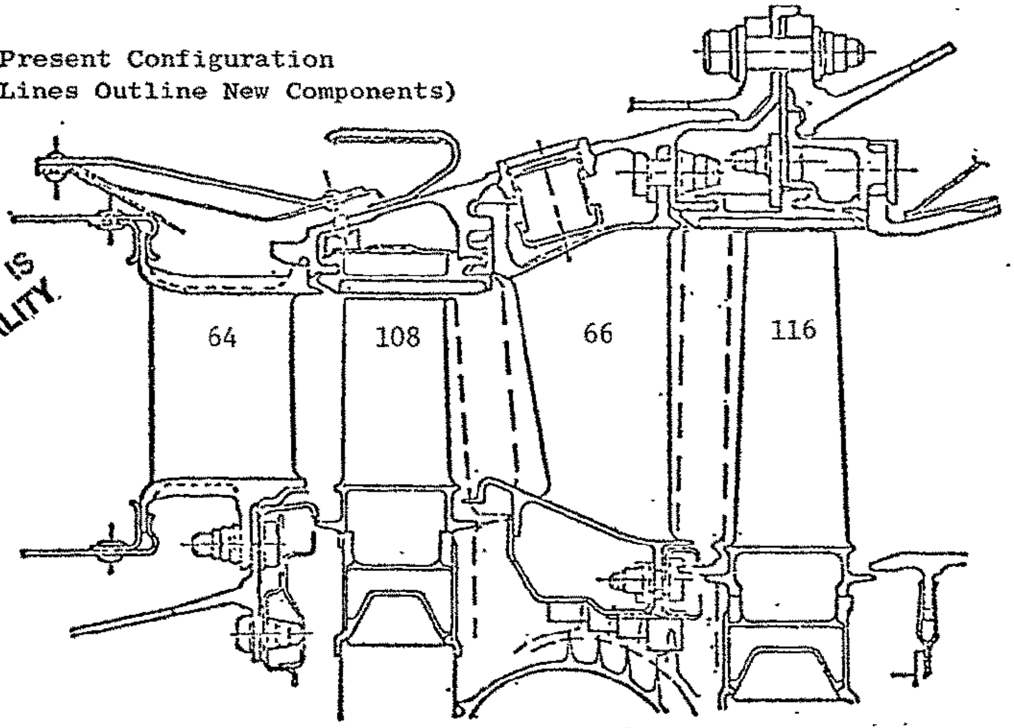
Shroud Support Roundness Improvement - Turbine efficiency will be improved by the reduction in blade tip-shroud clearance of 0.2 mm. This reduction will be accomplished by two means: 1) A better match of rotor-stator transient response, and 2) improved shroud roundness control. Both will be accomplished by improved mechanical and cooling concepts.

The individual performance improvement items and their predicted effects are summarized in Table XVI. Improvement estimates apply to new and deteriorated engines. The new single-shank turbine will eliminate the parasitic leakage that now exists in field engines due to the undesirable separation of the twin shanks.

Listed below, are some of the features of the mechanical design of the new turbine:

- Wide chord blades and vanes - CF6-50 type
- Lower shank bending stresses
- Low vibratory stress design
- No mating face braze
- Fewer blade airfoils (20 percent)

Present Configuration
(Dashed Lines Outline New Components)



New Configuration

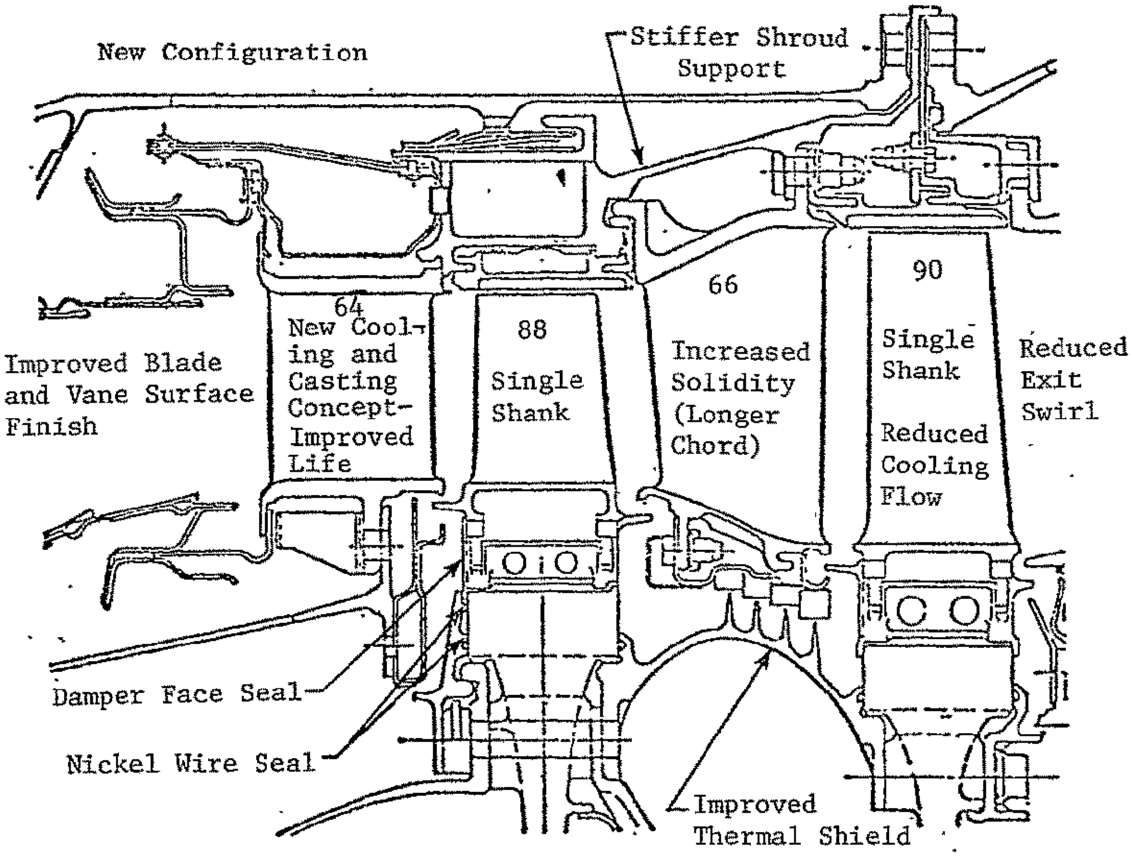


Figure 53. Comparison of Current and Single-Shank Turbine.

Table XVI. Estimated Performance Improvements.

	Cooling Air $\% W_{25}$	$\Delta\eta_T$ %	$\Delta\left(\frac{\Delta P_T}{P_T}\right)$
• Increased Life Features – Thicker Blade Edges – Increased Chord – Improved Cooling	+0.1	-0.40	0
• Reduced Exit Swirl		+0.75	-1.5
• Increased Solidity Stage 2 Vane		+0.14	
• Reduced Stage 2 Blade Cooling Flow	-0.2	+0.03	
• Improved Cavity Seals (Reduced Purge Flow)	-0.4	+0.1	
• Improved Blade and Vane Finish		+0.2	
• Shroud Support Roundness Improvement Reduce Clearance by 0.2 mm		+0.45	
NET	-0.5	+1.27	-1.5

The predicted net effect of the changes will be to reduce EGT by 21° C and to reduce cruise sfc 1.3 percent for new engines and 1.6 percent at 3000 hours. The technical assessment of the high pressure turbine aerodynamic improvement package is summarized in Figure 54.

5.1.12.2 Boeing

This concept is an improvement for the CF6-6 turbine only and was not evaluated by Boeing because the B747 uses CF6-50 engines.

5.1.12.3 Douglas

The HPT aero improvements are internal to the engine and do not affect the airframe. The concept increases the aircraft OEW by 68 kg. Significant block fuel savings are calculated as shown in Table XVII.

Table XVII. HPT Aerodynamic Improvement Block Fuel Savings (Min. Fuel Analysis).

	Range	ΔFuel	
	km	kg	%
DC-10-10	645	-103.4	-1.3
	1690	-215.0	-1.3
	3700	-449.5	-1.4

TITLE HPT Aerodynamic Improvement (CF6-6)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC 2)		Δ%SFC 3)
T/O	SLS	-1.8		-2.3
T/O	0 (0)/0.25	-1.8		-2.3
CLIMB	7620 (25000)/0.80	-1.6		-1.9
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-1.3		-1.6
MAX CRUISE	10668 (35000)/0.85/+10°C	-1.1		-1.4
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-1.4		-1.7
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	38 kg (-84)	(1)	-48 kg (-104)

(1) ΔWf, kg/hr (lb/hr) 2) New Engine 3) At 3000 Hours

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +22.7 kg (+50 LB.)

ΔCG, cm (in) - 0.5 cm (0.21 in.) fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $10,700 Increase

RETROFIT - Not Evaluated

INSTALLATION COST - New engine - not applicable

MAINTENANCE

MATERIAL - -$9.00/Engine Flight Hour (Reduction)

DIRECT LABOR - -0.25 Manhours/Engine Flight (Reduction)

INVESTMENT SPARES RATIO - ≈7% spare Modules

RETROFIT CAPABILITY Turbine module interchangeable with existing turbine module following minor modification to turbine mid frame

OTHER IMPACTS

Figure 54. CF6-6 HPT Aerodynamic Improvement Screening Assessment.

5.1.13 Cooled Cooling Air - Water Injection (CF6-6)

5.1.13.1 General Electric

Compressor discharge bleed air is used to cool the blades of the HPT. It was proposed to reduce the cooling air temperature by water injection. The lower temperature cooling air allows a reduction in airflow which improves engine sfc. Figures 55 and 56 show the concept. At takeoff, climb, and thrust reverse, water is injected into the cooling air stream. The water is vaporized and the cooling air temperature is reduced due to the heat of vaporization.

The water injection system will be designed as an add-on feature to the existing hardware. Rework of the compressor rear frame and Stage 1 nozzle support will be required to install it inside the engine plus whatever changes are necessary to add the external system. The Stage 1 blade will be redesigned to operate with the reduced flow. It will not be compatible with an engine without the cooling system.

Because the blade cannot operate with reduced flow unless the flow is cooled, the water injection system must be highly reliable. One method of achieving this is to provide three or four independent systems, each doing a part of the cooling job so that the loss of one will not result in providing totally uncooled air to the blades. This system would need a cockpit indicator to alert the pilot to the system failure.

The required water flows were determined as 8.4 kg/min for takeoff and thrust reverse and as 0.9 kg/min for climb. A reduction of 1.4 percent of engine flow for cooling was calculated for the system. The power requirement for the pump was assessed as a 0.3 point reduction in turbine efficiency. The net effect would be a 0.6 percent cruise sfc reduction.

In summary, the technical assessment is shown in Figure 57.

5.1.13.2 Boeing

This concept was chosen to be evaluated for the CF6-6 engine only; therefore, there is no evaluation by Boeing. However, the concept is also applicable to the CF6-50 engine.

5.1.13.3 Douglas

This concept has been qualitatively evaluated and judged to be undesirable. This evaluation was made based on experience with water injection systems in transport aircraft.

Some of the reasons are:

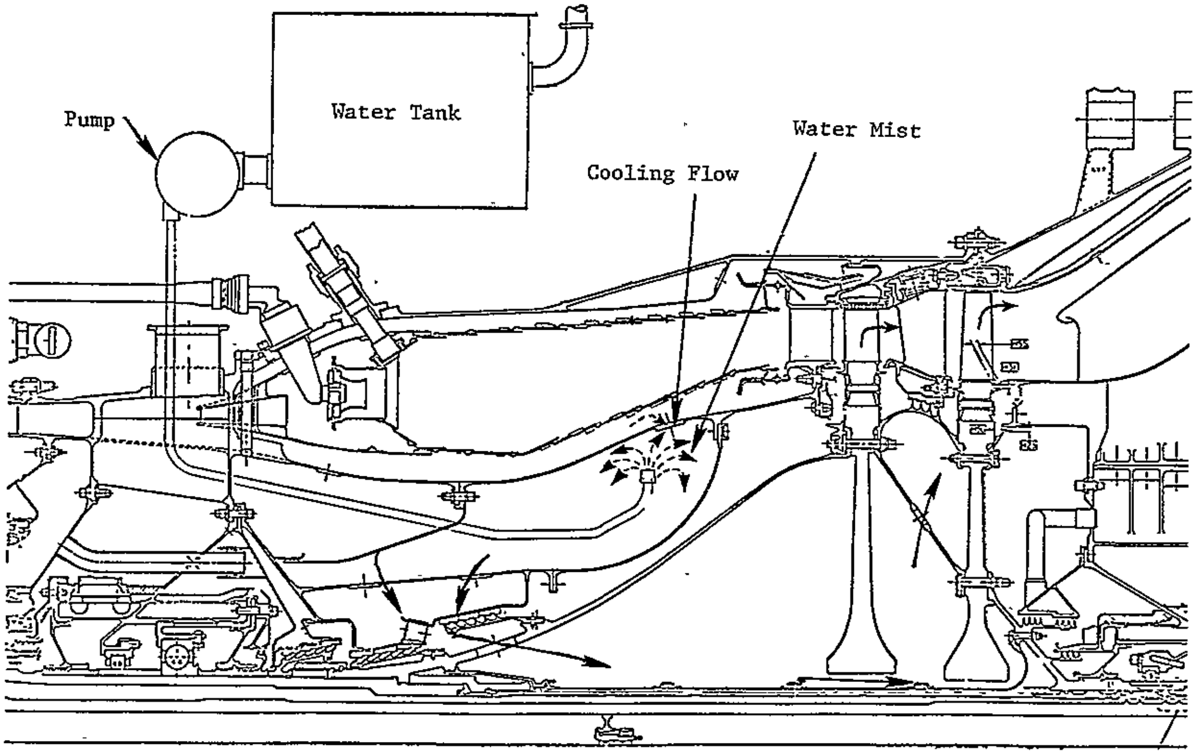


Figure 55. Water Mist Cooled Blade Air Concept.

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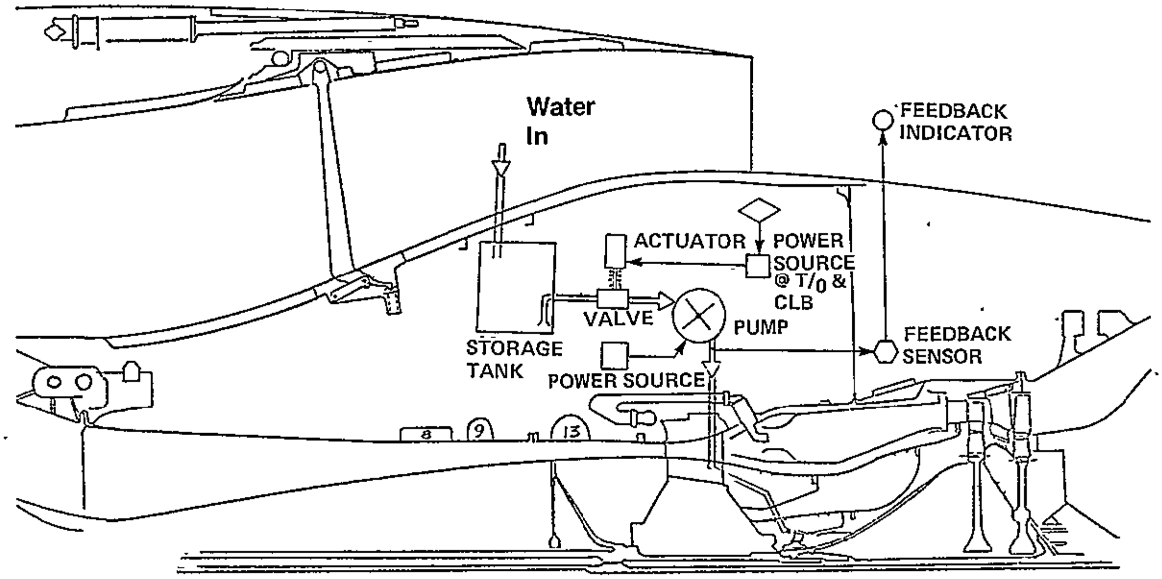

Figure 56. Water Mist Cooling Control Schematic.

TITLE Cooled Cooling Air - Water Injection (CF6-6)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC	
T/O	SLS	-1.0	
T/O	0 (0)/0.25	-1.0	
CLIMB	7620 (25000)/0.80	- .8	
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	- .6	
MAX CRUISE	10668 (35000)/0.85/+10°C	- .6	
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	- .6	
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-20 (-44)	(1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - Hardware: +22.7 kg (+50 lb) Water: 104 kg (230 lb)2)

ΔCG, cm (in) - Hardware: N/A, Water: 0.69 cm (0.27 in.) Fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $28,000 (Increase)

RETROFIT - $28,000 Attrition, $113,000 Campaign

INSTALLATION COST - Included in New engines, $2400 on retrofit

MAINTENANCE

MATERIAL - -$1.30/engine flight hour (reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY The system is retrofittable. Rework of compressor rear frame and stage 1 nozzle support required. Redesigned HPT blades cannot be used in current engine. External piping required. 2) Requires 230 lb. water based on the following flow dates: 18.5 lb/min for takeoff and thrust reverser; 1.9 lb/min for climb. System operational indicator required.

OTHER IMPACTS

Figure 57. CF6-6 Cooled Cooling Air - Water Injection Screening Assessment.

- Purified water is required to prevent scaling and formation of deposits. This purified water will cost $1 or more per gallon.

- Additional servicing, additional training and additional ground equipment will be required.

- Use of water injection has resulted in the erroneous use of unpurified water and fuel with resultant expensive damage. This could occur with this concept.

- Provisions to protect against water freezing will be needed for the aircraft on ground and in flight.

- Inclusion of a 0.1 cubic meter or larger water tank with servicing provisions will have a large and (but nonrecurring) cost to the airframe. Provisions for the tail engine on a trijet will be particularly expensive.

5.1.14 Cooled Cooling Air - Air/Air Heat Exchanger (CF6-6)

5.1.14.1 General Electric

This concept proposes a reduction of HPT cooling air by cooling the coolant in a heat exchanger using fan air as a heat sink. Figures 58 and 59 illustrate the system. Cooling air is bled from the compressor rear frame, ducted to a heat exchanger, and returned to the core of the engine through the turbine midframe struts. The heat sink is fan air, extracted from the forward end of the fan duct and rejected near the fan exhaust nozzle.

The Stage 1 blade must be specifically designed for this application and cannot be used in the current engine. The compressor rear frame must be modified to accept this system but will probably be usable on the current engine. Noninterchangeable fan duct modifications and system modifications will be required as necessary for heat exchanger and ducting.

The hot side of the heat exchanger system will be pressurized at compressor discharge pressure. Loss of integrity of any part of the system will result in high leakage of high temperature air into potentially sensitive areas. For safety, the system will require shutoff valves in all ducts which automatically close in the event of system pressure loss. This system can be designed such that the turbine blades will continue to receive full flow; but without the benefit of reduced temperature cooling air, turbine blade life will suffer unacceptably during takeoff. It is, therefore, recommended that multiple independent heat exchangers be utilized so that a failure will not result in a catastrophic situation for the turbine blades.

Because of the nature of the system described above, a maintainability requirement must be imposed upon the system as follows: All heat exchangers

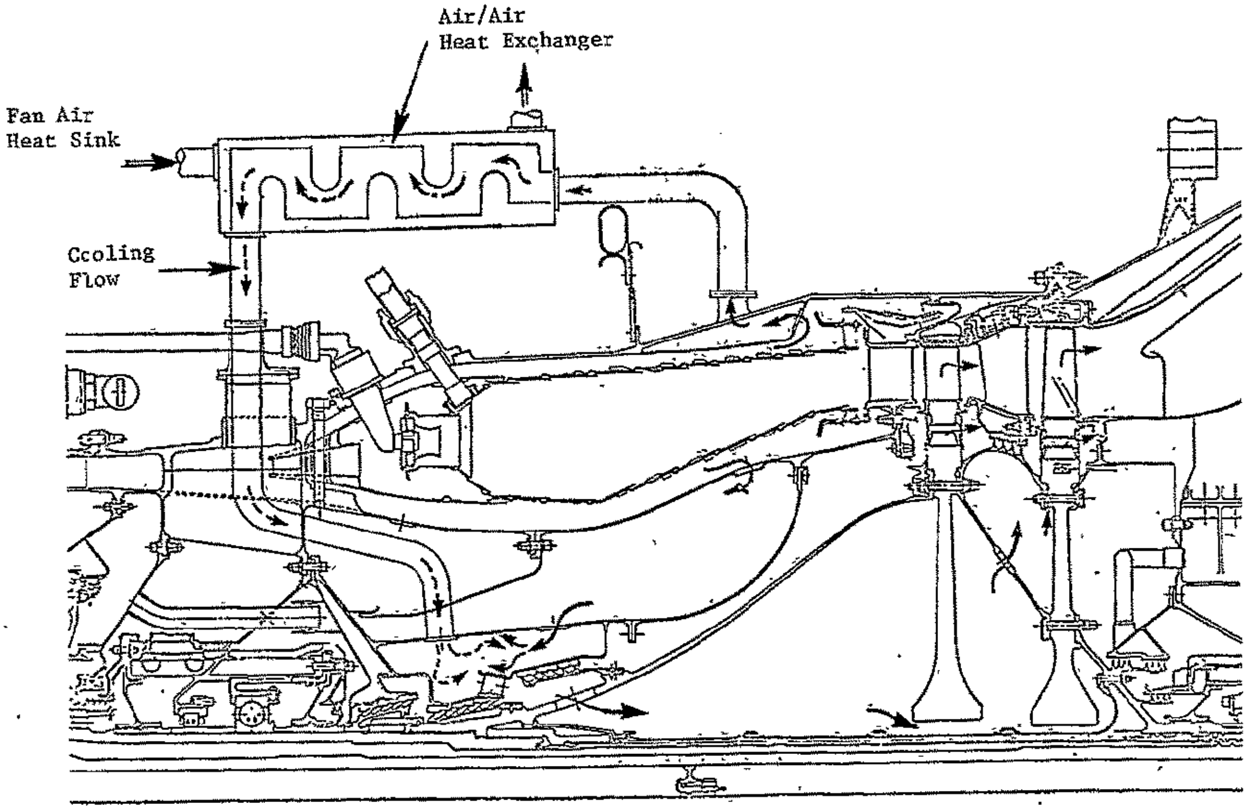

Figure 58. Air Cooled Blade Air Concept.

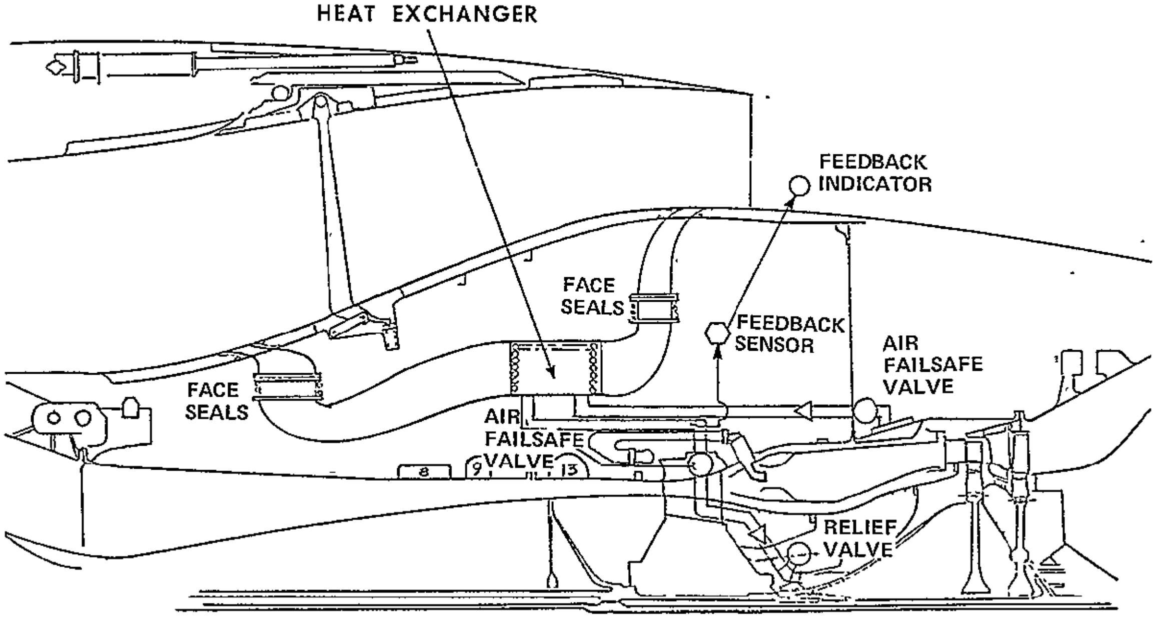

Figure 59. Air Cooled Blade Air Control Schematic.

and automatic valving for the system must be accessible, repairable, or replaceable from the outside of the engine. In addition, operation failure of any of the heat exchanger loops must result in a cockpit indication of the problem.

A reduction of 1.1 percent of engine flow for HPT cooling was calculated for this system. The pressure loss of the fan air and the effect of heat addition were accounted for as a reduction of 0.14 point in turbine efficiency. The net effect would be a 0.6 percent reduction in cruise sfc.

The technical assessment of this concept is shown in Figure 60.

5.1.14.2 Boeing

This concept was chosen to be evaluated for the CF6-6 and, therefore, was not evaluated by Boeing. The concept is also applicable to the CF6-50 engine.

5.1.14.3 Douglas

This concept requires an indication system to inform the flight engineer of a malfunction. Wiring and a display would be incorporated into the airframe.

The cooled coolant system with the air/air heat exchanger increases the aircraft OEW by 185 kg. The fuel savings for the minimum fuel case are shown in Table XVIII.

5.1.15 Cooled Cooling Air - Fuel/Air Heat Exchanger (CF6-6)

5.1.15.1 General Electric

This concept is similar to air/air system except that fuel is used as a heat sink (Figures 61 and 62). The engine fuel cools an intermediate fluid external to the engine. The intermediate fluid, in turn, cools the cooling air which is bled from the compressor rear frame, directed through the exchanger, and returned to the core of the engine through the turbine midframe struts.

Similar to the air/air system, the Stage 1 blade must be specifically designed for this application and cannot be used in the current engine. The compressor rear frame must be modified to accept this system but will probably be usable on the current engine. System modifications will be required as necessary for heat exchanger and ducting.

The hot side of the exchanger system will be at compressor discharge pressure. Loss of integrity of any part of the system will result in high leakage of high temperature air into potentially sensitive areas. For safety reasons, the system will require shutoff valves in all ducts which automatically close in the event of system pressure loss. It is felt this system can be designed such that the turbine blades will continue to receive full flow; but, without the benefit of reduced temperature cooling

Table XVIII. Cooled Cooling Air - Air/Air Heat Exchanger Block Fuel Savings (Min. Fuel Analysis).

	Range	ΔFuel	
	km	kg	%
DC-10-10	645	-30.4	-0.4
	1690	-70.8	-0.4
	3700	-163.3	-0.5

TITLE Cooled Cooling Air - Air/Air Heat Exchanger (CF6-6)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-.8
T/O	0 (0)/0.25	-.8
CLIMB	7620 (25000)/0.80	-.5
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.6
MAX CRUISE	10668 (35000)/0.85/+10°C	-.6
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.6
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-20 (-44 lb)(1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +61.7 kg (+136 LB.)

ΔCG, cm (in) - 0.23 cm (0.09 in.) FWD.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $50,000 Increase

RETROFIT - $50,000 Attrition, $135,000 Campaign

INSTALLATION COST - Included in New Engines, $2400 on Retrofit

MAINTENANCE

MATERIAL - - $1.30/Engine Flt Hour (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY The system is retrofittable. Rework of compressor rear frame and fan duct required. Redesigned HPT blades cannot be used in current engine. System modifications required for heat exchanger and ducting. System operational indicator required.

Figure 60. CF6-6 Cooled Cooling Air - Air/Air Heat Exchanger Screening Assessment.

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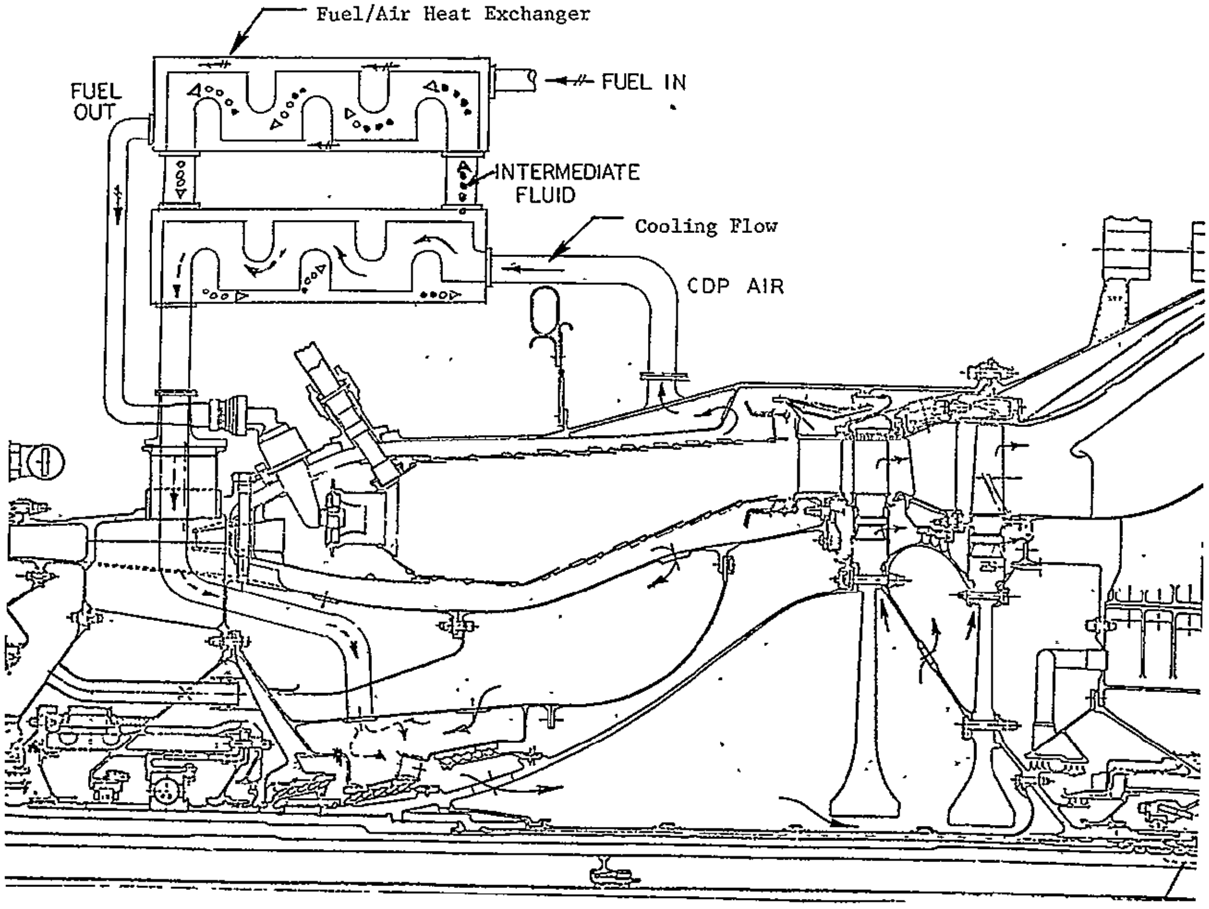

Figure 61. Fuel Cooled Blade Air Concept.

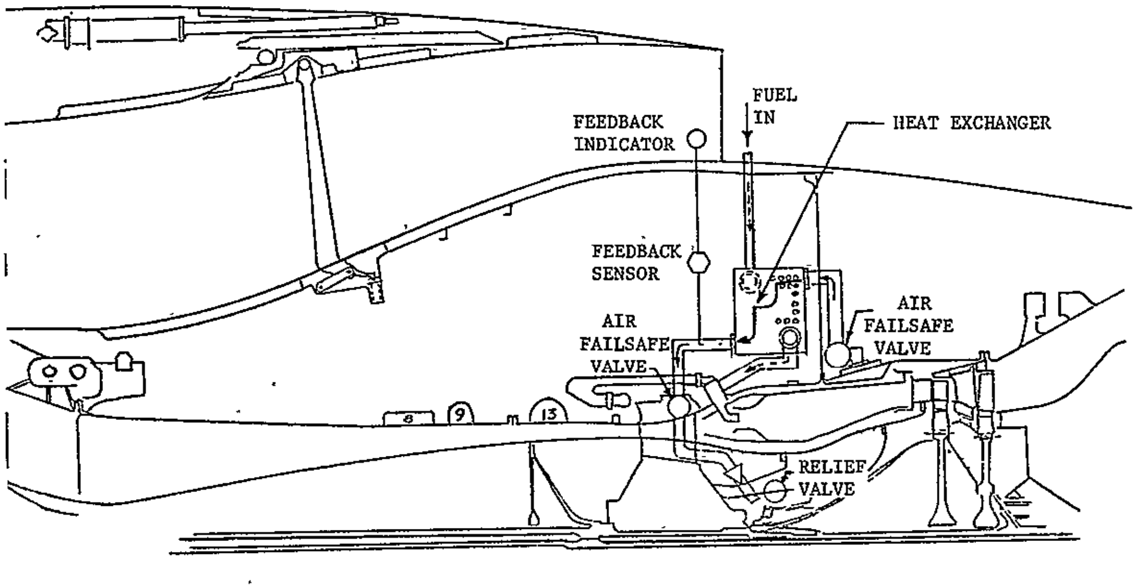

Figure 62. Fuel Cooled Blade Air Control Schematic.

air, the turbine blade life will suffer unacceptably during takeoff. It is recommended that multiple independent heat exchangers be utilized so failure will not result in a catastrophic situation for the turbine blades.

A problem associated with this system is fuel coking. Above certain levels of temperature, jet aviation fuels began to break down and form deposits which can restrict or completely block flow. The heat exchanger design must be carefully executed to avoid any hot spots which might result in this problem. Care must be exercised so that, during all phases of flight, the fuel temperature does not exceed recommended limits.

Because of the nature of the system described above, a maintainability requirement must be imposed upon the system as follows: All heat exchangers and automatic valving for the system must be accessible, repairable, or replaceable from the outside of the engine. In addition, operational failure of any of the heat exchanger loops must result in a cockpit indication of the problem.

The core engine flow required for HPT cooling was calculated to be reduced by 1.0 percent for this system. The additional energy requirement for the pressure loss of the fuel in the heat exchanger and the energy increase effect of the fuel temperature rise was not accounted for in the performance estimates. The net effect would be a 0.6 percent reduction in cruise sfc. The technical assessment is summarized in Figure 63.

5.1.15.2 Boeing

This concept was chosen to be evaluated for the CF6-6 engine only; therefore, there is no evaluation by Boeing. However, the concept is also applicable to the CF6-50 engine.

5.1.15.3 Douglas

This concept requires an indication system to inform the flight engineer of a malfunction. Wiring and display would be incorporated into the airframe.

The cooled coolant system with the fuel/air heat exchanger system increases aircraft OEW by 210 kg. The following fuel savings for the minimum fuel case are shown in Table XIX.

5.1.16 High Pressure Turbine Active Clearance Control - Variable Source Bleed (CF6-6)

5.1.16.1 General Electric

The HPT Stage 1 tip clearance is set by the takeoff requirements resulting in a larger tip clearance at cruise than required (Figure 64).

The intent of this performance improvement change is to reduce the clearance during cruise only to achieve better sfc while not affecting the

TITLE COOLED COOLING AIR - FUEL/AIR HEAT EXCHANGER (CF6-6)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-.9
T/O	0 (0)/0.25	-.9
CLIMB	7620 (25000)/0.80	-.8
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.6
MAX CRUISE	10668 (35000)/0.85/+10°C	-.6
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-1.1
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-18 kg -40 (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +69.9 kg (+154 Lb.) (with intermediate fluid)

ΔCG, cm (in) - 0.30 cm (0.12 in.) FWD

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $92,000 Increase

RETROFIT - $92,000 Attrition, $177,000 campaign

INSTALLATION COST - Included in New Engines, $2400 on Retrofit

MAINTENANCE

MATERIAL - $1.30/Engine Flt. Hour (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY The system is retrofittable. Rework of compressor rear frame, redesigned HPT blades cannot be used in current engine.

System modifications required for heat exchanger and ducting. External piping required. System operational indicator required.

OTHER IMPACTS

Figure 63. CF6-6 Cooled Cooling Air - Fuel/Air Heat Exchanger Screening Assessment.

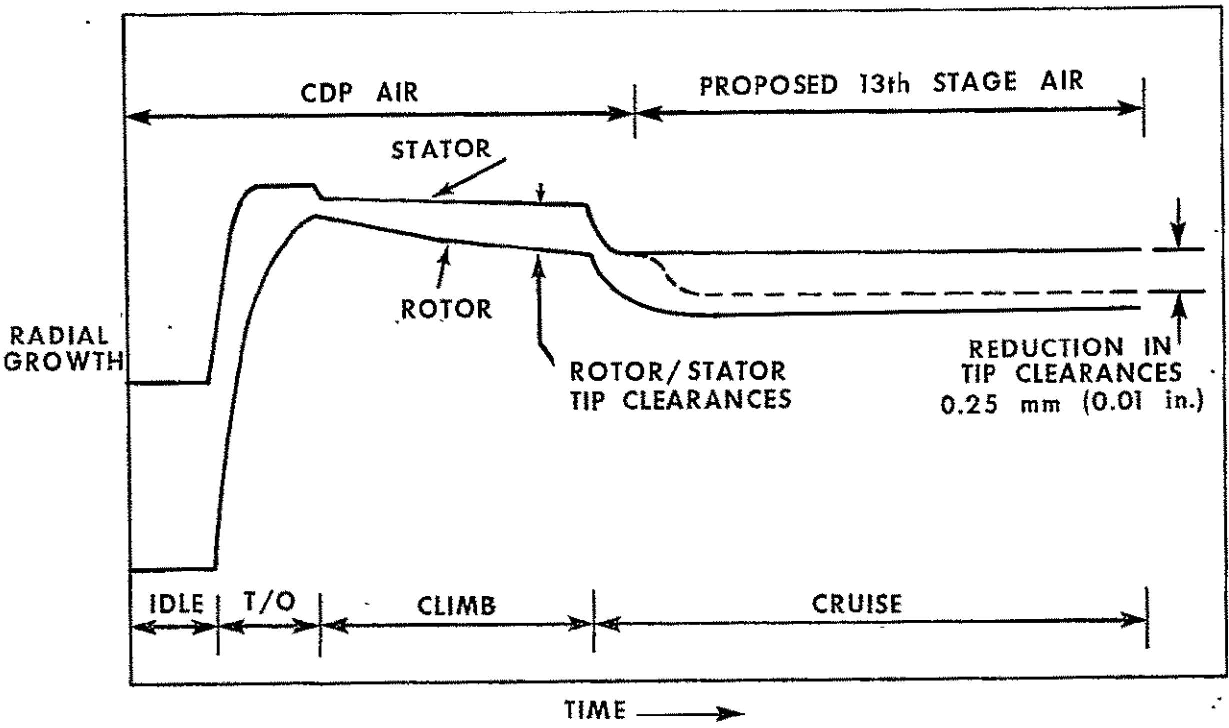

Figure 64. Rotor/Stator Clearance.

Table XIX. Cooled Cooling Air – Fuel/Air Heat Exchanger Block Fuel Savings (Min. Fuel Analysis).

	Range	ΔFuel	
	km	kg	%
DC-10-10 (CF6-6)			
	645	-43.5	-0.5
	1690	-80.7	-0.5
	3700	-174.2	-0.5

clearance during other portions of the flight. This requires some controllable feature which can be turned on or off during specific parts of the flight.

As currently designed, the primary cooling for the Stage 1 nozzle shroud supports is compressor discharge air, which impinges through the nozzle support cone upon the Stage 1 shroud aft support hook, and the air which is bled around the Stage 1 shroud forward support hook. The outer surface of the forward shroud support is bathed in low velocity thirteenth stage air. The result of this environment is that the structure temperature is very close to the compressor discharge air temperature. If thirteenth stage air were used with high effectiveness to cool the support, its temperature could be reduced significantly. Thirteenth stage air is 83° C cooler than compressor discharge air at cruise.

Figures 65 and 66 illustrate a possible concept for this type cooling. The bulk of the structure is now isolated from the high velocity compressor discharge air which is used for Stage 1 shroud cooling. A baffle, which is capable of producing high effective impingement cooling, is situated to give primary temperature control of the support in the vicinity of the Stage 1 shroud. As is schematically shown, the airflow into this baffle cavity may be either thirteenth stage or compressor discharge air. The philosophy of operation is to maintain compressor discharge flow through the baffle during all parts of the flight other than cruise. During cruise, the selector valve will introduce the cooler thirteenth stage air into the baffle cavity and produce the desired effect of cooling the structure and reducing clearance (dashed lines of Figure 64).

The introduction of a new system to the engine which requires a valve and certain controls to effectively operate it must necessarily reduce reliability. It must be pointed out here that, should the valve and/or system fail in such a manner as to operate with thirteenth stage cooling air throughout the mission, extensive tip rubs would occur. No structural failure of the turbine would be expected as a result; however, the tip rub effects are irreversible and the resultant performance loss could be recovered only by rebuilding the turbine and reestablishing clearance. It is, therefore, mandatory that the system be designed so that failure can result only in the maintenance of CDP cooling throughout the entire flight. If this situation can be achieved, the only detrimental effect would be failure to achieve the desired performance improvement during cruise; subsequent repair of the system external components could restore it to its former working order.

Changes internal to the engine would be to fixed structure and would have minimum impact on the overall engine maintainability. Changes external to the engine would be to piping with the addition of a control valve. This system would be accessible by raising the core cowling and would be designed to have minimum impact on overall engine or component maintainability.

The reduction of the blade tip clearance at cruise was approximately 0.25 mm and resulted in an improvement of 0.8 percent in turbine efficiency.

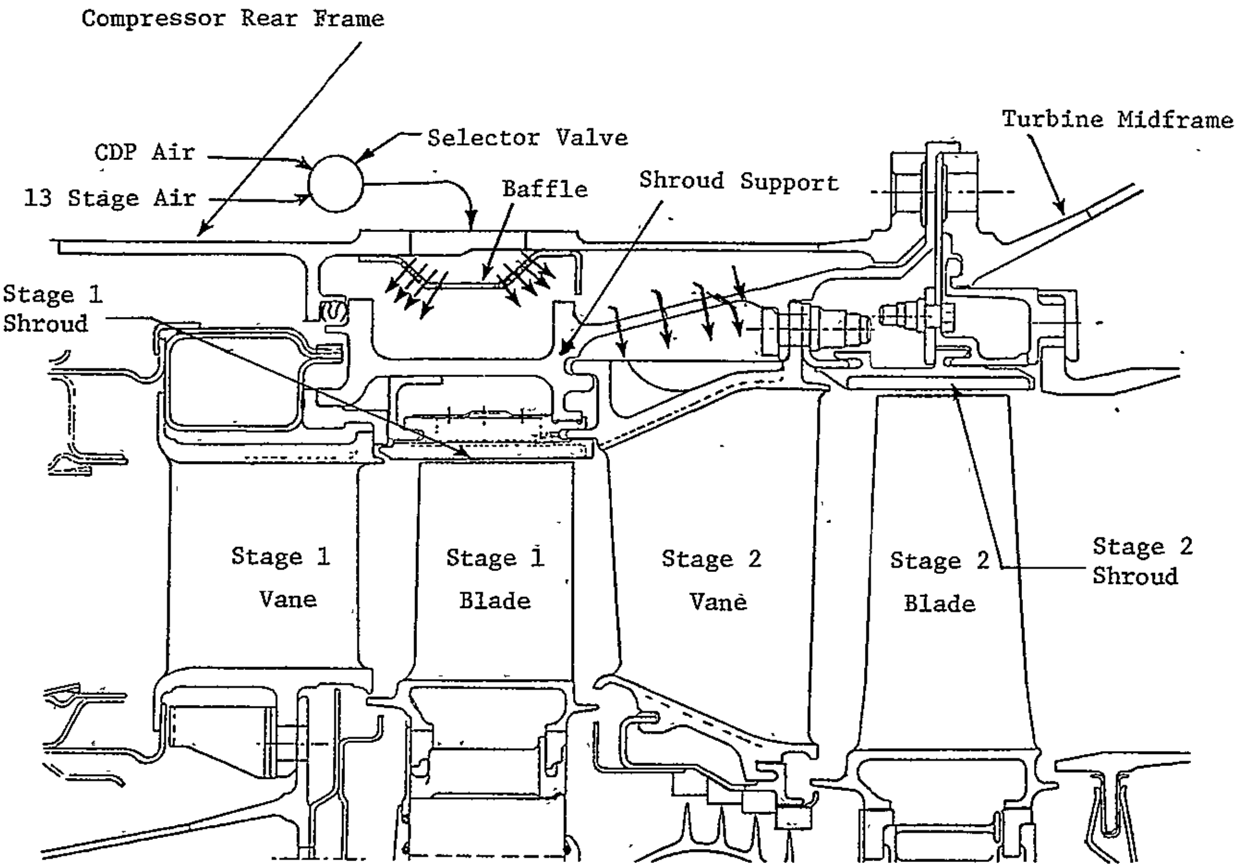

Figure 65. Active Clearance Control (CF6-6).

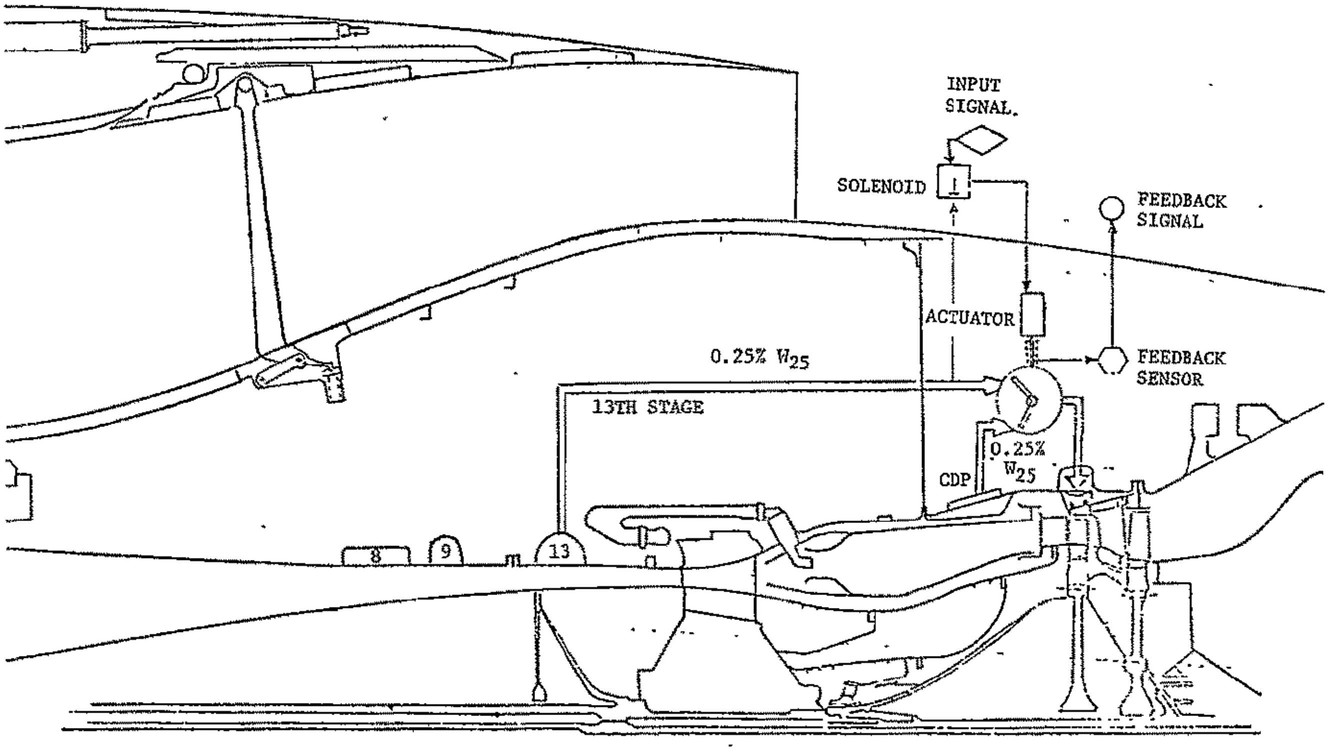

Figure 66. HPT Active Clearance Control System Utilizing Variable Source Air (CF6-6).

Predicted CF6-6 cruise sfc improvement is about 0.6 percent for new engines. This concept would also provide a performance retention; however, it was not evaluated. The technical assessment of this concept is shown in Figure 67.

5.1.16.2 Boeing

This concept has been studied for the CF6-6 engine and, therefore, was not evaluated by Boeing. However, it would also be applicable to the CF6-50.

5.1.16.3 Douglas

This active clearance device required the addition of a malfunction detection system in the aircraft cockpit. The OEW increases by 45 kg. Block fuel savings are summarized in Table XX for the minimum fuel analysis.

5.1.17 High Pressure Turbine Active Clearance Control - Variable Source Bleed (CF6-50)

5.1.17.1 General Electric

After the completion of the screening study, it was decided to study an active clearance control system for the CF6-50 engine. The CF6-50 system proposed is similar to the -6 system but uses tenth stage compressor bleed air instead of thirteenth stage air (Figure 68). Compressor discharge and tenth stage air are routed through mixing valves which combine precise amounts of each bleed airflow to obtain the desired air temperature and pressure. A control regulates the mixing valve position by sensing engine speed, ambient pressure and time since the last throttle movement. The air mixture is directed by the manifolds into an annular air chamber which surrounds the shroud supporting structure. Impingement holes are located in this manifold to direct precise amounts of air against the structural elements of the shroud support. By controlling the temperature of the cooling air, the growth of the structural elements is controlled and thereby the rotor/stator clearance.

The control system schematic is shown in Figure 68. This figure shows the relationship between the main engine control, timer, air valves and added engine piping.

The assessment of the CF6-50 active clearance control concept is similar to the CF6-6 concept summarized in Figure 67. Predicted CF6-50 cruise sfc improvement is about 0.6 percent for a deteriorated engine and 0.4 percent for a new engine with improved sfc retention capability.

An abbreviated economic assessment was performed by General Electric and is presented in Section 5.2.3 and Table LI.

5.1.17.2 Boeing/Douglas

Boeing and Douglas did not evaluate the CF6-50 active clearance control concept, but the block fuel savings are assumed to be similar to CF6-6 results.

Table XX. HP Turbine Active Clearance Control with Variable Source Bleed Block Fuel Savings (Min. Fuel Analysis).

	Range	ΔFuel	
	km	kg	%
DC-10-10 (CF6-6)	645	-9.1	-0.1
	1690	-60.8	-0.4
	3700	-158.8	-0.5

TITLE HPT ACTIVE CLEARANCE CONTROL - VARIABLE SOURCE BLEED (CF6-6)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC	
T/O	SLS	0	
T/O	0 (0)/0.25	0	
CLIMB	7620 (25000)/0.80	0	
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.6	
MAX CRUISE	10668 (35000)/0.85/+10°C	-.6	
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.6	
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	0	(1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +15 kg (+33 Lb.)

ΔCG, cm (in) - 0.08 cm (0.03 in.) FWD

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $29,000 Increase

RETROFIT - ATTRITION - $38,000 Increase

INSTALLATION COST - Included in New Engines, $4500 on Retrofit

MAINTENANCE

MATERIAL - $0.05/Engine Flt. Hr. (Increase)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY System retrofittable with modifications to compressor rear frame and stage 1 nozzle OD cooling air screen. External piping required.

OTHER IMPACTS

Figure 67. CF6-6 HPT Active Clearance Control - Variable Source Bleed Screening Assessment.

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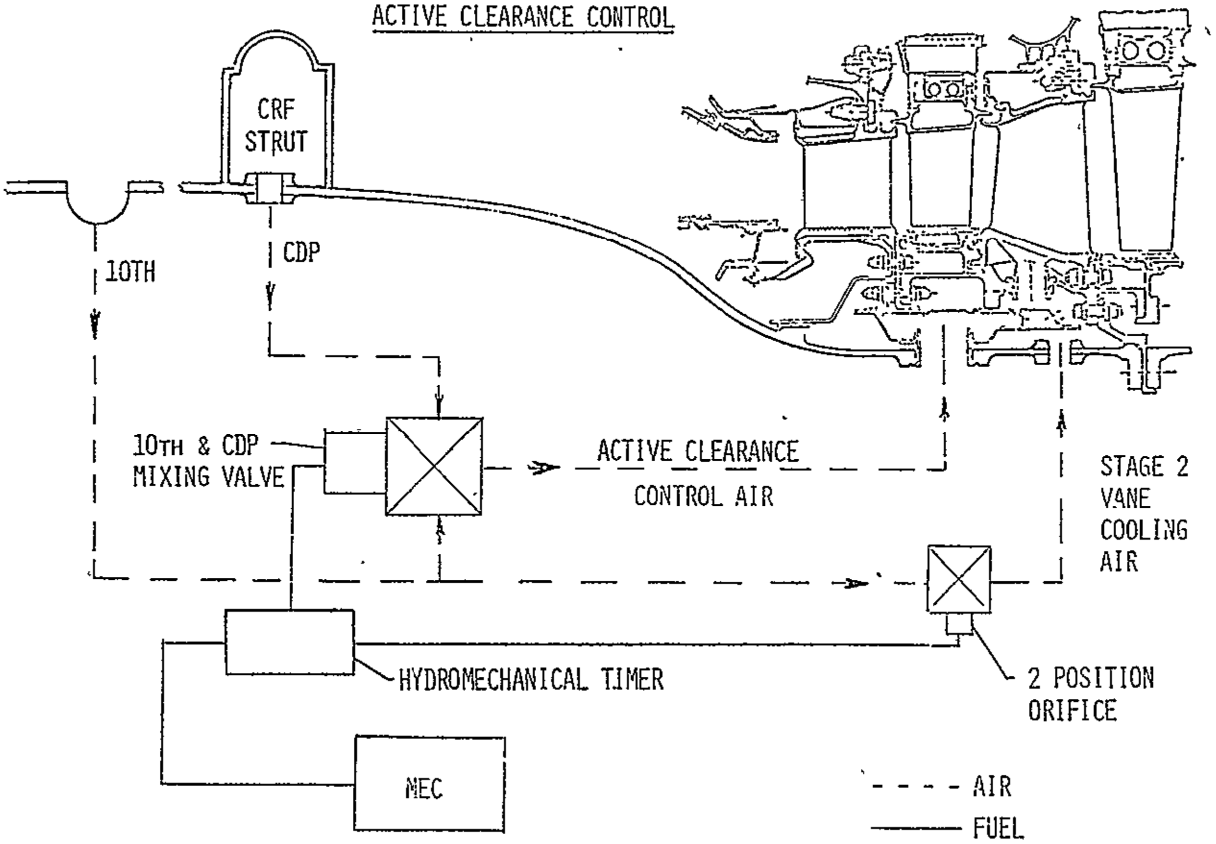

Figure 68. Active Clearance Control Schematic.

5.1.18 High Pressure Turbine Active Clearance Control - Electrical Resistance Heating (CF6-6)

5.1.18.1 General Electric

This improvement item is similar to the previous concept except that electric heating is used instead of variable source bleed air.

Figures 69 and 70 illustrate the manner in which this would be accomplished. The support structure would be heated 89° C above normal to attain the same minimum clearances now achieved with the current stator. During cruise, the electrical heater would be turned off and the temperature would return to that of compressor discharge air resulting in a turbine blade tip clearance reduction of 0.7 mm.

While further studies would be needed, it is also possible the blade tip clearance could be tailored by this technique for better matching during all portions of the flight. Blade tip clearance losses currently being caused by tip rubs during certain transient conditions, such as rapid decels, accels, or reaccels with a hot rotor, might also be avoided.

All turbine hardware will be interchangeable with the new Stage 2 nozzle support. Compressor rear frame modifications will be required to admit the electrical leads. Other changes are required as necessary to support the electrical power generation equipment.

The electrical system provides several challenges for life and reliability. Failure of the system to operate will result in irreversible tip rub damage and opened-up clearances. Engine teardown is required to restore proper clearances. Thus, while failure of the system would not be expected to cause a failure of the engine, it would result in the system having lost its purpose. High reliability is, therefore, demanded of the system. Potential problem areas would be as follows:

- Burnout or breakage of the heating element.
- Failure of electrical leads through the pressure vessel.
- Failure of generating system.

Changes to the engine fixed structure would have minimum impact on overall engine maintainability, but periodic inspection of the generator output would be essential to the product reliability. Changes external to the engine would be in the power takeoff area and to configuration in routing the electric cable. This system would be designed to have minimum impact on overall engine or component maintainability. The system would be complete within the nacelle envelope but would require interface with the aircraft via a system operational indicator.

The clearance reduction at cruise was assessed to improve HP turbine efficiency by 1 percent. Electrical power requirements were assumed to be

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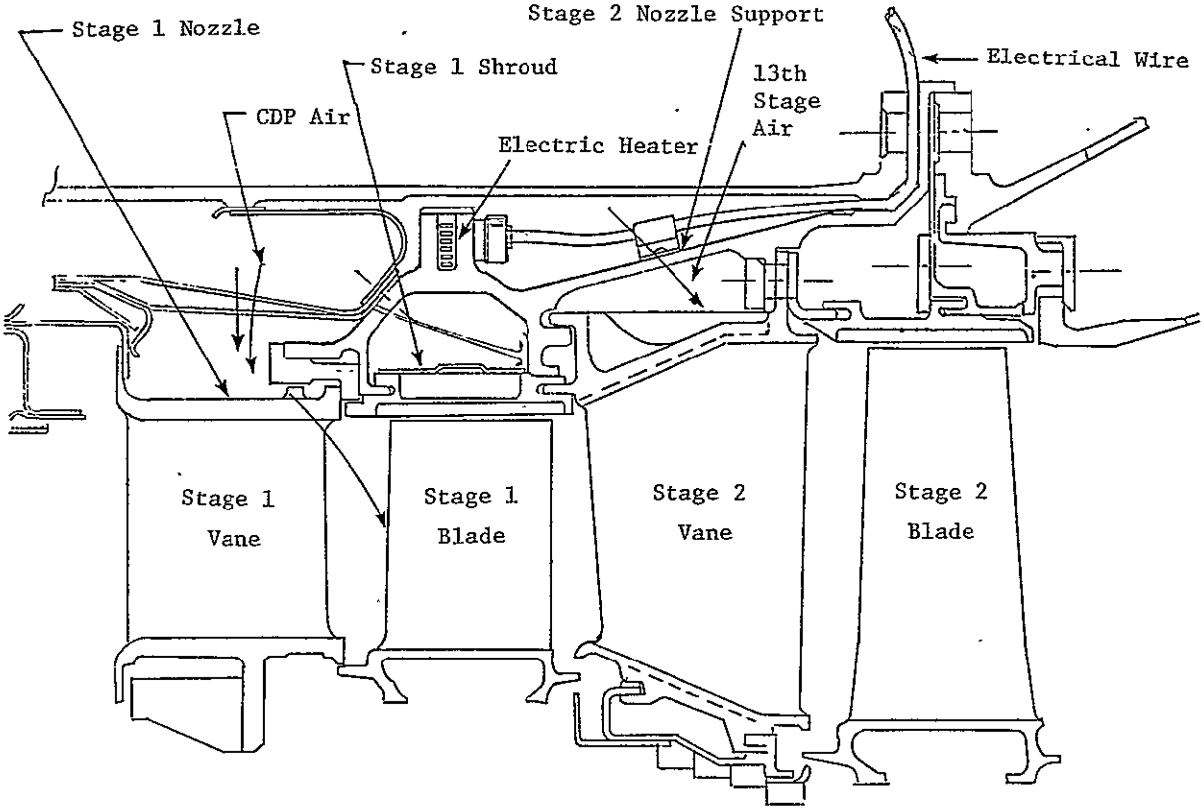


Figure 69. Active Clearance Control - Electrical Resistance Heating.

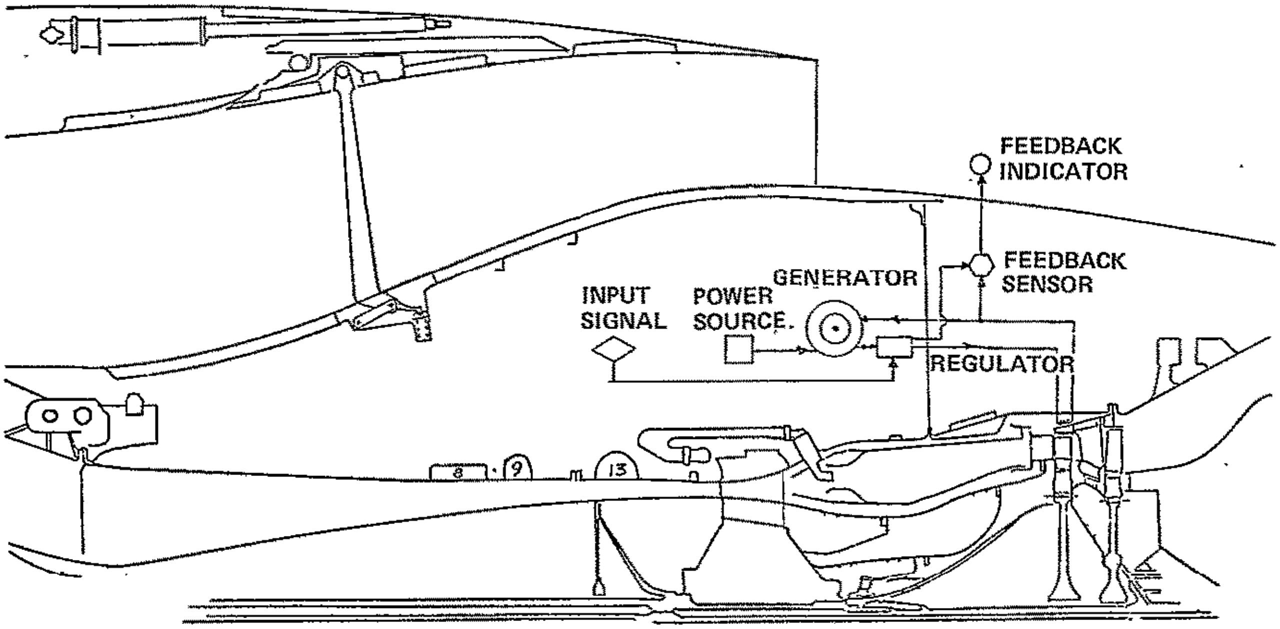


Figure 70. Active Clearance Control - Electrical Resistance Heating, Control Schematic.

provided by the aircraft. A summary of the technical assessment is shown in Figure 71. Predicted cruise sfc reduction is 0.8 percent.

5.1.18.2 Boeing

This concept has been evaluated for the CF6-6 engine and was, therefore, not studied by Boeing. However, it would also be applicable to the CF6-50.

5.1.18.3 Douglas

The section of the nacelle in which the electrical resistance heating concept is located is aft of the fire seal where the temperature environment is in the order of 555° C. While a ceramic heating element could be incorporated, normal insulated wiring will not take this temperature; and a major development would be required to cool and support the feed wires. Other areas of concern are:

- Electrical connection reliability because of high vibration and heat.
- Potential reliability problems from high current drain on aircraft electrical system.
- Life expectancy of the concept will be extremely important since failure to heat at the proper time will cause a tip rub and performance can only be restored by engine overhaul.
- At present, the DC-10 can be dispatched with one generator out. To prevent the loss of the heating system with the loss of a constant speed drive (CSD) or generator, the heating system would have to be fed from the central power control in the fuselage so that two generators could feed three engines. Separate large power feeder cables to handle the 30 kW/engine load will add considerable weight and complexity to the system.
- The output of one full generator would have to be devoted to the heating system and a priority control system would be needed so galleys and other high electrical loads could not be used during the heating period.

Another area that needs evaluation to determine the practicality of the concept is how the system is activated. Since there will be a thermal lag, it will probably have to be turned on before takeoff, and if needed during thrust reversal, prior to landing. Other activation considerations are for a waveoff and touch-and-go training flights.

Based on the available data and information, this concept is judged to be too complex for application to current aircraft.

TITLE Active Clearance Control-Electrical Resistance Heating (CF6-6)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	0
T/O	0 (0)/0.25	0
CLIMB	7620 (25000)/0.80	0
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.8
MAX CRUISE	10668 (35000)/0.85/+10°C	-.7
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.7
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	0 (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +18 kg (+40 Lb.)

ΔCG, cm (in) - 0.28 cm (0.11 in.) FWD

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $43,000 Increase

RETROFIT - Do not evaluate at this time

INSTALLATION COST - Not Evaluated

MAINTENANCE -

MATERIAL - $0.15 /Engine Flt. Hr. (Increase)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY System retrofittable with modifications to compressor rear frame for wiring, external wiring required

OTHER IMPACTS

Figure 71. CF6-6 HPT Active Clearance Control - Electrical Resistance Heating Screening Assessment.

5.1.19 High Pressure Turbine "Hard" Blade Tips (CF6-6, -50)

This approach offered the potential for performance improvement/retention through prevention of the blade tip loss resulting from erosion, oxidation, and/or shroud rub. Design analysis and review of recent design improvements on the CF6-50 engine indicate that improved tip cooling should significantly reduce the effects of erosion and oxidation. Efforts outside the Performance Improvement Program continued toward that end.

Relative to shroud rubbing, it has been concluded that the main thrust in the Performance Improvement Program should be directed at retaining the roundness of the shrouds and achieving a better growth match between the rotor and stator using the concepts of the other HPT programs.

As to "hard" blade tips and blade tips in general, there is ample supporting feasibility work in progress outside the Performance Improvement Program addressed at improving blade tip life which precludes the desirability of including comparable effort in this program. The results of these programs will be sufficient to establish the future of blade tips in the CF6 family of engines. Therefore, this concept was not studied further as a Performance Improvement concept.

5.1.20 Low Pressure Turbine Active Clearance Control (CF6-6)

5.1.20.1 General Electric

The CF6-6 LPT casing shroud and nozzle support hooks are currently cooled by impinging air on them through a series of tubes which are located between the casing shell and the honeycomb shrouds. This system employs ninth stage compressor bleed air which is piped back and enters a series of ports located at 12 o'clock and 6 o'clock. The ports at 12 o'clock distribute air circumferentially around the upper half of the case and those at 6 o'clock distribute air around the lower casing half.

The CF6-50 approach is an external cooling system which employs fan discharge air (Figure 72). An external system similar to the CF6-50 system was proposed for the CF6-6. This would involve designing a larger piping system in the fan reverser, a "kiss" seal and manifold for the transition between the reverser piping and the cooling "birdcage", and a birdcage similar to the CF6-50 design. Some existing piping external to the LPT casing would have to be redesigned in order to prevent interference with the new piping configuration. The extent of these changes was not defined.

The present cooling system and the proposed cooling system for the CF6-6 engine would not have been interchangeable. Modular interchangeability would be adversely affected. Fan reversers, compressor cases, compressor rear frames and LPT modules all would have to be reworked together. The extensive nature of the rework necessary to implement the cooling system change requires rework kits.

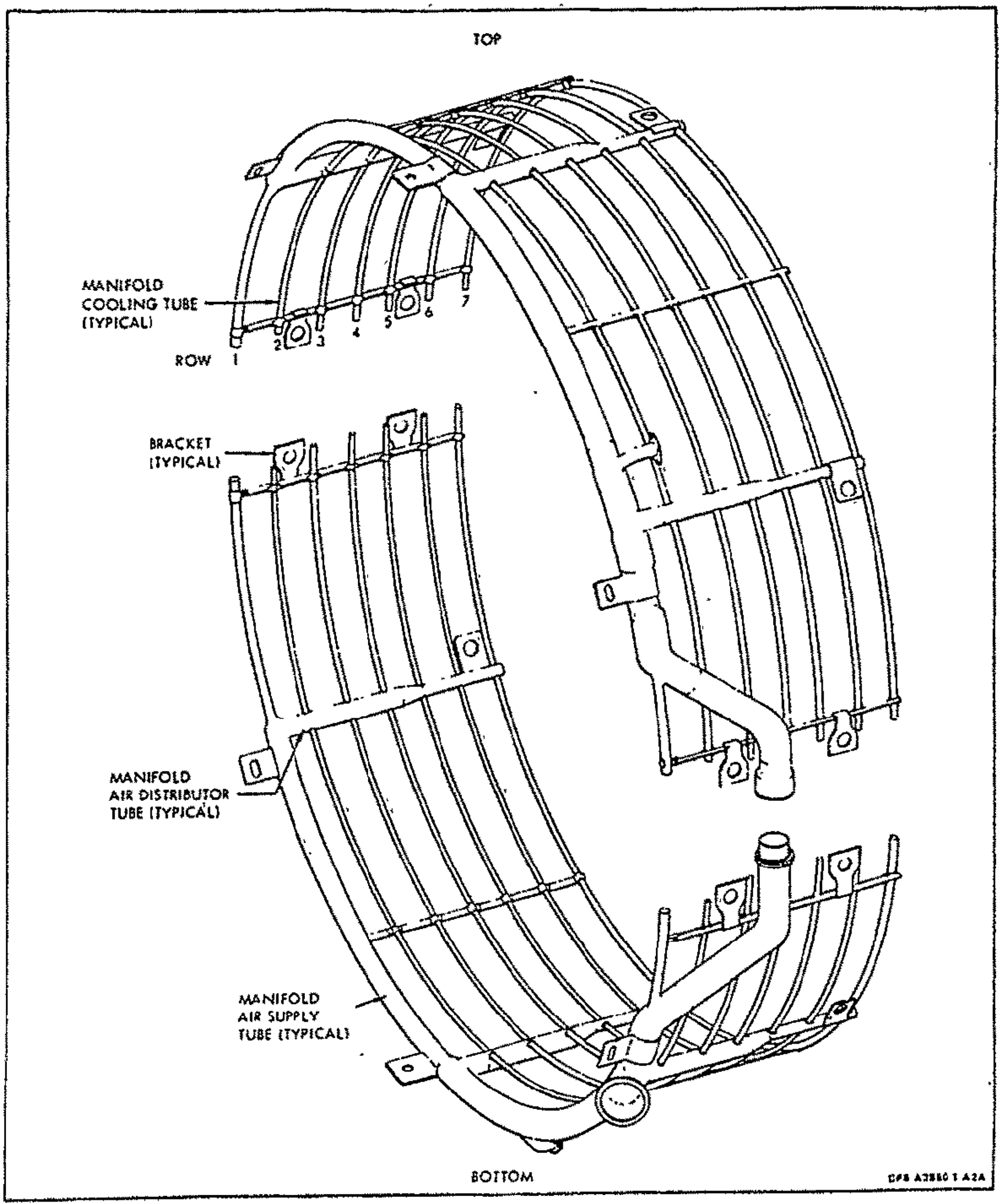


Figure 72. CF6-50 LPT Case Cooling Manifolds.

The use of lower energy fan air rather than ninth stage compressor bleed air and the reduction of the radial clearances between the turbine blades and the LPT casing due to the increased cooling of the casing would provide a cruise sfc reduction of 0.1 percent. The system assessment is shown in Figure 73.

5.1.20.2 Boeing

This concept has been studies for the CF6-6 and was, therefore, not studied by Boeing. However, a similar system could also be designed for the CF6-50 engine.

5.1.20.3 Douglas

The concept is internal to the engine and has no airframe effects. There is no OEW increase, and the block fuel savings which were evaluated for the minimum fuel are shown in Table XXI.

5.1.21 Low Pressure Turbine Active Clearance Control (CF6-50)

5.1.21.1 General Electric

After the completion of the screening study, it was decided to redesign the active clearance control system for the CF6-50 engine because of the cooling system and modular interchangeability problems with the CF6-6. The CF6-50 LPT case is currently cooled by an impingement manifold mounted externally. Discharge air from the fan is bled through a pipe located in the fan reverser. This air enters a plenum in the fan reverser where the reverser fits the radial fire seal. On the aft side of the plenum, the fan discharge air feeds into a piping system which is connected to the LPT case manifold. The manifold consists of air distribution tubes and a series of tubes axially spaced to impinge the fan discharge air on the case above the nozzle and shroud support hooks. Figure 73 shows the manifold with all other hardware removed. The case cooling manifolds were designed primarily to assure adequate case life by reducing thermal gradients between the hooks and casing skin during transient engine operation and to maintain an overall casing temperature at takeoff consistent with the design life requirements of the part.

The present LPT case cooling manifold flows 0.47 pound per second of fan discharge air at takeoff. The design and analysis of a new system with approximately twice the flow capability will be accomplished. Figure 74 shows the CF6-50 cross section with a schematic of the impingement manifold. The small diameter tubes which impinge air on the casing will be increased in diameter to handle the additional airflow. The number of impingement holes in the tubes will be increased. Axially-oriented cooling tubes at both horizontal split lines will be added in order to provide a means for impingement cooling of the flanges. The piping leading from the fan reverser plenum will be increased in cross-sectional area to be capable of providing more flow. The pipe which connects the "kiss" seal to the LPT

Table XXI. LP Turbine Active Clearance Control Block Fuel Savings (Min. Fuel Analysis).

	Range	ΔFuel	
	km	kg	%
DC-10-10 (CF6-6)	645	-6.4	-0.1
	1690	-15.4	-0.1
	3700	-34.5	-0.1

TITLE LPT Active Clearance Control (CF6-6)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-.1
T/O	0 (0)/0.25	-.1
CLIMB	7620 (25000)/0.80	-.1
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.1
MAX CRUISE	10668 (35000)/0.85/+10°C	-.1
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.1
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-1.8 kg.(-4) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - 0
ΔCG, cm (in) - 0

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES
NEW ENGINE - $10,000 Increase
RETROFIT - ATTRITION - $10,000 Increase
INSTALLATION COST - $200

MAINTENANCE
MATERIAL - -$0.10/Engine Flt. Hr. (reduction)
DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY Cooling systems are not interchangeable. Modular interchangeability is affected. Fan reverser, compressor case, compressor rear frame and LP turbine modules must all be reworked together.

OTHER IMPACTS

Figure 73. CF6-6 LPT Active Clearance Control Screening Assessment.

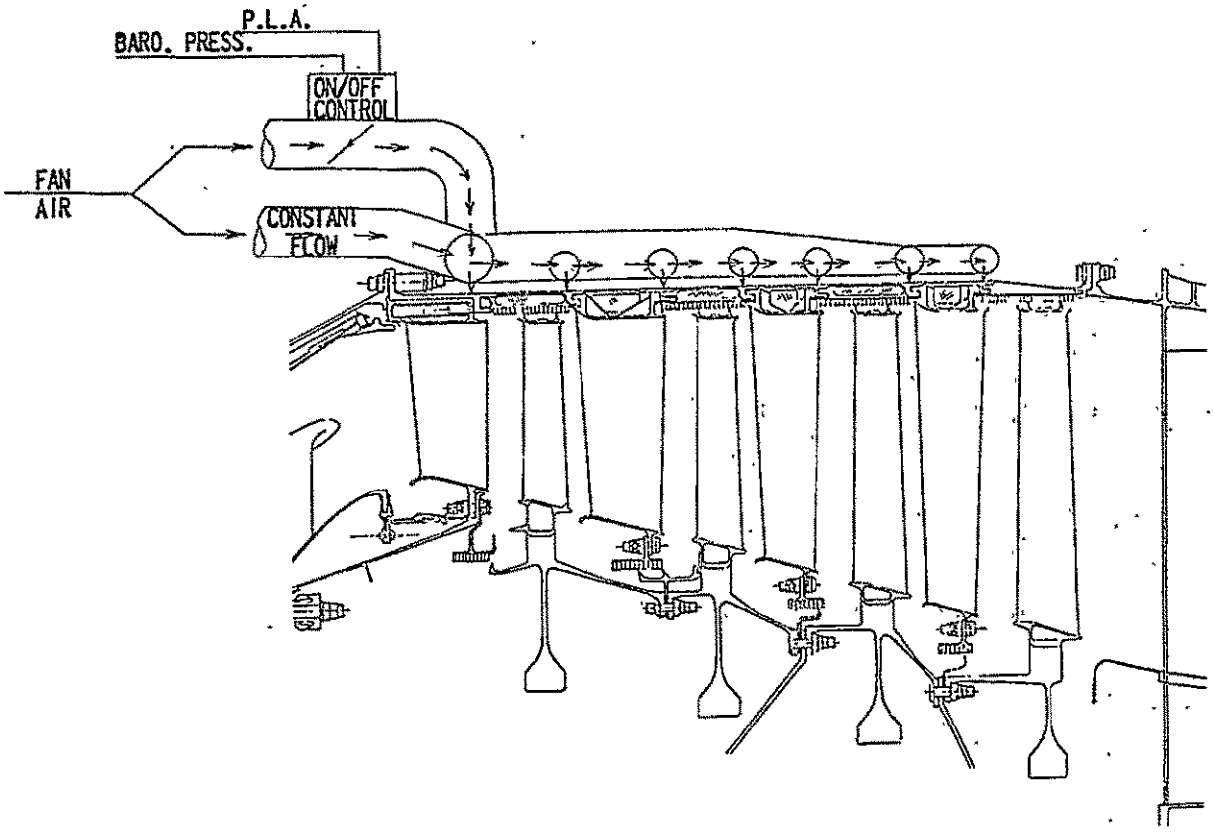


Figure 74. CF6-50 LPT Active Clearance Control.

cooling manifold will be redesigned for dual circuit flow. One of the flow circuits will be designed to provide fan discharge air continuously to the LPT cooling manifold at approximately the current rates. The second circuit will be provided with a flow body and slave controls which will enable an increased amount of flow to be supplied to the manifold when desired. In actual revenue service, the power setting control would be open for all power settings of flight idle or higher. The barometric pressure control would be activated at a designated altitude as cruise is approached.

During takeoff and climb up to the designated altitude, the constant supply of cooling air will maintain casing temperatures at levels required for casing life. The power setting circuit is open, but the pressure valve is closed. At the designated altitude, the pressure valve opens, allowing the total flow to increase. This increased impingement cooling will reduce the case diameter, thereby closing down the blade tip running clearance during cruise operation. When the engine power is retarded to flight idle, the power setting switch shuts off the supplementary airflow even when the aircraft is above the altitude required to activate the pressure valve. The purpose of the reduction back to constant flow level is to allow the casing to grow back out in preparation for landing and reverse thrust actuation. Otherwise, this would result in excessive shroud rubs.

Figure 75 shows a sketch of the rubout of a typical LPT honeycomb shroud. The rubout results from the relative radial and axial motion of the rotor and stator components during transient operation through a throttle burst from idle to takeoff for an engine using the current LPT case cooling system. The arrows indicate the direction of the blade tip motion relative to the shroud. Time is nonlinear along the path. As shown in the sketch, a relatively more open clearance may exist between the blade and shroud at cruise as compared with takeoff by virtue of both radial and axial growth differences between the rotor and stator. It is estimated that the level of improvement attainable by added case cooling at cruise would be approximately 0.5 mm per stage. This is equivalent to an LPT efficiency improvement of 0.4 percent or a cruise sfc reduction of 0.3 percent for the CF6-50 engine. These estimates include the effects of reduced leakage across the Stage 2 through 4 interstage seals as well as the four rotor blade/shroud stages.

5.1.21.2 Boeing/Douglas

Boeing and Douglas did not evaluate this system for the CF6-50. However, the block fuel savings should be higher in proportion to the sfc reductions (2.8 times) relative to the CF6-6 system results.

5.1.22 Low Pressure Turbine Stage 1 Incidence (CF6-50)

5.1.22.1 General Electric

The present CF6-50 Stage 1 LPT blade is aerodynamically unchanged from its original design. However, during previous performance improve-

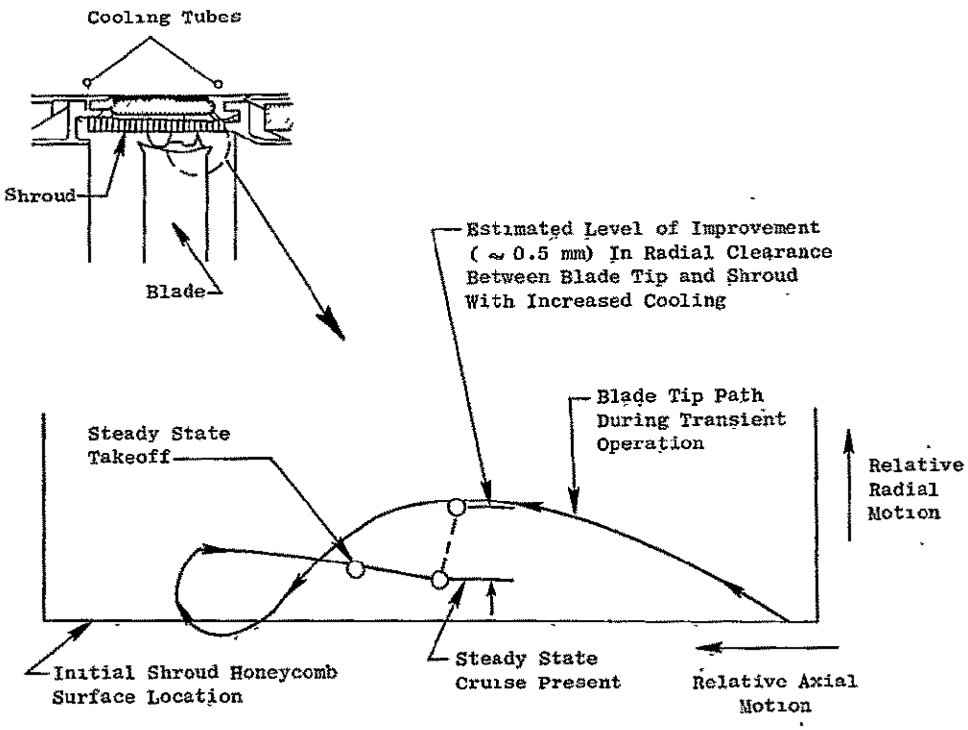


Figure 75. Typical Shroud Rubout Pattern With Current CF6-50 LPT Case Cooling System.

ment programs, the nozzles have been modified to increase the LPT flow functions. Consequently, the blade airfoil incidence angle is too large for peak efficiency (Figure 76). Recambering of the airfoil to change the incidence from -18.5° to -4° will match the nozzle exit flow and will increase the LP turbine efficiency by 0.12 point. This will be accomplished by a casting change to the airfoil; all other portions of the blade are unchanged.

The predicted sfc reduction for this concept is 0.1 percent for all power settings. The technical assessment is shown in Figure 77.

5.1.22.2 Boeing

New low pressure turbine Stage 1 blades would not necessitate changes to the nacelle or airframe, and there would be no change in airplane operating empty weight. An engine price increase of $4000 per shipset and maintenance cost reduction of 15 cents per engine hour would be the only changes required in airplane price and maintenance cost. The 0.1 percent improvement in sfc results in a 0.1 percent savings in block fuel and negligible gain in range and payload capabilities (Table XXII).

5.1.22.3 Douglas

The change is internal to the engine and has no airframe effect. Minimum fuel analysis block fuel savings for the DC-10-30 are summarized in Table XXII.

5.1.23 Reduced Leakage Low Pressure Turbine Interstage Seals (CF6-50)

The CF6-50 rotating interstage seals at Stages 3 and 4 consist of a one-toothed sheet metal seal. A two-toothed machined seal design, similar to the CF6-6, was evaluated for Stages 3 and 4 with regard to performance improvements due to the reduction of leakage flow (Figure 78). Stage 2 already has a two-tooth seal.

The performance improvement for two-toothed seals in Stages 3 and 4 was estimated at -0.075 percent Δ sfc. However, the selling price for the two rotating seals was estimated to increase by $5000 and new tooling of about $100,000 would be required. The weight increase was estimated at 1 kg.

Because of the modest performance gain potential of this concept which is well within the accuracy band of measurement, it was felt that the cost increase is not warranted; and the concept was, therefore, discontinued from this study.

5.1.24 Long Duct Mixed Flow Nacelle (CF6-50)

5.1.24.1 General Electric

During the last five years, General Electric has been actively engaged in resolving the pros and cons of many propulsion ideas that could lead to

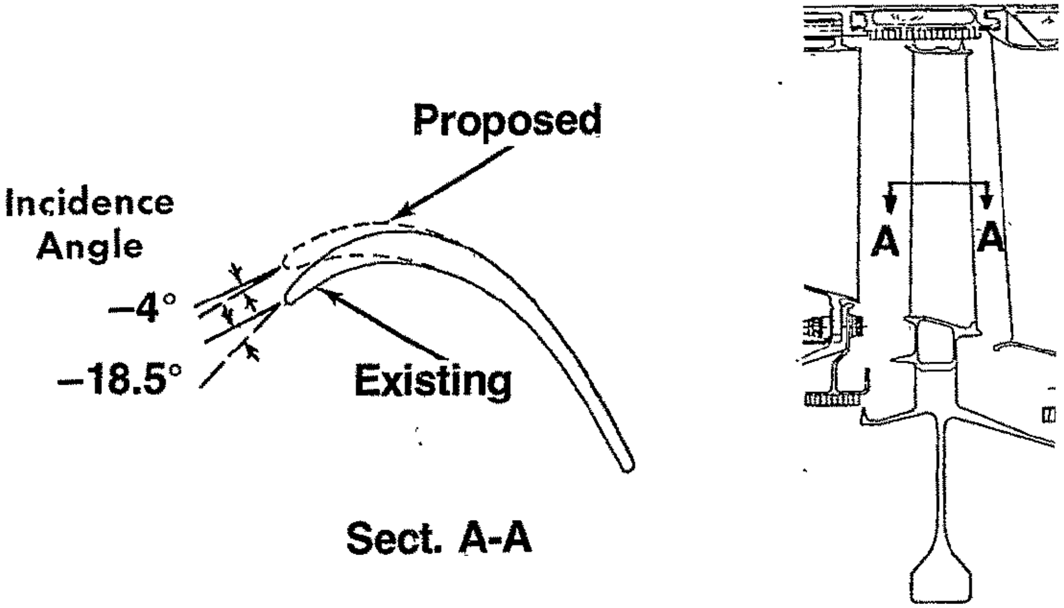


Figure 76. LPT Stage 1 Redesign.

TITLE LPT Stage 1 Incidence (CF6-50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC
T/O	SLS	-.1
T/O	0 (0)/0.25	-.1
CLIMB	7620 (25000)/0.80	-.1
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.1
MAX CRUISE	10668 (35000)/0.85/+10°C	-.1
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.1
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-1.8 kg (-4) (1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - 0

ΔCG, cm (in) - 0

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $1000 Increase

RETROFIT - $1000 Attrition, $16,000 Campaign

INSTALLATION COST - Negligible

MAINTENANCE

MATERIAL - -$0.15/Engine Flt. Hr. (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY Stage 1 LP turbine blades interchangeable as sets.

OTHER IMPACTS

Figure 77. CF6-50 LPT Stage 1 Incidence Screening Assessment.

Table XXII. LPT Stage 1 Incidence Block Fuel Savings (Min. Fuel Analysis) (CF6-50).

	RANGE	ΔFUEL	
	km	kg	%
DC-10-30			
	805	-8.2	-0.1
	2735	-25.4	-0.1
	6275	-68.0	-0.1
B-747-200			
	770	-9	-0.1
	3460	-45	-0.1
	6195	-90	-0.1

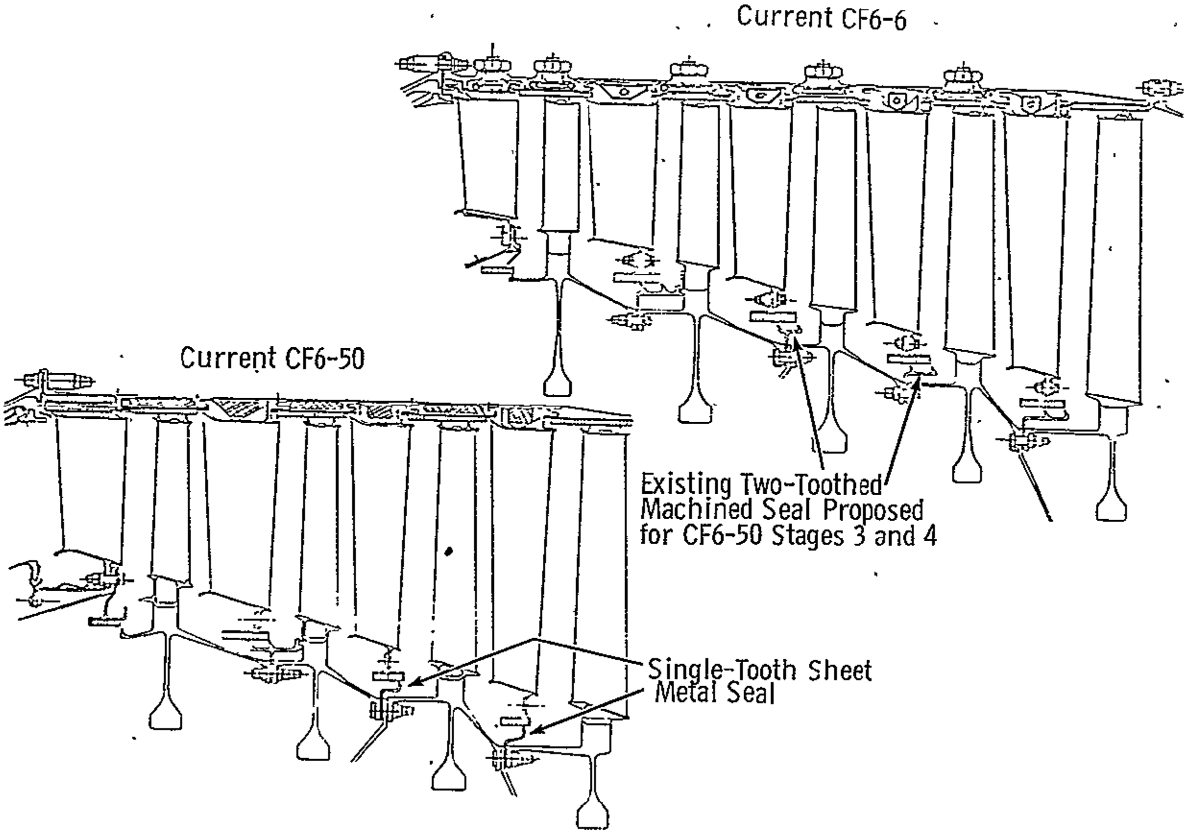


Figure 78. LPT Seals.

greater fuel efficiency from existing engines. One of these concepts is a long duct mixed flow (LDMF) propulsion system which offers a significant fuel consumption reduction when advanced technology is applied in key areas (Figure 79). A detailed write-up of the long duct nacelle is presented in Appendix A.

Internal performance (without external flow effects) of the LDMF nacelle was calculated with the following assumptions (Figure 80):

- 70 percent mixing effectiveness.
- 0.6 percent additional fan duct/mixer pressure loss relative to the current separate flow design.
- C-D exhaust nozzle with an area ratio of 1.003 and a throat area (A8) of 21,009 cm^2.

The calculated difference in sfc is based on uninstalled thrust. Fan duct and mixer pressure losses are included; pylon internal pressure loss improvements and fan cowl scrubbing drag improvements are not included. The technical summary is as presented in Figures 81, 82, and 83.

5.1.24.2 Boeing

The complete Long Duct Mixed Flow Nacelle evaluation is shown in Appendix A. The results for two different nacelle designs (a conventional design nacelle and an advanced structure nacelle) are shown in Tables XXIII and XXIV. The advanced structure design is a lightweight design utilizing advanced structure that was developed for this study. The conventional design is provided to show the amount of weight reduction that would be achieved by the advanced structure design.

5.1.24.3 Douglas

The Long Duct Mixed Flow Nacelle study is summarized in a separate report which is presented in Appendix A. The very significant block fuel savings for the minimum fuel analysis and 70 percent mixing effectiveness as proposed by General Electric are shown in Table XXIV.

5.1.25 Short Core Exhaust (CF6-50)

5.1.25.1 General Electric

The short core exhaust nozzle is proposed as a replacement for a deactivated core reverser nozzle or long fixed core nozzle, both of which are in use on the CF6-50 high bypass turbofan engine (Figure 84). A comparison of the short exhaust system with the current system is shown in Figure 85. The short core exhaust nozzle includes an outer cowl with an integral core cowl support ring and exhaust nozzle liner and a two-piece centerbody consisting of a forward section and an aft section.

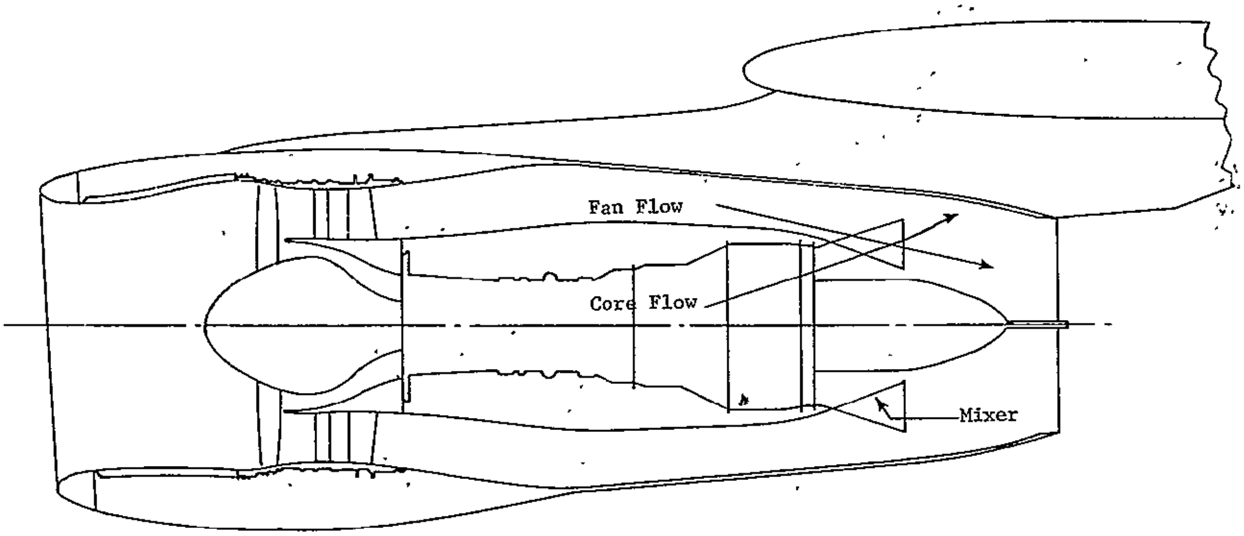
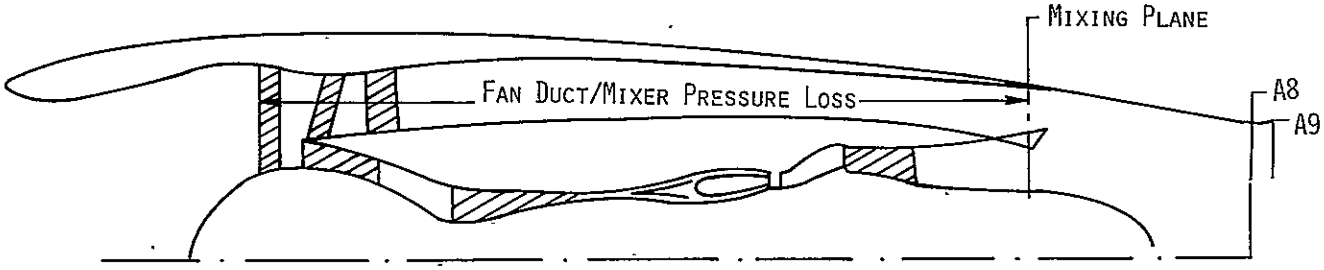


Figure 79. Long Duct Mixed Flow Nacelle.



- Mixing Effectiveness = 70%
- Additional Fan Duct/Mixer Pressure Loss = 0.6%
- C-D Exhaust Nozzle
  - Area Ratio, A9/AE8 = 1.003
  - Physical Throat Area, A8 = 21,009 cm^2
- SFC based on Uninstalled Thrust (Included are Fan Duct and Mixer Pressure Losses. Not Included are Pylon Internal Pressure Loss Improvements and External Drag Improvements).

Figure 80. Mixed Flow Cycle Assumptions.

TITLE LONG DUCT MIXED FLOW NACELLE, CF6-50 FOR BOEING 747-200

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION	Δ% SFC 2)	
	ALT, m (ft)/M		
T/O	SLS	-0.7	
T/O	0 (0)/0.25	-1.0	
CLIMB	7620 (25000)/0.80	-2.7	
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-1.6 3)	
MAX CRUISE	10668 (35000)/0.85/+10°C	-2.3	
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-0.5	
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	0	(1)

(1) ΔWf, kg/hr (lb/hr)

2) See Figure 80

3) See Figure 83

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb)	-	TURBINE REVERSER	-227 kg (-500 LB.)
		MIXER & BULLET	+134 kg (+295 LB.)
		Δ WEIGHT	- 93 kg (-205 LB.)
ΔCG, cm (in)	-	4.3 cm(1.7") FWD	

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $60,000 Increase (Mixer & Bullet)

RETROFIT - Not Applicable

INSTALLATION COST - Modest Reduction; Assume negligible

MAINTENANCE

MATERIAL - 0 4)

DIRECT LABOR - 0 4)

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY ASSUMED TO BE APPLICABLE FOR NEW ENGINES ONLY

OTHER IMPACTS NOTE 4) MIXED FLOW NACELLE INSTALLATION ACCESSIBILITY AND PRESSURIZATION OF CORE COWL NOT INCLUDED IN THIS ESTIMATE.

Figure 81. Screening Assessment of Long Duct Mixed Flow Nacelle, CF6-50 for Boeing 747-200.

TITLE LONG DUCT MIXED FLOW NACELLE, CF6-50 FOR DOUGLAS DC - 10-30

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC 2)	
T/O	SLS	-0.7	
T/O	0 (0)/0.25	-1.0	
CLIMB	7620 (25000)/0.80	-2.7	
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-1.6 3)	
MAX CRUISE	10668 (35000)/0.85/+10°C	-2.3	
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-0.5	
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	0	(1)

(1) ΔWf, kg/hr (lb/hr)

2) See Figure 80 for Assumptions

3) See Figure 83

ESTIMATED WEIGHT DATA

Turbine Reverser	-227	(-500 lb)
Mixed & Bullet	+134	(+295 lb)
ΔWeight	-93	(-205 lb)

PER ENGINE, kg (lb) -

ΔCG, cm (in) - -4.3 cm (1.7 in.) Fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $66,000 (Mixer and Bullet)

RETROFIT - Not Applicable

INSTALLATION COST - Modest Reduction; Assume Negligible

MAINTENANCE

MATERIAL - 0 4)

DIRECT LABOR - 0 4)

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY ASSUMED TO BE APPLICABLE FOR NEW ENGINES.

OTHER IMPACTS NOTE 4) MIXED FLOW NACELLE INSTALLATION ACCESSIBILITY AND PRESSURIZATION OF CORE COWL NOT INCLUDED IN THIS ESTIMATE.

Figure 82. Screening Assessment of Long Duct Mixed Flow Nacelle, CF6-50 for Douglas DC-10-30.

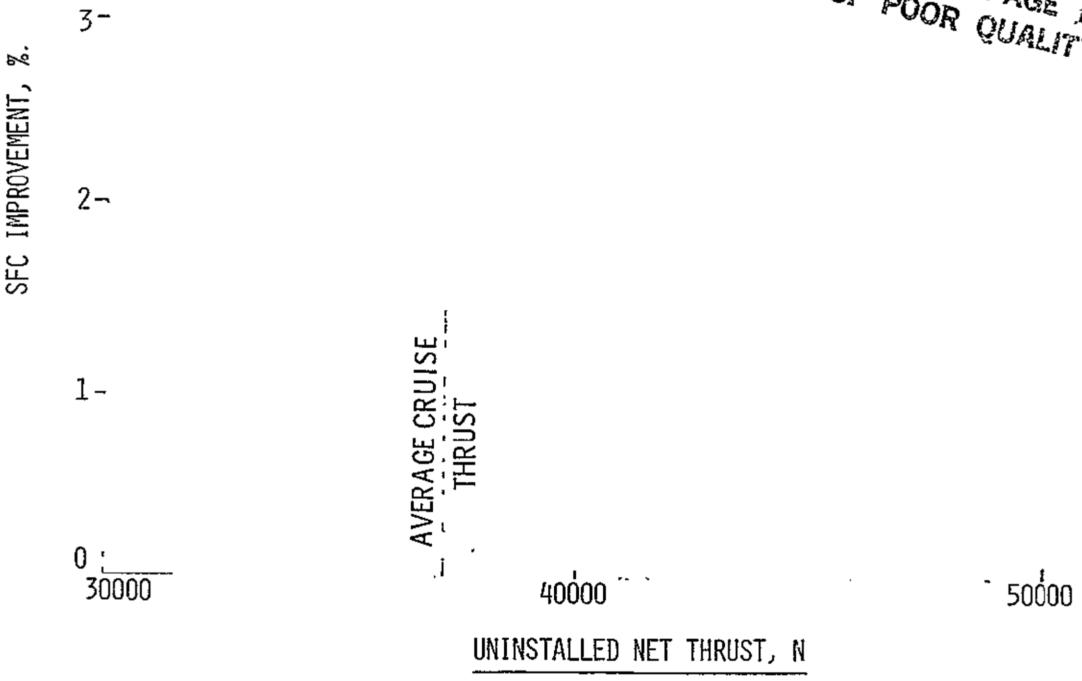


Figure 83. Percent SFC Improvement Mixed Flow vs. Separated Flow CF6-50 M 0.85/10,668 M (Mixing Effectiveness, 70 Percent).

Table XXIII. Boeing Technical Analysis Results, Long Duct Mixed Flow Nacelle (CF6-50).

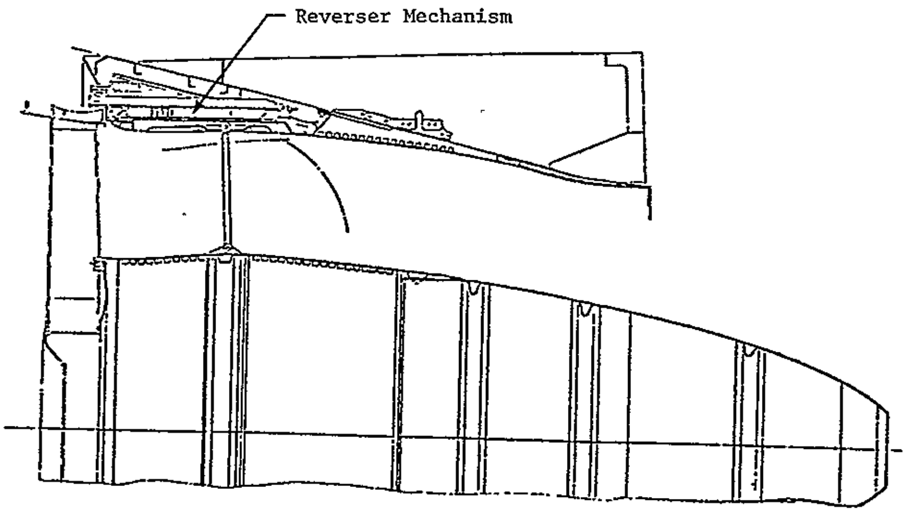
Engine Performance Data

Power Setting	Flight Condition	Δ% sfc
Takeoff	Sea Level Static	-2.0
Takeoff	0.250 Mn/0 Alt.	-2.4
Climb	0.800 Mn/7620 m	-4.5
Cruise, Fn = 36,000/40,000 N	0.850 Mn/10,668 m	-3.5
Max Cruise	0.850 Mn/10,668 m/+10° C	-4.1
Cruise, Fn 31,000 N	0.700 Mn/7620 m	-1.0
Hold, Fn = 29,000 N	0.325 Mn/457 m	0

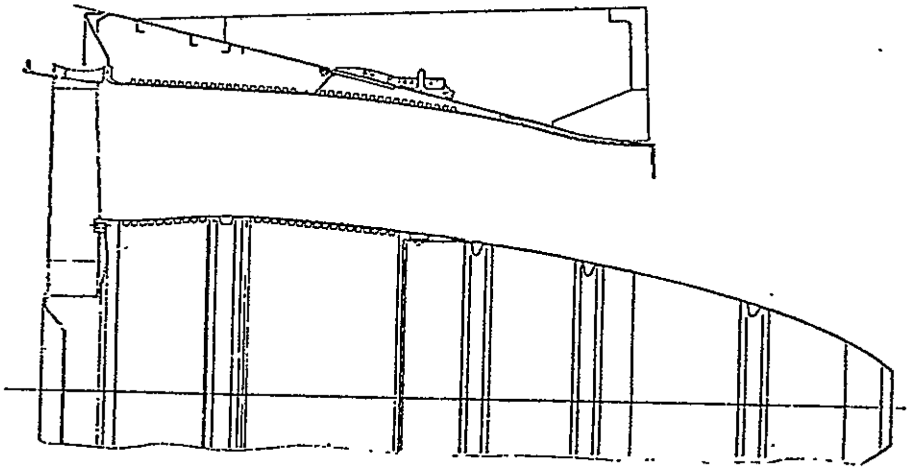
	Conventional Design Nacelle	Advanced Structure Nacelle
Operating Weight Empty Change	+3700 kg	+1548 kg
Airplane Performance Changes		
Range (Max TOGW)	-72 km	+129 km
Payload (On Limited Routes)	-748 kg, or -8 pass.	+1429 kg, or +15 pass.
Field Performance (ΔTOGW, Constant Field)		
Acceleration Limited	-91 kg	-91 kg
Climb Limited	-998 kg	-998 kg
Enroute Climb Performance (ΔGW, Const. Alt.)	-2631 kg	-2631 kg
Noise	Takeoff; -2 EPNdB: Sideline; -2.3 EPNdB: Cutback; -0.5 EPNdB: Approach; 0 EPNdB	
Maintenance Cost	0	0
Investment Spares Ratio	0	0
Airplane Price Change	+$860,000	+$860,000

Table XXIV. Long Duct Mixed Flow Nacelle Block Fuel Savings (Min. Fuel Analysis) (CF6-50).

	RANGE	ΔFUEL	
	km	kg	%
DC-10-30			
	805	-252.2	-2.5
	2735	-1037.8	-4.1
	6275	-2862.7	-4.9
B-747-200 (Conventional Design Nacelle)			
	770	-132	-1.2
	3460	-513	-1.3
	6195	-1120	-1.5
B-747-200 (Advanced Structure Nacelle)			
	770	-209	-1.8
	3460	-880	-2.1
	6195	-1801	-2.4



Core Reverser Nozzle



Long Fixed Core Nozzle

Figure 84. Current CF6-50 Core Nozzles.

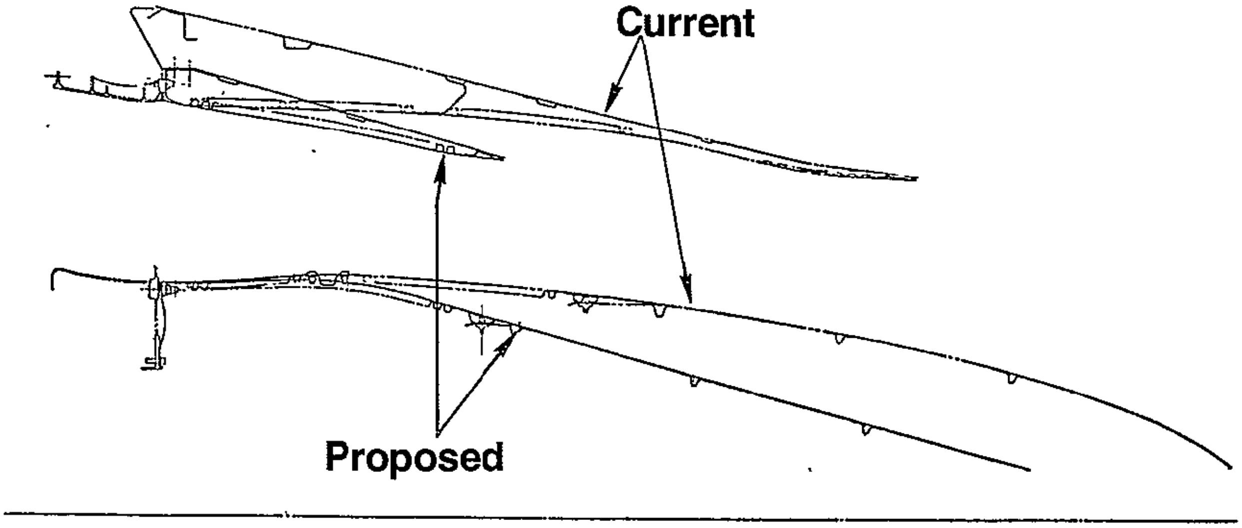


Figure 85. Short Core Nozzle.

The long fixed core exhaust nozzle was introduced for those airlines which do not require the core stream to be reversed in meeting their landing requirements. Operators who are favored with long runways and good weather conditions have already deactivated the core stream reversers to reduce weight and maintenance costs. The long fixed core exhaust nozzle maintained essentially the flow lines of the turbine reverser/nozzle. Both the long fixed core and short core exhaust systems provide significant weight reductions by removal of the deflector structure, blocker doors, and actuation and position sensing hardware.

The short core exhaust results in reduced diameter fan flow lines aft of the fan reverser and necessitates recontouring the engine core cowl, as well as the core nozzle. The reversal function, particularly, the housing of the stationary deflectors, requires a larger cowl diameter at the turbine rear frame. This causes the boattail angle (relative to the engine centerline) in the core nozzle region to be approximately 12° for the long nozzle rather than the 15° for the short nozzle.

The short core exhaust nozzle is physically interchangeable with either the turbine reverser or long fixed nozzle provided that the modified turbine rear frame No. 7 bearing oil supply and scavenge tubes, the new aircraft core cowl doors, and pylon fairings are incorporated concurrently with the change. Depending upon the design of the aft hat closeout on the new cowl doors which is yet to be defined, the forward flange may also have to be scalloped to provide space for the tubes to pass between the closeout and the flange. Once the short core exhaust nozzle is installed, it is possible to reinstall the turbine reverser or the long fixed nozzle only if the original aircraft cowl doors and pylon fairings are reinstalled. Hence, there will be a commonality problem unless an operator converts his entire fleet.

The reduced diameter cowling and shorter nozzle, therefore, reduce both weight and scrubbing drag. A nozzle drag reduction resulting in approximately 1 percent sfc reduction has been predicted for the short core exhaust nozzle.

In 1974 and 1975, General Electric and Douglas conducted a series of model tests directed at performance improvement of the CF6-50 engine core exhaust system. These tests confirmed the potential for improvement and preliminary design studies were initiated by General Electric and Douglas. Subsequent work effort included additional model tests and full scale diagnostic tests. The additional model tests included wind tunnel tests in which Douglas determined an interference drag reduction potential of 2 percent. Full scale tuft and pressure surveys conducted on a DC-10 by Douglas substantiated that the interference drag observed on the model actually exists on the airplane. More recently, static and wind tunnel model tests were conducted to "tune" the internal flowpath to achieve the desired nozzle flow area for engine thermodynamic cycle matching. These tests confirmed the results of the initial tests.

The technical assessment of the short core exhaust nozzle improvement is presented in Figure 86.

TITLE SHORT CORE EXHAUST (SCRUBBING DRAG, CORE DUCTΔP, PYLON/CORE COWL MODIFICATION)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC (2)
T/O	SLS	- .4
T/O	0 (0)/0.25	- .5
CLIMB	7620 (25000)/0.80	- .9
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-1.0
MAX CRUISE	10668 (35000)/0.85/+10°C	-1.0
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	- .9
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-20 (-44) (1)

(1) ΔWf, kg/hr (lb/hr) (2) Engine Related Performance Improvement

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) -45 (-100 LB.) (reduction) vs. long fixed core exhaust nozzle
- -147 (-325 Lb.) (reduction) vs. current core reverser nozzle

ΔCG, cm (in) - 2.54 cm (1 in.) fwd. per 100 Lb. reduction

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $37,000 reduction relative to long fixed core exhaust nozzle

RETROFIT - ATTRITION - $63,000 reduction relative to core reverser (does not include core cowl changes)

INSTALLATION COST - Modest reduction - assume negligible; retrofit at convenience.

MAINTENANCE

MATERIAL - -$1.10/engine flight hour (reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5% spares

RETROFIT CAPABILITY The short core nozzle requires pylon hinge line, core cowl and pylon/short core nozzle fairing changes

OTHER IMPACTS No change in noise levels predicted. New core cowl required.

Figure 86. Screening Assessment for the Short Core Exhaust (Scrubbing Drag, Core Duct ΔP, Pylon/Core Cowl Modification).

5.1.25.2 Boeing

The short core nozzle concept requires changes to the pylon hinge line, core cowl and pylon/short core nozzle fairing. The baseline from which these changes are defined is a CF6-50 engine without a core thrust reverser but with the core engine exhaust geometry the same as in engines with the core thrust reverser (long fixed core nozzle).

The core reverser nozzle is shortened and the side cowls are recontoured to provide a smooth blend from the fan exhaust nozzle to the core engine nozzle as shown in Figure 85. The hinge supports for the core cowl are revised to relocate the hinge line on the core cowls. The strut skin and fairing are extended to match the new core cowl lines without change to the strut side or trailing edge angles. These modifications result in a drag increase of 1 percent.

The shortened nozzle reduces the engine weight by 45 kg (relative to the long fixed core nozzle). The revised hinge supports for the core cowl and slightly longer strut result in a 6.8 kg weight increase which provides a net reduction of 38.2 kg per engine/nacelle or a 152.8 kg reduction in aircraft operating empty weight (OEW).

The uninstalled sfc improvements as estimated by General Electric were used for the installed performance in the aircraft performance analysis. No external drag reduction was credited to the system. In addition to providing these sfc improvements, this concept provides a reduction in maintenance cost of $1.10 per engine hour.

The individual engine price reduction of $37,000 for the new nozzle and an associated nacelle price increase of $262,000 per shipset result in a total aircraft price increase of $114,000. This is the price increase used in the economic analysis.

The results of the technical analysis of this concept are presented in Table XXV. A block fuel savings of 0.4 percent was projected for the 770 km flight and 0.1 percent for the longer flight. The benefit in reduced nacelle weight and improved internal performance is accounted for along with the increased external nacelle drag on block fuel savings. The effect of the increased external nacelle drag has a greater impact on the long range flights than on the short range flights. Thus, a smaller savings is shown for the longer flights. The change in range at maximum takeoff gross weight and in aircraft payload on limited routes was negligible.

5.1.25.3 Douglas

The short core nozzle as shown in Figure 87 reduces the internal and external skin friction and reduces weight. Model tests and full scale diagnostic tests show that interference drag occurs with the current CF6-50 installation on the DC-10-30. Model tests indicate that installation of the short core exhaust nozzle along with attendant pylon fairing effects could reduce this interference drag up to an amount equal to 2 percent of aircraft drag.

The changes required are a shorter primary exhaust nozzle, a revised core cowl door, revised door attachments and modification to the lower pylon. The short core nozzle reduces aircraft OEW by 166 kg relative to an aircraft with core reverser nozzles and produces significant fuel savings. The fuel burned savings for the DC-10-30 for the minimum fuel analysis are shown in Table XXV. A 1 percent reduction in aircraft drag due to lower interference drag was assumed in the estimate.

Table XXV. Short Core Nozzle Block Fuel Savings (Minimum Fuel Analysis).

	Range	Fuel	
	km	kg	%
DC-10-30 (2% Δsfc)	805	-123.8	-1.25
	2735	-468.6	-1.83
	6275	-1330	-2.26
B747-200	770	-41	-0.4
	3460	-50	-0.1
	6195	-109	-0.1

5.1.26 Vortaway Vortex Suppressor (CF6-6, -50)

5.1.26.1 General Electric

The Vortaway vortex suppressor consists of a series of jets in the lower surface of the inlet that induce a secondary airflow around the lower lip of the inlet and create an aerodynamic screen or blockage for flow along the lower surface of the inlet (Figure 88). The effect of this secondary flow and/or aerodynamic curtain is to modify the location of the stagnation line around which an inlet vortex can exist. If sufficient secondary flow can be induced, it is equivalent to a headwind and the stagnation line can

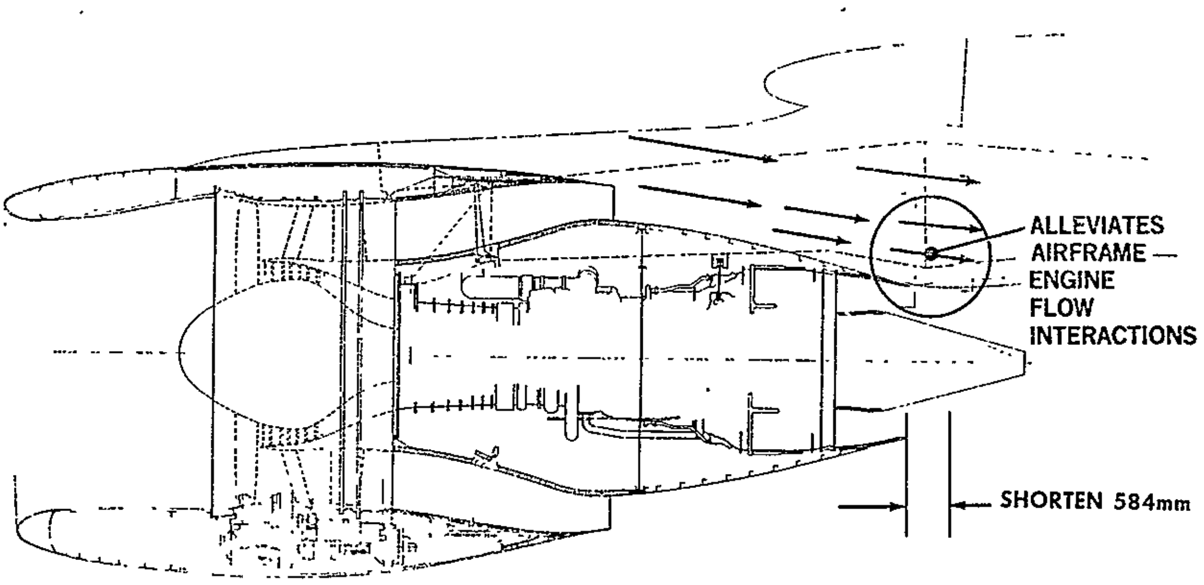


Figure 87. Short Core Cowl/Nozzle.

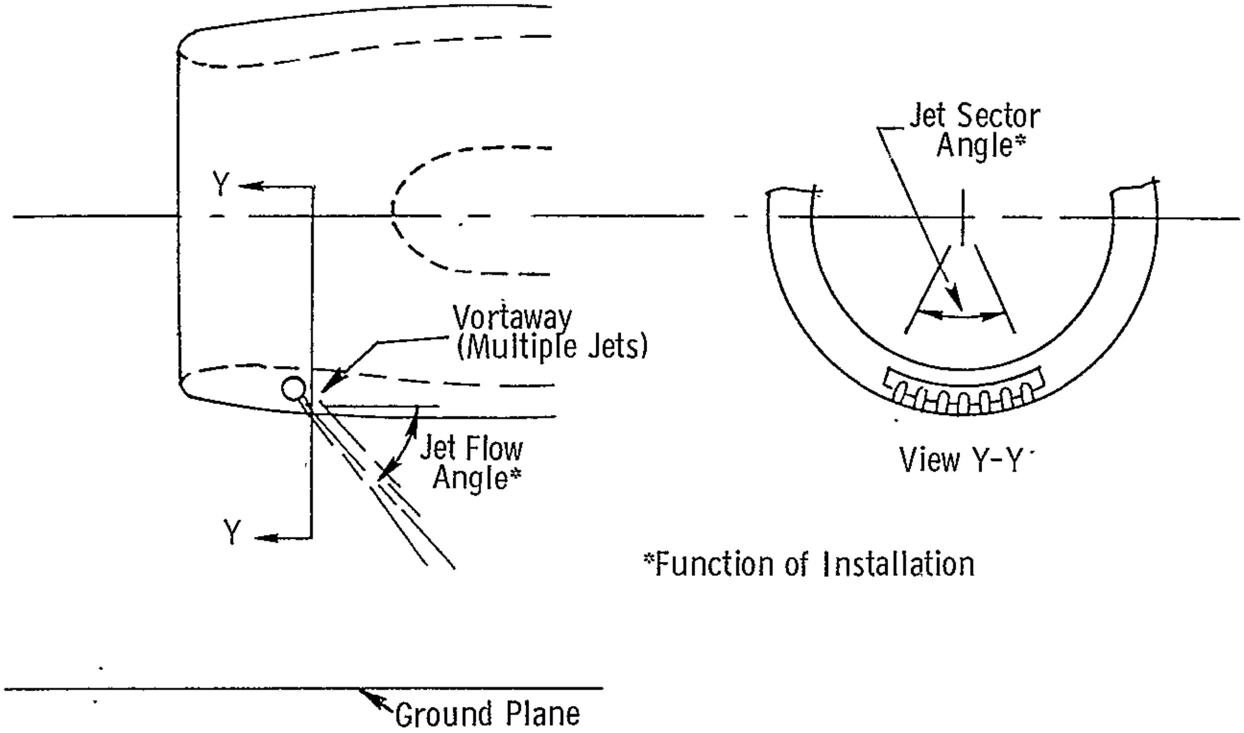


Figure 88. Aft Blowing Vortex Suppressor.

be eliminated in much the same way as if the inlet were moving forward over the ground. When the induced flow is low or the blockage effect is weak, the vortex may continue to exist; but its effect is reduced so that less and smaller material is loosened from the ground to be ingested with the inlet flow. Also, it has been observed that a large percentage of the small material that is loosened from the ground is captured by the induced airflow and is carried harmlessly under the inlet. The prototype Vortaway consists of a curved manifold installed inside the inlet with jets or nozzles flush with the nacelle lower skin. Alternate configurations of the Vortaway could be poppets that extend from the lower surface of the inlet in proportion to the applied pressure and bring into play an arrangement of jets designed for optimum flow entrainment for the particular operating condition. This poppet could be of cylindrical form that slides out of a recess or it could be a pivoting arrangement that protrudes when air pressure is applied.

The Vortaway is installed in the inlet aft of the anti-icing duct and is readily accessible for removal/maintenance through the access doors. The pneumatic valve is located adjacent to the anti-icing valve.

Interchangeability of engines is unaffected since the Vortaway installation is completely in the inlet as an accessory to the anti-icing system. Controls and switches are required external to the inlet.

Foreign object damage and airfoil erosion are reduced in the booster and HP compressor blading in direct proportion to the reduction in ingested material. Parts life is increased, FOD repair costs are decreased, and aerodynamic performance of the airfoils is maintained.

The Vortaway has been assessed on its potential of reducing engine deterioration at 3000 hours engine life as shown in Figure 89. The predicted deteriorated engine cruise sfc reduction was 0.2 percent for the CF6-6 (DC-10-10 installation) and 0.3 percent for the CF6-50 (DC-10-30 installation).

5.1.26.2 Boeing

This concept was not evaluated by Boeing because the Vortaway was designed specifically for the DC-10 airplane.

5.1.26.3 Douglas

The Vortaway requires a switching device and a means to prevent operation in flight. The DC-10 currently has a wheel speed generator which can be used to switch the Vortaway on Below 55 km/hr. A squat switch can be added to the landing gear which would make the system inoperative in the air. Figure 90 shows a test unit which was fabricated in a joint Douglas/GE program. The Vortaway vortex suppressor increases the aircraft OEW by 20 kg. Block fuel savings for both domestic and international operations are presented in Table XXVI for the minimum fuel analysis case at 3000 hours.

TITLE Vortaway - Vortex Suppressor (CF6-6, -50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	CF6-6 2) Δ% SFC		CF6-50 2) Δ%SFC
T/O	SLS	-.2		-.3
T/O	0 (0)/0.25	-.2		-.3
CLIMB	7620 (25000)/0.80	-.2		-.3
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-.2		-.3
MAX CRUISE	10668 (35000)/0.85/+10°C	-.2		-.2
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-.2		-.3
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	- 5.4 (-12)	(1)	-7.3(-16)

(1) ΔWf, kg/hr (lb/hr)

2) At 3000 Hours

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - + 6.8 kg (+15 Lb.)

ΔCG, cm (in) - 0

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $15,000 Increase

RETROFIT - ATTRITION - $15,000

INSTALLATION COST - $ 1,900 (GE estimate)

MAINTENANCE

MATERIAL - $2.00/Engine Flt. Hour (Reduction)

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY Interchangeability of engines is unaffected. External controls and switches required.

OTHER IMPACTS Wing Engines Only

Figure 89. Screening Assessment for the Vortaway-Vortex Suppressor (CF6-6 and CF6-50).

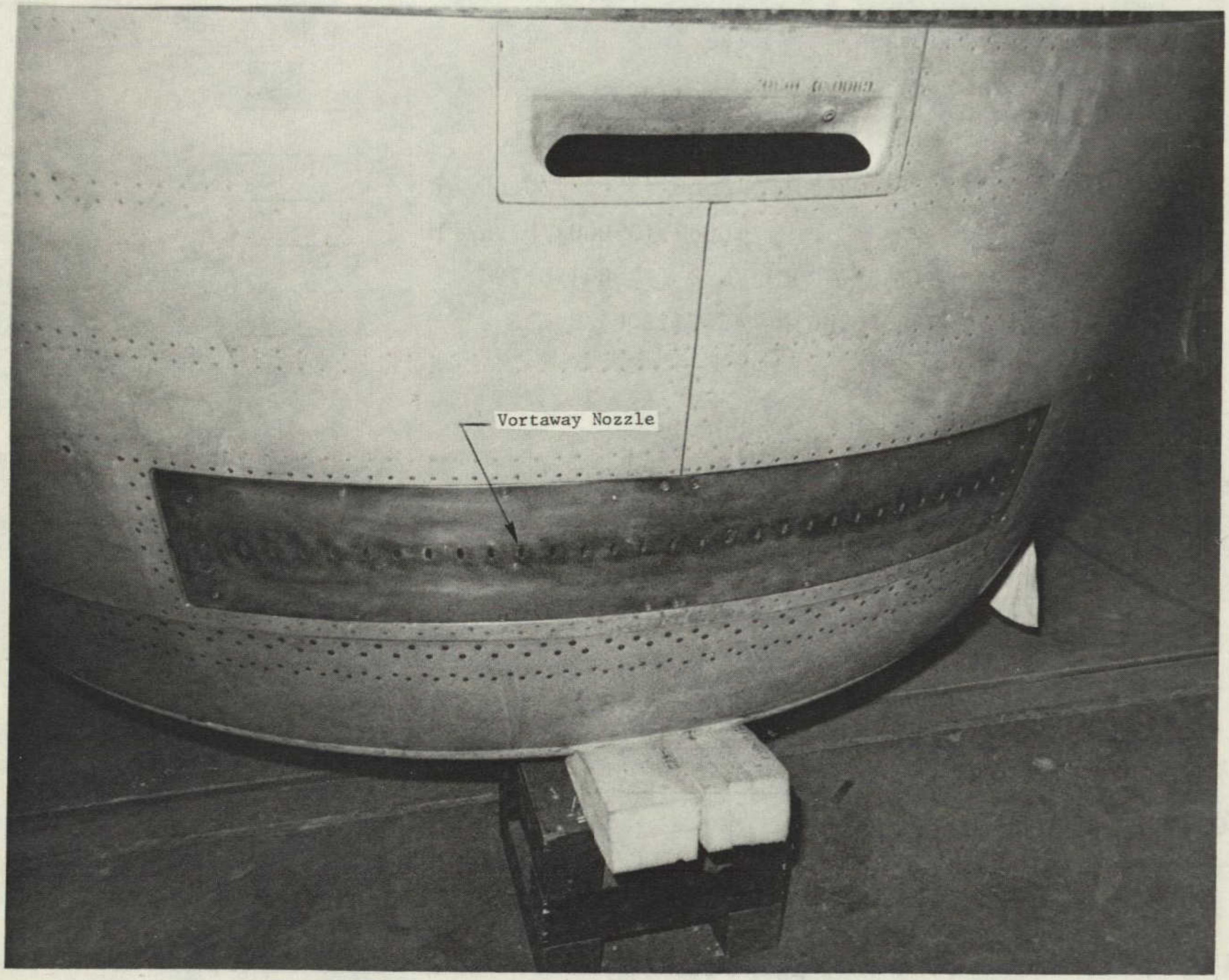


Figure 90. Vortaway Test Unit.

Table XXVI. Vortaway - Vortex Suppressor Block Fuel Savings at 3000 hours (Min. Fuel Analysis).

	Range	ΔFuel	
	km	kg	%
DC-10-10 (CF6-6)	645	-14.5	-0.2
	1690	-40.8	-0.2
	3700	-90.3	-0.3
DC-10-30 (CF6-50)	805	-15.9	-0.2
	2735	-49.9	-0.2
	6275	-137.4	-0.2

5.1.27 Improved Nacelle System

The suggested improvements to the nacelle system consisted of the following items:

- Reduced Core Cowl Gap
- Elimination of Fire Shield
- Optimized Nacelle Cooling

Analysis and evaluation indicate that study of the subject concept should be discontinued on the following bases:

Reduced Gap

Further analysis showed that the performance loss is less than originally predicted because the fan air scooped into the aft compartment is boundary layer air with a lower momentum than free stream air.

Fire Shield Elimination

Douglas has rejected the elimination of the radial fire shield on current aircraft because of cost and interchangeability considerations. They have, however, endorsed the removal of the radial fire shield on new engines/

aircraft, and General Electric is proceeding with the development of future CF6-50 engines without a radial fire shield.

Removal of the radial fire shield primarily reduces engine weight (about 27 kg) which would result in very modest performance improvement. Systems affected by this change are:

- Compartment cooling
- Compartment venting
- Configuration hardware support/bracketry
- Fire detection system
- Fire extinguishing system
- Compressor rear frame

Elimination of the radial fire shield will probably require recertification flight testing of the aircraft for compartment temperature and fire extinguishing.

"Optimized" Cooling

It is believed that fan cooling air through the 12 o'clock strut can be reduced by about 50 percent. (From 0.25 kg/second to 0.12 kg/second at takeoff.) The sfc improvement is small and, again, this impacts aircraft recertification and probably would be rejected by the aircraft companies.

In view of the above referenced ongoing effort and of the very modest resulting improvements, it was recommended that no further study or design work be conducted on the subject concept.

5.1.28 Modified Controls (CF6-6, -50)

5.1.28.1 General Electric - Power Management System

This change introduces a power management control system to the CF6 engine which will contribute directly to fuel savings by:

- Providing more accurate control of thrust, thus reducing the adder required to get the minimum engine up to guarantee thrust. Hence, the entire fleet operates at a slightly lower fuel flow level.
- Eliminating the fan speed (N1) overshoot which normally occurs immediately after setting takeoff power. This will directly reduce peak exit gas temperature (EGT) and peak fuel flow.

- Improving retention of original engine performance level by preventing inadvertent pilot overboost or overtemperature (optional) of the engine.

The proposed system interconnection is shown in Figure 91 and the schematic is shown in Figure 92. Introducing this system involves the following changes to the CF6 engine installation:

New components are added as follows:

1. A Power Management Control (PMC) - This is an on-engine analog limited authority electronic control with the engine ratings in its computer memory. The rated corrected fan speed is computed for inputs of T2, PS11, and power lever position. This value is then controlled closed loop through the main engine control (MEC) by modulating fuel flow as required. (If the EGT option is included, this loop will also limit EGT to the redline as a maximum, regardless of N1 demand.)

2. An electrical engine inlet temperature (T2) sensor is mounted in the inlet ahead of the fan blades.

3. Four static pressure taps (PS11) are added in essentially that same plane in the inlet.

4. A bayonet type N1 sensor is added in the fan frame, insertable from outside the engine. The sensor has two separate windings, one for PMC use and one for cockpit N1 indicator.

5. A dual winding alternator replaces the present core speed (N2) tachometer, one winding for PMC power generation and one for cockpit N2 indication.

6. An airframe-furnished potentiometer is added in the cockpit to send an electrical signal of power level position to the PMC.

7. Necessary interconnecting electrical cables.

Existing components are modified as follows:

1. The fan frame and "A" sump are redesigned to accept the new N1 sensor.

2. The MEC will now incorporate an electrohydraulic servovalve (torquemotor) to accept the N1 error signal from the PMC. In addition, the basic schedule of N2 versus power lever angle (PLA) will be converted to corrected core speed (N2K) versus PLA.

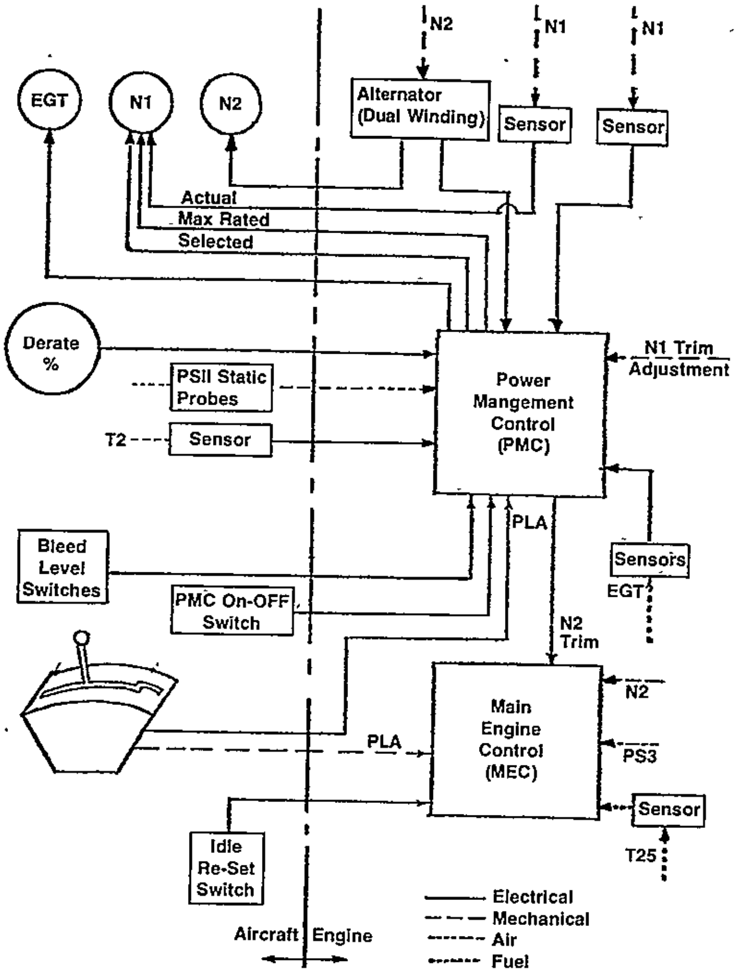


Figure 91. PMC Interconnection Drawing.

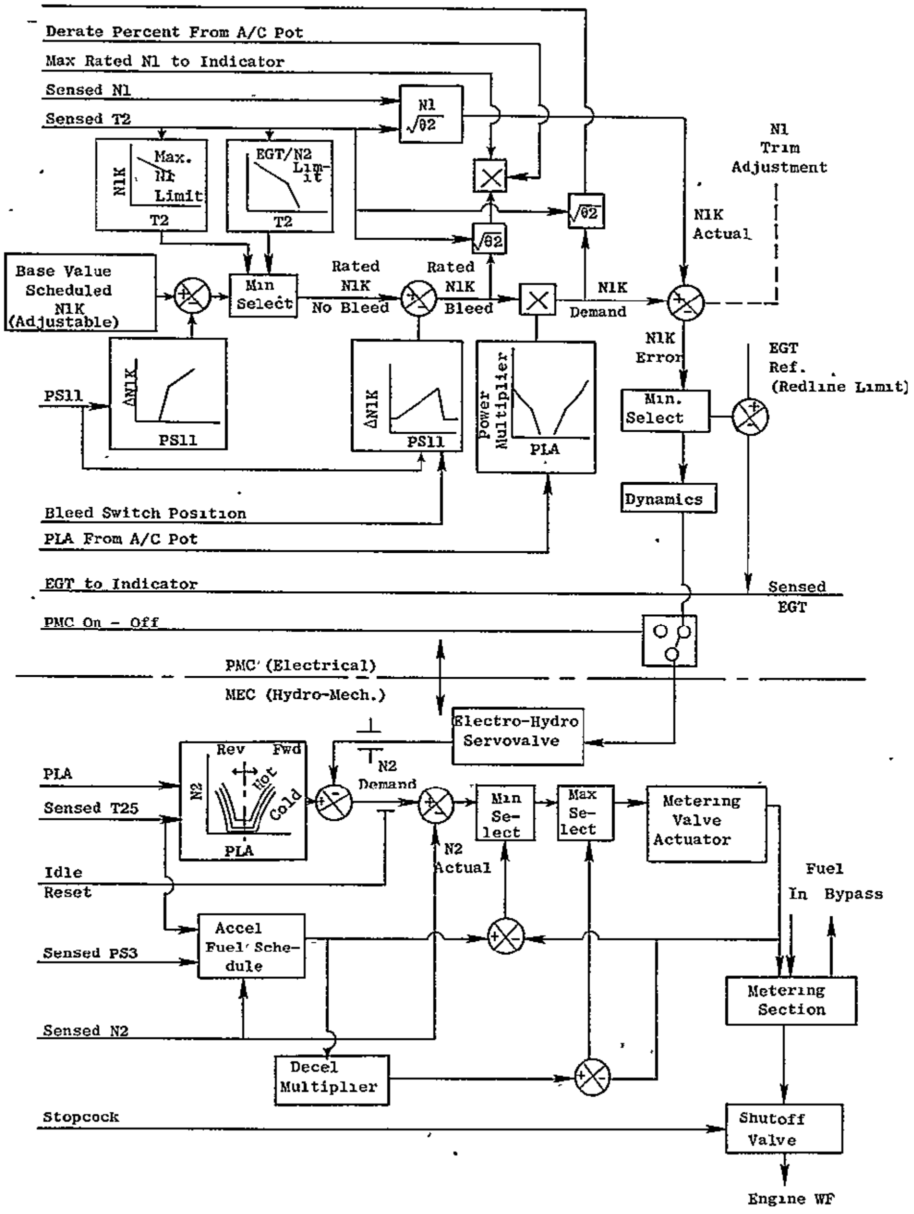


Figure 92. PMC Schematic.

Existing components are deleted as follows:

1. N2 tachometer.

2. N1 sensors.

There will be additional aircraft interfaces: Mounting and routing for PS11 and T2 sensors and signals, potentiometer added to throttle quadrant, electrical connections between control and aircraft, new interface for EGT instrumentation signal, new removal envelope and interface connection for N1 signal, new removal envelope and interface connection for N1 signal, clear envelope for PMC, clear envelope for generator, and clear envelope for added MEC features.

The PMC system affects performance and aircraft operation in the following ways:

1. Direct control of N1 to ±0.72 percent of schedule (including a ±0.35 percent error in the pilot's throttle setting accuracy when operating below the corner point) will allow the engine rating to be set lower than the present ratings which must allow for a larger N1 tolerance due to indirect N1 control (direct N2 control).

2. Direct N1 control will also prevent overboost and retard performance deterioration.

3. If the EGT limiting option is included, inadvertent turbine overtemperature events resulting from operation outside of normal procedural limitations will be automatically prevented, further retarding performance deterioration.

4. With EGT limiting function included, turbine damage during some stall events would be reduced and performance deterioration would thus be retarded.

5. Operation of the airplane in an essentially constant N1 cruise mode will allow elimination of excessive airplane accelerations and decelerations and, thereby, provide fuel savings.

6. N1 and EGT overshoot during the thrust setting transient is reduced with the new control system. The 2 spread of N1 is reduced from:

$$^{+1.62}_{-1.28}\%\ \text{N1 to } \pm 0.68\%\ \text{N1.} \quad \text{(Figure 93)}$$

The technical assessment for the PMC system is shown for CF6-6 and CF6-50 application in Figure 94. The predicted cruise sfc improvements are 0.2 percent for a new engine and 0.4 percent at 3000 hours engine life.

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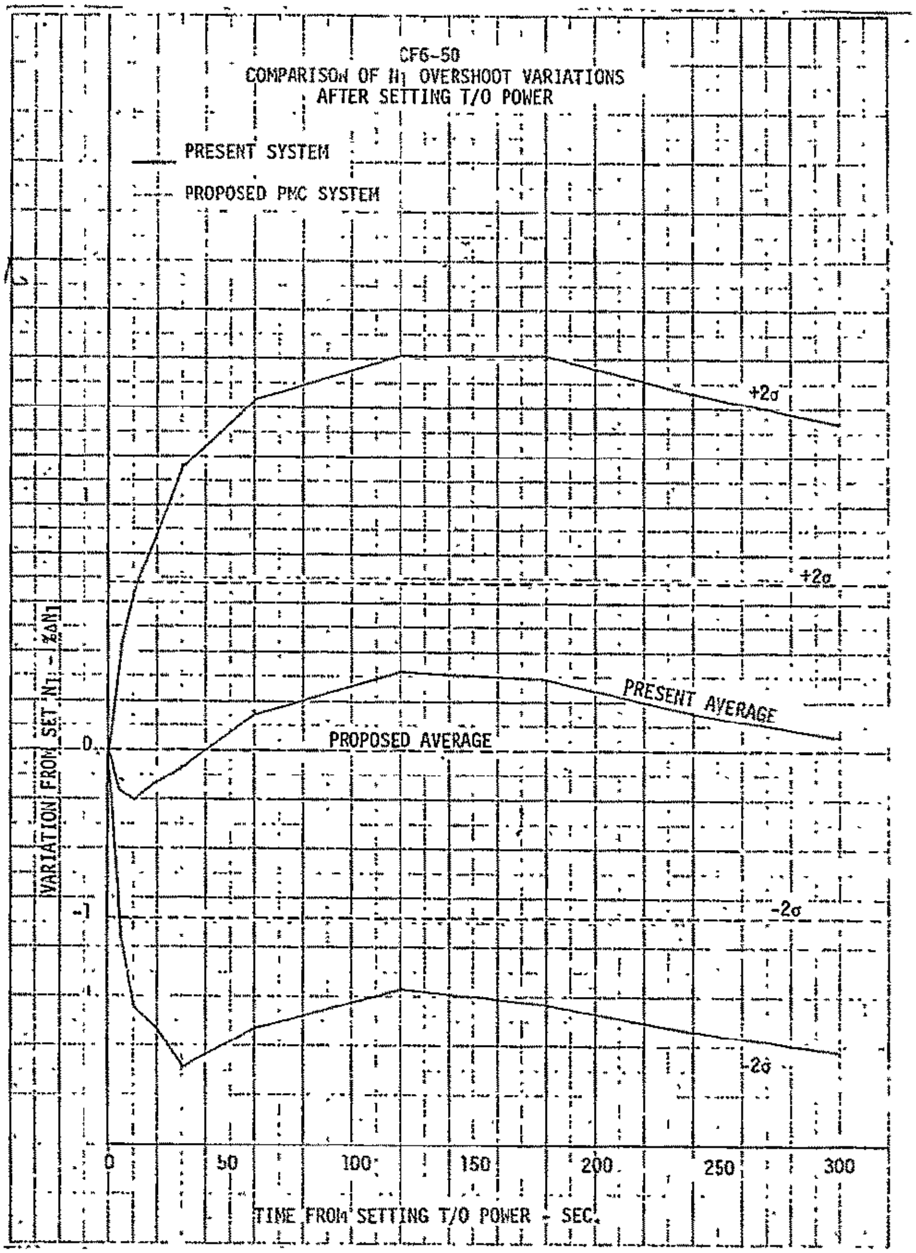


Figure 93. CF6-50 Comparison of N_1 Overshoot Variations After Setting T/O Power.

TITLE Modified Controls - Power Management Control System (CF6-6, -50)

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC [2)]	Δ% SFC [3)]
T/O	SLS	-1.0	-1.1
T/O	0 (0)/0.25	-1.0	-1.1
CLIMB	7620 (25000)/0.80	-0.2	-0.4
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-0.2	-0.4
MAX CRUISE	10668 (35000)/0.85/+10°C	-0.2	-0.4
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	-0.2	-0.4
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-3.6(-8) (1)	-7.3 (-16.0)

(1) ΔWf, kg/hr (lb/hr)

2) New Engine 3) At 3000 Hours

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - + 15 kg (+33 Lb.)

ΔCG, cm (in) - 0.36 cm (0.14 in.) Fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $44,000 Increase

RETROFIT - Not Evaluated

INSTALLATION COST - Included in new engine

MAINTENANCE

MATERIAL - -$0.65/Engine Flt. Hour (Reduction)

DIRECT LABOR - Negligible.

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY System is retrofittable but non -interchangeable. Additional A/C interfaces required for mounting and routing of sensors, signals and electrical connections (Figure 91) requires new alternator, T2 sensor, bleed and PMC switches, derate and N2 indicators and PMC computer.

OTHER IMPACTS

Figure 94. Screening Assessment of Modified Controls - Power Management Control System (CF6-6 and CF6-50).

5.1.28.2 General Electric - Full Authority Digital Electronic Control (FADEC)

This change replaces the present main engine control with a Full Authority Digital Electronic Control (FADEC), a solid-state device incorporating advanced digital microprocessor technology to provide much greater flexibility than the present control in controlling present variables (fuel flow, variable stator vanes (VSV), and variable bleed valves (VBV) and accommodating additional variables suggested for fuel economy such as active turbine clearance control and variable compressor bleed. The FADEC operated in conjunction with a backup control which includes electrohydraulic output elements which actuate the controlled variables and hydromechanical control elements which provide for continued safe operation of the engine in the event of FADEC malfunction.

Figure 95 is a schematic showing the CF6-50 control system with the FADEC incorporated. Major changes from the present system are as follows:

- Items Deleted - Main Engine Control, Core Inlet Temperature Sensor, VSV Reset Actuator, Reverse Thrust Limiter, and VBV Mechanical Feedback.
- Items Added - The FADEC Unit, Backup Control, Fan Inlet Temperature Sensor, VBV Servovalve, VSV and VBV Position Transducers, Electrical Cables, and provisions for sensing fan inlet pressure.
- Items Changed - Fan Speed Sensor (magnetic pickups in fan bearing sump region rather than on fan casing), Tachometer Generator (replaced by alternator), and mounting provisions for the fan inlet temperature sensor.

To utilize FADEC properly, digital electronic devices would be required in the aircraft to provide an accurate power demand to the engine and to accept and process the digital condition monitoring data supplied by the FADEC. Also, with the current FADEC concept, a connection is required with the aircraft electrical system to provide backup power to the control and to permit ground check-out of the control and associated equipment without running the engine.

The FADEC affects performance and aircraft operation in the following ways:

- Direct control of N1 to ±0.5 percent of schedule (assuming negligible error in the digital power demand from the aircraft) will allow engine ratings to be set lower than the present ratings which must account for a larger N1 tolerance due to indirect control (through N2).
- Direct control will also prevent overboost and thus, retard performance deterioration.

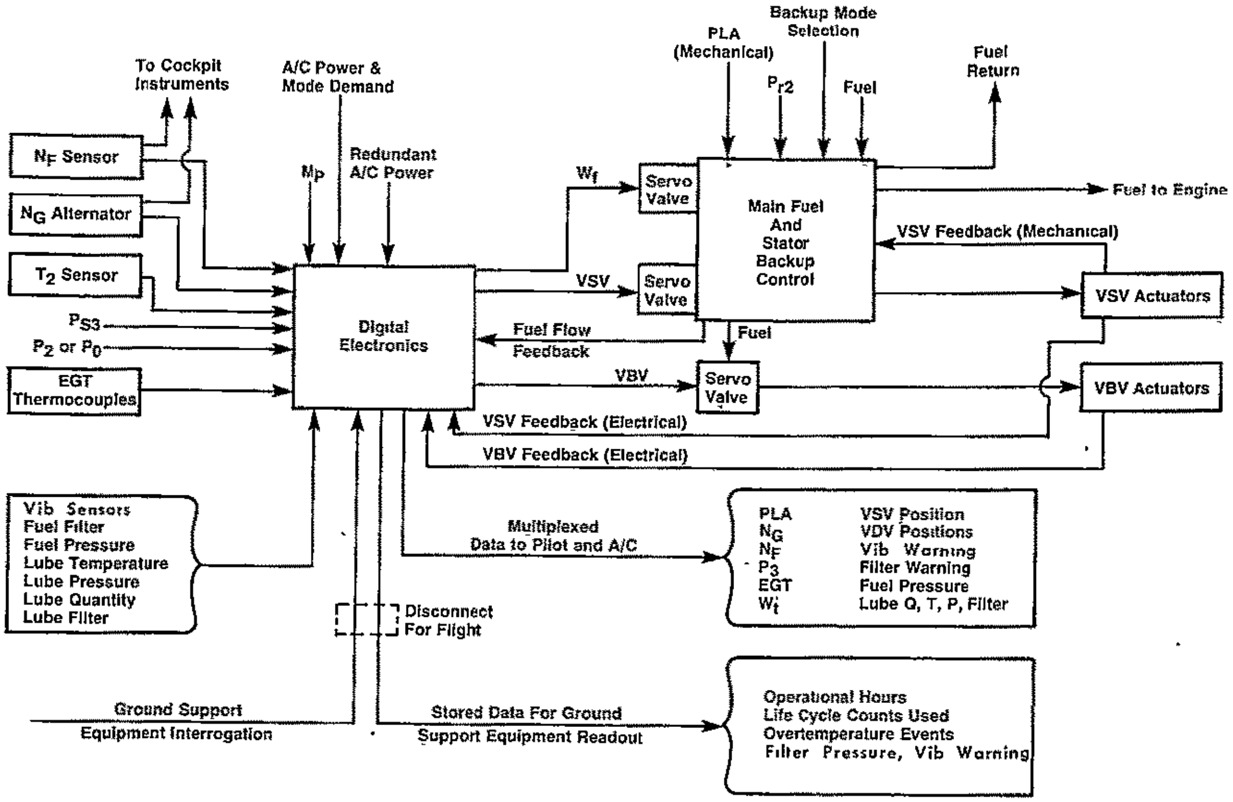


Figure 95. FADEC Overall Schematic (CF6-50).

- Performance deterioration due to turbine overtemperature will be retarded by automatic limiting of EGT, possibly corrected with P3/P2 to provide a better measure of turbine inlet conditions (demonstarated on QCSEE engine-tolerance study needed to quantify for CF6).

- Performance deterioration due to stall will be retarded by rapid stall detection and correction. The FADEC computer program will include a simplified engine model based on sensed inputs which will quickly sense stall and initiate a programmed sequencing of controlled variables to clear the stall and restore the operating condition existing prior to the stall, if possible, with variables biased to preclude restall.

- The FADEC will control the Variable Bleed Valve independently from the Variable Stator Vanes so that each can be scheduled for best sfc at cruise for all flight speeds and ambient conditions.

- Ground idle and flight idle reduction with associated fuel saving may be possible by introducing a transient Variable Stator Valve schedule (different from steady-state) which, in conjunction with a higher acceleration fuel schedule, provides faster acceleration rates (transient model evaluation of this is necessary).

- Partially compensate for HPT efficiency loss as the engine deteriorates by adjusting the Variable Stator Valves to maintain the proper N1-to-N2 relationship. This function should also eliminate the need for the VSV feedback cable reset actuator.

- The FADEC can easily accomplish the computation and signalling necessary to control bleed air for active turbine clearance control.

- FADEC, through its digital electronic demand and data link with the aircraft, will serve as an accurate, fast responding element in the aircraft speed control loop, thus providing better accuracy and stability in this operating mode than presently available.

- Instrumentation and condition monitoring data which are now transmitted to the aircraft by means of individual wires for each variable can be transmitted on one pair of wires by the FADEC using multiplexed digital electronic signals, thereby saving electrical wiring weight.

- Maintenance man-hour and cost reductions will be realized as a result of the FADEC fault isolation features. The simplified engine model in the FADEC memory will identify sensor failure automatically and eliminate need for troubleshooting such failures. FADEC will also include a ground interrogation feature which will allow very rapid identification of faulty system components.

The technical assessment for FADEC is shown for CF6-6 and CF6-50 application in Figure 96. The predicted cruise sfc improvements are 0.3 percent for a new engine and 0.5 percent at 3000 hours engine life.

A technical recommendation report on digital electronic controls is presented in Appendix B.

5.1.28.3 Boeing

The evaluation of General Electric's electronic control assessment factors is given in Table XXVII. Also shown are estimates of the assessment factors for a dual channel, full authority electronic control with simple, fuel metering valve (no HMC backup control). Boeing feels that this concept has the best capability for future application and should be evaluated.

It should be noted that all weight numbers assume implementation of the cockpit-to-engine data links so as to minimize wire weight. If this aspect is not carefully treated, the weight increments could easily be two to three times the values shown. A technical recommendation report on digital electronics controls is provided in Appendix B.

5.1.28.4 Douglas

Power Management System

The General Electric concept introduces computational functions that already exist in the DC-10. However, production incorporation of this concept before 1982 is considered to be improbable.

FADEC

It is believed that cost effective application to electronic propulsion controls requires integration with aircraft power management and flight controls. The in-depth studies required are beyond the scope and cannot be done with the schedule of the current study contract. It is judged that application of such a control system in the DC-10 by 1982 is improbable. Integrated digital electronic propulsion controls are believed to offer benefits, particularly in reducing pilot workload. They will probably be in future aircraft beyond the 1980 to 1982 time period or possibly earlier when incorporating a new engine such as the CFM56, but it is doubtful in current aircraft with current engines.

5.1.29 Cabin Air Recirculation (CF-6, -50)

5.1.29.1 General Electric

A fuel saving concept proposed by Douglas for DC-10 aircraft involves the addition of recirculation loops in the cabin air distribution system. The conditioned air for the cabin of the aircraft is provided by three air-

TITLE Modified Controls - Full Authority Digital Electronic Control (CF6-6, -50)-FADEC

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC 2)	Δ%SFC 3)
T/O	SLS	-1.0	-1.1
T/O	0 (0)/0.25	-1.0	-1.1
CLIMB	7620 (25000)/0.80	- .3	- .5
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	- .3	- .5
MAX CRUISE	10668 (35000)/0.85/+10°C	- .3	- .5
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70	- .3	- .5
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325	-5.4(-12.)	(1) -9 (-20.)

(1) ΔWf, kg/hr (lb/hr) 2) New Engine, 3) At 3000 hours

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) - +8 kg.(+18 lb)

ΔCG, cm (in) - 0.2 cm (0.08 in.) fwd.

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE - $98,000 Increase

RETROFIT - Not Evaluated

INSTALLATION COST - Included in new engine

MAINTENANCE

MATERIAL - -$0.55/engine flt. hour (reduction)

DIRECT LABOR - negligible

INVESTMENT SPARES RATIO - 5%

RETROFIT CAPABILITY System is retrofittable but non-interchangeable. Figure 95 is a schematic showing the CF6-50 control system with the FADEC incorporated. Major changes from the present system are as follows:

1. Items Deleted - Main Engine Control, Core Inlet Temperature Sensor, VSV Re-Set Actuator, Reverse Thrust Limiter, and VBV Mechanical Feedback.
2. Items Added - The FADEC unit, back-up Control, Fan Inlet Temperature Sensor, VBV Servovalve, VSV and VBV Position Transducers, Electrical Cables, and provisions for sensing fan inlet pressure.
3. Items Changes - Fan speed sensor (magnetic pick-ups in fan bearing sump region rather than on fan casing), tachometer generator (replaced by alternator), and mounting provisions for the fan inlet temperature sensor.

Figure 96. Screening Assessment for Modified Controls, Full Authority Digital Electronic Control (FADEC) (CF6-6 and CF6-50).

Table XXVII. Boeing Evaluation of GE Control Assessment Factors.

ITEM	Power Management Control System with CF6 PMC Figure 94	Full Authority Digital Electronic Control with Simplified HMC (FADEC) Figure 96	Proposed Alternate (Dual-Channel Full-Authority Electronic Control with Simple Fuel Metering Valve)
PERFORMANCE DATA (ΔSFC)	OK	OK	Same as FADEC
ESTIMATED WEIGHT DATA (Per Engine)	+ 15 kg (OK)	H/M Backup Control should be same as CF6 Control. Using 7x7 Control System Study Data, ΔWT should be +14 kg (i.e., 6 kg more than simplified backup) when CF6 Control is used.	+ 9 kg
PRICES New Engine	+ $44,000 (OK)	+ $98,000 Assuming $44,000 is correct for the PMC, we believe the FADEC System cost should be no greater (and probably less) than the PMC System.	≈ $40,000
MAINTENANCE MATERIAL	- $0.65/Engine Flight Hour (Appears too low)	- $0.55/Engine FLT HR - FADEC has more capability for preventing engine deterioration (e.g., stall sensing and clearing, active turbine clearance control). Thus, the reduction in maintenance cost should be at least equal to the PMC System and probably considerably more.	- $0.80/Engine FLT HR

conditioning packs which are driven by engine bleed. Recirculation of the cabin air allows 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 proposed recirculation system is composed of two recirculation loops which would be installed in the drop ceiling areas of the cabin. These areas are readily accessible through doors and removable panels in the ceiling. Each recirculation loop consists of a filter to remove smoke from the air, an electric fan to drive the recirculation air, and the appropriate ducting and controls as shown schematically in Figure 97.

The recirculation loops would be installed to connect with the air distribution system as shown in Figure 98. One loop would recirculate the forward and mid-cabin areas and the second loop the aft cabin area. Cabin air is drawn up by the fan, through a grill and filter assembly in the ceiling, and discharged through a check valve into the supply manifold. It mixes in the manifold with fresh air from the air cycle refrigeration packs before entering the cabin.

Normally, for fuel saving, the environmental control system would be operated during flight with both recirculation fans on and with the three packs operating at 50 percent of their maximum normal flow. In this mode, the total flow (recirculated plus fresh air) will be approximately the same as on current DC-10 airplanes. Flow reduction through the packs is accomplished by modifying the pack flow control valves to provide dual flow limits at 100 percent and 50 percent of normal rated flow. The engine compressor bleed airflow rates for the two modes are shown below:

	Compressor Bleed Airflow kg/sec	
Flight Condition	Without Recirculation	With Recirculation
M 0.2/SL Takeoff	3.63	2.00
M 0.83/35K Cruise	3.22	1.82
M 0.5/15K Hold	3.80	2.14

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 screening assessment, shown in Figure 99, indicates a cruise sfc reduction of 0.7 percent.

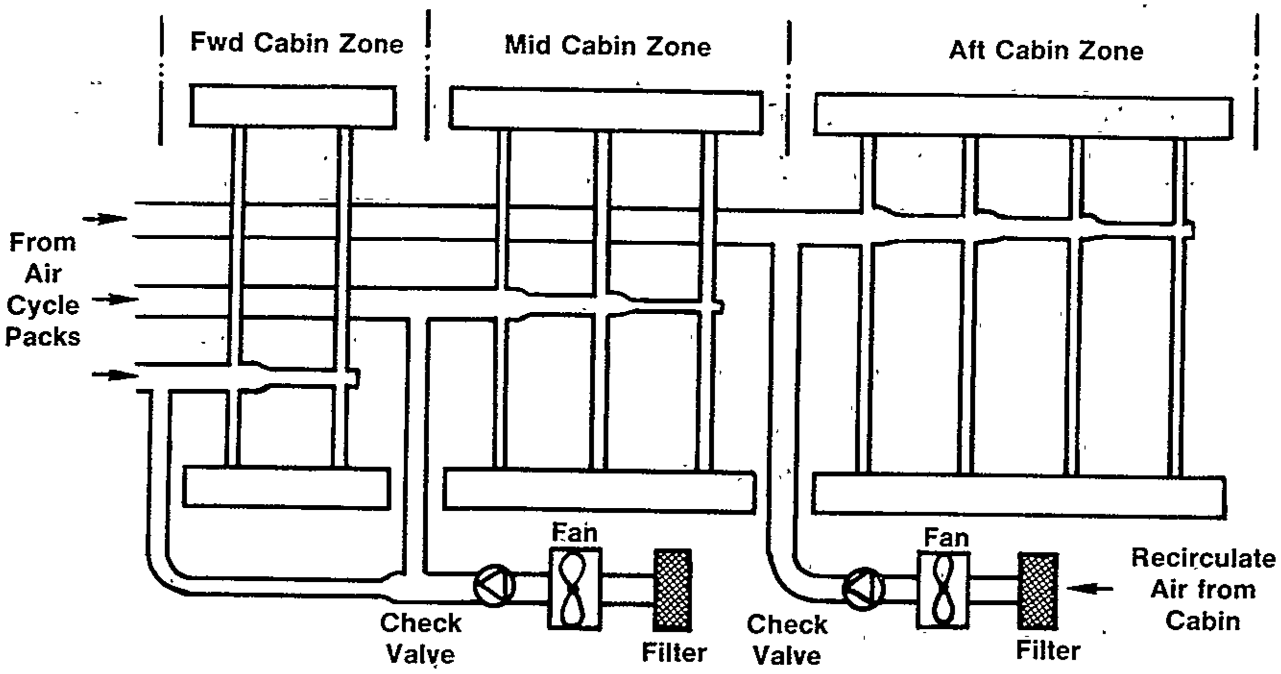


Figure 97. Cabin Air Recirculation System.

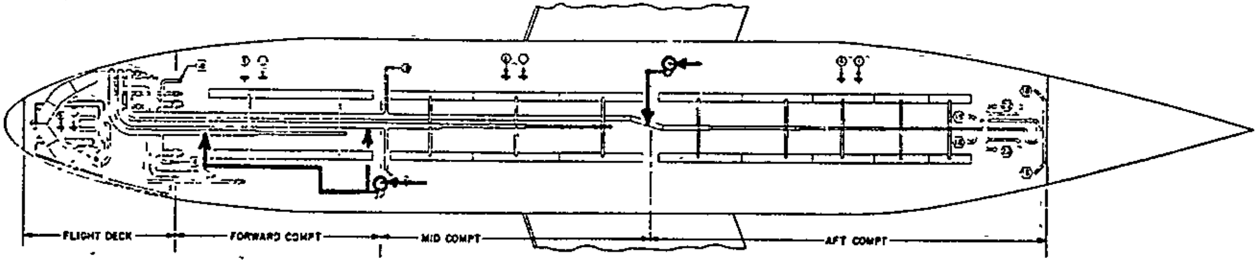


Figure 98. Cabin Air Recirculation System Installation Locations.

TITLE CABIN AIR RECIRCULATION

ESTIMATED PERFORMANCE DATA

POWER SETTING	FLIGHT CONDITION ALT, m (ft)/M	Δ% SFC	
T/O	SLS		
T/O	0 (0)/0.25		
CLIMB	7620 (25000)/0.80		
CRUISE, Fn, N (lb)=37800 (8500)	10668 (35000)/0.85	-0.7	
MAX CRUISE	10668 (35000)/0.85/+10°C		
CRUISE, Fn, N(lb)=31100 (7000)	7620 (25000)/0.70		
HOLD, Fn, N(lb)=28900 (6500)	457 (1500)/0.325		(1)

(1) ΔWf, kg/hr (lb/hr)

ESTIMATED WEIGHT DATA

PER ENGINE, kg (lb) -

ΔCG, cm (in) -

ESTIMATED ECONOMIC DATA - 1977 DOLLARS

PRICES

NEW ENGINE -

RETROFIT -

INSTALLATION COST -

MAINTENANCE

MATERIAL - $0.45/Flight hour Reduction

DIRECT LABOR - Negligible

INVESTMENT SPARES RATIO -

RETROFIT CAPABILITY

OTHER IMPACTS

Figure 99. Cabin Air Recirculation Screening Assessment.

5.1.29.2 Boeing

This system was not evaluated by Boeing.

5.1.29.3 Douglas

It was estimated that the recirculation system would increase the airplane operating empty weight (OEW) 84 kg. The performance improvement and weight change were input into the DC-10 airplane performance computer programs and the resultant improvement in fuel burned determined. The results for the DC-10-10 and DC-10-30 for the minimum fuel cases are shown in Table XXVIII.

Table XXVIII. Cabin Air Recirculation Block Fuel Savings (Min. Fuel Analysis).

	Range	ΔFuel	
	km	kg	%
DC-10-10 (CF6-6)	645	-45.8	-0.6
	1690	-99.8	-0.6
	3700	-217.7	-0.7
DC-10-30 (CF6-50)	805	-55.8	-0.6
	2735	-167.8	-0.7
	6275	-442.7	-0.8

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 turbine inlet temperature when the bleed flow is reduced. The maintenance cost improvement occurs primarily because the recirculation system is used during takeoff and climb.

Adaptation of this system should actually improve the cabin environmental quality because it will reduce the ozone content and increase the humidity during high-altitude cruise. The combination of reduced fuel consumption, improved economics and improved cabin environmental quality is expected to result in incorporation into newly produced and existing airplanes.

5.2 ECONOMIC ANALYSIS

This section describes the economic analysis of the concepts which were evaluated in the technical analysis. It consists of the Boeing economic analysis, the Douglas economic analysis, a General Electric analysis for selected concepts, a sensitivity study of the economic analysis results and a summary.

5.2.1 Boeing

The economic analysis for each General Electric engine component improvement concept was made using a minimum fuel burn mission profile because:

- It is assumed that airlines will increasingly convert to fuel efficiency profiles as energy efficiency gains increase in importance worldwide.
- The differences in delta fuel burn between minimum fuel burn and minimum DOC mission profiles were negligible.

A comparison of the minimum fuel burn mission profile and the minimum DOC mission profile on the fan improvement package is presented in Table XXIX. This concept was chosen because its high fuel savings would highlight any significant differences between the two flight profiles, if they existed.

Three ranges were chosen for this study based on average worldwide 747 usage history. World average range was used to determine the study ranges, because it is more representative of 747 range usage than any single airline's usage. Average range for all 747's was used rather than just 747-200B. The basic range used in this study is the average range (3460 km). The other study ranges were evaluated primarily to show ROI sensitivity to range.

Economic analysis has shown incremental return on investment (ROI) to be sensitive to range as shown in Figure 100. For all 13 concepts which were evaluated, as trip distance increased, so did incremental ROI. However, in only one concept (R150 HPT blades) did range effect the acceptability of the concept. Also, the uncertainty in the ROI input values (annual fuel savings, maintenance effects, etc.) is deemed to be greater than the range effect on ROI in this case. This concept should be considered unacceptable except for an airline with high average range usage.

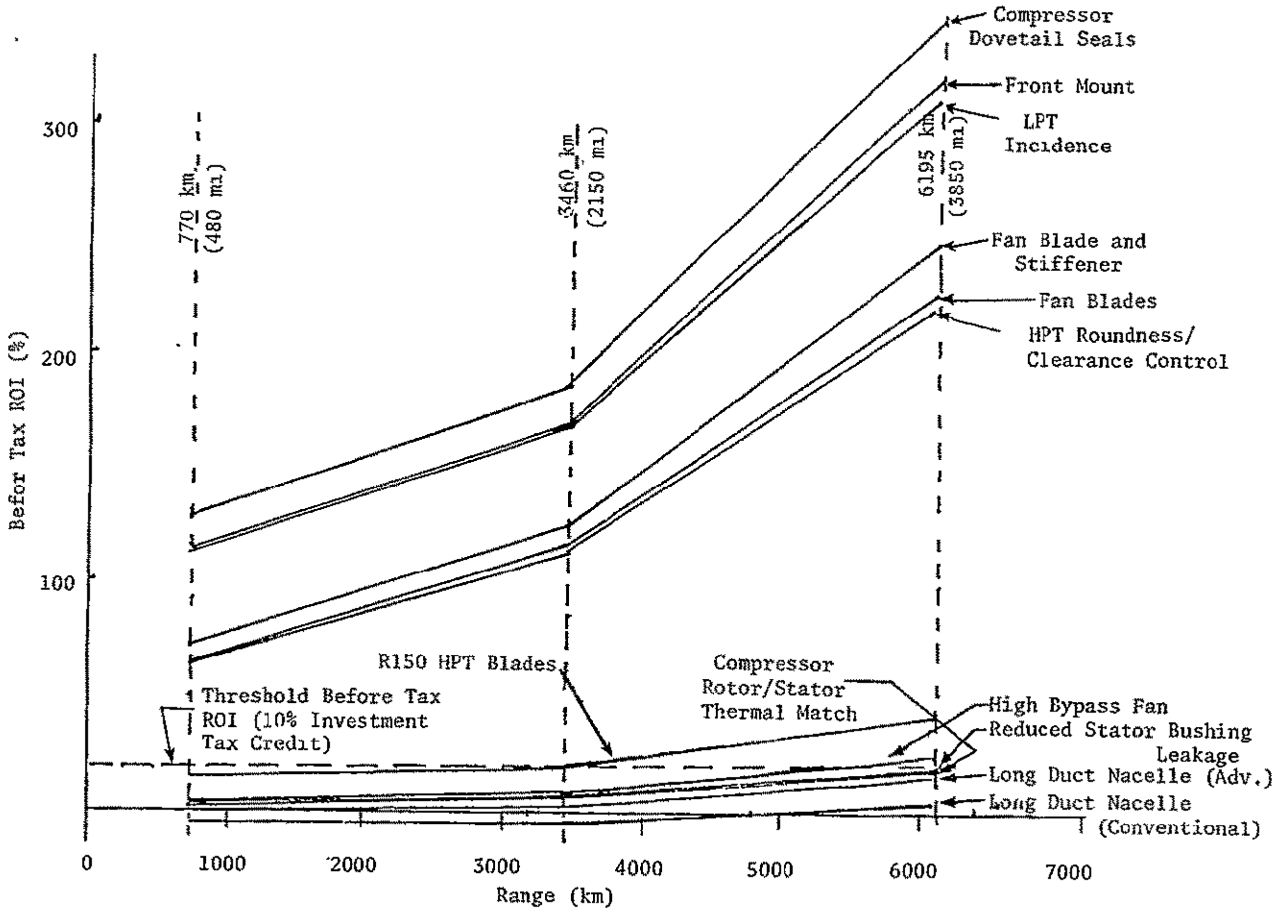
The engine component improvement concepts were evaluated for new production, attrition retrofit, and campaign retrofit. Three fuel prices, 7.93 cents, 11.89 cents, and 15.85 cents/liter (30 cents, 45 cents, 60 cents/gal.) were used at three study ranges, 772 km, 3460 km and 6195 km (480 mi, 2150 mi, and 3850 mi). Rounded values of the fuel prices per liter are shown in this report for purposes of simplification. Payback and before-tax ROI were calculated for each concept for which data were available.

Table XXX shows the payback and the incremental ROI for: 1) new engines, 2) attrition retrofit, and 3) campaign retrofit for the three fuel prices.

The cross-hatched areas in Table XXX show those concepts or portions of concepts which were unacceptable to the airlines based on incremental ROI's. New production for R150 HPT blades is presented separately in Table XXXI, because this is the only concept considered marginal by the airlines. At the shorter ranges and lower fuel prices, this concept would have unacceptable ROI's; only at longer ranges and higher fuel prices would this concept be

Table XXIX. Comparison of Minimum Fuel and Minimum DOC Analysis for Fan Package for Boeing 747.

Title	Mission Range km	Minimum Fuel Burn			Minimum DOC		
		Brake Release Gross Wt. kg	Block Fuel kg	Block Time hr	Brake Release Gross Wt. kg	Block Fuel kg	Block Time hr
Baseline	772	233,468	11,404	1.300	233,590	11,540	1.284
	3460	265,896	41,114	4.351	266,395	41,690	4.273
	6195	303,436	75,837	7.451	304,447	76,994	7.297
Fan Improvement (Blade & Stiffener)	770	233,246	11,281	1.300	233,373	11,422	1.284
	3459	265,029	40,407	4.351	265,533	40,974	4.272
	6195	301,744	74,350	7.451	302,742	75,488	7.296



NOTE: Short Core Exhaust is not shown since all of its ROI's are negative.

Figure 100. Boeing ROI Range Sensitivity, New Production Fuel - 12 Cents/Liter (45 Cents/Gallon).

Table XXX. Payback and ROI - Boeing Analysis (Min. Fuel Analysis).

TITLE	RANGE (KM)	PAYBACK/BEFORE TAX R O I. (YEARS/PERCENT)																	
		NEW ENGINE FUEL PRICE						ATTRITION RETROFIT FUEL PRICE						CAMPAIGN RETROFIT FUEL PRICE					
		8¢/LITER		12¢/LITER		16¢/LITER		8¢/LITER		12¢/LITER		16¢/LITER		8¢/LITER		12¢/LITER		16¢/LITER	
		Years	Percent	Years	Percent	Years	Percent	Years	Percent	Years	Percent	Years	Percent	Years	Percent	Years	Percent	Years	Percent
FAN IMPROVEMENT	770	1 80 Yrs	55 50%	1.36 Yrs	73 56%	1 09 Yrs	91.58%	3 22 Yrs	24.16%	2.44 Yrs	36 32%	1 96 Yrs	47 71%	15.54 Yrs	16.74%	11.74 Yrs	11.17%	9.53 Yrs	56.94%
(BLADES & STIFFENERS)	3460	1 11	90.18	0 81	123.14	0 64	156 09	1.99	46 85	1 46	66.70	1 15	85 85	9.39	7.27	7.81	-0.05	5.53	5.45
	6195	0 57	176 53	0.41	243 89	0.32	311 26	1 02	97.54	0.74	135 53	0 58	173 30	5.60	9.86	5.54	20.65	2.77	30.53
FAN IMPROVEMENT	770	2.11	47 16	1 57	63 84	1.24	80.43	2 11	43 54	1.57	61.66	1 24	79.08	23.26	23.24	17.22	18.59	13.67	14.70
(BLADES ONLY)	3460	1.24	80 58	0 89	112.08	0 70	143.56	1 24	79 24	0.89	111 49	0 70	143 28	13.65	15.36	9.83	7.80	7.66	2.41
	6195	0.62	160.69	0 44	225.83	0 34	290.96	0.62	160 49	0 44	225.77	0.34	290.94	6.85	0.56	4.87	9.98	3.78	18.29
FRONT MOUNT	770	1 16	86 41	0 92	108 86	0.76	131.31												
	3460	0 78	127.98	0 60	166.24	0.49	204 51												
	6195	0.41	242 64	0 31	319.87	0 25	397 09												
COMPRESSOR ROTOR/STATOR	770	18.25	-2.35	14.26	0.64	11.59	3.29												
THERMAL MATCH	3460	12.98	2.70	9.63	6.13	7.80	9.55												
	6195	6.50	12.09	4.84	18.72	3.98	24.17												
REDUCED STATOR	770	16.06	-0.79	12.35	2.70	9.79	5.82												
BUSHING LEAKAGE	3460	12.59	2.27	9.56	6.11	7.35	9.72												
	6195	8.40	14.24	4.50	19.35	3.65	25.08												
COMPRESSOR DOVETAIL	770	1 03	96.70	0.80	125.29	0.63	153 87	1.03	95 82	0.80	124.86	0.66	153 65						
SEALS	3460	0.72	138 99	0 54	183 59	0.44	228.98	0 92	138 67	0 54	183.86	0.44	228 93						
	6195	0 39	259.01	0 29	346.15	0 23	434 02	0.39	258 97	0 29	346.50	0.23	434 02						
HPT	770	2 09	49.14	1.58	63.28	1.29	77.37												
ROUNDNESS CONTROL	3460	1 21	82.95	0 90	111 31	0.72	139.67												
	6195	0.62	160.95	0 46	218.85	0 36	176 76												
R150 HPT BLADES	770	9 62	6 15	6.32	13.45	4.70	19 87	9.62	7.57	6.32	2.34	4.70	11.07	31.51	-30.15	25.61	-21.21	18.34	-19.55
	3460	7 19	11.00	4 74	19 67	3 54	27 56	7.19	0.87	4.74	10.31	3.54	20.71	28.85	-26.13	18.49	-19.69	13.78	-14.59
	6195	3 69	26.28	2 45	40.64	1 83	54 59	3.69	19.16	2.45	36.18	1.83	51.72	14.39	-15.34	9.54	-7.19	7.13	-0.48
LPT	770	1.15	86 98	0 89	112.71	0.72	138.44	1.15	85 85	0.89	112.13	0 72	138.12	19.49	-19.50	14.20	-15.09	11.55	-11.14
STAGE 1 INCIDENCE	3460	0.80	125 04	0 60	165 54	0 49	206 04	0.80	124.61	0 60	165 36	0.49	205.96	12.98	-15.15	9.57	-7.47	7.75	-2.53
	6195	0 43	233 06	0.32	311 81	0.26	390.57	0 43	233 01	0.32	311.80	0 26	390 56	6.67	0.49	5.13	8.43	4.10	15.57
INCREASED FAN DIAMETER	770	15.61	-0.49	11.82	3.15	9.52	6.31												
	3460	10.91	4.28	8.15	8.42	6.50	12.88												
	6195	6.53	16.27	4.21	23.27	3.27	29.97												
SHORT CORE EXHAUST	770	9.7	6.8	7.0	11.6	5.6	16.5	9.7	7.6	7.0	0.1	5.4	6.7						
	3460	16.3	0.3	12.4	2.5	10.5	5.0	15.4	16.5	12.4	12.6	10.4	5.0						
	6195	6.5	11.5	5.6	15.8	3.7	19.7	6.5	0.3	5.6	6.8	4.1	10.8						
LONG DUCT MIXED FLOW	770	20.59	-3.67	13.23	1.62	8.37	5.41												
NACELLE	3460	16.05	-0.83	10.43	4.93	7.73	9.72												
ADVANCED	6195	7.82	9.52	6.15	27.55	3.54	28.15												
LONG DUCT MIXED FLOW	770	36.54	-8.5	23.02	-4.0	16.81	-1.39												
NACELLE	3460	24.60	-8.09	15.97	-3.38	15.61	2.0												
CONVENTIONAL	6195	15.64	1.20	6.30	7.26	6.61	12.57												

UNACCEPTABLE

MARGINAL

acceptable to the airlines. All other concepts (not cross-hatched) have acceptable incremental ROI's for the airlines.

Table XXXII shows the summary evaluation for the median range and fuel price, showing fuel savings, before-tax ROI's and ROI acceptability.

Tables XXXIII, XXXIV, and XXXV rank the engine component improvement concepts according to annual fuel conservation, annual cash savings, and ROI.

It should be noted that concepts which rank high on annual fuel conservation and annual cash savings may rank low with respect to ROI. The R150 HPT blade concept, for example, ranks high in fuel conservation and cash savings but is only marginally acceptable for ROI. On the other hand, compressor dovetail seals rank toward the bottom for fuel conservation and cash savings, yet this concept has the highest incremental ROI of all the concepts studied.

Direct operating costs (DOC) were calculated for the baseline 747 airplane using the ground rules specified in Table XXXVI. Incremental DOC's were then calculated for each engine component improvement concept to show the delta DOC savings. The results are presented in Table XXXVII as a percentage of the baseline DOC.

Table XXXI. Boeing Economic Analysis for R150 HPT Blades, New Engine (Min. Fuel Analysis).

Title	Range km	Payback/Before Tax ROI (Years/Percent) Fuel Price					
		8¢/Liter		12¢/Liter		16¢/Liter	
		Years	Percent	Years	Percent	Years	Percent
R150 HPT Blades	770	9.62	6.15	6.32	13.45	4.70	19.87
	3,460	7.19	11.00	4.74	19.67	3.54	27.56
	6,195	3.69	26.28	2.45	40.64	1.83	54.59

5.2.2 Douglas

Douglas evaluated a total of 49 updated engine component improvement concepts. This included 10 new production CF6-6 concepts and 11 retrofit-attrition or retrofit-campaign CF6-6 concepts. For the CF6-50, 18 new production concepts and 10 retrofit-attrition or retrofit-campaign modifications

Table XXXII. Boeing Economic Summary Evaluation (Min. Fuel Analysis).

	Fuel Saved (kg/plane/year @3460 km/Trip)	Before Tax ROI (%) @3460 km/Trip, 12¢/Liter Fuel			ROI Acceptability*		
		New Engine	Attrition Retrofit	Campaign Retrofit	New Engine	Attrition Retrofit	Campaign Retrofit
Fan Improvement (Blades and Stiffener)	537,797	123.14	66.70	- 0.05	A	A	NA
Fan Improvement (Blades Only)	351,635	112.08	111.49	- 7.80	A	A	NA
Increased Fan Diameter	906,615	8.82	-	-	NA	-	-
Front Mount	93,038	166.24	-	-	A	-	-
Compressor Rotor/ Stator Thermal Match	51,738	6.13	-	-	NA	-	-
Reduced Stator Bushing Leakage	27,624	6.21	-	-	NA	-	-
Compressor Dovetail Seals	34,460	183.99	183.86	-	A	A	-
HPT Roundness Control	241,320	111.31	-	-	A	-	-
R150 HPT Blades	244,740	19.67	10.81	-19.69	Marginal	NA	NA
LPT Stage 1 Incidence	34,460	165.54	165.36	- 7.47	A	A	NA
Long Duct Mixed Flow Nacelle (Advanced)	613,648	4.93	-	-	NA	-	-
Long Duct Mixed Flow Nacelle (Conventional)	334,358	- 3.38	-	-	NA	-	-
Short Core Exhaust	37,880	2.5	-12.5	-	NA	NA	-

*A = Acceptable
NA = Not Acceptable
- = Not Evaluated

Table XXXIII. Annual Fuel Conservation Ranking - Boeing Analysis (Min. Fuel Analysis).

Title	Annual Fuel Savings (kg/airplane @3460 km/trip)
Increased Fan Diameter	906,615
Long Duct Mixed Flow Nacelle (Advanced)	613,648
Fan Improvement (Blades and Stiffener)	537,797
Fan Improvement (Blades Only)	351,635
Long Duct Mixed Flow Nacelle (Conventional)	334,358
R150 Turbine Blades	244,740
HPT Roundness Control	241,320
Front Mount	93,038
Compressor Rotor/Stator Thermal Match	51,738
Short Core Exhaust	37,880
Compressor Dovetail Seals	34,460
LPT Stage 1 Incidence	34,460
Reduced Stator Bushing Leakage	27,624

Table XXXIV. Annual Cash Savings (Fuel Maintenance and Insurance), New Production (3460 KM/Trip, 12 Cents/Liter Fuel) - Boeing Analysis (Min. Fuel Analysis).

Title	Annual Cash Savings ($/Airplane)
Increased Fan Diameter	$176,900
Fan Improvement (Blades and Stiffener)	99,200
Fan Improvement (Blades Only)	61,800
HPT Roundness Control	46,800
R150 HPT Blades	35,400
Long Duct Mixed Flow Nacelle (Advanced)	21,600
Front Mount	19,900
Long Duct Mixed Flow Nacelle (Conventional)	11,300
Compressor Rotor/Stator Thermal Match	10,900
Short Core Exhaust	9,700
Compressor Dovetail Seals	7,000
LPT Stage 1 Incidence	7,000
Reduced Stator Bushing Leakage	5,700

Table XXXV. ROI Ranking - New Production (3460 KM/Trip, 12 Cents/Liter Fuel) - Boeing Analysis (Min. Fuel Analysis).

Title	Before Tax ROI (Percent)
Compressor Dovetail Seals	184
Front Mount	166
LPT Stage 1 Incidence	166
Fan Improvement (Blades and Stiffener)	123
Fan Improvement (Blades Only)	112
HPT Roundness Control	111
R150 HPT Blades	20
Increased Fan Diameter	9
Reduced Stator Bushing Leakage	6
Compressor Rotor/Stator Thermal Match	6
Long Duct Mixed Flow Nacelle (Advanced)	5
Short Core Exhaust	3
Long Duct Mixed Flow Nacelle (Conventional)	- 3

Table XXXVI. 747 Baseline Direct Operating Cost Calculation International Rules.

	Boeing 1977
Crew Pay ($/Block Hour) 3 Man Crew	$(33.54\ F_W + 24.639)F_U + 43.20$
Fuel ($/Liter)/($/Gal.)	0.12/0.45
Nonrevenue Factor	1.02 on Fuel and Maintenance
Airframe Maintenance	Based on 747 History
Engine Maintenance	Provided by G.E. (See Screening Study)
Burden (Man-Hour/Direct Labor Man-Hours)	2.0
Maintenance Labor Rate ($/Man-Hours)	9.70
Investment Spares Ratio Airframe Engine	 0.06 0.30
Depreciation Schedule (Years/% Residual)	15/10
Insurance (% of Total Price/Year)	0.5
Utilization (Block Hours/Year)	Provided by American Airlines (See Economic Anlysis Procedure)

Table XXXVII. Direct Operating Cost Savings, New Production at 3460 KM/Trip, 12 Cents/Liter Fuel) - Boeing Analysis.

Title	ΔDOC Savings (%)
Fan Improvement (Blades and Stiffener)	0.83
Increased Fan Diameter	0.79
Fan Improvement (Blades Only)	0.51
HPT Roundness/Control	0.39
Long Duct Mixed Flow Nacelle (Advanced)	0.28
R150 HPT Blades	0.22
Front Mount	0.16
Compressor Dovetail Seals	0.05
LPT Stage 1 Incidence	0.05
Compressor Rotor/Stator Thermal Match	0.04
Short Core Exhaust	0.03
Reduced Stator Bushing Leakage	0.02
Long Duct Mixed Flow Nacelle (Conventional)	-0.07

were studied. All proposed engine component improvements were evaluated for new production introduction, but only those improvements suitable for retrofit were considered on a retrofit-attrition or retrofit-campaign basis.

The component improvement concepts studied for each engine are listed in Table XXXVIII. The CF6-6 was operated on the DC-10-10 while the CF6-50 applied to the DC-10-30.

Table XXXIX presents the annual fuel savings in kg (lb) achieved with the introduction of the engine improvement concepts on the DC-10-10 and DC-10-30 airplanes for the minimum fuel, median range analysis. At the stage lengths shown, the amount of fuel saved annually varied from approximately 384,600 to 22,700 kg for the CF6-6 engine operated on the DC-10-10 and from about 1,624,800 to 21,000 kg for the CF6-50 applied to the DC-10-30.

Throughout the study, the DC-10-10 was simulated in U.S. domestic operations, while the DC-10-30 was operated in international service. Three study fuel prices were used for each type of operation. Domestic fuel prices were 7.93 cents (30 cents), 11.80 cents (45 cents), and 15.85 cents (60 cents) per liter (gal) and international fuel prices were 10.57 cents (40 cents), 14.53 cents (55 cents) and 18.49 cents (70 cents) per liter (gal). Rounded values of the fuel price per liter are shown in this report for the purpose of simplification.

The components offering the greatest fuel saving potential on the CF6-6 were both Fan Improvement concepts and the HPT Aerodynamic Improvement. The fan improvement concepts also looked good on the CF6-50, as did the Long Duct Mixed Flow Nacelle and the Short Core Exhaust concepts. The Short Core Exhaust was evaluated for three levels of drag reduction, namely, the nominal case Δdrag = 2 percent (1 percent nozzle and 1 percent aircraft), Δdrag = 3 percent (1 percent nozzle and 2 percent aircraft), and Δdrag = 1 percent for nozzle only. The Long Duct Mixed Flow Nacelle was also evaluated for three assumptions: mixing effectiveness = 70 percent as proposed by General Electric, mixing effectiveness = 80 percent and mixing effectiveness = 80 percent plus an additional 2 percent sfc improvement for advanced nacelle features which are expected to reduce engine deterioration. Included are directed reverser flow, load sharing nacelle, and inlet vortex control; all of which will minimize ingestion, erosion, and ovalization.

An example of the work that was done in determining the net annual direct operating cost savings provided by the engine modifications for each airplane is shown in Table XL. These DOC savings were calculated at the three representative stage lengths under both minimum DOC and minimum fuel cruise conditions.

The annual DOC savings generated with the introduction of the engine modifications on the DC-10-10 and DC-10-30 are given in Table XL . These savings are achieved by the DC-10-10 at a stage length of 1690 km and a fuel price of 12 cents per liter. DC-10-30 DOC savings are at a 2735 km stage length with fuel price at 15 cents per liter. The annual DOC savings shown in this chart varied from approximately \$206,200 to \$4,100 for the DC-10-10; while for

Table XXXVIII. Engine Component Improvement Concepts Studies By Douglas.

Title	Engine(s)
Fan Improvement (Blades and Stiffener)	CF6-6/CF6-50
Fan Improvement (Blades Only)	CF6-6/CF6-50
HPT Active Clearance Control - Variable Source Bleed	CF6-6
HPT Active Clearance Control - Electrical Resistance Heating	CF6-6
HPT Roundness Control	CF6-50
R150 HPT Blades	CF6-50
HPT Aerodynamic Improvement	CF6-6
Cooled Cooling Air - Air/Air Heat Exchanger	CF6-6
Cooled Cooling Air - Fuel/Air Heat Exchanger	CF6-6
Front Mount	CF6-6/CF6-50
Compressor Rotor/Stator Thermal Match	CF6-50
Reduced Stator Bushing Leakage	CF6-50
Compressor Dovetail Seals	CF6-50
LPT Active Clearance Control	CF6-6
LPT Stage 1 Incidence	CF6-50
Long Duct Mixed Flow Nacelle	CF6-50
Short Core Exhaust	CF6-50
Vortaway - Vortex Suppressor	CF6-6/CF6-50
Cabin Air Recirculation	CF6-6/CF6-50

Table XXXIX. Engine Improvement Annual Fuel Savings Per Aircraft - Douglas Analysis (Min. Fuel, Median Range).

Concepts	DC-10-10 @ 1690 km kg (lb)/AC/YR (CF6-6)	DC-10-30 @ 2735 km kg (lb)/AC/YR (CF6-50)
Fan Improvement (Blade and Stiffener)	384,595 (847,872)	399,618 (880,992)
Fan Improvement (Blades Only)	323,166 (712,448)	262,030 (577,668)
HPT Active Clearance Control - Variable Source Bleed	89,472 (197,248)	---
HPT Active Clearance Control - Electrical Resistance Heating	36,056 (79,488)	---
HPT Roundness Control	---	97,275 (214,452)
HPT Roundness Control (3,000 hrs.)	---	198,494 (437,598)
R150 HPT Blades	---	185,787 (409,584)
HPT Aerodynamic Improvement	316,489 (697,728)	---
Cooled Cooling Air-Air/Air Heat Exchanger	104,161 (229,632)	---
Cooled Cooling Air-Fuel/Air Heat Exchanger	118,850 (262,016)	---
Front Mount	69,441 (153,088)	70,985 (156,492)
Compressor Rotor/Stator Thermal Match	---	37,245 (82,110)
Reduce Stator Bushing Leakage	---	21,033 (46,368)
Compressor Dovetail Seals	---	24,538 (54,096)
LPT Active Clearance Control	22,702 (50,048)	---
LPT Stage 1 Incidence	---	24,538 (54,096)
Long Duct Mixed Flow Nacelle - 70% Mixing Efficiency	---	1,002,550 (2,210,208)
Long Duct Mixed Flow Nacelle - 80% Mixing Efficiency	---	1,158,542 (2,554,104)
Long Duct Mixed Flow Nacelle - 80% Mixing Efficiency with 2% Improvement in Deterioration	---	1,624,763 (3,581,928)
Short Core Exhaust - 3% Drag Reduction	---	678,737 (1,496,334)
Short Core Exhaust 1% Drag Reduction	---	226,108 (498,456)
Short Core Exhaust - 2% Drag Reduction	---	452,655 (997,878)
Vortaway - Vortex Suppressor	42,065 (92,736)	48,200 (106,260)
Cabin Air Recirculation	146,894 (323,840)	162,126 (357,420)

Table XL. Example of Method for Determining DOC Savings.

DC-10-10 Net Annual DOC Savings Per Aircraft at 1690 km Statute Miles - Minimum Fuel, Douglas Analysis (CF6-6)

DOC Elements	HPT Active Clearance Control - Variable Source Bleed		HPT Aero Improve.	Vortaway - Vortex Suppressor		LPT Active Clearance Control	
	New Production	Retro-Attrition	New Production	New Production	Retro-Attrition	New Production	Retro-Attrition
Insurance	-433	-559	-154	-405	-405	-140	-140
Airframe - Materials	0	0	0	-350	-350	0	0
Engine - Materials	-489	-489	160,924	19,796	19,796	993	993
Nonfuel Savings	-922	-1,048	160,770	19,041	19,041	853	853
Fuel Savings @ 8¢/liter (30¢/gal)	8,556	8,556	30,267	4,026	4,026	2,167	2,167
DOC Savings	7,634	7,508	191,037	23,067	23,067	3,020	3,020
Fuel Savings @ 12¢/liter (45¢/gal)	12,834	12,834	45,393	6,025	6,025	3,243	3,243
DOC Savings	11,912	11,786	206,163	25,066	25,066	4,096	4,096
Fuel Savings 16¢/liter (60¢/gal)	17,112	17,112	60,533	8,052	8,052	4,348	4,348
DOC Savings	16,190	16,064	221,303	27,093	27,093	5,201	5,201

DC-10-30 Net Annual DOC Savings Per Aircraft at 2735 km Statute Miles - Minimum Fuel, Douglas Analysis (CF6-50)

DOC Elements	Vortaway - Vortex Suppressor		LP Turbine Stage 1 Incidence			HPT Roundness Control	HPT Roundness Control (3000 hrs)
	New Production	Retro-Attrition	New Production	Retro-Attrition	Retro-Campaign	New Production	New Production
Insurance	-831	-831	0	0	-403	-299	-299
Airframe - Materials	-319	-319	0	0	0	0	0
Engine - Materials	20,460	20,460	1,536	1,536	1,536	-9,206	9,206
Nonfuel Savings	19,310	19,310	1,536	1,536	1,053	-9,505	8,907
Fuel Savings @ 11¢/liter (40¢/gal)	6,521	6,521	3,352	3,352	3,352	13,051	26,700
DOC Savings	25,831	25,831	4,888	4,888	4,405	3,546	35,607
Fuel Savings @ 15¢/liter (55¢/gal)	8,974	8,974	4,608	4,608	4,611	17,948	36,718
DOC Savings	28,284	28,284	6,144	6,144	5,664	8,443	45,625
Fuel Savings @ 18¢/liter (70¢/gal)	11,437	11,437	5,873	5,873	5,871	22,856	46,745
DOC Savings	30,747	30,747	7,409	7,409	6,924	13,351	55,652

Table XLI. Engine Improvement Annual DOC Savings ($) Per Aircraft - Douglas Analysis (Min. Fuel, Median Range, Mid Fuel Price).

Concept	DC-10-10 @ 1690 km Fuel Price = 12¢/Liter (45¢/gallon) (CF6-6)	DC-10-30 @ 2735 km Fuel Price = 15¢/Liter (55¢/gallon) (CF6-50)
Fan Improvement (Blades and Stiffener)/ Fan Improvement (Blades and Stiffener) Retrofit Attrition	70,138	88,862
Fan Improvement (Blades only) Retrofit Campaign	51,572	51,623
Fan Improvement (Blades Only)/Fan Improvement (Blades Only) Retrofit Attrition	53,516	55,526
Fan Improvement (Blades and Stiffener) Retrofit Campaign	68,181	84,969
HPT Active Clearance Control - Variable Source Bleed	11,912	--
HPT Active Clearance Control - Variable Source Bleed Retrofit Attrition	11,786	--
HPT Active Clearance Control - Electrical Resistance Heating	Dropped	--
HPT Roundness Control	--	8,443
HPT Roundness Control (3000 hr)	--	45,625
R150 HPT Blades/R150 HPT Blades Retrofit - Attrition	--	33,095
R150 HPT Blades Retrofit Campaign	--	29,608
HPT Aerodynamic Improvement	206,163	--
Cooled Cooling Air - Air/Air Heat Exchanger/ Cooled Cooling Air - Air/Air Heat Exchanger Retrofit Attrition	27,038	--
Cooled Cooling Air - Air/Air Heat Exchanger Retrofit Campaign	25,766	--
Cooled Cooling Air - Fuel/Air Heat Exchanger/ Cooled Cooling Air - Fuel/Air Heat Exchanger Retrofit Attrition	28,520	--
Cooled Cooling Air - Fuel/Air Heat Exchanger Retrofit Campaign	27,248	--
Front Mount	14,861	18,132
Compressor Rotor/Stator Thermal Match	--	9,274
Reduced Stator Bushing Leakage	--	5,111
Compressor Dovetail Seals/Compressor Dovetail Seals Retrofit Attrition	--	6,144
LPT Active Clearance Control/ LPT Active Clearance Control Retrofit Attrition	4,096	--
LPT Stage 1 Incidence/LPT Stage 1 Incidence Retrofit Attrition	--	6,144
LPT Stage 1 Incidence Retrofit Campaign	--	5,664
Long Duct Mixed Flow Nacelle - 70% Mixing Efficiency	--	175,281
Long Duct Mixed Flow Nacelle - 80% Mixing Efficiency	--	204,077
Long Duct Mixed Flow Nacelle - 80% Mixing Efficiency with 2% sfc Improvement in Deterioration	--	290,138
Short Core Exhaust - 3% Drag Reduction	--	128,990
Short Core Exhaust - 1% Drag Reduction	--	45,431
Short Core Exhaust - 2% Drag Reduction	--	87,249
Vortaway - Vortex Suppressor/Vortaway Vortex Suppressor Retrofit Attrition	25,066	28,284
Cabin Air Recirculation	25,010	33,946

the DC-10-30, they varied from $290,100 to $5,100.

Those components providing the greatest cash DOC savings on the CF6-6 were both Fan Improvement concepts and the HPT Aerodynamic Improvement. On the CF6-50 the Long Duct Mixed Flow Nacelle, the Short Core Exhaust with 2 or 3 percent total drag reduction as well as the Fan Improvement concepts offered sizable DOC savings. The Fan Blades concept achieved less maintenance cost savings than the Fan Blades and Stiffener Concept and, therefore, did not fare as well in the DOC savings comparison as it had on fuel savings alone.

Table XLII shows an example of the incremental return on investment and payback period data that were calculated for all concepts for both the DC-10-10 and DC-10-30 at the three representative ranges for three applicable fuel prices under both cruise conditions.

In ranking the concepts, it was learned that the outcome was not affected by the cruise condition considered; so, all the ranking and summarized data were done based on the minimum fuel cruise condition at Mach 0.85. Generally, the price of fuel did not significantly affect the selection of the economically acceptable components.

Those CF6-6 engine improvement components that met the economic acceptability criteria for introduction on the DC-10-10 are listed in Tables XLIII to XLV. The concepts are ranked in order, starting with the concept offering the highest fuel savings, ROI's and DOC savings. These rankings remained essentially the same regardless of stage length or fuel price. Assuming a stage length of 1690 km and a fuel price of 12 cents per liter (45 cents per gallon), the annual fuel savings achieved by the acceptable components varied from 384,595 kg (847,872 lb) for the Fan Improvement to 42,065 kg (92,736 lb) for the Vortaway concept. The ROI's varied from 600 percent with a payback period of 0.17 year for the HPT Aerodynamic Improvement to 26 percent for the Vortaway with a payback period of 3.74 years. The annual DOC savings ranged from $206,200 for the HPT Aerodynamic Improvement to $14,900 for the Front Mount.

Since the HPT Aerodynamic Improvement provided excellent maintenance cost savings and good fuel savings for a relatively low investment, it was the most economically viable engine concept studied on the DC-10-10.

Since the engine ratios estimated by General Electric (generally, 5-7 percent) were lower than the airlines' suggested 30 percent, the ROI sensitivities to this factor were determined for components on both the DC-10-10 and DC-10-30. Shown in Table XLVI are the results for the DC-10-10 concepts at an average stage length of 1690 km and fuel prices of 8 cents and 12 cents per liter.

All the engine improvements selected as economically acceptable with the General Electric spares ratio remained so with the 30 percent spares ratio on both airplanes. The exception to this was the Vortaway concept for retrofit-attrition which was marginally acceptable with General Electric's estimate at the lower fuel prices. Maintaining a 30 percent spares ratio, this concept also became marginal at the higher fuel price of 12 cents per liter.

Table XLII. Example of DC-10-10 Minimum Fuel Comparative ROI's (1977 Dollars) - Domestic Operations; Douglas Analysis.

Fuel Price (¢/liter)	Range km	Front Mount	HPT Active Clearance Control		HPT Aerodynamic Improvement	Vortaway - Vortex Suppressor	
		New Production	New Production	Retro-Attrition	New Production	New Production	Retro-Attrition
8	645	88%	-16%	-44%	404%	15%	5%
		Payback 1.13 yr	Payback — yr	Payback — yr	Payback .25 yr	Payback 5.72 yr	Payback 5.72 yr
	1,690	128%	3%	-19%	556%	24%	16%
		Payback .78 yr	Payback 11.97 yr	Payback — yr	Payback .18 yr	Payback 4.06 yr	Payback 4.06 yr
	3,700	142%	8%	-12%	590%	26%	18%
		Payback .71 yr	Payback 8.33 yr	Payback — yr	Payback .17 yr	Payback 3.78 yr	Payback 3.78 yr
12	645	113%	-11%	-37%	435%	17%	8%
		Payback .89 yr	Payback — yr	Payback — yr	Payback .23 yr	Payback 5.27 yr	Payback 5.27 yr
	1,690	165%	10%	-11%	600%	26%	19%
		Payback .61 yr	Payback 7.67 yr	Payback — yr	Payback .17 yr	Payback 3.74 yr	Payback 3.74 yr
	3,700	184%	17%	-3%	639%	28%	22%
		Payback .54 yrs.	Payback 5.39 yr	Payback — yr	Payback .16 yr	Payback 3.44 yr	Payback 3.44 yr
16	645	138%	-8%	-33%	467%	19%	10%
		Payback .73 yr	Payback — yr	Payback — yr	Payback .21 yr	Payback 4.89 yr	Payback 4.89 yr
	1,690	202%	16%	-4%	644%	28%	22%
		Payback .49 yr	Payback 5.64 yr	Payback — yr	Payback .16 yr	Payback 3.46 yr	Payback 3.46 yr
	3,700	226%	24%	5%	688%	31%	25%
		Payback .44 yr	Payback 3.99 yr	Payback 5.86 yr	Payback .15 yr	Payback 3.17 yr	Payback 3.17 yr

Table XLIII. DC-10-10 Annual Fuel Conservation Ranking, Douglas Analysis (Min. Fuel, Median Range - 1690 KM, CF6-6).

Concepts for CF6-6	Annual Fuel Savings kg (lb)/AC/Year
Fan Improvement (Blades and Stiffener)	384,595 (847,872 lb)
Fan Improvement (Blades Only)	323,166 (712,448 lb)
HPT Aerodynamic Improvement	316,489 (697,728 lb)
Cabin Air Recirculation	146,894 (323,840 lb)
Front Mount	69,441 (153,088 lb)
Vortaway - Vortex Suppressor	42,065 (92,736 lb)

Table XLIV. DC-10-10 Annual ROI Ranking, Douglas Analysis (Min. Fuel, Median Range - 1690 KM, Fuel Price - 12 Cents/Liter or 45 Cents/Gallon, CF6-6).

Concepts for CF6-6	Before Tax ROI (%)
HPT Aerodynamic Improvement	600
Front Mount	165
Fan Improvement (Blades and Stiffener)	67
Cabin Air Recirculation	64
Fan Improvement (Blades Only)	65
Vortaway - Vortex Suppression	26

Table XLV. DC-10-10 Annual DOC Savings Per Aircraft, Douglas Analysis (Min. Fuel, Median Range - 1690 KM, Fuel Price - 12 Cents/Liter or 45 Cents/Gallon, CF6-6).

Concepts for CF6-6	Annual △ DOC Savings ($)
HPT Aerodynamic Improvement	$206,200
Fan Improvement (Blades and Stiffener)	70,100
Fan Improvement (Blades Only)	53,500
Cabin Air Recirculation	25,000
Vortaway - Vortex Suppressor	25,000
Front Mount	14,900

Table XLVI. ROI Sensitivity to Engine Spares Ratio, DC-10-10 at 1690 KM (Min. DOC), CF6-6, Douglas Analysis.

	Fuel Price - 8¢ Liter		Fuel Price - 12¢ Liter	
Percent Spares	5 - 7%	30%	5 - 7%	30%
Fan Improvement (Blades and Stiffener)	53	47	73	64
Fan Improvement (Blades and Stiffener) Retrofit - Attrition	31	27	46	42
Fan Improvement (Blades Only)	50	44	70	63
Fan Improvement (Blades Only) Retrofit - Attrition	46	41	68	61
Front Mount	137	105	178	137
HPT Aerodynamic Improvement	565	465	614	506
Vortaway - Vortex Suppressor	26	23	29	26
Vortaway - Vortex Suppressor Retrofit - Attrition	19*	15*	23	19*

*Marginal

Those CF6-50 engine improvement components that met the economic acceptability criteria for introduction on the DC-10-30 are listed in Tables XLVII through XLIX. The concepts are ranked in order starting with the concept offering the highest fuel savings, ROI's, and DOC savings. These rankings remained essentially the same regardless of stage length or fuel price. Assuming a stage length of 2735 km and a fuel price of 15 cents per liter (55 cents per gallon), the annual fuel savings achieved by the acceptable components varied from 1,624,763 kg (3,581,928 lb) for the Long Duct Mixed Flow Nacelle (80 percent Mixing Efficiency with 2 percent sfc improvement in deterioration) to 24,538 kg (54,096 lb) for the LPT Stage I Incidence. The ROI's under these same assumptions varied from 12,882 percent with a payback period of 0.01 year for the Short Core Exhaust with 3 percent Drag Reduction to 25 percent with a payload period of 3.81 years for the R150 HPT Blades concepts. The annual DOC savings ranked from $290,100 for the Long Duct Mixed Flow Nacelle (90 percent Mixing Efficiency with 2 percent sfc improvement in deterioration) to $6100 for the LPT Stage 1 Incidence.

ROI's for the Short Core Exhaust concept were extremely high with virtually no payback period, since fuel savings were very good. The initial cash investments required for these components actually represented savings in purchase costs when compared to the baseline DC-10-30 with the baseline CF6-50 engine.

Although fuel savings achieved by the Long Duct Mixed Flow Nacelle concepts were extremely good, 4.1 percent, 4.7 percent and 6.6 percent for the three mixing effectiveness assumptions, the very high initial investment of $660,520, including spares, caused the ROI's to be lower than expected. The ROI's for the 70 percent, 80 percent and 80 percent mixing effectiveness plus 2 percent sfc improvement in deterioration were 26 percent, 30 percent, 30 percent and 44 percent, respectively, at a stage length of 2735 km and fuel at 15 cents per liter. This concept demonstrates the effect a high purchase price has on the economic viability of an engine improvement even with extremely high potential fuel savings.

Table L presents all 49 engine component improvement concepts studied by engine type. Those components that were economically acceptable, marginal or unacceptable are noted. Each engine modification economic viability was reviewed by Douglas and the airline subcontractors before being established as an acceptable, usable modification deserving of airline consideration and potential adoption.

For the HPT Roundness Control, the Long Duct Mixed Flow Nacelle and the Short Core Exhaust and their variations based on difference fuel saving estimates, all versions of each component were determined to be economically acceptable. However, the HP Turbine Roundness Control, the Long Duct Mixed Flow Nacelle version with 80 percent mixing effectiveness and 2 percent sfc improvement in deterioration and the Short Core Exhaust version with 3 percent drag reduction were the most viable for introduction on the DC-10-30.

Table XLVII. DC-10-30 Annual Fuel Conservation Ranking, Douglas Analysis (Min. Fuel, Stage Length - 2735 KM, CF6-50).

Concepts for CF6-50	Annual Fuel Savings kg(lb)/AC/Year
Long Duct Mixed Flow Nacelle 80% Mixing Efficiency with 2% sfc Improvement in Deterioration	1,624,763 (3,581,928)
Long Duct Mixed Flow Nacelle 80% Mixing Efficiency	1,158,542 (2,554,104)
Long Duct Mixed Flow Nacelle 70% Mixing Efficiency	1,002,550 (2,210,208)
Short Core Exhaust - 3% Drag Reduction	678,737 (1,496,334)
Short Core Exhaust - 2% Drag Reduction	452,637 (997,878)
Fan Improvement (Blades and Stiffener)	399,618 (880,992)
Fan Improvement (Blades Only)	262,030 (577,668)
Short Core Exhaust - 1% Drag Reduction	226,100 (498,456)
HPT Roundness Control (3,000 hr)	198,494 (437,598)
R150 HPT Blades	185,787 (409,584)
Cabin Air Recirculation	162,126 (357,420)
HPT Roundness Control	97,275 (214,452)
Front Mount	70,985 (156,492)
Vortaway - Vortex Suppressor	48,200 (106,260)
Compressor Dovetail Seals	24,538 (54,096)
LPT Stage 1 Incidence	24,538 (54,096)

Table XLVIII. DC-10-30 Annual ROI Ranking, Douglas Analysis (Min. Fuel, Stage Length - 2735 KM, Fuel Price - 15 Cents/Liter or 55 Cents/Gallon, CF6-50).

Concepts for CF6-50	Before Tax ROI (%)
Short Core Exhaust - 3% Drag Reduction	12,882
Short Core Exhaust - 2% Drag Reduction	8,713
Short Core Exhaust - 1% Drag Reduction	4,537
Compressor Dovetail Seals	217
Front Mount	201
LPT Stage 1 Incidence	195
HPT Roundness Control (3000 hr)	145
Cabin Air Recirculation	87
HPT Roundness Control	85
Fan Improvement (Blades & Stiffener)	85
Fan Improvement (Blades Only)	67
Long Duct Mixed Flow Nacelle 80% Mixing Efficiency With 2% sfc Improvement in Deterioration	44
Vortaway - Vortex Suppressor	30
Long Duct Mixed Flow Nacelle 80% Mixing Efficiency	30
Long Duct Mixed Flow Nacelle 70% Mixing Efficiency	26
R150 HPT Blades	25

Table XLIX. DC-10-30 Annual DOC Savings Per Aircraft, Douglas Analysis (Min. Fuel, Stage Length - 2735 KM, Fuel Price - 15 Cents/Liter or 55 Cents/Gallon, CF6-50).

Concepts for CF6-50	Annual Δ DOC Savings ($)
Long Duct Mixed Flow Nacelle 80% Mixing Efficiency With 2% sfc Improvement in Deterioration	290,100
Long Duct Mixed Flow Nacelle 80% Mixing Efficiency	204,100
Long Duct Mixed Flow Nacelle 70% Mixing Efficiency	175,300
Short Core Exhaust - 3% Drag Reduction	129,000
Fan Improvement (Blades and Stiffener)	88,900
Short Core Exhaust - 2% Drag Reduction	87,200
Fan Improvement (Blades Only)	55,500
HPT Roundness Control (3000 hr)	45,600
Short Core Exhaust - 1% Drag Reduction	45,400
Cabin Air Recirculation	33,900
R150 HPT Blades	33,100
Vortaway - Vortex Suppressor	28,300
Front Mount	18,100
HPT Roundness Control	8,400
Compressor Dovetail Seals	6,100
LPT Stage 1 Incidence	6,100

Table L. Evaluation of Economic Acceptability - Douglas Analysis.

Concept	CF6-6		CF6-50	
	Acceptable	Not Acceptable	Acceptable	Not Acceptable
Fan Improvement (Blades and Stiffener)	X		X	
Fan Improvement (Blades and Stiffener) Retrofit - Attrition	X		X	
Fan Improvement (Blades and Stiffener) Retrofit - Campaign		X		M
Fan Improvement (Blades only)	X		X	
Fan Improvement (Blades only) Retrofit - Attrition	X		X	
Fan Improvement (Blades only) Retrofit - Attrition		X		X
HPT Active Clearance Control - Variable Source Bleed		X	-	-
HPT Active Clearance Control - Variable Source Bleed Retrofit - Attrition		X	-	-
HPT Active Clearance Control - Electrical Resistance Heating		Dropped	-	-
HPT Roundness Control/ HPT Roundness Control (3000 hr)	-	-	X	
R150 HPT Blades	-	-	X	
R150 HPT Blades Retrofit - Attrition	-	-	M	
R150 HPT Blades Retrofit - Campaign	-	-		X
HPT Aerodynamic Improvement	X		-	-
Cooled Cooling Air - Air/Air Heat Exchanger		X	-	-
Cooled Cooling Air - Air/Air Heat Exchanger Retrofit - Attrition.		X	-	-
Cooled Cooling Air - Fuel/Air Heat Exchanger Retrofit - Campaign		X	-	-
Cooled Cooling Air - Fuel/Air Heat Exchanger		X	-	-
Cooled Cooling Air - Fuel/Air Heat Exchanger Retrofit - Attrition		X	-	-
Cooled Cooling Air - Fuel/Air Heat Exchanger Retrofit - Campaign		X	-	-
Front Mount	X		X	
Compressor Rotor/Stator Thermal Match	-	-		M
Reduced Stator Bushing Leakage	-	-		M
Compressor Dovetail Seals	-	-	X	
Compressor Dovetail Seals Retrofit-Attrition	-	-	X	
LPT Active Clearance Control		X	-	-
LPT Active Clearance Control Retrofit - Attrition		X	-	-
LPT Stage 1 Incidence	-	-	X	
LPT Stage 1 Incidence Retrofit - Attrition	-	-	X	
LPT Stage 1 Incidence Retrofit - Campaign	-	-		X
Long Duct Mixed Flow Nacelle - 70% Mixing Efficiency	-	-	X 1)	
Long Duct Mixed Flow Nacelle - 80% Mixing Efficiency	-	-	X	
Long Duct Mixed Flow Nacelle - 80% Mixing Efficiency with 2% sfc Improvement in Deterioration	-	-	X	
Short Core Exhaust - 3% Drag Reduction	-	-	X	
Short Core Exhaust - 1% Drag Reduction	-	-	X	
Short Core Exhaust - 2% Drag Reduction	-	-	X	
Vortaway - Vortex Suppressor	X		X	
Vortaway - Vortex Suppressor Retrofit - Attrition	M		M	
Cabin Air Recirculation	X		X	

M = Concept marginally acceptable at longer stage lengths and higher fuel prices.
1) Acceptable for stage lengths of 2735 km (1700 miles) and above.

5.2.3 General Electric

An abbreviated economic assessment was performed by General Electric for the two concepts which were evaluated in the screening study for the CF6-6 engine in the DC-10-10 airplane but later proposed for the CF6-50 engine. These are the High Pressure and Low Pressure Turbine Active Clearance Control concepts. The economic analysis results for these concepts in the DC-10-30 and the B-747-200 airplanes for median range and mid fuel cost are presented in Tables LI and LII.

5.3 SUMMARY OF SCREENING STUDY

Results of the feasibility study are summarized in Tables LIII, LIV, and LV in terms of payback period, ROI, and fuel savings. The data shown are for new engines, the median range and mid fuel price, and for the minimum fuel operation analysis case of the mission study. The median range and mid fuel prices, which are dependent on the aircraft/mission, are shown below:

Aircraft	Mission	Median Range km (mi)	Mid Fuel Price ¢/Liter (¢/gal)
DC-10-10 (CF6-6)	US Domestic	1690 (1050)	12 (45)
DC-10-30 (CF6-50)	International	2735 (1700)	15 (55)
B-747-200 (CF6-50)	US Domestic	3460 (2150)	12 (45)

The concepts as applied to a particular study aircraft are economically categorized by payback period. Table LIII shows the concepts with a high economic ranking and a payback period under two years; Table LIV shows the medium economic ranking concepts with a payback period of 2 to 5 years; and Table LV shows the economically low ranking concepts with a payback period over 5 years. The concepts, ranked in order of the fuel savings for each economic category, are also shown graphically in Figure 101. The shaded areas indicate the range of fuel savings dependent on the airplane application (DC-10-10, DC-10-30, and B-747-200). For example, the Fan Improvement (blades and stiffener) indicates a lower value (507) for the DC-10-10 and an upper value (670) for the B-747-200, as shown in Table LIII.

From the results of the technical and economic assessments, several concepts were judged to be sufficiently attractive for consideration for development. This consideration was based on sfc reduction, projected fuel savings, maintenance costs, payback period, airline acceptability, and the probability of introduction on new engines as well as retrofit.

Listed below are the engine concepts selected for further development along with the engine model studied:

Table LI. HPT Active Clearance Control (CF6-50) New Production, Median Range, Mid Fuel Price.

Aircraft	Range (km)	Fuel Price ¢/Liter	Fuel Savings (1000 Liters/AC/YR)	ROI (%)	Payback (yr)
DC-10-30	2735	15	155.6	21	4.4
B-747-200	3460	12	180.9	12	6.9

Table LII. LPT Active Clearance Control (CF6-50) New Production, Median Range, Mid Fuel Price.

Aircraft	Range (km)	Fuel Price ¢/Liter	Fuel Savings (1000 Liters/AC/YR)	ROI (%)	Payback (yr)
DC-10-30	2735	15	66.6	23	4.1
B-747-200	3460	12	109.0	23	4.1

Table LIII. Economic Ranking - High Payback 0-2 Years (New Engines, Median Range, Mid Fuel Price, Min. Fuel Analysis).

Concept	Payback (Years)	ROI (%)	Fuel Savings (1000 Liters/yr/AC)
Fan Improvement (Blades and Stiffener)	1.5/1.2/0.8 (1)	67/85/123	507/541/670
Short Core Exhaust - 2% Drag Reduction (2) (DC-10-30)	--/0.01/--	--/8713/--	--/575/--
Fan Improvement (Blades Only)	1.6/1.5/0.9	65/67/112	420/352/439
HPT Aerodynamic Improvement	0.2/--/--	600/--/--	420/--/--
HPT Roundness Control (3)	--/0.7/0.9	--/145/111	--/269/299
Cabin Air Recirculation (DC-10-10)	1.6/1.2/--	64/87/--	201/219/--
Front Mount	0.6/0.5/0.6	165/201/166	91/95/117
Compressor Dovetail Seals	--/0.5/0.5	--/217/184	--/34/42
LPT Stage 1 Incidence	--/0.5/0.6	--/195/165	--/34/42

Notes:
(1) DC-10-10/DC-10-30 /747-200
(2) For 2% Δ SFC
(3) At 3000 Hours

Table LIV. Economic Ranking - Medium Payback 2-5 Years (New Engines, Median Range, Mid Fuel Price, Min. Fuel Analysis).

Concept	Payback (Years)	ROI (%)	Fuel Savings (1000 Liters/yr/AC)
Long Duct Mixed Flow Nacelle - 70% Mixing Efficiency (DC-10-30)	--/3.8/-- (1)	--/26/--	--/1329/--
R150 HPT Blades	--/3.8/4.7	--/25/20	--/250/307
HPT Active Clearance Control - Variable Source Bleed (2)	--/4.4/--	--/21/--	--/156/--
LPT Active Clearance Control (2)	--/4.1/4.1	--/23/23	--/66.6/109
Vortaway - Vortex Suppressor	3.8/3.3/--	26/30/--	76/64/--

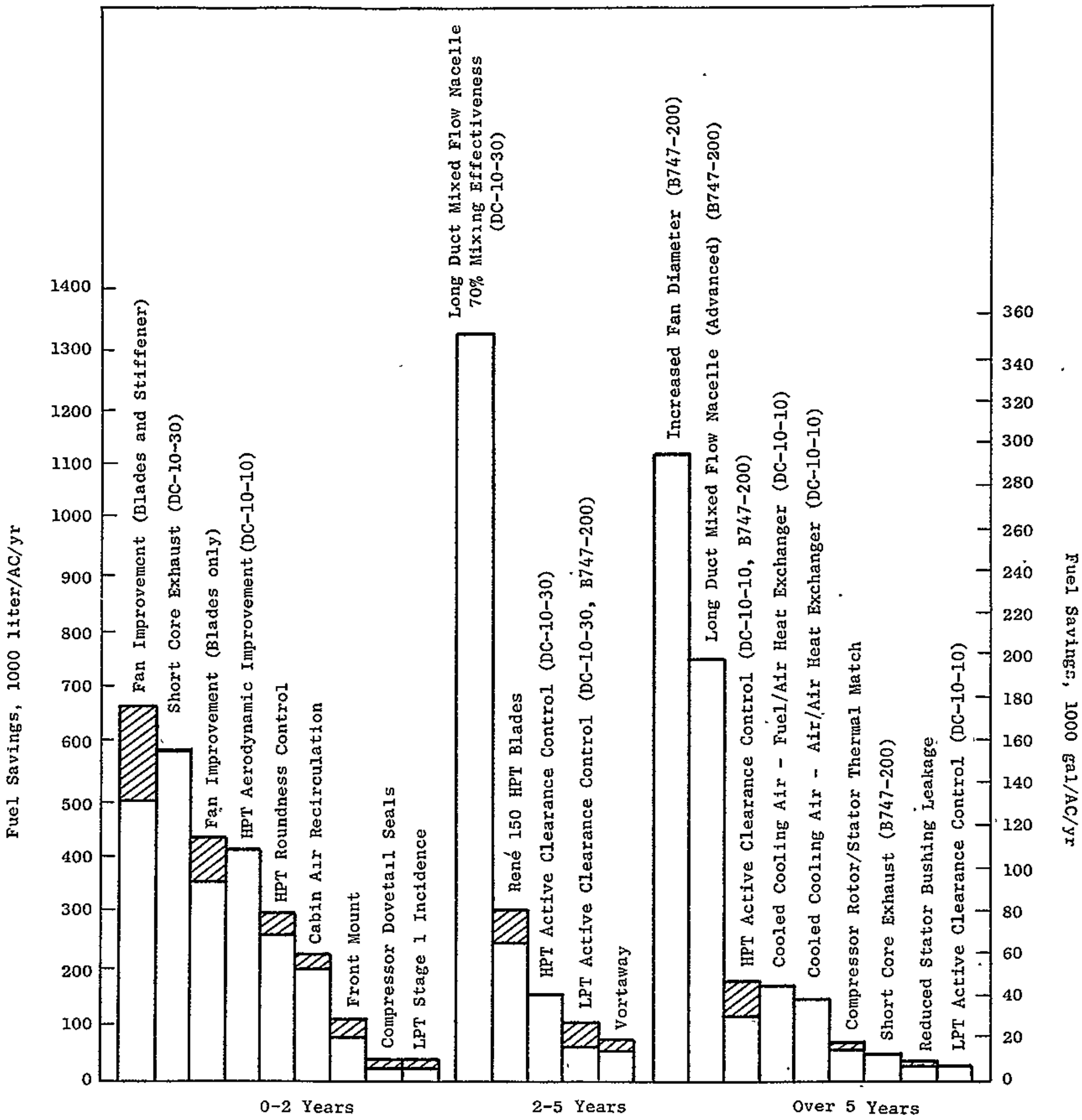
Notes: (1) DC-10-10/DC-10-30/747-200

(2) General Electric Assessment

Table LV. Economic Ranking - Low Payback Over 5 Years (New Engines, Median Range, Mid Fuel Price, Min. Fuel Analysis).

Concept	Payback (Years)	ROI (%)	Fuel Savings (1000 Liters/yr/AC)
Increased Fan Diameter (747-200)	-/-/8.2 (1)	-/-/9	-/-/1128
Long Duct Mixed Flow (2) Nacelle (747-200)	-/-/10.4	-/-/5	-/-/765
HPT Active Clearance Control-Variable Source Bleed	7.7/-/6.9	10/-/12	117/-/181
Cooled Cooling Air-Fuel/ Air Heat Exchanger	10.3/-/-	5/-/-	178/-/-
Cooled Cooling Air Air/Air Heat Exchanger	5.9/-/-	15/-/-	151/-/-
Compressor Rotor/Stator Thermal Match	-/8.5/9.6	-/8/6	-/53/64
Short Core Exhaust (747-200)	-/-/12.4	-/-/3	-/-/49
Reduced Stator Bushing Leakage	-/8.0/9.6	-/9/6	-/30/34
LPT Active Clearance Control	7.8/-/-	9/-/-	30/-/-

Notes: (1) DC-10-10/DC-10-30/747-200
(2) Advanced



Note: Shaded area indicates range of fuel saving dependent on airplane application (DC-10-10, DC-10-30 and B747-200).

Figure 101. Concept Comparison, Fuel Savings vs. Payback (Median Range).

- Fan Improvement, CF6-6 and CF6-50
- Short Core Exhaust, CF6-50
- HPT Aerodynamic Improvements, CF6-6
- HPT Roundness Control, CF6-50
- Front Mount, CF6-6 and CF6-50
- HPT Active Clearance Control, CF6-6 and CF6-50
- LPT Active Clearance Control, CF6-6 and CF6-50

The Cabin Air Recirculation concept, applicable to both the CF6-6 and CF6-50, was the only airplane modification studied. This concept was also judged attractive for further development.

As noted above, all but three of the selected concepts are directly applicable to both engine models. The Short Core Exhaust and the HPT Aerodynamic Improvement concepts apply only to one particular model because of specific configuration differences relative to the exhaust nozzle and the HPT. The HPT Roundness Control technology, however, is also applicable to the CF6-6 engine.

Important factors in determining the economic ranking of the selected concepts were sfc (fuel savings) and maintenance cost savings. The sensitivity of return on investment (ROI) and payback period with regard to these factors was calculated for the selected concepts. The results are presented in Table LVI for the median range and mid fuel cost for new production based on the minimum fuel mission analysis for the three aircraft. The sensitivities for the DC-10-10 aircraft (CF6-6 engines) are, in general, greater than for the DC-10-30 and the B-747-200 aircraft with CF6-50 engines. Also, ROI and payback period are more sensitive to sfc (fuel savings) than to maintenance cost savings.

Because of the sensitivity of both ROI and payback period to sfc, the range of uncertainty for the predicted values of sfc was determined. These values for the selected concepts are shown in Table LVII.

The fuel savings for the selected engine improvement concepts were calculated for an assumed production through 1990 using General Electric high and low market forecasts. This fuel savings estimate is based on an average engine life of 15 years and an average retrofit life of 7-1/2 years. The Fan Performance Improvement, Front Mount and HP Turbine Active Clearance Control concepts were applied to both engine models; the short core exhaust, HP Turbine Roundness Control and LP Turbine Active Clearance Control were applied to only one engine model. The results are shown in Table LVIII which lists the concepts in order of the fuel savings. The total estimated fuel savings for the selected seven engine improvements amount to 7-1/2 to 10-1/2 billion liters (2 to 2-3/4 billion gallons).

Table LVI. ROI and Payback Sensitivities With Regard to Fuel Savings and Maintenance Cost Savings for the Selected Concepts (Medium Range, Mid Fuel Cost, New Production, Min. Fuel Analysis).

Concept	% Δ ROI / % Δ sfc	% Δ Payback / % Δ sfc	% Δ ROI / % Δ Maint. Cost	% Δ Payback / % Δ Maint. Cost
Fan Improvement (Blades and Stiffener)	-1.53/-0.83/-0.78 (1)	2.43/1.05/0.99	-1.05/-0.17/-0.18	1.39/0.17/0.20
Short Core Exhaust	--/-0.95/-2.67	--/1.46/0.68	--/-0.21/-2.0	--/0.36/0.48
HPT Aerodynamic Improvement	-0.22/--/--	0.15/--/--	-0.78/--/--	0/87/--/--
HPT Roundness Control	--/-0.8/-0.73	--/1.01/0.88	--/-0.19/-0.2	--/0.21/-0.21
Front Mount	-0.65/-0.72/-0.8	0.77/0.89/0.69	-0.32/-0.26/-0.33	0.33/0.27/0.31
HPT Active Clearance Control	-2.0/-1.14/-1.39	1.48/1.49/1.75	-0.4/-0.2/-0.33	0.11/0.11/0.23
LPT Active Clearance Control	-1.33/-1.43/-1.48	0.99/1.82/1.85	-0.67/-0.23/-0.35	0.17/0.28/0.28
Cabin Air Recirculation	-0.83/-0.89/--	1.06/0.13/--	-0.21/-0.12/--	0.16/0.12/--

(1) DC-10-10/DC-10-30/747-200

Table LVII. Specific Fuel Consumption Uncertainties for the Selected Concepts.

Concept	Engine Model	Uncertainty Range (sfc)
Fan Improvement (Blade and Stiffener)	CF6-6 CF6-50	1.4-1.8 1.6-2.2
Short Core Exhaust	CF6-50	0.7-1.3
HPT Aerodynamic Improvements	CF6-6	1.0-1.6
HPT Roundness Control	CF6-50	0.3-0.6
Front Mount	CF6-6 & CF6-50	0.1-0.4
HPT Active Clearance Control	CF6-6 & CF6-50	0.3-0.8
LPT Active Clearance Control	CF6-6	0.1-0.2
Cabin Air Recirculation	CF6-6 & CF6-50	-

Table LVIII. Estimated CF6 Fleet Fuel Savings (Medium Range, Min. Fuel Analysis).

Concept	Engine Application	Fuel Savings In Million Liters (Gallons)	
		High Market Forecast	Low Market Forecast
Fan Improvement (Blades and Stiffener)	-6, -50	3997 (1056)	2861 (756)
Short Core Exhaust	-50	1730 (457)	1173 (310)
HPT Aerodynamic Improvement	-6	1120 (296)	855 (226)
HPT Roundness Control	-50	1506 (398)	1207(319)
Front Mount	-6, -50	799 (211)	590 (156)
HPT Active Clearance Control	-6, -50	916 (242)	613 (162)
LPT Active Clearance Control	-6, -50	348 (92)	231 (61)
TOTAL		10,416 (2752)	7,530 (1990)

6.0 CONCLUDING REMARKS

A feasibility analysis of performance improvement and retention concepts for the CF6-6 and CF6-50 engines was developed in cooperation with the Boeing and Douglas aircraft companies and American and United airlines. This analysis proved to be a valuable tool for assessing the technical and economic viability and facilitated the selection of improvement concepts for further development.

As a result, the following engine improvement concepts were selected for immediate development:

- Fan Improvement for the CF6-6 and CF6-50
- Short Core Exhaust for the CF6-50
- High Pressure Turbine Aerodynamic Improvements for the CF6-6
- High Pressure Turbine Roundness Control for the CF6-50
- Front Mount for the CF6-6 and CF6-50
- High Pressure Turbine Active Clearance Control for the CF6-50
- Low Pressure Turbine Active Clearance Control for the CF6-50

The Cabin Air Recirculation, a DC-10 modification, was also selected for development.

It is recommended that the initiation of development of Rene' 150 HPT blades for commercial use be considered upon completion of current on-going development programs and upon assessment of the results of these programs.

Implementation of these concepts into the total CF6 fleet during the 1980 to 1990 time period will not only reduce aircraft operating and maintenance costs, but will also yield significant fuel savings (7-1/2 to 10-1/2 billion liters).

APPENDIX A

LONG DUCT MIXED FLOW NACELLE STUDY

I. INTRODUCTION AND SUMMARY

A. Introduction

The economic success of wide-body commercial aircraft is primarily the result of the development of high bypass ratio, high thrust engines. The selection of appropriate nacelle arrangement and the finding of geometric ground rules for locating nacelles relative to large chord wings have become extremely important. The military precursor program (the C-5A with the TF39 engine) has proven, at least on a high-wing layout, that satisfactory installed engine performance is possible if separate flow configuration nacelles are mounted ahead of, and substantially below, the aircraft wing.

For aircraft employing low-wing layouts, ground clearance of the nacelles becomes a real problem if C-5A type nacelle-to-wing geometry is imitated. Excessive landing gear length would be the result. Consequently, all of the commercial aircraft nacelles can be seen to be relatively "close-coupled" compared with C-5A.

The reduction in sfc brought about by the use of the high bypass engine was large enough so that a fully refined analysis of the nacelle layout and geometry was not essential. The aircraft and the engines that evolved were a major step forward from their predecessors and were designed, flight tested, and put into service in programs of short time span which also included strong competitive pressures between each other.

Since the introduction into service of these new aircraft and more particularly since the dramatic escalation in the cost of aviation fuel, ways are being sought to make these aircraft and engines even more fuel efficient. During the last 5 years, General Electric has been actively engaged in resolving the pros and cons of many propulsion ideas that could lead to greater fuel efficiency from existing engines. One of these concepts is a Long Duct Mixed Flow (LDMF) propulsion system that potentially offers a significant fuel consumption reduction when advanced technology is applied in key areas.

The objective of this study were to provide preliminary designs of CF6-50 engines installed in LDMF nacelles, establish performance and weight differences, conduct economic analyses to determine the effects and the introduction of this system would have on a commercial airline, and scope out a development plan together with cost data. General Electric provided the data on nacelle internal performance while Douglas and Boeing estimated nacelle external performance and established any other installation effects such as changes to interference drag. The weights were a combination of engine and airframe estimates with General Electric having prime responsibility for the exhaust mixer and exhaust nozzle centerbody. Selected outputs from a GE mixed flow cycle deck were used for performance estimates by both Douglas and Boeing.

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B. Summary

Long Duct Mixed Flow Nacelle studies by General Electric, Douglas and Boeing are presented. The General Electric study describes the related experience and background for the performance estimates. The airframer studies describe the nacelle design, performance, noise, materials, weights, and the technical and economic analyses. The results of the technical analysis for the two airplanes with the assumption of a 70 percent mixing effectiveness and advanced structure are as follows:

Aircraft	Range	ΔFuel	
	km	kg	%
DC-10-30	805	- 252	-2.6
	2735	-1038	-4.1
	6275	-2863	-4.9
B-747-200	770	- 209	-1.8
	3460	- 880	-2.1
	6195	-1801	-2.4

As expected, there is a difference in fuel savings depending on the installation; however, the payoffs are very significant for both airplanes.

A comparison of the economic analysis results for the median range, mid fuel price and minimum fuel analysis is shown below:

Aircraft	Fuel Price ¢/Liter (¢/Gal)	Payback (Years)	R01 (%)	Fuel Savings (1000 Liters/Year/AC)
DC-10-30	15 (55)	3.8	26	1329
B-747-200	12 (45)	10.4	5	765

The aircraft flyover noise reductions are estimated at 3 decibels for the DC-10 and 2 decibels for the B-747.

II. CONCLUSIONS

The Long Duct Mixed Flow Nacelle concept offers very significant performance improvements and fuel savings.

The payoff of this performance improvement concept depends very much on the advanced lightweight structures and on the aircraft/nacelle installation.

For the assumed mixing effectiveness of 70 percent, the block fuel savings amount from 2.6 to 4.9 percent for the DC-10-30 and to 1.8 to 2.4 percent for the B-747-200.

III. GENERAL ELECTRIC STUDY

A. Related Experience and Data Base

The aerodynamic characteristics of a number of mixed flow exhaust systems spanning a broad range in applicable bypass ratio and mixer operating characteristics have been evaluated by General Electric in scale model size since the early 1960's. Significant among these relative to the CF6 Engine Component Improvement Program are two IR&D programs where extensive model testing was done on high bypass ratio turbofan configurations. The first program, conducted in 1970, investigated the performance of a confluent free mixer, an 18 lobe partial mixer, and an 18 lobe full mixer at bypass ratios of approximately 6. Measured data included overall force, wall pressure distributions, flow surveys (fixed, traversing, and rotating rakes), and flow visualization.

The second program was conducted in 1971 and 1972. This program investigated in detail the effects of real engine components on the mixed flow performance. The model simulated the details of the fan frame and OGV's, the fan duct, upper and lower duct pylons, side pylons, and core tangential turbine frame as well as the 18 lobe partial mixer and exhaust nozzle. Figure A-1 shows photographs of the mixer model.

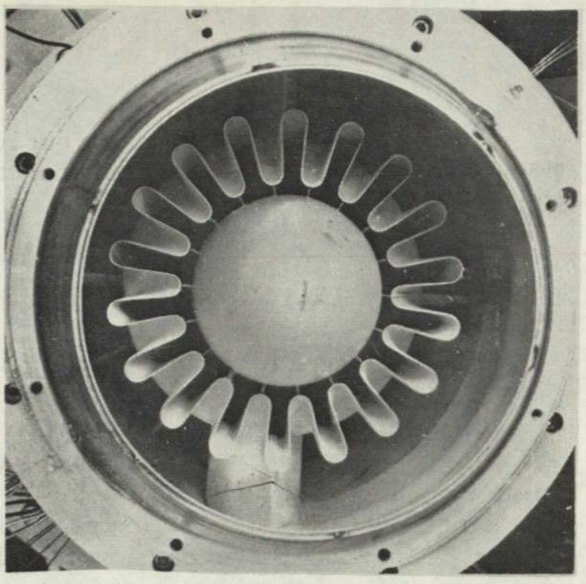
This 12 percent scale model was tested over a range of nozzle pressure ratios and core-to-fan temperature ratios. Simulation of realistic operating characteristics of fan and core total pressure distortion, turbine discharge swirl, and cycle total pressure mismatch was included. Measured data included overall force, wall pressure distributions, and flow surveys by continuous traversing rakes.

In addition, tests were also conducted of a simulated fan-only reverser system where the effects of core thrust spoiling and reverse duct flow phenomena were evaluated and measured.

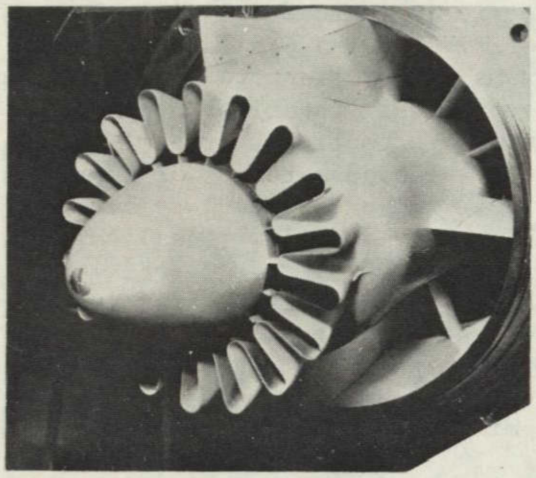
Full scale engine test programs have also been run statically for various mixer/nozzle configurations for both the CF700 and CFM56 engines. These tests have provided data for bypass ratios of approximately 2 and 6, respectively.

B. Mixer Design

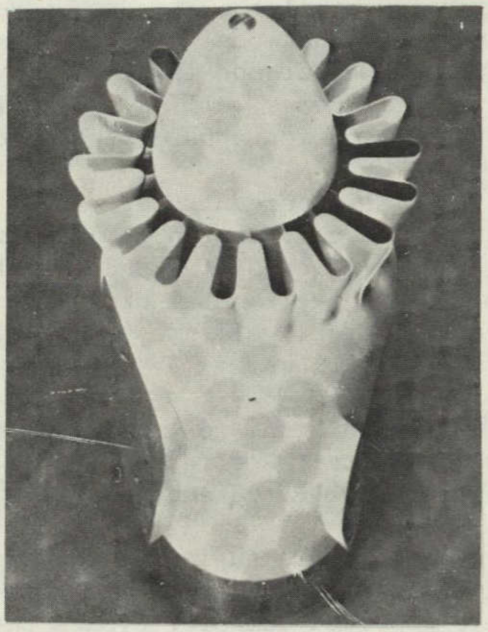
A layout of the baseline mixer is shown in Figure A-2. The daisy type mixer has 17 lobes circumferentially spaced on the basis of 19 lobes with two adjacent lobes removed to accommodate the pylon. Portions of the lobe side walls are chem-milled to reduce weight. The forward end of the mixer is fastened to the turbine frame with further support being provided by links which fasten the aft end of each lobe trough to the plug.



Partial Mixer Model



Mixer, Shroud Removed



Partial Mixer

Figure A-1. 1971-72 Mixer Model.

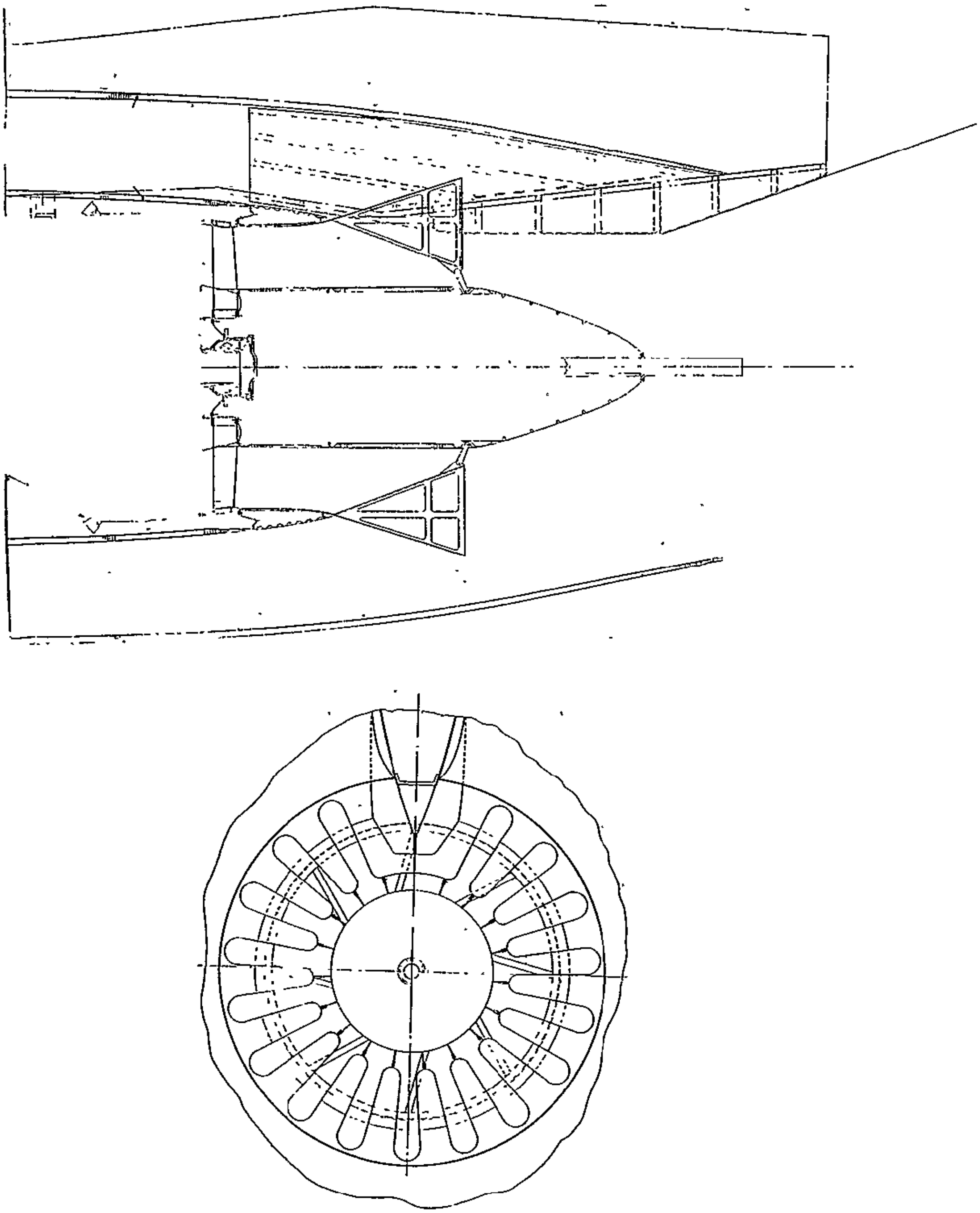


Figure A-2. Mixer Fan & Core, 17 Chutes Based on 19 Long Cowl CF6/50.

The aerodynamic flowpath of the mixer is based on a scale model mixer which was tested by General Electric in 1972. Figure A-3 shows values for the pertinent geometric parameters used in estimating the mixer performance.

C. Performance

The performance of the long duct nacelle is based on estimated cruise-condition duct losses of 2.34 percent in the fan duct and 1.34 percent in the core duct. As shown in Figure A-4, these values include all losses from the frame entrance to the mixing plane. The mixing effectiveness of 70 percent is based on Frost and GE data as shown in Figure A-5.

Performance comparisons for three power settings are summarized in Table A-I. At a given power setting, these comparisons are based on constant uninstalled thrust. This thrust includes the effect of scrubbing drag on the separate flow nacelle.

Mixed flow engine internal performance data were provided by General Electric to Douglas and Boeing at the selected mission conditions required for the evaluation of fuel savings and noise.

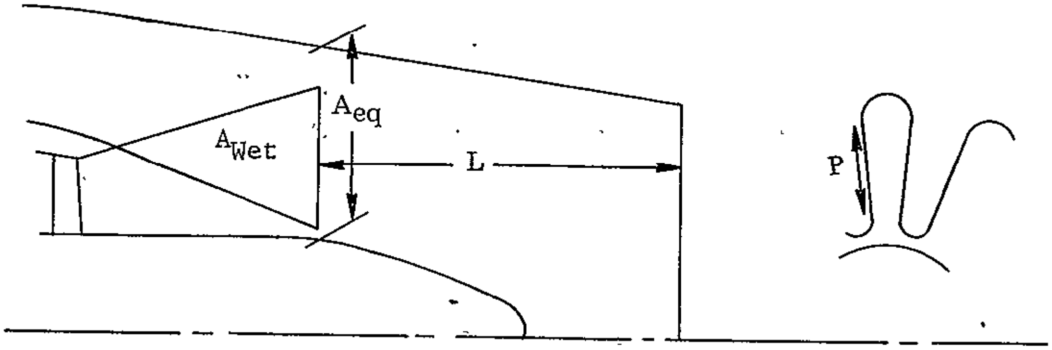
IV. DOUGLAS STUDY

A. Summary

The Long Duct Mixed Flow Nacelle has been studied as a means to reduce the fuel consumed by DC-10 aircraft. The study involved several advance technology concepts which improve aircraft performance and reduce noise. The major feature of the design involved forced mixing, a directed flow reverser, the use of composite materials, improved acoustic treatment, and other items which decreased engine deterioration. The combined effect of these features will improve the performance of the aircraft up to 7 percent. The flyover noise levels are further estimated to be reduced by 3 decibels. The weight of the nacelle, using composite materials, will be 8 percent lighter than the current nacelle with turbine reverser. The basic composite materials selected will be composite hybrids which can withstand temperatures up to 315° C. The basic construction for duct walls is a thin-walled design using composite face skins bonded to a honeycomb core.

B. Introduction

The Long Duct Mixed Flow Nacelle is an advanced design concept which has been under study at the Douglas Aircraft Company for a number of years. The study presented herein was conducted by the Douglas Aircraft Company for the General Electric Company. This study was, in turn, a part of General Electric's effort for NASA's Engine Component Improvement Program. The primary emphasis here was on identifying the maximum fuel savings potential. The results of a prior NASA study conducted by Douglas Aircraft Company (Reference 1) was used as a starting point for conducting this study.



L = Mixing chamber length

P = Perimeter of mixer at mixing plane

$D_{eq} = \sqrt{\left(\frac{4}{\pi}\right) A_{eq}}$ = Equivalent diameter of mixing chamber at mixing plane

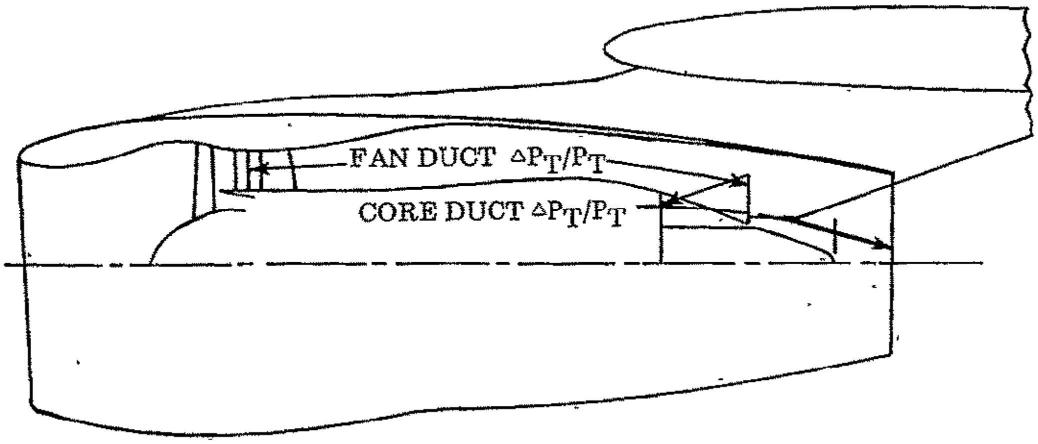
$$\frac{L}{D_{eq}} = 0.61$$

$$\frac{P}{D_{eq}} = 8.16$$

$$\frac{PL}{{D_{eq}}^2} = 4.98$$

$A_{wet} = 5.64\ \text{in}^2$ (fan side)

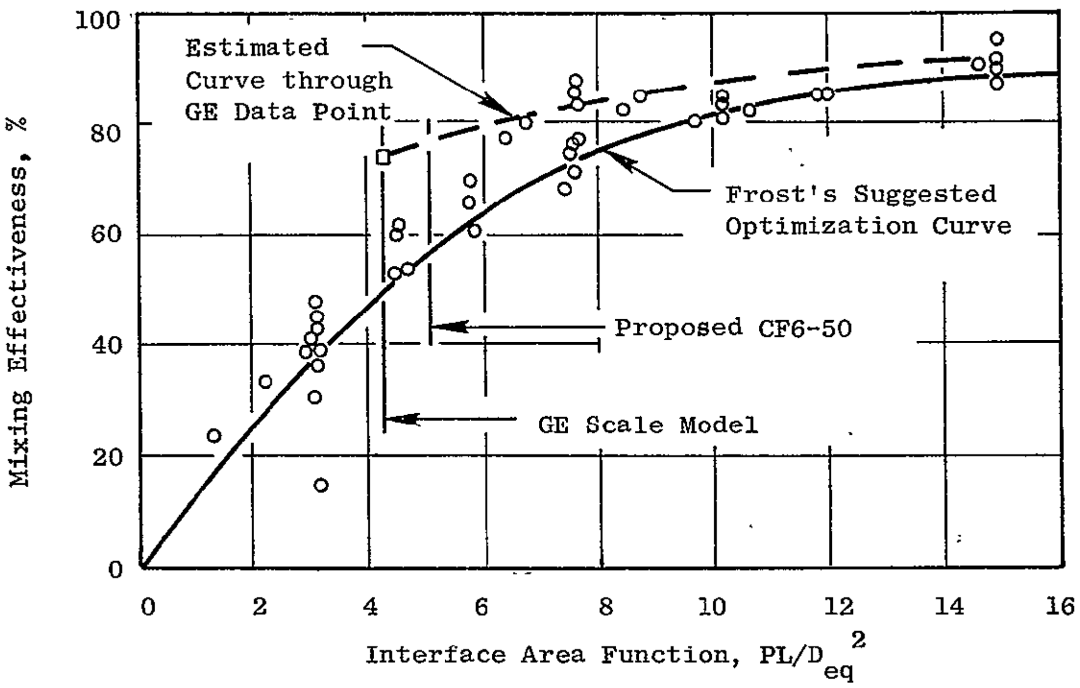
Figure A-3. Mixer Geometry.



$$\left(\frac{\Delta P_T}{P_T}\right) \text{FAN} = 2.34\%$$

$$\left(\frac{\Delta P_T}{P_T}\right) \text{CORE} = 1.34\%$$

Figure A-4. Estimated Duct Pressure Losses at Cruise, Long Duct Configuration.



○ Frost Data

□ GE Data

P = Wetted Perimeter of Mixer at Mixing Plane (cm)

L = Length of Mixing Chamber from Mixing Plane to Nozzle Exit (cm)

D_{eq} = Equivalent Diameter of Total Flow Area at Mixing Plane

Figure A-5. Comparison of Mixing Effectiveness for GE Scale Model and Proposed CF6 Mixer.

Table A-I. Long Duct Mixed Flow vs Separate Flow Estimated Performance Comparison for Boeing 747-200, Including Scrubbing Drag on Separate Flow Nacelle.

Power Setting	Flight Conditions (Alt/Mp)	Thrust* (N)	Fan Speed %	Δ% sfc
Takeoff	Sea Level Static	230,000	111	-2.0
Cruise	10,668 m/Mach 0.85	36,000/40,000	93/97	-3.5
Max Cruise	10,668 m/Mach 0.85/+10 °C	49,000	105	-4.1

*$F = F_{g_{fan}} + F_{g_{core}} - D_{ram} - D_{scrub}$.

F = Thrust

$F_{g_{fan}}$ = Fan Gross Thrust

$F_{g_{core}}$ = Core Gross Thrust

D_{ram} = Ram Drag

D_{scrub} = Engine Scrubbing Drag

Since the study of Reference 1, technology advancements in engine installations have been made by Douglas through a continuing research and development program (Reference 2). The features of the initial study have been revised to reflect these advancements. These revised features along with other advanced design concepts have been incorporated to compose the contents of this study. The resultant advanced integrated nacelle installation is depicted in Figure A-6. The major features of this advanced integrated nacelle are forced mixing, composite long duct, improved pylon, directed flow reverser, load sharing composite core cowl, improved acoustic treatment, composite inlet, aerodynamically improved inlet, inlet vortex control, and a recirculating fuel system.

C. Discussion

1. Advance Technology Concepts

A number of advance technology concepts was used in the designing of the Long Duct Mixed Flow Nacelle. The basic concepts are to improve performance and reduce noise. The correlation between these advance technology concepts and the advance integrated nacelle features in Figure A-6 is shown in Table A-II.

a. Improved Performance

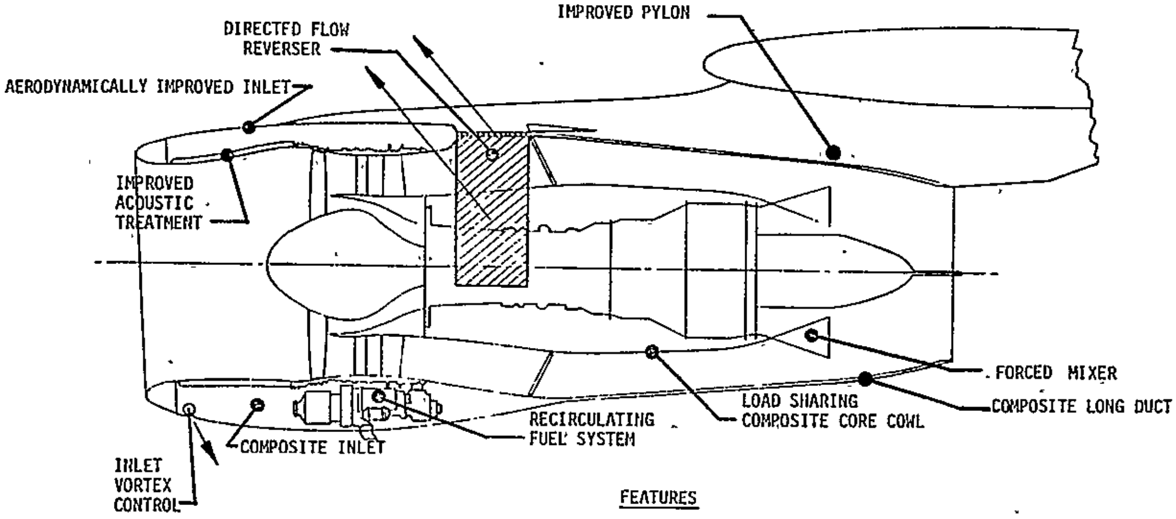
The improved performance concept is divided into four subsections: Improved internal performance, drag reduction, reduced engine deterioration and weight reduction.

Improved Internal Performance

Two features were incorporated in the advance design nacelle which improved the internal performance of the engine. These features are forced mixing and a recirculating fuel system.

Forced Mixing - The forced mixer is a mechanical device that promotes rapid mixing between the primary and fan flows. The particular design used in this study is a 17 lobe daisy nozzle. This type of forced mixer creates a large shear perimeter between the primary and fan flow. The concept behind this type of mixing is that it creates turbulent mixing which forces the transfer of energy from the hot primary flow to the cooler fan flow. This process improves the propulsive efficiency of the aircraft by reducing the effect of jet velocity resulting in reduced cruise fuel consumption.

Recirculating Fuel System - Most aircraft drive the electrical alternators with a constant speed drive to maintain accurate electrical frequency control. The constant speed drive is driven by an engine gearbox which operates through a wide range of rpm's and is dependent on engine power setting. The constant speed drive's output speed is controlled by a self-contained oil system which also serves as a self-lubricating system. A considerable amount of heat is generated by the system and is dissipated



FEATURES

- Forced mixer improves propulsive efficiency and reduces jet noise
- Composite long duct reduces drag and accomodates additional acoustic treatment without weight increase
- Improved Pylon to minimize interference drag
- Directed flow reverser reduces engine erosion and reduces airplane stopping distance
- Load sharing composite core cowl reduces engine deterioration
- Improved acoustic treatment reduces noise
- Composite inlet reduces weight
- Aerodynamically Improved inlet improves performance
- Inlet vortex control reduces engine erosion
- Recirculating fuel system reduces cooling losses

Figure A-6. Douglas Advanced Integrated Nacelle.

Table A-II. Correlation Between Advance Integrated Nacelle Feature and Advance Technology Concepts - Douglas Study.

ADVANCE INTEGRATED NACELLE FEATURES	ADVANCE TECHNOLOGY CONCEPTS				
	IMPROVED PERFORMANCE				REDUCED NOISE
	Improved Internal Performance	Reduced Drag	Reduced Engine Deterioration	Reduced Weight	
Forced Mixing	X				X
Composite Long Duct		X		X	X
Improved Pylon		X			
Directed Flow Reverser			X		
Load Sharing Composite Core Cowl			X		
Improved Acoustic Treatment					X
Composite Inlet				X	
Aerodynamically Improved Inlet		X			
Inlet Vortex Control			X		
Recirculating Fuel System	X				

through an air/oil cooler positioned in the fan stream. The air/oil cooler creates a performance loss which is due to the blockage and pressure drop through the cooler. It is the intention of this feature to eliminate the air/oil cooler and use the aircraft's airplane wing fuel tanks as a heat sink. By using this process, there will not be any performance losses incurred in the fan stream. Further, by adding heat to the fuel tank, a cruder grade of fuel could be used which has a higher freezing point.

Reduced Drag

Two features were added to the Long Duct Mixed Flow Nacelle to reduce the overall drag of the pod and pylon. These features helped to improve the performance of the aircraft.

Composite Long Duct and Improved Pylon - The current DC-10 has a short fan duct nacelle. In this configuration, the fan exhaust causes high Mach number scrubbing drag along the pylon and core cowl. Due to the local pressure field under the wing, an adverse shock wave occurs which causes flow separation. The long duct nacelle encloses the entire fan stream and has sufficient area to maintain a low Mach number until the flow reaches the exit nozzle. This nozzle is located aft of the pylon so that this external surface of the nacelle and the pylon is exposed only to the free stream velocity. The elimination of high Mach number scrubbing drag and separation tendencies improves installed performance. When the long duct is installed, some pylon fairings or surface camber may be required to minimize interference drag.

Aerodynamically Improved Inlet - The upper loft line of the upper barrel will be modified by slightly adding more camber to the upper surface. This new line prevents high Mach number shock waves from occurring during elevated cruise velocities and helps maintain laminar flow during second segment climb. The modified loft line indirectly improves performance and will be incorporated with the change to the composite outer barrel structure.

Reduced Engine Deterioration

Three features incorporated in the advance integrated nacelle reduce the engine's deterioration rate as well as reducing engine maintenance costs. This is accomplished by eliminating the ingestion of sand, dirt and objects which could cause physical damage to the fan or compressor and by the sharing of engine loads under high thrust, high "g" conditions, over a period of time. This continued ingestion of sand and dirt causes compressor blades and airfoils to erode which causes the engine's performance to deteriorate. The ingestion of debris also causes dirt to build up on airfoil surfaces which causes a decrease in performance due to distorted shape of the stator and compressor blades. The ingestion of larger objects which nick blades can result in blade failures and expensive overhauls.

Engines also deteriorate under high thrust and high "g" load conditions that causes the cylindrical engine case to ovalize. Because of these conditions, higher than desired tip clearances are required between rotating and fixed portions of the engine. If the proper clearance is not provided in the initial build of the engine, rubbing occurs and clearances widen during service operation. With the larger than optimum clearances, engine performance is lost.

Directed Flow Reverser - One of the design features to reduce debris ingestion is a directed flow reverser. The principle behind this scheme is to direct fan flow upward and forward so the flow does not impinge the ground. This is accomplished by concentrating the reverser cascades in the upper two-thirds of the nacelle (lower 120° blanked off). With the proper cascade design, engine reingestion will not occur, even though the aircraft's velocity is zero knots. By directing the flow, the effect of flap blanking will be eliminated, allowing flap drag to be maintained during low speed landing rolls. The use of this directed reverser offers economic advantages to airlines that are not directly related to performance. Some of these are reduced brake wear, brake overhaul costs and less reverser maintenance because of the use of an improved actuation system.

Load Sharing Composite Nacelle - Under high thrust and high "g" load conditions, the cylindrical cases of the engine tend to ovalize. Because of these conditions, larger than desired tip clearances must be maintained between rotating and fixed portions of the engine. This problem can be alleviated by taking advantage of the nacelle structure and allowing the loads induced by ovalization to be reacted into the nacelle and subsequently into the pylon. The limiting of engine case ovalization allows the engine to maintain smaller rotating to fixed structural clearances. This tighter tip clearance provides for better performance which reduces fuel consumption and lowers the deterioration rate of the engine by reducing tip blade rubbing. There is also a reduction in overhaul expense due to the lowering of the required number of parts being replaced.

The key to designing a load sharing nacelle is to provide the proper and direct load paths within the nacelle and pylon structure without increasing the overall weight by a considerable amount. Preliminary designs show that a load sharing nacelle can be developed with very little weight penalty due to the excellent physical properties of composite structures.

Inlet Vortex Control - Sand and debris are ingested by wing mounted engines during low speed operations on the ground. The inlet vortex is a contributor to this particular ingestion which results in engine erosion. Inlet vortex control is accomplished by directing high velocity jets down and aft from the lower surface of the inlet. This prevents formation of the inlet vortex by inducing an effective forward velocity on the lower surface of the inlet. Eliminating the inlet vortex will decrease erosion due to particle ingestion.

Weight Reduction

By reducing the weight of the nacelle, a fuel saving is recognized. Below is a brief statement of what materials are used and why they reduce nacelle weight.

Composite Long Duct and Composite Inlet - The feasibility of the Long Duct Mixed Flow Nacelle was made possible by the use of advance composites. A weight saving of 15-20 percent was associated with the use of these materials over similar metallic materials. The basic reason for the weight saving is that composite materials have a higher strength-to-weight ratio.

b. Noise Reduction

The noise is reduced by the Long Duct Mixed Flow Nacelle which helps relieve some of the public pressure relating to this topic. There are three basic features which help reduce the decibel level around the nacelle. These features are stated below and amount to a reduction of 3 decibels.

Forced Mixing

The mixer will lower jet noise by reducing the maximum velocities in the exhaust flow. It will also help reduce the turbine noise level in that some noise attenuation will result as the noise progresses through the turbulent flow behind the mixer.

Composite Long Duct

The Long Duct Mixed Flow Nacelle has a larger area which is acoustically treated than the current short duct nacelle. The additional treatment absorbs some of the noise emitted by fan and turbine flows. This provides the long duct with a decrease in overall nacelle noise.

Improved Inlet Acoustic Treatment

Several inlet inner barrel designs are being evaluated to reduce the noise level. The bulk absorber treatment, double layer honeycomb, and multi-degree of freedom construction are considered as candidate inlet noise absorption systems. More testing is required before the final choice will be made. Whichever construction is selected, it is expected to result in improved noise attenuation.

2. Performance Evaluation

Three performance cases have been evaluated. The effects on specific fuel consumption are shown in Table A-III. Case 1 is using the basic internal

Table A-III. Long Duct Mixed Flow Nacelle Performance Improvements - Douglas Study.

	$\left(\frac{\Delta SFC}{SFC}\right)$ INTERNAL %			$\left(\frac{\Delta SFC}{SFC}\right)$ % EXTERNAL SCRUBBING	$\left(\frac{\Delta SFC}{SFC}\right)$ INSTALLED %			$\left(\frac{\Delta D}{D}\right)$ -%- INTERFERENCE
	CASE 1	CASE 2	CASE 3		CASE 1	CASE 2	CASE 3	
Takeoff	-2.1	-2.8	-4.8	NIL	-2.1	-2.8	-4.8	NIL
Climb	-4.4	-5.1	-7.1	1.1	-3.3	-4.0	-6.0	NIL
Hold	-3.3	-4.0	-6.0	1.6	-1.7	-2.4	-4.4	NIL
Cruise								
75%	-3.8	-4.5	-6.5	1.5	-4.3	-5.0	-7.0	-2.0
85%	-4.0	-4.7	-6.7	1.5	-4.5	-5.2	-7.2	-2.0
95%	-4.3	-5.0	-7.0	1.5	-4.8	-5.5	-7.5	-2.0
Descent	NIL	NIL	-2.0	NIL	NIL	NIL	-2.0	NIL

NOTES
Case 1) 70% Mixing Efficiency (GE Input)
Case 2) 80% Mixing Efficiency
Case 3) 80% Mixing Efficiency plus 2% sfc for Advanced Features

OF POOR QUALITY

performance supplied by GE. This performance is based on a mixing efficiency of 70 percent. A more optimistic mixing efficiency of 80 percent was assumed in Case 2. In Case 3, a further sfc credit of 2 percent was assumed to result during the life of an engine because of the additional advanced features incorporated in the nacelle which are expected to significantly reduce engine deterioration.

These values were input into the DC-10 airplane performance computer program and the effect on fuel burned determined for three ranges. The detailed fuel savings results are shown in Tables A-IV through A-IX and are summarized in Table A-X.

The fuel savings results were used to make an airline economic analysis to determine the cost effectiveness of the long duct nacelle based on direct fuel savings (Table A-XI). This evaluation does not give any credit for payload range improvement, or more important, the effect on direct operating cost when an airplane is being sized for a given payload range.

3. Noise

The long duct nacelle noise is lower because the maximum jet exhaust velocity is reduced and additional acoustic treatment can be incorporated. The maximum jet velocity is reduced by mixing the fan and turbine flows. Since jet noise generation follows V^8 power law, lowering peak velocities reduces noise. The noise reduction estimates are shown in Table A-XII. To accomplish these noise reductions, improved and 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.

Table A-IV. DC-10-30, GE CF6-50 Engines, Long Duct Mixed Flow Nacelle, Case 1, 70% Mixing Efficiency Minimum Fuel.

MTOGW = 251,748 kg (555,000 lb)
OEW = 121,565 kg (268,000 lb)
Payload = 23,436 kg (151,660 lb)
(252 passengers at 93 kg (205 lb)/passenger
ΔOEW = -74 kg (-163 lb)

International Reserves, 370 km (200 n mi)
alternate
Mach = 0.82
Std. Day

Range/Profile	805 km/11,890 m (500 mi/39,000 ft)			2735 km/10,670-11,890 m (1700 mi/35/39,000 ft)			6275 km/9450/10,670-11,890 m (3900 mi/31/35/39,000 ft)		
Segment	Current Eng. Fuel, kg (lb)/ Time (hr)	LDMF Nacelle Fuel, kg (lb)/ Time (hr)	Δ Fuel (%)	Current Eng. Fuel, kg (lb)/ Time (hr)	LDMF Nacelle Fuel, kg (lb)/ Time (hr)	Δ Fuel (%)	Current Eng. Fuel, kg (lb)/ Time (hr)	LDMF Nacelle Fuel, kg (lb)/ Time (hr)	Δ Fuel (%)
Engine Start & Taxi Out	327 (720 lb)/ 0.150	327 (720 lb)/ 0.150	0.0	345 (760 lb)/ 0.150	345 (760 lb)/ 0.150	0.0	381 (840 lb)/ 0.150	381 (840 lb)/ 0.150	0.0
Takeoff & Accelerate to 610 m (2000 ft)	612 (1,350 lb)/ 0.023	610 (1,344 lb)/ 0.023	-0.4	680 (1,500 lb)/ 0.026	676 (1,491 lb)/ 0.026	-0.6	862 (1,900 lb)/ 0.033	854 (1,883 lb)/ 0.033	-0.9
Long Range Climb	3,536 (7,795 lb)/ 0.243	3,438 (7,580 lb)/ 0.243	-2.8	3,572 (7,874 lb)/ 0.227	3,443 (7,590 lb)/ 0.227	-3.6	4,208 (9,276 lb) 0.255	3,990 (8,797 lb)/ 0.255	-5.2
Cruise	3,865 (8,521 lb)/ 0.619	3,699 (8,155 lb)/ 0.619	-4.3	19,390 (42,747 lb)/ 2.897	18,472 (40,722 lb)/ 2.897	-4.7	51,782 (114,158 lb)/ 6.989	49,131 (108,313 lb)/ 6.989	-5.1
Long Range Descent	660 (1,454 lb)/ 0.307	673 (1,485 lb)/ 0.307	+2.1	661 (1,458 lb)/ 0.308	675 (1,489 lb)/ 0.308	+2.1	662 (1,460 lb)/ 0.310	679 (1,496 lb)/ 0.310	+2.5
Approach & Landing	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0
Taxi In	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0
Block Fuel/Time	9,907 (21,840 lb) 1.509	9,654 (21,284 lb)/ 1.509	-2.5	25,555 (56,340 lb)/ 3.775	24,518 (54,052 lb)/ 3.775	-4.1	58,802 (129,640 lb)/ 7.904	55,942 (123,329 lb)/ 7.904	-4.9
Reserves	8,118 (17,896 lb)/	7,947 (17,521 lb)/	-2.1	9,521 (20,990 lb)/	9,285 (20,470 lb)/	-2.5	12,109 (26,696 lb)/	11,752 (25,908 lb)/	-3.0

Table A-V. DC-10-30, GE CF6-50 Engines, Long Duct Mixed Flow Nacelle, Case 1, 70% Mixing Efficiency Minimum DOC.

MTOGW = 251,748 kg (555,000 lb)
OEW = 121,565 kg (268,000 lb)
Payload = 23,436 kg (51,660 lb)
(252 passengers at 93 kg (205 lb)/passenger)
ΔOEW = -74 kg (-163 lb)

International Reserves, 370 km (200 n mi) alternate
Mach = 0.85
Std Day

Range/Profile	805 km/11,890 m (500 mi/39,000 ft)			2735 km/10,670-11,890 m (1700 mi/35/39,000 ft)			6275 km/9450-10,670-11,890 m (3900 mi/31/35/39,000 ft)		
Segment	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	Δ Fuel (%)	Current Eng. Fuel kg (lb) Time (hr)	LDMF Nacelle Fuel kg (lb) Fuel (hr)	Δ Fuel (%)	Current Eng. Fuel kg (lb) Time (hr)	LDMF Nacelle Fuel kg (lb) Time (hr)	Δ Fuel (%)
Engine Start & Taxi Out	327 (720 lb)/ 0.150	327 (720 lb)/ 0.150	0.0	345 (760 lb)/ 0.150	345 (760 lb)/ 0.150	0.0	381 (840 lb)/ 0.150	381 (840 lb)/ 0.150	0 0
Takeoff & Accelerate to 610 m (2000 ft.)	612 (1,350 lb)/ 0.023	610 (1,344 lb)/ 0.023	-0.4	680 (1,500 lb)/ 0.026	676 (1,491 lb)/ 0.026	-0.6	862 (1,900 lb)/ 0.033	854 (1,883 lb)/ 0.033	-0.9
High Speed Climb	3,769 (8,309 lb)/ 0.250	3,664 (8.078 lb)/ 0.250	-2.8	3,799 (8,375 lb)/ 0.231	3,666 (8.083 lb)/ 0.231	-3.5	4,542 (10,013 lb)/ 0.262	4,303 (9,486 lb)/ 0.262	-5.3
Cruise	3,986 (8,788 lb)/ 0.574	3,814 (8.408 lb)/ 0.574	-4.3	20,520 (45,238 lb)/ 2.767	19,573 (43,151 lb)/ 2.767	-4.6	55,341 (122,004 lb)/ 6.682	52,513 (115,770 lb)/ 6.682	-5.1
High Speed Descent	771 (1,700 lb)/ 0.304	788 (1,736 lb)/ 0.304	+2.1	767 (1,690 lb)/ 0.304	783 (1,727 lb)/ 0.304	+2.2	758 (1,672 lb)/ 0.304	775 (1,709 lb)/ 0.304	+2.2
Approach & Landing	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0
Taxi In	227 (500 lb)/ 0.100	227 (500 lb)/ 0 100	0.0	227 (500 lb)/ 0 100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0
Block Fuel/Time	10,372 (22,867 lb)/ 1.468	10,110 (22,836 lb)/ 1.468	-2.5	27,018 (59,563 lb)/ 3.645	25,950 (57,212 lb)/ 3.645	-3.9	62,791 (138,429 lb)/ 7.598	59,733 (131,688 lb)/ 7.598	-4.9
Reserves	8,181 (18,035 lb)	8,006 (17,650 lb)	-2.1	9,677 (21,334 lb)	9,434 (20,797 lb)	-2.5	12,440 (27,426 lb)	12,064 (26,597 lb)	-3.0

Table A-VI. DC-10-30, GE CF6-50 Engines, Long Duct Mixed Flow Nacelle, Class 2, 80% Mixing Efficiency Minimum Fuel.

MTOGW = 251,748 kg (555,000 lb)
OEW = 125,565 kg (268,000 lb)
Payload = 23,436 kg (51,660 lb)
(252 passengers at 93 kg (205 lb)/passenger)
△OEW = -74 kg (-163 lb)

International Reserves, 370 km (200 n mi.)
alternate
Mach = 0.82
Std. Day

Range/Profile	805 km/11,890 m (500 mi/39,000 ft)			2735 km/10,670-11,890 m (1700 mi/35/39,000 ft)			6275 km/9450-10,670-11,890 m (3900 mi/31/35/39,000 ft)		
Segment	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	△ Fuel (%)	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	△ Fuel (%)	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	△ Fuel (%)
Engine Start & Taxi Out	327 (720 lb)/ 0.150	327 (720 lb)/ 0.150	0.0	345 (760 lb)/ 0.150	345 (760 lb)/ 0.150	0.0	381 (840 lb)/ 0.150	381 (840 lb)/ 0.150	0.0
Takeoff & Accelerate to 610 m (2000 ft.)	612 (1,350 lb)/ 0.023	610 (1,344 lb)/ 0.023	-0.4	680 (1,500 lb)/ 0.026	676 (1,491 lb)/ 0.026	-0.6	862 (1,900 lb)/ 0.033	854 (1,883 lb)/ 0.033	-0.9
Long Range Climb	3,536 (7,795 lb)/ 0.243	3,410 (7,517 lb)/ 0.243	-3.6	3,572 (7,874 lb)/ 0.227	3,414 (7,527 lb)/ 0.227	-4.4	4,208 (9,276 lb)/ 0.255	3,944 (8,694 lb)/ 0.255	-6.3
Cruise	3,865 (8,521 lb)/ 0.619	3,672 (8.096 lb)/ 0.619	-5.0	19,390 (42,747 lb)/ 2.897	18,339 (40,430 lb)/ 2.897	-5.4	51,782 (114,158 lb)/ 6.989	48,701 (107,366 lb)/ 6.989	-5.9
Long Range Descent	659 (1,454 lb)/ 0.307	673 (1.484 lb)/ 0.307	+2.1	661 (1,458 lb)/ 0.308	675 (1,488 lb.)/ 0.308	+2.1	662 (1,460 lb)/ 0.310	678 (1,495 lb)/ 0.310	+2.4
Approach & Landing	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0
Taxi In	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0
Block Fuel/Time	9,906 (21,840 lb)/ 1.509	9,599 (21,161 lb)/ 1.509	-3.1	25,555 (56,340 lb)/ 3.775	24,356 (53,696 lb)/ 3.775	-4.7	58,802 (129,640 lb)/ 7.904	55,465 (122,278 lb)/ 7.904	-5.7
Reserves	8,118 (17,896 lb)	7,898 (17,411 lb)/	-2.7	9,521 (20,990 lb)	9,224 (20,336 lb)	-3.1	12,109 (26,696 lb)	11,673 (25,734 lb)	-3.6

Table A-VII. DC-10-30, GE CF6-50 Engines, Long Duct Mixed Flow Nacelle, Case 2, 80% Mixing Efficiency Minimum DOC.

MTOGW = 251,748 kg (555,000 lb)
OEW = 125,565 kg (268,000 lb)
Payload = 23,436 kg (51,660 lb)
(252 passengers at 93 kg (205 lb)/passenger)
△OEW = -74 kg (-163 lb)

International Reserves, 370 km (200 n mi) alternate
Mach = 0.85
Std Day

Range/Profile	805 km/11,890 m (500 mi/39,000 ft)			2735 km/10,670-11,890 m (1700 mi/35/39,000 ft)			6275 km/9450-10,670-11,890 m (3900 mi/31/35/39,000 ft)		
Segment	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	△ Fuel (%)	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	△ Fuel (%)	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	△ Fuel (%)
Engine Start & Taxi Out	327 (720 lb)/ 0.150	327 (720 lb)/ 0.150	0.0	345 (760 lb)/ 0.150	345 (760 lb)/ 0.150	0.0	381 (840 lb)/ 0.150	381 (840 lb)/ 0.150	0.0
Takeoff & Accelerate to 610 m (2000 ft.)	612 (1,350 lb)/ 0.023	610 (1,344 lb)/ 0.023	-0.4	680 (1,500 lb)/ 0.026	676 (1,491 lb) 0.026	-0.6	862 (1,900 lb)/ 0.033	854 (1,883 lb)/ 0.033	-0.9
High Speed Climb	3,769 (8,309 lb)/ 0.250	3,633 (8,010 lb)/ 0.250	3.6	3,800 (8,375 lb)/ 0.231	3,632 (8,008 lb)/ 0.231	-4.4	4,542 (10,013 lb)/ 0.262	4,252 (9,373 lb)/ 0.262	-6.4
Cruise	3,986 (8,788 lb)/ 0.574	3,786 (8,347 lb)/ 0.574	-5.0	20,520 (45,238 lb)/ 2.767	19,420 (42,814 lb)/ 2.767	-5.4	55,341 (122,004 lb)/ 6.682	52,061 (114,773 lb)/ 6.682	-5.9
High Speed Descent	771 (1,700 lb)/ 0.304	788 (1,737 lb)/ 0.304	+2.2	767 (1,690 lb)/ 0.304	783 (1,727 lb)/ 0.304	+2.2	758 (1,672 lb)/ 0.304	776 (1,710 lb)/ 0.304	+2.3
Approach & Landing	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0
Taxi In	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0
Block Fuel/Time	10,372 (22,867 lb)/ 1.468	10,051 (22,158 lb)/ 1.468	-3.1	27,018 (59,563 lb)/ 3.645	25,763 (56,800 lb)/ 3.645	-4.6	62,791 (138,429 lb)/ 7.598	59,231 (130,579 lb)/ 7.598	-5.7
Reserves	8,181 (18,035 lb)	7,955 (17,538)	-2.8	9,677 (21,334 lb)	9,371 (20,660)	-3.2	12,440 (27,426)	11,982 (26,416)	-3.7

Table A-VIII. DC-10-30, GE CF6-50 Engines, Long Duct Mixed Flow Nacelle, Case 3, 80% Mixing Efficiency With 2% Improvement in Deterioration Minimum Fuel.

MTOGW = 251,748 kg (555,000 lb)
OEW = 125,565 kg (268,000 lb)
Payload = 23,436 kg (51,660 lb)
(252 passengers at 93 kg (205 lb)/ passenger)
ΔOEW = -74 kg (-163 lb)

International Reserves, 370 km (200 n mi) alternate
Mach = 0.82
Std Day

Range/Profile	805 km/11,890 m (500 mi/39,000 ft)			2735 km/10,670-11,890 m (1700 mi/35/39,000 ft)			6275 km/9450-10,670-11,890 m (3900 mi/31/35/39,000 ft)		
Segment	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	Δ Fuel (%)	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	Δ Fuel (%)	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	Δ Fuel (%)
Engine Start & Taxi Out	327 (720 lb)/ 0.150	327 (720 lb)/ 0.150	0.0	345 (760 lb)/ 0.150	345 (760 lb)/ 0.150	0.0	381 (840 lb)/ 0.150	381 (840 lb)/ 0.150	0.0
Takeoff & Accelerate to 610 m (2000 ft.)	612 (1,350 lb)/ 0.023	610 (1,344 lb)/ 0.023	-0.4	680 (1,500 lb)/ 0.026	676 (1,491 lb)/ 0.026	-0.6	862 (1,900 lb)/ 0.033	854 (1,883 lb)/ 0.033	-0.9
Long Range Climb	3,536 (7,795 lb)/ 0.243	3,334 (7,350 lb)/ 0.243	-5.7	3,572 (7,874 lb)/ 0.227	3,324 (7,328 lb)/ 0.227	-6.9	4,208 (9,276 lb)/ 0.255	3,818 (8,416 lb)/ 0.255	-9.3
Cruise	3,865 (8,521 lb)/ 0.619	3,596 (7,928 lb)/ 0.619	-7.0	19,390 (42,747 lb)/ 2.897	17,960 (39,594 lb)/ 2.897	-7.4	51,782 (114,158 lb)/ 6.989	47,546 (104,820 lb)/ 6.989	-8.2
Long Range Descent	660 (1,454 lb)/ 0.307	660 (1,455 lb)/ 0 307	+0.1	661 (1,458 lb)/ 0.308	662 (1,459 lb)/ 0.308	+0.1	662 (1,460 lb)/ 0.310	665 (1,466 lb)/ 0.310	+0.4
Approach & Landing	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0
Taxi In	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0
Block Fuel/Time	9,907 (21,840 lb)/ 1.509	9,434 (20.797 lb)/ 1.509	-4.8	25,555 (56,340 lb)/ 3.775	23,874 (52,632 lb)/ 3.775	-6.6	58,802 (129,640 lb)/ 7.904	54,171 (119,425 lb)/ 7.904	-7 9
Reserves	8,118 (17,896 lb)	7,746 (17,077 lb)	-4.6	9,521 (20,990 lb)	9,045 (19,941 lb)	-5.0	12,109 (26,696 lb)	11,424 (25,186 lb)	-5.7

Table A-IX. DC-10-30, GE CF6-50 Engines, Long Duct Mixed Flow Nacelle, Case 3, 80% Mixing Efficiency With 2% Improvement in Deterioration Minimum DOC.

MTOGW = 251,748 kg (555,000 lb)
OEW = 125,565 kg (268,000 lb)
Payload = 23,436 kg (51,660 lb)
(252 passengers at 93 kg (205 lb)/passenger)
ΔOEW = -74 kg (-163 lb)

International Reserves, 370 km (200 n mi) alternate
Mach = 0.85
Std Day

Range/Profile	805 km/11,890 m (500 mi/39,000 ft)			2735 km/10,670-11,890 m (1700 mi/35/39,000 ft)			6275 km/9450-10,670-11,890 m (3900 mi/31/35/39,000 ft)		
Segment	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	Δ Fuel (%)	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	Δ Fuel (%)	Current Eng. Fuel kg (lb)/ Time (hr)	LDMF Nacelle Fuel kg (lb)/ Time (hr)	Δ Fuel (%)
Engine Start & Taxi Out	327 (720 lb)/ 0.150	327 (720 lb)/ 0.150	0.0	345 (760 lb)/ 0.150	345 (760 lb)/ 0.150	0.0	381 (840 lb)/ 0.150	381 (840 lb)/ 0.150	0.0
Takeoff & Accelerate to 610 m (2000 ft.)	612 (1,350 lb)/ 0.023	610 (1,344 lb)/ 0.023	-0.4	680 (1,500 lb)/ 0.026	676 (1,491 lb)/ 0.026	-0.6	862 (1,900 lb)/ 0.033	854 (1,883 lb)/ 0.033	-0.9
High Speed Climb	3,770 (8,309 lb)/ 0.250	3,552 (7,830 lb)/ 0.250	-5.8	3,799 (8,375 lb)/ 0.231	3,539 (7,803 lb)/ 0.231	-6.8	4,542 (10,013 lb)/ 0.262	4,112 (9,065 lb)/ 0.262	-9.5
Cruise	3,986 (8,788 lb)/ 0.574	3,709 (8,176 lb)/ 0.574	-7.0	20,520 (45,238 lb)/ 2.767	19,008 (41,905 lb)/ 2.767	-7.4	55,341 (122,004 lb)/ 6.682	50,840 (112,082 lb)/ 6.682	-8.1
High Speed Descent	771 (1,700 lb)/ 0.304	772 (1,703 lb)/ 0.304	+0.2	767 (1,690 lb)/ 0.304	768 (1,693 lb)/ 0.304	+0.2	758 (1,672 lb)/ 0.304	761 (1,677 lb)/ 0.304	+0.3
Approach & Landing	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0	680 (1,500 lb)/ 0.067	680 (1,500 lb)/ 0.067	0.0
Taxi In	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0	227 (500 lb)/ 0.100	227 (500 lb)/ 0.100	0.0
Block Fuel/Time	10,373 (22,867 lb)/ 1.468	9,877 (21,773 lb)/ 1.468	-4.8	27,018 (59,563 lb)/ 3.645	25,243 (55,652 lb)/ 3.645	-6.6	62,791 (138,429 lb)/ 7.598	57,855 (127,547 lb)/ 7.598	-7.9
Reserves	8,181 (18,035 lb)	7.802 (17,201 lb)	-4.6	9,677 (21,334 lb)	9,189 (20,257 lb)	-5.0	12,440 (27,426 lb)	11,724 (25,847 lb)	-5.8

Table A-X. Long Duct Mixed Flow Nacelle Block Fuel Saving Summary (DC-10-30, CF6-50 Engines).

	Range (km)	Minimum Fuel Δ Fuel (kg)	(%)	Minimum DOC Δ Fuel (kg)	(%)
Case 1 - 70% Mixing Eff.	805	253	-2.5	262	-2.5
	2735	1037	-4.1	1068	-3.9
	6275	2860	-4.9	3058	-4.9
Case 2 - 80% Mixing Eff.	805	307	-3.1	321	-3.1
	2735	1199	-4.7	1255	-4.6
	6275	3337	-5.7	3560	-5.7
Case 3 - 80% Mixing Eff. plus 2% sfc for Advanced Features	805	473	-4.8	496	-4.8
	2735	1681	-6.6	1775	-6.6
	6275	4631	-7.9	4936	-7.9

Table A-XI. Long Duct Mixed Flow Nacelle, Comparative ROI's (1977 Dollars) - International Operations (DC-10-30, CF6-50 Engines).

Fuel Price (¢/Liter)	Range (km)	MINIMUM FUEL			MINIMUM DOC		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
11	805	4% Payback 11.14 yr	7% Payback 8.85 yr	16% Payback 5.50 yr	5% Payback 10.27 yr	9% Payback 8.18 yr	18% Payback 5.07 yr
	2735	17% Payback 5.29 yr	21% Payback 4.53 yr	31% Payback 3.17 yr	19% Payback 4.95 yr	23% Payback 4.17 yr	34% Payback 2.89 yr
	6275	38% Payback 2.59 yrs	45% Payback 2.20 yr	64% Payback 1.57 yr	43% Payback 2.32 yr	50% Payback 1.98 yr	71% Payback 1.42 yr
15	805	10% Payback 7.74 yr	14% Payback 6 20 yr	25% Payback 3.91 yr	11% Payback 7.15 yr	15% Payback 5.75 yr	27% Payback 3.61 yr
	2735	26% Payback 3.77 yr	30% Payback 3.24 yr	44% Payback 2.28 yr	28% Payback 3.53 yr	33% Payback 2.98 yr	48% Payback 2.08 yr
	6275	54% Payback 1.86 yr	63% Payback 1.59 yr	88% Payback 1.14 yr	60% Payback 1.67 yr	70% Payback 1.43 yr	98% Payback 1.02 yr
19	805	15% Payback 5.93 yr	19% Payback 4.77 yr	33% Payback 3.03 yr	16% Payback 5.49 yr	21% Payback 4.43 yr	35% Payback 2.80 yr
	2735	34% Payback 2.93 yr	39% Payback 2.52 yr	56% Payback 1.78 yr	36% Payback 2.74 yr	43% Payback 2.32 yr	62% Payback 1.62 yr
	6275	69% Payback 1.45 yr	81% Payback 1.24 yr	113% Payback 0.89 yr	77% Payback 1.30 yr	90% Payback 1.12 yr	125% Payback 0.80 yr

NOTES:

Case 1) 70% Mixing Efficiency
Case 2) 80% Mixing Efficiency
Case 3) 80% Mixing Efficiency plus 2% sfc
for Advanced Features

Table A-XII. Estimated Noise Reduction (ΔEPNdB) for Long Duct Nacelle with Mixer Nozzle and Bulk Treatment in the Inlet at Maximum Certified Gross Weight.

TOGW = 267,624 kg LGW = 197,770 kg

Airplane Configuration	Takeoff	Sideline	Approach @ Max Flaps
DC-10-30/CF6-50C	3 - 4	3 - 4	2 - 3

a. Inlet Noise

For inlet radiated fan noise, "bulk absorber material" is used in the nose cowl because of its superior ability to absorb high frequency turbomachinery noise. Bulk-material refers to a felt batting material installed behind the porous perforated face sheet in place of air-filled cavities.

b. Fan Discharge Noise

For noise radiated from the fan discharge ducts, there are two noise reduction concepts. The first is straightening of the fan exit guide vanes. The second is increasing the area acoustically treated. The most appropriate lining design for this increased area is a perforated face sheet made from advanced fibers bonded to a composite and a honeycomb core with appropriate provisions for drainage.

c. 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. Moreover, the current corrugated core design would be changed to a honeycomb core design to gain additional treated area if high temperature titanium can be milled to foil thicknesses. This is because the corrugations block almost half the holes in the perforated face sheet. Turbine treatment was incorporated on the wall of the centerbody and the wall of the mixed flow nozzle downstream of the exit plane of the mixer.

4. Weights

After selecting the materials and construction of the Long Duct Mixed Flow Nacelle, a weight estimation was made for the total 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 weight are compared in Tables A-XIII and A-XIV. As shown in the tables, the Long Duct Mixed Flow Nacelle with composites in approximately 8 percent lighter than current pods with turbine reversers. This leaves an 363 kg cushion which will absorb any changes between preliminary and final design. The weights show from a later design study to be considerably less than those that were input into the DC-10-30 airplane performance computer program to calculate fuel savings. As a result, the fuel savings presented in Tables A-IV through A-X are conservative.

Table A-XIII. Douglas Nacelle Weight Comparison CF6-50 Engine Buildup (EBU) of 359 kg and Engine not Included.

	Current Nacelle with Turbine Reversers (kg)	Long Duct Mixed Flow with Composites (kg)	% Changes 1)
Wing	1467	1342	-8.71
Tail	1282	1181	-7.89
Total A/C	4216	3865	-8.46

1) Percent change with respect to current pods with turbine reversers.

5. Material Selection and Installation Design

a. Material Selection

To be able to incorporate the Long Duct Mixed Flow Nacelle 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 50 percent graphite (Thornel 300, Fibrite) and 50 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 275 grams per square yard. 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 need for 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. The Kevlar and graphite are used in a biwoven hybrid and the weak characteristics of one material are compensated for by the strength of the other material.

Table A-XIV. Douglas Nacelle Weight Comparisons, CF6-50 Engine Build-Up (EBU) of 359 kg and Engine Not Included.

Component	Current Pod With Turbine Reversers (kg)		Long Duct Mixed Flow With Composites (kg)	
	Wing	Tail	Wing	Tail
Nose Cowl	280	---	253	---
Fan Cowl Doors	127	163	106	140
Fan Reverser	828	838	764	773
Outer Core Cowl Doors	---	---	71	71
Turbine Reversers	232	232	---	---
Mixer & Bullet	---	---	99	99
Mixed Nozzle	---	---	49	49
Bellmouth	---	49	---	49
Total	1467	1282	1342	1181
Total A/C	4216		3865	

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 layup time and labor costs. This cost savings outweighs the weight increase caused by using the heavier fabric.

A polyimide resin (matrix) system is used in the composite face skins. The polyimide resin has not had as an extensive testing program in industry as epoxy resin and will require development. Several advantages make this development worthwhile. An increase in impact resistance occurs when a polyimide resin is substituted for an epoxy resin in the use of composite panels. Polyimide resin also has a higher service temperature (232° C) than that of an epoxy (177° C) and better fire resistance than epoxy resins.

The core material chosen is a nylon phenolic or Nomex* honeycomb. This material is used in all areas except in the inner barrel of the inlet. The cell size and core thickness vary 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 corrosion with graphite fibers and the vulnerability to secondary lightining 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 A-7. The Federal Aviation Administration (FAA) requires that any material in a fire zone be able to withstand 1093° C for 15 minutes. To meet this requirement, tests conducted by Douglas show proper selection of materials and construction will provide the necessary fire resistance.

b. Installation Design

The construction used in the Long Duct Mixed Flow Nacelle is described in this section. The location of each component is shown in Figure A-8 for an engine installation in the wing position. The construction of the tail nacelle is similar to that of the wing.

Nose Cowl

The inlet of the current baseline design has three inner barrel 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. The nose cowl is attached to the engine by a series of 22 attachments on the inner barrel.

In order to reduce weight, several sections of the nose cowl were changed to composites. The antiicing lip assembly and the titanium bulkheads

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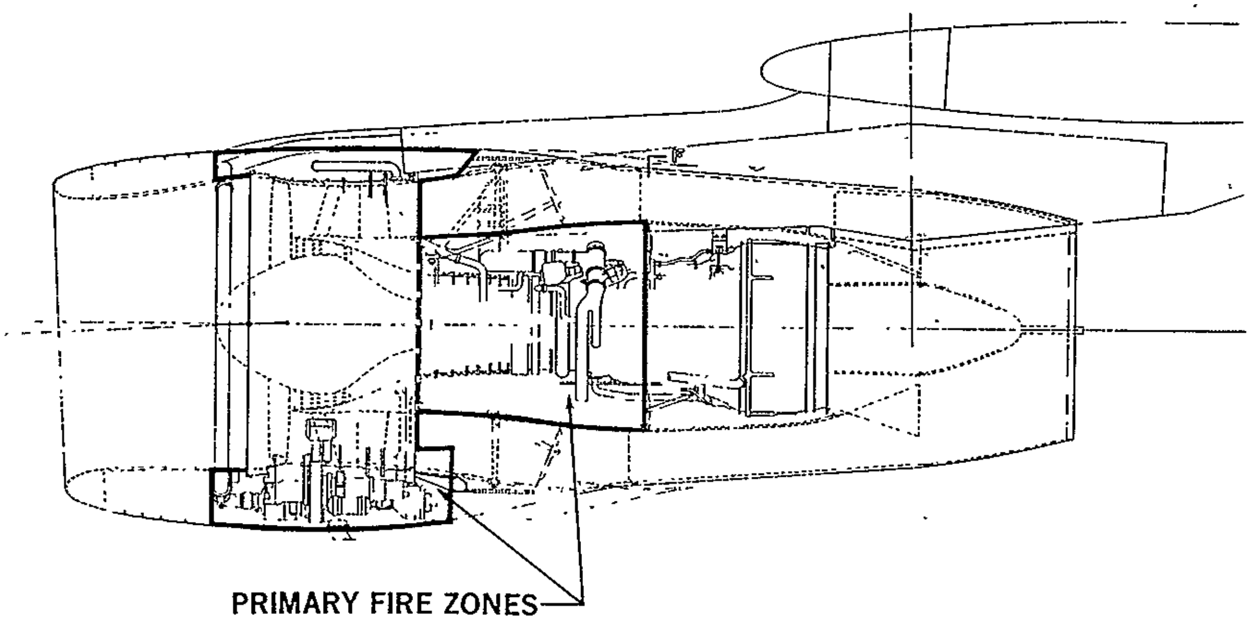
*Nomex is DuPont's trademark for nylon phenolic honeycomb.



- FIRE ZONES REQUIRE 2000°F, 15-MINUTE FIRE CONTAINMENT CAPABILITY

Figure A-7. Nacelle Advanced Composites Fire Resistance Requirement - Douglas Study.

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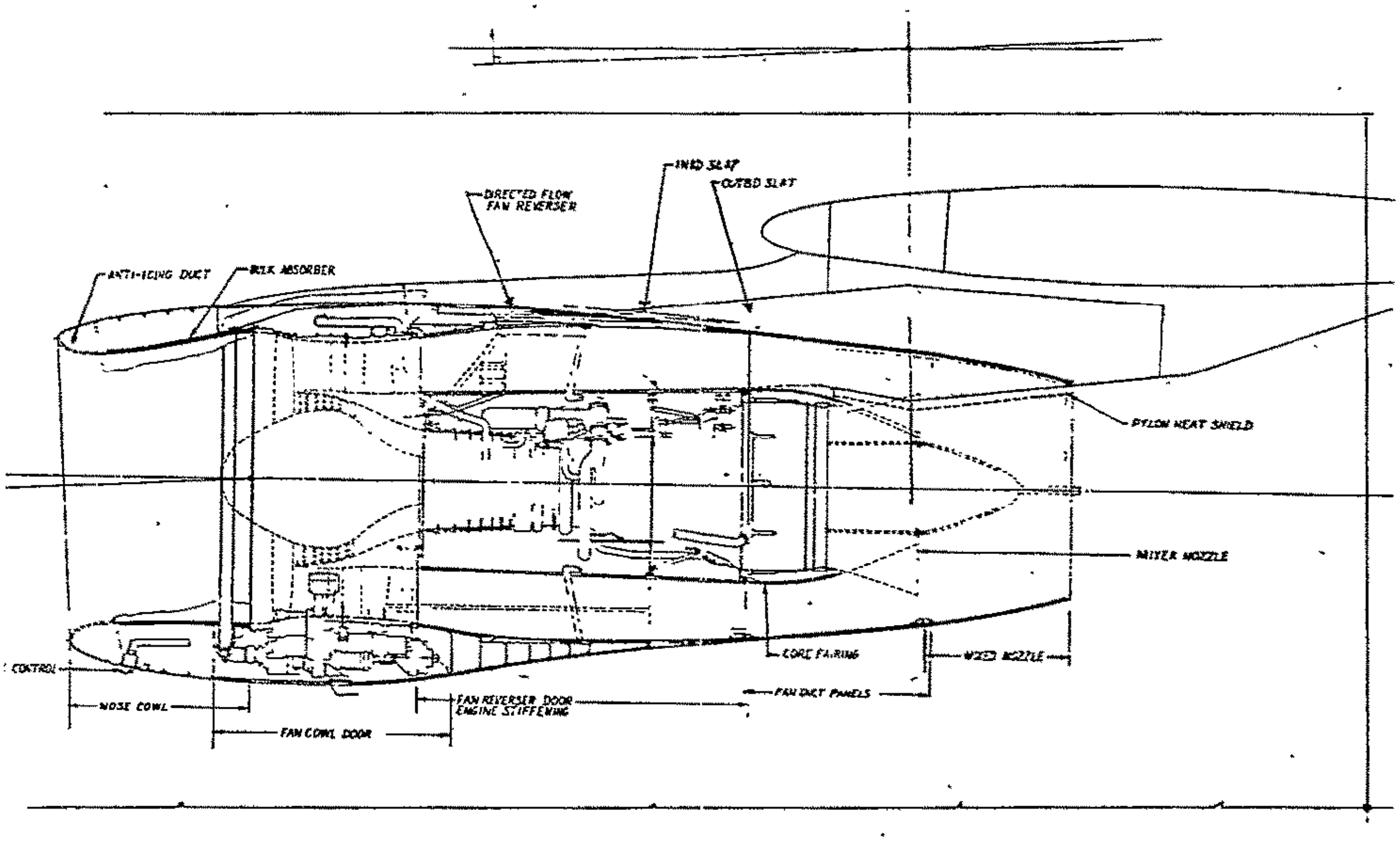

Figure A-8. Long Duct Mixed Flow Nacelle - DC-10 CF6-50 Engine.

were not changed due to the high temperature environment in this area. The inlet inner barrel was changed to a composite design incorporating an acoustical bulk absorber. The outer skin was changed from aluminum skin and stringer design to a similar composite design. A continuous engine attach flange replaced the individual fittings to improve the load distribution.

The construction of the inner barrel is shown in Figure A-9. The inlet barrel is divided into three panels. Each panel is similar in design but not identical. The panels are of integrally woven or sewn design. The face skins are of Kevlar and the webs are of fiber glass. The use of the Kevlar face skins provides for excellent impact resistance to enable maintenance personnel to walk in the inlet. The fiber glass is chosen for the structural webs over a lighter graphite fiber because of its ability to be woven on industrial looms. The fiber glass also has good compressive strength. The integrally woven or sewn panel is cocured with three plies of biwoven graphite fabric. The additional impervious fabric serves as a pressure barrier while the woven structure facilitate acoustic requirements. To increase the acoustical characteristics of the panel a bulk absorber was placed in the upper panels. This may be Kevlar rope, fiber glass batting or Scotfelt.

To manufacture the inner barrel panels, the following steps are required:

1) The panel is integrally woven on an industrial loom.
2) Rubber mandrels are then fed through the unimpregnated fabric.
3) The entire panel is impregnated with a polyimide resin and cocured with the graphite fabric.
4) When cured, the mandrels are removed and replaced with Kevlar rope.

The use of composites in the inner barrel necessitates a continuous engine attach flange. The continuous flange distributes loads evenly into the composite panels. If the loads are not evenly distributed, the composite panels would have to be strengthened to handle point loads.

The outer aerodynamic surface or outer barrel of the nose cowl is made of seven plies of graphite/Kevlar hybrid fabric strengthened by graphite stringers. The structure is broken down into three similar, but not identical panels. This construction can be seen in Figure A-10. 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 fitted 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.

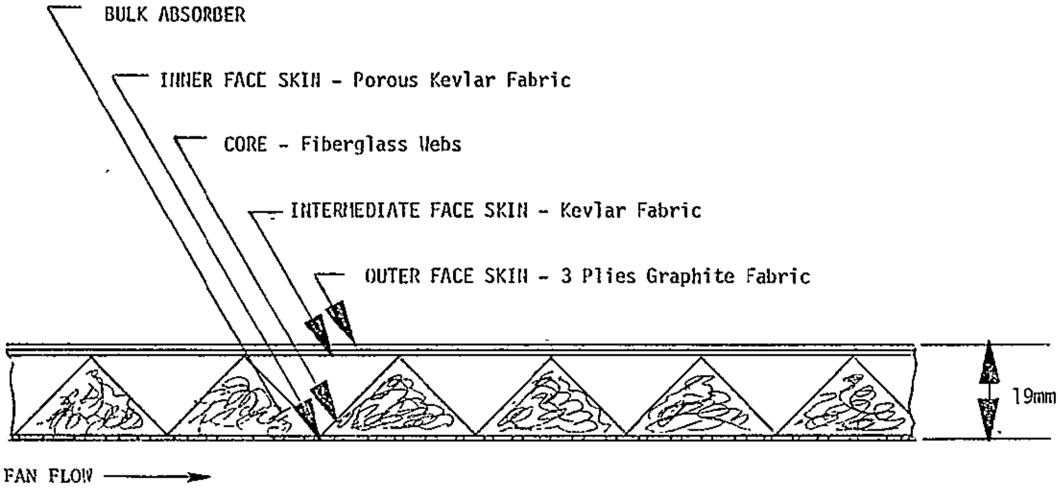

Figure A-9. Nose Cowl, Inner Barrel Construction.

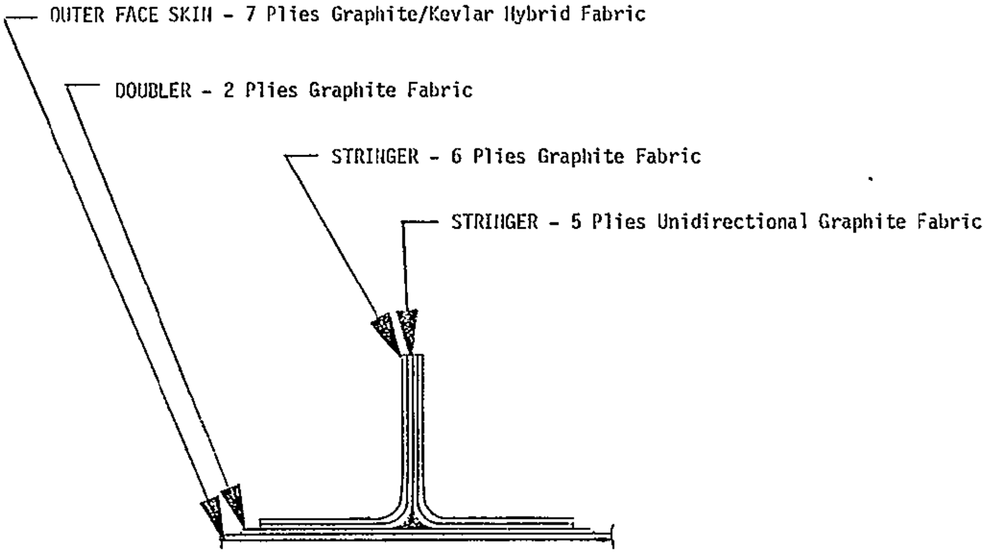

Figure A-10. Nose Cowl, Outer Barrel Construction.

Fan Cowl Door

The fan cowl door, shown in Figure A-8, is designed to provide access to the engine accessories. There are two doors per nacelle. The doors are similar but not identical. The doors are currently made of bonded aluminum honeycomb sandwich construction. 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 and two duct installations. The left-hand door has two duct installations, an access door, and a pressure relief door. Each door has incorporated two hold-open rods for support during maintenance operations.

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 saving of approximately 17 percent was accomplished. The outer face skin, made of graphite/Kevlar 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 A-11. This construction is similar for both right and left-handed doors. The outer face skin of the door is composed of two plies of graphite/Kevlar hybrid fabric. The core consists of a Nomex-honeycomb material. The core is approximately 25 mm thick and has a cell size of 5 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.

Fan Reverser

The directed flow case stiffened fan reverser, shown in Figure A-8, is designed to provide reverse thrust during the landing roll. The cascades and blocker doors are designed to provide flow directed primarily forward and upward. The reverser's length is extended to help carry the loads of the engine case. Composite materials were used to minimize the weight of the fan reverser.

The basic construction of the inner barrel wall is shown in Figure A-12. 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

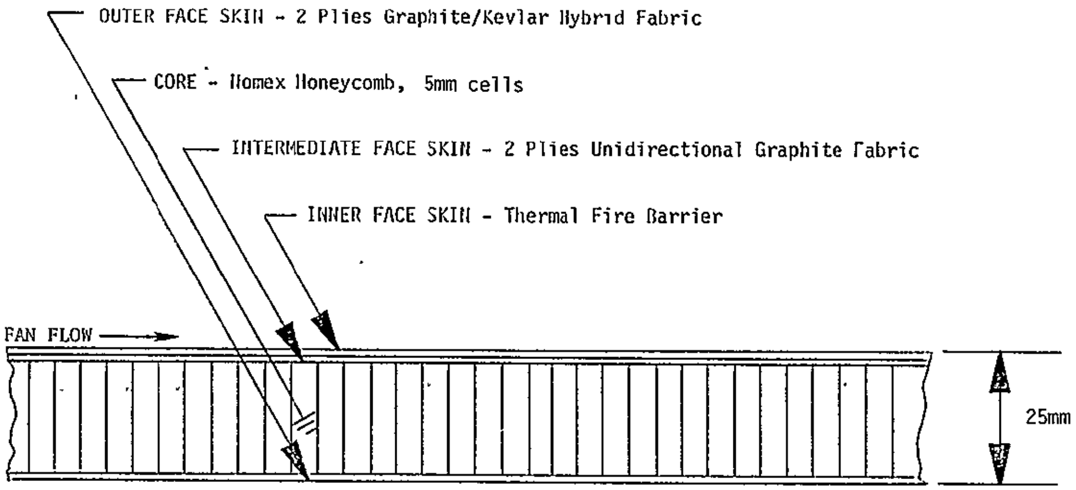

Figure A-11. Fan Cowl Door Construction.

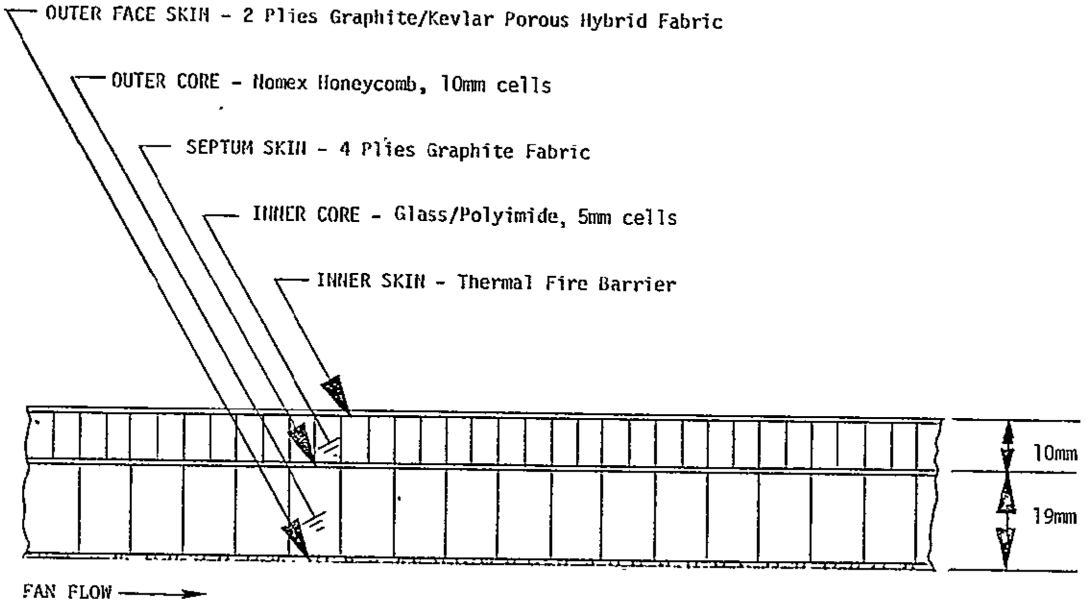

Figure A-12. Fan Reverser, Inner Barrel Construction.

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 A-7). 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 A-13. 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.

Aft Fan Duct

The aft fan duct has been designed with a lightweight composite honeycomb construction. The duct enables incorporation of additional sound absorbing surface. The aft fan duct panels are located as shown in Figure A-8. There are two similar but not identical panels per nacelle. The panels are designed to withstand the hoop tension loads created by the pressure differential between fan air and ambient air. They also transfer the nozzle loads forward to the fan reverser.

The composite honeycomb construction of the aft fan duct panels is shown in Figure A-14. The outer face skin is composed of three plies of graphite/Kevlar hybrid fabric. The inner face skin is two plies of graphite/Kevlar porous hybrid fabric. The inner skin will be porous to provide for acoustic treatment. The selection of the graphite/Kevlar fabric was chosen for commonality with the outer face skin. The only difference between the face skins is that the inner skin will be a style of high porosity where the outer will be an impervious style. The core is made up of 10 mm Nomex honeycomb which is required for acoustic treatment. The selection of this core is to eliminate a corrosion problem which is common with an aluminum core and a porous face skin. The Nomex core has very little deterioration when exposed to environmental conditions present in the nacelle. The core also has excellent shear load characteristics needed to facilitate the hoop tension loads present in the area.

A titanium frame is designed to cover the perimeter of each aft fan duct panel. The frame serves as a device to distribute loads uniformly onto the composite panels. The frame also increases the rigidity of the duct. A primary reason for selecting titanium rather than the lighter aluminum is for its compatibility with composite materials in a co-curing manufacturing process.

Core Fairing

The core fairing is located as shown in Figure A-8. Its purpose is to provide an aerodynamic surface for fan air. The basic construction is shown in Figure A-15. The outer face skin is perforated titanium

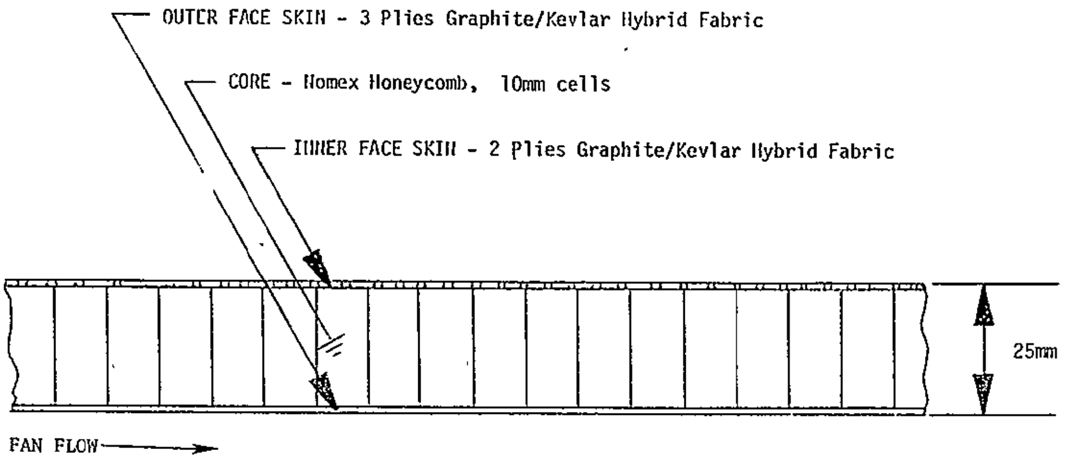

Figure A-13. Fan Reverser, Outer Barrel and Blocker Door Construction.

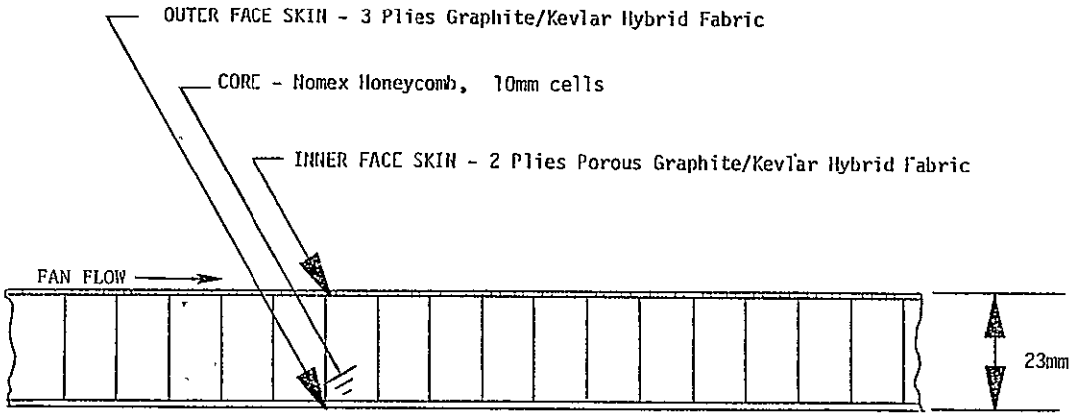

Figure A-14. Aft Fan Duct Panel Construction.

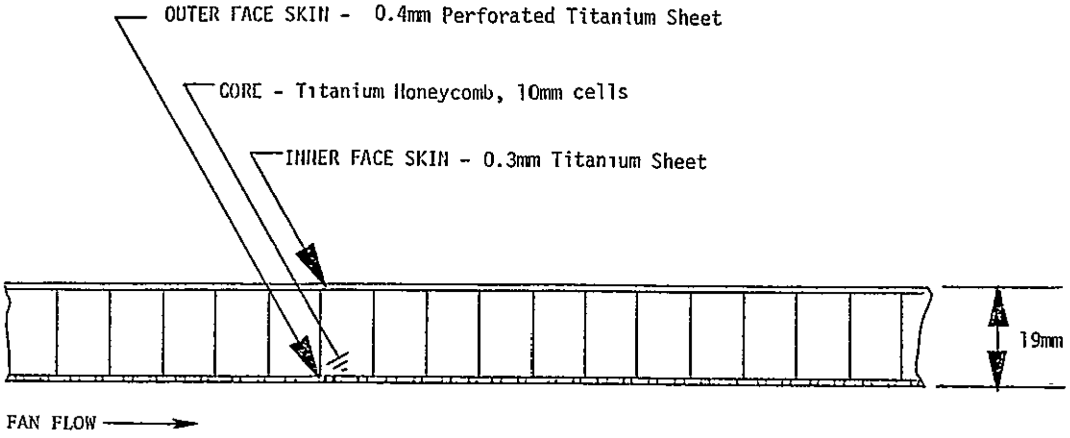

Figure A-15. Core Fairing Construction.

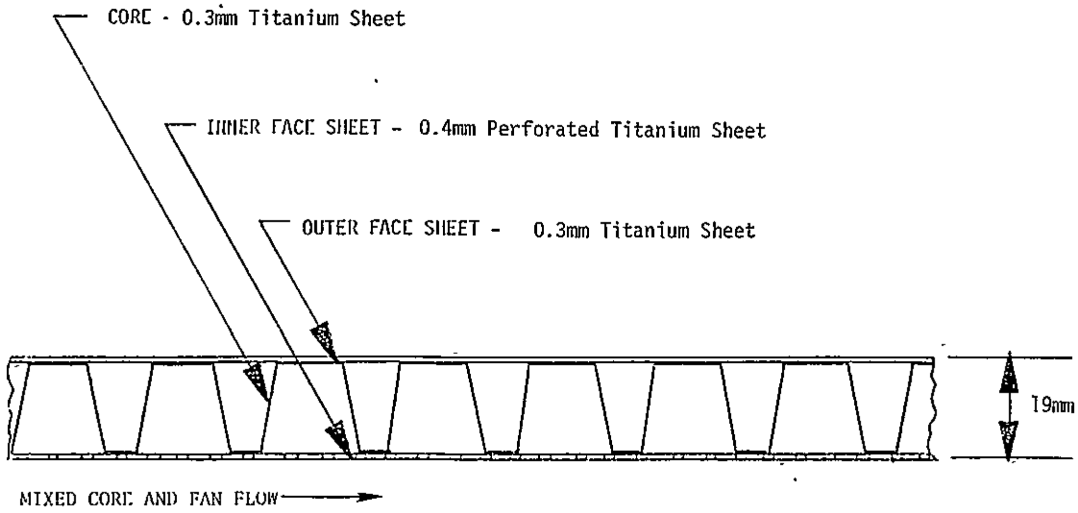

Figure A-16. Mixed Nozzle Construction.

(Ti-6Al-4VA, 315° C Max) sheet. The inner face skin is similar to the outer, but not perforated. The core is a titanium honeycomb with 10 mm cells and 19 mm deep. It is expected that the temperature in the compartment will not exceed 315° C.

Mixed Nozzle

The mixed nozzle directs the flow created by the mixing of fan and turbine air as shown in Figure A-8. The shape of the duct produces aerodynamic loads which are transferred to the front engine mount through the keep members in the aft fan duct and fan reverser. The nozzle is a single piece which is bolted to the pylon. The panel has a perforated inner face skin to provide for acoustic treatment of turbine noise. 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 (540° 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 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 may not be known until full scale tests are conducted.

The basic construction of the mixed nozzle is shown in Figure A-16. The inner perforated titanium face skin has a thickness of 0.4 mm. The outer impervious titanium face skin has a thickness of 0.3 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 0.3 mm. This eliminates the possibility of using a honeycomb design becuase of its nominal gage thickness of 0.08 mm. The design developed was a continuous trapezoidal hat section. The wall thickness is 0.3 mm. The skins and the core will be brazed together in the sandwich construction.

D. References

1. K.E. Nordstrom, A.H. March, and D.F. Sargisson, "Conceptual Design Study of Advanced Acoustic - Composite Nacelles," NASA CR-132702, July 1975.

2. R.T. Kawai, "Advanced Integration Technology to Improve Installed Propulsion Efficiency," AIAA Paper No. 76-665, presented at AIAA/SAE 12th Propulsion Conference, Palo Alto, California, July 26-29, 1976.

V. BOEING STUDY

A. Design Description

The Long Duct Mixed Flow Nacelle (LDMF) concept requires extensive modifications to existing hardware. However, in order to best understand the comparison of the Long Duct Mixed Flow 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.

Figure A-17 provides the basic layout of a long duct nacelle with improved sfc obtained by forced mixing of the primary and fan exhaust streams. The base nacelle for comparison is the current CF6-50 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° boattail 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 are 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.

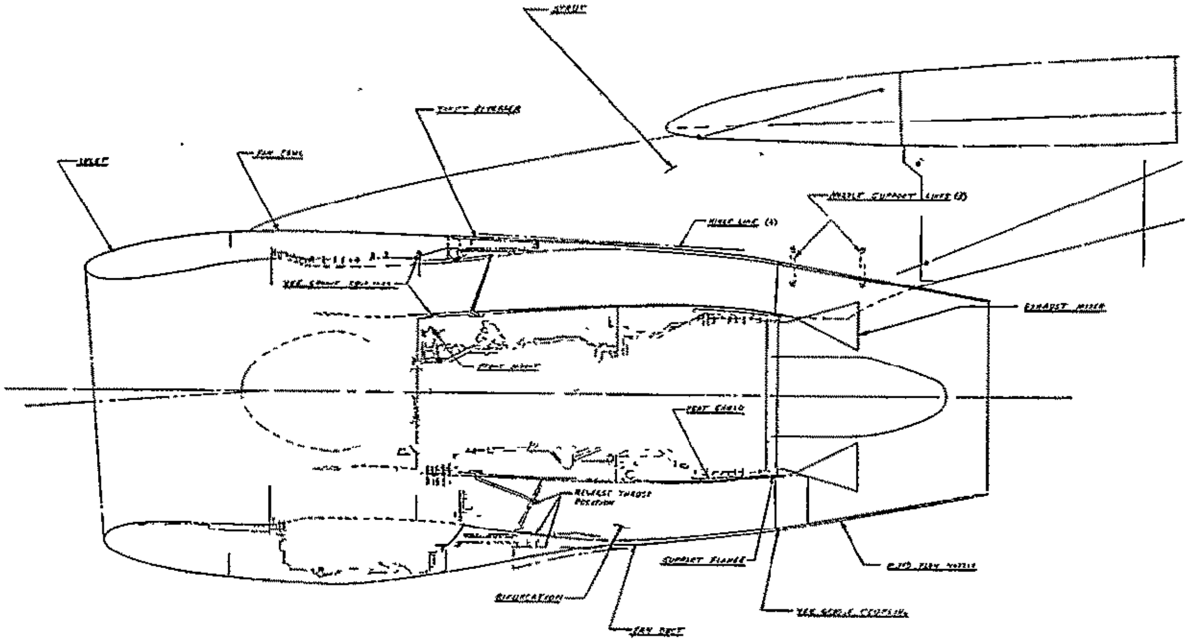

Figure A-17. CF6-50 LDMF Nacelle 747 Inboard Installation Performance Improvement Study.

Contours are as shown in Figure A-18. 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 A-19.

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 is the same as the existing CF6-50 reverser, 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. In the reverse thrust mode when the fan air is not being mixed with the exhaust gas, the allowable temperature is 538° C 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 A-17 indicates the installation of 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 CF6-50E/747-200B installations, and the current strut stiffness was assumed to be applicable.

Weights - Weight estimates are provided for two 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. As Table A-XV shows, the advanced structure design reduces the weight penalty for incorporating a forced mixer from 3700 kg per airplane to 1548 kg per airplane.

The weight shown for the advanced structure design is based on the incorporation of several design features involving a high technical risk.

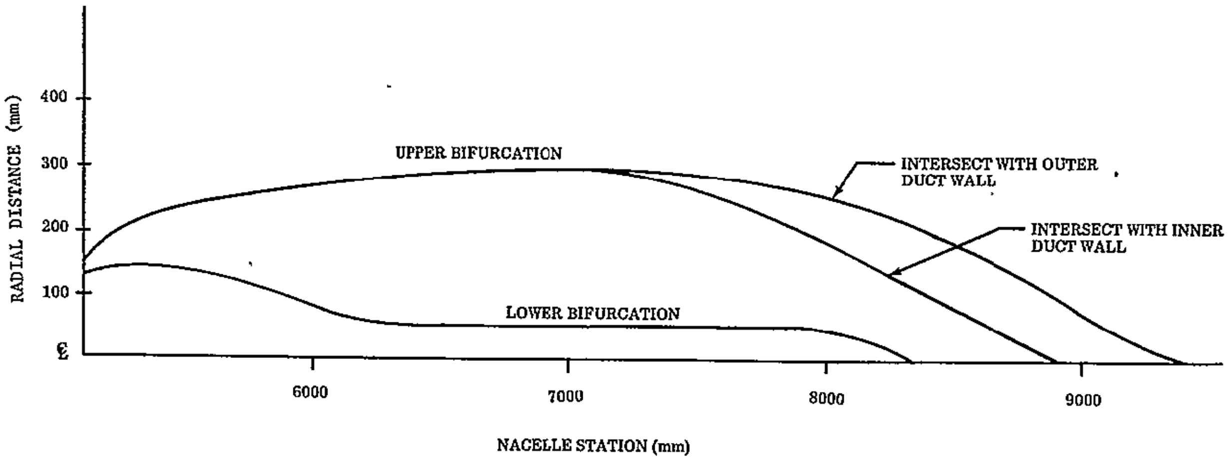

Figure A-18. Boeing CF6-50 LDMF Nacelle - Fan Duct Bifurcation.

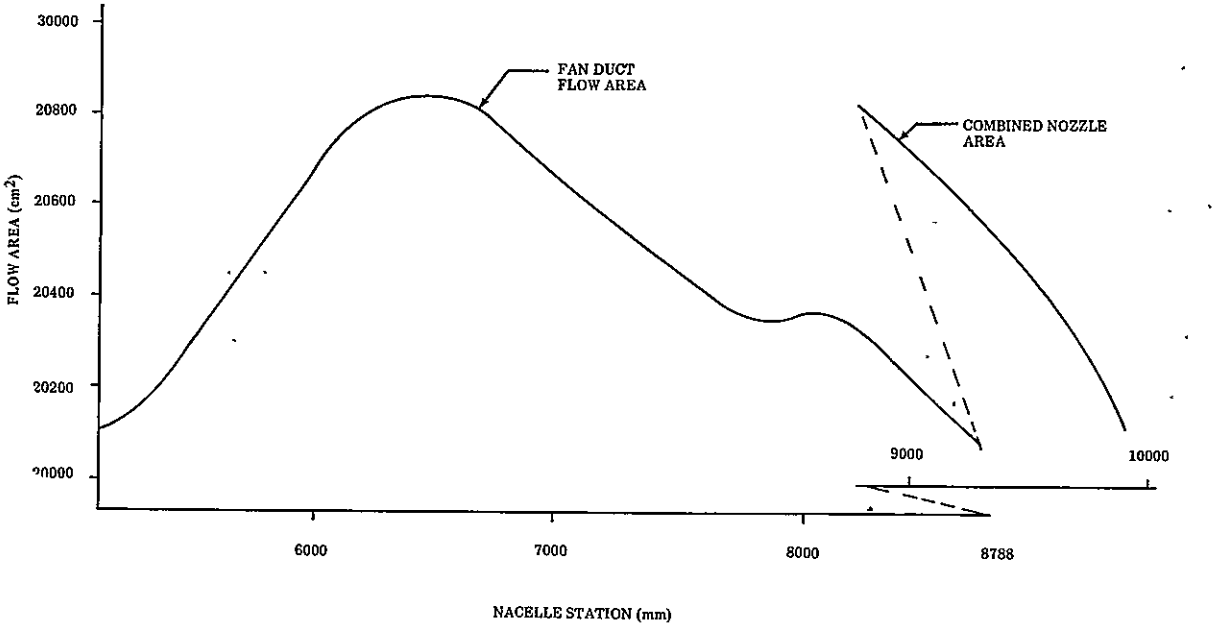

Figure A-19. Boeing CF6-50 LDMF Fan Flow Area.

Table A-XV. Boeing Weight Estimate - CF6-50 Mixed Flow Nacelle.

COMPONENTS	BASELINE CF6-50 747	ADVANCED STRUCTURE MIXED FLOW NACELLE	CONVENTIONAL MIXED FLOW NACELLE
	kg	kg	kg
Inlet	329	329	329
Fan Cowl	152	152	152
Fan Duct & Thrust Rev.	736	978	1188
Exhaust Nozzle	102	116	363
Plug	23	37	37
Mixer	0	147	147
Core Cowl	80	0	0
Strut ΔWt	BASE	+ 50	+ 86
TOTAL	1422	1809	2302
TOTAL ΔWT PER ENGINE FOR NACELLE, STRUT & T/R	BASE	+387	+880
WING ΔWT PER AIRPLANE	BASE	+ 0	+180
TOTAL ΔWT/AIRPLANE FOR MIXED FLOW	BASE	+1548	+3700

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, 12.7 mm 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 CF6-50/747 engines. Analysis and testing are required to confirm this.
- It was 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 (+1548 kg per airplane) and the conventional nacelle (+3700 kg per airplane).

Propulsion System Performance - The sfc improvement estimate provided by General Electric for the maximum cruise condition was verified using the mixed flow cycle assumptions shown in Figure A-20. While the mixer effectiveness is a little higher than Boeing's model test experience indicates, it is within the Boeing data scatter band and was, therefore, used unchanged. The Long Duct Mixed Flow Nacelle design eliminates core cowl scrubbing drag and substitutes a duct pressure loss. This elimination of scrubbing drag was converted to a sfc benefit. The sfc improvement versus uninstalled net thrust provided by General Electric for the 0.85 MN/10,668 m cruise condition was corrected for the elimination of scrubbing drag and is presented as Figure A-20. These curve values along with the corrected percent sfc for the takeoff, climb, and hold conditions shown in Table A-XVI were used to calculate the block fuel savings.

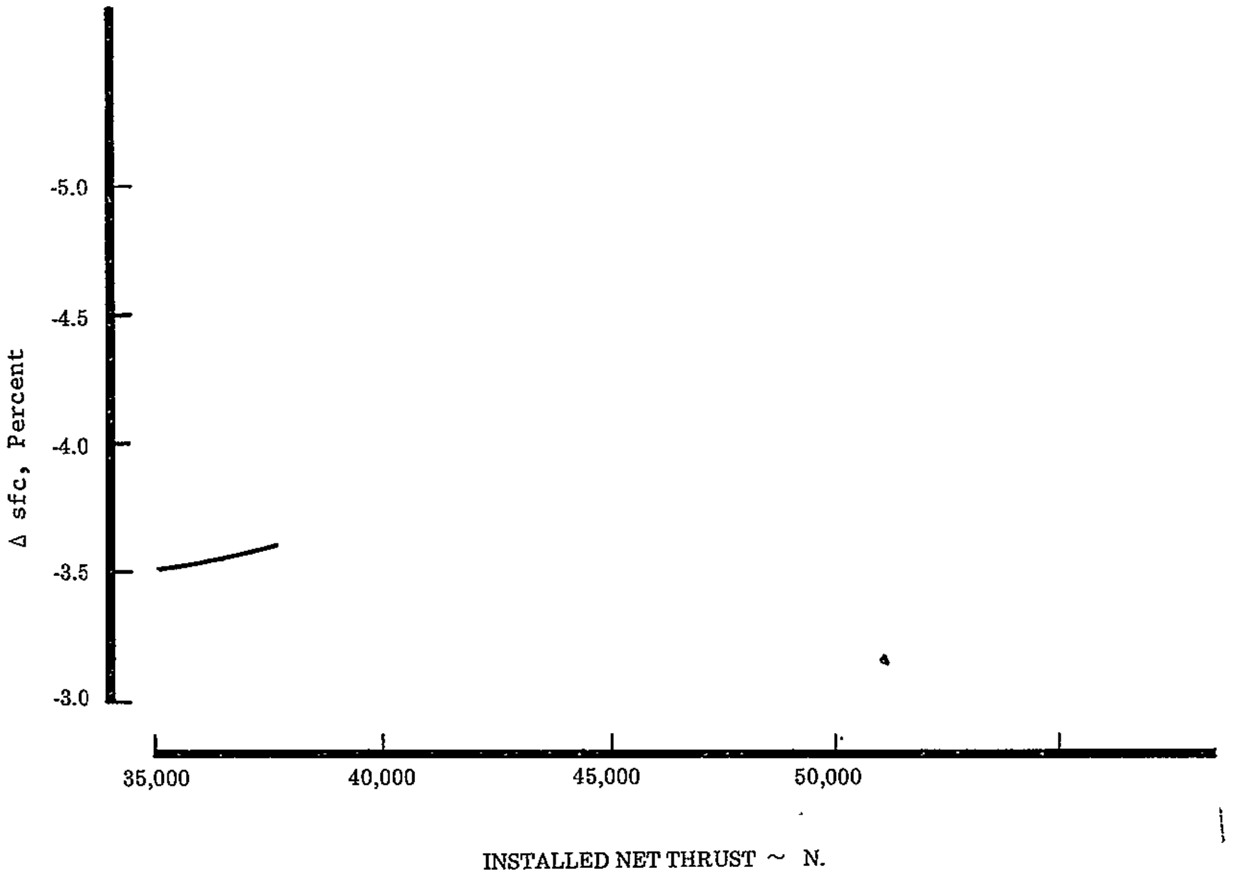

Figure A-20. Boeing CF6-50 SFC Improvement Mixed Flow vs. Separate Flow (0.85 MN/10,668 M).

Table A-XVI. Technical Analysis Results, Long Duct Mixed Flow Nacelle (CF6-50).

Engine Performance Data

Power Setting	Flight Condition	Δ% SFC
Takeoff	Sea Level Static	-2.0
Takeoff	0.250 Mn/0 Alt.	-2.4
Climb	0.800 Mn/7620 m	-4.5
Cruise, Fn = 36,000/40,000 N	0.850 Mn/10,668 m	-3.5
Max Cruise	0.850 Mn/10,668 m/+10^{o}C	-4.1
Cruise, Fn = 31,000 N	0.700 Mn/7620 m	-1.0
Hold, Fn = 29,000 N	0.325 Mn/457 m	0

	Conventional Design Nacelle	Advanced Structure Nacelle
Operating Weight Empty Change	+3700 kg	+1548 kg
Airplane Performance Changes		
Range (Max TOGW)	-72 km	+129 km
Payload (On Limited Routes)	-748 kg, or -8 pass.	+1429 kg, or +15 pass.
Block Fuel 770 km	-132 kg (-1.2%)	-209 kg (-1.8%)
3460 km	-513 kg (-1.3%)	-880 kg (-2.1%)
6195 km	-1120 kg (-1.5%)	-1801 kg (-2.4%)
Field Performance (ΔTOGW, Constant Field)		
Acceleration Limited	-91 kg	-91 kg
Climb Limited	-998 kg	-998 kg
Enroute Climb Performance (ΔGW, Const. Alt.)	-2631 kg	-2631 kg

Noise Takeoff; -2 EPNdB: Sideline; -2.3 EPNdB: Cutback; -0.5 EPNdB: Approach; 0 EPNdB

	Conventional Design Nacelle	Advanced Structure Nacelle
Maintenance Cost	0	0
Investment Spares Ratio	0	0
Airplane Price Change	+$860,000	+$860,000

Aerodynamics - The increase in wetted area and its associated roughness due to the nacelle extension to accommodate the mixer results in a 1.5 percent increase in friction and excrescence drag. Interference drag was assumed to be the same as the current CF6-50 installation.

Noise - It was assumed that there would be no change in the engine noise treatment associated with the addition of the mixer, and that only jet component noise reductions would affect the total airplane noise. Estimates were made for takeoff, cutback and approach power settings. Exhaust gas conditions of the baseline and mixed flow versions of the CF6-50 were used for determining the jet component noise reductions listed below:

Takeoff	-3 EPNdB
Sideline	-3 EPNdB
Cutback	-2 EPNdB
Approach	-0 EPNdB

Engine component noise levels derived from 747/CF6-50 flight test data were used together with the reduced jet noise components to estimate the total airplane noise reduction relative to the baseline. Estimates of total airplane noise reductions due to the addition of the mixer are:

Takeoff	-2	EPNdB
Sideline	-2.3	EPNdB
Cutback	-0.5	EPNdB
Approach	-0	EPNdB

B. Technical Analysis Results

The incremental changes in drag, weight and sfc were applied to the baseline airplane and analyzed over the mission profile.

The mission analysis provided the block fuel changes shown in Table A-XVI. The conventional nacelle design with its 3700 kg operating empty weight increase showed a block fuel savings of slightly over 1 percent, but it causes a reduction of 748 kg in payload and 72 km in range capability. The 1548 kg operating empty weight increase of the advanced structure design results in approximately twice the level of fuel savings as the conventional design and provides a 129 km range increase at maximum takeoff gross weight or a 1429 kg payload increase on weight limited routes. While this advanced structure design shows some potentially significant performance improvements, there are several design features that have a high technical risk and would need a more detailed investigation before they can be substituted.

C. Economic Analysis Results

The economic analysis results for the median range (3460 km) and mid. fuel price (12 cents/liter) are shown below:

B-747-200	Payback (Year)	ROI (%)
Advanced Structure	10.4	5
Conventional Structure	20.0	-3

D. Recommendations

The successful application of a forced mixer on the CF6-50/747-200B 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 percent 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 percent 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 percent 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. As illustrated by a comparison of the results of the advanced structure and conventional nacelle designs in Table A-XVI, 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 is dependent upon 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 Long Duct Mixed Flow 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 are required to validate this assumption. If changes in placement are required, additional investigations of wing strength and flutter will also be required.

APPENDIX B

DIGITAL ELECTRONICS CONTROLS STUDY

I. INTRODUCTION AND SUMMARY

A. Introduction

Digital controls were studied with regard to potential aircraft fuel savings. Because of their later service introduction date, it was decided to prepare a technical recommendation report for follow-on programs instead of proceeding with detail screening and an economic analysis. General Electric and Boeing's recommendations are presented in this report.

B. Summary

This report presents technical recommendations by General Electric and Boeing regarding digital electronic controls. The General Electric study describes the related experience and background and recommends a development program. The Boeing study analyzes the potential performance benefits of digital controls and proposes study items for follow-on programs. Finally, General Electric comments on Boeing's recommendations are presented.

II. GENERAL ELECTRIC DIGITAL CONTROLS

A. Background

During the past seven years, the General Electric Aircraft Engine Group has conducted an aggressive program to develop digital controls for future engine applications. Laboratory breadboard development, circuit design, and bench and environmental tests have been conducted. The resulting digital controls have been applied as the control systems of the ATEGG series of demonstrator engines. Corporate laboratories of General Electric, as well as aerospace electronic departments, have been utilized by the Aircraft Engine Group to aid in building a digital control capability upon an extensive production and application experience with on-engine analog electronic controls.

On-engine, air-cooled, full authority digital control systems have been constructed and successfully engine tested by General Electric for the GE/NASA Quiet Clean Short Haul Experimental Engine (QCSEE). These controls feature low noise automatic power management modes, very fast engine thrust increase for STOL operation, and a failure indication and corrective action strategy which automatically synthesizes a lost sensor signal for continued uninterrupted engine operation. The QCSEE digital engine control is shown in Figure B-1. It is made up of medium scale integrated (MSI) circuits in potted modules.

Currently, the GE/Navy Full Authority Digital Electronic Control (FADEC) is being designed and constructed for application on the J101-VCE and GE23 JTDE variable cycle engines. Sea level and altitude cell operation of an F404 supersonic turbofan engine is also anticipated. FADEC features the multivariable digital control of the very high order variable cycle engine. A mockup of the on-engine, fuel-cooled FADEC is shown on Figure B-2. FADEC construction is large scale integrated (LSI) circuits on hybrid alumia multilayer boards.

General Electric is also participating (with Systems Controls, Inc. as cocontractor) in the USAF Multivariable Control Program to assure that the best of modern control theories are applied in the programming of the FADEC control.

B. Development Program

A 24-month program of digital control design, construction, and test is recommended to lead to in-flight demonstration. A digital control, drawing upon General Electric QCSEE, FADEC, and EEE programs, would be constructed for the CF6. It would provide control of fuel flow, variable stator vanes, and variable bleed valves. Automatic power management modes emphasizing low fuel consumption in cruise and long engine life during takeoff and climb would be included. Digital multiplexed data to and from the aircraft would be included and integrated with the airframe format chosen. Thus, both thrust level and

Figure B-1. QCSEE Digital Engine Control.

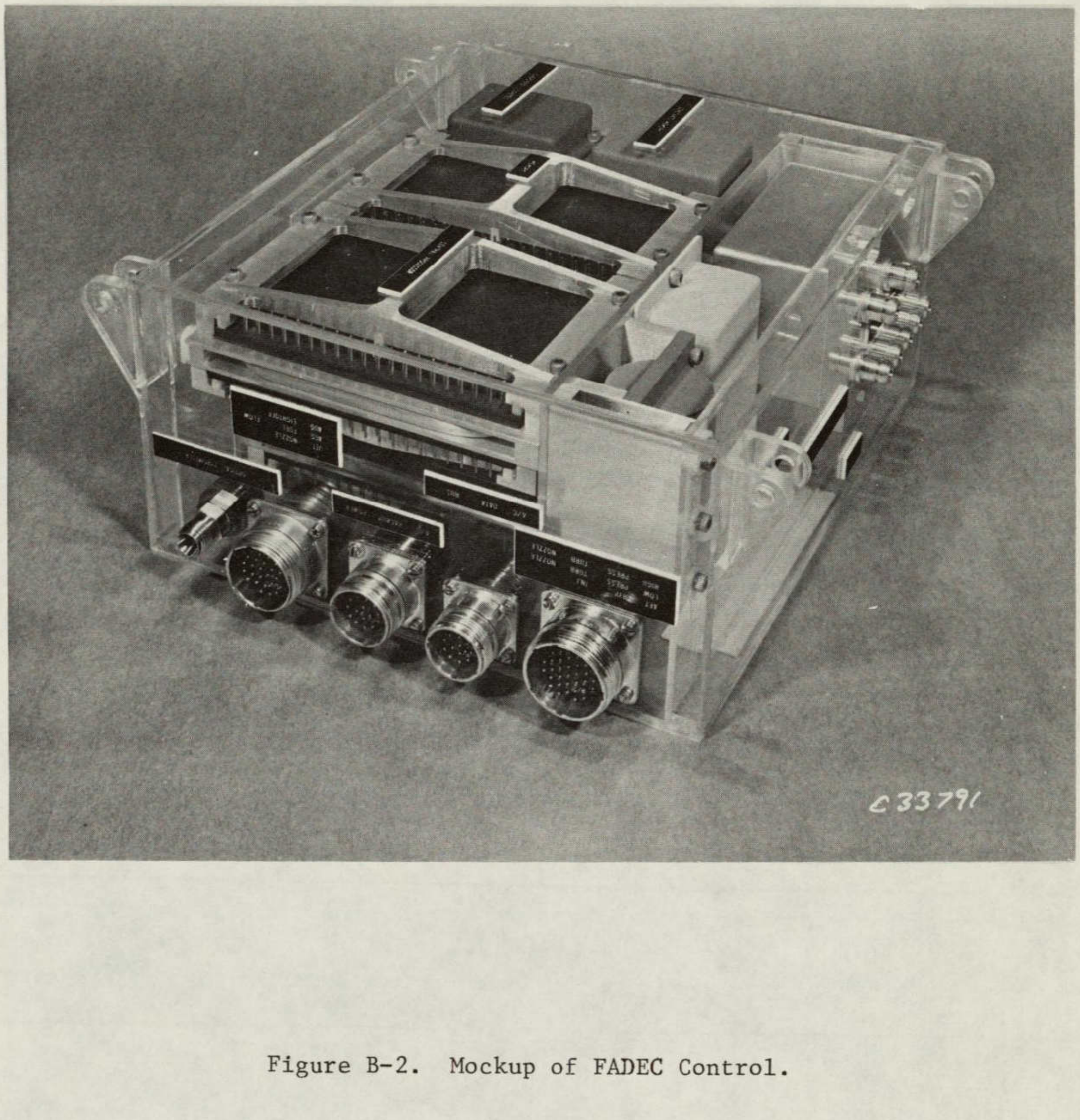

Figure B-2. Mockup of FADEC Control.

mode commands would be utilized from the aircraft and engine control data provided upon command to the aircraft to assure overall fast and accurate power managements.

The present production proven hydromechanical control would be retained as a standby backup. It would be available for engine operation either through pilot selection or automatically, should the digital control fail. The digital control would itself include internal redundancies, failure indication and corrective action, and self-test. Each of these techniques have been applied by General Electric on earlier digital controls.

To minimize cost of the flight demonstration, minimum changes would be made to the production CF6-50. The present gearbox, electrical sensors and actuators would be retained and used by the digital control. As a result, no control alternator would be mounted and airframe power will be used. This is contrary to GE production practice which favors a dedicated engine control alternator. It is believed justified for cost reasons on this program and acceptable due to the availability in backup redundancy of the hydromechanical control.

General Electric would build and test the digital control, including bench test, environmental test, closed loop dynamic tests, systems test with the engine fuel system and actuators, and finally engine cell test. The hydromechanical control would be modified to add the necessary transfer valve. Tests of the engine with the hydromechanical control would be conducted to demonstration operation in the backup mode and safe transfer into the backup mode.

Electrical and mechanical engineering support would be provided during the flight test period. A spare digital control (and two spares in the case of the four engine option) would be constructed and tested for substitution as required during the flight test program.

III. BOEING DIGITAL CONTROLS STUDY

A. Summary

This discussion supports the effort within the NASA Performance Improvement 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 limitation of hydromechanical 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 Electronic Propulsion Control System (EPCS) that was recently tested in a cooperative program between Boeing and United Technologies.

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"), including many advanced monitoring and self-healing features and utilized control laws superior to those obtainable in mechanical implementation (Reference 1).

This report identifies fuel savings and other economic benefits from such an EPCS-like baseline system. The savings fall in the "1 percent 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. Fiber optics should, therefore, be considered for the follow-on generation of digital electronic controls. Fiber optics are light, reliable and immune from induced transients. A follow-on study to this program is proposed to address the benefits from and installation problems with fiber optics for data links and compatible sensors and equipment.

In the preparation for the event 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, proposed 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.

B. 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.

1. Direct Fuel Savings

a. Engine Trim

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

- Fuel usage during a full engine ground trim is on the order of 2300-3800 liters per engine.
- Airlines using this trim procedure average 3 to 4 trims per engine per year.
- 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 (approximately $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 percent is expected by changing from hydromechanical to electronic controls. For those airlines using the "fuel economy" trim, a fuel saving of about 0.1 percent is expected.

b. Eliminatation 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 a longer time to climb to the desired cruise altitude and additional climb fuel usage. For example, the 747 with CF6-50 engines operated at 10 percent climb derate burns about 90 to 230 kg 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 50-75 kg) compared to all engines operated at climb rating (as would occur with individual electronic engine controls).

c. 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:

- Rapid and accurate setting of desired thrust (N1).
- 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.

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 equalization 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 operated the EPCS system in a simulated go-around engine acceleration were convinced that the rapidity of commanding and obtaining rated go-around power without overboost (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.

2. Engine Maintenance

a. 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

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*"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.

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., electronic) 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 sfc 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 percent for an engine to deteriorate to an overhaul condition, we estimate fuel savings on the order of 0.3 - 0.5 percent.

b. 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 (Reference 2) pointed out the benefit of doing compressor maintenance more frequently when the engine is already in the shop for hot section maintenance. Epstein (Reference 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.

c. 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.

3. 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 shutdowns) 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 the operational costs of the advanced propulsion controls will not offset the fuel and maintenance savings. 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.

a. Failure Rates

Hydromechanical Controls

The delay and cancellation rate chargeable to the CF6-50 controls and accessories is approximately 1.2 per 1000 departures for the 747 installation. Of these, the fuel and stator vane control accounts for approximately 0.3 per 1000 departures.

The number of in-flight shutdowns (IFSD) chargeable to the CF6-50 controls and accessories is approximately 7 per million engine hours. Of these, the fuel and stator vane control accounts for 2 to 3 per million engine hours. Similar numbers apply to the other engines certified for use on the 747.

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 shutdowns and dispatch delays. Based on available failure rates for contemporary aircraft electronics, a Mean-Time Between Failure (MTBF) of approximately 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 + 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 occassional 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 occassionally 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 approximately 1000 hours. This will still be satisfactory for early service with parallel redundant channels.

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.

b. Removal Times

Reference 5 gives typical power plant accessory replacement times for the CF6 engines. The time given for removal of the CF6 fuel control and pump is 45 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 turnarounds 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.

c. Failure Confirmation

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

d. Repair, Test, and Return to Service

Bench time required to repair and check out a current technology digital air data computer is about 2 hours. Since the electronic engine control computer would be of about the same complexity, it is expected the repair and check out 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 reassembly 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 check out of a digital electronic control. This does not represent the total cost to an airline, since installation on the engine and engine trim require additional time.

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C. Areas Needing Future Investigation

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

Table B-I lists the broad potential for fuel conservation through the use of electronic propulsion control system (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:

- 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).
- TSFC improvement and retention by means of new control loops (e.g., variable nozzle area, active clearance control).
- Improved engine control laws to provide better airplane speed stability at cruise (reduce throttle motion during cruise autothrottle operation, thereby decreasing fuel burn).

Table B-I. Fuel Conservation Potential - Electronic Propulsion Controls.

• *SFC 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

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.

1. Use of Fiber Optics

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 yield 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 maintenace 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, lightweight 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.

2. SFC Improvement and Retention

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 discussed in the initial engine design process may now have sufficient potential for mission fuel saying 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).

3. Improved Airplane Speed Stability at Cruise

Figure B-3 illustrates the typical relationship of thrust available (Power Lever Angle (PLA) - constant) and thrust required (airplane gross weight = constant). Two features are apparent.

- A gradual decrease in PLA is needed to maintain constant Mach number as fuel is burned off during cruise.
- The desired cruise Mach number for maximum range is near the bucket of the "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 flexiblity 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.

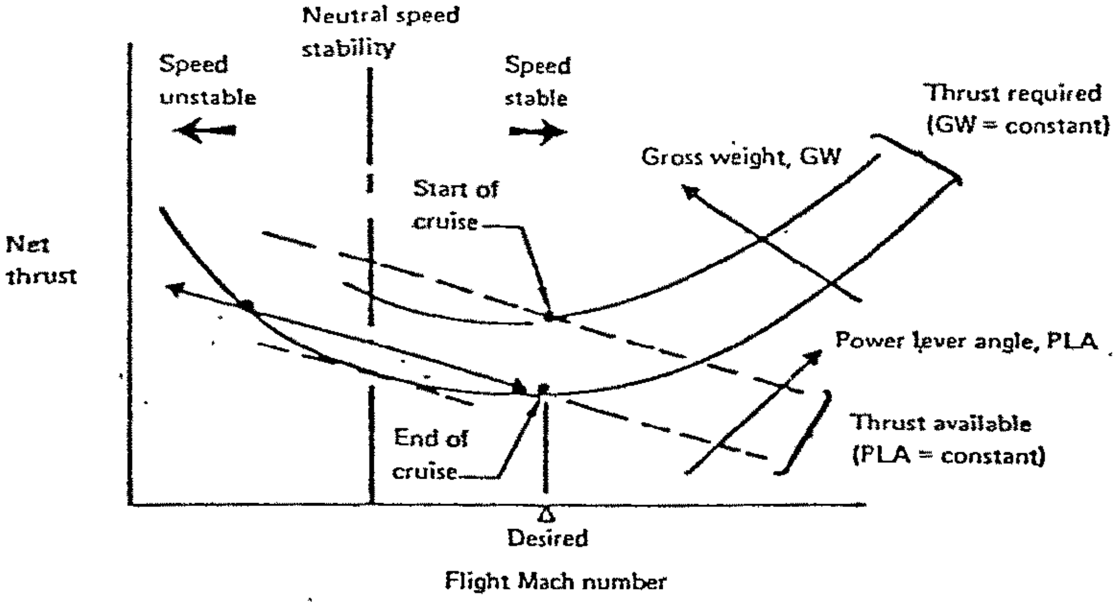

Figure B-3. Thrust/Mach Stability During Cruise.

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 are 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.

IV. GENERAL ELECTRIC COMMENTS ON THE BOEING RECOMMENDATIONS

Two areas of emphasis in the Boeing recommendation are commented upon:

A. Backup Control

B. Optical Techniques

Each of these requires further integration and agreement between the airframe and engine manufacturer. It is anticipated that such systems agreements can be reached early (first 3 months) in the proposed program.

A. Backup Control

General Electric is currently conducting a program of design, construction, and test of a hydromechanical backup control for use with future digital engine controls. This program is sponsored by USAF-AFAPL. The program considered and traded off electronic, fluidic, and hydromechanical approaches. Parallel (standby) vs. series (trim) systems were also compared. It was concluded that for maximum in-flight reliability in both the primary and backup modes the hydromechanical approach in a parallel or standby arrangement was superior.

The General Electric approach recommended for the CF6 digital control demonstration utilizes this arrangement. The hydromechanical control offers a flight proven backup which provides all the control features available today in the CF6 production control. The hydromechanical control is not subject to the same failure mechanisms, such as out-of-specification environments, which could affect the primary digital control. The primary digital control as envisioned by GE includes a number of internal redundancies such as redundant clocks, and the failure indication and corrective action strategy for the sensors. Thus, many failures will be accommodated within the primary digital control without revisions to the backup hydromechanical unit.

Our goal is the development and in-service use of digital engine controls to the point where they become precise and reliable. This point has not been reached and proven yet. The backup hydromechanical approach provides a low risk means during the interim transition period to establish the transport engine digital control.

B. General Electric Activities in Optical Techniques for Engine Controls

General Electric has conducted in-house developments and is currently under a NASA-Lewis contract to investigate optical sensors for propulsion control. The in-house IR&D program has laboratory tested fiber optic excited, and signal transmission from, digital shaft encoders for use with digital engine remote on-engine sensors. This work was performed at General Electric's Research Laboratory and was sponsored by the Aircraft Engine Group. A second fiber optic application addressed at General Electric has been to conduct the pyrometer signal from the turbine blade pyrometer to the digital engine control without the requirement to first amplify the signal with separate electronics at the sensor. A General Electric/USAF diagnostic program has demonstrated this concept.

The General Electric/NASA-Lewis program has considered a number of optical applications for future digital engine controls including temperature, flow, pressure, and position measurement. Currently, an optical sensor for clearance control is being investigated for feasibility as part of this contract effort.

General Electric recognizes the potential advantages of optical techniques for signal transmission and for certain sensors in future engine controls. General Electric is prepared to accept and transmit digital interface data to and from the aircraft should fiber optics be adopted by the airframer for propulsion control or diagnostics.

APPENDIX C

LIST OF SYMBOLS

ALF	Aft Looking Forward
ALT	Altitude, m (ft)
A/C	Aircraft
Ae_8	Effective Core Nozzle Throat Area, cm^2 (in^2)
A_8	Physical Core Nozzle Throat Area, cm^2 (in^2)
A_9	Physical Core Nozzle Exit Area, cm^2 (in^2)
BITE	Built-In Test Equipment
BRGW	Brake Release Gross Weight, kg (lb)
CDP	Compressor Discharge Pressure
CG	Center of Gravity
COE	Coefficient of Expansion
CRF	Compressor Rear Frame
CSD	Constant Speed Drive
CTOL	Conventional Takeoff and Landing
D	Drag, N (lb)
DOC	Direct Operating Cost ($)
EEE	Energy Efficient Engine
EGT	Exit Gas Temperature ° C (° F)
EPCS	Electronic Propulsion Control System
EPNdB	Effective Perceived Noise Level, dB
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FOD	Foreign Object Damage
Fn	Net Thrust, N (lb)

LIST OF SYMBOLS (Continued)

FADEC	Full Authority Digital Electronic Control
HMC	Hydromechanical Control
HPT	High Pressure Turbine
IFSD	In-Flight Shut Down
IR&D	Independent Research and Development
ITC	Investment Tax Credit
LDMF	Long Duct Mixed Flow
LPT	Low Pressure Turbine
MEC	Main Engine Control
M, Mp	Flight Mach Number
MTBF	Mean Time Between Failures
n	Number of Years
N1, N_F	Fan Speed (rpm)
N2, N_G	Core Speed (rpm)
N1K	Corrective Fan Speed - $N1\sqrt{\theta_2}$ (Rpm)
N2K	Corrected Core Speed - $N2\sqrt{\theta_{25}}$ (Rpm)
NPV	Net Present Value
OEW	Operating Empty Weight, kg (lb)
OGV	Outlet Guide Vane
PLA	Power Lever Angle (Degrees)
PMC	Power Management Control
Po	Ambient Pressure (kg/cm^2)
P3	HP Compressor Discharge Total Pressure, kg/cm^2 (lb/in^2)
PS3	HP Compressor Discharge Static Pressure, kg/cm^2 (lb/in^2)
PS11, PS22	Bypass Stream Inlet Static Pressure, kg/cm^2 (lb/in^2)

LIST OF SYMBOLS (Continued)

P_T	Total Pressure, kg/cm^2 (lb/in^2)
QCSEE	Quiet Clean Short-Haul Experimental Engine
QEC	Quick Engine Change
R	Discount Rate
ROI	Return on Investment
sfc	Specific Fuel Consumption, $\frac{\text{kg}}{\text{hr N}}$ $\left(\frac{\text{lb}}{\text{hr lb}}\right)$
SL	Sea Level Altitude, m (ft)
SLS	Sea Level Static
TMF	Turbine Midframe
T/O	Takeoff
TOGW	Takeoff Gross Weight
T_2	Inlet Total Temperature, ° K (° R)
T_{25}	Fan Discharge Temperature, ° K (° R)
ηT	Turbine Efficiency
VBV	Variable Bypass Valve
VSV	Variable Stator Vane
WT	Weight, kg (lb)
Wf	Fuel Flow, kg/hr (lb/hr)
W_{25}	Compressor Airflow, kg/hr (lb/hr)
Δ	Change or Difference
θ_2	Inlet Temperature Correction Factor - $T_2/288$, ° K ($T_2/519$, ° R)
θ_{25}	Compressor Inlet Temperature Correction Factor - $T_{25}/288$, ° K ($T_{25}/519$, ° R)

LIST OF SYMBOLS (Concluded)

AA	American Airlines
BCAC	Boeing Commercial Airplane Company
DAC	Douglas Aircraft Company
GE	General Electric
UAL	United Airlines

APPENDIX D

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