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STUDY OF THE APPLICATION OF ADVANCED TECHNOLOGIES TO LAMINAR-FLOW CONTROL SYSTEMS FOR SUBSONIC TRANSPORTS

May 1976

VOLUME I: SUMMARY

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16 Abstract

A study was conducted to evaluate the technical and economic feasibility of applying laminar flow control to the wings and empennage of long-range subsonic transport aircraft compatible with initial operation in 1985. For a design mission range of 10,186 km (5500 n mi), advanced technology laminar-flow-control (LFC) and turbulent-flow (TF) aircraft were developed for both 200- and 400-passenger payloads, and compared on the basis of production costs, direct operating costs, and fuel efficiency.

As a part of the study, parametric analyses were conducted to establish the optimum geometry for LFC and TF aircraft, advanced LFC system concepts and arrangements were evaluated, and configuration variations maximizing the effectivness of LFC were developed. For the final LFC aircraft, analyses were conducted to define maintenance costs and procedures, manufacturing costs and procedures, and operational considerations peculiar to LFC aircraft.

Compared to the corresponding advanced technology TF transports, the 200- and 400-passenger LFC aircraft realized reductions in fuel consumption up to 28.2%, reductions in direct operating costs up to 8.4%, and improvements in fuel efficiency, in ssm/lb of fuel, up to 39.4% Compared to current commercial transports at the design range, the LFC study aircraft demonstrate improvements in fuel efficiency up to 131%

Research and technology requirements requisite to the development of LFC transport aircraft were identified

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FOREWORD

Contract NAS1-13694 between the National Aeronautics and Space Administration and the Lockheed-Georgia Company, effective November 25, 1974, provided for the study of the application of advanced technologies to laminar-flow-control systems for subsonic transport aircraft. The contract was sponsored by the Aeronautical Systems Division of the Langley Research Center and jointly managed by *R. D. Wagner* and *J. B. Peterson, Jr.*

At the Lockheed-Georgia Company, the study was performed under the cognizance of *R. H. Lange,* Manager of the Transport Design Department, with *R. F. Sturgeon* serving as study manager. Principal contributors to the study include the following.

J. A. Bennett	Aerodynamics
H. V. Davis	Production Costs
F. R. Etchberger	Design
R. S. Ferrill	Thermodynamics/Propulsion
H. D. Hall	Maintenance
L. B Lineberger	Structures
L. E. Meade	Materials/Manufacturing
E. Stephens	Weights
G. Swift	Acoustics
S. G. Thompson	Operating Costs

This document, which comprises Volume I Summary, and Volume II. Analyses, is the final technical report summarizing the studies performed and is submitted in fulfillment of the terms of the above contract.

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1.0 INTRODUCTION

The recognition of potential long-term shortages of petroleum-based fuel, evidenced by increasing costs and limited availability since 1973, has emphasized the need for improving the efficiency of long-range transport aircraft. This requirement forms a common theme in the recent literature devoted to the analysis of future transport aircraft systems (ref. 1-5). All of these analyses recognize the contribution of aerodynamic drag reduction to aircraft efficiency and that, of the variety of drag reduction concepts which have been subjected to critical analysis, laminar flow control offers the greatest improvement.

Both the theoretical methods and the engineering and design techniques requisite to the application of laminar flow control have been reasonably well-known since the mid-1940's. The validity of this background and the potential of laminar flow control were partially evaluated in the 1960-1966 period by the X-21A Laminar Flow Control Demonstration Program conducted by Northrop (ref. 6-9). This program, which included analysis, design, fabrication, and flight test investigations, realized significant decreases in aircraft drag and fuel consumption and demonstrated technical feasibility by achieving predictable and repeatable system performance at chord Reynolds numbers up to 40×10^6. However, the program was terminated before full operational practicability in a realistic environment was established. Since essentially no development has been undertaken since the termination of the X-21A program, questions related to the economic and operational feasibility of laminar flow control have remained unanswered.

The current and projected influence of fuel costs and availability on airline operations, combined with the technological innovations of the past decade, provide a reasonable justification for the further development of laminar flow control as applied to long-range transport aircraft This report summarizes the results of studies conducted to evaluate the technical and economic feasibility of applying laminar flow control to long-range subsonic transport aircraft for initial operation in 1985 In performing the evaluation, parametric analyses are conducted to define optimum advanced technology configurations for laminar-flow-control and turbulent-flow transports designed for the same mission. For selected configurations, conceptual designs, manufacturing costs and procedures, and maintenance costs and procedures are developed. The relative benefits are evaluated through comparisons of the selected laminar flow control transports with similarly optimized turbulent-flow transports Advances in technology necessary for the development of practical laminar flow control transports are identified and the research and development programs requisite to such advances are outlined.

2.0 STUDY APPROACH

This section outlines the basic assumptions and criteria which are fundamental to all aspects of the study Included is a definition of study objectives, assumed technology levels, mission requirements, design criteria, and the overall study plan employed to achieve the stated objectives

2.1 STUDY OBJECTIVES

The study summarized in this report has two primary objectives:

(1) The evaluation of the technical and economic feasibility of applying laminar flow control to the wings and empennage of long-range subsonic transports aircraft.

(2) The identification of advances in specific technology areas requisite to such application

2.2 SCOPE

All analyses conducted as a part of this study are consistent with the guidelines and requirements outlined below

(1) Basic Study Missions

- 200-Passenger Mission

  Design Payload –
  23,769 kg (52,400 lb), consisting of 200 passengers and 4536 kg (10,000 lb) of belly cargo

  Design Range –
  10,186 km (5500 n mi)

  FAR Field Length (SLS) –
  3353 m (11,000 ft)

- 400-Passenger Mission

  Design Payload –
  47,538 kg (104,800 lb) consisting of 400 passengers and 9072 kg (20,000 lb) of belly cargo

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Design Range –
10,186 km (5500 n mi)

FAR Field Length (SLS) –
3353 m (11,000 ft)

(2) **Aircraft Life Cycle**

- The assumed life cycle of the aircraft evaluated in this study is shown in figure 1 For initial passenger operation in 1985, the airframe, LFC system, and propulsion system technology levels identified in this figure are appropriate

- Based on the assumed life cycle, the following guidelines are used for the economic analyses of study aircraft:

  All costs are expressed in January 1, 1975 dollars
  Total aircraft production – 350
  Aircraft production rate – 3/mo
  Fuel prices

$0.066/1	($0.25/gal)
$0.132/1	($0.50/gal)
$0 264/1	($1 00/gal)

- All aircraft evaluated are compatible with the Air Traffic Control Systems and the general operating evironment envisioned for the post-1985 time period.

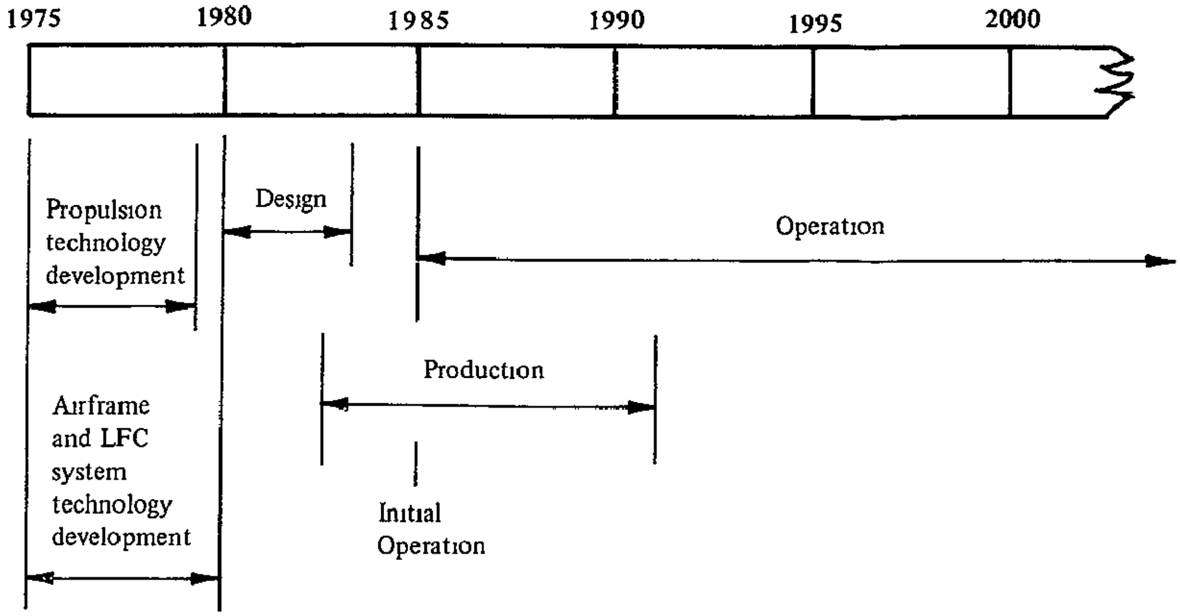


Figure 1. – Aircraft life cycle

(3) **Design Criteria**

- The aircraft studies satisfy the requirements for type certification in the transport category under Federal Aviation Regulations – Part 25, and are capable of operating under pertinent FAA rules.

- All aircraft satisfy the noise requirements of Federal Aviation Regulations – Part 36 minus 10 EPNdB.

(4) **Laminar Boundary-Layer Stability Criteria**

- For the aircraft described in this summary volume, the value of the boundary-layer crossflow Reynolds number, R_n is increased by a factor of 1 8 above the minimum critical value for stability The value of the boundary-layer tangential flow Reynolds number R_e, is increased by 200 above the minimum critical value for stability. Volume II of this report includes a description of LFC aircraft configurations developed for compatibility with criteria for a stable laminar boundary layer.

(5) **Configuration Constraints**

- This study is directed toward a practical commercial transport aircraft for initial operation in 1985. Therefore, only conventional aircraft configurations are evaluated Variations which maximize the effectiveness of laminar flow control, such as flying wings or aircraft with aspect ratios sufficiently high to require external struts, are not considered

- The configurations of this study recognize the preference of commercial airlines for low-wing passenger aircraft

- The configurations of this study do not use the fuselage for fuel storage. The fuel volume available in the wing, the wing carry-through structure, and external fuel tanks is employed as required.

2.3 REFERENCE TECHNOLOGY LEVEL

The following characterizes the general level of technology which will be available for commercial transport aircraft entering service in 1985 and is therefore assumed for study aircraft.

(1) *Aerodynamics* – The available aerodynamics technology is limited to the use of advanced airfoil sections, as reflected in the supercritical airfoil concept.

(2) *Flight Controls* – With the exception of the empennage size and weight reductions afforded by the use of relaxed static stability, standard hydro-mechanical flight controls are used

(3) *Propulsion Systems* – Primary propulsion engines for study aircraft are based on the parametric STF-429 engines defined by reference 10.

(4) *Materials* – Study aircraft utilize composite materials in aircraft secondary structure to the extent that 21% of the total airframe weight is composite material This results in study aircraft with structural weights which are 90 percent of those for comparable current transports.

(5) *Aircraft Systems* – Hydraulic, environmental, electrical, and fuel systems for study aircraft are comparable to those of current transport aircraft.

2.4 STUDY PLAN

The general approach used in conducting the total study is illustrated by figure 2. Starting with a common data base, parametric configuration analyses were conducted to evaluate the effect of aircraft geometry, operational, and performance parameters on the fuel efficiency of both laminar-flow-control (LFC) and turbulent-flow (TF) transport aircraft for 200- and 400-passenger payloads at the design range In this phase of the study, the characteristics of LFC system elements are represented parametrically to permit the investigation of a large number of configuration variations. Based on these parametric investigations, preliminary baseline configurations were selected for both LFC and TF aircraft on the basis of minimum fuel consumption for the design mission.

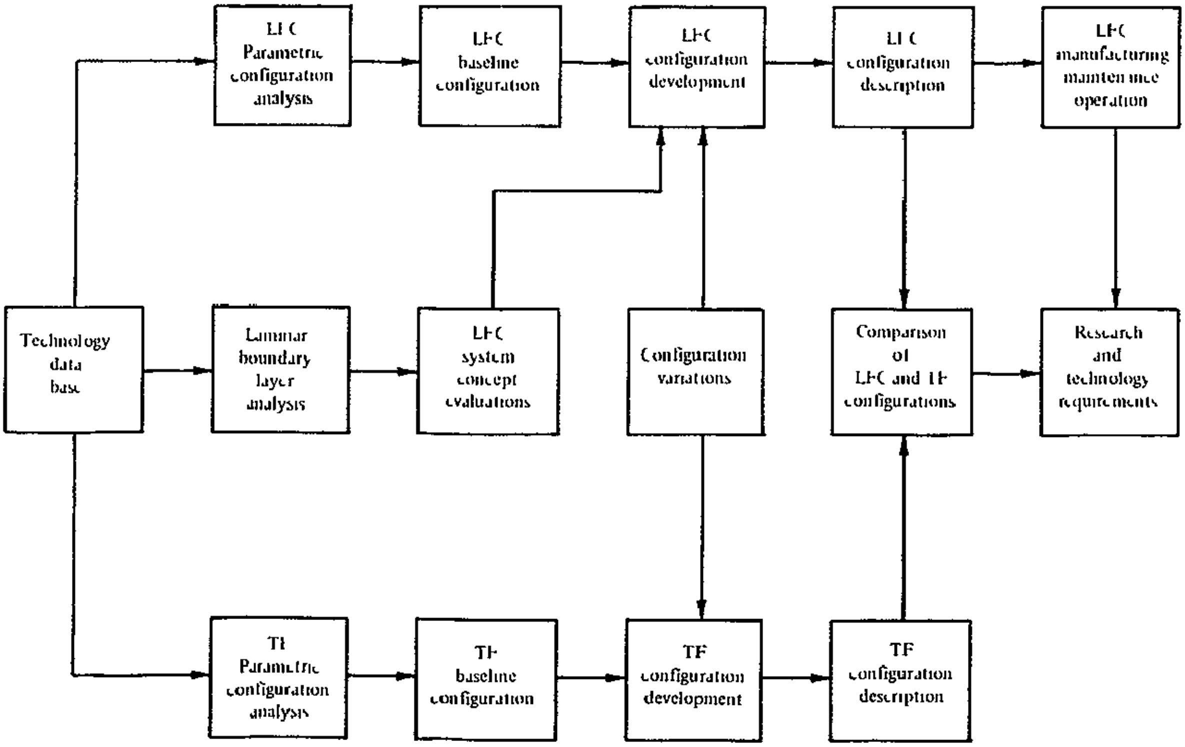


Figure 2. – Study plan

In the LFC concept evaluation phase, potential improvements in LFC system performance through the application of technology advances were investigated. Included were evaluations of advanced concepts for

(1) LFC surfaces

(2) Ducting and distribution systems

(3) LFC suction units

(4) Advanced materials for LFC surfaces and internal components

(5) Advanced manufacturing procedures for LFC system elements

To the extent possible, evaluations were conducted as independent trade studies. For elements which are configuration sensitive, as for example, LFC suction units, the LFC baseline configuration was used as a vehicle for concept evaluation.

For advanced LFC concepts determined to be technically feasible and offer significant performance improvements, conceptual designs were developed and the LFC baseline configuration was modified as required to accommodate the concept. The performance of each configuration variation was evaluated on the basis of fuel consumption for the design mission The LFC system elements comprising the most fuel-efficient configurations were combined to form preferred LFC configurations for both design payloads.

For the selected LFC configurations, design details, manufacturing costs and procedures, and maintenance costs and procedures were developed to permit realistic comparisons with the TF configurations modified to reflect all technology advantages incorporated into the LFC configurations.

In the evaluation and comparison phase, the relative benefits of LFC were evaluated through comparisons of the selected LFC configurations with the selected TF configurations. As a part of this evaluation, all pertinent performance, operational, and cost parameters were compared, including a definition of relative direct operating costs as a function of assumed fuel prices, LFC system maintenance costs, and LFC system production costs.

The identification of Research and Technology Requirements necessary to permit development of practical LFC commercial transports is a direct output of investigations conducted in the concept evaluation phase and the evaluation and comparison phase of the study

3.0 CONFIGURATION DEVELOPMENT

As outlined in the study plan, the procedure employed in the development of final study aircraft included parametric analyses to define baseline configurations, the investigation of alternative LFC system concepts, and the evaluation of aircraft configuration variations. Subsequently, the LFC system concepts and aircraft configuration variations which minimized fuel consumption were incorporated into the baseline configuration in the development of final study aircraft. This section summarizes the results of these investigations.

3.1 PARAMETRIC CONFIGURATION ANALYSES

As the initial task in the selection of baseline configurations for subsequent detailed investigations, a comprehensive analysis was conducted to evaluate the influence of aircraft performance and geometry parameters on the fuel efficiency of commercial transport aircraft. These analyses were conducted for both 200- and 400-passenger TF aircraft, and for 200- and 400-passenger LFC aircraft.

3.1 1 PARAMETRIC PROCEDURES

A conventional wide-body fuselage configuration, sized for the required passenger and cargo payload with associated accommodations, was used for all parametric analyses. The procedure used in the selection of the LFC baseline configurations is illustrated by figure 3. As outlined in this figure, an initial matrix of LFC aircraft was exercised with fuselage geometry, main propulsion

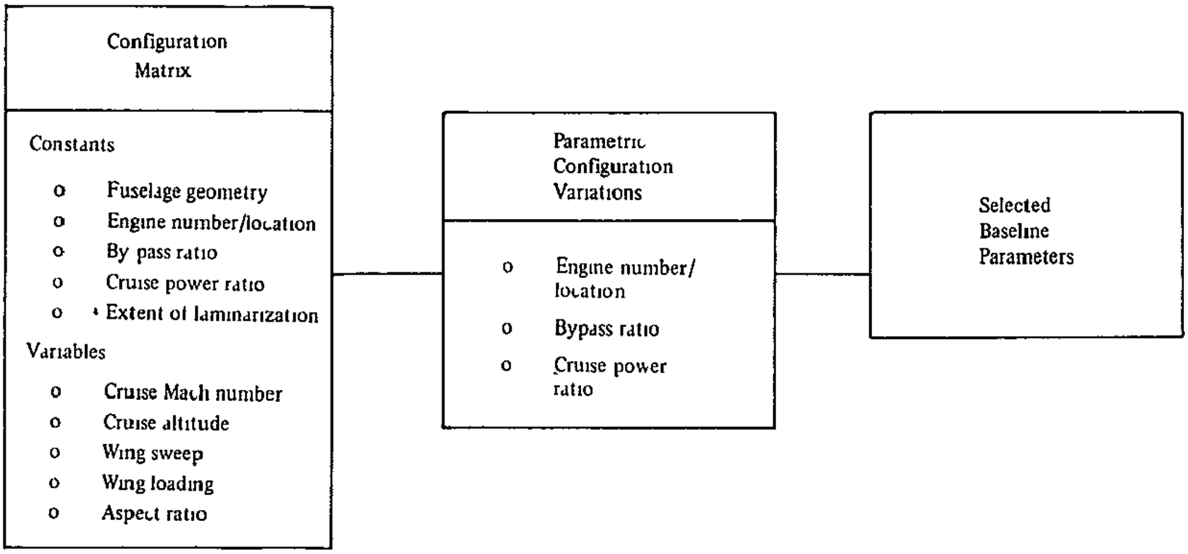


Figure 3. — Baseline selection procedure

engine characteristics, and the chordwise extent of laminarization held constant. The influence of the variables shown in table 1 was evaluated by allowing aircraft size to vary as required to perform the specified mission All combinations of the variables listed in table 1 were considered, resulting in the evaluation of a matrix of 768 aircraft configurations

TABLE 1. LFC CONFIGURATION MATRIX

M	0.70	0.75	0.775	0.80
H, m, (ft)	10,973 (36,000)	12,192 (40,000)	13,411 (44,000)	
Λ, rad (deg)	0	0.175 (10)	0.349 (20)	0.524 (30)
W/S, kg/m^2 (lb/ft^2)	391 (80	488 (100)	586 (120)	683 (140)
AR	8	10	12	14

In general, the parametric configurations defined by the first phase of the analysis do not satisfy airport performance requirements For parametric configurations which minimize fuel consumption, as determined from the configuration matrix, engine number and location, cruise power ratio, and bypass ratio were varied to define point-design configurations compatible with takeoff distance and second-segment climb requirements The LFC baseline configurations were selected from these point-design configurations on the basis of fuel efficiency and compatibility with projected airline traffic.

3.1.2 PARAMETRIC RESULTS

The following summarizes the implications of the data generated in the parametric analysis of LFC aircraft:

(1) *Cruise Mach number* – Fuel consumption of LFC aircraft is minimized by selecting a cruise M of 0.75 or less. On the basis of DOC, the optimum cruise M is between 0.76 and 0.79, depending on aircraft configuration.

(2) *Cruise Altitude* – Both fuel consumption and DOC are minimized for LFC aircraft by selecting the lowest cruise altitude which permits a reasonable match of cruise and takeoff thrust requirements.

(3) *Wing Geometry* – Within the constraints imposed by considering only conventional aircraft configurations, fuel consumption of LFC aircraft is minimized by selecting the highest wing loading and aspect ratio and lowest wing sweep compatible with fuel volume requirements for the design mission.

(4) *Engine Bypass Ratio* – An engine bypass ratio of 6.0 minimizes fuel consumption, provides reasonable airport performance, and does not incur a significant penalty in DOC.

(5) *Number and Location of Primary Engines* – To minimize both the influence of engine noise on the laminar boundary layer and the loss of laminar area due to pylon/wing interference, it is desirable to employ fuselage-mounted engines on LFC aircraft.

If selection of the baseline configuration were based entirely on the minimization of fuel consumption, the parametric analyses of the preceding section dictate the selection of an LFC baseline with an unswept wing, a cruise M of 0.75, and the maximum aspect ratio and wing loading compatible with structural and wing volume constraints. In addition to minimizing fuel consumption for the design mission, the resultant configuration eliminates potential spanwise contamination problems attending the cross-flow inherent in the boundary layer of swept-wing aircraft

However, in view of the more favorable direct operating costs at higher cruise speeds and the current and projected flow of airline traffic at speeds of M = 0.80 or greater, a cruise M of 0.80 was determined to be appropriate for the aircraft of this study. Consequently, the LFC baseline configuration and all subsequent configurations developed during the course of the study were designed for cruise at M = 0.80 The optimum wing geometry for cruise at M = 0.80 is defined by a quarter-chord wing sweep of 0.396 rad (22.7 deg), a wing loading of 537 kg/m^2 (110 lb/ft^2), and an aspect ratio of 14.

3.2 LFC SYSTEM CONCEPT EVALUATIONS

Laminar-flow-control aircraft are distinguished from conventional turbulent-flow aircraft by the incorporation of a suitable surface for removing a portion of the boundary layer, ducting to collect the accumulated flow, and suction units to create the pressure differentials requisite to system operation The benefits obtained through the application of LFC, in the form of reduced drag and fuel consumption, are reduced by the weight and fuel flow of the systems peculiar to the LFC aircraft. The desirability of minimizing LFC system penalties is obvious. Consistent with the technology level assumed for the study aircraft, advanced materials, design concepts, and manufacturing procedures were evaluated to permit the selection of LFC system elements which minimize the weight, cost, and complexity of LFC aircraft This section summarizes the evaluation of alternative concepts for LFC surfaces, ducting and distribution systems, and suction units.

3.2.1 LFC SURFACES AND DUCTING

3.2.1.1 Materials

Candidate LFC surface materials were evaluated for application to both slotted and porous surface configurations. Materials were evaluated relative to the following criteria:

- Strength
- Flight environmental resistance
- Resistance to impact
- Micro-surface smoothness
- Weight
- Cost

Throughout the evaluations, consideration was given to the fabrication, installation, and maintenance requirements peculiar to LFC surfaces.

Slotted Surfaces – Materials compatible with the requirements of slotted LFC surfaces include aluminum and titanium. Considering the requirement for cutting numerous slots with widths of 0.076 mm (.003 in) to 0 254 mm (0 010 in), the fabrication characteristics of aluminum are advantageous. The slot edges of an aluminum surface can be chemically or anodically treated for corrosion protection

Fiber reinforced composite materials are generally not suitable for use in a slotted LFC surface Exposure of the slot edges to the environment results in material degradation due to the entry of moisture into the laminate.

Porous Surfaces – A variety of materials are available within the industry in porous or perforated form However, the relatively low volume air flow requirement of LFC surfaces, ranging from 0 015 to 0.15 $m^3/sec/m^2$ (0 05 to 0.5 $ft^3/sec/ft^2$), requires a porosity appreciably below that of commonly available materials The uniformity of porosity and the maximum size of each porous opening is critical in obtaining uniform LFC over the wing surface. The available porous materials, used for sound suppression in engine nacelles, generally exhibit openings far in excess of the maximum size acceptable for LFC surfaces.

A listing of candidate porous materials for application to LFC surfaces is presented in table 2 Property improvements requisite to utilization of the most promising materials for LFC surfaces are outlined in table 3

TABLE 2. CANDIDATE POROUS LFC SURFACE MATERIALS

						Weight		Cost	
Material	Porosity	Strength	Flight environment	Impact	Surface smoothness	$kg/m^3 \times 10^4$	lb/in^3	$\$/m^2$	$\$/ft^2$
Hi density polyethylene-porex	Yes	No	Yes	Yes	Yes	0.060	0.022	6.4-21.5	.6-2
Porous acoustic glass fabric PI	No	Yes	Unknown	Yes	No	.193	.07	21.5	2
Sintered stainless steel wire mesh	Yes	Yes	No	Yes	Yes	.415	.15	538	50
Sintered stainless steel powder	Yes	No	Yes	Yes	Yes	.415	.15	645	60
Molded graphite epoxy	No	Yes	Yes	Unknown	No	.138	.05	645	60
Perforated aluminum	No	Yes	Yes	Yes	No	.277	.10	108	10
Woven composite structure	No	Yes	No	Yes	No	23.9-71.8* (kg/m^2)	.5-1.5* (lb/ft^2)	483-1075	45-100

* Entire sandwich panel structure

TABLE 3. REQUIRED PROPERTY IMPROVEMENTS FOR POROUS LFC SURFACE MATERIALS

Porex - Porous Thermoplastic With Reinforcement	Strength, apply porous plastic technology to reinforced plastics
Glass Fabric - Epoxy or PI	Improve pososity, surface smoothness, and long-time resistance to flight environment
Advanced Composite Reinforced Plastic	Improve porosity, surface smoothness, and long-time resistance to flight environment
Woven Composite Structure	Improve resistance to flight environment and surface smoothness

3.2.1.2 Design Concepts

The technology level on which study aircraft are based limits the use of composite materials to fairings and secondary aircraft structure. Primary structure is aluminum designed to currently accepted industry standards. The early operational date of study aircraft precludes the use of bonded composite materials for primary structure such as the wing and tail components

Design Considerations – Since this study is directed toward the application of LFC to a production commercial passenger transport, the systems to be considered for use must lend themselves to attaining repeatability in mass production and test, and exhibit operational repeatability in day-to-day airline operations with the application of economically acceptable airline-industry methods of maintenance and overhaul.

To satisfy these requirements, LFC systems must be designed, manufactured, installed, and tested in an extensive prototype program so that a production run of airplanes can be expected to meet specification standards with little or no individual tuning. In addition, it must be possible to maintain the LFC systems with a minimum of abnormal maintenance procedures while meeting the stringent airline requirements for vehicle dispatch in an intercontinental operational environment.

Based on these considerations and a recognition of the sensitivity of laminar flow to surface smoothness, non-structural LFC surface panels were utilized. Thus, damaged panels become expendable, at least to the extent that they are line-replaceable, and minimize dispatch delay in normal operations. The replaced panel can be repaired or scrapped depending on the type and extent of damage. Another important feature of bolt-on panels is that they may be removed to gain access to the wing box for fuel system inspection and maintenance. Thus, normal wing access panel closures can be employed in the basic wing surface below the LFC surface panels.

Selected Surface Configuration – Early anslyses indicated the importance of minimizing the thickness of LFC surface panels in order to maximize the thickness of the structural wing box. This approach saves weight in both the box structure and in the LFC surface panels. The approach also allows for maximizing the space available in leading and trailing edges for installing necessary ducting plus the normal flap, spoiler, and aileron systems.

A number of LFC surface configurations were studied. All configurations were of non-structural construction, fastened to basic wing structure with a mechanical fastener system consisting of net diameter holes in the surface panel and over-size holes in basic structure with floating, sealed, dome-type plate nuts attached to basic structure. This floating panel concept facilitates maintenance and repair and avoids transmitting structural loads to the LFC panels.

The selected LFC surface and ducting configuration is illustrated schematically in figure 4. The surface is constructed of a slotred aluminum outer sheet, an intermediate sheet of Kevlar containing drilled throttling holes, and a solid inner sheet of Kevlar. The outer sheet is separated from the intermediate sheet and supported by light-weight Kevlar filler strips oriented spanwise to form ducts to carry the air sucked through the surface to the throttling holes located in the intermediate sheet.

The inner sheet is separated from the intermediate sheet by light-weight Kevlar corrugations oriented chordwise forming collector ducting to carry air forward or aft as required to the trunk ducts in the wing leading and trailing edges.

3.2.1.3 Manufacturing Concepts

Applicable manufacturing techniques were identified and evaluated for creating suction slots or perforations in LFC surfaces. Three manufacturing techniques were considered for creating slots.

(1) *Saw* – A jewelers saw may be used to cut slots as narrow as 0.051 mm (.002 in). The saw slot width tolerance is .013 mm (.0005 in). Therefore, the minimum practical size is 0.076 mm (.003 in). With a potential of sawing slots up to 0.38 m/min (15 in/min), industry experience has only achieved rates on the order of 0.18 m/min (7 in/min).

(2) *Electron Beam* – The electron beam can cut clean slots, but the minimum width that can be controlled to reasonable accuracy is on the order of 0.127 mm (0.005 in). The electron beam is slower than the laser by a factor of two.

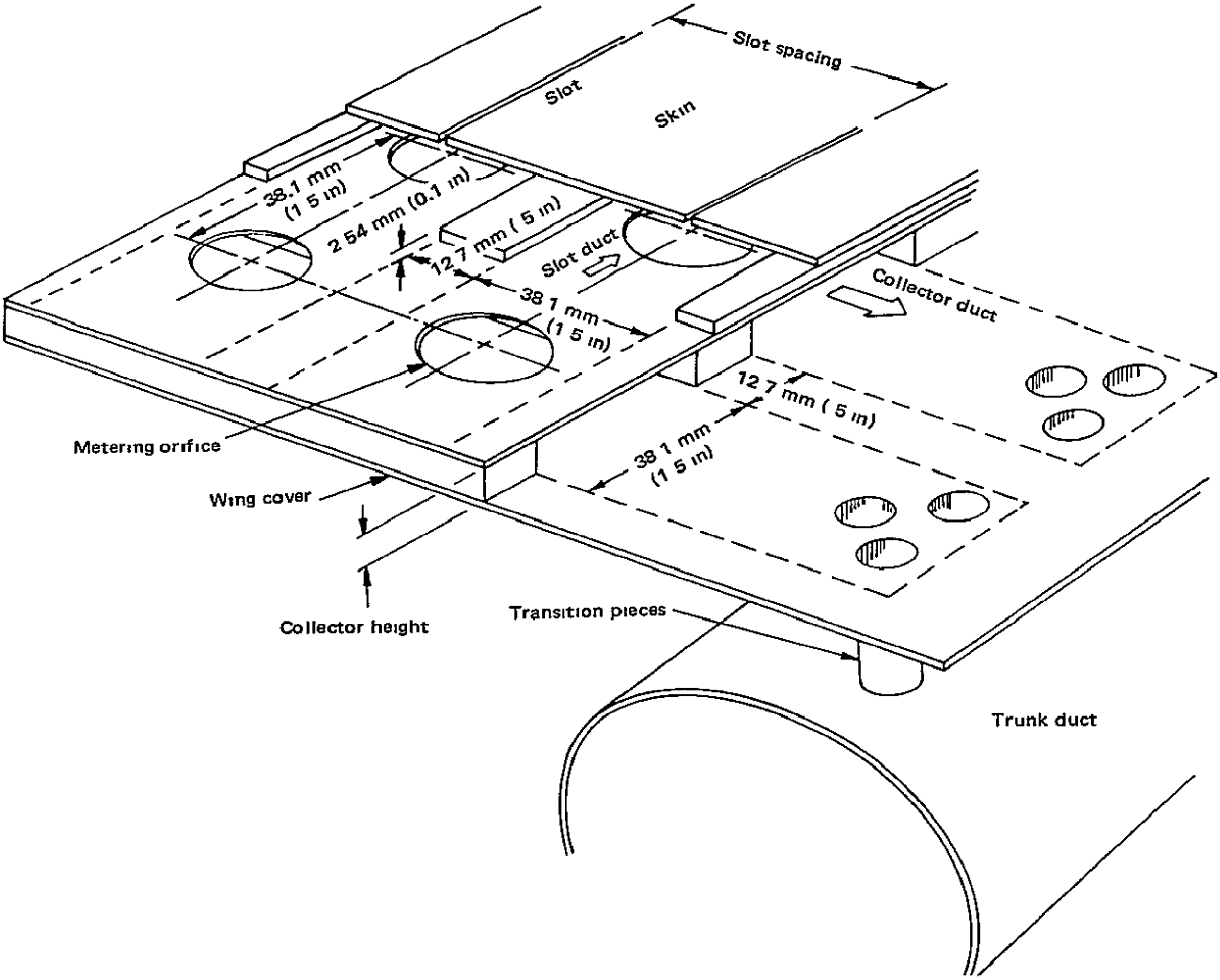


Figure 4. — Schematic of ducting and distribution system

(3) *Laser* – The laser can cut slots as narrow as 0.051 mm (.002 in) at rates of 7.62 m/min (300 in/min) and can be fully automated. This appears to be the most promising method for the fabrication of slotted LFC surfaces.

The following summarizes the results of investigations conducted to evaluate manufacturing concepts for perforated and porous LFC surfaces:

(1) *Laser and Electron Beam* – These methods for perforating composite facings burn the plastic matrix around the holes and are therefore unsatisfactory for this application.

(2) *Drill* – The method, which is easily automated, provides exact placement of perforations. However, the practical minimum hole size is much larger than the 0.254 mm (.010 in) diameter maximum considered usable for LFC. Drill life due to the plastic resin abrasiveness is very low. While drilling rates of 90 holes/min are possible in aluminum, rates on the order of 32 holes/min are more common in practice. Drilling holes in cured composites leaves fibers exposed to the environment that are impractical to seal.

(3) *Inherent Porosity* – Micro porosity created during the processing of the reinforced plastic composite facings appears to be the best method for fabricating porous LFC surfaces. Current technology abounds in processes for non-reinforced porous plastics. Many processes also exist for leather-like materials having fibrous reinforced porous construction Efforts underway in current programs are resulting in reinforced composites that are suitable for LFC surfaces

Manufacturing composite surfaces with inherent porosity, either by controlled resin content or foaming, or by inclusion of fugitive materials, produces a porous composite with the fibers coated with resin and sealed from the environment.

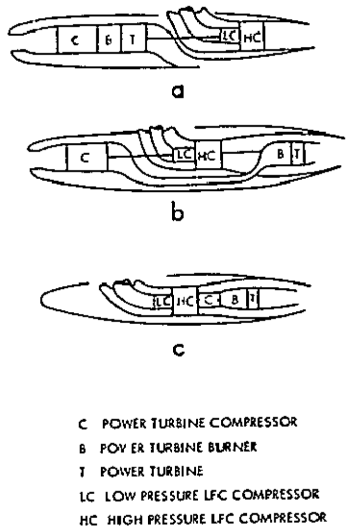
3.3.2 LFC SUCTION UNITS

The suction units for LFC aircraft are comprised of a suction pump, or compressor, and a power unit The basic design requirements for the compressor are dictated by the aircraft characteristics which define the quantity of airflow and the pressure ratio through which the compressor must pump the air. The varied airplane requirements for takeoff, climb, cruise, approach and landing impose broad bands to these requirements. However, the scope of the current study requires operation of the LFC system only during cruise at constant altitude Therefore, the requirements placed on the LFC suction units are minimal, as compared to units required to operate under all flight conditions.

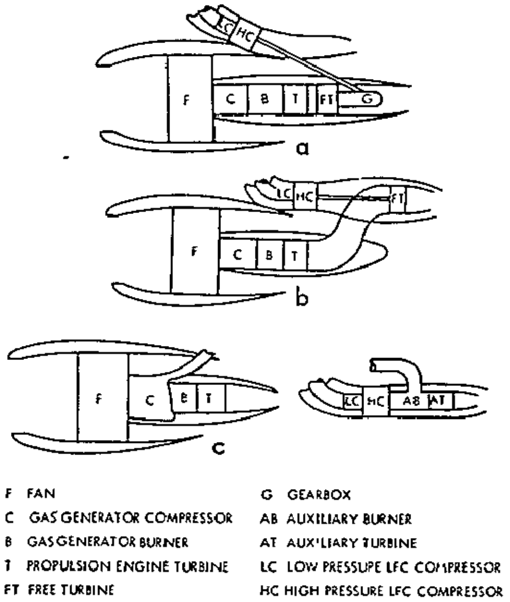
An evaluation of alternative suction units was conducted to permit the selection of the optimum configuration for the study aircraft. The units considered are illustrated in figure 5.

3.3.2.1 Independent Suction Power Systems

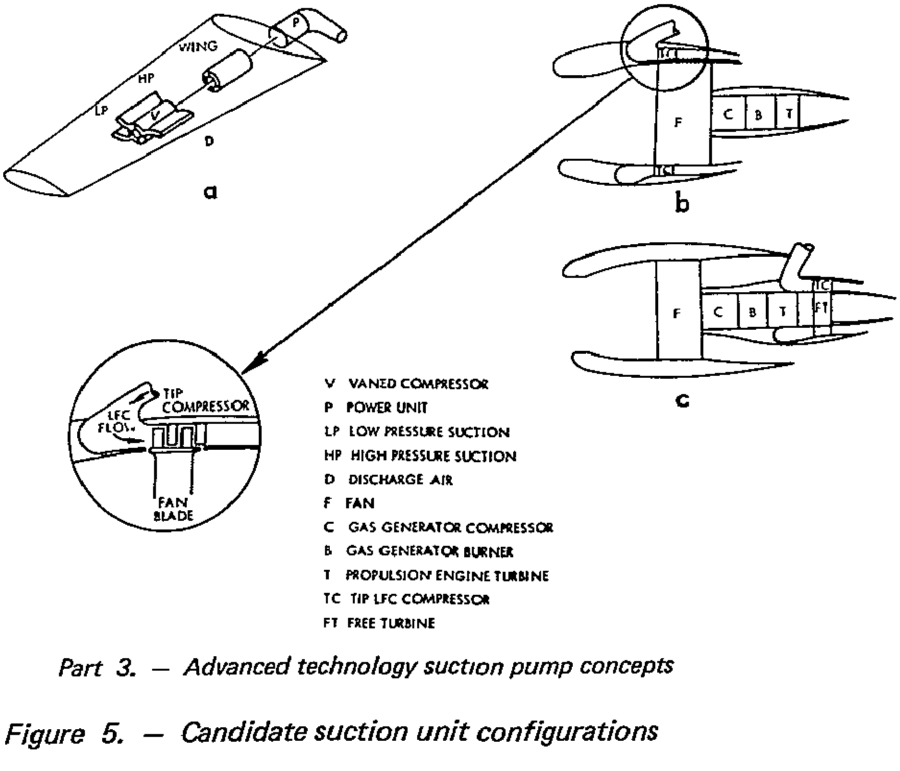
Options for independently powered units are shown in part 1 of figure 5. Configuration (a) uses a conventional shaft engine with a rear drive directly coupled to the suction compressor and has the advantage of a ram inlet for the power unit, but requires complicated ducting for the power unit exhaust and suction unit inlet Configuration (b) separates the power unit compressor from its burner and turbine and overcomes the ducting complexity with a superior exhaust configuration but suffers from alignment problems, length, and weight. Configuration (c) is the simplest and most compact unit For this configuration, a portion of the air leaving the suction unit enters the power unit, which performs in the manner of a conventional fan engine gas generator However, the elevated temperature of the suction air seriously degrades the efficiency of this unit Detailed analyses of independently powered suction units show that configuration (a) provides the best compromise of weight and fuel consumption.



Part 1 — Independently powered suction pump concepts



Part 2 — Integrated suction pump concepts



Part 3. — Advanced technology suction pump concepts

Figure 5. — Candidate suction unit configurations

3.2 2.2 Integrated Suction Power Systems

Attending the incorporation of an LFC suction system is both a potential supply of air aboard the airplane and a requirement for drive power. There are a variety of potential applications for such a supply of air, including the numerous pneumatic aircraft systems. Additionally, there are power systems aboard the airplane from which the LFC suction system may be powered Integration of these systems appears to offer attractive possibilities for decreasing weight and improving performance by designing the LFC airflow to perform additional functions or designing a power system already aboard the airplane to supply all or part of the LFC suction system power requirements

Integrated Power Units — Of the integrated units shown in part 2 of figure 5, configurations (a) and (b) both require a suction pump location in close proximity to the primary propulsion engine with which they are integrated. Evaluation of airplane configurations compatible with such units shows that wing-mounted primary propulsion engines create excessive disturbance to the airflow over the wing surface and aft-fuselage-mounted propulsion engines result in prohibitive suction air ducting problems The bleed-burn system of (c) offers advantages of remote location of the suction unit from the primary propulsion engine while affording the performance advantages of an integrated system.

The bleed-burn system has significant advantages over the independently powered system when the primary propulsion engine is configured to permit bleeding of air from the core engine without the penalties frequently associated with the mismatch of the core engine resulting from high-pressure compressor bleed Consequently, this unit was selected for the final LFC aircraft.

Integrated Pneumatic/Power Systems — The possibilities of integrating the LFC suction system with airplane pneumatic and auxiliary power systems were investigated with the result that there is little potential benefit from such integrations. The Environmental Control System (ECS) requires only 19 percent of the flow available from one unit of a two-unit suction system Simultaneously, the ECS system requires an air pressure nearly four times that available from the suction unit. Any performance gains from such an integration would be modest at best and would be far outweighed by the added weight and complexity required to overcome these gross incompatibilities

Integration of the suction system power unit with the Auxiliary Power Unit (APU) presents similar gross incompatibilities. The power capability of the suction power unit far exceeds the requirements for an APU. The requirement for operation of an APU under static airplane conditions while parked at the terminal is contrary to the concept of avoiding operation of the suction system at low altitude because of contamination Avoiding this incompatibility requires de-clutching of the suction compressor from the suction power unit and either bleeding the power unit or driving a separate compressor to provide the ground air normally provided by an APU for primary engine starting and ground ECS. This arrangement could be provided but the adverse impact on suction system interchangeability, weight, cost, complexity, and reliability out-weigh the penalties of a separate APU.

The possibility of using the suction airflow discharge to blow the wing surfaces for takeoff performance improvement is obvious Examination of this possibility reveals, however, that a wing leading edge or flap blowing system requires a complicated ducting and distribution system as well as a complex valving system in the vicinity of the suction compressor., There is little likelihood of achieving commonality with LFC system ducting. Since wing volume available for LFC system ducting represents a serious design constraint, there is no possibility of satisfying additional ducting requirements. Operation of the suction system in the terminal area is objectionable from the standpoint of contamination. Venting the suction compressor inlet to ambient results in excessive noise levels for a blowing system unless the units are severely throttled

The airplane terminal area performance is generally quite satisfactory and any performance improvements from this type of system integration are more than overbalanced by the associated complexities and problems.

Advanced Technology Suction Pump Concepts — Advanced suction pump concepts, shown in part 3 of figure 5, include the vane pump, illustrated by configuration (a), and systems in which the suction pump is incorporated into the main propulsion unit in the form of a suction pump located on the fan tip or on a turbine tip, as illustrated by (b) and (c) The vane pump was found to be excessively large and heavy. Problems associated with the suction pump located on the fan or turbine tip of the primary propulsion engines present problems arising from clearances, tolerances, and seals, and are beyond the technology level assumed for the current study.

3.3 CONFIGURATION VARIATIONS

Many of the LFC system concepts impact overall aircraft design to an extent which requires the definition of a specific aircraft configuration for concept evaluation. In addition, there are feasible airframe configuration variations which offer the potential of greater compatibility with LFC system requirements and a resultant improvement in fuel efficiency. This section summarizes the evaluation of such LFC system concepts and aircraft configuration variations.

Due to the stringent design constraints attending the LFC aircraft developed to satisfy the criteria for a stable laminar boundary layer, this aircraft was used as the baseline for the evaluation of configuration variations. The results of the variations evaluated for this aircraft, designated the LFC-200-S configuration, are equally applicable to the LFC-200-R and LFC-400-R configurations described in this summary.

The procedure followed in conducting these evaluations included the development of an initial LFC baseline configuration, definition of LFC system concepts and aircraft variations, modification of the baseline configuration to accommodate the concept or variation, optimization of the modified configuration, and comparison of this configuration with the baseline From these comparisons, the LFC system concepts and aircraft variations which minimized fuel consumption were combined into final LFC configurations.

Figure 6 summarizes the characteristics of the configurations evaluated and outlines the sequence in which the variations were conducted As illustrated by figure 6, a net reduction in fuel consumption is achieved through the modification of the baseline configuration to include the use of external fuel and relaxed static stability In addition, although not providing a reduction in fuel consumption relative to the baseline configuration, the utilization of bleed/burn suction units results in reduced fuel consumption in configurations which are compatible with the use of fuselage-mounted units Consequently, these variations are incorporated into the final study aircraft

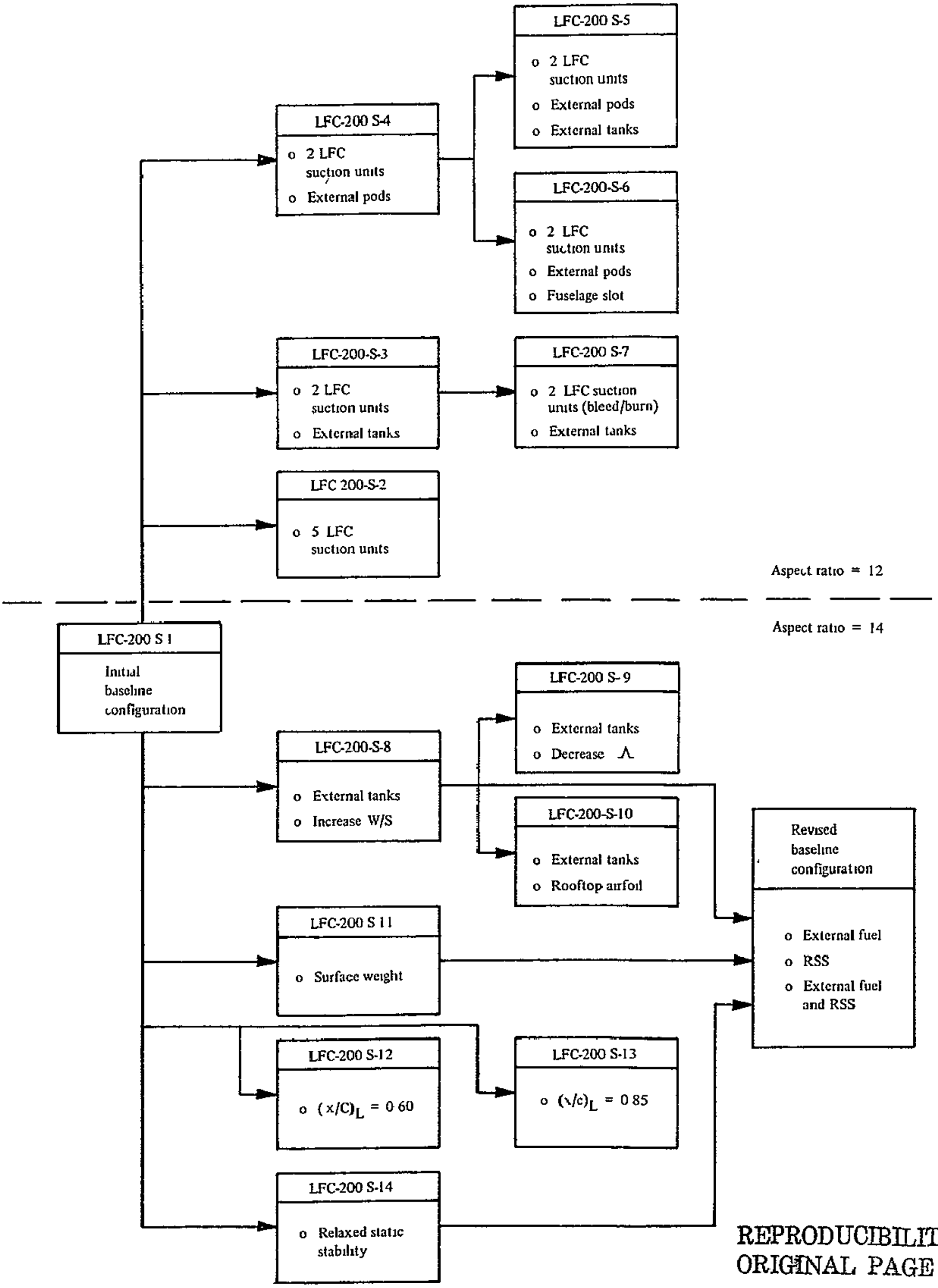


Figure 6. — Sequence of configuration variations

4.0 CONFIGURATION DESCRIPTIONS

The configuration characteristics selected in the preceding section for the final LFC aircraft established a basis for the detailed development of aircraft and LFC systems. This section presents a summary description of the selected 200- and 400-passenger LFC and TF aircraft

4.1 LFC CONFIGURATIONS

4.1.1 LFC-200-R

The LFC-200-R configuration is a wide-body configuration capable of transporting 200 passengers, their baggage, and 4536 kg (10,000 lb) of cargo over the intercontinental range of 10,186 km (5500 n mi) at Mach 0 80 The wide-body cabin is designed to accommodate 40 first-class and 160 tourist-class passengers The cabin is arranged in a two-aisle configuration with the required entry/escape doors, lavatories, and passenger service stations. Galley and baggage provisions are located below the cabin floor. The flight deck, with provisions for a crew of three, provides necessary controls and instrumentation required for long-range commercial operation.

As shown in figure 7, LFC-200-R is a low-wing T-tail monoplane with four aft-fuselage-mounted propulsion engines. External fuel tanks are located on each wing tip. The airplane and power plants are designed to meet community noise level requirements specified by FAR Part 36 minus 10 EPNdB

The LFC-200-R wing is a moderately swept, high-aspect-ratio structure with outboard ailerons By using aileron deflection, full-span flaps are provided to meet required field performance. Spoilers are located over the inboard flap segments. Fuel is carried in the total span of the wing, including the cross-fuselage wing box and in the two tip tanks. As illustrated by figure 8, the upper and lower wing surfaces are provided with suction capability to 75% chord. Empennage LFC surfaces extend to 65% chord The ducting arrangement and the installation of the bleed-burn suction units is shown in figure 9. Characteristics of the suction units are summarized in figure 10

4.1.2 LFC-400-R

The LFC-400-R airplane is a wide-body configuration designed to transport 400 passengers, their baggage, and 9072 kg (20,000 lb) of cargo over the intercontinental range of 10,186 km (5500 n mi) at a speed of Mach 0.80 The wide-body fuselage accommodates 80 first-class and 320 tourist-class passengers in a two-aisle cabin configuration The cabin provides the required entry/escape doors, lavatories and passenger service stations required for long-range operation. The flight deck has provisions for 3 crew members and controls and instrumentation compatible with international flight requirements.

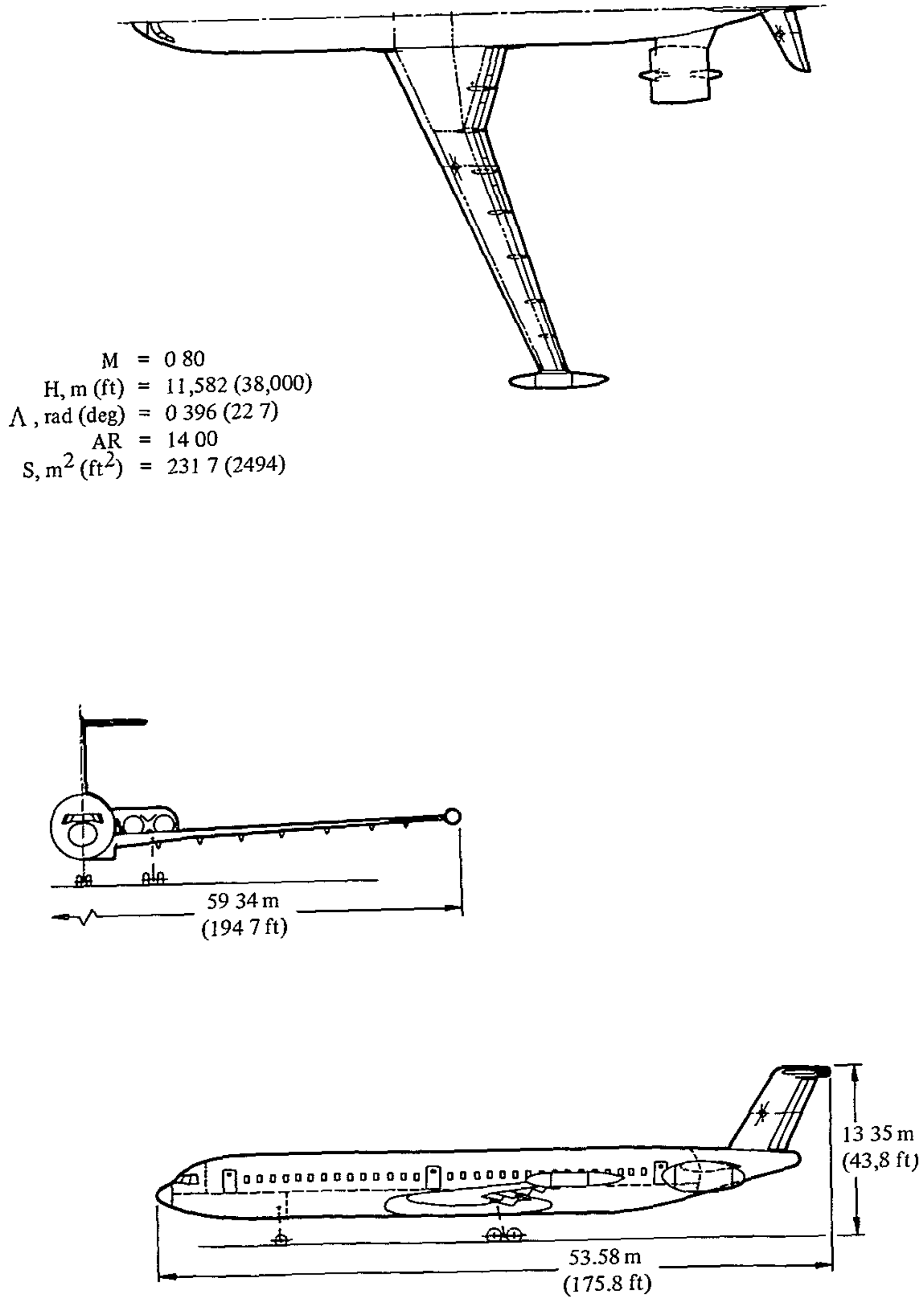


Figure 7. — General arrangement, LFC-200-R

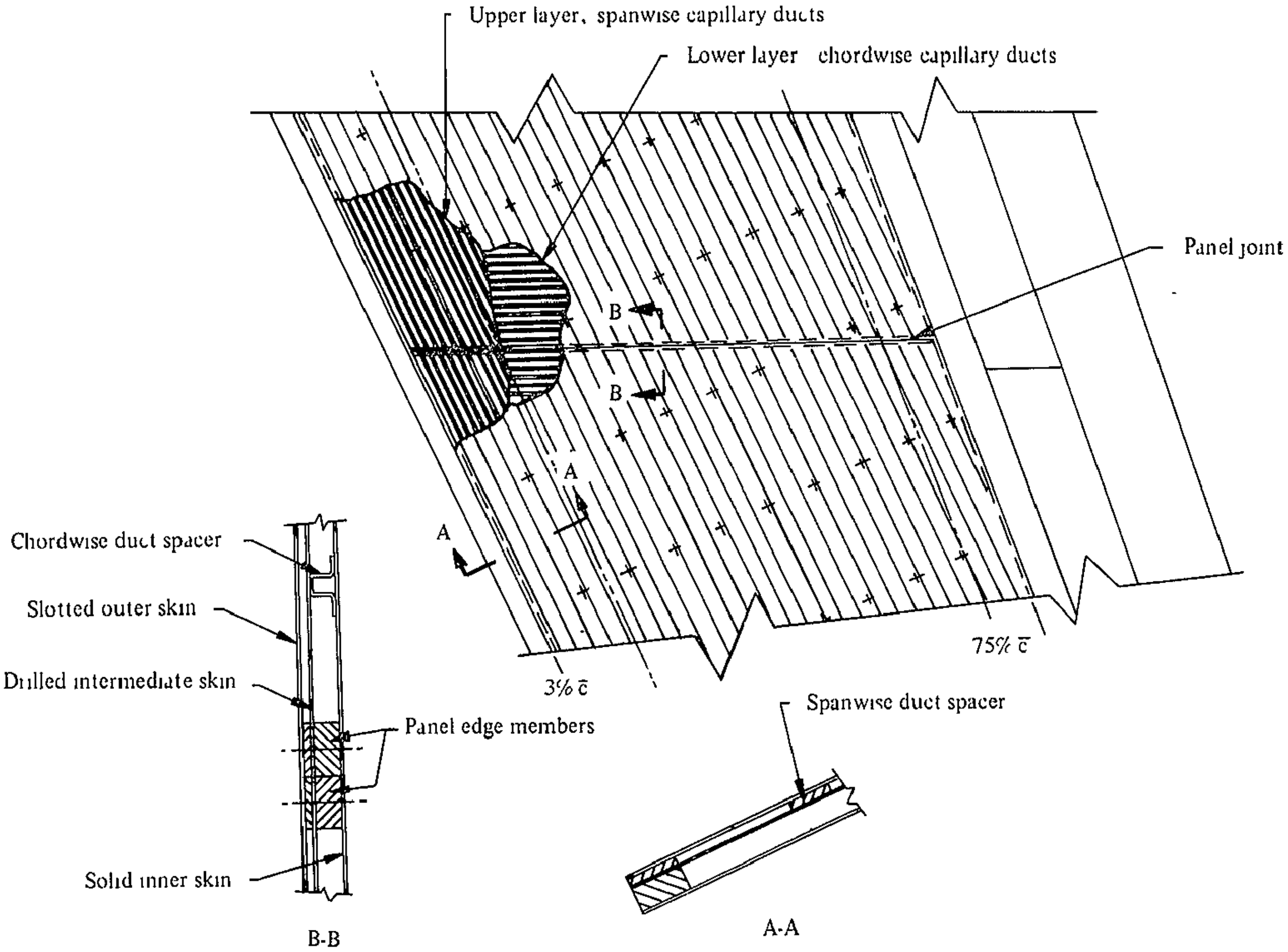


Figure 8. — Typical LFC surface panel

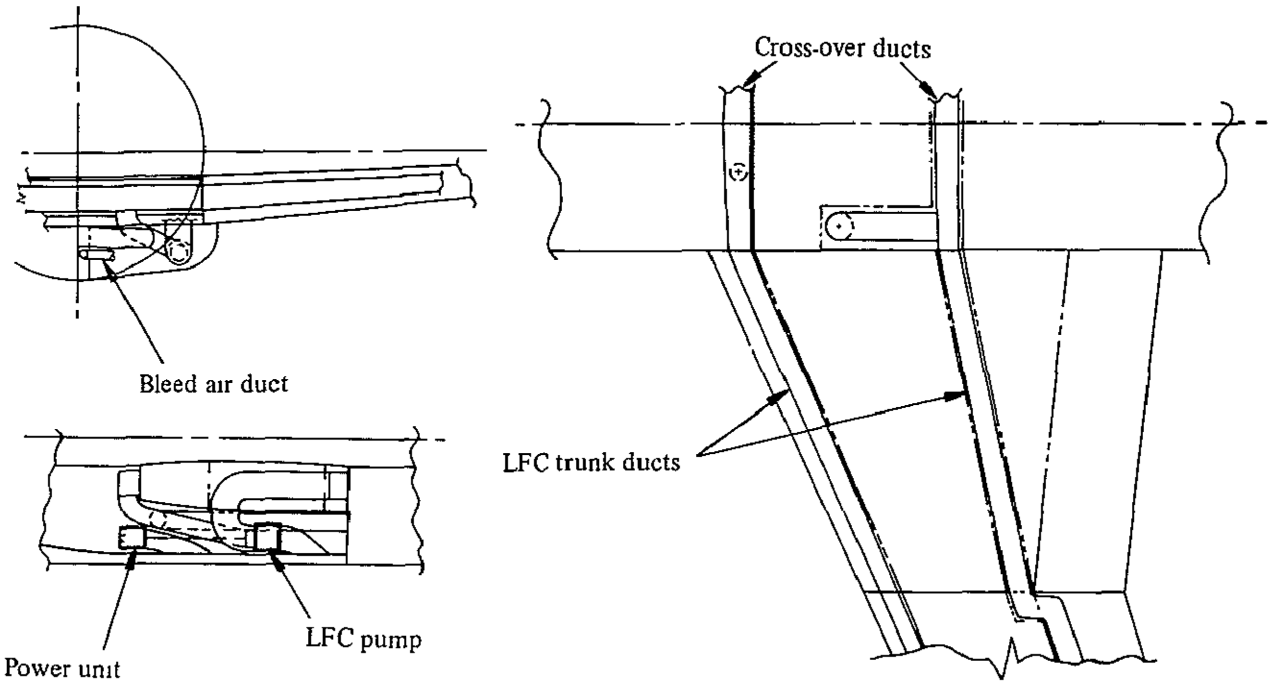
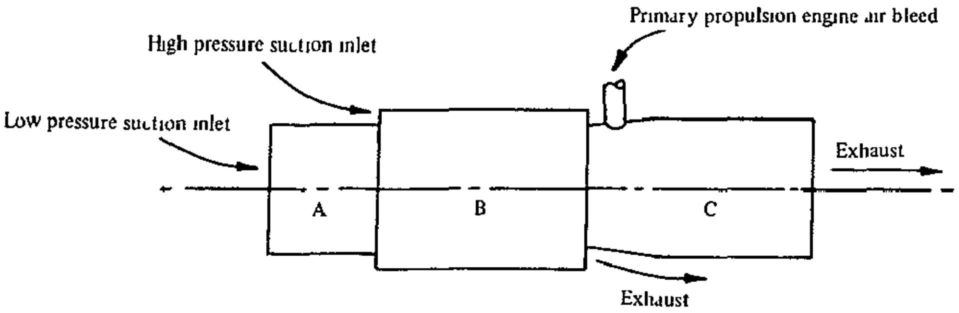


Figure 9. — LFC suction unit installation, LFC-200-R



	A Boost compressor	B Main compressor	C Power unit
Diameter	26.9 cm (10.6 in)	31.9 cm (12.5 in)	28.4 cm (11.2 in)
Length	22.4 cm (8.8 in)	43.2 cm (17.0 in)	47.8 cm (18.8 in)
Weight	10.9 kg (24.0 lb)	25.9 kg (57.2 lb)	84.4 kg (186 lb)*
Sea level equivalent conditions			
Shaft power output	—	—	649.9 Kw (871.5 H.P.)
Net thrust	—	0	0
Fuel flow	—	—	45.3 g/sec (359.7 lb/hr)*
Cruise conditions Altitude = 11582 m (38,000 ft), 0.8 Mach			
Net thrust	—	0	0
Fuel flow	—	—	8.00 g/sec (63.5 lb/hr)*

*Includes penalties to primary propulsion engine weight and fuel flow resulting from bleed plus bleed ducting weight and pressure losses

Figure 10. — Bleed-burn powered suction unit, LFC-200-R

As shown in figure 11, LFC-400-R is a low-wing T-tail monoplane with four aft-fuselage-mounted propulsion engines The wing is a moderately swept, high aspect ratio structure with outboard ailerons. Full-span flaps are provided to meet required field performance. Spoilers are located over the inboard flaps. Fuel is carried in the full span of the wing, including the cross fuselage wing box.

Except for dimensional differences, the LFC surface and ducting system are identical to those of the 200-passenger aircraft. Specific characteristics of the bleed-burn suction units for LFC-400-R are described by figure 12.

4 2 TF CONFIGURATIONS

Optimized advanced technology turbulent-flow aircraft were developed to establish reference levels of fuel consumption and economic performance for use in evaluating the benefits of the final LFC aircraft. Based on the results of the configuration variations conducted for the LFC aircraft, applicable variations of the TF baselines were evaluated to ensure the selection of TF configurations demonstrating optimized fuel efficiency

4.2.1 TF-200

As illustrated by figure 13, the TF-200 configuration is very similar to the selected LFC-200 aircraft. The fuselages are identical and both configurations employ four aft-fuselage-mounted engines, a T-tail, tip-mounted external fuel tanks, and relaxed static stability. The major observable configurational differences in the selected LFC and TF aircraft are in the aspect ratio and wing sweep. LFC-200 configurations have an aspect ratio of 14.0 and a wing sweep of 0 396 rad (22.7 deg), while the corresponding values for TF-200 are 12 5 and 0 436 rad (25 deg).

4.2.2 TF-400

The general arrangement of the selected TF-400 configuration is shown in figure 14.

As in the case of the 200-passenger aircraft, the 400-passenger TF and LFC configurations are very similar Fuselage, empennage, and engine arrangements are the same. The primary differences are in the use of 0.12 $\bar{c}$ leading edge devices on the TF-400 aircraft, aspect ratio, and wing sweep The LFC-400 configurations have an aspect ratio of 14.0 and a wing sweep of 0 396 rad (22.7 deg). The TF-400 aircraft has an aspect ratio of 12 2 and a wing sweep of 0.436 rad (25 deg).

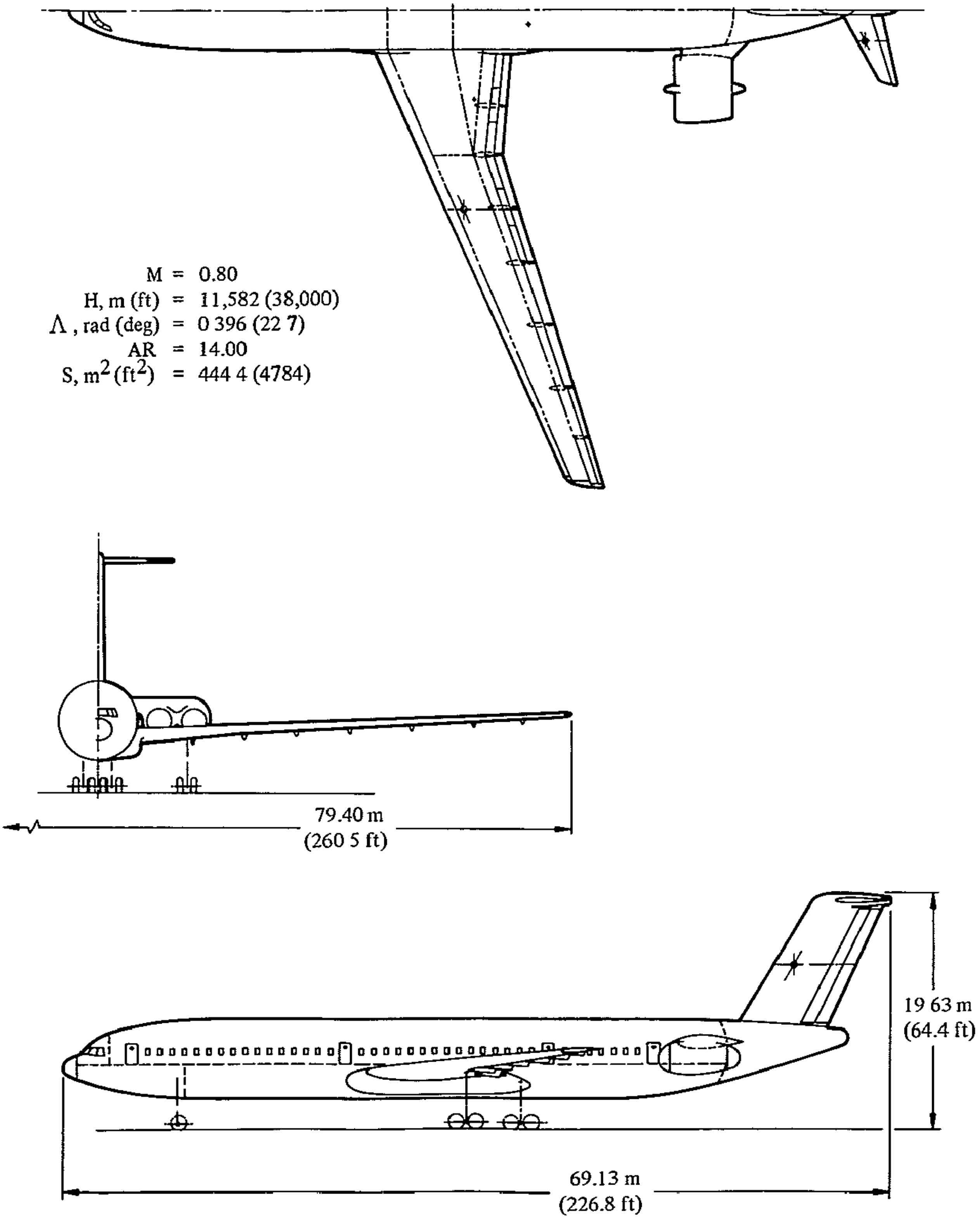
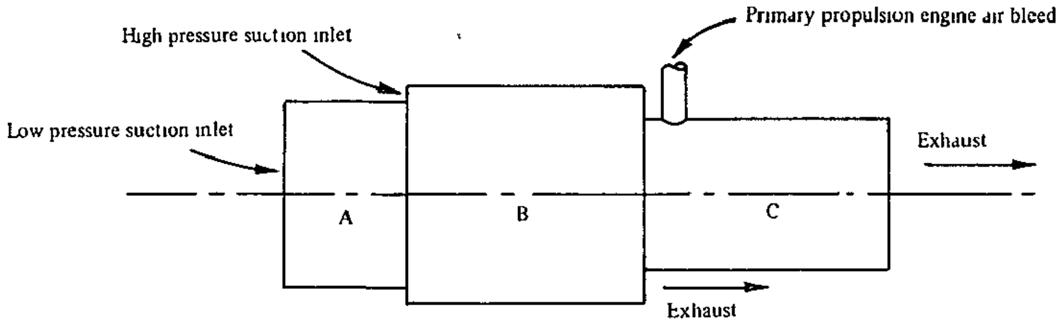


Figure 11. — General arrangement, LFC-400-R



	A Boost compressor	B Main compressor	C Power unit
Diameter	38 1 cm (15 0 in)	44 5 cm (17 5 in)	31 0 cm (12 2 in)
Length	25 4 cm (10 0 in)	48 8 cm (19 2 in)	50 0 cm (19 7 in)
Weight	25 1 kg (55 4 lb)	57 9 kg (127 7 lb)	114 8 kg (253 lb)*
Sea level equivalent conditions			
Shaft power output	—	—	1282 9 Kw (1720 4 H P)
Net thrust	—	0	0
Fuel flow	—	—	89 0 g/sec (706 3 lb/hr)*
Cruise conditions Altitude = 11582 m (38,000 ft), 0 8 Mach			
Net thrust	—	0	0
Fuel flow	—	—	15 7 g/sec (124 7 lb/hr)*

* Includes penalties to primary propulsion engine weight and fuel flow resulting from bleed plus bleed ducting weight and pressure losses

Figure 12. — Bleed-burn powered suction unit, LFC-400-R

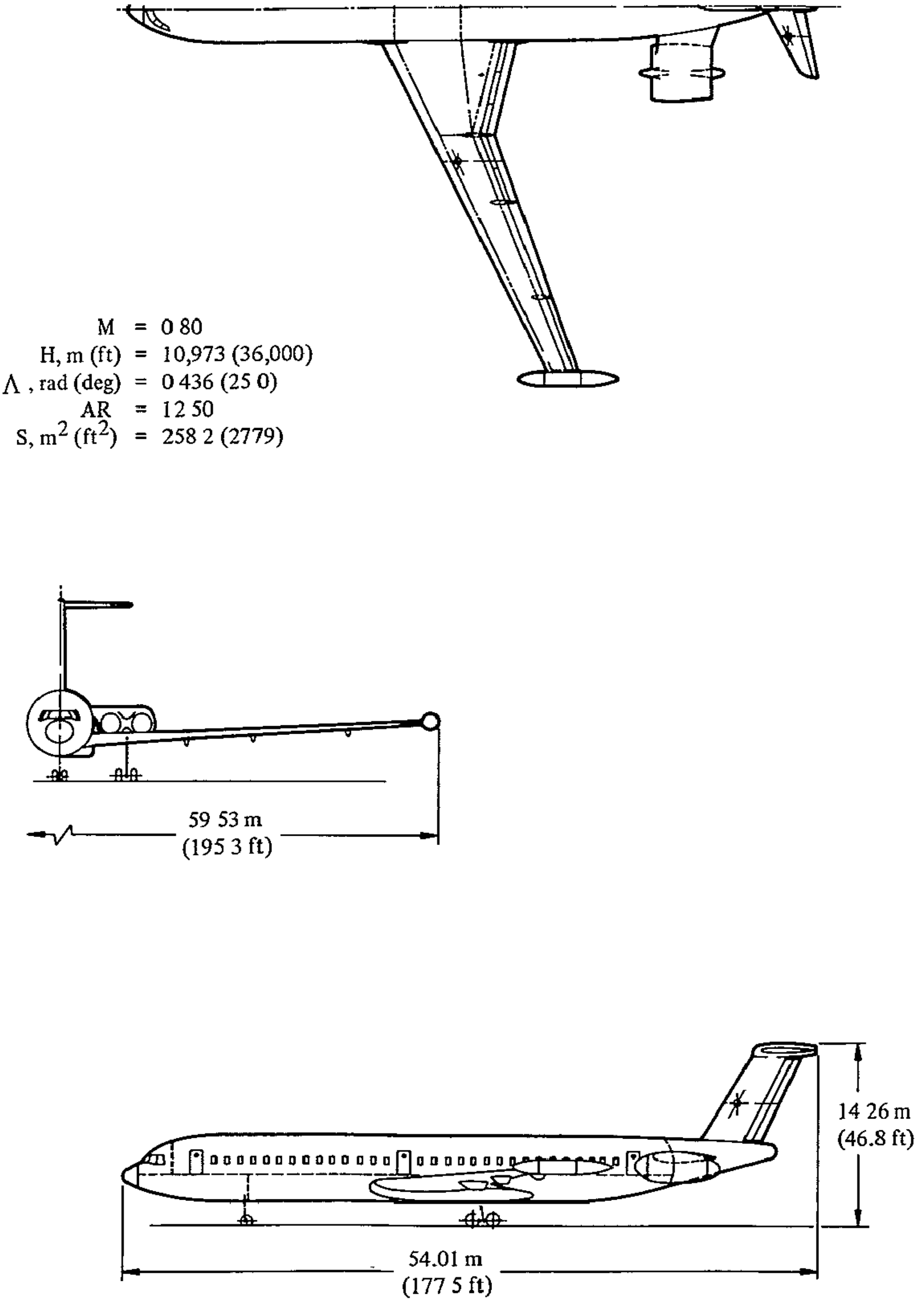


Figure 13. — General arrangement, TF-200

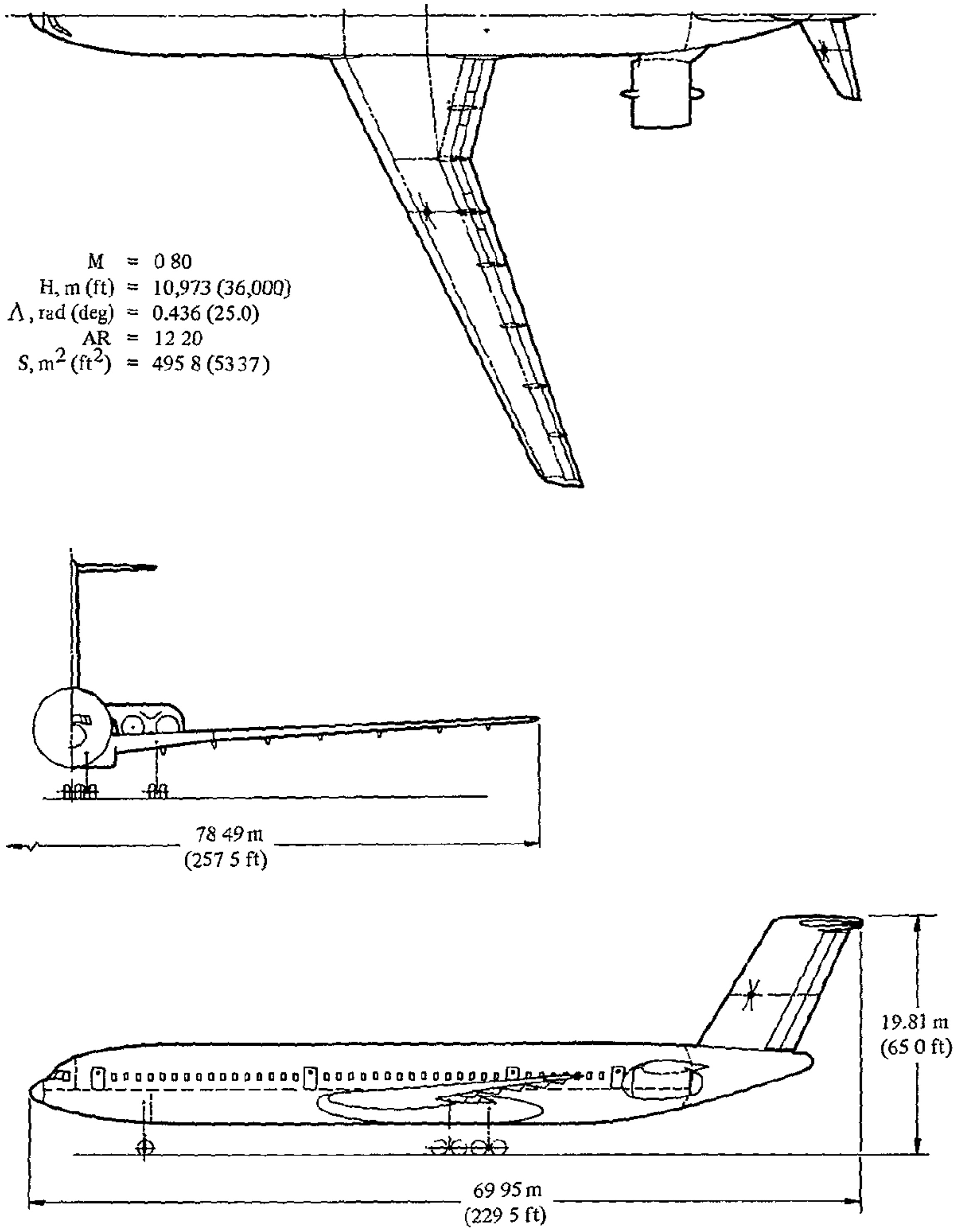


Figure 14. — General arrangement, TF-400

5.0 COMPARISON OF LFC AND TF AIRCRAFT

The ultimate objective of the study summarized herein is a comparison of the relative performance and economics of advanced technology laminar-flow-control and turbulent-flow transport aircraft optimized for the same mission.

In this section, the optimized LFC and TF aircraft described in the preceding section are compared on the basis of weight, drag, fuel consumption, and cost. Production, research and development, and direct operating cost comparisons are included. For the LFC aircraft, the sensitivity of DOC to variations in the price of fuel, maintenance costs, production cost, and average stage length is evaluated. Summary comparisons are presented to illustrate the influence of configuration variations on LFC and TF aircraft, the relative fuel efficiency and DOC of 200- and 400-passenger transports, and the relative fuel efficiency of the study aircraft and current commercial transports.

5.1 COMPARISON OF 200-PASSENGER AIRCRAFT

Table 4 summarizes the geometry, weights, performance, fuel efficiency, and economics of the final 200-passenger TF and LFC aircraft. With the same cruise Mach number and payload, these aircraft have the same productivity. The major geometrical difference is in the aspect ratio of 14.0 for the LFC aircraft and 12.5 for the TF configuration. As required by differences in gross weight and wing loading, there are also variations in the reference wing areas of the aircraft. It will be observed that the L/D of the LFC aircraft is about 28 percent greater than that of the TF aircraft.

Fuel consumption of LFC-200-R is 28.2% less than that of TF-200. Compared to TF-200, the improvement in fuel efficiency for LFC-200-R is 39.4%.

Detailed comparisons of weight, drag, and cost are presented in the sections which follow.

5.1.1 WEIGHT

Table 5 presents a comparison of weight elements for the 200-passenger aircraft. The weight penalty of 3260 kg (7187 lb) for the LFC system on LFC-200-R is balanced by the reduced weight of the airframe and propulsion systems for the smaller LFC aircraft, with the result that the empty weight of LFC-200-R is 1.8% less than that of TF-200. Due to the much lower fuel requirement of the LFC aircraft, the gross weight of LFC-200-R is 12.0% less than that of TF-200.

TABLE 4. SUMMARY COMPARISON OF 200-PASSENGER TF AND LFC AIRCRAFT

Characteristic	TF-200		LFC-200-R	
Cruise M	0.80		0.80	
Cruise altitude, m (ft)	10,973	(36,000)	11,582	(38,000)
Wing sweep, rad (deg)	0.436	(25.0)	0.396	(22.7)
Aspect ratio	12.50		14.00	
Wing loading, kg/m^2 (lb/ft^2)	652	(133.47)	640	(131.00)
Wing t/c ratio	0.1075		0.1088	
Wing area, m^2 (ft^2)	258.2	(2779)	231.7	(2494)
Cruise L/D	22.63		28.76	
Engine thrust, N (lb)	114,936	(25,840)	96,913	(21,788)
Bypass ratio	6.00		6.00	
Cruise power ratio	0.87		0.78	
Gross weight, kg (lb)	173,434	(382,351)	152,687	(336,612)
Empty weight, kg (lb)	75,300	(166,006)	73,932	(162,990)
Block fuel, kg (lb)	58,788	(129,604)	42,198	(93,028)
Fuel efficiency, skm/kg fuel (ssm/lb fuel)	34.65	(9.77)	48.29	(13.62)
Flyaway cost, \$10^6	23.218		23.503	
DOC, ¢/skm (¢/ssm)				
Fuel price, \$/l (\$/gal)				
0.066 (0.25)	0.804	(1.294)	0.761	(1.224)
0.132 (0.50)	1.046	(1.684)	0.935	(1.505)
0.264 (1.00)	1.532	(2.465)	1.284	(2.066)

TABLE 5 COMPARISON OF WEIGHT ELEMENTS FOR 200-PASSENGER TF AND LFC AIRCRAFT

Item	TF-200		LFC-200-R	
	kg	lb	kg	lb
Wing	21,120	46,560	19,910	43,894
Horizontal Tail	902	1989	782	1725
Vertical Tail	929	2049	829	1828
Fuselage	14,404	31,755	14,276	31,472
Landing Gear	7318	16,134	6734	14,846
Nacelle/Pylon	2529	5575	2143	4725
Propulsion System	10,901	24,032	9250	20,392
Systems & Equipment	17,197	37,912	16,748	36,921
LFC System				
Surfaces			2188	4823
Engines			252	555
Engine Installation			312	688
Ducting			508	1121
Weight Empty	75,300	166,006	73,932	162,990
Operating Equipment	6608	14,567	6453	14,227
Operating Weight	81,908	180,573	80,384	177,217
Payload	23,769	52,400	23,769	52,400
Zero Fuel Weight	105,677	232,973	104,153	229,617
Fuel	67,757	149,378	48,534	106,995
Gross Weight	173,434	382,351	152,687	336,612

5.1.2 DRAG

Drag coefficients based on the reference wing area are listed for the 200-passenger aircraft in table 6. With the exception of the laminarized wing and empennage and a corresponding decrease in total interference and roughness drag, components of the TF and LFC aircraft have essentially equal drag. Relative to TF-200, the profile drag is reduced by 35.7% for LFC-200-R. The total drag reduction is 23 5%.

5.1.3 COST

Production, research and development, and direct operating costs for the final 200-passenger TF and LFC aircraft are compared in tables 7, 8, and 9 Since the LFC aircraft are somewhat smaller than the TF aircraft, the empty manufacturing cost of the basic airframe and engines is lower for these aircraft. However, the addition of $1 049 million for LFC system costs on LFC-200-R results in a 1.2% increase in flyaway cost for the LFC aircraft. It is interesting to note that the LFC system cost represents 5 0% of the total empty manufacturing cost

R&D Costs are largely dependent upon the aircraft production costs. The greater production cost of the LFC aircraft and the increase in flight test requirements for the additional LFC systems is reflected in the R&D cost comparisons of table 8.

Table 9 presents a breakdown of direct operating costs for the TF and LFC aircraft selected for the 200-passenger mission At a fuel price of $0 093/1 ($0 35/gal), the DOC of the LFC aircraft is lower than that of the TF aircraft by 7.8%. As a result of the additional maintenance required for LFC system elements, direct maintenance costs for LFC-200-R are greater than those of TF-200 by 17.0% The combination of reduced maintenance costs for the smaller main propulsion engines and the lower fuel consumption of LFC aircraft compensates for the additional LFC system maintenance. Fuel costs for LFC-200-R are lower than those for TF-200 by 28.1%

5.2 COMPARISON OF 400-PASSENGER AIRCRAFT

Characteristics of the final 400-passenger TF and LFC aircraft are summarized in table 10. As in the case of the 200-passenger aircraft,the 400-passenger aircraft provide the same productivity and therefore are directly comparable in terms of fuel efficiency and cost The geometry of the TF and LFC aircraft differs primarily in the selection of aspect ratio The TF aircraft has an aspect ratio of 12 2, while the LFC aircraft has an aspect ratio of 14.0 Both of the 400-passenger aircraft have a wing loading of 684 kg/m^2 (140 lb/ft^2) Differences in wing area are consistent with gross weight variations among the aircraft. L/D of the LFC aircraft is about 27% greater than that of the TF configuration

The fuel consumption of LFC-400-R is 26.7% less than that of TF-400. Compared to TF-400, the improvement in fuel efficiency for LFC-400-R is 36.4%.

Detailed comparisons of weight, drag, and cost for the 400-passenger aircraft are presented in the sections which follow.

TABLE 6. COMPARISON OF C_D COMPONENTS FOR 200-PASSENGER TF AND LFC AIRCRAFT

Item	TF-200 $S_W = 258\ 2\ m^2$ (2779 ft^2)	LFC-200-R $S_W = 231\ 7\ m^2$ (2494 ft^2)
Wing	0067	0028
Fuselage	0044	0050
Upsweep	0002	0002
Pylon	0001	.0001
Nacelle	0013	0013
Horizontal Tail	.0006	0002
Vertical Tail	0007	0003
Compressibility	0011	0011
Interference	0004	0002
Roughness	0004	0002
Profile	0159	0114
Trim	0012	0012
Induced	.0106	0110
Total	0277	0236

TABLE 7. COMPARISON OF PRODUCTION COSTS FOR 200-PASSENGER TF AND LFC AIRCRAFT

Cost Element	TF-200	LFC-200-R
Empty Mfg Cost	10.590	10.119
LFC System		
Surfaces		0 587
Ducting		0.085
Engines/Installation		0.377
Total Empty Mfg Cost	10.590	11 168
Sustaining Eng/Fee/Warranty	6 536	6 709
Airframe Cost	17 126	17 877
Engine Cost	3.365	2.909
Avionics Cost	.500	.500
R&D Cost	2 227	2.217
Total Flyaway Cost	23 218	23.503
	Millions of Dollars	

TABLE 8 COMPARISON OF R&D COSTS FOR 200-PASSENGER TF AND LFC AIRCRAFT

Cost Element	TF-200	LFC-200-R
Tech Data	15 987	15 817
Design Engineering	355 272	351 492
Development Tooling	214 291	207 873
Development Test Articles	99 757	102 432
Flight Test	34.033	38 419
Special Support Equipment	4 263	4 218
Development Spares	55 808	55 687
Total	779 411	775 938
	Millions of Dollars	

TABLE 9. COMPARISON OF DOC ELEMENTS FOR 200-PASSENGER TF AND LFC AIRCRAFT

Cost Element	TF-200		LFC-200-R	
	$	%	$	%
Flying Operations	10,153	55.3	8138	48.1
Flight Crew	2548	13.9	2472	14 6
Fuel and Oil	6926	37 7	4977	29 4
Hull Insurance	679	3 7	689	4 1
Direct Maintenance	3220	17.5	3766	22 2
Airplane				
Labor	409	2 2	408	2.4
Materials	618	3 4	642	3 8
Engine				
Labor	262	1.4	258	1.5
Materials	1151	6 3	995	5.8
LFC System				
Labor			164	1.0
Materials			369	2.2
Maintenance Burden	780	4.2	930	5.5
Depreciation	4993	27 2	5028	29 7
Total DOC per Flight	18,366	100 0	16,932	100 0

Fuel Price = $0 093/l ($0 35/gal)

TABLE 10. SUMMARY COMPARISON OF 400-PASSENGER TF AND LFC AIRCRAFT

Characteristic	TF-400	LFC-400-R
Cruise M	0.80	0.80
Cruise altitude, m (ft)	10,973 (36,000)	11,582 (38,000)
Wing sweep, rad (deg)	0.436 (25.0)	0.396 (22.7)
Aspect ratio	12.20	14.00
Wing loading, kg/m^2 (lb/ft^2)	684 (140.00)	684 (140.00)
Wing t/c ratio	0.1037	0.1033
Wing area, m^2 (ft^2)	495.8 (5337)	444.4 (4784)
Cruise L/D	23.60	29.90
Engine thrust, N (lb)	220,269 (49,521)	211,502 (47,550)
Bypass ratio	6.00	6.00
Cruise power ratio	0.88	0.71
Gross weight, kg (lb)	348,982 (769,361)	312,654 (689,273)
Empty weight, kg (lb)	156,785 (345,645)	155,556 (342,959)
Block fuel, kg (lb)	112,700 (248,456)	82,599 (182,096)
Fuel efficiency, skm/kg fuel (ssm/lb fuel)	36.17 (10.20)	49.35 (13.91)
Flyaway cost, $\$10^6$	37.208	38.343
DOC, ¢/skm (¢/ssm)		
Fuel price, $/l ($/gal)		
0.066 (0.25)	0.649 (1.045)	0.612 (0.985)
0.132 (0.50)	0.882 (1.419)	0.782 (1.259)
0.264 (1.00)	1.347 (2.167)	1.123 (1.808)

5.2.1 WEIGHT

A comparison of weight elements for the 400-passenger aircraft is provided by table 11. The LFC system weight penalty is 6009 kg (13,247 lb), or 3.0% of the empty weight for LFC-400-R. The empty weight of LFC-400-R is 1.0% less than that of TF-400. The reduced fuel requirement of the LFC aircraft results in a gross weight for LFC-400-R which is 10.4% less than that of TF-400

5.2.2 DRAG

Drag coefficients for the 400-passenger TF and LFC aircraft are listed in table 12. The distribution of drag is generally similar to that described for the 200-passenger aircraft. Laminarization of the wings and empennage provides a reduction of 36.6% in profile drag for the LFC-400-R aircraft. Based on total drag, the corresponding value is 22.2%.

5.2.3 COST

Production, research and development, and direct operating costs for the 400-passenger aircraft are listed in tables 13, 14, and 15.

TABLE 11. COMPARISON OF WEIGHT ELEMENTS FOR 400-PASSENGER TF AND LFC AIRCRAFT

Item	TF-400		LFC-400-R	
	kg	lb	kg	lb
Wing	55,527	122,415	52,825	116,457
Horizontal Tail	1595	3517	1291	2847
Vertical Tail	2384	5255	2004	4417
Fuselage	27,550	60,736	27,331	60,253
Landing Gear	14,900	32,848	13,908	30,662
Nacelle/Pylon	4774	10,524	4588	10,114
Propulsion System	19,766	43,576	18,765	41,369
Systems & Equipment	30,289	66,774	28,845	63,593
LFC System				
Surfaces			4442	9792
Engines			385	849
Engine Installation			478	1053
Ducting			704	1553
Weight Empty	156,785	345,645	155,566	342,959
Operating Equipment	14,969	33,000	14,691	32,385
Operating Weight	171,754	378,645	170,257	375,344
Payload	47,537	104,800	47,537	104,800
Zero Fuel Weight	219,291	483,445	217,794	480,144
Fuel	129,691	285,916	94,861	209,129
Gross Weight	348,982	769,361	312,655	689,273

TABLE 12. COMPARISON OF C_D COMPONENTS FOR 400-PASSENGER TF AND LFC AIRCRAFT

Item	TF-400 $S_W = 495\ 8\ m^2\ (5337\ ft^2)$	LFC-400-R $S_W = 444\ 4\ m^2\ (4784\ ft^2)$
Wing	0062	0026
Fuselage	0037	0042
Upsweep	0001	0001
Pylon	0001	0001
Nacelle	0012	0013
Horizontal Tail	0005	0002
Vertical Tail	0010	0004
Compressibility	0011	0011
Interference	0004	.0002
Roughness	0004	0002
Profile	0147	0104
Trim	0012	0012
Induced	0120	0126
Total	0279	0242

TABLE 13. COMPARISON OF PRODUCTION COSTS FOR 400-PASSENGER TF AND LFC AIRCRAFT

Cost Element	TF-400	LFC-400-R
Empty Mfg Cost	17 241	16 524
LFC System		
Surfaces		892
Ducting		109
Engines/Installation		538
Total Empty Mfg Cost	17 241	18 063
Sustaining Eng/Fee/Warranty	9 752	10 035
Airframe Cost	26 993	28 098
Engine Cost	5 873	5 673
Avionics Cost	500	500
R&D Cost	3 842	4 073
Total Flyaway Cost	37 208	38 344
	Millions of Dollars	

TABLE 14. COMPARISON OF R&D COSTS FOR 400-PASSENGER TF AND LFC AIRCRAFT

Cost Element	TF-400	LFC-400-R
Tech Data	28 338	31 433
Design Engineering	629.734	698.511
Development Tooling	385 553	379.540
Development Test Articles	148 314	152 673
Flight Test	59.543	68 164
Special Support Equipment	7 557	8 382
Development Spares	85 475	86 883
Total	1,344.514	1,425 586
	Millions of Dollars	

TABLE 15 COMPARISON OF DOC ELEMENTS FOR 400-PASSENGER TF AND LFC AIRCRAFT

Cost Element	TF-400		LFC-400-R	
	$	%	$	%
Flying Operations	17,372	57.4	13,788	49.7
Flight Crew	3023	10.0	2942	10.6
Fuel and Oil	13,261	43.8	9724	35.1
Hull Insurance	1088	3.6	1122	4.0
Direct Maintenance	4870	16.1	5690	20.5
Airplane				
Labor	570	1.9	569	2.1
Materials	983	3.2	1025	3.7
Engine				
Labor	287	1.0	285	1.0
Materials	2008	6.6	1940	7.0
LFC System				
Labor			228	0.8
Materials			398	1.4
Maintenance Burden	1022	3.4	1243	4.5
Depreciation	8028	26.5	8255	29.8
Total DOC per Flight	30,270	100.0	27,733	100.0
Fuel Price = $0.093/l ($0.35/gal)				

As shown by table 13, the LFC system cost of $1.539 million accounts for 8.5% of the total empty manufacturing cost for LFC-400-R. Total flyaway cost of the LFC-400-R aircraft is 3.1% greater than that of TF-400.

R&D costs for the final study aircraft are compared in table 14. As in the case of the 200-passenger comparisons, the higher production costs of the LFC aircraft and the additional flight test requirements imposed by the LFC systems results in somewhat higher R&D costs for the LFC aircraft.

A comparison of direct operating cost elements for the 400-passenger TF and LFC aircraft is presented in table 15. For the selected fuel price of $0.093/l ($0.35/gal), the DOC for LFC-400-R is 8.4% less than that of TF-400. The addition to direct maintenance costs due to the LFC system is 16.8%. Fuel costs for LFC-400-R are reduced by 26.7% relative to TF-400.

5.3 EVALUATION OF DOC SENSITIVITY

5.3.1 FUEL PRICE, LFC MAINTENANCE COST, AND LFC PRODUCTION COST

From May 1973 to July 1975, a period of slightly more than two years, the average price paid by international carriers for a gallon of jet fuel increased from \$0.029/l (\$0.11/gal) to \$0 093/l (\$0.35/gal), an increase of 218% Current indications are that the price of fuel will continue to increase for the foreseeable future. Therefore, it is reasonable and informative to examine the influence of increases in fuel price above the current level on the relative DOC of turbulent-flow and laminar-flow-control transport aircraft.

Figure 15 illustrates the variation of DOC with fuel price for the final study aircraft. In this figure, the DOC for each of the final LFC aircraft and the corresponding TF aircraft is shown as a function of fuel price The point of intersection of the LFC and TF curves defines the fuel price above which the LFC aircraft provides lower DOC than the TF aircraft. Following are the fuel prices at which the LFC and TF aircraft have equal DOC

	FUEL PRICE	
	\$/l	\$/gal
LFC-200-R	0.026	0.11
LFC-400-R	0.026	0.10

Figure 15 also illustrates the impact of variations in the cost of maintaining LFC systems on DOC In generating these data, the maintenance costs peculiar to the LFC system were varied by a factor of ± 0.5. This variation of 50% about the nominal LFC system maintenance cost changes the fuel price at which LFC and TF aircraft have equal DOC by about \$0.016/l (\$0 06/gal).

A similar sensitivity study was conducted to evaluate the influence of variations in the production cost of LFC system elements on DOC. As shown by figure 16, a variation of ± 20% in the production cost of the LFC system has a relatively small impact on the relative DOC of TF and LFC aircraft This variation changes the fuel price at which LFC and TF aircraft have equal DOC by about \$0.011/l (\$0.04/gal).

5.3.2 STAGE LENGTH

The preceding comparisons of fuel efficiency and DOC were based on an assumed average stage length equal to the design range of 10,186 km (5500 n mi). To gain insight into the relative performance of LFC and TF transports under varying operating conditions, a study was conducted to evaluate the influence of average stage length on DOC. The results of this analysis, completed for the LFC-200-R and the TF-200 configurations, are shown in figure 17

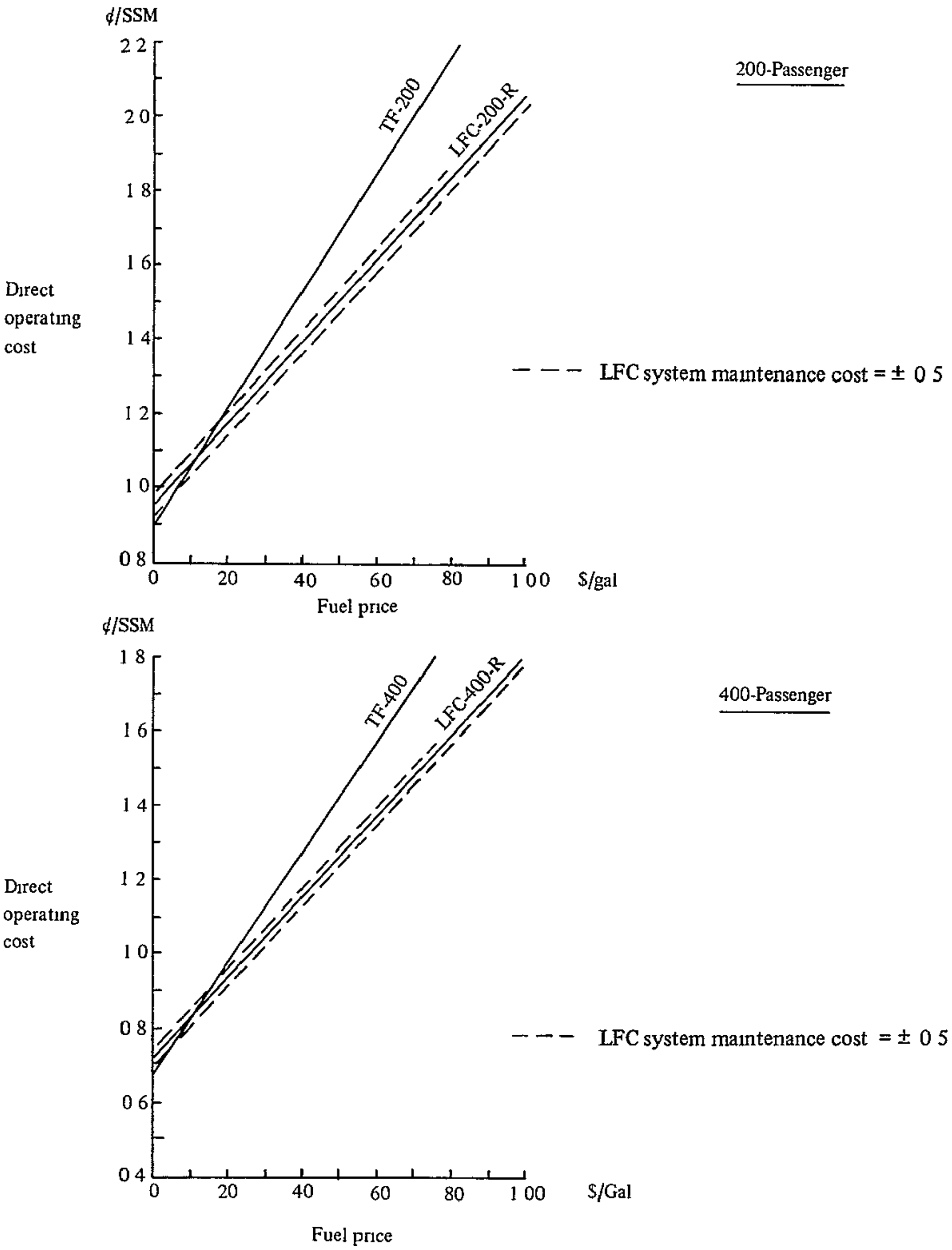


Figure 15. — Sensitivity of DOC to fuel price and LFC maintenance cost

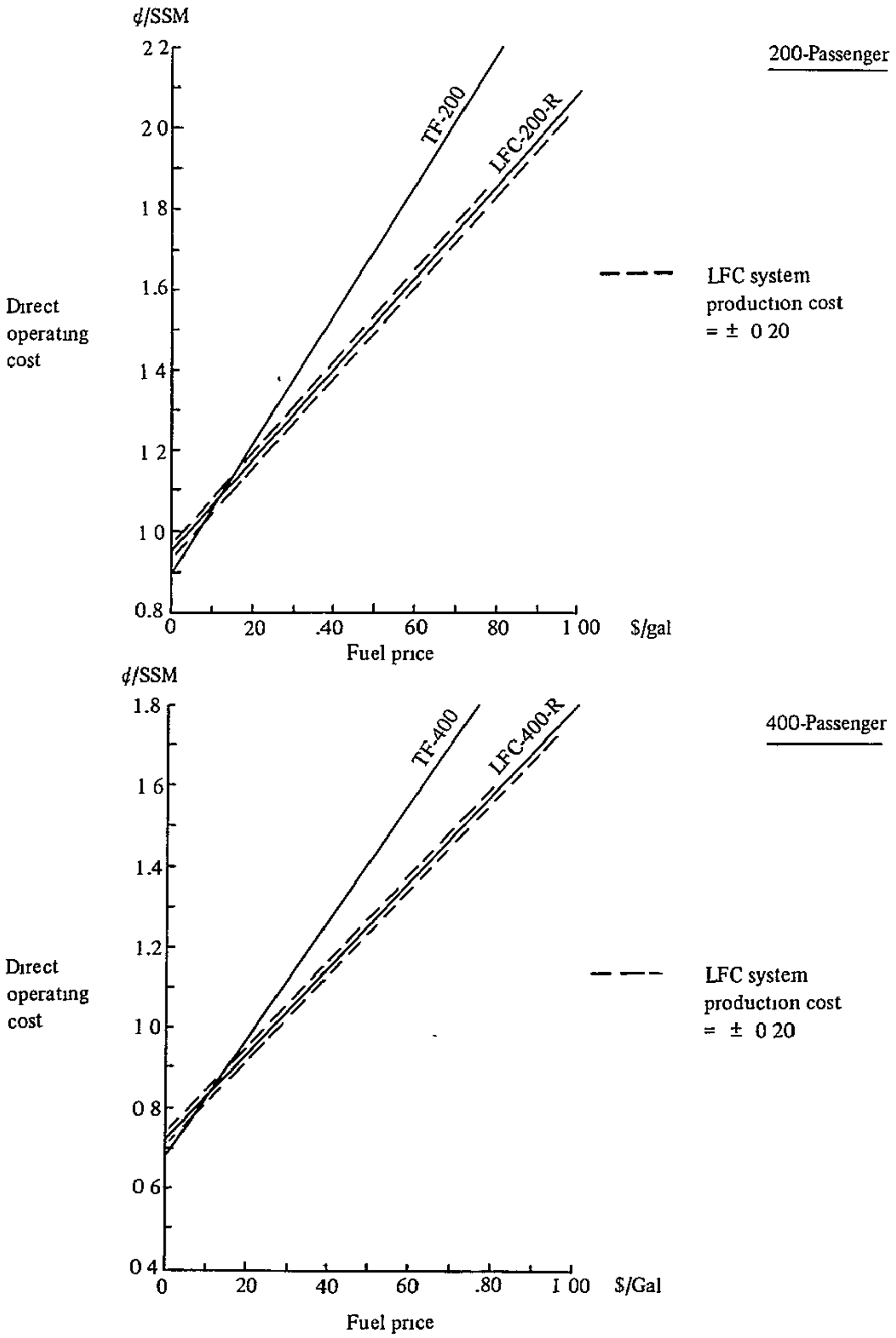


Figure 16. — Sensitivity of DOC to fuel price and LFC production cost

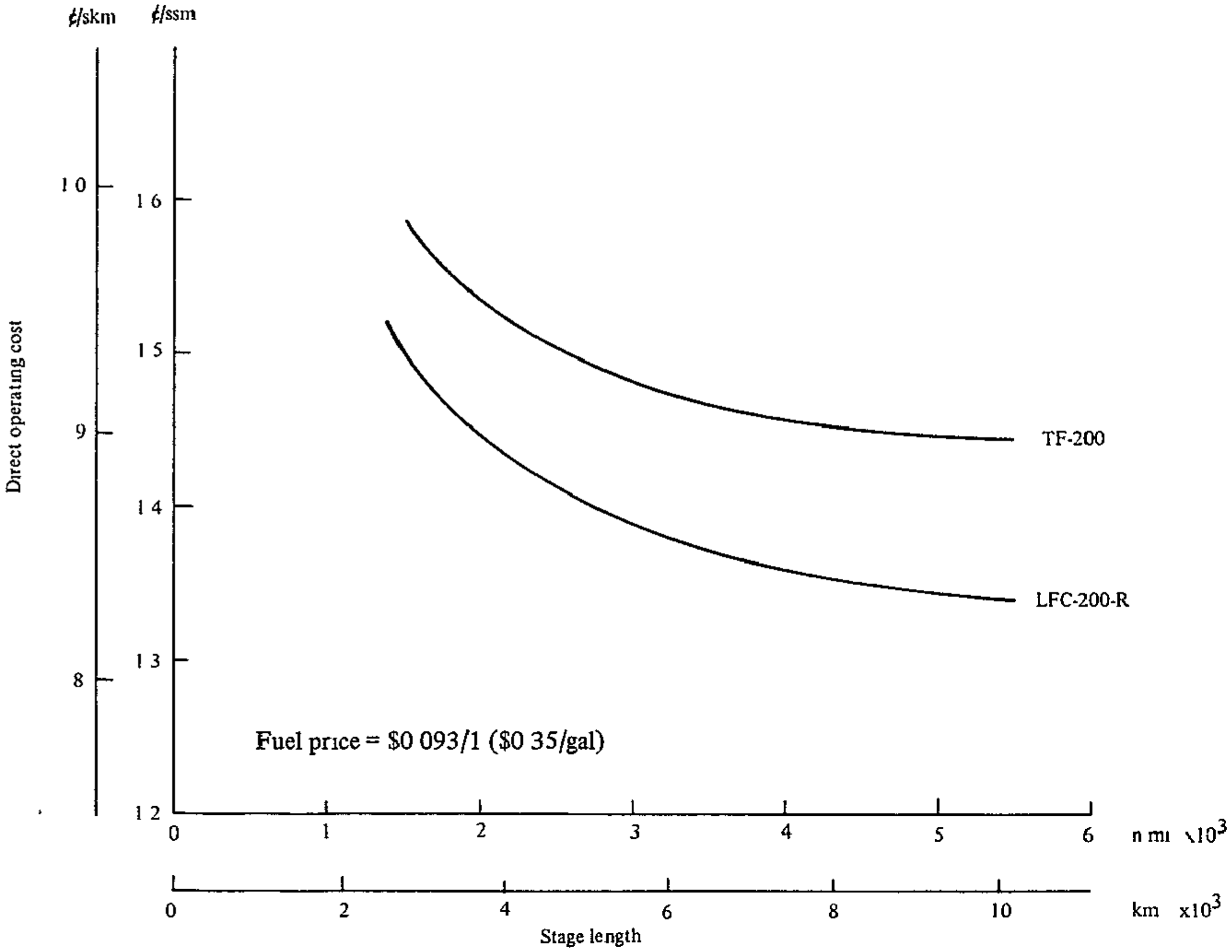


Figure 17. — Sensitivity of DOC to stage length, TF-200 and LFC-200-R

The DOC for both the TF and LFC aircraft are observed to follow the anticipated trend in that DOC increases as stage length is reduced below the design range However, due to the additional system elements on the LFC aircraft which have maintenance requirements sensitive to the number of operating cycles, the DOC of LFC-200-R increases at a faster rate than that of TF-200. At the design range of 10,186 km (5500 n mi), the DOC of LFC-200-R is 7 8% less than that of TF-200 This value decreases to 6.2% at 5556 km (3000 n mi) and 3 5% at 2778 km (1500 n mi)

5.4 SUMMARY COMPARISONS

To establish a reference frame for the evaluation of study results, this section compares the relative impact of configuration variations on TF and LFC aircraft, summarizes the fuel efficiency and DOC of 200- and 400-passenger aircraft, and relates the fuel efficiency of study aircraft to that of current commercial transports.

5 4.1 CONFIGURATION VARIATIONS

In the development of final LFC and TF configurations, a number of configuration variations were evaluated to ensure the selection of optimum aircraft for final comparisons As a result of the configuration evaluations, it was established that fuel efficiency was improved by adding external fuel tanks and relaxed static stability to the 200-passenger configurations and by adding relaxed static stability to the 400-passenger configurations. The relative benefits of such variations for TF and LFC 200- and 400-passenger aircraft are summarized in table 16

TABLE 16 REDUCTIONS IN FUEL CONSUMPTION FOR LFC AND TF CONFIGURATION VARIATIONS

Configuration	Variation								
	External fuel			RSS			External fuel RSS		
	kg	lb	%	kg	lb	%	kg	lb	%
TF-200	1620	3571	2.6	1713	3775	2.8	2989	6587	4.8
LFC-200-R	156	345	0.4	418	921	0.9	601	1326	1.4
TF-400				6428	14171	5.4			
LFC-400-R				2758	6081	3.2			

It is important to observe that all of the configuration variations result in a greater reduction in fuel consumption for both the 200- and 400-passenger TF aircraft than for the corresponding LFC configurations. For example, the addition of external fuel and RSS to TF-200 results in a 4.8% reduction in fuel consumption while the benefit for LFC-200-R is 1.4%. Similarly, the use of RSS on TF-400 provides a 5.4% reduction in fuel consumption. The corresponding LFC configuration benefits by maximum of 3.2%.

These results are to be expected, since any decrease in the size of the wing and empennage, which results from the addition of both external fuel and RSS, provides a greater benefit to TF aircraft than LFC aircraft. Performance of the TF aircraft is improved by reductions in both weight and drag Since the drag of the wings and empennage of the LFC aircraft is only 35% of that of the TF aircraft, the drag reduction afforded by resizing is of little significance, and the LFC aircraft benefits primarily through the weight reduction

5.4.2 FUEL EFFICIENCY

A summary comparison of the fuel consumption, the fuel savings afforded by the addition of LFC, and the fuel efficiency of the four final study aircraft is outlined in table 17. The reduction in fuel consumption is 28.2% for the 200-passenger LFC aircraft and 26.7% for the 400-passenger configuration. Improvement of fuel efficiency is 36.4% for LFC-400-R and 39 4% for LFC-200-R.

The greater fuel savings and improvement in fuel efficiency of the 200-passenger LFC aircraft as compared to the 400-passenger LFC aircraft is a result of the relative performance of the TF configurations used for comparison. Of all of the final study aircraft, only the TF-400 has adequate wing volume to permit the use of leading edge devices. As a result, the takeoff performance of this configuration permits a better match of cruise and takeoff thrust requirements, with an attendant improvement in fuel efficiency relative to the TF-200 configuration.

TABLE 17 SUMMARY COMPARISON OF FUEL EFFICIENCY

Configuration	Block fuel			Fuel efficiency		
	kg	lb	%	s km/kg	ssm/lb	%
TF-200	58,788	129,604		34.65	9.77	
LFC-200-R	42,198	93,028	-28.2	48.29	13.62	39.4
TF-400	112,700	248,456		36.17	10.20	
LFC-400-R	82,599	182,096	-26.7	49.35	13.91	36.4

5.4.3 DIRECT OPERATING COST

Table 18 summarizes comparisons of DOC for the final study aircraft based on the current fuel price of $0.093/1 ($0.35/gal) for international carriers. At this fuel price, the DOC of the 200-passenger LFC aircraft is 7.8% below that of the TF-200 configuration The DOC reduction for LFC-400-R is 8.4%, as compared to TF-400.

5.4.4 COMPARISON WITH CURRENT TRANSPORTS

The comparisons of section 5.4 2 showed that the fuel efficiency of the LFC study aircraft is 36.4% to 39.4% greater than that of the comparable TF study aircraft. However, a realistic evaluation of the study aircraft requires consideration of the performance of the advanced technology TF transports which were developed for comparison with the LFC study aircraft. Based on the data of reference 5, figure 18 shows the fuel efficiency of representative current commercial transports as a function of stage length The corresponding curves for the 200-passenger study aircraft are included for comparison. At a stage length of 5631 km (3500 s mi), the TF and LFC transports demonstrate improvements in fuel efficiency of 9 7% and 50%, respectively, when compared to the best of the current transports. At the design range of 10,186 km (6333 s mi) for the study aircraft, the fuel efficiency of TF-200 is 63 8% greater than that of current transports. Compared to the same transport at this range, the fuel efficiency of LFC-200-R is greater by 130.8%.

TABLE 18. SUMMARY COMPARISON OF DOC

Configuration	**DOC**	
	¢/s km	**¢/ssm**
TF-200	901	1 450
LFC-200-R	831	1.337
TF-400	743	1.195
LFC-400-R	.681	1 095
Fuel price = $0 093/1 ($0.35/gal)		

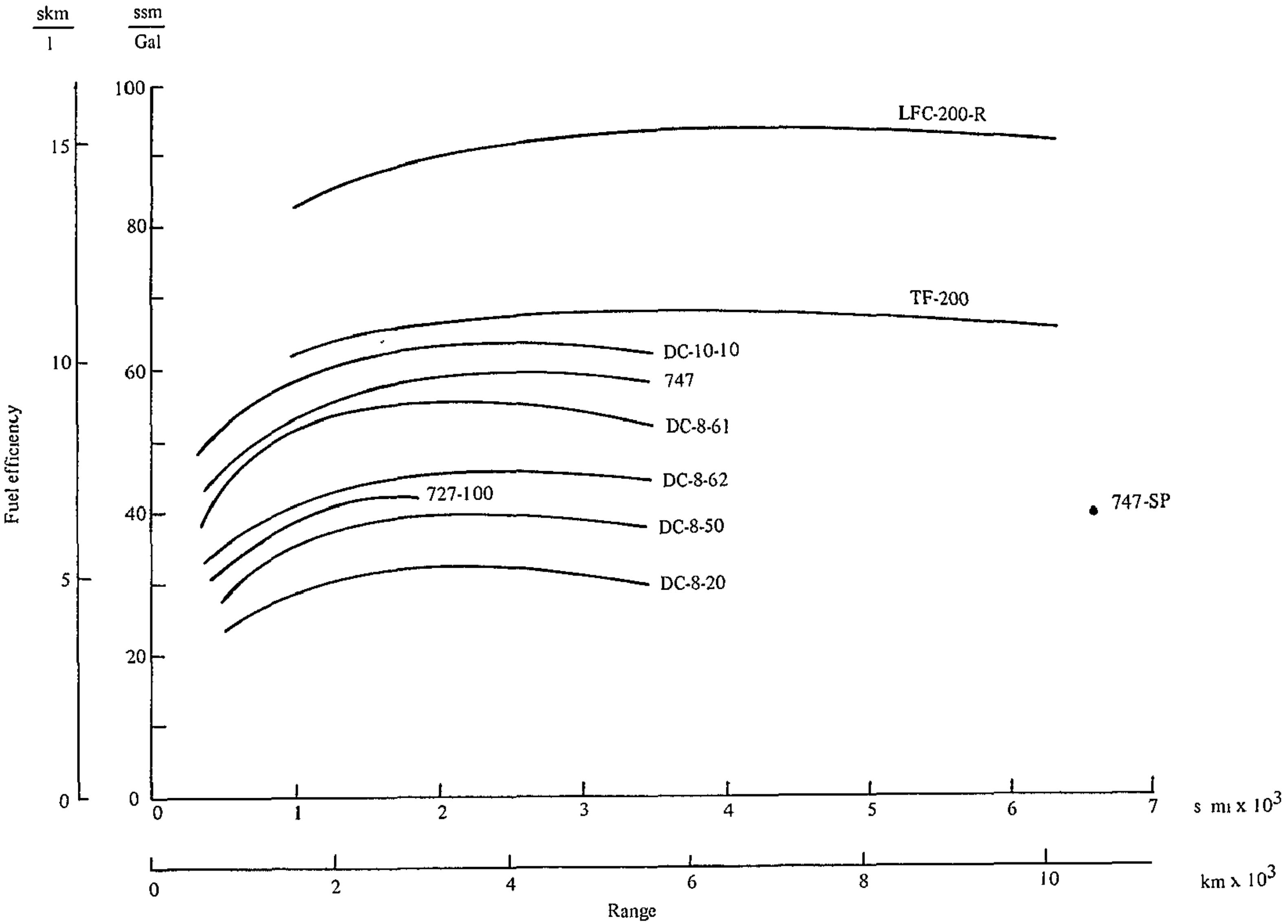


Figure 18 — Fuel efficiency comparisons

6.0 RESEARCH AND TECHNOLOGY REQUIREMENTS

The technical feasibility of laminar flow control was demonstrated over a decade ago by the X-21A program and the economic advantages of LFC transports, based on a realistic assessment of the penalties attending the incorporation of LFC on a transport aircraft, were quantified in the preceding section Although the technical feasibility has been established and a realistic assessment of economic feasibility has been conducted, it is anticipated that two basic requirements must be satisfied before LFC is employed on an operational commercial transport:

(1) Aircraft manufacturers must be convinced that the technology is available to develop and build LFC aircraft without assuming unreasonable levels of risk in satisfying performance guarantees.

(2) The commercial airlines must be convinced of both the economic advantages and the reliability of LFC transports in the airline operating environment.

It is anticipated that these requirements can be satisfied only through a flight validation program which duplicates or closely approximates the airline operating environment. A properly coordinated flight validation program is required to establish the viability of LFC in the profit-oriented commercial airline environment characterized by high utilization rates and stringent schedule requirements. Such a program can provide the data necessary to perform economic evaluations based on observed performance, reliability, and maintainability factors and will permit a realistic comparison of the economic advantages of LFC as compared to alternative fuel-conservation techniques

As evidenced by the X-21A program, the technology requisite to the demonstration of the technical feasibility of LFC was available in 1960 However, the technology necessary for the development of an LFC aircraft compatible with routine operation in the airline environment is not available. The following Research and Technology requirements have been identified for the development of commercial LFC transport aircraft.

LFC Airfoil Development

(1) Analytical definition and experimental verification of laminar boundary-layer stability criteria.

(2) Development of computational methods.

(3) Development of a family of LFC airfoils for varying mission requirements.

(4) Investigation of trailing-edge trimming devices for stabilizing LFC suction requirements for off-design conditions.

LFC System Development

(1) Definition of LFC suction level limits and the corresponding aerodynamic performance variations.

(2) Development of surface design techniques and evaluation of the sensitivity of surface configurations to design tolerances and deterioration.

(3) Development of design concepts for ducting to reduce variations in suction flow levels and suction distribution

(4) Development of suction unit concepts and control systems to minimize variations in suction flow levels.

LFC Surface Materials

(1) Development of porous surface materials.

(2) Investigation of the effect of surface micro-smoothness on suction requirements

(3) Investigation of surface contamination and the development of appropriate cleaning procedures.

(4) Evaluation of environmental compatibility of candidate surface materials.

(5) Investigation of fluorocarbon leading-edge materials and hydrophobic coatings to eliminate potential insect contamination problems.

Design

(1) Analysis and testing of high-aspect-ratio wings

(2) Evaluation of the relative merits of structural and non-structural LFC surfaces and the materials, joining methods, panel sizes, and maintenance procedures appropriate for each surface configuration

(3) Development of mechanical devices for cleaning the wing leading edge

(4) Development of design techniques for the integration of ducting, control surfaces, and actuators into the wing trailing edge.

Manufacturing

(1) Development of representative tooling for manufacturing LFC surfaces.

(2) Development of quality control procedures for manufacturing LFC surfaces.

(3) Validation of LFC surface manufacturing costs

7.0 CONCLUSIONS

Major conclusions of the study, categorized according to study phase, are summarized below It should be observed that both aircraft and LFC system configurations are extremely sensitive to the requirements of the design mission Therefore, the conclusions of this study are of limited applicability for LFC aircraft with varying mission requirements.

Parametric Configuration Analyses

1. On the basis of minimum fuel consumption, the optimum cruise speed for LFC aircraft is $M \leq 0.75$.
2. On the basis of minimum DOC, the optimum cruise speed for LFC aircraft is $M = 0.76 - 0\ 79$.
3. Fuel consumption of LFC aircraft is minimized by selecting the maximum wing loading and aspect ratio consistent with design and performance constraints.
4. For 200-passenger transport aircraft, fuel efficiency is limited by wing volume constraints.
5. For 400-passenger transport aircraft, fuel efficiency is limited by airport performance constraints.

LFC System Concepts

1. No porous materials are currently available which are compatible with the requirements of LFC surfaces.
2. The laser may be adapted to slotting or perforating LFC surfaces with a resultant decrease in both manufacturing cost and time
3. For the time frame considered in this study, non-structural slotted LFC surfaces are most compatible with the requirements of a commercial transport aircraft.
4. If independently-powered suction units are used, operation on ram air is more efficient than operation on suction air.
5. If adequate volume is available for ducting, bleed-burn suction power units are more efficient than independent units or other integrated unit configurations.

(6) No performance improvement is achieved through integration of the suction pumps with the aircraft ECS, APU, or high-lift systems.

(7) If it is determined that an insect contamination problem exists, several in-flight cleaning methods are sufficiently promising to justify further development

Aircraft Configurations

(1) The addition of external fuel tanks to aircraft with a wing volume constraint improves fuel efficiency

(2) The incorporation of relaxed static stability improves the fuel efficiency of all study aircraft.

(3) Both external fuel and relaxed static stability provide a greater improvement in fuel efficiency for the TF aircraft than for the LFC aircraft.

Configuration Comparisons

(1) Compared to advanced technology TF aircraft of equal productivity, the 200- and 400-passenger LFC study aircraft achieve reductions in fuel consumption of 28.2% and 26 7% respectively

(2) Compared to advanced technology TF aircraft of equal productivity, the 200- and 400-passenger LFC study aircraft achieve reductions in DOC of 7 8% and 8.4%, respectively, at a fuel price of $0 093/1 ($0.35/gal).

(3) Compared to current commercial transport aircraft, the TF and LFC study aircraft demonstrate fuel efficiency improvements of 64% and 131%, respectively, at the design range.

Research and Technology Requirements

(1) Technology development is required in several areas, including LFC airfoil and system development, materials, design, and manufacturing.

(2) The development of an LFC demonstrator vehicle is of primary importance.

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