DESIGN CONSIDERATIONS FOR LAMINAR-FLOW-CONTROL AIRCRAFT*

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SUMMARY

A study was conducted to investigate major design considerations involved in the application of laminar flow control to the wings and empennage of long-range subsonic transport aircraft compatible with initial operation in 1985. For commercial transports with a design mission range of 10,186 km (5500 n mi) and a payload of 200 passengers, parametric configuration analyses were conducted to evaluate the effect of aircraft performance, operational, and geometric parameters on fuel efficiency. Study results indicate that major design goals for aircraft optimization include maximization of aspect ratio and wing loading and minimization of wing sweep consistent with wing volume and airport performance requirements.

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.

This paper summarizes the initial phase of studies conducted to evaluate the technical and economic feasibility of applying laminar flow control to long-range subsonic transport aircraft (ref. 6). The primary objective of the investigations reported herein is the evaluation of the impact of both configuration and mission performance parameters on the fuel efficiency of laminar-flow-control aircraft.

SYMBOLS AND ABBREVIATIONS

Values are given in both SI and U. S. Customary Units. The measurements and calculations were made in U. S. Customary Units.

AR	aspect ratio	S	area, m^2 (ft^2)
BPR	engine bypass ratio	SLS	sea level standard
DOC	direct operating cost, ¢/skm (¢/ssm)	W/S	aircraft wing loading, kg/m^2 (lb/ft^2)

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H	cruise altitude, m (ft)
LFC	laminar flow control
M	Mach number
η	ratio of required to available thrust at cruise
Λ	wing sweep angle, rad (deg)

PROCEDURES

Assumptions and Criteria

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

(1) Basic Study 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)

(2) Aircraft Life Cycle

- The life cycle of the aircraft evaluated in this study assumes initial passenger operation in 1985. The assumed technology level for all aircraft elements is compatible with this operational date.
- All aircraft evaluated are compatible with the Air Traffic Control Systems and the general operating environment envisioned for the post-1985 time period.

(3) Design Criteria

- The aircraft studied 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) 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 are limited to the fuel volume available in the wing, with wing center-section fuel volume employed as required.

Baseline Aircraft Configuration

Figure 1 illustrates the conventional wide-body fuselage configuration, sized for the required passenger and cargo payload with associated accommodations, used for all parametric analyses. The parametric configurations use five LFC suction units with two pylon-mounted units per wing semi-span and one tail-mounted unit. This LFC suction unit arrangement was selected to minimize ducting requirements within the wing and ensure adequate volume for fuel and ducting over the wide range of wing geometries considered. Subsequent analyses indicated the desirability of utilizing two fuselage-mounted LFC suction units for aircraft configurations compatible with this arrangement. A non-structural LFC surface configuration is assumed, with a weight of 7.323 kg/m^2 (1.5 lb/ft^2) above that of the basic wing structure. Suction requirements for the parametric studies are consistent with those outlined in reference 7. Laminar areas of the wings and empennage for parametric aircraft are illustrated by figure 1. In a later phase of the study, it was determined that the chordwise extent of laminarization shown in this figure is very near that which provides minimum total fuel consumption.

Parametric Variations

The procedure used in the selection of configuration parameters is illustrated by figure 2. As outlined in this figure, an initial matrix of LFC aircraft was exercised in the Generalized Aircraft Sizing Program with fuselage geometry, main propulsion engine characteristics, and the chordwise extent of laminarization held constant. These initial parametric investigations considered both three and four aft fuselage-mounted primary propulsion engines. An engine bypass ratio of 7.50 and a cruise power ratio of 0.80 were used. For fixed values of these parameters, 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. 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 precisely satisfy takeoff distance and second-segment climb gradient 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 final configuration parameters were selected from these point-design configurations on the basis of fuel efficiency and compatibility with projected airline traffic.

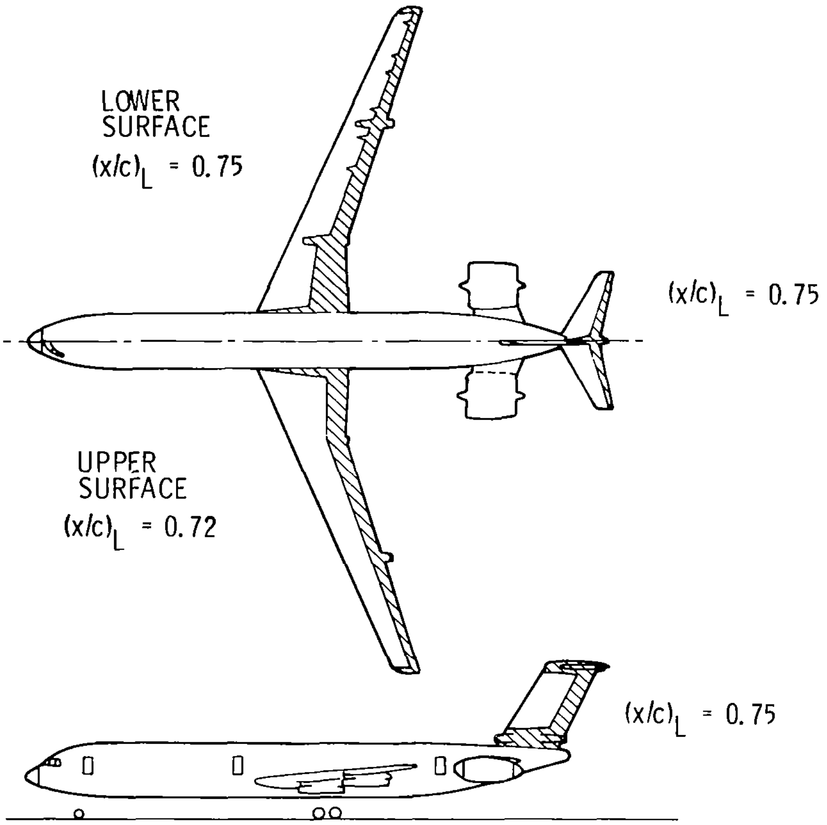

FIGURE 1. BASELINE CONFIGURATION FOR PARAMETRIC ANALYSES

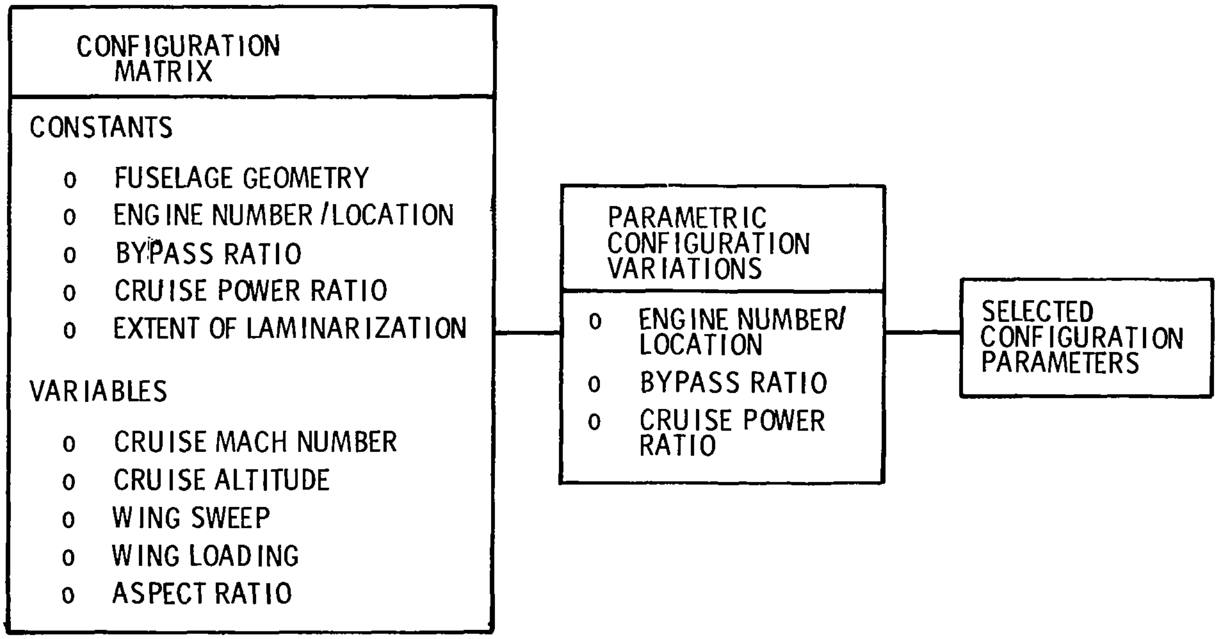

FIGURE 2. PARAMETER SELECTION PROCEDURE

RESULTS AND DISCUSSION

Wing Geometry and Cruise Parameters

Figures 3 and 4 illustrate representative results of the parametric study. For a cruise altitude of 10,973 m (36,000 ft), these figures show the effect of variations in wing loading, aspect ratio, and cruise Mach number on block fuel for wing sweep angles of 0 and 0.524 rad (30 deg). These data show that minimum block fuel is realized for a cruise Mach number of 0.75. For all cruise speeds, fuel consumption is minimized by configurations with unswept wings, high wing loading, and high aspect ratio.

Of particular significance in the selection of LFC configuration parameters is the fuel volume limit, shown as a dashed line in figures 3 and 4. The combination of a relatively small payload, a long mission range, and the wing volume required for ducting and distribution of LFC suction air, places a severe constraint on the selection of wing parameters. In these figures, only the values of wing loading and aspect ratio which lie above the fuel volume limit line represent aircraft configurations with adequate fuel volume to satisfy the design mission requirements.

Figure 5 summarizes the block fuel requirements of M = 0.75 and M = 0.80 LFC configurations as a function of wing sweep angle for an aspect ratio of 14. All of the configurations represented by the curves of this figure have the minimum fuel volume required for the design mission and thus represent the optimum LFC configurations compatible with practical design constraints. It is significant, and not unexpected, that cruise at M = 0.75 results in a lower block fuel requirement than cruise at M = 0.80 for all wing sweep angles. The minimum block fuel for M = 0.75 aircraft is realized by an unswept wing, while a wing sweep of about 0.384 rad (22 deg) minimizes block fuel for M = 0.80 aircraft.

The influence of cruise M and wing sweep on block fuel and DOC is shown in figure 6 for configurations with a wing loading of 537 kg/m^2 (110 lb/ft^2) and an aspect ratio of 14. It will be observed that fuel consumption is minimized by selecting a cruise M of 0.75 or less, but that minimum DOC occurs for a cruise M of about 0.78.

Figures 7 and 8 illustrate the effect of cruise altitude and cruise M on block fuel and DOC for configurations with the same wing loading and aspect ratio for wing sweep angles of 0 and 0.349 rad (20 deg). For either wing sweep, minimum block fuel is obtained at the lowest altitude considered at a cruise M of 0.75 or less. Minimum DOC is also realized by cruising at the lowest altitude, but optimum cruise M is from 0.75 to 0.79, depending on altitude and wing sweep.

Engine Parameters

The parametric configurations defined in the configuration matrix were based on a constant cruise power ratio of 0.80, and do not recognize a field length constraint. For a representative configuration geometry, bypass ratio and cruise power ratio variations were conducted as required to satisfy the specified FAR field length requirement of 3353 m (11,000 ft). In conducting these variations, it was determined that a cruise altitude of 11,582 m (38,000 ft) allowed a better match of cruise and takeoff thrust requirements than cruise at 10,973 m (36,000 ft).

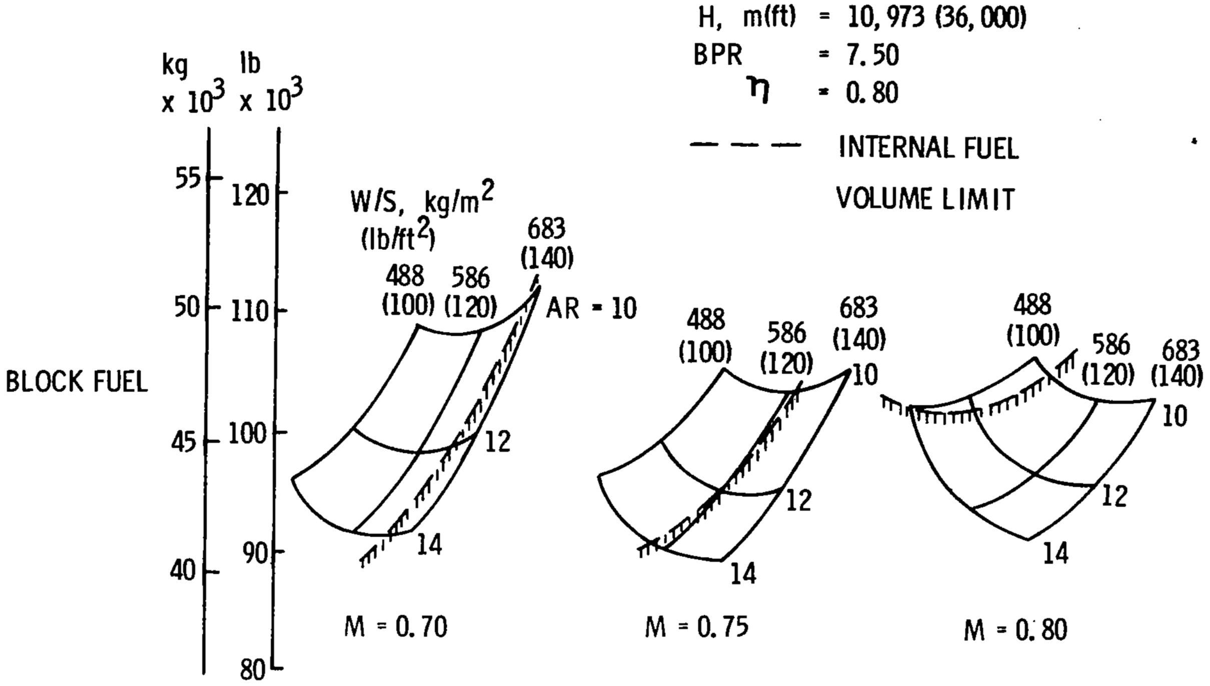

FIGURE 3. BLOCK FUEL VS. WING LOADING AND ASPECT RATIO, $\Lambda = 0$

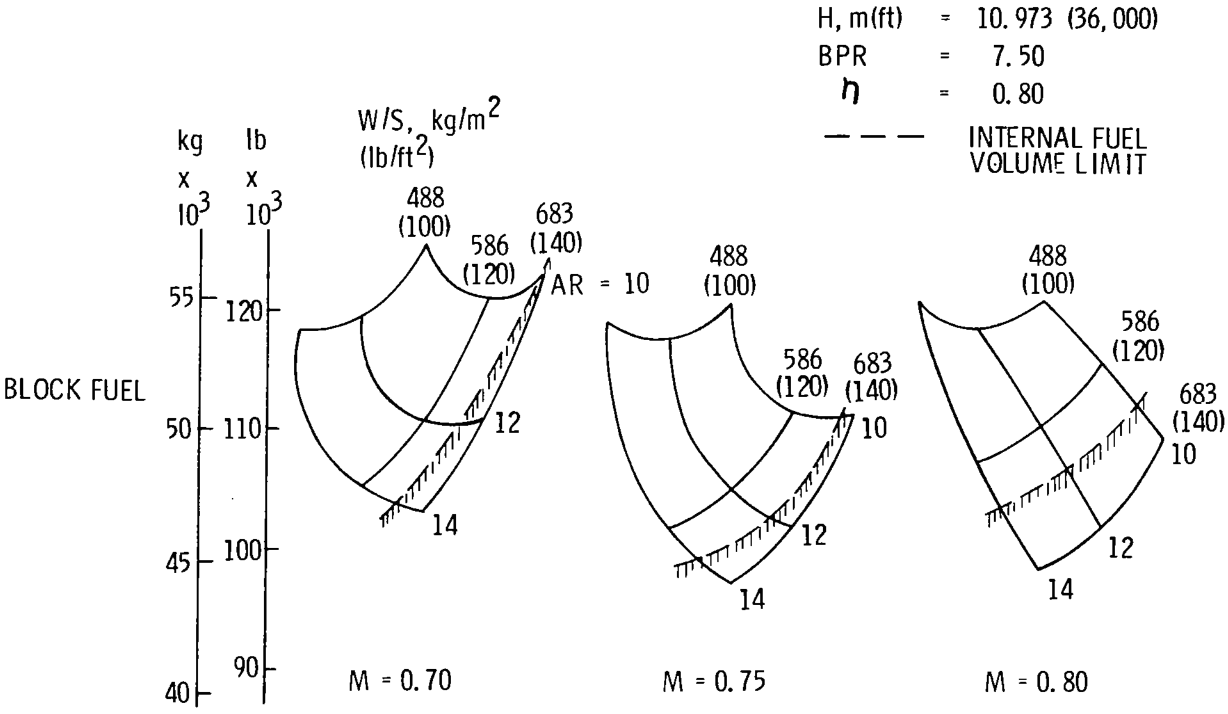

FIGURE 4. BLOCK FUEL VS. WING LOADING AND ASPECT RATIO, $\Lambda = 0.524$ RAD (30 DEG)

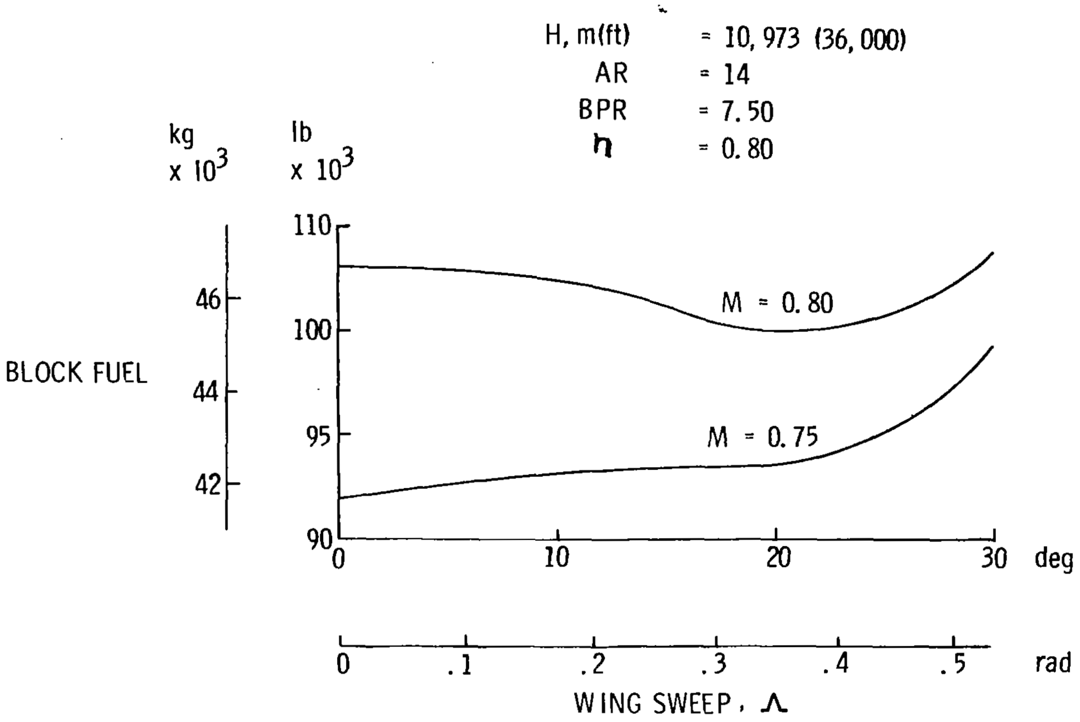

FIGURE 5. BLOCK FUEL VS. WING SWEEP

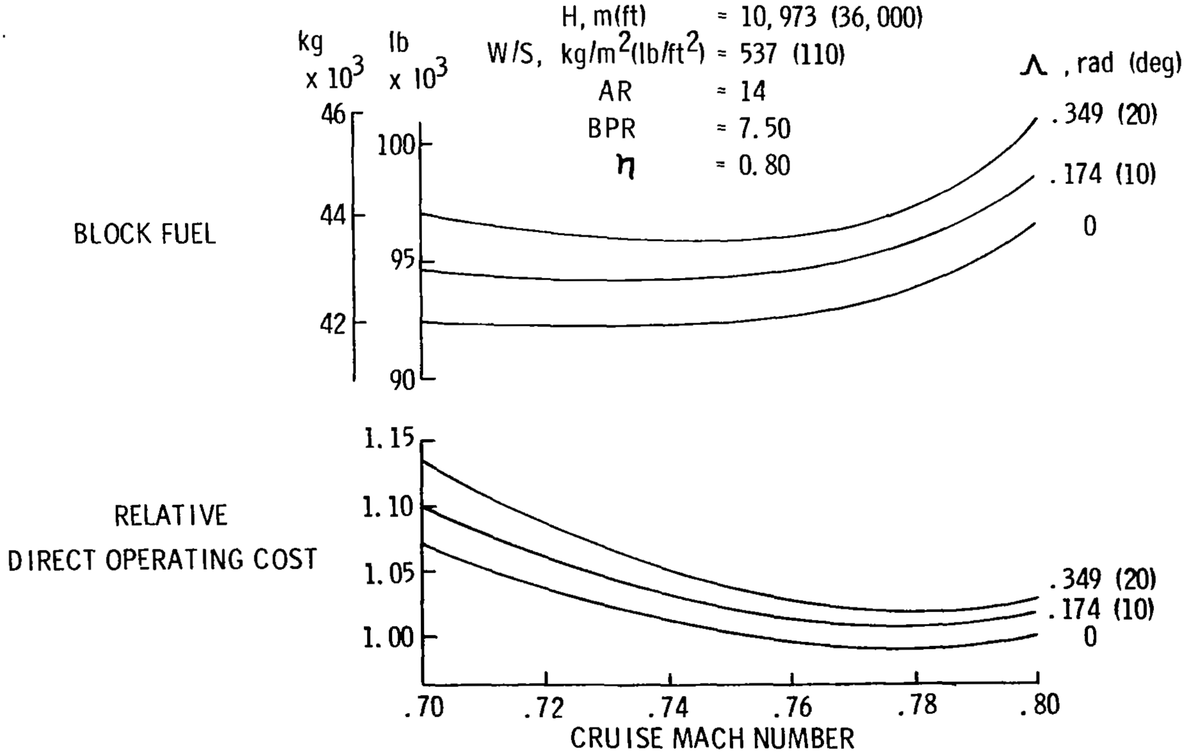

FIGURE 6. EFFECT OF WING SWEEP AND CRUISE MACH NUMBER ON BLOCK FUEL AND RELATIVE DOC

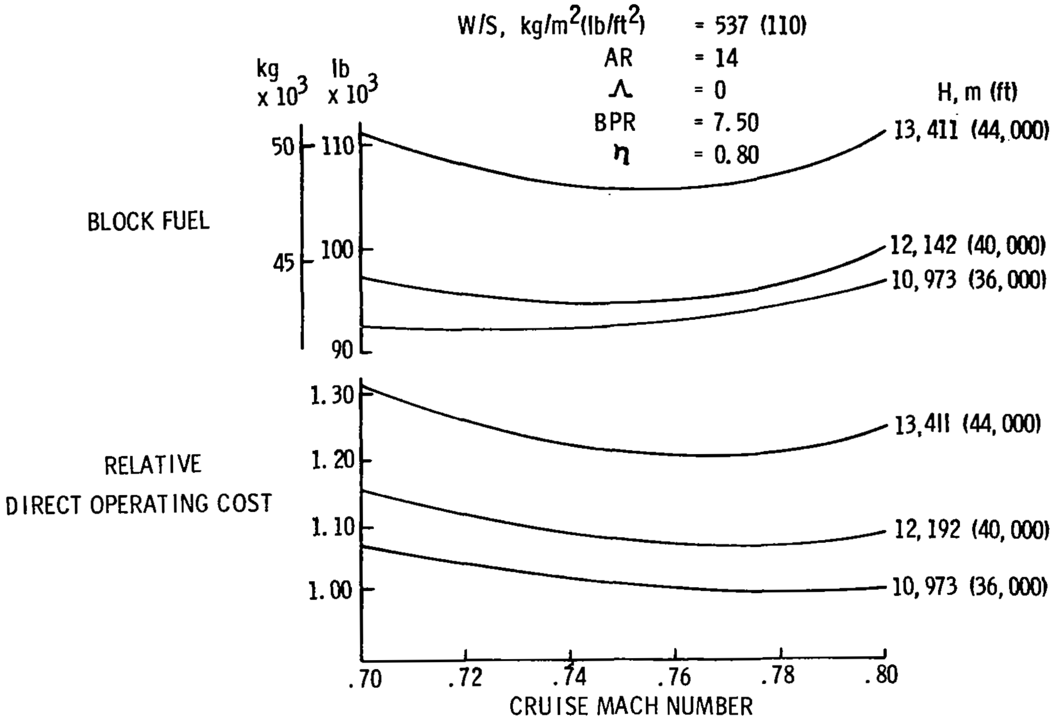

FIGURE 7. EFFECT OF CRUISE ALTITUDE AND CRUISE MACH NUMBER ON BLOCK FUEL AND RELATIVE DOC, $\Lambda = 0$

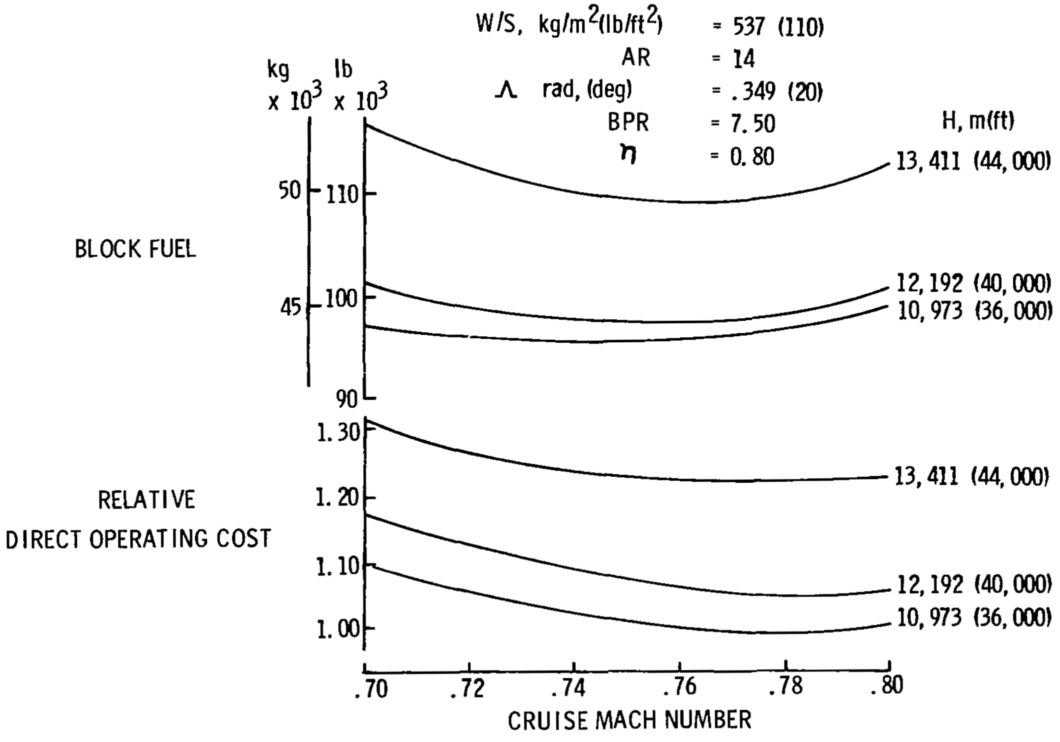

FIGURE 8. EFFECT OF CRUISE ALTITUDE AND CRUISE MACH NUMBER ON BLOCK FUEL AND DOC, Λ = 0.349 RAD (20 DEG)

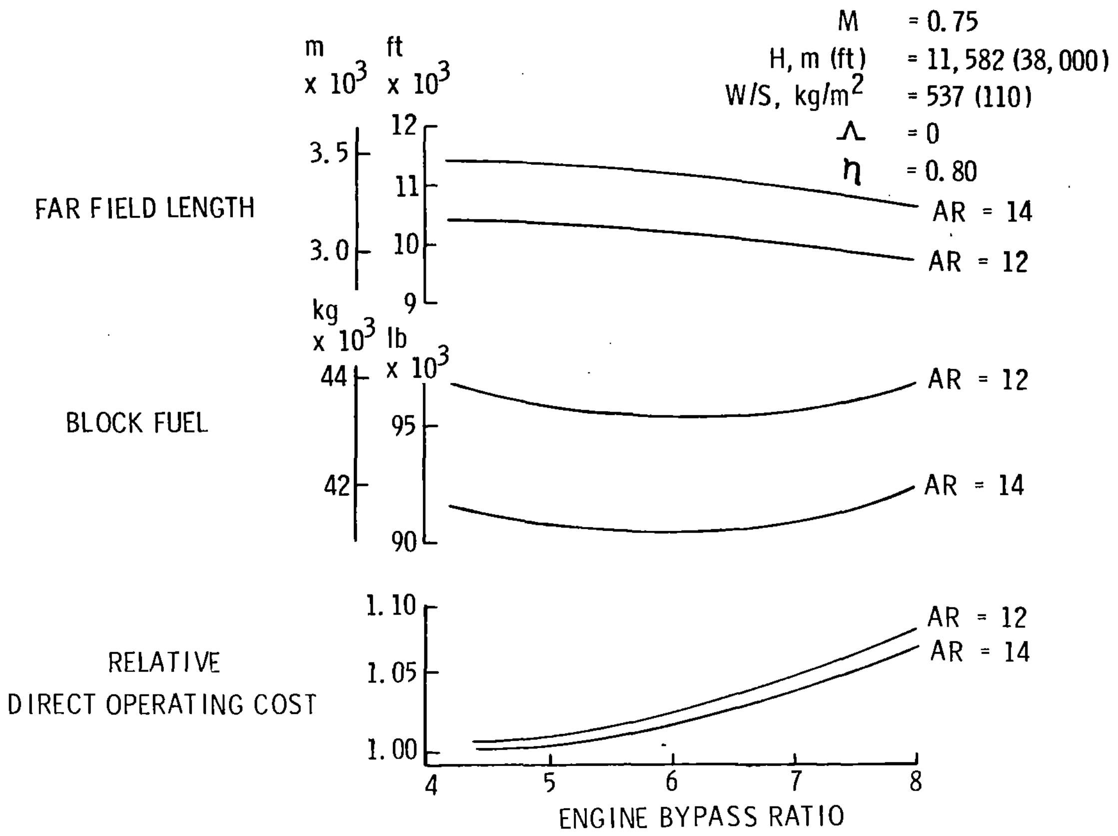

FIGURE 9. ENGINE BYPASS RATIO VARIATIONS

The variation of FAR field length, block fuel, and DOC with aspect ratio and engine bypass ratio is shown in figure 9 for M= 0.75 aircraft with fixed wing sweep and wing loading. Configurations with the lower aspect ratio demonstrate better takeoff performance, but block fuel and DOC are minimized by the high-aspect-ratio configurations. Fuel consumption is minimized by selecting a bypass ratio of about 6.0. This value also represents a reasonable compromise relative to takeoff performance and DOC.

CONCLUSIONS

The following summarizes the design considerations implied by the data generated in the parametric analysis of LFC transport aircraft for the specified mission:

(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 above 10,670 m (35,000 ft) 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 and LFC ducting 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. The use of four fuselage-mounted engines provides better takeoff and second-segment climb performance and minimizes block fuel.

If selection of configuration parameters is based entirely on the minimization of fuel consumption, the preceding analyses dictate the development of LFC aircraft with a cruise M of 0.75 or less and near-zero wing sweep. However, the practical considerations of somewhat improved direct operating costs at M = 0.80 or greater cannot be ignored. Consequently, it is likely that future studies of LFC transport aircraft and programs leading to the ultimate development of such aircraft will accept the fuel consumption penalty attending the selection of higher cruise speeds.

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