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APPLICATION OF ADVANCED AERODYNAMIC CONCEPTS TO LARGE SUBSONIC TRANSPORT AIRPLANES

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Air Force Systems Command
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NOTICE

This technical report has been reviewed and is approved for publication.

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A preliminary design study has been made to identify the performance advantages obtained when advanced aerodynamic technology aircraft are used to perform subsonic military air missions requiring long range (10 000 nmi) or high endurance (24 hr) with heavy payloads (250 000 lb and 400 000 lb, respectively). The study consisted of two phases; the first included evaluating the performance benefits by individually applying various advanced aerodynamic concepts and recommending areas where additional research and development work are necessary to develop, apply, and further identify the potential of the most promising concepts. The second phase

included configuring integrated advanced technology aircraft (long-range airplane, and high endurance airplane) that incorporated the most promising compatible aerodynamic concepts. Comparisons were made with corresponding conventional aerodynamic technology configurations designed for similar missions.

The results indicated that laminar flow control offers the greatest single performance benefit for large military transport aircraft. With 60% of the wing and tail wetted areas laminarized, fuel savings of 29% and gross weight reductions of 17% were identified. Advanced high-speed airfoils that offer a high probability of success were established as the best supporting concept to be utilized in combination with other advanced concepts.

Application of a compatible set of advanced aerodynamic concepts considered feasible for the 1985 time period resulted in fuel savings of 63% and weight reduction of 42% for the long-range airplane. The fuel savings and weight reduction for the high endurance airplane were 54% and 28%, respectively. The concepts combined to attain these improvements were: wingtip fins, high-speed airfoils, body boundary layer control or compliant skin, laminar flow control, aft center of gravity, wing-body contouring, and integration of these into a configuration using a high aspect ratio wing.

Recommendations are given for additional system studies and more detailed design and development work to establish more fully the potential of the various aerodynamic concepts.

FOREWORD

This is the final technical report on the application of advanced aerodynamic concepts to large transport airplanes. This report, which has been assigned Boeing document number D6-75748 for internal use, covers work performed by the Boeing Commercial Airplane Company, Seattle, Washington, under the technical direction of Dr. Charles E. Jobe, Air Force Flight Dynamics Laboratory/FXM, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

Dr. W. M. Howard was the program manager, Dr. W. Pfenninger was the technical director, and R. M. Kulfan was the principal investigator. Others supporting the effort were W. F. Minkler, J. K. Murakami, R. D. Anderson, T. Derbyshire, D. N. Hunt, and W. N. Wright.

The work was performed under contract F33615-75-C-3013.

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ABBREVIATIONS AND SYMBOLS

A	Area
adv	Advanced
alt	Altitude
A/P	Airplane
AR	Aspect ratio = b^2/S
ATT	Advanced Technology Transport
A_{wet}	Wetted area
b	Span
BLC	Boundary layer control
c	Chord
$\bar{c}$	Mean aerodynamic chord
C_D	Drag coefficient = D/qS
C_{D_F}	Friction drag coefficient
C_{D_i}, C_{D_I}	Induced drag coefficient = $C_L{}^2/\pi AR_e$
C_{D_M}	Drag coefficient due to compressibility, Mach number
C_{D_o}	Drag coefficient at zero lift
C_{D_p}	Profile drag coefficient
C_f	Local friction coefficient
C_F	Average friction coefficient
c.g.	Center of gravity
C_ℓ	Section lift coefficient
℄	Centerline
C_L	Lift coefficient = L/qS

conf.	Configuration
C_p	Pressure coefficient
D	Drag
D_i	Induced drag
e	Oswald efficiency factor
eng	Engine
ft	Foot, feet
g	Gravity
h	height
horz	Horizontal
hr	Hour
IOC	Indirect operating cost
k	Kilo
ℓ	Length
L	Lift
lb	Pound
lb/ft	Pound per foot
L/D	Lift/drag
LE	Leading edge
LFC	Laminar flow control
LRC	Long-range cruise
M	Mach number, moment
max	Maximum
M_{crit}	Critical Mach number for drag rise

min	Minimum, minute
misc	Miscellaneous
nmi	Nautical mile
OEW	Operational empty weight
P	Pressure
pass. mi	Passenger mile
PL	Payload
psi	Pounds per square inch
q	Dynamic pressure
R&D	Research and Development
R_e, R_N, $Re\ell$	Reynolds number
ref.	Reference
Res	Fuel reserves
$R_{e_{tran}}$, R_{X_T}	Transition Reynolds number
s	Slot depth
S	Wing area
SAS	Stability Augmentation System
SFC	Specific fuel consumption
SL	Sea level
SLST	Sea level static thrust
t	Thickness
T	Thrust
TAC	Terminal Area Compatibility study
t/c	Thickness/chord ratio

TE	Trailing edge
TOFL	Takeoff field length
TOGW	Takeoff gross weight
turb	Turbulence
T/W	Thrust-to-weight ratio
U	Velocity
U_s	Velocity in boundary layer
U_∞	Freestream velocity
U_τ	Friction velocity
VCW	Variable camber wing
vert	Vertical
W	Weight
WRBM	Wing root bending moment
W/S	Wing loading
x	Streamwise direction

Symbols

α	Angle of attack
β	Wing-fin incidence angle
δ	Boundary layer thickness
Δ	Incremental amount
η	Fraction of semispan
λ	Wing taper ratio
Λ	Sweep angle
%	Percent
π	pi = 3.1416

Subscripts

cru	Cruise
des	Design
max	Maximum
min	Minimum
ref	Reference
turb	Turbulence

1.0 INTRODUCTION

The fuel shortages that have been experienced since the 1973-74 Arab oil embargo and the subsequent sharp increase in fuel price since that time provide ample reason for the reevaluation of every means of improving air transport performance and the assessment of each from the standpoint of decreasing operating costs and fuel consumption. Aerodynamic concepts that have the potential to increase significantly the lift/drag (L/D) ratio, range, endurance, and performance of subsonic transport aircraft have been demonstrated in theory and experiment. The purpose of the study reported herein was to identify the performance advantages that will be obtained when advanced aerodynamic technology aircraft are used to perform subsonic military air missions requiring long-range or high endurance capability with heavy payloads. The study consisted of two phases:

I. Perform a survey and performance evaluation of various advanced aerodynamic concepts that could favorably impact the next generation of transport designs. Identify the research and development (R&D) necessary to effectively incorporate the most promising concepts into future transport designs.

II. Derive two aircraft configurations, long-range airplane and high endurance airplane, incorporating the most promising compatible aerodynamic improvements. Compare each of the advanced aerodynamic technology configurations with a conventional aerodynamic technology configuration designed for a similar mission.

It was known at the beginning of the study that laminar flow control (LFC) was one of the most promising concepts. Therefore, considerable effort was made toward defining an integrated configuration to exploit its potential benefits. Many technical discussions with Dr. W. Pfenninger have provided assistance in this effort. Additional materials concerning integrated LFC airplanes generated as a result of complementary studies by Dr. Pfenninger are reported in a separate report.[1]

The individual aerodynamic concept benefits are presented and discussed in section 2.0. The general state of readiness and recommendations for further research and development are also presented in section 2.0. A combination of the various concepts into advanced long-range and high endurance configurations is described in section 3.0.

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[1]Pfenninger, W., "Design Considerations of Large Low-Drag Suction Airplanes With Large Payloads and Extreme Range and Endurance," in preparation.

2.0 PHASE I: ADVANCED AERODYNAMIC CONCEPT EVALUATION

The recent emphasis on conserving fuel has lead to an upsurge in investigating and developing aerodynamic concepts to improve the aerodynamic efficiency of commercial and military aircraft.[2-6] These advanced concepts studies included:

- Reexamination of relatively old ideas; e.g., laminar flow control (LFC), boundary layer control (BLC), and oblique wings in view of advances in supporting technologies and in manufacturing techniques
- Improved aerodynamics by virtue of extensive experimental investigations and new sophisticated theoretical aerodynamic design and analysis capabilities
- More recent aerodynamic innovations; e.g., advanced high-speed airfoils and compliant skins

The number of different aerodynamic concepts is large. Many of the concepts have similar specific objectives but differ in the level of design, sophistication, and degree of current development. The aerodynamic concepts considered for this study were reviewed and then subjected to the following selection criteria:

1. The concepts must be applicable to airplane designs that would accomplish the objective long-range and high endurance missions.
2. Past and/or recent studies indicate that the concept offered potential improvements for large subsonic airplanes.
3. It was desired to consider concepts that had sufficient background data to permit valid evaluations of the probable merits.
4. The concepts were to be aerodynamic or aerodynamic related.

It was also desired to address all of the major drag components. In some instances, this resulted in considering aerodynamic concepts that are currently under development and as such have a rather limited amount of aerodynamic data available and virtually no configuration integration experience.

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[2] Nagel, A. L. et al., "Future Long-Range Transports–Prospects for Improved Fuel Efficiency," AIAA paper 75-316, February 1975.
[3] Goodmanson, L. T. and Gratzer, L. B., "Recent Advances in Aerodynamics for Transport Aircraft," AIAA paper 73-9, January 1973.
[4] Polhamus, E. C., "Subsonic and Transonic Research," paper 3, NASA SP-292, November 1971.
[5] Clay, C. W. and Sigalla, A., "The Shape of the Future Long-Haul Transport Airplane," AIAA paper 75-305, February 1975.
[6] *Fuel Conservation Possibilities of Terminal Compatible Aircraft,* NASA CR-132608, March 1975.

No new concept development investigations were undertaken. The guiding objectives were to recognize the uncertainties in the concept potential, to project reasonable improvements in the concept development, and to consider various approaches in utilizing the concepts to permit a valid evaluation of the relative merits of each concept.

2.1 AERODYNAMIC CONCEPTS

The aerodynamic concepts that have been considered in this study were grouped into five categories and summarized in table 1.

Table 1.—Aerodynamic Concepts Considered

Boundary Layer Drag Reduction Concepts

- Laminar Flow Control
- Boundary Layer Control
- Compliant Skin

Induced Drag Reduction/Modification Concepts

- Wingtip Fins
- Split Wingtips
- Wingtip-Mounted Engines
- Tandem Wing Lifting Surfaces
- Drag Versus Weight Aspect Ratio Optimization

Airfoil Concepts

- Natural Laminar Flow Airfoils
- Advanced High-Speed Airfoils
- High Lift/Drag Airfoils

Variable Geometry Concepts

- Variable Camber Wing
- Variable Sweep Oblique Wing

Miscellaneous Concepts

- Advanced Aerodynamic Design Methodology
- Wing-Body Contouring
- Aft-Body Shape
- Low Trim Drag (aft c.g.)

The boundary layer drag reduction concepts provide a direct reduction in drag by artificially promoting laminar flow, by reducing turbulent flow skin friction, or by eliminating boundary layer separation.

The induced drag reduction concepts all attempt to reduce the drag associated with the lift production of the airplane. Wingtip fins, split wingtips, and tip-mounted engines alter the lift distribution, the nature of the tip vortices, and the kinetic energy of the vortex system. Ultimately, however, the effect is felt as a reduction in the pressure drag of the airplane. The remaining induced drag reduction items identified in table 1 may be classed as aerodynamic-related items that improve the aerodynamic efficiency versus structural weight trade, particularly in view of the use of advanced structural materials and with fuel consumption being considered as a measure of relative merit.

The airfoil concepts that have been considered provide improved aerodynamic efficiency by different mechanisms. The natural laminar flow airfoils provide a direct drag reduction by promoting a longer run of laminar flow and, thereby, reducing the friction drag. Advanced high-speed airfoils provide more indirect benefit by virtue of their greater local Mach number capability before developing shocks of sufficient strength to increase drag or cause shock-induced boundary layer separation. This increased sectional Mach number capability provides the designer with a much greater degree of flexibility in optimizing the trade between aircraft speed, wing sweep, thickness, and aspect ratio. The high L/D airfoils are useful in developing wings capable of high lift at subcritical flight speeds.

The best aerodynamic airfoil shape differs for subsonic, supersonic, or mixed-flow environments. The variable camber wing (VCW) provides the capability for optimizing the airfoil shape for operation over a wide range of Mach numbers or a large variation of angle of attack. The variable sweep oblique wing concept provides significant drag reductions for low supersonic speeds and has the capability to optimize the wing sweep over the complete operating speed regime from takeoff and landing to the cruise conditions.

The miscellaneous concepts improve the aerodynamic efficiency of the completely integrated aircraft design.

The concepts are discussed in greater detail in the following sections. Each of these concepts has been evaluated individually; however as shown in figure 1, the maximum benefits are achievable by a combination of compatible concepts.

2.2 BASIS FOR COMPARISON AND EVALUATION

In order to assess the impact of each of the aerodynamic concepts on the performance characteristics and fuel utilization of large military transports, reference configurations employing conventional aerodynamic technology were developed to meet the two specified design missions:

- *Long-range airplane:* 250 000-lb payload and unrefueled ranges up to 10 000 nmi
- *High endurance airplane:* 400 000-lb payload with a loiter capability up to 24 hr within 250 nmi from the base

Each of these reference configurations utilized propulsion, structural, flight controls, and systems technology improvements projected for 1985 in the NASA-funded study by Boeing.[6] The type of aerodynamic technology employed in the Boeing 747 and C-5A designs was assumed. The detailed characteristics of these reference configurations are discussed in section 3.0.

Each aerodynamic concept was evaluated by modifying the reference configuration to incorporate the concept. The results of previous system studies were used to guide the applications. In some instances, it was necessary to develop an intermediate reference configuration for evaluating the concept under consideration. Alternate applictions were

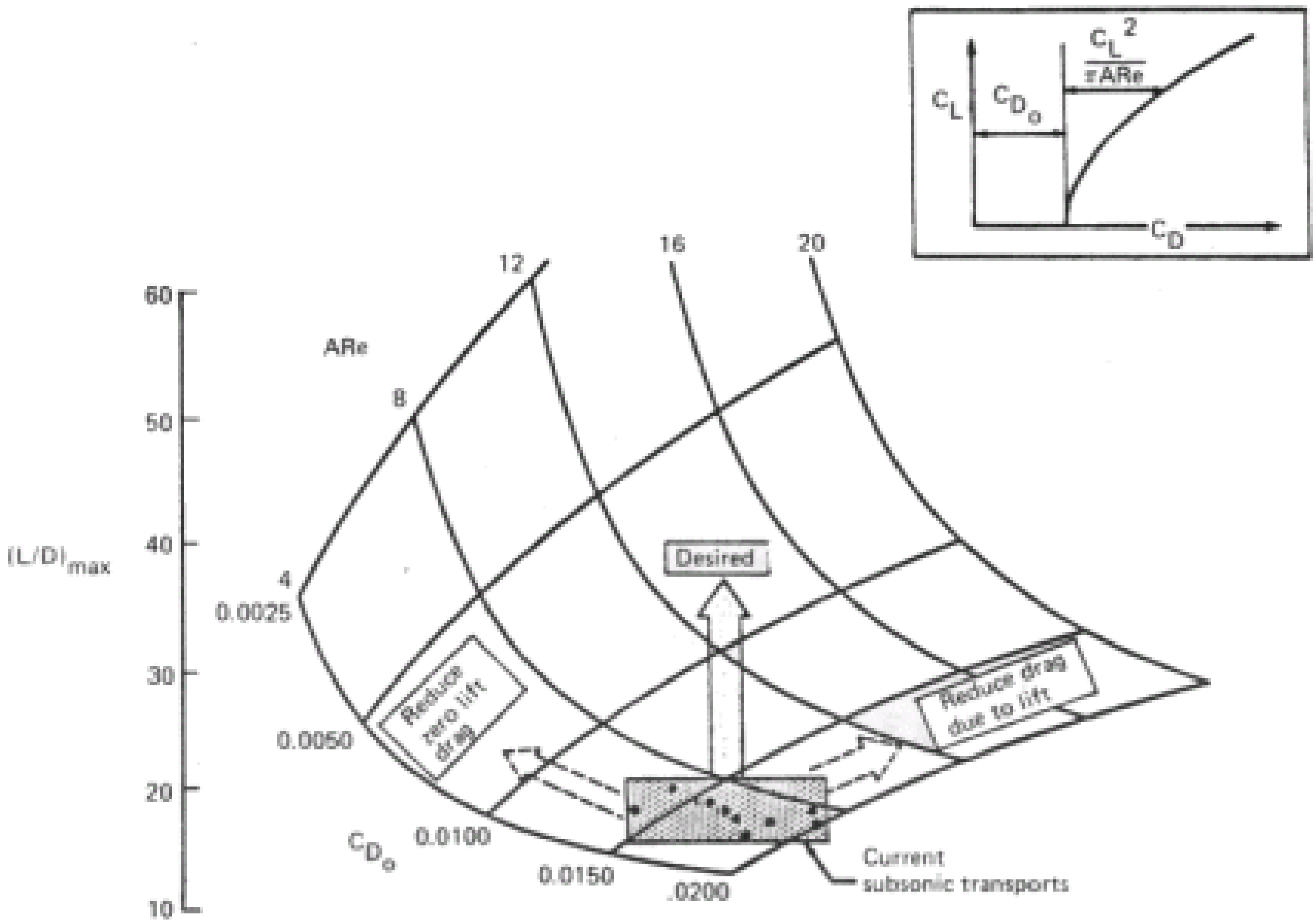


Figure 1.–Effect of Aspect Ratio and C_{D_o} on $(L/D)_{max}$

considered to bracket the potential benefits associated with the concept. In every case, the particular reference configuration and the configuration employing an advanced aerodynamic concept differed *only* in the changes necessary to efficiently incorporate the concept.

The reference configuration, modified to include the aerodynamic concept under consideration, was then evaluated to determine the direct effect on airplane drag. These evaluations used the results of previous similar studies, available experimental data, or theoretical evaluations of the study configurations. The indirect effects on other items such as structural efficiency, propulsion efficiency, airplane weight, or airplane systems were then determined by using available applicable data, performing analyses, or qualitative assessments.

Estimates were then made to determine the net influence of the concept application on the airplane's performance, size, and fuel consumption. The guiding objective of each concept analysis was to perform consistent evaluations that would determine or bracket the potential benefits and define research and development programs necessary to fully identify the potential benefits. The concept evaluations were made primarily on the reference long-range cruise (LRC) airplane model 767-736, shown in figure 2. The detailed characteristics of this configuration are presented in section 3.4

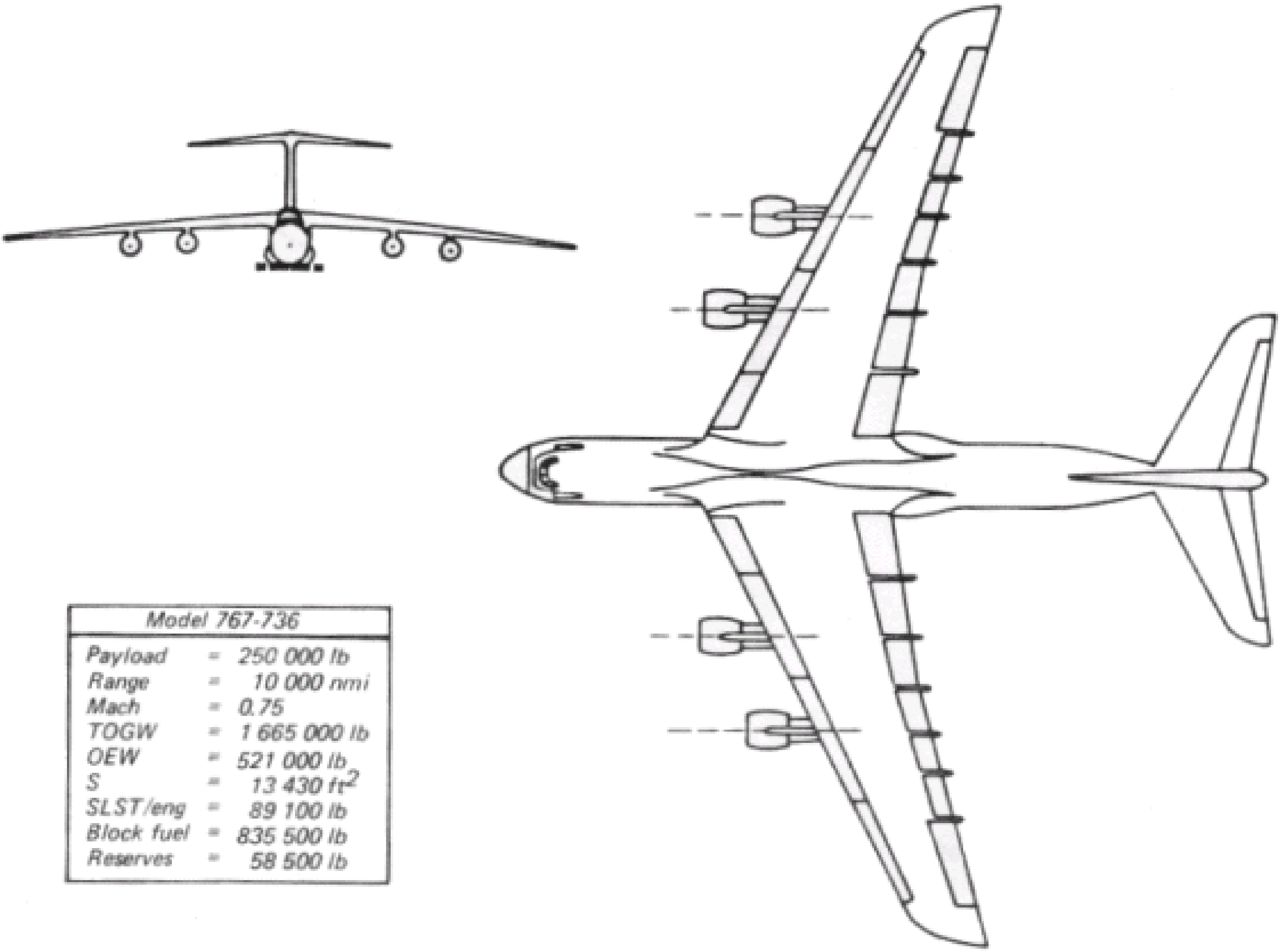
Figure 3 contains a breakdown of the cruise drag for this reference long-range airplane. The major drag items on this configuration are the induced drag and the wing profile drag. The body profile drag is a smaller drag item. However, reductions in the wing profile drag and induced drag would result in the body profile drag contribution becoming relatively more significant. Figure 3 also shows the general impact that reductions in the major drag components would have on the gross weight and fuel consumption of the reference airplane.

The uncycled aerodynamic efficiency, ML/D, corresponds to the estimated aerodynamic improvement with the wing area equal to the corresponding reference airplane wing area. As the aerodynamic efficiency is increased, the gross weight necessary to perform the design mission decreases. This lighter airplane requires a smaller wing and, consequently, the total airplane encounters a slight reduction in aerodynamic efficiency. The net improvement in aerodynamic efficiency of the final-sized configuration relative to the reference airplane is the cycled aerodynamic efficiency.

The results of the concept applications study are summarized in section 2.3. Section 2.4 contains a discussion of the aerodynamic concepts and the evaluation details.

2.3 SUMMARY OF EVALUATIONS

The main results of the comparative evaluations of the impact of advanced aerodynamic concepts on the LRC airplane are summarized in figures 4, 5, and 6. The improvements in aerodynamic efficiency, ML/D, are shown in figure 4. The reductions in takeoff gross weight (TOGW) and fuel savings are shown in figures 5 and 6, respectively. Estimates of the system penalties have been included in these evaluations. In figure 4, the uncycled aerodynamic improvement corresponds to the aerodynamic improvement with the wing, engine, and tail sizes equal to the reference airplane.



Model 767-736		
Payload	=	250 000 lb
Range	=	10 000 nmi
Mach	=	0.75
TOGW	=	1 665 000 lb
OEW	=	521 000 lb
S	=	13 430 ft^2
SLST/eng	=	89 100 lb
Block fuel	=	835 500 lb
Reserves	=	58 500 lb

Figure 2.—Reference Conventional Aerodynamic Technology Long-Range Cruise Airplane—Model 767-736

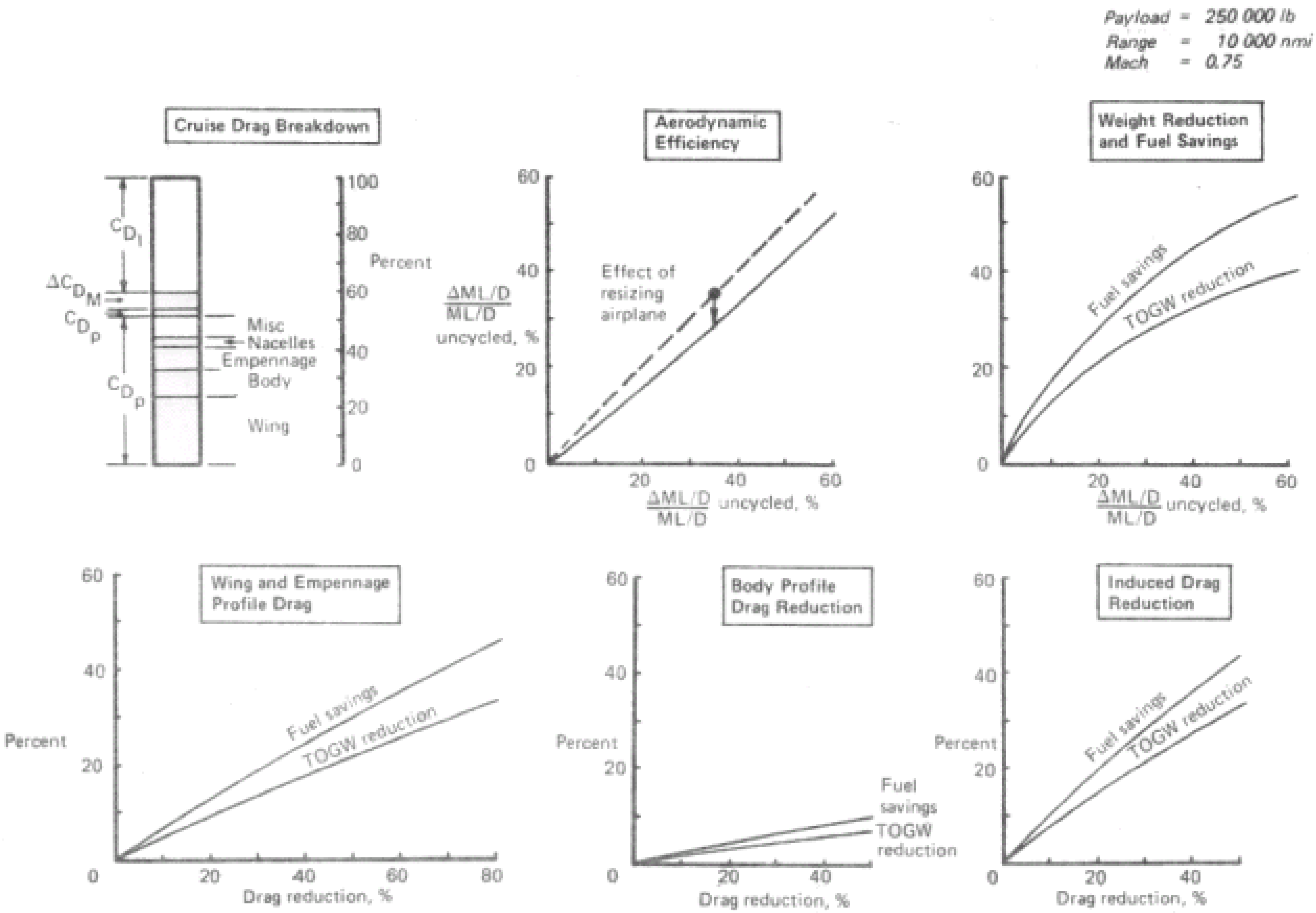


Figure 3.—Long-Range Cruise Airplane (767-736) Sensitivity to Aerodynamic Improvements—With no System Penalties

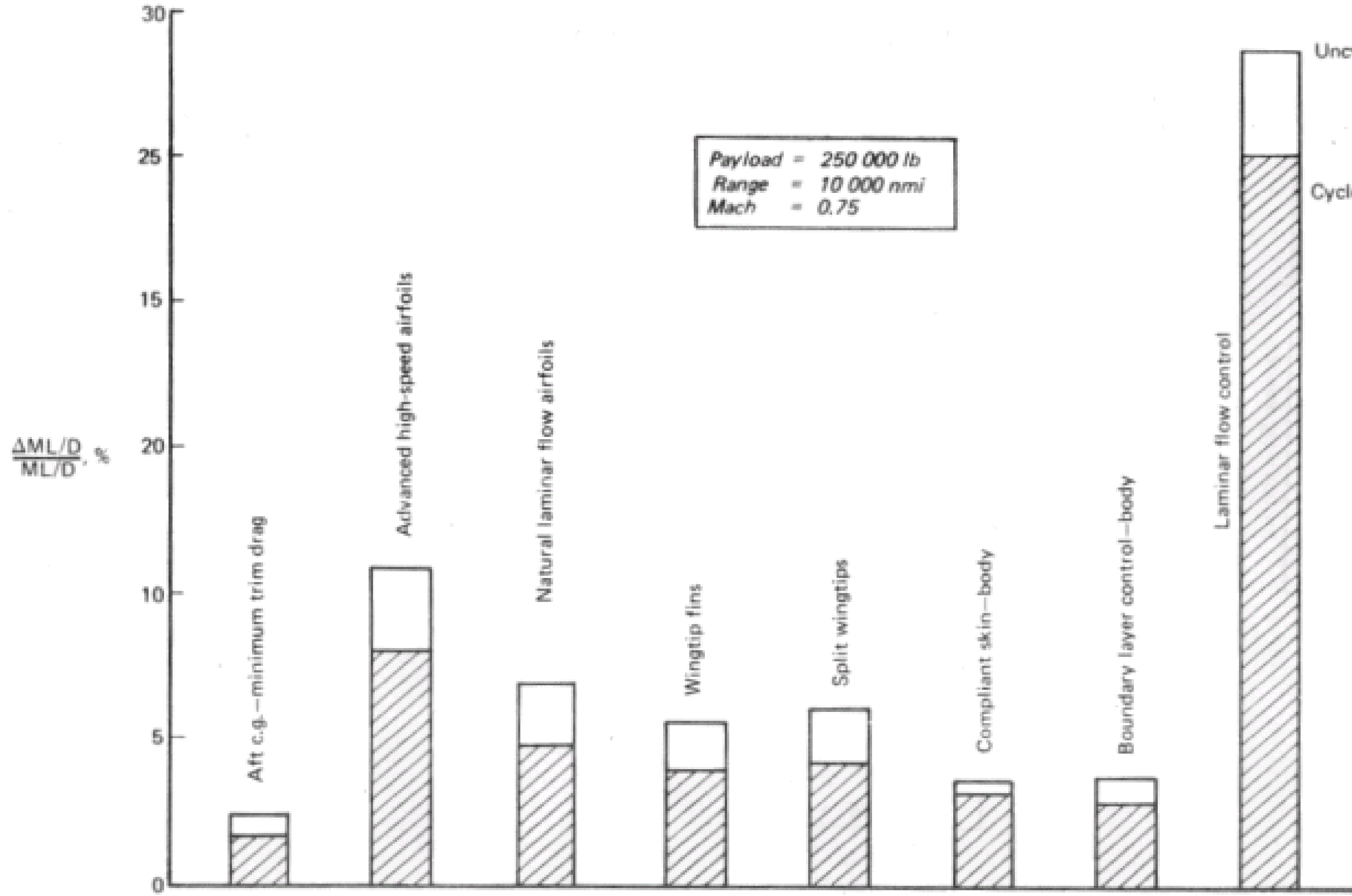


Figure 4.—Aerodynamic Efficiency Improvements for Individual Aerodynamic Concept Applications—With System Penalties

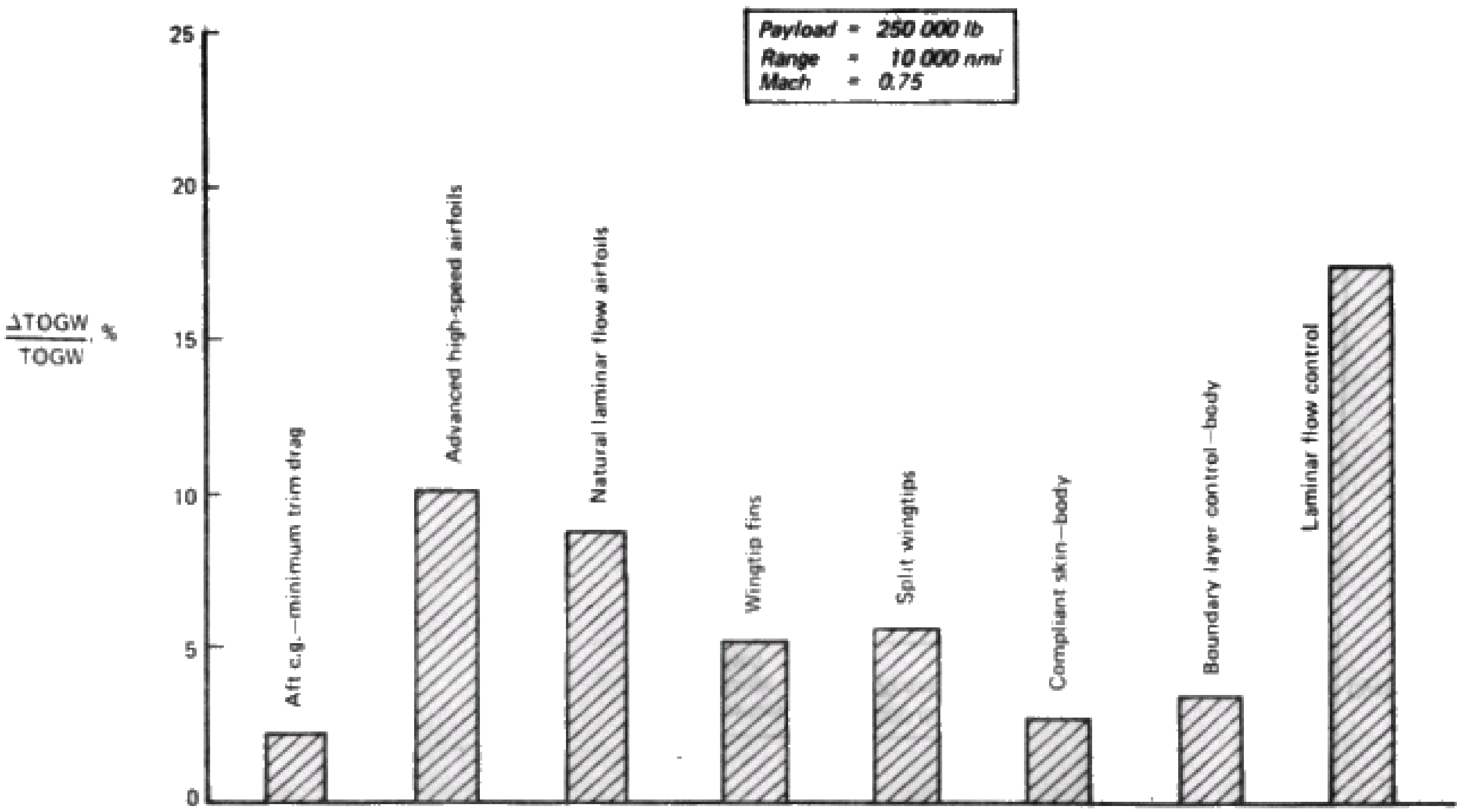


Figure 5.—Gross Weight Reduction for Individual Aerodynamic Concept Applications—With System Penalties

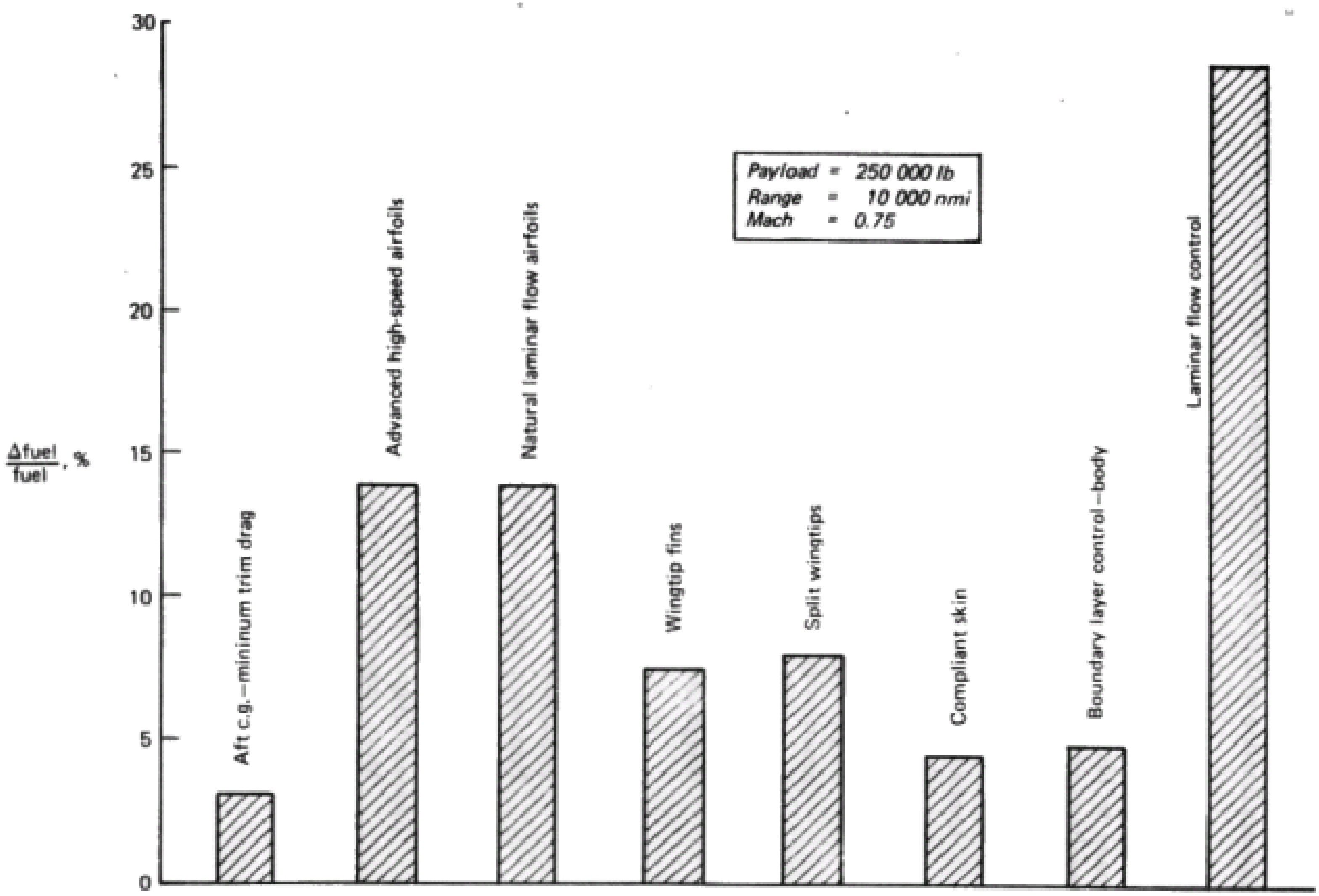


Figure 6.—Fuel Savings for Individual Aerodynamic Concept Applications—With System Penalties

These results indicate that laminar flow control individually offers the greatest potential relative to the other concepts. This evaluation of LFC is conservative, since the trailing-edge (TE) control areas were not laminarized; therefore, only about 60% of the wing and tail wetted area had laminar flow. Full-chord laminar flow with LFC appears feasible with projected improvement in manufacturing techniques.

It should be noted that the performance benefits of the concepts are very dependent on the reference configuration and design mission. This is discussed further in the design range and endurance studies (sec. 3.6). In the following sections, an attempt has been made to identify the evaluation ground rules and to explore the sensitivity of the results to major design variables.

The relative merits of the various study concepts are highlighted below.

- Laminar Flow Control
  - Greatest potential performance benefit for long-range or high endurance airplanes
  - Detailed system studies required to assess system penalties
  - Flight vehicles necessary to establish operational and maintenance practicality
  - Large incentive to improve manufacturing techniques and surface tolerances to promote full-chord laminar flow
  - Additional benefits including induced drag improvement and thick-wing design flexibility need to be assessed

- Advanced High-Speed Airfoils
  - Proven concept, high probability of success
  - Most compatible concept, desired for LFC, required for natural laminar flow airfoils
  - Promising retrofit capability to existing airplanes having early technology airfoils by leading-edge (LE) modifications
  - Offers great deal of design flexibility; speed, sweep, thickness, and span trades

- Increased Aspect Ratio (AR)
  - Most important nonaerodynamic-related item that depends primarily on structures technology
  - Fuel as new figure of merit as opposed to gross weight leads to higher aspect ratios
  - Other possibilities requiring system evaluations include braced wings and possible benefits with active controls

- Advanced Design Methodology
  - New methods, broader data base offers large benefits in developing aerodynamic concepts; e.g., laminar flow, and high-speed airfoils
  - Develop modifications to existing designs
  - New possibilities in inboard wing design trades with body contouring to be explored

- Tip Fins
  - Encouraging wind tunnel results
  - Promising retrofit capability
  - All hinges on structural weight penalty (currently being studied)

- Natural Laminar Flow Airfoils
  - Moderate benefits for large wings limited by the long chords
  - New design studies desired in view of advanced techniques and methodology
  - Short term alternative to LFC

- Compliant Skins—Body BLC
  - Promising, but uncertain with limited existing knowledge and data base
  - Body LFC another alternative but all need detailed explorations

- Split Tips
  - Another approach to increase effective aspect ratio for modest gains
  - Needs aerodynamic development and structural evaluations
  - Advanced application possibilities as active controls

- Variable Camber Wing
  - Limited direct value for point-designed low-speed transports
  - Possibly attractive with LFC or natural laminar flow airfoils with continuous upper surface skin to promote laminar flow
  - Adaptable to high lift requirements

- Wingtip Engines
  - Significant aerodynamic benefits reported
  - More theoretical, experimental, system studies necessary to evaluate

- Variable Sweep Oblique Wing
  - Low-speed point design airplane cannot derive benefits associated with varied speed and/or mission capability

- Low Trim Drag
  - Small gain with flight control support development—active controls

- High L/D Airfoil
  - Cruise performance benefits small to uncertain

- Tandem Wing
  - Low structural weight primary objective
  - Possibility with natural laminar flow airfoils—wings smaller than for conventional configuration

The initial phase of the study reported herein concentrated on the individual aerodynamic concept assessments. The most desirable approach to improve the aerodynamic efficiency of a transport airplane is to incorporate compatible aerodynamic improvements that address all the major drag items to reduce the profile drag, induced drag, and compressibility drag. Advanced concepts, identified in figure 7, have been included in the integrated advanced technology long-range and high endurance configurations developed in Phase II of the contract study.

Figure 8 indicates that the various aerodynamic concepts that have been considered in this study are compatible with one another.

2.4 DISCUSSION OF CONCEPTS

This section presents the details of the aerodynamic concept evaluations studies. A brief description is given of the aerodynamic nature of each concept. The concept application philosophy and evaluation methods are summarized. The results of supporting studies that were conducted to determine the sensitivity to variations of some of the significant parameters are shown. These results also have been used in formulating the research and development recommendations.

The conception and subsequent development of the various aerodynamic concepts have involved many individuals and different agencies. No attempt has been made to extend the proper recognition and credits.

2.4.1 ADVANCED HIGH-SPEED AIRFOILS

The aerodynamic features of the advanced high-speed airfoil are illustrated in figure 9 for a Mach number that results in a localized area of supersonic flow on the upper surface of the airfoil.

At moderate subsonic Mach numbers, the relatively large variation in upper surface curvature on a conventional airfoil produces an area of supersonic flow that is terminated by a strong shock wave. This shock produces a pressure drag associated directly with the shock strength. Furthermore, the shock may separate the boundary layer and result in a further substantial drag increase.

The high-speed airfoil by virtue of its reduced upper surface curvature produces a partly isentropic recompression of the local supersonic flow on the airfoil surface. As a result of this nearly ideal recompression, the terminating shock wave can be kept weak until significantly higher freestream Mach numbers are reached.

In the past decade, considerable effort[7-9] has been devoted to the development of high-speed airfoils for transport applications. The airfoil development progress is illustrated in figure 10. The initial emphasis was to use this advanced airfoil technology to increase cruise speeds.

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[7] Blackwell, J. A., *Aerodynamic Characteristics of an 11-Percent-Thick Symmetrical Airfoil at Mach Numbers Between 0.3 and 0.85*, NASA TMX-1831, July 1969.

[8] Whitcomb, R. T. et al., "Supercritical Wing Technology—A Progress Report on Flight Evaluations," NASA FRC Edwards, California, February 1972.

[9] Wallace, R. E. and Monk, J. R., "A Technique for Testing Airfoil Sections at Transonic Speeds," *J. of Aircraft*, vol. 3, no. 1, January-February 1966.

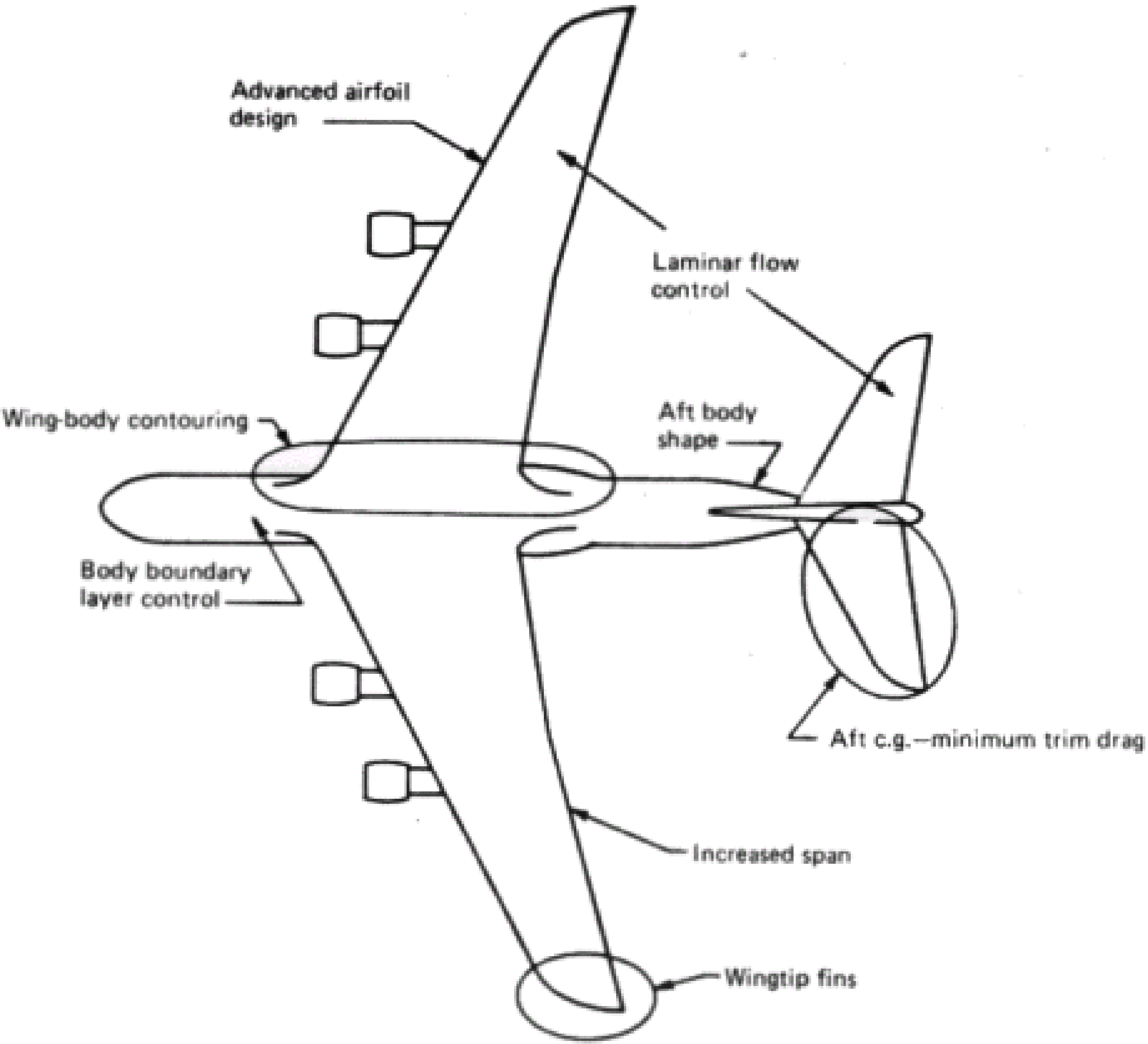

Figure 7.—Integrated Advanced Design Items

Symbol	Degree of compatibility
○	Complementary
◒	Questionable
●	Not compatible

	Laminar flow control	Boundary layer control	Compliant skin	Natural laminar flow airfoils	Advanced high-speed airfoils	High L/D airfoils	Variable camber airfoils	Wingtip fins	Split wingtips	Wingtip-mounted engines	Tandem wings	Load—aspect ratio	Externally braced wings	Variable sweep oblique wing	Wing-body contouring	Aft-body shape	Low trim drag (aft c.g.)
Laminar flow control		○	○	◒	○	◒	◒	○	○	○	○	○	○	◒	○	○	○
Boundary layer control	○		◒	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Compliant skin	○	◒		○	○	○	○	○	○	○	○	○	○	○	◒	○	○
Natural laminar flow airfoils	◒	○	○		◒	◒	◒	○	○	○	○	○	○	○	○	○	○
Advanced high-speed airfoils	○	○	○	◒		◒	○	○	○	○	○	○	○	○	○	○	○
High L/D airfoils	◒	○	○	◒	◒		◒	○	○	○	○	○	○	◒	○	○	○
Variable camber airfoils	◒	○	○	◒	○	◒		○	○	○	○	○	○	○	○	○	○
Wingtip fins	○	○	○	○	○	○	○		●	●	○	○	○	●	○	○	○
Split wingtips	○	○	○	○	○	○	○	●		●	○	○	○	●	○	○	○
Wingtip-mounted engines	○	○	○	○	○	○	○	●	●		◒	○	○	●	○	○	○
Tandem wings	○	○	○	○	○	○	○	○	○	◒		○	○	○	○	○	○
Load—aspect ratio	○	○	○	○	○	○	○	○	○	○	○		○	○	○	○	○
Externally braced wings	○	○	○	○	○	○	○	○	○	○	○	○		●	○	○	○
Variable sweep oblique wing	◒	○	○	○	○	◒	○	●	●	●	○	○	●		○	○	○
Wing-body contouring	○	○	◒	○	○	○	○	○	○	○	○	○	○	○		○	○
Aft-body shape	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○		○
Low trim drag (aft c.g.)	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	

Figure 8.—Concept Compatibility

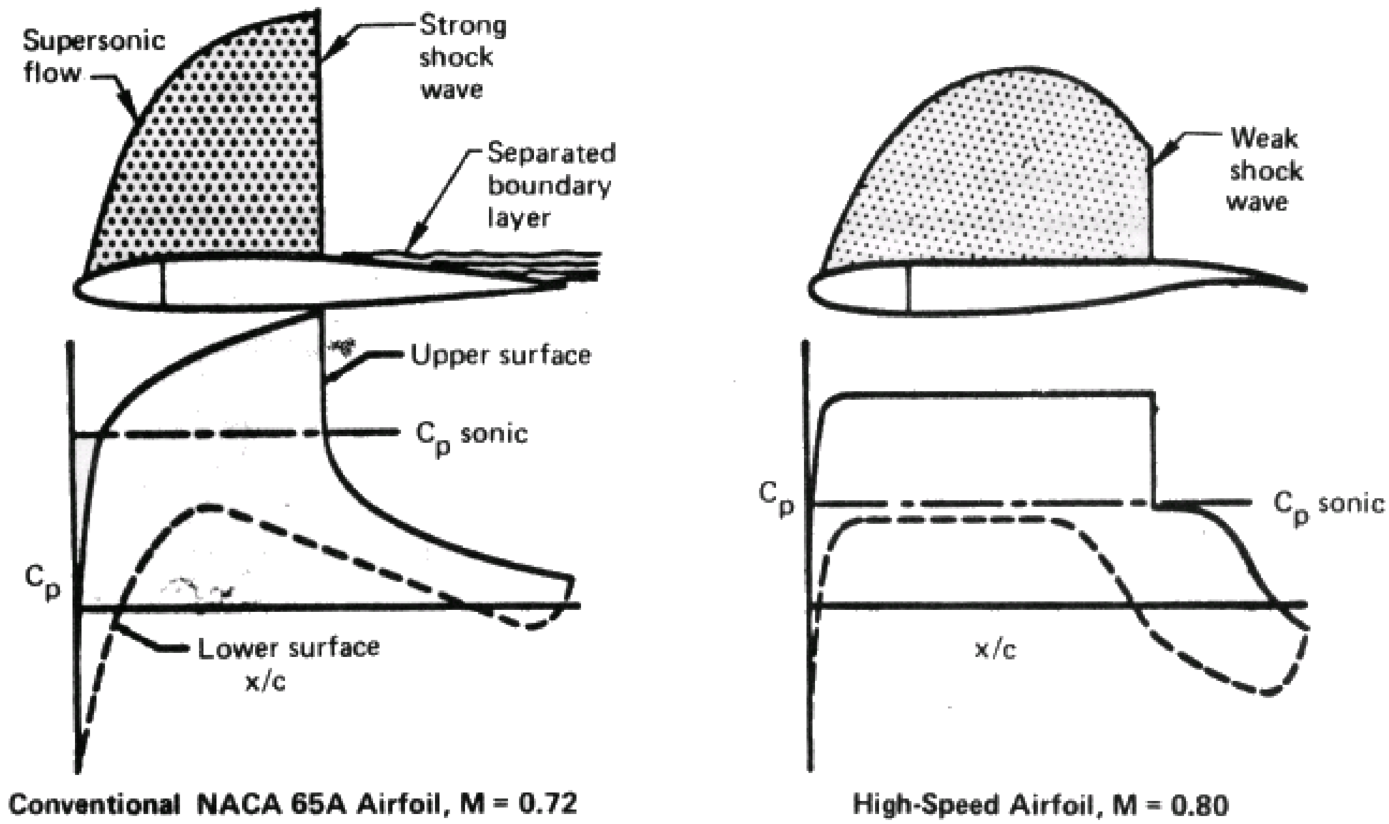

Figure 9.—Conventional and High-Speed Airfoil Comparison

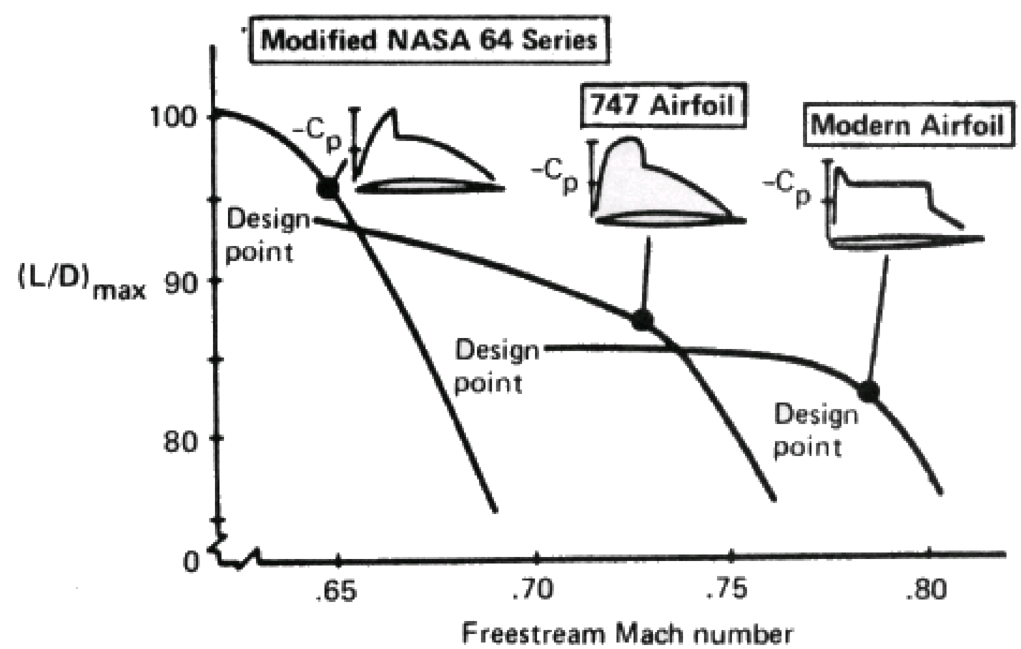

Figure 10.—Progress in Airfoil Aerodynamics

More recently, attention has been directed toward trading the advanced airfoils extra speed capability for extra thickness to achieve a lighter structure, or for extra thickness plus increased aspect ratio to improve aerodynamic efficiency, or for reduced wing sweep with a constant structural span to improve aerodynamic efficiency.

Although thicker airfoils are structurally efficient and weigh less, they increase the form drag (fig. 11). In previous evaluations of design parameters for long-range transport airplanes, the increase in drag resulted in extra fuel burned and cancelled the advantage of the lighter wing structure. Figure 12 illustrates this trade.

Results from a recent NASA-funded study by Boeing[6] indicated significant fuel savings by utilizing advanced technology airfoils on thinner wings with less sweep and higher aspect ratios relative to existing transport airplanes. In order to identify the overall performance improvements with the use of advanced high-speed airfoils as distinct from wing thickness and wing AR trades, the following approach was adopted:

1. Airfoil critical Mach number improvements of 0.03 and 0.05 relative to 747 airfoil technology were selected.

2. Wing outboard thickness/chord (t/c) ratios of 11% and 9% were considered.

3. The profile drag variation with airfoil thickness was the same for all of the airfoils.

4. For each airfoil and thickness combination, the wing sweep was selected to retain a constant wing critical Mach number. The minimum wing-quarter-chord wing sweep was limited to 8.5°. This sweep resulted in a straight trailing edge.

5. The wing structural span (wing spar length) and wing area were held constant.

The ΔM_{crit} = 0.03 airfoils represent currently available low profile drag high-speed airfoils. the ΔM_{crit} = 0.05 airfoils represent a reasonable projection of increased speed capability with the same profile drag levels.

The aerodynamic characteristics of the study configurations were estimated by methods used by the contractor for preliminary design configurations on which no wind tunnel data exist. In general, the procedures are based on empirical/theoretical extensions of applicable experimental data. The weight estimates for the wing geometry variations were obtained by statistical weight calculation methods.

The wing geometries that were studied to evaluate the high-speed airfoil potential benefits are summarized in table 2.

Model 767-736 is the reference LRC airplane (fig. 2). Models 767-736-1 and 767-736-2 are derivatives of this configuration with the indicated wing geometry changes.

Model 767-738 (fig. 13) is a version of the LRC airplane that incorporates the high-speed airfoil technology. This configuration, because of its reduced wing sweep, was used as the reference configuration for evaluating natural laminar flow airfoils

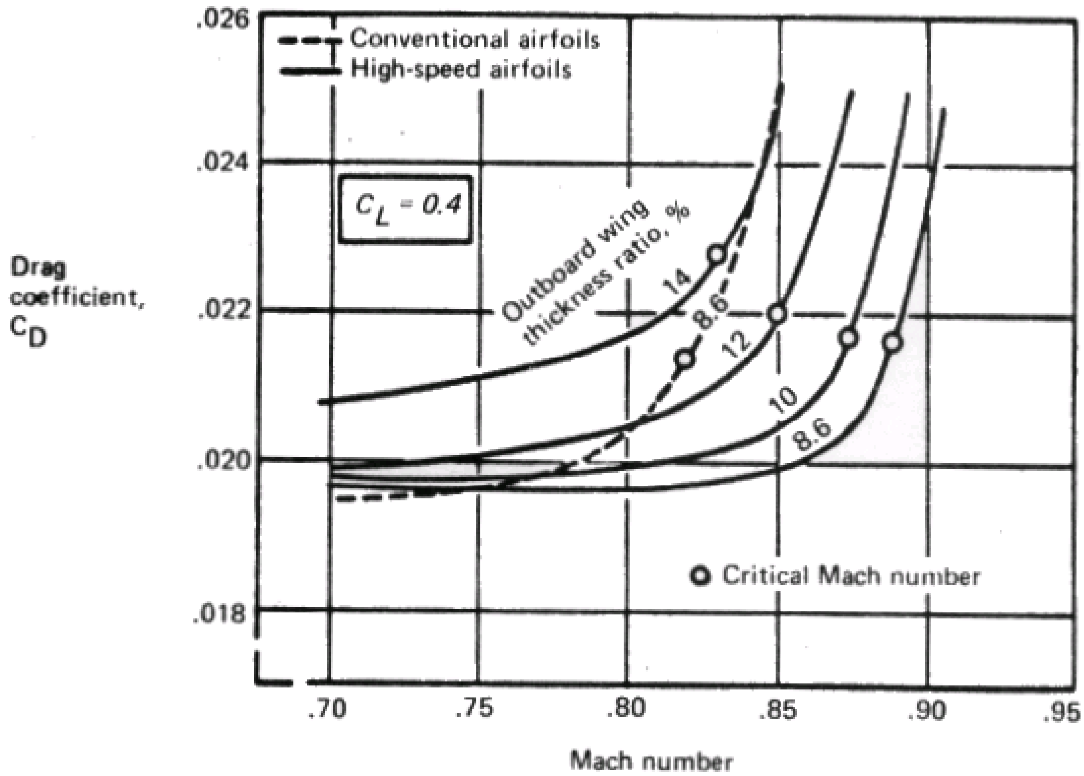

Figure 11.—Typical Drag Versus Wing Thickness Variation

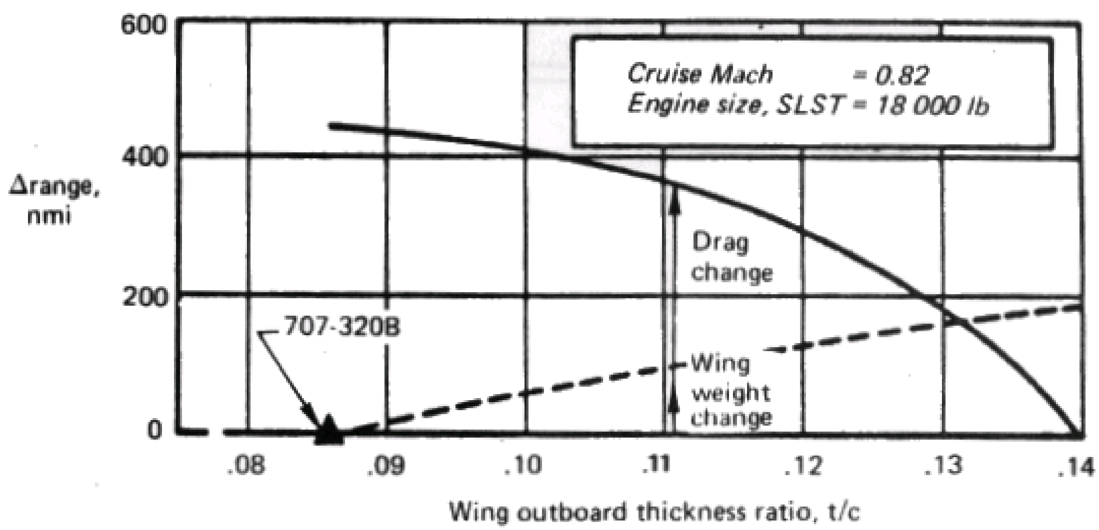

Figure 12.—Range Versus Wing Thickness
(Constant Cruise Speed)

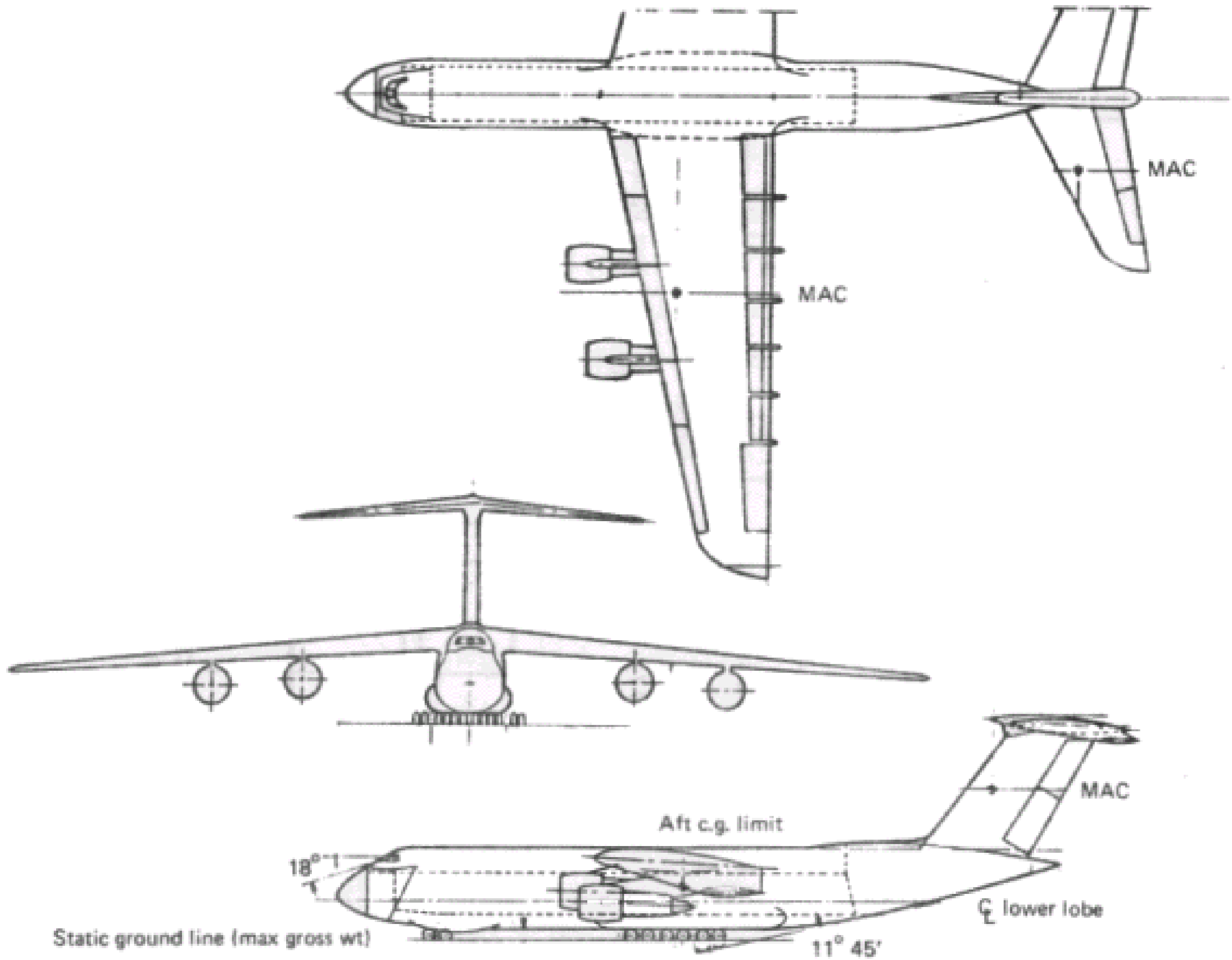

Figure 13.—Long-Range Airplane Incorporating High-Speed Airfoil—Model 767-738

Table 2.—Wing Definitions for the High-Speed Airfoil Study

Configuration Model no.	Wing no.	Airfoil	ΔM_{crit} airfoil	$\Lambda_{c/4}$	AR_{aero}	Outboard t/c, %
767-736	1	Conventional	Base for t/c = 11%	25.0°	7.75	11
767-736-1	2	High speed	+0.03	13.5°	8.92	11
767-736-2	3	Adv high speed	+0.05	8.5°	9.23	11
767-738-1	4	Conventional	Base for t/c = 9%	15.0°	8.8	9
767-738	5	High speed	+0.03	8.5°	9.23	9
767-738-2	6	Adv high speed	+0.05	8.5°	9.23	9

(sec. 2.4.2) and laminar flow control (sec. 2.4.3). Models 767-738-1 and 767-738-2 are derivatives of this configuration.

The calculated uncycled L/D ratios for long-range configurations with each of these wing geometries are shown in figure 14. The aerodynamic efficiency improvements through the use of the high-speed airfoils include:

- Reduced induced drag associated with the aerodynamic AR increase as wing sweep is reduced. This provided the greatest aerodynamic benefit for the LRC airplane.
- Reduced compressibility drag
- Increased $(ML/D)_{max}$ by prolonging the drag rise Mach number

These aerodynamic data along with the estimated weight changes were used to size each configuration to meet the design mission objectives. The sized airplane characteristics for each of these configurations are summarized in table 3.

The relative benefits of using current high-speed airfoils (ΔM_{crit} = 0.03) and advanced high-speed airfoils having an additional critical Mach number increase of 0.02 are shown in figure 15.

In order to define the effect of various levels of critical Mach number improvements relative to 747/C-5A airfoil technology, additional airfoils were defined having critical Mach improvements up to ΔM_{crit} = 0.05. The results of this study are illustrated in figure 16.

The wing sweep required to produce the wing design critical Mach of 0.775 is shown in figure 16. The results imply:

1. Depending upon the wing thickness, the aerodynamic efficiency improvements, gross weight reductions, and fuel savings increase rapidly with critical Mach improvements up to the condition when the minimum wing sweep is achieved.

2. Critical Mach improvements beyond this condition for minimum wing sweep produce smaller relative improvements.

Payload = 250 000 lb
Range = 10 000 nmi
Wing area = 13 430 ft²

Symbol	Model no.	Airfoil	ΔM_{crit}	$\Lambda_{c/4}$	AR
- - - - -	767-736	Conventional	0.0 (ref)	25.0°	7.75
———	767-736-1	High speed	0.03	13.5°	8.92
—·—	767-736-2	Adv high speed	0.05	8.5°	9.23

Symbol	Model no.	Airfoil	ΔM_{crit}	$\Lambda_{c/4}$	AR
- - - - -	767-738-1	Conventional	0.0 (ref)	15.0°	8.8
———	767-738	High speed	0.03	8.5°	9.23
—·—	767-738-2	Adv high speed	0.05	8.5°	9.23

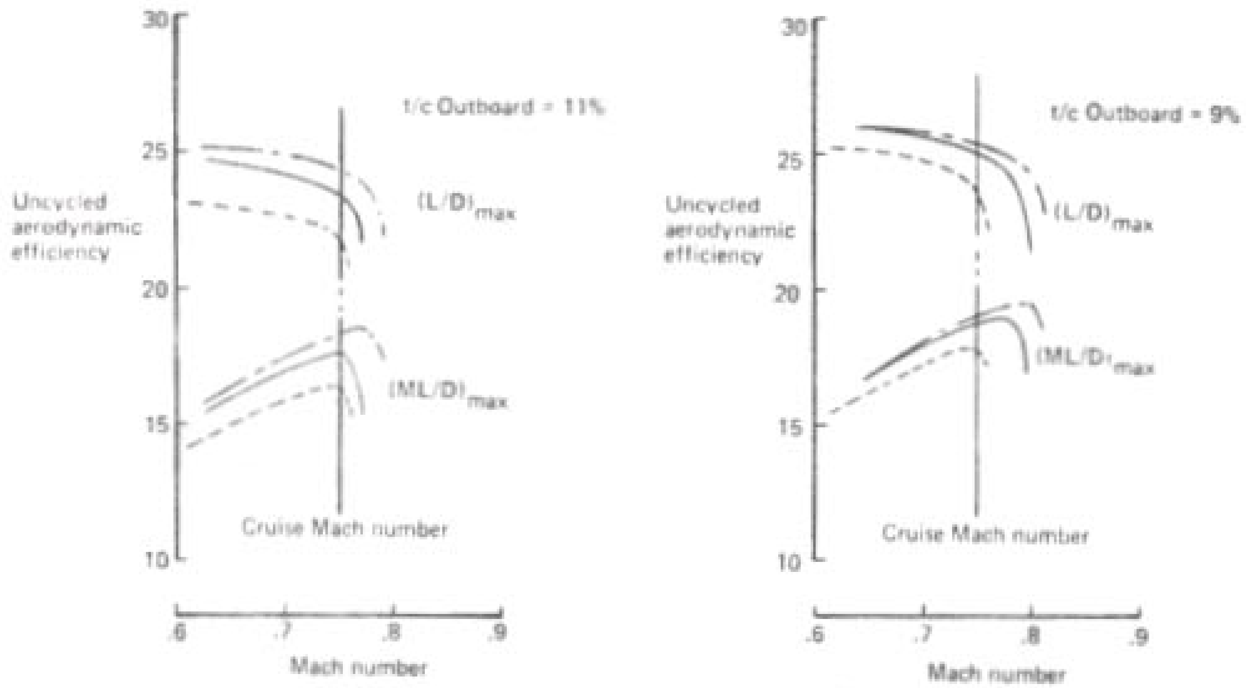

Figure 14.—Effect of High-Speed Airfoil Technology on Long-Range A/P Lift/Drag Ratio

Table 3.—Effect of Airfoil Thickness and High-Speed Technology

Study configuration		1	2	3	4	5	6
		767-736 Reference	767-736-1	767-736-2	767-738-1	767-738	767-738-2
Weights	TOGW, lb	1,665,000	1,545,600	1,485,600	1,538,700	1,465,100	1,446,500
	OEW, lb	521,000	491,500	476,900	498,500	480,600	475,900
	OEW/TOGW	0.313	0.318	0.321	0.324	0.328	0.329
	Payload, lb	250,000	250,000	250,000	250,000	250,000	250,000
	Payload/TOGW	0.150	0.162	0.168	0.163	0.171	0.173
Geometry	Wing area, ft^2	13,430	12,460	11,980	12,410	11,820	11,660
	Aspect ratio/$\Lambda_{c/4}$	7.75/25°	8.92/13.5°	9.23/8.5°	8.8/15°	9.23/8.5°	9.23/8.5°
	Wing t/c inboard/outboard, %	12.4/11.0			11.0/9.0		
	SLST/eng, lb	89,100	82,700	79,500	82,300	78,400	77,400
	T/W	0.214					
	W/S, lb/ft^2	124					
	Body length, ft	244.4					
Performance	Cruise Mach	0.75					
	Altitude, ft	30,000					
	Range factor	15,720	16,610	17,060	16,910	17,580	17,730
	L/D	21.2	22.4	23.0	22.8	23.7	23.9
	ΔM_{crit} airfoil	0.0 (base)	0.03	0.05	0.0 (base)	0.03	0.05
	Productivity−(payload/TOGW) × Mach	0.1125	0.1215	0.1260	0.1223	0.1283	0.1298
	Block fuel, lb	835,500	749,900	706,600	736,300	683,300	669,600
	Block fuel/lb payload	3.34	3.00	2.83	2.95	2.73	2.68

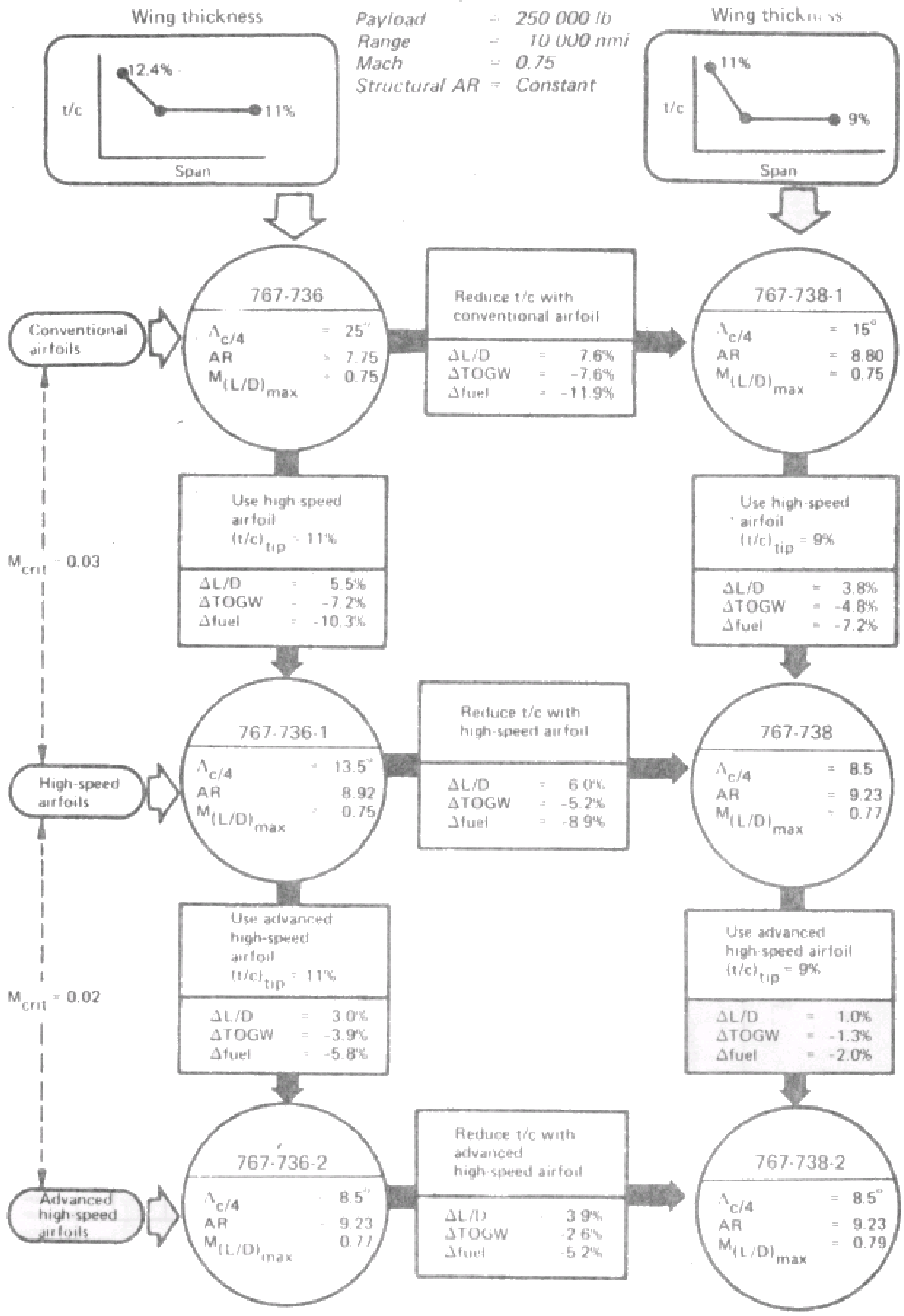

Figure 15.—High-Speed Airfoil and Wing Thickness Effects on the Long-Range Airplane

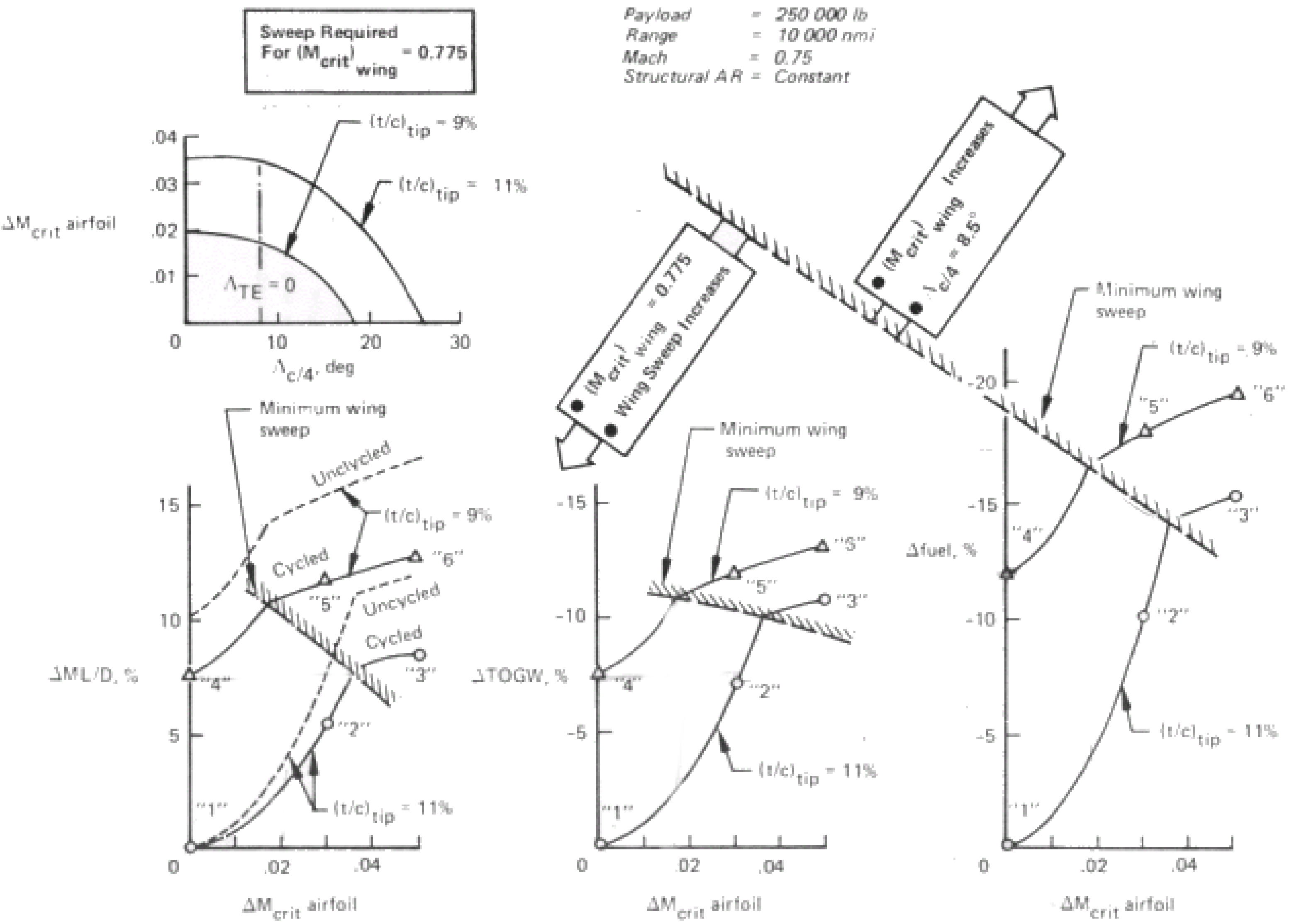

Figure 16.—Effect of High-Speed Airfoil Technology Improvements Relative to 747 Airfoil Technology Configuration—Model 767-736

The airfoil critical Mach improvement that produces the minimum wing sweep depends also on the wing design lift coefficient and on the design cruise speed. The relative effects of these variables are shown in figure 17. These results suggest that:

1. The current technology high-speed airfoils ($\Delta M_{crit} = +0.03$) are adequate to obtain the benefits of advanced airfoil technology for the LRC airplane of this study ($M_{cru} = 0.75$, $C_{L_{cru}} = 0.5$).

2. Advances in high-speed airfoils will be beneficial for the higher speed configurations ($M_{cru} > 0.75$) or for the high design lift coefficient.

Applying the high-speed airfoils to the high endurance configuration, as shown in figure 18, has little benefit because of the low cruise Mach number ($M = 0.65$).

High-Speed Airfoil Evaluation Conclusions:

1. Relative to the reference long-range airplane model 767-736 (fig. 2), the application of an advanced high-speed airfoil with $\Delta M_{crit} = 0.035$ produces the following benefits:

$(ML/D)_{uncycled}$ increase	= 11%
$(ML/D)_{cycled}$ increase	= 8%
TOGW reduction	= 10%
Fuel savings	= 14%

2. The relative performance improvements associated with high-speed airfoils are dependent on the reference configuration. The benefits relative to a 9% t/c wing long-range airplane would be less than half of the aforementioned values.

3. High-speed airfoils would have little effect on the high endurance airplane because of its lower design cruise speed.

4. The reduction in wing sweep achievable with the use of high-speed airfoils is beneficial in supporting other aerodynamic concepts. Low wing sweep is desired for laminar flow control, since the suction requirements are reduced. Low sweep is required for wings with natural laminar flow airfoils because of the boundary layer instability associated with spanwise flow.

2.4.2 NATURAL LAMINAR FLOW AIRFOILS

Pressure gradients have a decisive influence on the stability and transition of a laminar boundary layer.[10] The low drag of laminar flow airfoils is achieved by designing for long stretches of laminar boundary layer. This objective is generally achieved by

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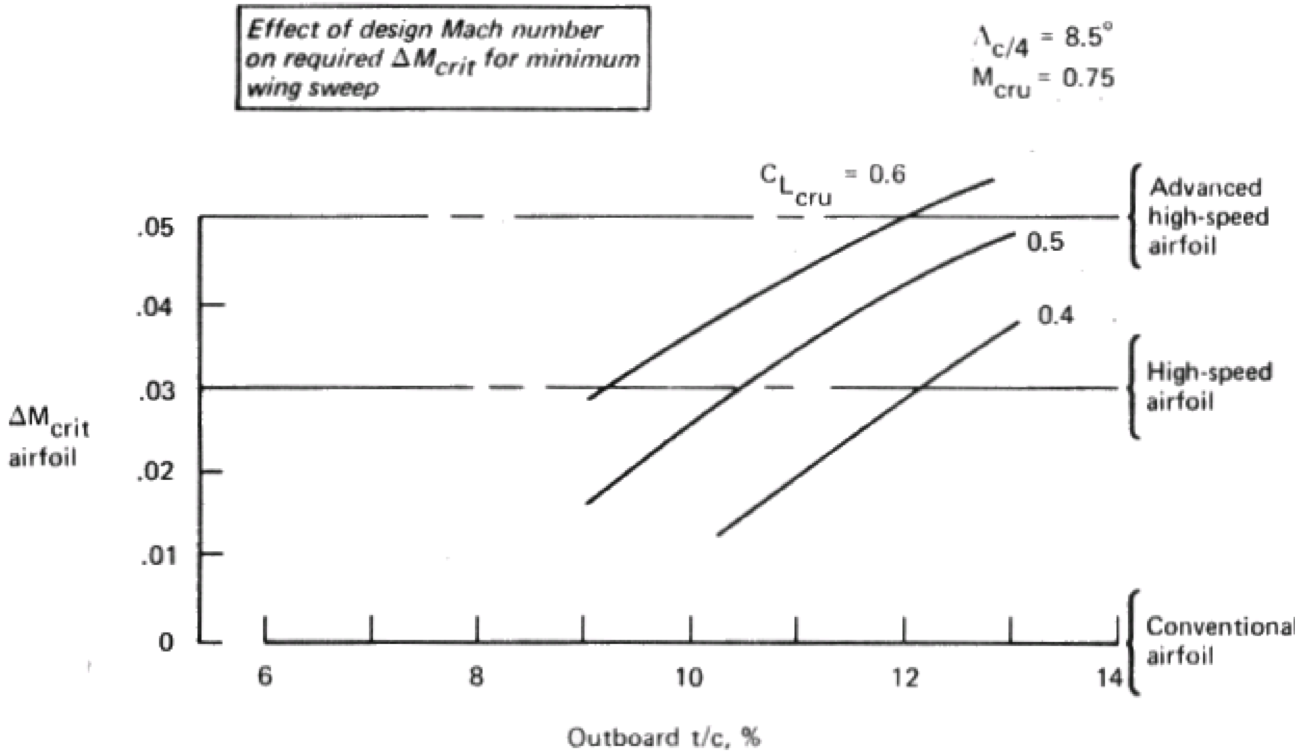
[10] Schlichting, H., "Boundary Layer Theory," Pergamon Press, 1955.



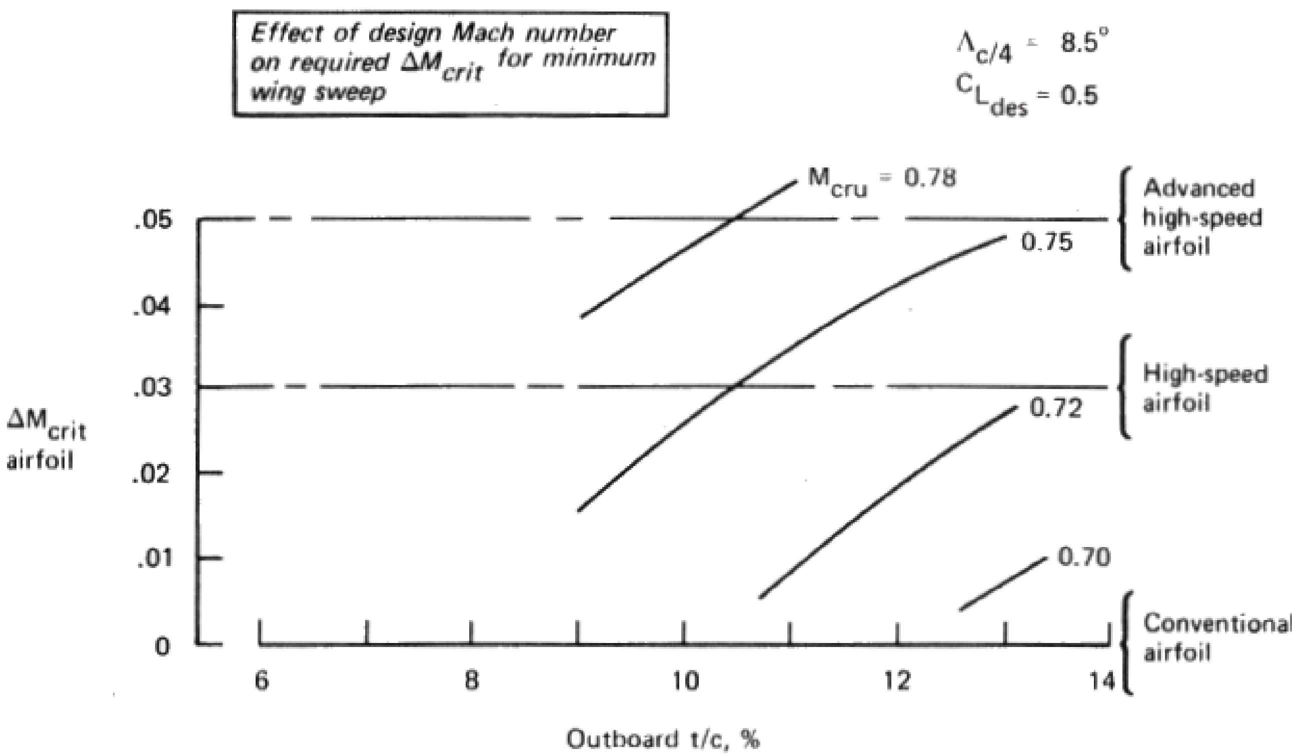


Figure 17.—Effect of Wing Thickness, Lift, and Mach Number on Required M_{crit} Improvement

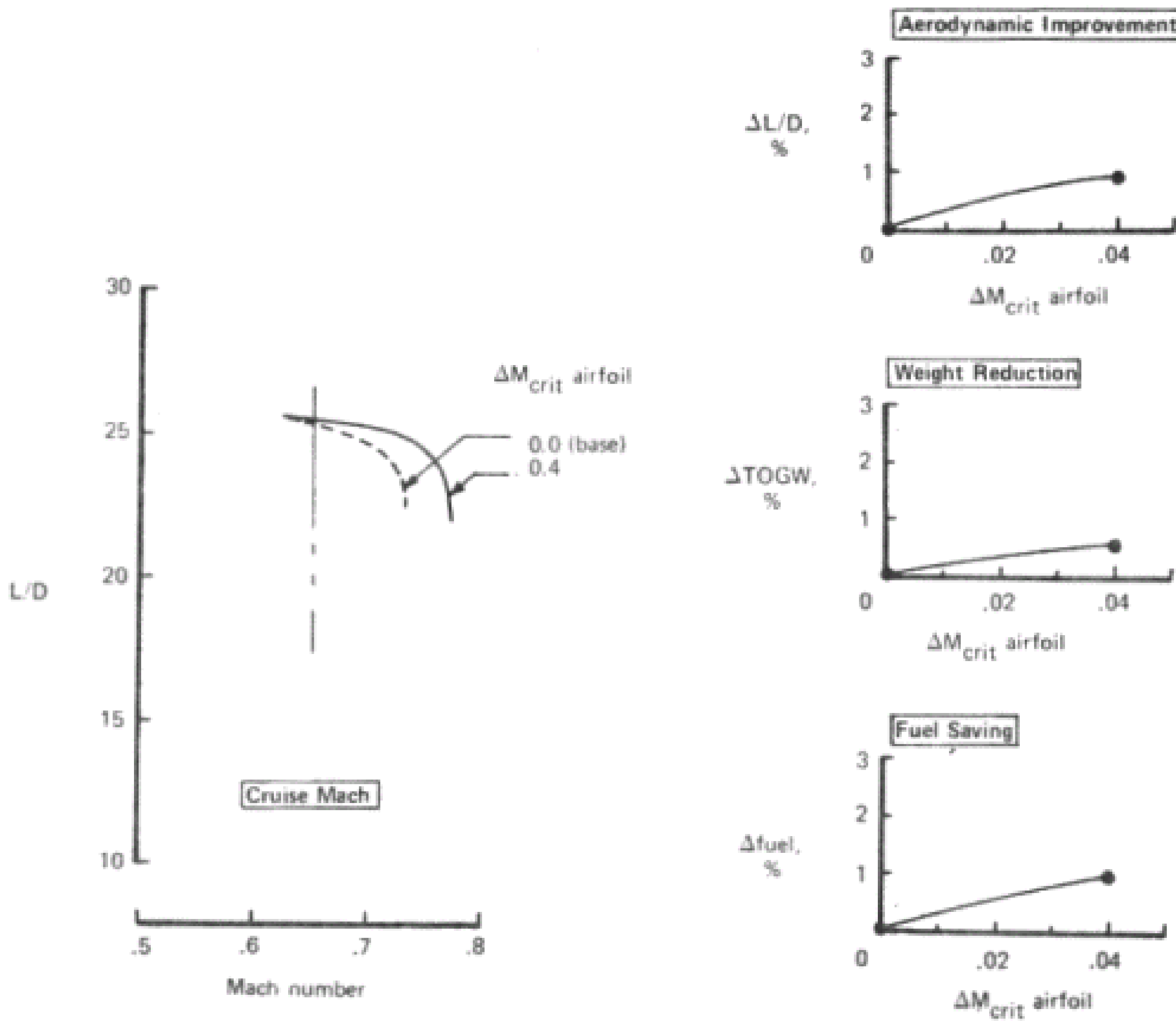


Figure 18.– Effect of High-Speed Airfoil Technology on High Endurance A/P, Model 767-739

moving the point of maximum thickness and, therefore, the point of minimum pressure a considerable distance aft of the leading edge. Figure 19 shows a typical theoretical pressure distribution and boundary layer transition location for a modern high-speed natural laminar flow airfoil design. Figure 20 indicates the profile drag sensitivity to transition location. The experimental data of figure 21 are typical of the drag characteristics of natural laminar flow airfoils.

The desired shift in the position of the pressure minimum can only be obtained over a relatively narrow range of incidence angles. This gives rise to the low-drag bucket characteristic of laminar airfoils. The transition location rapidly moves forward for other angles of incidence; the drag rapidly increases accordingly. The lift coefficient (C_L) range of the drag bucket can be controlled by the amount of camber (i.e., design lift coefficient) shown by the data[11] in figure 22.

The data of figure 23 indicate that relative to the fully turbulent flow profile drag level, drag reductions of more than 50% have been achieved.

The achievement of laminar flow is strongly affected by the Reynolds number. The experimental data of figures 24 and 25 show that the amount of laminar flow and the width of the drag bucket are dependent on the Reynolds number. The numerous wind tunnel experiments that have been conducted in the past with laminar airfoils have probably illustrated more the historical improvement in wind tunnel designs than improvement in airfoil designs. The achievement of laminar flow in wind tunnels is critically dependent upon the freestream turbulence intensity. As wind tunnel designs improved and turbulence intensity reduced, greater stretches of laminar flow were achieved at higher test Reynolds numbers. The laminar boundary layer is insensitive to the turbulence in the atmosphere which is a much larger scale than wind tunnel turbulence fluctuations. The early flight test data obtained with the King Cobra[12,13] shown in figure 23 are better than the low drag reductions achieved in the wind tunnel tests.

The aerodynamic benefits of natural laminar flow airfoils include:

1. Profile drag is reduced.

2. Drag is improved due to lift characteristics, since the boundary layer at the wing trailing edge is thinner than that for fully turbulent flow.

3. The roughness and excrescence drag are reduced, since the wing surface must be smooth to achieve laminar flow.

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(11) Abbot, I. H. and Von Doenhoff, A. E., "Theory of Wing Sections," Dover Publications, 1959.

(12) Smith, F. and Higton, D. J., "Flight Tests on King Cobra FZ.440 to Investigate the Practical Requirements for the Achievement of Low Profile Drag Coefficients on a Low Drag Airfoil," RAE report and memoranda 2375, August 1945.

(13) Gray, W. E. and Fullam, P. W. J., "Comparison of Flight and Tunnel Measurements on a Highly Finished Wing (King Cobra)," RAE report AERO 2383, June 1950.

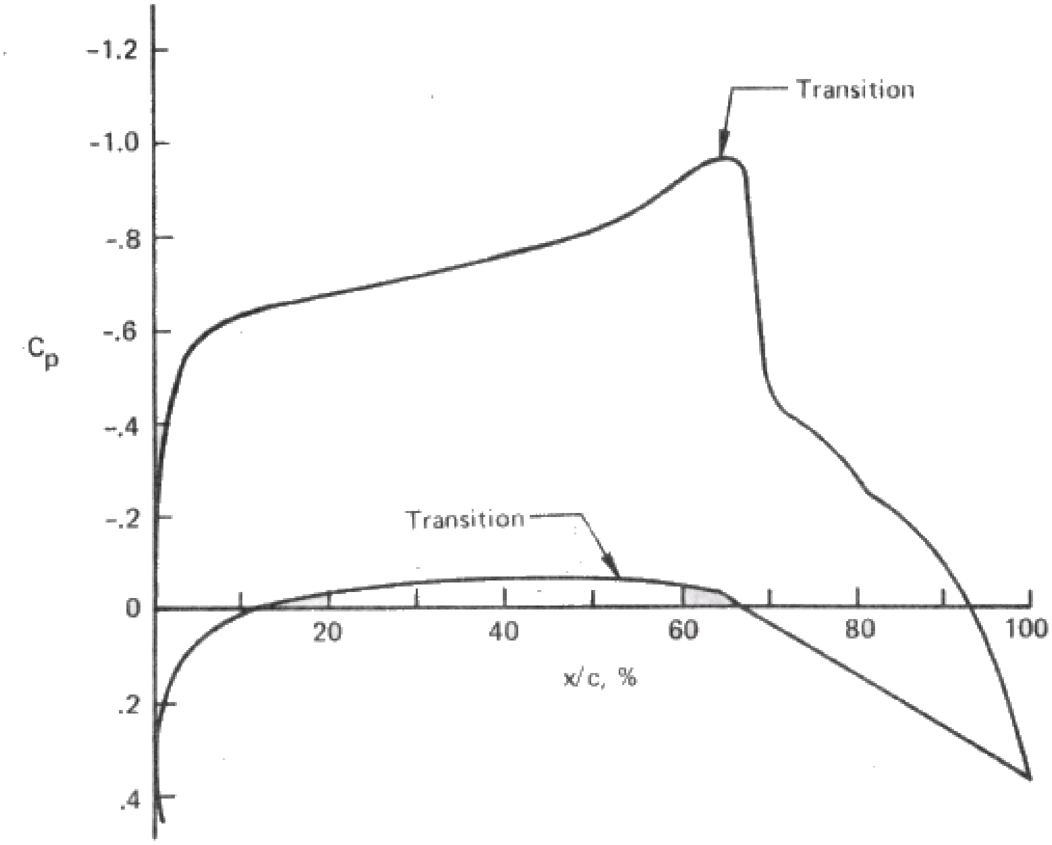

Figure 19.—Typical High-Speed Laminar Airfoil Pressure Distribution

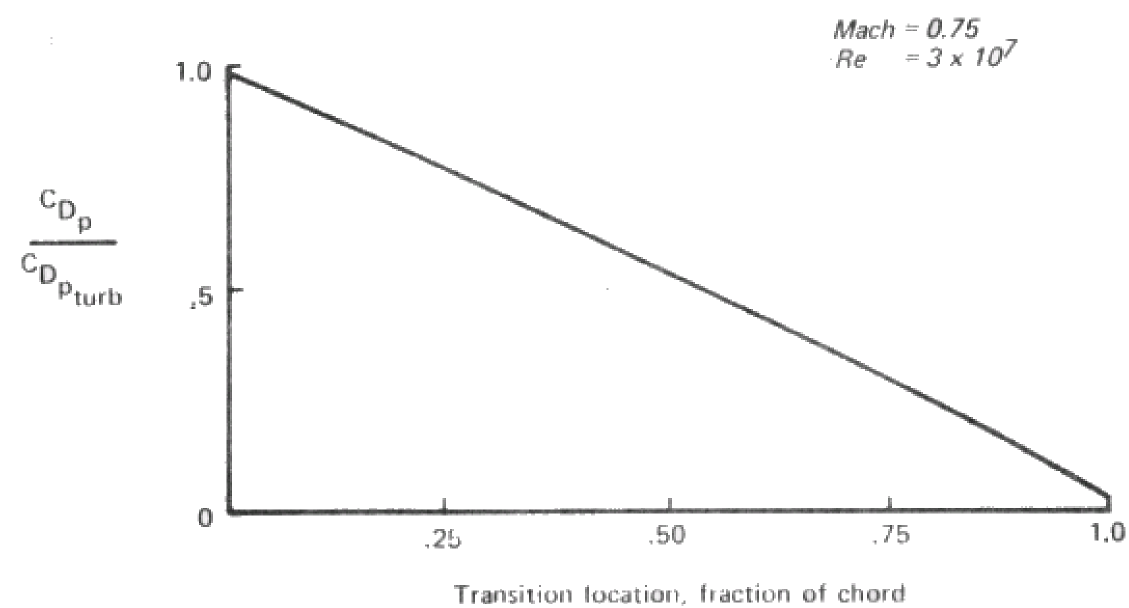

Figure 20.—Profile Drag Variation With Transition Location

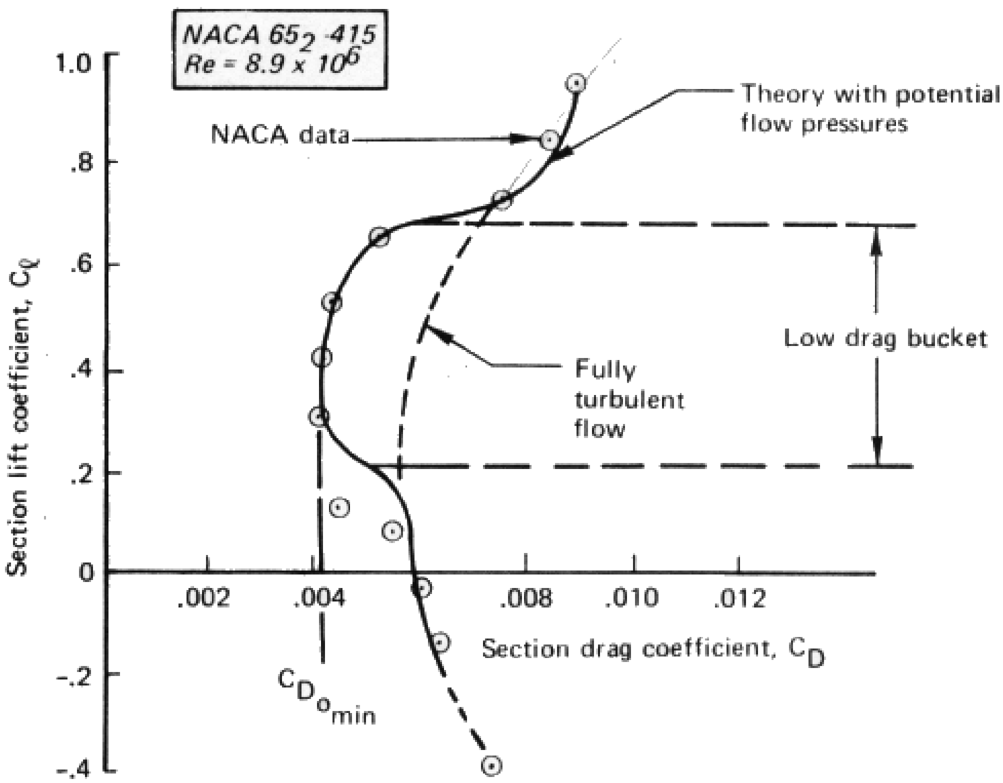

Figure 21.—Laminar Airfoil Drag Polar

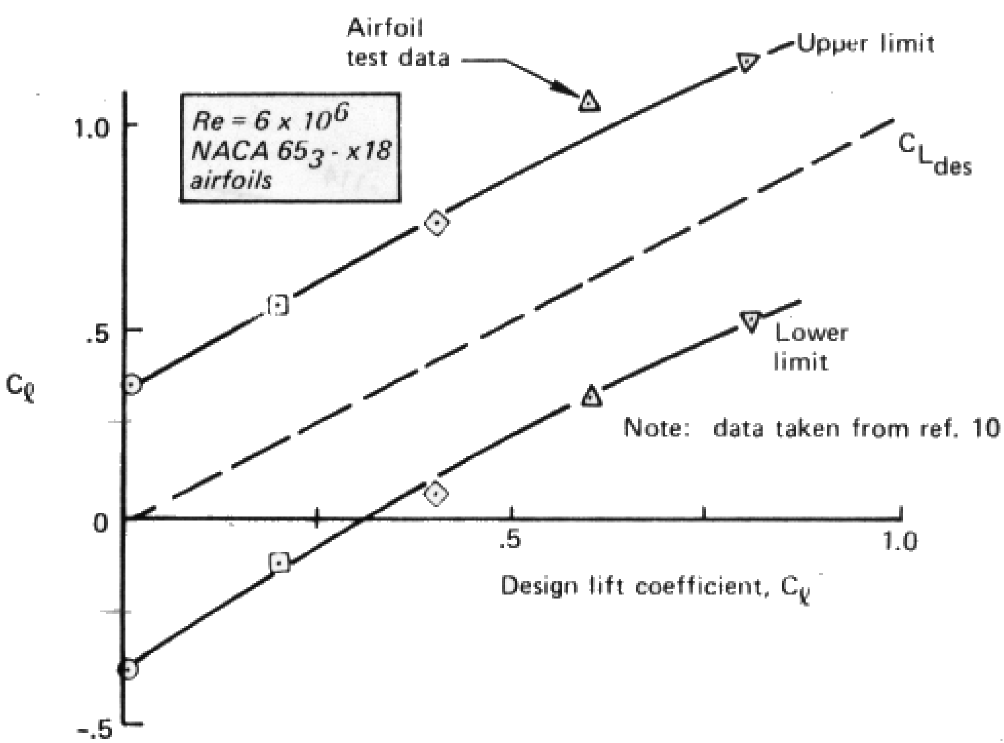

Figure 22.—Drag Bucket Variation With Design C_L

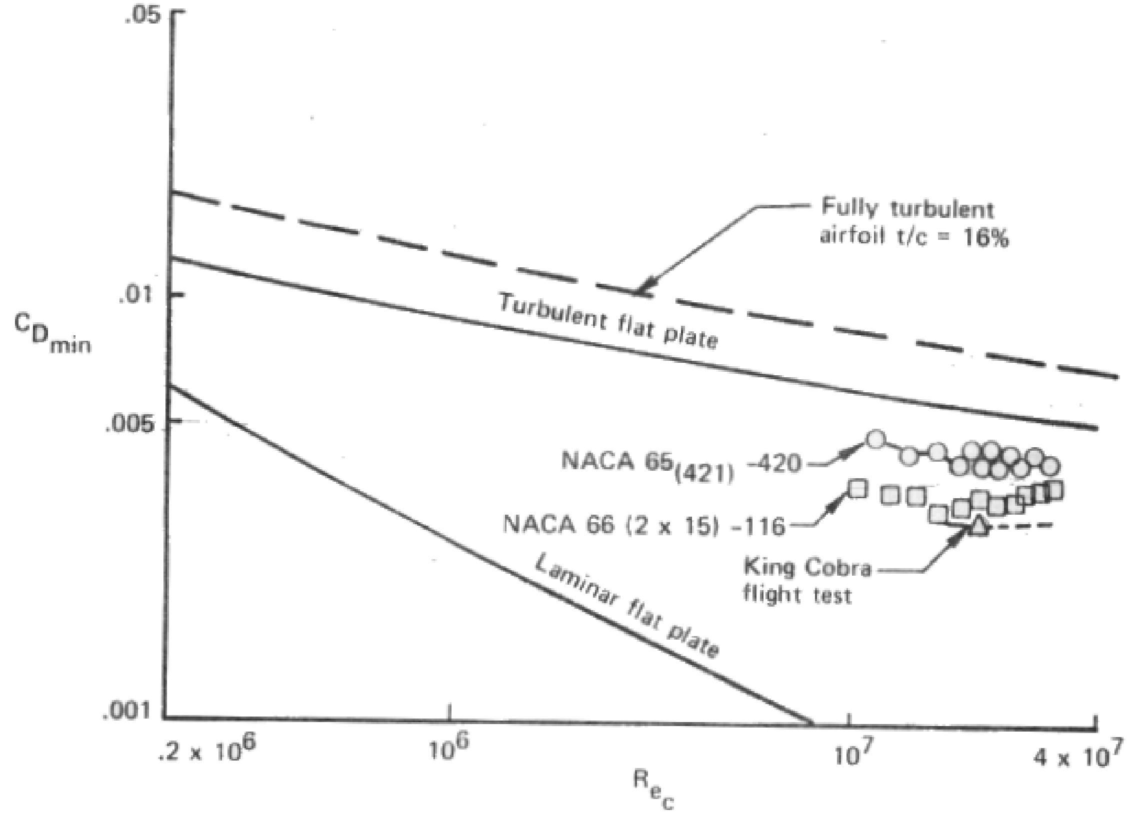

Figure 23.—Minimum Drag Load Versus Reynolds Number

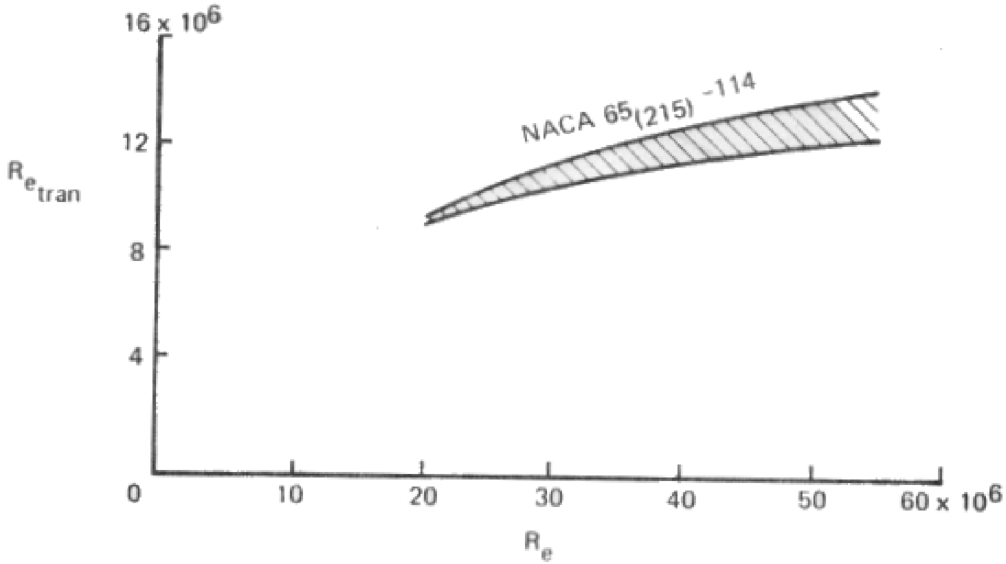

Figure 24.—Transition Reynolds Number Versus Chord R_e

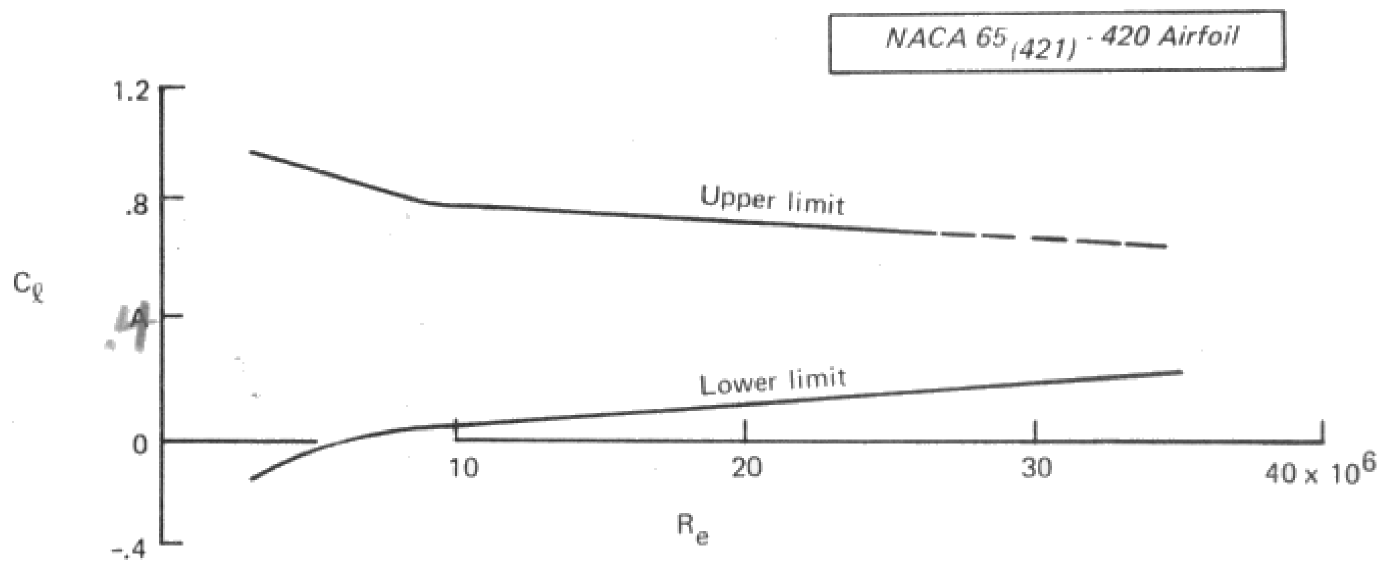

Figure 25.—Drag Bucket Width Versus Reynolds Number

The laminar boundary layer on an airplane configuration is critically sensitive to a number of factors in addition to the wing and airfoil designs that include:

- Surface roughness and waviness
- LE sweep
- Junction areas such as the wing-body intersection
- Acoustic disturbance either from the engines or nearby turbulent flow areas
- Operational disturbances such as insect deposits, rain, and ice
- Flight conditions; Reynolds number and Mach number

In order to evaluate the potential benefits of applying natural laminar flow airfoils to the baseline configurations, the following criteria have been used:

1. Laminar flow airfoils on wing and tail surfaces
2. The maximum run of laminar flow by the most critical of the following two conditions:

   $$\text{Transition } R_{\ell} \leqslant 12 \times 10^{6}$$

   $$\text{Transition } x/c \leqslant 0.6$$

3. Airfoil critical Mach number slightly better than current 747 technology airfoils
4. Wing sweep less than 10°
5. Wing-mounted nacelles with minimal acoustic disturbances
6. Smooth surfaces that allow laminar flow
7. No LE devices
8. Turbulent flow near the junctions of wing-body, tail-body, etc., confined to 9° turbulent wedges

Criteria 2 and 3 represent projected advances in the current state of the art but are felt to be achievable with the currently available aerodynamic design methods through coordinated experimental and theoretical development studies. Criteria 5 is a feasible through not critical objective that provides reduced wing weights through load relief. Criteria 6 is a necessary condition that appears realistic with improved manufacturing techniques and maintenance procedures.

Study Configurations

Four configurations were evaluated to assess the potential benefits of natural laminar flow airfoils. These included two reference fully turbulent flow configurations having wing aspect ratios of 9.23 and 15.0 and two comparable configurations employing natural laminar flow airfoils. The lower AR reference turbulent flow configuration was the reduced sweep configuration of the high-speed airfoil study (model 767-738, fig. 13). The higher wing AR configuration has shorter wing chords and, therefore, allowed longer relative stretches of laminar flow. The geometrical characteristics of these study configurations are summarized in table 4.

Table 4.—Natural Laminar Flow Airfoil Study Configuration Wing Geometry—Long-Range Mission

Configuration		Airfoil type	AR	λ	$\Lambda_{c/4}$	$C_{L_{des}}$	$M_{(L/D)_{max}}$
Number	Model no.						
A	767-738	High speed—fully turbulent	9.23	0.37	8.5°	0.5	0.77
B	767-738-3	High speed—natural laminar					0.75
C	767-738-4	High speed—fully turbulent	15.0	0.50		0.7	0.73
D	767-738-5	High speed—natural laminar					0.71

The reference turbulent flow configurations and the corresponding natural laminar flow configurations used comparable high-speed airfoil technology. The difference in the sized airplane characteristics can, therefore, be attributed to the benefit of achieving natural laminar flow It was necessary to use high-speed airfoils to allow the wing sweep to be reduced to avoid LE sweep-induced boundary layer transition.

The uncycled cruise drag polars for each of these four configurations are shown in figure 26. The cruise Mach numbers for the higher AR configurations are less than those of the lower AR configurations. This is the result of the reduced critical Mach number because of the higher design lift coefficient associated with the larger aspect ratio.

The effect of natural laminar flow airfoils on the uncycled aerodynamic efficiency of the study configurations is summarized in figure 27. The aerodynamic efficiency improvements of the natural laminar flow configurations are referenced to the corresponding equal AR fully turbulent airplane. The net effect on the required gross weight and fuel consumption is shown in figure 28.

The benefits of using natural laminar flow airfoils depend strongly upon the aspect ratio of the wing. Higher AR wings have shorter chord lengths and, therefore, achieve longer relative stretches of laminar flow. The higher AR wings have not been structurally evaluated to determine appropriate fatigue and flutter penalties. The results do illustrate the importance of striving for shorter wing chords.

Configuration		AR	Mach	Altitude, ft	Transition, x/c		
Number	Model no.				Wing	Horiz	Vert
Ⓐ	767-738	9.23	0.75	35 000	Fully turbulent		
Ⓑ	767-738-3				0.20	0.32	0.22
Ⓒ	767-738-4	15.0	0.73	40 000	Fully turbulent		
Ⓓ	767-738-5		0.71		0.35	0.40	0.25

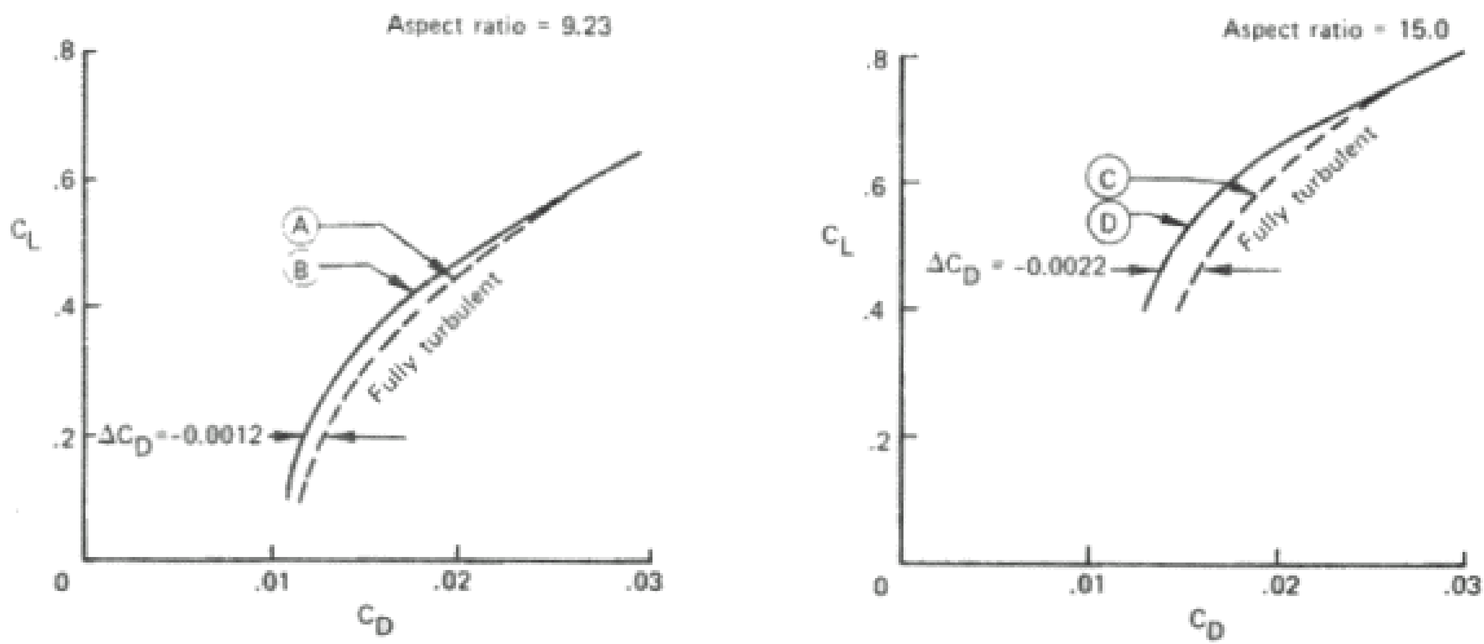

Figure 26.—Natural Laminar Flow Airplane Drag Polar Comparisons

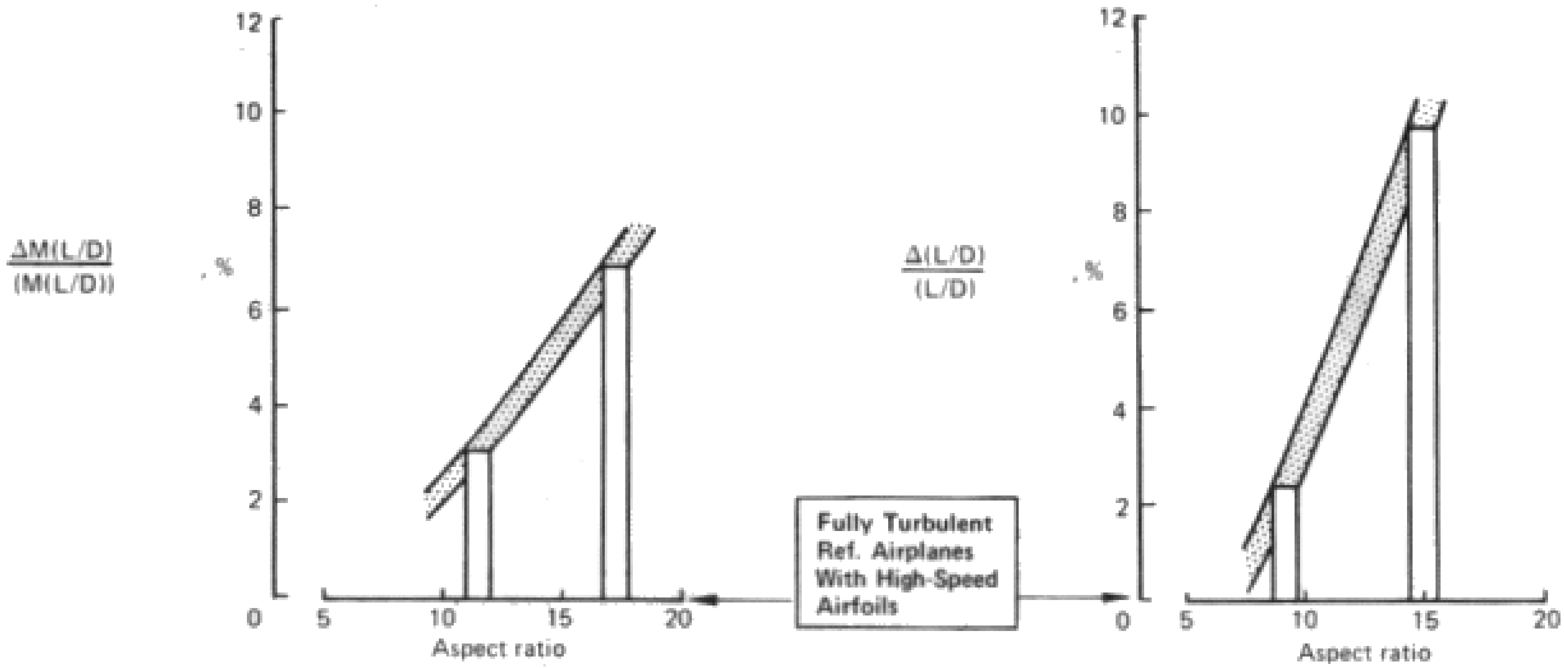

Figure 27.—Uncycled Aerodynamic Efficiency Improvement With Natural Laminar Flow Airfoils

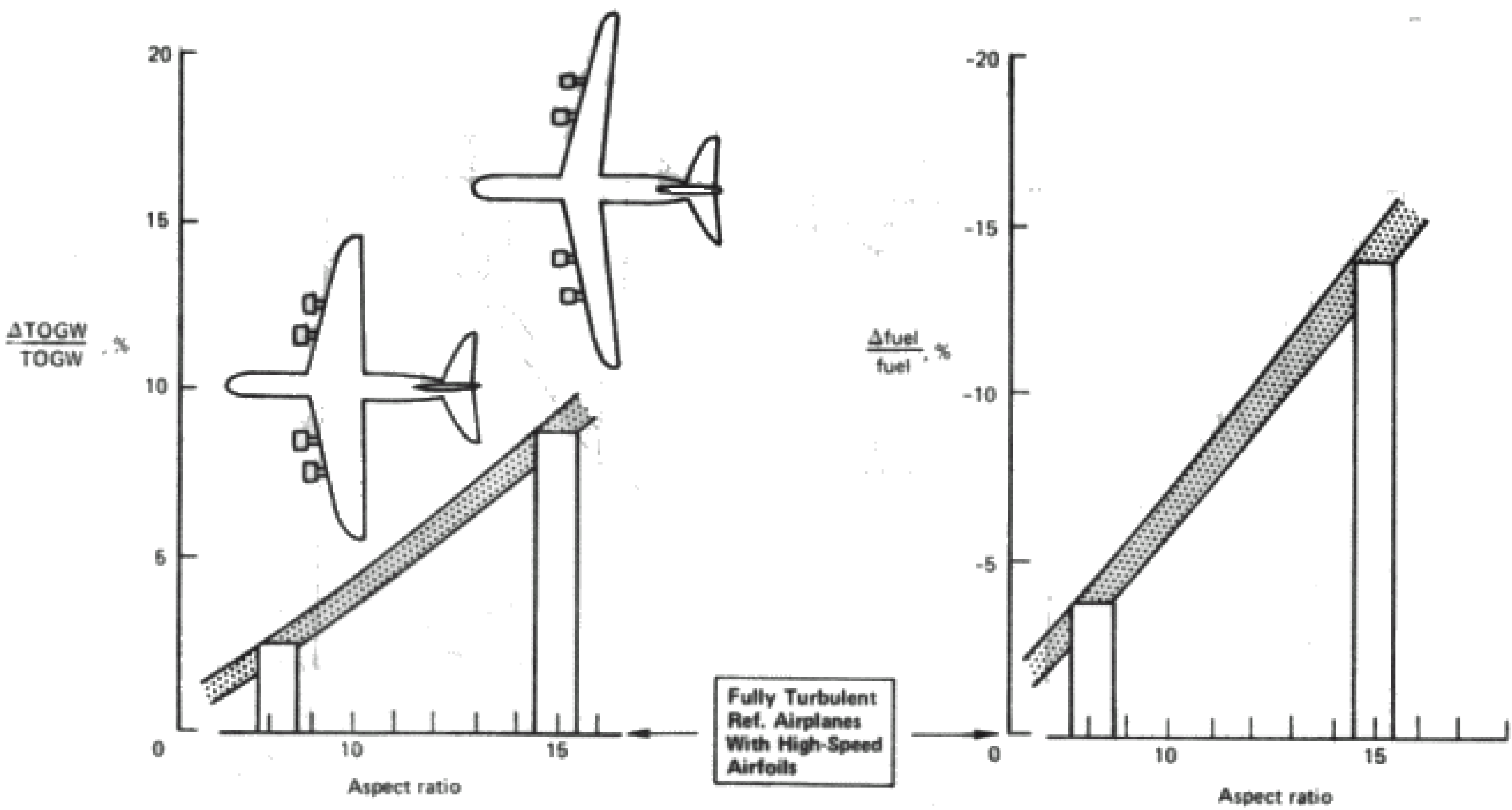

Figure 28.—Gross Weight and Fuel Burned Potential Reduction With Natural Laminar Flow Airfoils

Natural Laminar Flow Airfoil Conclusions

1. The benefits achieved with natural laminar flow airfoils depend on the fraction of chord over which laminar flow can be achieved.

2. Relative to the equivalent AR 15.0 fully turbulent flow LRC airplane (model 767-738-4), the natural laminar flow airfoil produced the following improvements:

$(ML/D)_{uncycled}$ increase	=	6.8%
$(ML/D)_{cycled}$ increase	=	4.5%
TOGW reduction	=	8.8%
Fuel savings	=	14.1%

3. Natural laminar flows would be slightly more beneficial on the high endurance airplane, since the reduced critical Mach number would not impact the endurance aerodynamic efficiency factor $(L/D)_{max}$.

2.4.3 LAMINAR FLOW CONTROL

Turbulent skin friction and the associated pressure drag constitute a major portion of the drag of an airplane. Consequently, achieving and maintaining appreciable stretches of laminar flow are desirable. The laminar boundary layer becomes increasingly unstable as the Reynolds number is increased. The natural instability of the laminar boundary layer may limit the application of natural laminar airfoils, as discussed in the previous section, to Reynolds numbers of approximately 12×10^6.

In principle, the laminar boundary layer (fig. 29a) can be artifically stabilized by sucking off the low energy air particles close to the surface. Various experimental test programs, most notably the flight tests of the X-21,[(14-16)] have shown conclusively that laminar flow control is technically feasible. Various system studies,[(17,18)] as illustrated in figure 29b, have shown that LFC offers large potential economic advantages. It remains to be demonstrated that the principle is operationally feasible for actual flight routes and practical from the standpoint of maintenance procedures.

[(14)] Whites, R. C. et al., "Laminar Flow Control on the X-21, *Astronautics and Aeronautics,* July 1966.

[(15)] Wheldon, W. G. and Whites, R. C., "Flight Testing of the X-21A Laminar Flow Control Airplane," AIAA paper 66-734, September 1966.

[(16)] Kosin, R. E., "Laminar Flow Control by Suction as Applied to the X-21 airplane," AIAA paper 64-284, July 1964.

[(17)] Lachmann, G. V., "Aspects of Design, Engineering, and Operational Economy of Low Drag Aircraft," *Boundary Layer and Flow Control Vol. 2*, Pergamon Press, 1961.

[(18)] Higman, T. and Hoefs, K., *A Comparison of Laminar Flow Control and Turbulent Airplane Designs*, Boeing document D6-24211TN, June 1969.

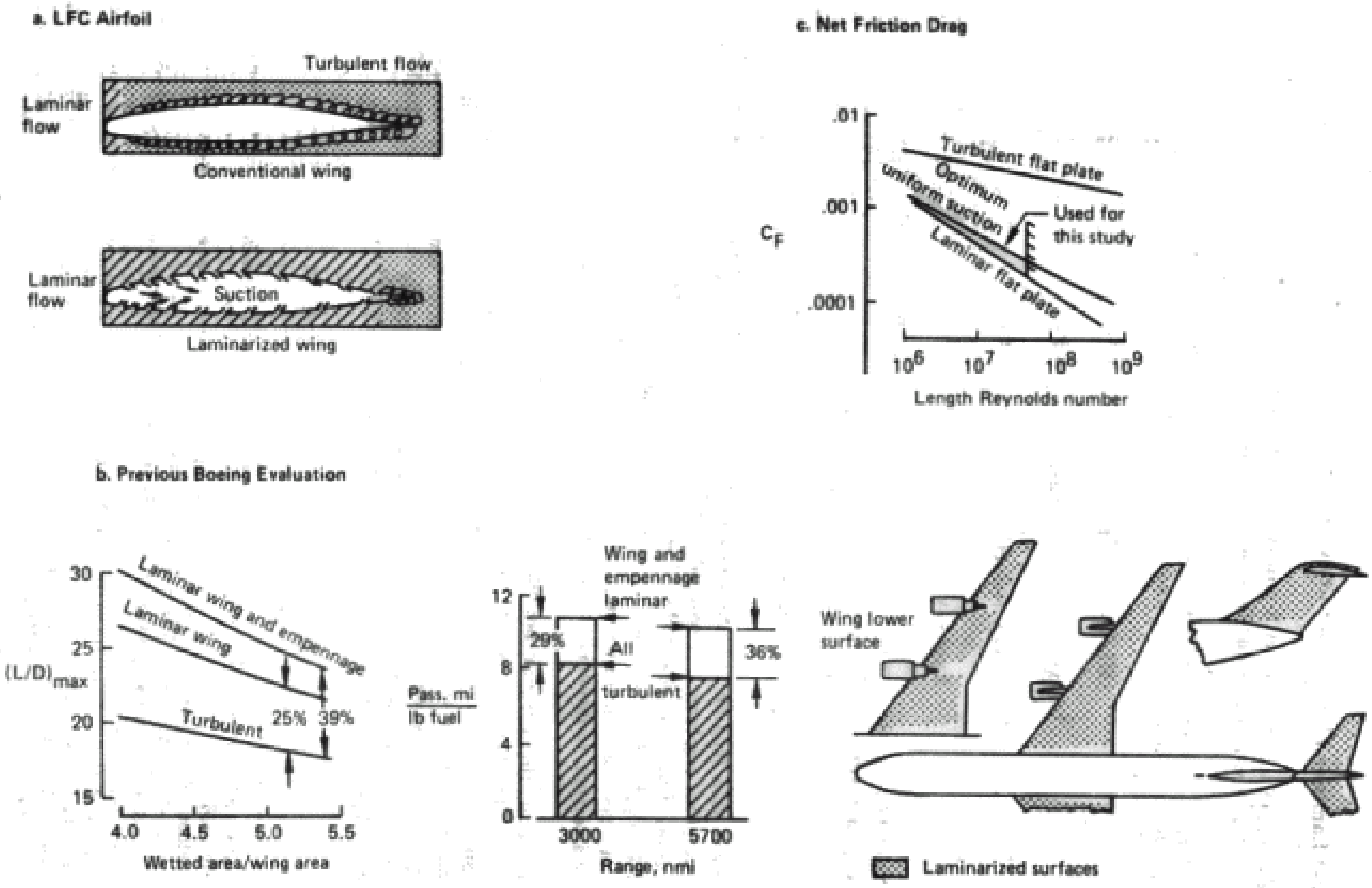

Figure 29.—Laminar Flow Control Background

LFC Benefits

The obvious direct benefit of laminar flow control is the substantial reduction in skin friction and profile drag associated with achieving nearly full-chord laminar flow. As shown in figure 29c, the net drag of an LFC surface including the equivalent suction drag associated with the power required by the suction system is only 10% to 20% of the fully turbulent drag level.

Laminar flow control by virtue of reducing the boundary layer buildup decreases the induced drag by reducing the loss in circulation associated with thick boundary-layer layers. This effect is more significant on sweptwings that normally experience a rapid thickening of the boundary layer near the wingtip associated with the spanwise flow within the boundary layer. LFC minimizes this spanwise flow. In addition, the usual significant increase in profile drag with thick wing sections does not occur with LFC wing sections.

Study Guidelines

The criteria that have been used to evaluate the potential benefits of LFC are similar to the ground rules adopted for the previously discussed natural laminar flow airfoils. The LFC evaluation ground rules included:

- Laminar flow control on the wings and tail except for the TE control surfaces
- The maximum run of laminar flow limited to Reynolds numbers less than 47×10^6
- Airfoil critical Mach number slightly higher than current 747 airfoils
- Wing-mounted nacelles with minimal acoustic disturbances
- Smooth surfaces that allow laminar flow
- No LE devices
- Turbulent flow near the junctions of wing-body, tail-body, etc., confined to turbulence wedges with 9^0 half angles

The achievement of laminar flow with LFC is susceptible to the same type of destabilizing disturbances as natural laminar flow airfoils, however, to a much smaller degree.

LFC Configurations

The study configurations that were used to evaluate the benefits of laminar flow control are summarized in table 5. These configurations included two reference turbulent flow configurations and two similar configurations that employed LFC on the wing and tail surfaces. Model 767-638 (fig. 13) and model 767-638-4 are the same two reference turbulent flows that were used to evaluate natural flow airfoils.

Table 5.—Laminar Flow Control Study Configurations—Long-Range Mission

Configuration		Wing geometry				Flow description
Number	Model no.	Airfoil	AR	λ	$\Lambda_{c/4}$	
1	767-738	High-speed airfoils	9.23	0.37	8.5°	Fully turbulent
2	767-738-5					LFC on wings and tail
3	767-738-4		15.0	0.50		Fully turbulent
4	767-738-6					LFC on wings and tail

The study configurations identified in table 5 used high-speed airfoils. It was necessary to use high-speed airfoils in the natural laminar flow evaluations so that the wing sweep could be small enough to allow natural laminar flow along the attachment line. The use of high-speed airfoils for a laminar flow control configuration is desirable but not absolutely necessary, since suction near the leading edge of sweptwings will alleviate the boundary layer instability associated with wing sweep as demonstrated in the X-21 flight test program.

Because of the large chord size of the AR = 9.23 configuration, the laminarized area on the inboard portion of the wing was limited by the maximum Reynolds number constraint (fig. 30). The shorter chords of the higher AR wing (AR = 15.0) allowed laminar flow to the TE flaps.

These study configurations have not been optimized to fully exploit the potential benefits of laminar flow control. With projected manufacturing technology improvements, full-chord laminar flow is considered feasible with LE and TE control surfaces. The results of this study should be viewed as a conservative appraisal of LFC benefits. The results of the natural laminar flow study and LFC study results are combined in figure 31 to illustrate the additional performance benefits with increasing the fraction of wing and tail wetted areas that are laminarized.

Study Results

The study results, as shown in figure 32, indicate that the performance benefits of LFC are insensitive to wing aspect ratio. Laminar flow on the long-range airplane resulted in a net aerodynamic efficiency, L/D, increase of 25% with a corresponding reduction in gross weight of 17% and a fuel savings of nearly 30% as compared to the high-speed airfoil fully turbulent flow reference airplane model 767-738. In these evaluations, a weight penalty of 1.5 lb/ft^2 of laminarized (suction) area was used (includes pumps and engines). The sensitivity of the performance benefits to the LFC system weights was investigated. The results (fig. 33a) indicate that the system weight is an important design consideration but will not affect the relative evaluations of this study. A current detailed NASA/Boeing design study[19] is evaluating the impact of LFC on the structural design characteristics of a composite material wing. These results will

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[19] "A Preliminary Design Study of a Laminar Flow Control Wing of Composite Materials for Long-Range Transport Aircraft," contract NAS 1-13872, study by Boeing Commercial Airplane Company, completion date January 1976.

Mach	=	0.75
Altitude	=	35 000 ft
R_{X_T}	$<$	47×10^6
AR	=	9.23

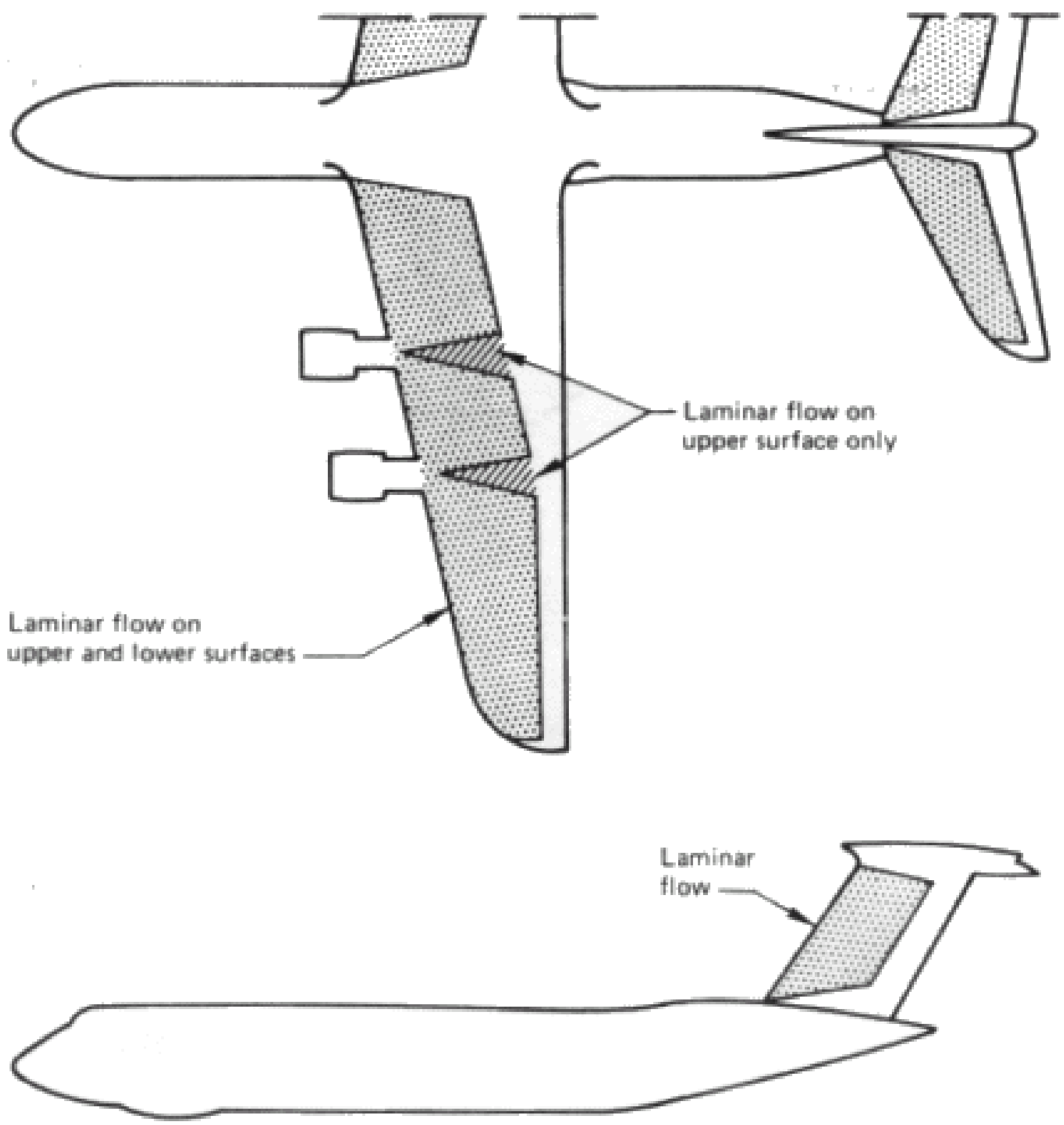


Figure 30.—Laminar Flow Areas—Model 767-738-5

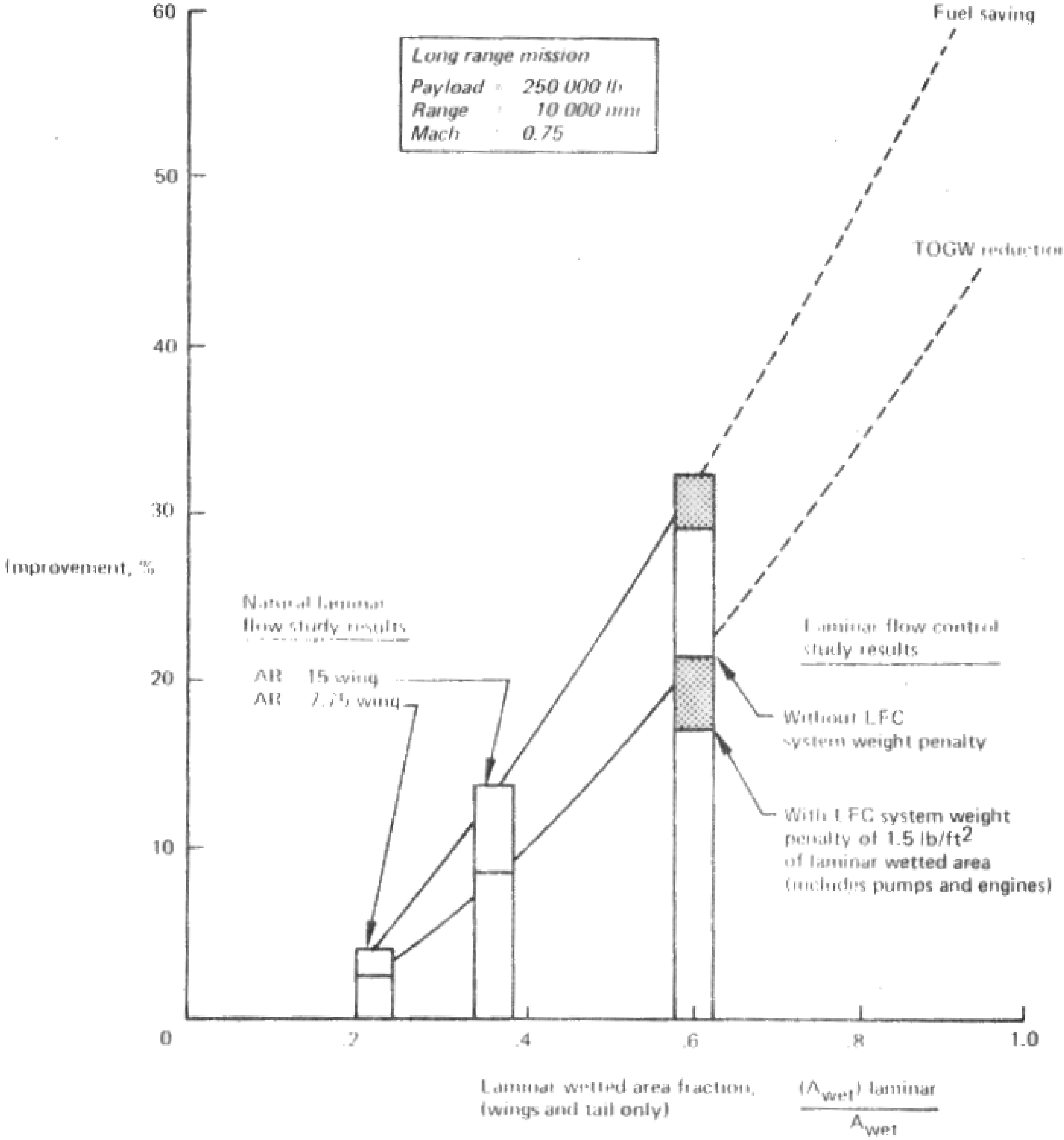


Figure 41.—Effect of Amount of Laminar Flow on Fuel Savings and Gross Weight Reduction

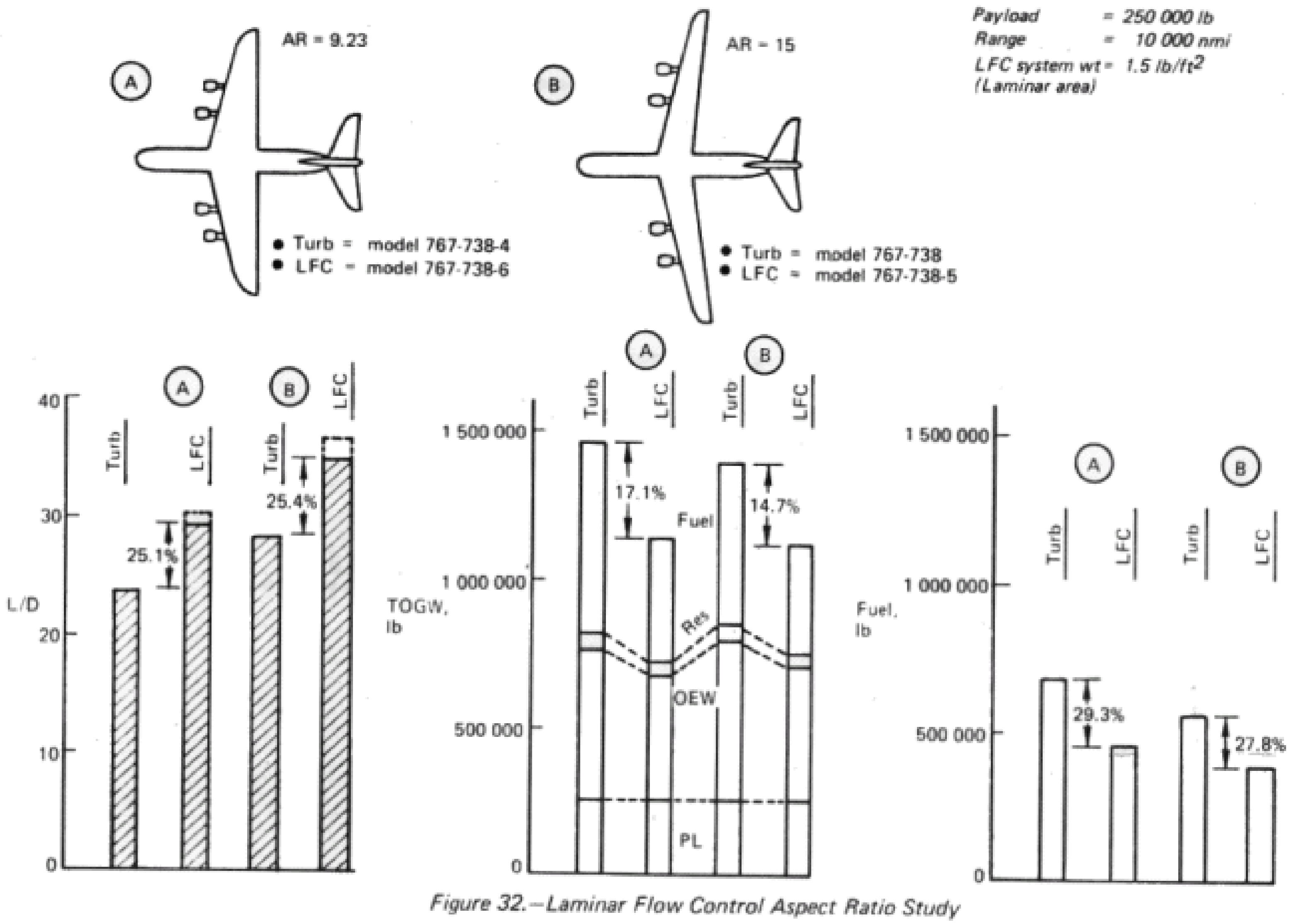


Figure 32.—Laminar Flow Control Aspect Ratio Study

Payload	=	*250 000 lb*
Range	=	*10 000 nmi*
Mach	=	*0.75*
AR	=	*9.23*

- LFC A/P = model 767-738-5
- Ref. turb A/P = model 767-738

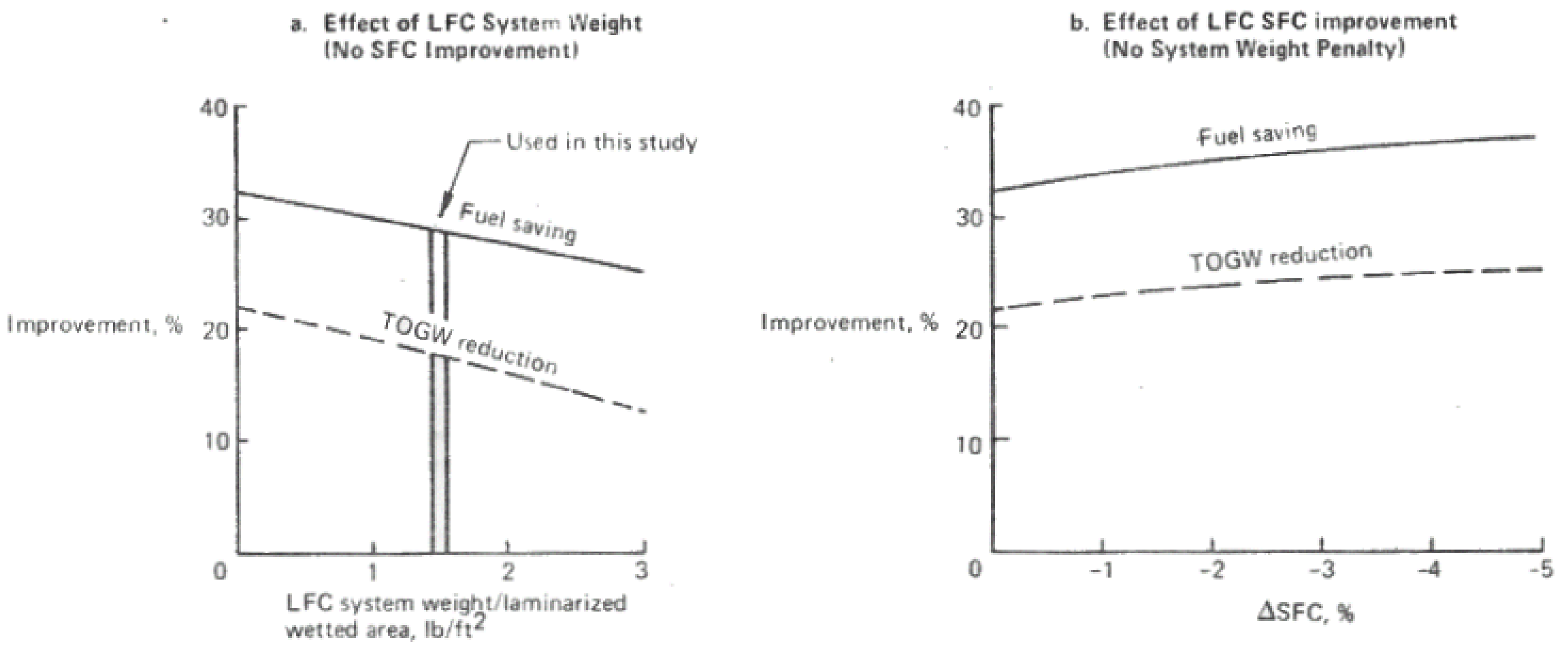


Figure 33.—Laminar Flow Control Improvement Sensitivities

provide valuable data for future LFC preliminary design studies. A previous LFC study[18] indicated that for an optimized system, the sucked air should be discharged at a velocity slightly greater than freestream velocity to minimize the overall fuel consumption and thrust requirements. This would allow an approximate 2% overall system specific fuel consumption (SFC) improvement. The sensitivity of the current study results to SFC improvements was investigated. These results, as illustrated in figure 33, indicate that a 2% improvement in SFC produces a comparable improvement in the fuel savings and gross weight reduction associated with laminar flow control. The major study results do not include this SFC benefit.

The effect of design range on the LFC performance benefits is shown in figure 34 for the AR = 9.23 configuration. These results are compared (fig. 35) with the corresponding results of earlier Boeing studies of LFC applications to commercial transports. These results indicate that for design ranges of greater than 4000 nmi, laminar flow control will result in approximately a 30% fuel savings for both military and commercial missions. The TOGW reduction associated with the use of LFC continues to improve as the design range increases.

LFC Evaluation Conclusions

1. With laminar flow on the wings and tail excluding the TE control surfaces, the following performance benefits were identified for the 10 000-nmi long-range airplane:

$L/D_{uncycled}$ increase	= 29%
L/D_{cycled} increase	= 25%
TOGW reduction	= 17%
Fuel savings	= 29%

2. The fraction of fuel saved with LFC levels off for design ranges above 4000 nmi, although the fractional gross weight reduction continued to increase with design range.

3. Relative to the comparable fully turbulent flow airplane, the fractional fuel savings and gross weight reduction are insensitive to the wing aspect ratio, since the length of laminar flow was limited by the TE flap and not by the maximum Reynolds number constraints.

4. With improved manufacturing techniques, laminarization of the TE control surface could be technically possible. The shorter chords of the higher AR wing would then allow full-chord laminarization and would substantially increase the performance benefits achievable with LFC. The relative performance benefits would then indicate a rather strong dependence on the wing aspect ratio for long-range designs.

5. The weight of the LFC system is a significant design consideration. The fuel savings and weight reduction achieved with LFC on the long-range airplane are

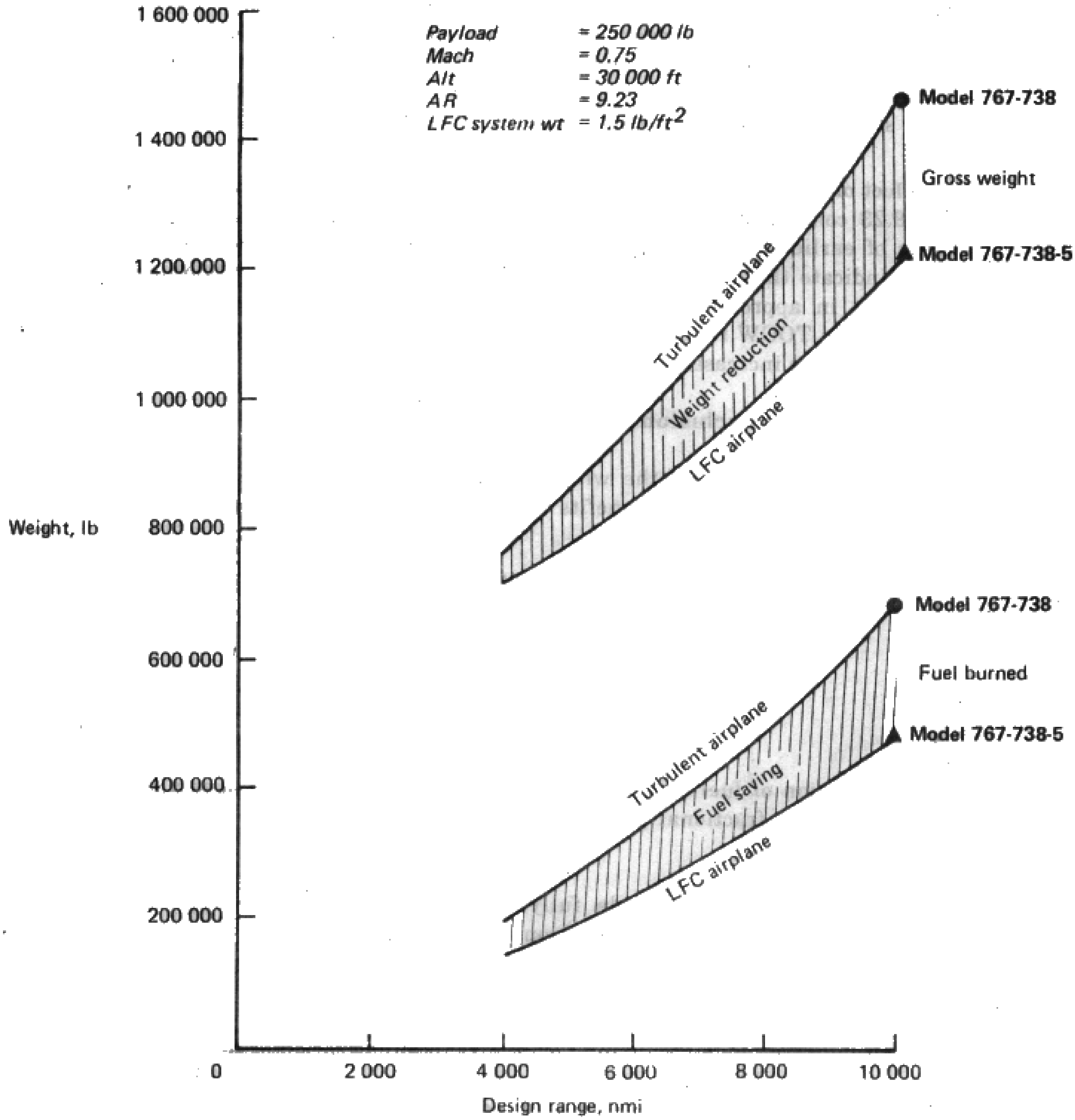
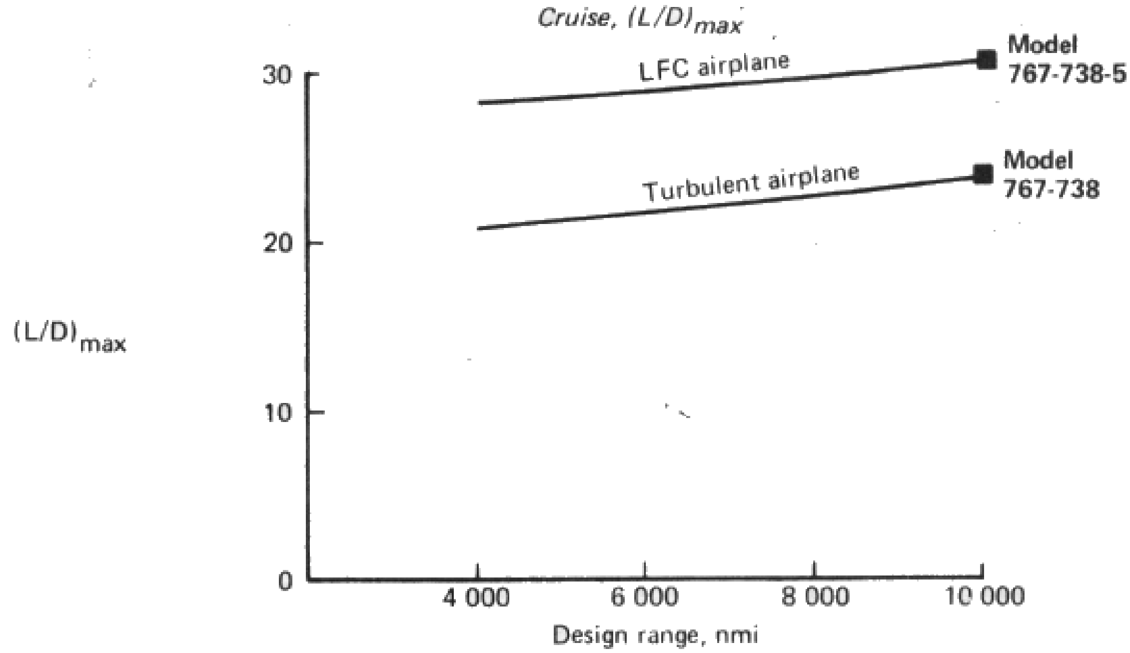


Figure 34.—Effect of Design Range on LFC Performance Benefits

Symbol	LFC study	Airplane type	Mission		Wing geometry		LFC system weight	Laminar areas
			Payload, lb	Mach	AR	$\Lambda_{c/4}$		
■	Current	Military	250 000	0.75	9.23	8.5°	1.5 lb/ft^2 of laminarized area	Wing, tails except for trailing-edge controls and turbulent wedge areas near junctions
△	Boeing 1969	Commercial	40 000	0.82 to 0.84	8.0	35.0°		
⊙	Boeing 1974			0.78	10.0	22.0°	2600 lb	



Model 767-738-5 Relative to 767-738

(LFC) (Turb)

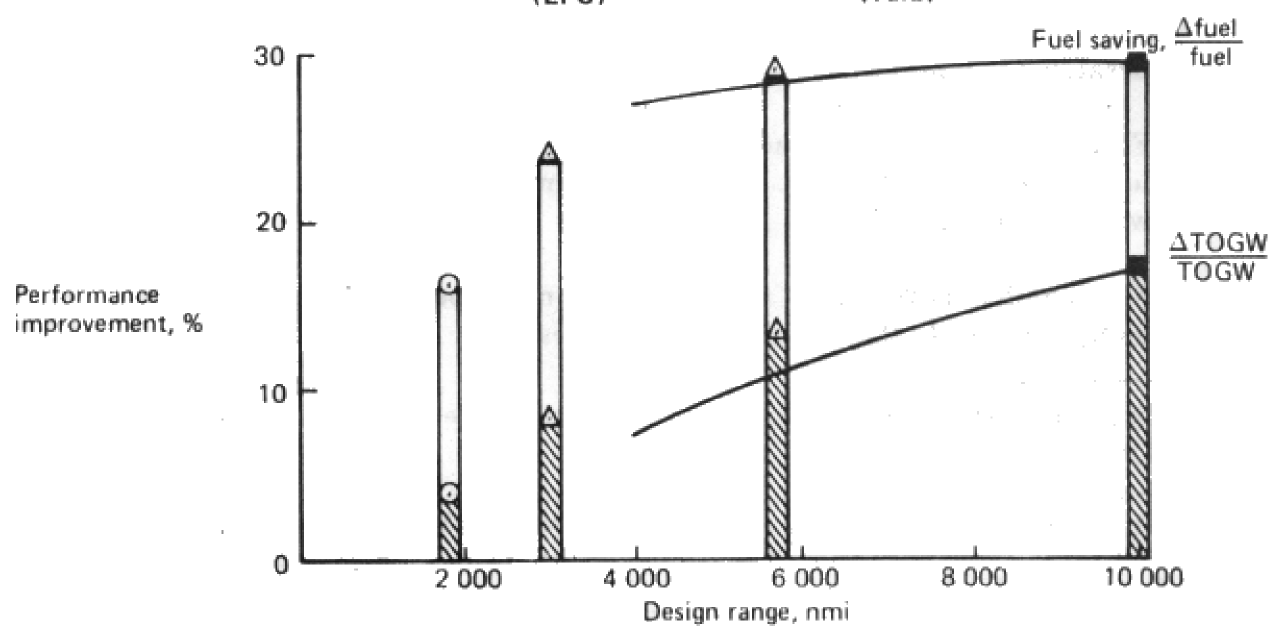


Figure 35.—Relative Performance Benefits With Laminar Flow Control

decreased 2.5% and 3.0%, respectively, for each additional 1 lb/ft^2 of laminarized area LFC system weight penalty.

6. A 2% increase in the overall system SFC by reaccelerating and discharging the sucked air would provide an additional 3% fuel savings and 1.5% TOGW reduction. The SFC benefits have not been included in the LFC evaluation results.

2.4.4 COMPLIANT SKINS

The earliest investigations concerning the use of compliant or flabby skins to reduce friction drag were directed toward prolonging laminar flow by damping the boundary layer oscillations that lead to transition-to-turbulent flow. Theoretical investigations[20] have indicated the possibility of achieving significant drag reductions. Experimental studies have been inconclusive. In addition, the required surface material is extremely fragile and is not practical for airplane applications.

Recently, a significant effort has been directed at examining the use of a compliant skin to reduce turbulent flow friction drag.[21,22] The experimental data, as shown in figure 36, indicate that significant reductions in friction drag have indeed been achieved. The widely varying results are attributed to a lack of understanding of the drag reduction mechanism. The required surface material characteristics are unknown. Consequently, many different surface materials have been tested; some have met with success; many others have failed to produce drag reductions.

Currently, it is believed that the compliant skin thickens the laminar sublayer (fig. 36) and reduces the Reynolds stresses by a redistribution of the energy spectrum within the turbulent boundary layer. The data shown in figure 36 also indicate that the maximum drag reductions are obtained when the surface is tuned to match the turbulent peak power frequency.

In a recent study,[23] rationale for limiting the application of compliant skins to the fuselage was offered, based on technical and practical considerations. Some of these considerations include:

- Fuselage has a distinct advantage relative to wings or tail surfaces, because of lower pressure gradients. Compliant skins have not been evaluated for surfaces with pressure gradients.

- Fuselage has fewer areas requiring routine inspection. Compliant skins will most likely complicate the inspection procedures.

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(20) George-Falvy, D., "Possibilities of Drag Reduction by the Use of Flexible Skin," *J. of Aircraft*, vol. 4, no. 3, May-June 1967.

(21) Fischer, M. G. and Ash, R. L., *A General Review of Concepts for Reducing Skin Friction, Including Recommendations for Future Studies*, NASA TMX-2894, March 1974.

(22) *On the Theory of Compliant Wall Drag Reduction in Turbulent Boundary Layers*, NASA CR-2387, April 1974.

(23) Fischer, M. C. et al., "Compliant Wall-Turbulent Skin-Friction Reduction Research," paper presented at AIAA Eighth Fluid and Plasma Dynamics Conference, June 1975.

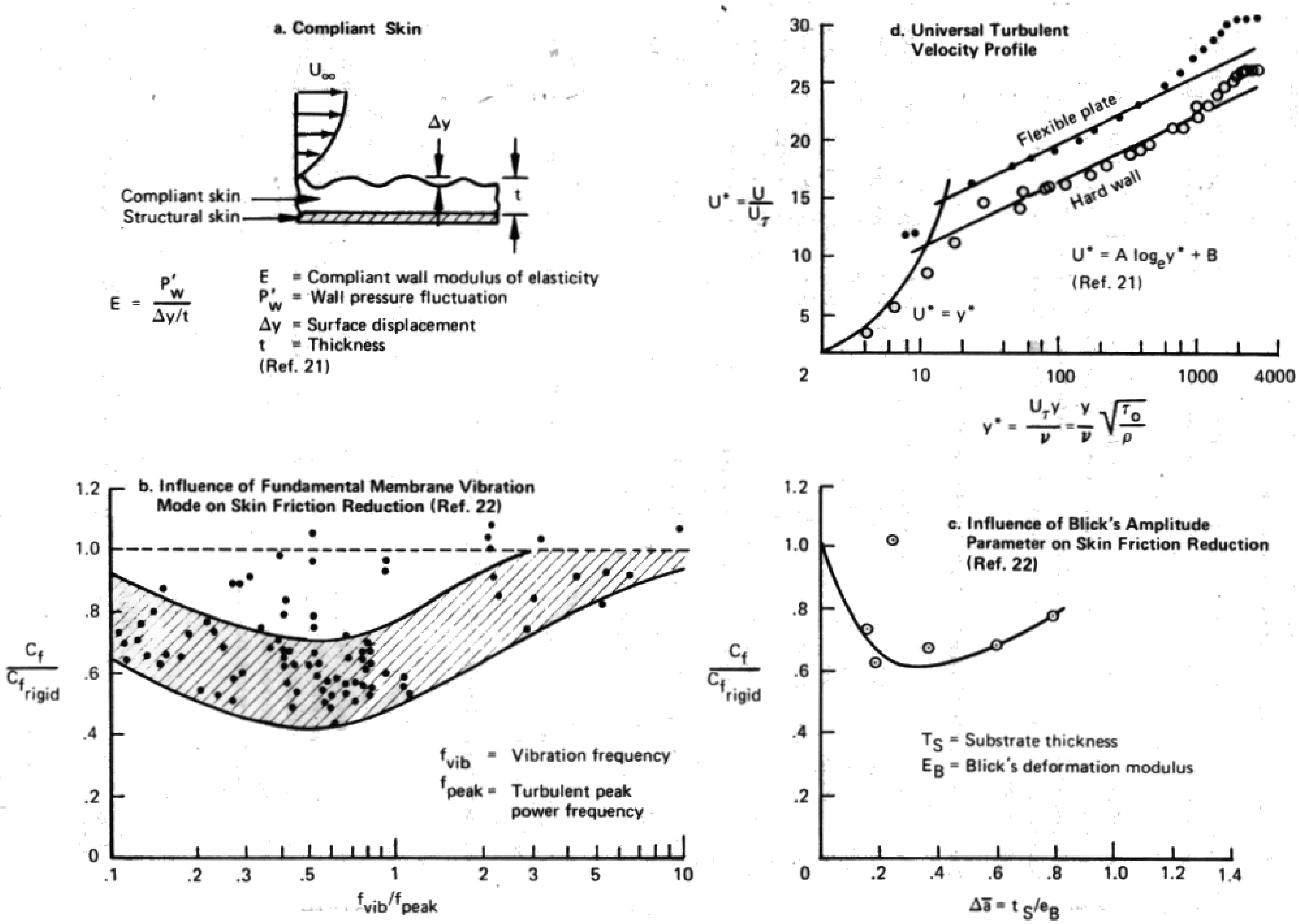


Figure 36.—Compliant Skin Background

- Reduced turbulent energy associated with the use of compliant skins could make a wing more susceptible to separation.

The current lack of understanding of the drag reduction mechanism and of the required surface characteristics permitted only a qualitative assessment of the potential benefits of a compliant skin.

The effects of applying a compliant skin to the reference LRC airplane (model 767-736) on approximately 85% of the fuselage area are summarized in figure 37. Assuming a 30% reduction in body friction drag, a 2% reduction in TOGW, and a 3% saving in fuel burned would be achieved with compliant skins weighing between 1/2 and 1 lb/ft^2 of application.

2.4.5 BODY BOUNDARY LAYER CONTROL

An alternate approach to reduce the fuselage drag would combine the use of low energy air injection through a ring slot around the front of the fuselage together with aft-body suction to prohibit separation and reduce the body profile drag. The preliminary data and analyses of figures 38 and 39 obtained from Dr. Bushnell of NASA-Langley Research Center indicate that the low energy slot injection can produce significant friction drag reductions primarily through the reduction of the local dynamic pressure near the slot. The slot thrust is an additional benefit. The forebody slot injection does not appreciably thicken the boundary layer near the aft end of the body and would, therefore, have no adverse effect on aft-body separation. The low energy air required for the slot injection system could be obtained from an aft-body suction system or from a wing-tail LFC system. Whether this would be the optimum procedure for disposing the air of an LFC system remains to be determined.

The combined body suction-injection system could potentially reduce the body drag by 25% to 30%. This would result in fuel savings and TOGW reduction comparable to those possible with a compliant skin.

2.4.6 WINGTIP FINS AND SPLIT WINGTIPS

The use of wingtip fins to reduce induced drag of transport aircraft has received considerable renewed interest. A substantial background of theoretical and, more recently, experimental data[(24)] concerning the aerodynamic characteristics of tip fins has been generated. The results of a recent Boeing theoretical and experimental investigation on the effect of incorporating wingtip fins on the 747 are of particular significance. Although the results were not directed toward the study reported herein, the design procedures and drag prediction methods used in the 747 study have been validated by the wind tunnel tests. These same theoretical tools were applied to the present study.

[(24)]Flechner, S. G. et al., *A High Subsonic Speed Investigation of the Effects of Vortex Diffusers (Winglets) at the Tip of a Representative Second Generation Jet Transport Wing*, proposed NASA TN L-10387, 1975.

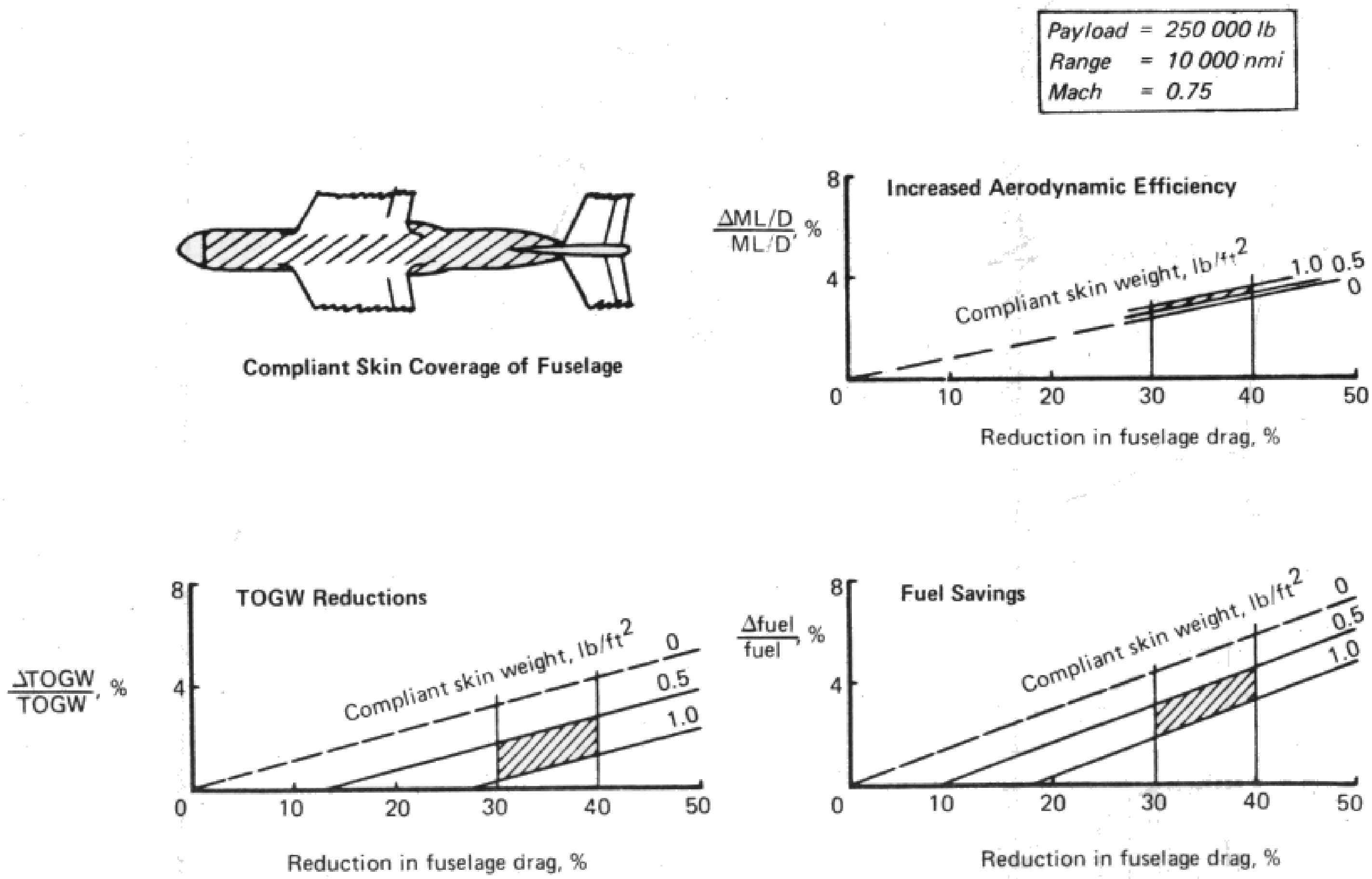
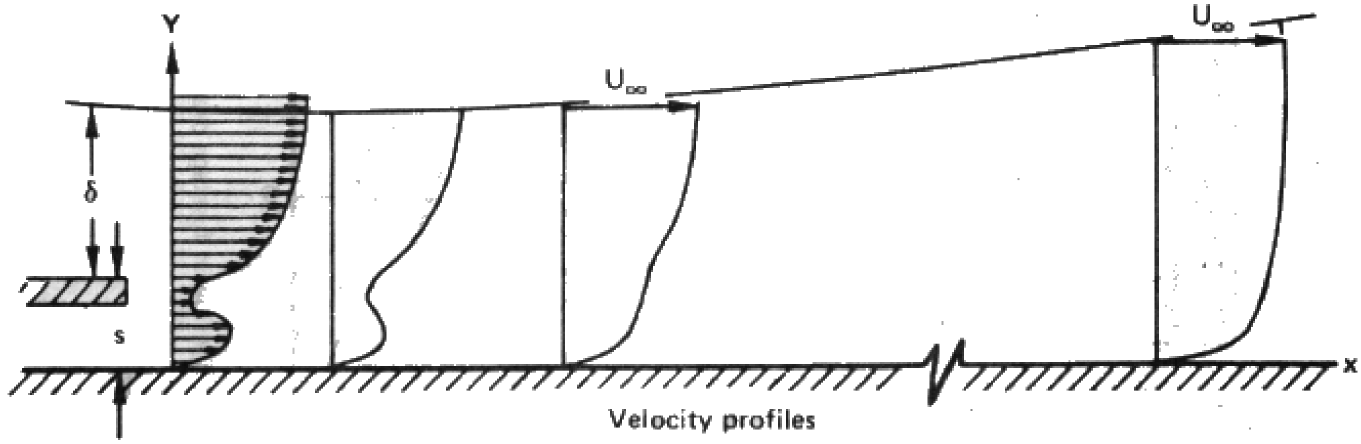


Figure 37.—Compliant Skin Evaluation

$U_s/U_\infty = 0.3$



Velocity profiles

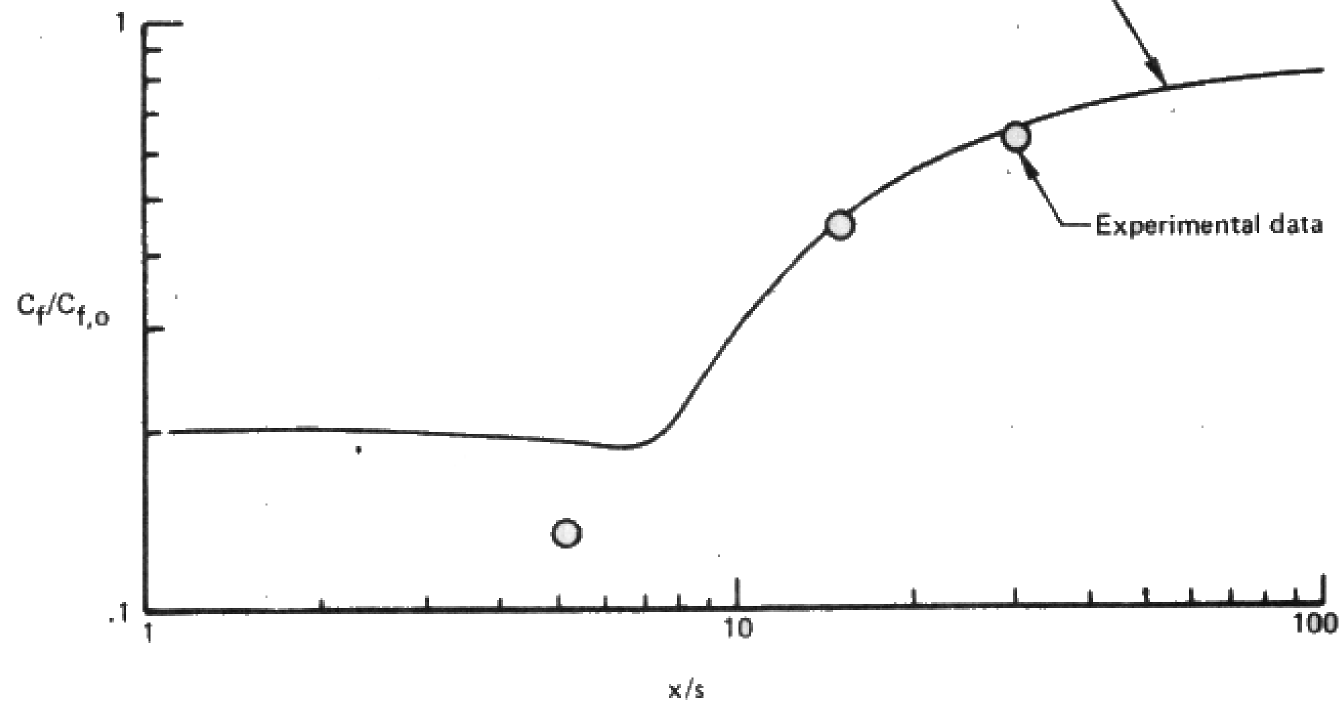


Figure 38.—Reduction in Turbulent Skin Friction Downstream of a Tangential Slot

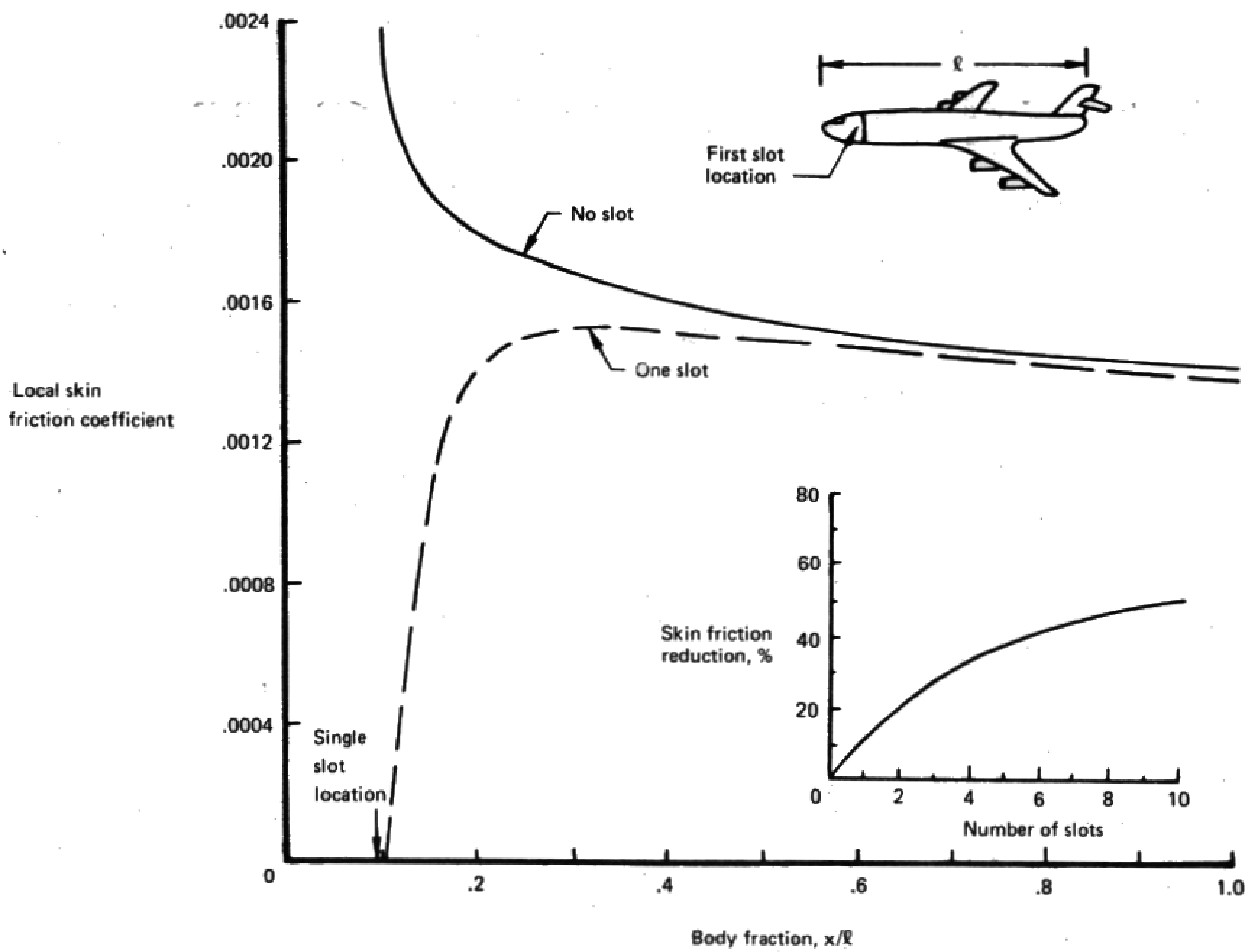


Figure 39.—Skin Friction Reduction on Transport Fuselage

Figure 40 illustrates the test-theory correlation. The sensitivity of the induced drag factor to the fin incidence angle is shown in figure 41. The following discussion is directed toward a single fin. However, the general principles of the single fin can also be applied to multiple fins (split wingtips); a separate discussion of multiple fins is not included. Reference 1 contains a detailed discussion of the use of split wingtip fins on an integrated LFC configuration.

Tip Fin Benefits

Tip fins alter the lift distribution and modify the TE vortices. The aerodynamic forces caused by the TE vortex system, however, are ultimately felt in the form of pressure forces on the wing-fin combination. As shown in figure 42, the tip fins develop a side force, increase the wing lift, and alter the wing spanwise load distribution. The increased wing lift results in a more efficient lifting surface; i.e., for a given total lift, a lower angle of incidence is required. This directly reduces the wing-induced drag. Additionally, the tip fins, which are oriented relative to the wing-induced local flow, develop side-force vectors that are inclined forward and directly produce an effective thrust component. The net effect shown in figure 43 is a sizable reduction in induced drag, which increases with greater tip fin heights.

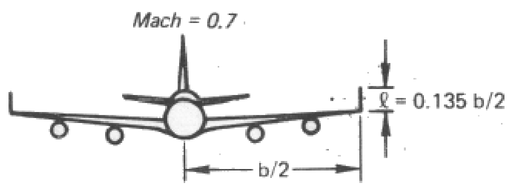
The altered wing load distributions, however, can increase the structural design loads. This is illustrated in figure 43 by the variation of wing root-bending moment with fin height. The theoretical data in this figure correspond to the wing-fin load distributions that produce minimum induced drag.

A study was made of the relative effects of wing root-bending moment on wing versus wing plus fin combinations. The results of this study are shown in figure 44 as the ratios of the induced drag and the wing root-bending moment to the corresponding values for an elliptically loaded wing. These results show that the minimum drag wing-fin combination has a greater wing root-bending moment than an elliptically loaded wing. However, wing-fin combinations can be designed to have root-bending moments less than the wing without fins while retaining substantial reductions in induced drag.

Although wing root-bending moment is often used as an indication of relative wing weights, detailed coordinated structual design and aerodynamic design studies will be required to identify the net impact of applying tip fins.

Tip Fin Study

The long-range airplane model 767-736 (fig. 2) was used as the reference configuration for evaluating the effects of the tip fins. A number of wingtip fins of different spans were applied to this reference configuration. The theoretical effects on the induced drag and wing root-bending moment are shown in figure 43. The effect of tip fins on the drag rise characteristics of the configuration was neglected. Existing preliminary weight estimates of tip fins were reviewed; the results were thought to be highly conservative, particularly in view of the potential weight relief benefits projected for the 1985 time period with advanced materials and active controls. For the present evaluation, no weight penalties were applied to the wing primary structure for the tip fins.



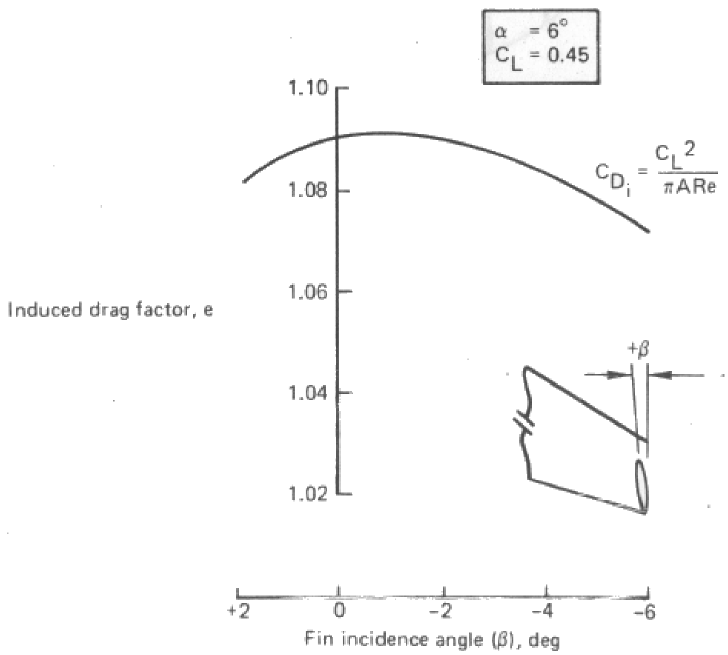


Figure 40.—Optimization of Wing Fin Incidence Angle

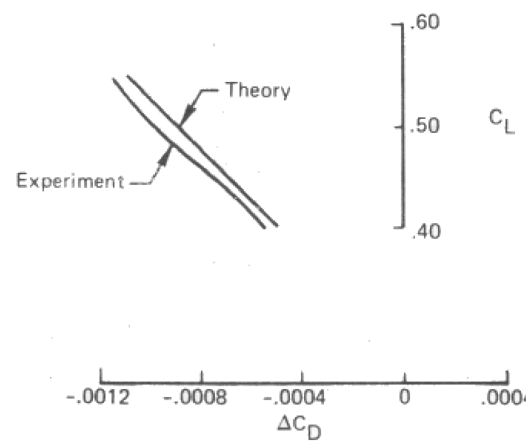


Figure 41.—Verification of Wing Fin Analysis

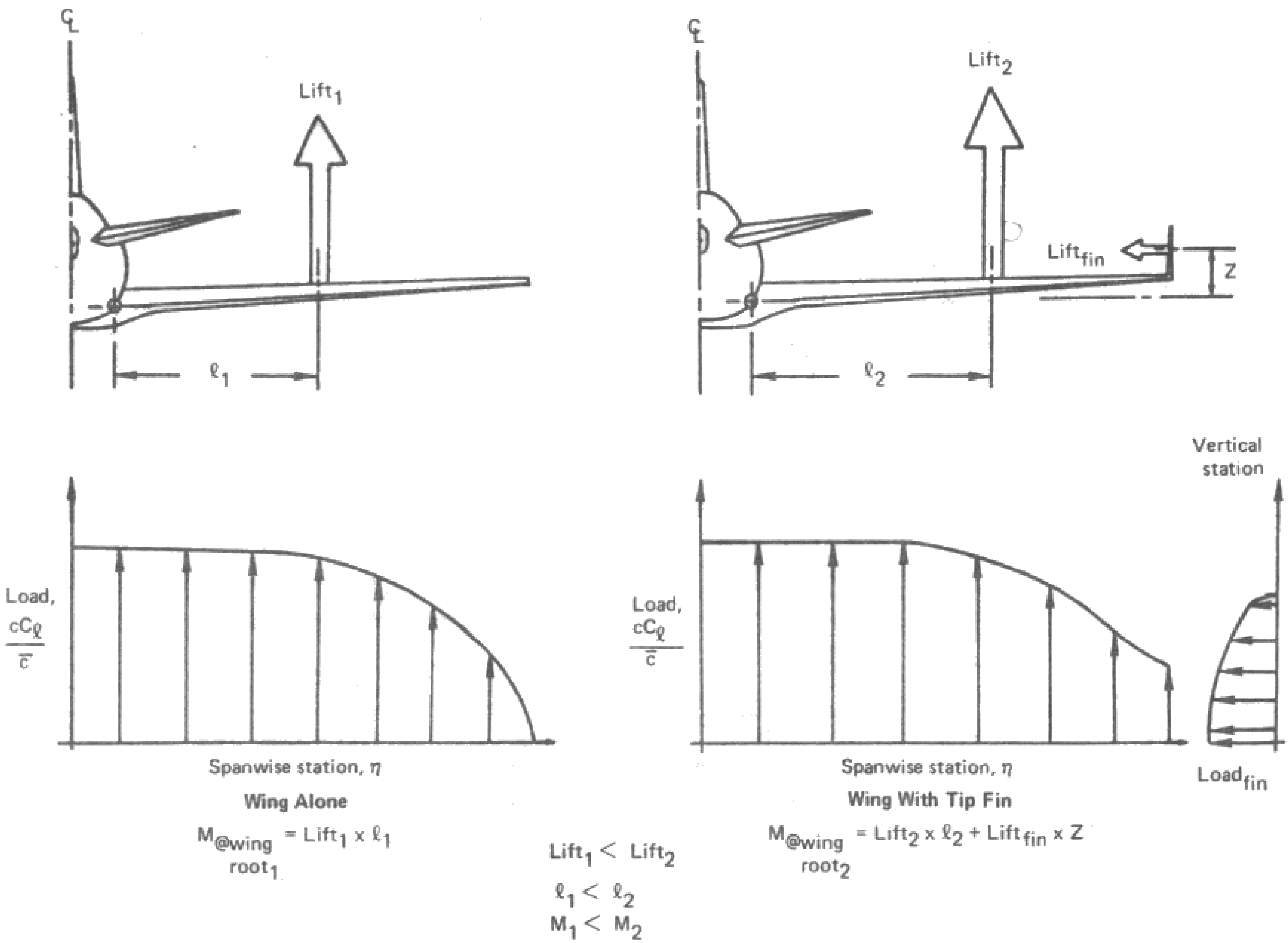


Figure 42.—Wing Load Distribution Comparison

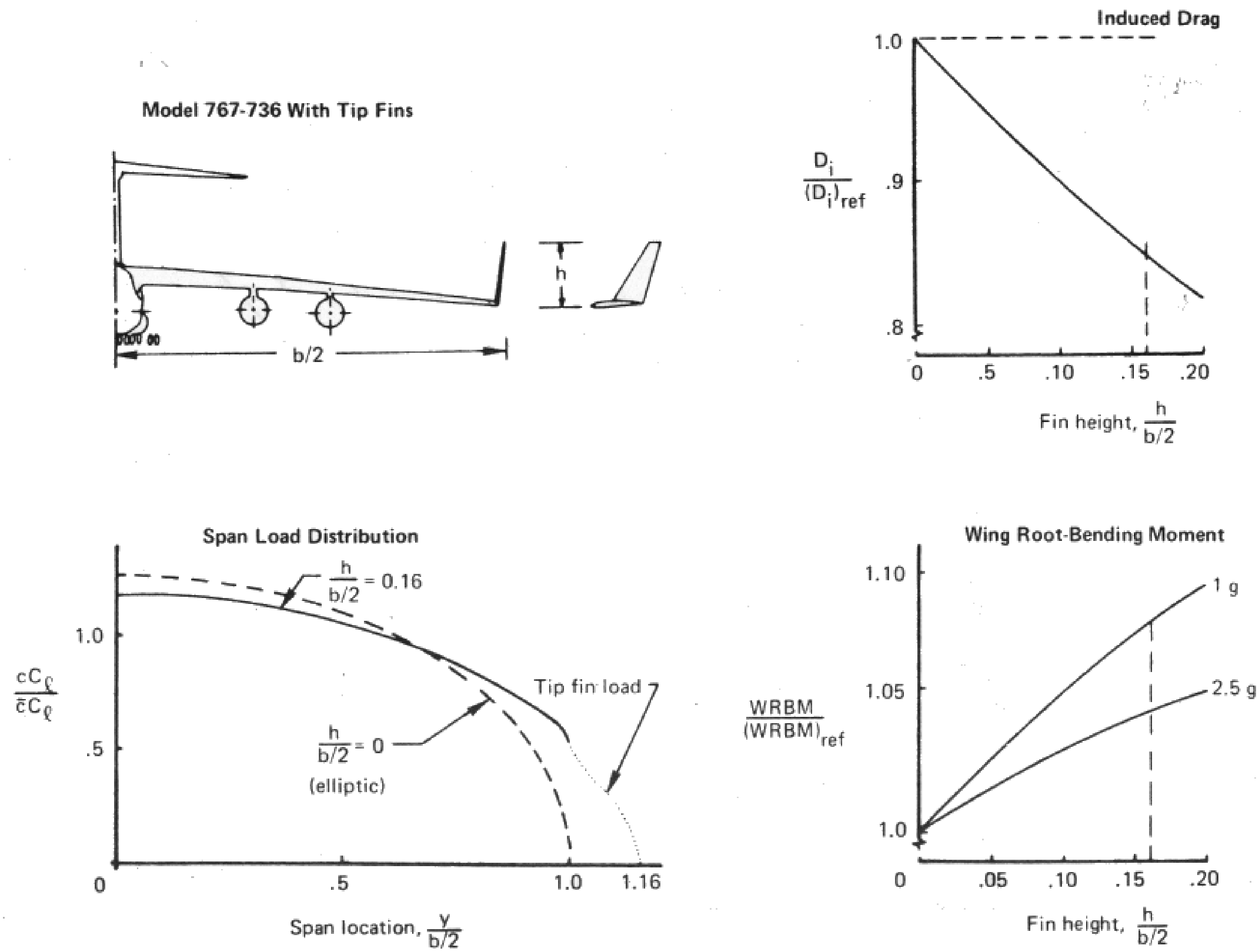


Figure 43.—Wingtip Fin Evaluation

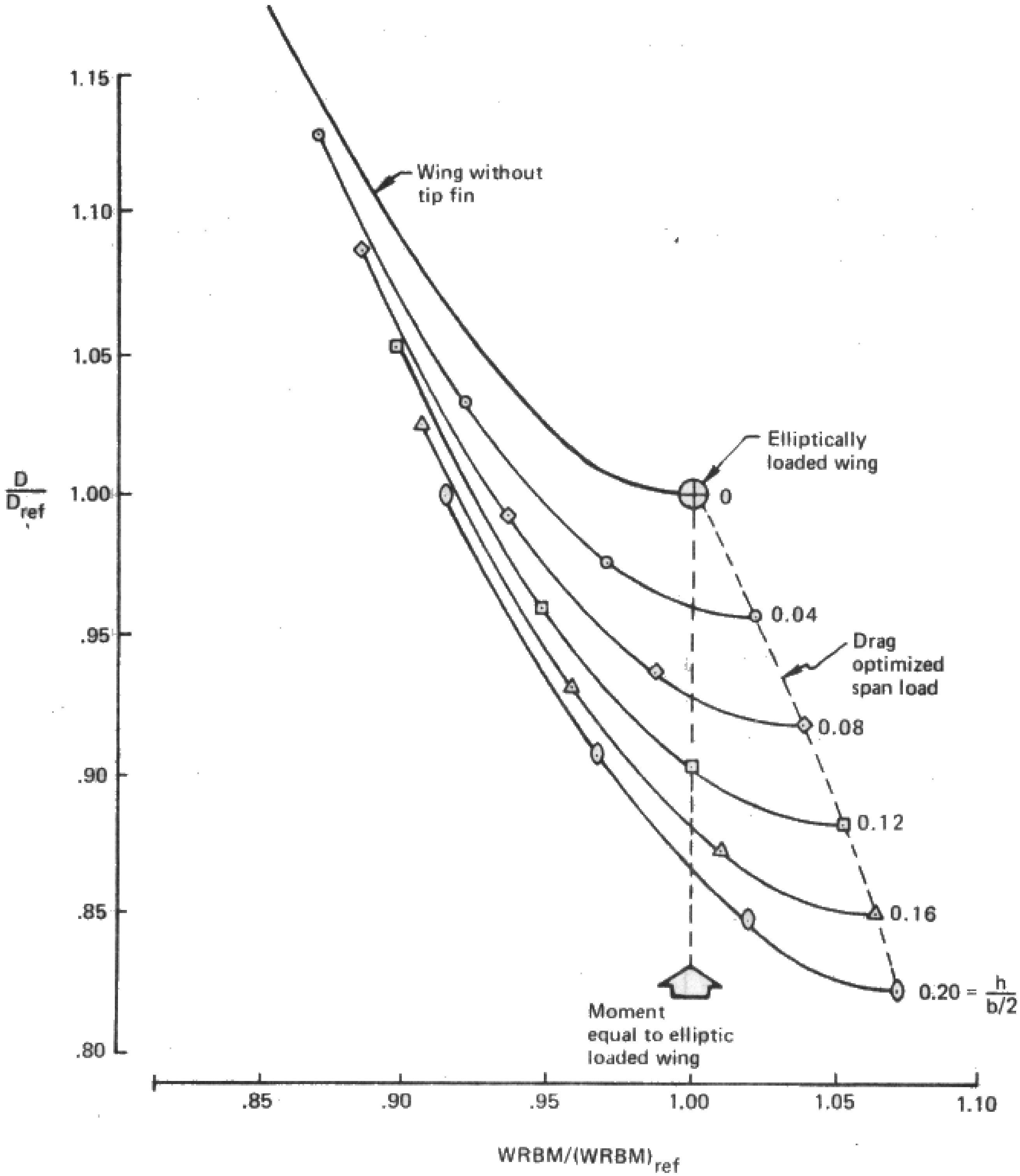


Figure 44.—Wingtip Fins Effect of Nonoptimum Span Load Distribution

Boeing is currently conducting a study for the Air Force Flight Dynamics Laboratory,[25] that includes detailed structural design and analyses of tip fins applied to the KC-135 and the C-141 military aircraft. The results should provide the necessary data for a more complete evaluation of the tip fins.

The net effects of applying the tip fins on the L/D ratio, TOGW, and fuel consumption are summarized in figure 45.

Tip Fin Conclusions

1. The benefits achieved with tip fins are dependent upon the tip fin height relative to the wing span.

2. For tip fins equal to 15% of the semispan length, the following improvements were obtained:

   L/D increase = 4%

   TOGW reduction = 5%

   Fuel savings = 7%

3. Detailed structural analyses of wingtip fins are required to fully identify the net benefits.

4. Tip fins might offer retrofit performance benefits to existing airplanes.

2.4.7 LOW TRIM DRAG

The trim drag characteristics of the reference configuration (model 767-736) were calculated to identify the potential aerodynamic improvement by aft center-of-gravity (c.g.) management to allow the airplane to trim for minimum total drag. For a nominal cruise lift coefficient of 0.46, the trim drag coefficient corresponding to the average cruise c.g. location is three drag counts ($\Delta C_{D_{trim}} = 0.0003$). The use of a full stability augmentation system (SAS) to allow an aft c.g. location corresponding to the minimum trim condition would result in a five drag-count reduction ($\Delta C_D = -0.0005$). This is slightly more than a 2% reduction in cruise drag. Relative to the baseline airplane, this drag reduction results in approximately a 2% reduction in the required TOGW.

2.4.8 REMAINING CONCEPTS

Tandem wings were found to have potential weight saving advantages. However, because of the low span, the aerodynamic efficiency is reduced compared to a conventional configuration. For the design mission of this study, the tandem wing concept did not offer any performance advantages and, therefore, was discarded from further study.

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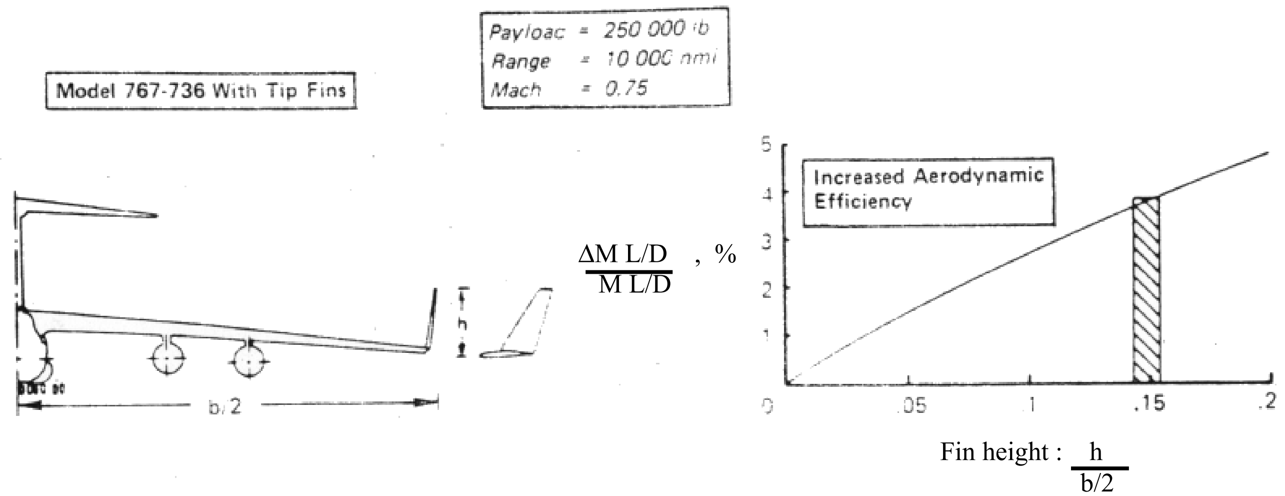
[25] "Design and Analysis of Winglets for Military Aircraft," contract F33615-75-C-3123, study by Boeing Commercial Airplane Company for the Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, study originated June 1975.



Performance benefits without structural weight evaluation

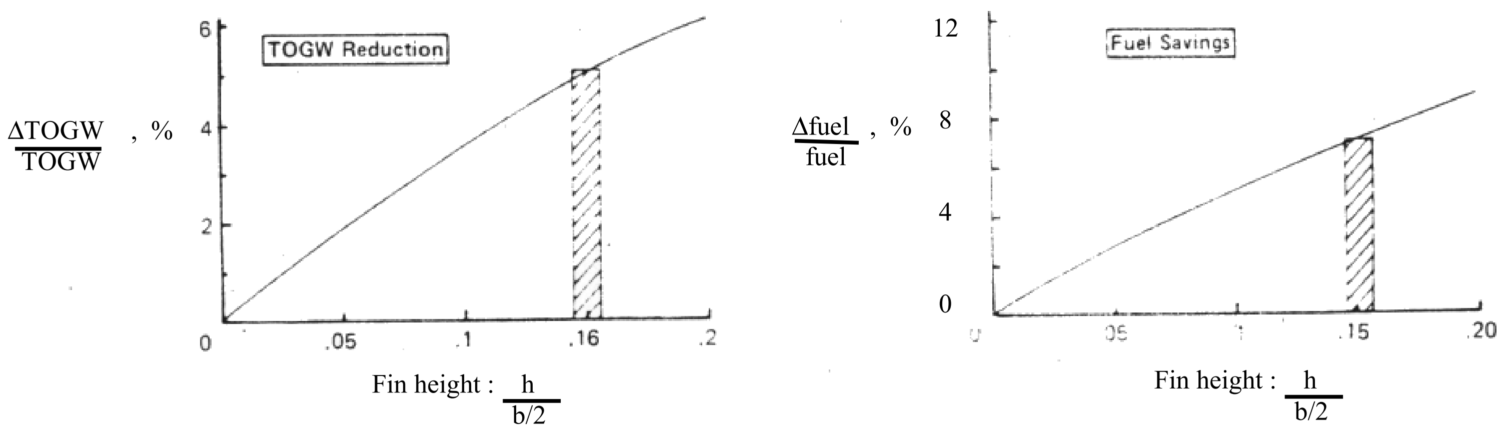


Figure 45.— Wingtip Fin Benefits

Braced wings offer a means for increasing the wing span over that of an equal weight cantilever wing. This provides a direct reduction in the induced drag. Increased span and reduced wing chord achievable with a braced wing arrangement are desirable for an LFC airplane to reduce the induced drag which becomes increasingly important after reducing the friction drag with LFC and to alleviate the laminarization problems. To identify the potential benefits of a braced wing design would require detailed structural analyses that were beyond the scope of this study. However, potential benefits achievable with braced wings for large military aircraft are discussed by Dr. Pfenninger in reference 1.

Variable geometry concepts, such as variable camber wings (VCW) and oblique variable sweep wings, are mainly directed toward aircraft that must operate over a large range of conditions; e.g., a fighter-attack aircraft that must have good transonic attack maneuverability as well as loiter and supersonic dash capabilities.

The areas where the VCW could improve performance on a long-range freighter-type airplane would be in the climb and loiter portions of the mission. Previous Navy studies[26] have indicated that the VCW can increase maximum usable C_L and increase L/D at off-design conditions. Both climb and loiter fuel could be lowered by as much as 10% with the use of the LRC airplane mission occurs at the destination. The loiter fuel is approximately 11 000 lb. A 10% reduction in loiter fuel would be 1100 lb, resulting in a gross weight reduction of 3100 lb. A 10% reduction in climb fuel would be a saving of about 4500 lb or a 0.25% reduction in gross weight. The combined benefits in climb and loiter would be less than 1/2% in TOGW.

The disadvantages of utilizing variable camber would include the loss of the LE slots, a loss in maximum lift ($\Delta C_{L_{max}} \approx 0.5$), and a corresponding loss in field length performance. The takeoff field length (TOFL) would increase by about 2300 ft.

It has been reported[27] that tip-mounted engines could reduce airplane drag. However, insufficient data were found to include this concept in the study. When more definitive data are available, this concept should be evaluated.

Wing-body contouring benefits were utilized in formulating the advanced configurations of this study. The fuselage shape at the wing root affects the flow over the inboard part of the wing, especially at high subsonic Mach numbers. Wing-body contouring has the objective to shape the fuselage so that more favorable flow conditions will result on the wing. For near sonic speeds, such area-ruling techniques become significant. Proper wing-body contouring lead to: (1) a reduction of wing-body interference drag; (2) a reduction or even elimination of drag-producing shock wave formation on the upper surface of the inboard part of the wing (at high subsonic Mach numbers) found on current airplanes; (3) an improvement in L/D ratio and; (4) a capability to cruise at near sonic speeds.

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[26] Gould, D., *Final Report–Variable Camber Wing–Phase I*, Boeing document D180-17606-1, October 1973.

[27] Snyder, M. H., Jr., and Zumwalt, F. W., "Effects of Wingtip-Mounted Propellers on Wing Lift and Induced Drag," *AIAA Journal of Aircraft*, pp 392-398, September-October 1969.

2.5 RECOMMENDED RESEARCH AND DEVELOPMENT

This section identifies the general state of readiness of the aerodynamic concepts that have been considered. General areas of R&D necessary to either establish, verify, or further develop the potential of the various aerodynamic concepts are also presented.

2.5.1 GENERAL STATE OF READINESS

The general state of readiness which inherently identifies areas where additional R&D work is needed can be grouped into the following four categories:

- Fundamental Understanding
- Design and Analysis Capability
- System Integration
- Flight or Operational Verification

These categories essentially trace the progressive steps that a new or advanced aerodynamic concept must follow to be integrated into the operational aircraft environment.

Initially after a new idea is conceived, a considerable effort is directed toward understanding the fundamental mechanism by which the aerodynamic benefits are physically achieved. This involves both experimental and theoretical investigations. The fundamental knowledge must also include identifying the favorable and/or unfavorable factors or conditions that either permit or prohibit achieving the potential benefits. Then, it is necessary to expand this knowledge by developing theoretical or empirical design and analyses capabilities. This stage also includes broadening the basic data base by developing specific test programs.

Detailed integration studies, such as structural, propulsion, flight controls, operational, etc., are necessary to identify the impact of the aerodynamic concept on other design and technology areas of the aircraft systems and operational environment. The results of these limited investigations then lead to complete system studies to determine the net benefits of applying the aerodynamic concept to particular aircraft design missions. Ultimately, it is desirable and often necessary to proceed with flight test programs in real or simulated operational environments.

The current state of readiness of each of the study concepts is summarized in figure 46. In general, the fundamental understanding of each of the aerodynamic concepts is sufficient for preliminary design applications. However, the exceptions included fuselage drag reduction techniques using BLC or compliant skins. Additional work is desired and, in some instances, necessary in the areas of system integration and in test and operational verification for all of the concepts.

Ⓐ Fundamental understanding
Ⓑ Design and analysis capability
Ⓒ System integration
Ⓓ Flight or operational verification

Symbol	Meaning
●	More work necessary
◒	More work desired
○	Sufficient for preliminary design application

	A	B	C	D
Laminar flow control	○	◒	◒	●
Boundary layer control	◒	●	●	●
Compliant skin	●	●	●	●
Natural laminar flow	◒	◒	●	●
Advanced high-speed airfoils	○	○	◒	◒
High L/D airfoils	○	○	●	●
Variable camber airfoils	○	○	◒	◒
Wingtip fins	○	○	●	●
Split wingtips	○	◒	●	●
Wingtip-mounted engines	●	●	●	●
Tandem wings	○	◒	◒	●
Load–aspect ratio	○	○	◒	◒
Externally braced wings	○	◒	◒	●
Variable sweep oblique wing	○	◒	◒	●
Wing-body contouring	○	○	◒	◒
Aft-body shape	◒	◒	○	●
Low trim drag (aft c.g.)	○	○	◒	◒

Figure 46.—Aerodynamic Concept State of Readiness

2.5.2 PROGRAM RECOMMENDATIONS

Recommended R&D for the various aerodynamic concepts is outlined in this section. It is important to note that the integration of the various desirable concepts should be accomplished in an efficient manner. The first step is to develop a more detailed preliminary design of the advanced airplane to meet the desired mission goals. Various trades should be accomplished in the process to help refine R&D needed on the concepts utilized. While in this process, the developmental progress of each aerodynamic concept should be monitored, and its applicability to the design updated. In addition, new concepts may become available and should be evaluated to see if they apply to the design.

For an airplane utilizing a combination of the appropriate advanced aerodynamic concepts, it is recommended that a demonstration or prototype airplane be flown and evaluated before any commitment to production. Requirements for the prototype flight investigations should be established early as a part of the preliminary design study.

Recommended R&D for the individual aerodynamic concepts is outlined in the following listing.

Advanced High-Speed Airfoils

Status:

- Analytical and wind tunnel data available, which confirm gains
- Some flight test data available
- Analytical and test work in progress to refine concept

Recommended R&D:

- Continue analytical and test investigations to refine airfoils
- Conduct systematic testing of 2-D airfoil families
- Conduct systematic testing of families of wings to correlate 2-D and 3-D results
- Develop full 3-D transonic analysis method

Natural Laminar Flow Airfoils

Status:

- Concept used and proven for low Reynolds number applications such as sailplanes
- Laminar flow achieved up to Reynolds number of 18 million on P-63 King Cobra flight tests(11) in 1945
- Analytical work in progress to design high-speed natural laminar flow airfoils

Recommended R&D

- High Reynolds number wind tunnel tests in low turbulence facility
- Continued analytical design work to develop high-speed natural laminar flow airfoils
- Conduct flight tests using glove concept
- Establish smoothness and waviness criteria
- Continue materials research to obtain smooth self-cleaning surfaces
- Investigate compatibility with high-lift devices and/or low-speed requirements

Laminar Flow Control

Status:

- The technical feasibility of LFC has been demonstrated in the research carried out by Dr. W. Pfenninger and his associates in the X-21 flight program. The economic feasibility has not been as well established, however, and depends upon:
  - The weight penalty for a practical bleed slot, duct configuration, and pumping system
  - Maintenance and operational costs, including effects of utilization differences, if any, associated with the LFC system
  - Initial airplane cost increment associated with LFC

Recommended R&D:

- At the conclusion of the X-21 program, a number of problems existed that required additional understanding for the successful application of LFC to transport aircraft. These problems still exist today in varying degrees and need further attention:
  - LE instability of boundary layer
  - Acoustic criteria
  - Allowable surface roughness, steps, and gaps
  - Relative humidity effects
  - Refinement of slot (or holes) and duct-flow details
  - High lift compatibility
  - Wing-mounted nacelle compatibility
  - Construction techniques permitting visual inspection of primary structures, integral fuel tanks, and a maintainable surface
  - Operational suitability data
  - Laminarization above X-21 Reynolds numbers, $R_N > 47 \times 10^6$.
- It is recommended that an LFC system be developed and demonstrated by prototype or research airplane flight tests in order to verify system performance prior to any production commitments.
- Aerodynamic investigations:
  - Investigations to identify optimum spacing and distribution of suction slots
  - Develop surface smoothness criteria
  - Further study of the characteristics of LE separation on swept wings
  - Obtain sweptwing test data at high Reynolds numbers
  - Airfoil Development—Analyses and testing are necessary to adapt existing techniques for designing high-speed airfoils to the conditions existing with
  - LFC and to evolve efficient airfoils.
  - High Lift System Development—Analyses and testing are required to develop a practical high lift system for a wing designed with LFC. LE devices may not be possible due to limitations on surface irregularities. Feasibility of suction slots in surfaces of leading- and trailing-edge flaps must be evaluated, and potential use of the LFC suction system to enhance the capability of the high lift system should be determined.
- Structures investigations:
  - A practical and efficient structural arrangement for the suction slots and ducting must be designed and tested; the strength, stiffness, and fatigue

properties must be evaluated. The design trades among wing thickness, area, aspect ratio, and distribution of usable wing fuel volume require analysis; the resulting effects on performance need to be assessed. The potential use of titanium and/or aluminum sandwich and composite structures should be considered. Panel testing is required, and manufacturing feasibility panels should be constructed to demonstrate the capability to meet aerodynamic criteria.

- Propulsion investigations:
  - Cycle studies and design analyses must be accomplished in order to develop an efficient concept for the LFC suction ducting, pumping, and power source. Acoustic design criteria are required. Component testing may be required in order to verify performance estimates.
  - A quiet engine will be required for the primary propulsion of an LFC airplane. The engine and nacelle components must be designed to achieve the low noise levels that are required for successful LFC on adjacent surfaces.
- Performance trade studies:
  - Airplane design studies must be accomplished in considerable detail in order to provide design guidance to development work and to evolve the most practical and efficient configuration for given mission requirements. The operational characteristics of an LFC airplane should be explored in depth so that rational criteria can be established for various parameters such as fuel reserves and thrust margins.
- System integration studies:
  - The aerodynamic, structural, and propulsion features of an LFC are intimately interrelated and must be coordinated in configuration design. These studies must be conducted in conjunction with detailed project design studies. Configuration wind tunnel testing should be included for aerodynamics, propulsion, and structures. It would be desirable if a large-scale panel could be constructed and flight tested prior to prototype commitment. Such a test could verify estimates based on wind tunnel model testing and would provide operational experience with the proposed structural concept.

Compliant Skin

Status:

- Turbulent skin friction reductions obtained in wind tunnel tests of flat panels
- Drag reductions related to frequency and amplitude characteristics of compliant skins
- Mechanism of drag reduction not fully understood; number of theories postulated
- Relatively soft compliant wall material required; modulus of elasticity $<$ 10 psi

Recommended R&D:

- Further research into mechanism of drag reduction; theoretical and wind tunnel tests
- Further research into characteristic of low modulus materials
- Tests on representative airplane components

- Isolate the parameters that govern the interaction between the compliant wall and the turbulent boundary layer
- Develop methods to guide application of the compliant skin
- Develop materials with desired characteristics and durability
- Determine impact on manufacturing and maintenance
- Verify drag reductions in the aircraft flight environment

Body BLC

Status:
- Turbulent skin friction reductions experimentally obtained; consistent with analytical predictions

Recommended R&D:
- Further research into drag reduction mechanism
- System integration studies; determine trades on application to airplane fuselage and relationship to other concepts such as LFC
- Conduct additional tests to investigate configuration variation effects
- Determine manufacturing and maintenance impact
- Verify drag reductions in flight tests

Wingtip Fins and Split Wingtips

Status:
- Theoretical fundamentals understood
- Induced drag reductions obtained in wind tunnel tests
- Theoretical methods verified experimentally
- Design and analysis capability exists; however, improved methods desired

Recommended R&D:
- Develop improved design and analysis methods
- Conduct structural layout and analysis of wing tip plus fin: weight, flutter, etc.
- Application to existing airplanes
- Conduct aerodynamic and structural design optimization studies
    - Fin geometry: height, chord, taper, number
    - Integrated wing plus fin design: airfoils, thickness, load distribution
- Variable geometry fin studies to examine:
    - Load alleviation potential
    - Induced drag modulation potential
    - Direct side force control with rudder possibilities
- Flight and wind tunnel verification of $C_{L_{max}}$, profile drag, and improvements to existing aircraft

Wing Body Contouring

Status:
- Methods available to accomplish designs

Recommended R&D:

- Determine relationship of manufacturing cost versus performance benefit

Wingtip-Mounted Engines

Status:

- Mechanism and potential uncertain

Recommended R&D:

- Further research to verify physical soundness of concept
- Tests to verify theoretical predictions if advantages are indicated by the analytical studies

3.0 PHASE II: MILITARY TRANSPORT CONFIGURATION INTEGRATION

The potential benefits of individually applying various advanced aerodynamic concepts were discussed in the previous sections. Maximum benefits, however, are achieved by a combination of compatible aerodynamic concepts. Therefore, the objective of the Phase II effort was to perform a design investigation that incorporated the most promising combinations of aerodynamic concepts in order to evaluate the performance potential by comparing the combinations with conventional aerodynamic designs. These conventional aerodynamic designs are the configurations that were used as the reference configurations for evaluating the individual aerodynamic concepts.

The design guidelines and ground rules used to develop the study configurations are discussed in this section. Comparisons of the conventional and advanced technology configuration descriptions and performance are presented. The results of design endurance and design range studies are also discussed.

3.1 FLIGHT PROFILES AND STUDY GROUND RULES

Two airplane configurations have been considered, each designed for a specific mission requirement:

- *Long-range mission:* 250 000-lb payload and unrefueled ranges up to 10 000 nmi
- *High endurance mission:* 400 000-lb payload with a loiter capability up to 24 hr within 250 nmi from the base

The flight profiles and mission rules are shown in figure 47. Advanced technology levels summarized in table 6 were defined for propulsion, structures, and flight controls. These technology levels have been used for the conventional aerodynamic technology configurations, as well as for the advanced aerodynamic technology configurations, so that the performance benefits associated with the aerodynamic improvements could be clearly defined. Additional design guidelines and operational constraints considered during the configuration development process are shown in table 7.

Throughout the entire study, the wing loading (W/S) and thrust-to-weight (T/W) were held constant and equal to:

$$W/S = 124 \text{ lb/ft}^2$$

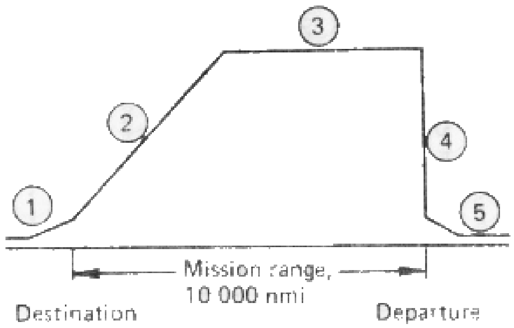
$$T/W = 0.214$$

These reduced the number of design variables and also tended to maintain consistent takeoff and landing performance.

The C-5A met the mission operational requirements and design guidelines except for the 10 000-nmi range objective and was used as the basis for developing both the

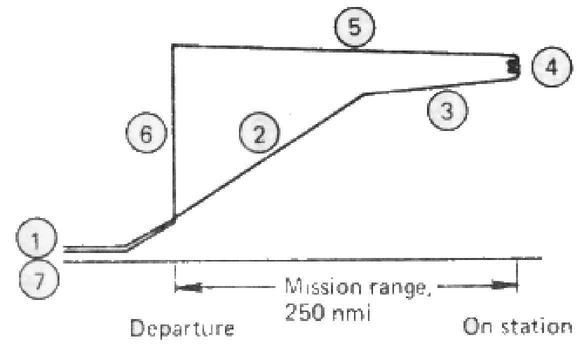
Long-Range Mission

Payload = 250 000 lb
Mach = 0.75



High Endurance Mission

Payload = 400 000 lb
Mach = 0.65



(1)	Taxi out and takeoff	5 min at normal-rated power 1 min at max power
(2)	En route climb	Intermediate power
(3)	Cruise	Best cruise Mach and altitude
(4)	Descend	No range, no fuel
(5)	Land, taxi in, reserves	5% of initial fuel Fuel for 30-min loiter at SL

5% increase in SFC throughout

(1)	Taxi out and takeoff	5 min at normal-rated power 1 min at max power
(2)	En route climb	Intermediate power
(3)	Cruise	Best cruise Mach and altitude (250-nmi climb and cruise)
(4)	Loiter	24-hr loiter on station (max endurance)
(5)	Return cruise	250 nmi at best cruise Mach and altitude
(6)	Descend	No range, no fuel
(7)	Land, taxi in, reserves	5% of initial fuel Fuel for 30-min loiter at SL

5% increase in SFC throughout

Figure 47.—Flight Profiles and Mission Rules

Table 6.—Boundary Layer Control Application Study—Technology Assumptions

Item	Baseline conventional technology configurations	Advanced aerodynamic technology configurations
Aerodynamics High speed Low speed	747-type aerodynamics	Selected advanced concepts for 1985 time period
Propulsion	T/W and SFC improvement projections for 1985 per TAC Low Energy Study	
Structures	Advanced composites, aluminum and titanium materials projected for 1985 operation per ATT Study Structural arrangement and materials selection to be consistent with the aerodynamic concept and systems requirements Integrated active control systems considered for maneuver and gust load alleviation, but not flutter suppression	
Flight controls	State-of-the-art flight controls hardware for 1985 including fly-by-wire control systems Alpha limiter All flying stabilizer Relaxed static stability	

Table 7.—General Design Guidelines

Item	Design ground rules
Payload definition	
Type:	
Long-Range A/P's	Tanks, troops, vehicles (250 000 lb)
High endurance A/P's	Large missiles (400 000 lb)
Density	Same as C-5A
Opening Dimensions	Same as C-5A
Fuselage cargo pressurization	Same as C-5A
Takeoff and landing	
Flotation	
Field type	Consistent with C-5A
Minimum takeoff distance	Design objectives
Landing distance	
Approach speed	
Turn radius	300 ft
Powerplant selection	
Fuels	Conventional fuels
Size	Matched to airframe requirements, less than 100 000-lb SLST/eng
Avionics	C-5A type

long-range and the high endurance airplanes. The high endurance airplane has a greater payload requirement. The payload, which could be contained in the C-5A fuselage, consisted of four missiles weighing 100 000 lb each.

The C-5A with a TOGW of 728 000 lb was the starting point selected for the baseline long-range airplane. Parametric/statistical weight data were used to derive weight estimates for a grown conventional structure C-5A. Payload, wing loading, tail volume coefficients, thrust loading, and body shape and size were held constant. The results shown in figure 48 relate the ratio of operational empty weight/takeoff gross weight (OEW/TOGW) to the airplane gross weight.

The component weights were then adjusted to account for the application of advanced composite structural materials. The estimated weight benefits for utilizing the advanced composite structural materials are shown in figure 48. These structural weight benefits are typical for the use of graphite-epoxy honeycomb primary structure and PRD-49 honeycomb secondary structure.

The propulsion system characteristics used in the current study (fig. 49) are consistent with currently projected propulsion technology trends.

3.2 AERODYNAMIC TECHNOLOGY SELECTION

The conventional airplanes were developed using a technology level of aerodynamic data equivalent to that of the 747. Therefore, these configurations employed current operational state-of-the-art aerodynamics.

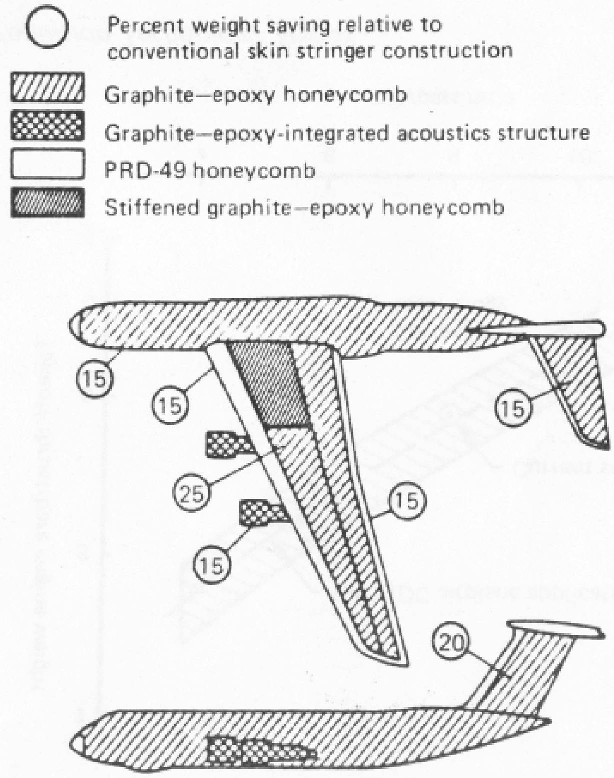
In order to identify an objective level of aerodynamic efficiency for the advanced aerodynamic technology configurations of this study, a preliminary investigation was first made to determine the sensitivity of the required TOGW and fuel burned of the long-range airplane to cruise L/D ratio. These results are shown in figure 50. Two levels of aerodynamic improvements are identified relative to the conventional aerodynamic technology level. The advanced aerodynamic concept potential level represents the full utilization of advanced aerodynamic concepts and supporting technologies. The moderately advanced aerodynamic concepts represent a conservative utilization of compatible advanced aerodynamic concepts. The advanced aerodynamic concept configurations developed in the current study are of this later category.

Figure 50 also shows the incremental gross weight reduction and fuel savings for successive improvements in L/D ratio of 5.0. These results illustrate the dramatic improvements achievable with rather modest increases in L/D ratios. The data shown in figure 50 are also shown in figure 51 in the form of weight and fuel payoff ratios. These results illustrate that increasing improvements in L/D ratio continue to reduce the required mission fuel and gross weight, however, at a diminishing rate.

With the moderately advanced aerodynamic level as an objective, the following compatible concepts were selected for developing the advanced aerodynamic technology long-range and high endurance airplanes.

Weight Reduction Due to Advanced Materials

Component	Weight saving, %
Wing	25
Horizontal tail	15
Vertical tail	20
Body	15
Main gear	10
Nose gear	10
Nacelle and strut	15



Long Cruise Airplane Weight Fraction

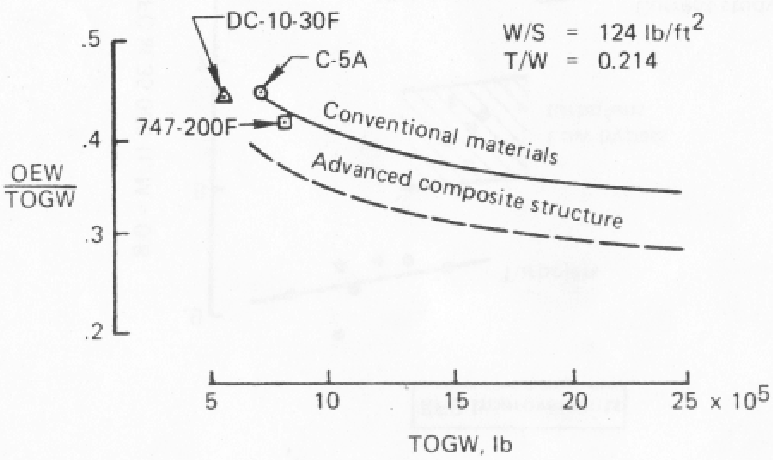


Figure 48.—Reference Long-Range Airplane—Weight Estimation

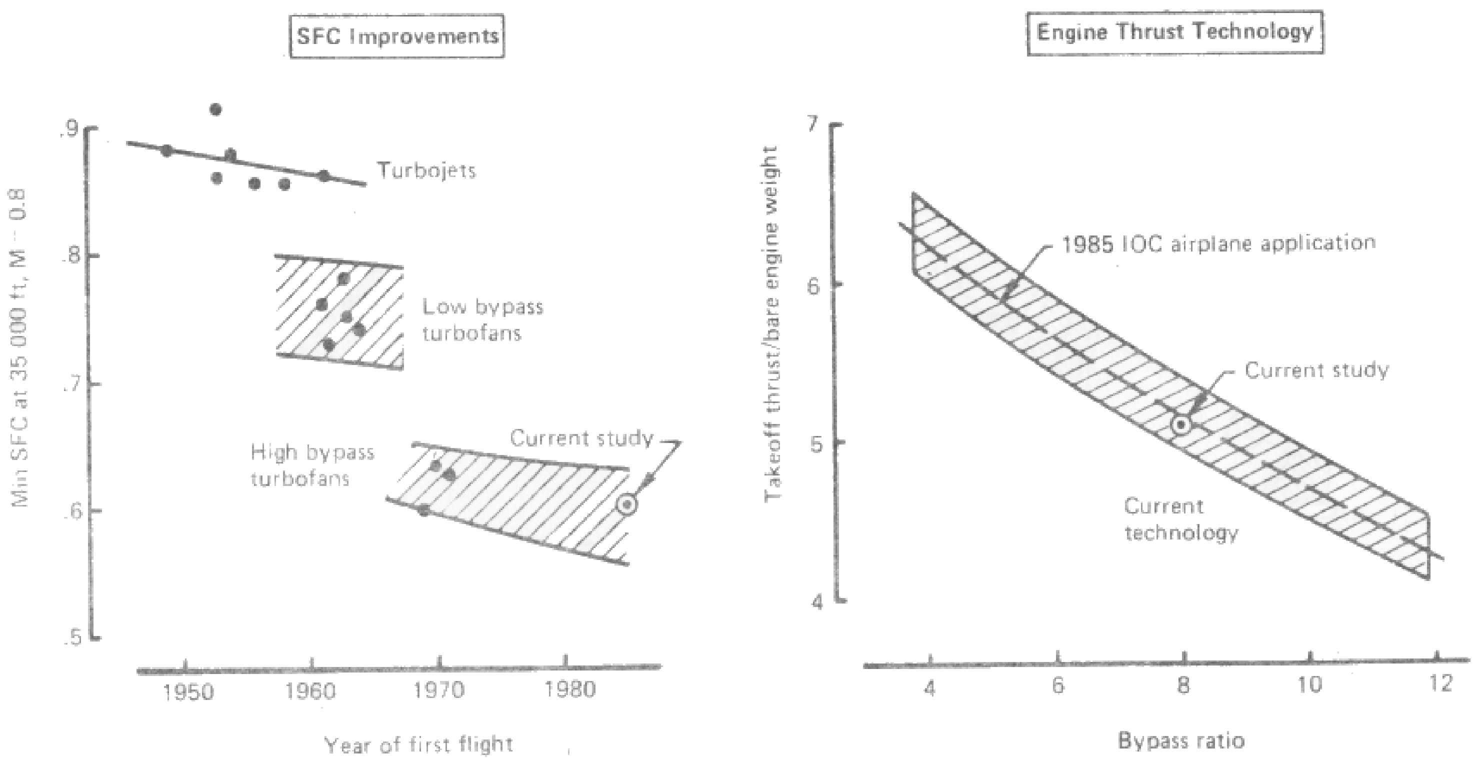


Figure 49.—Propulsion Technology Trends

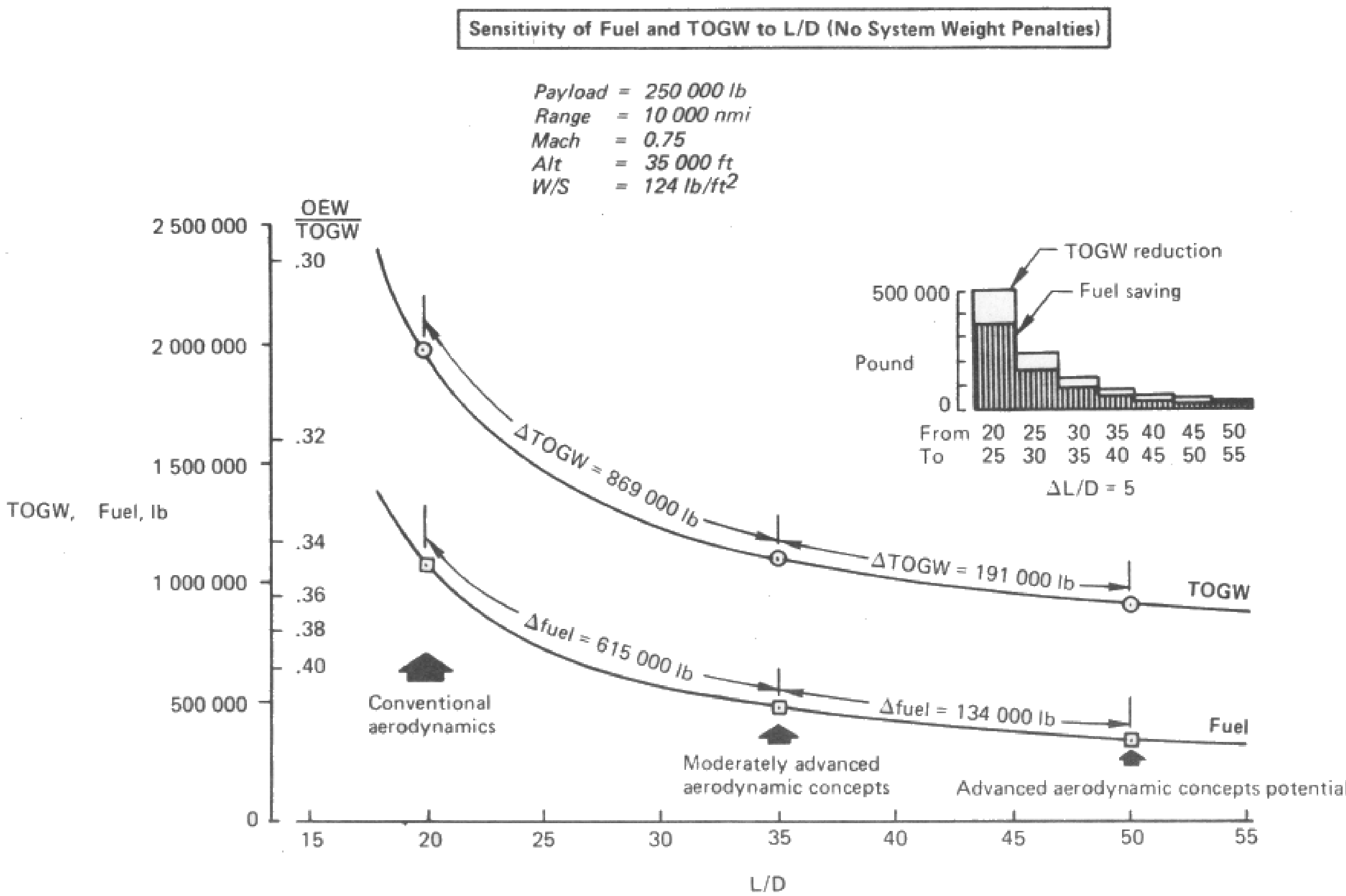


Figure 50.—Sensitivity of the Long-Range Airplane to L/D

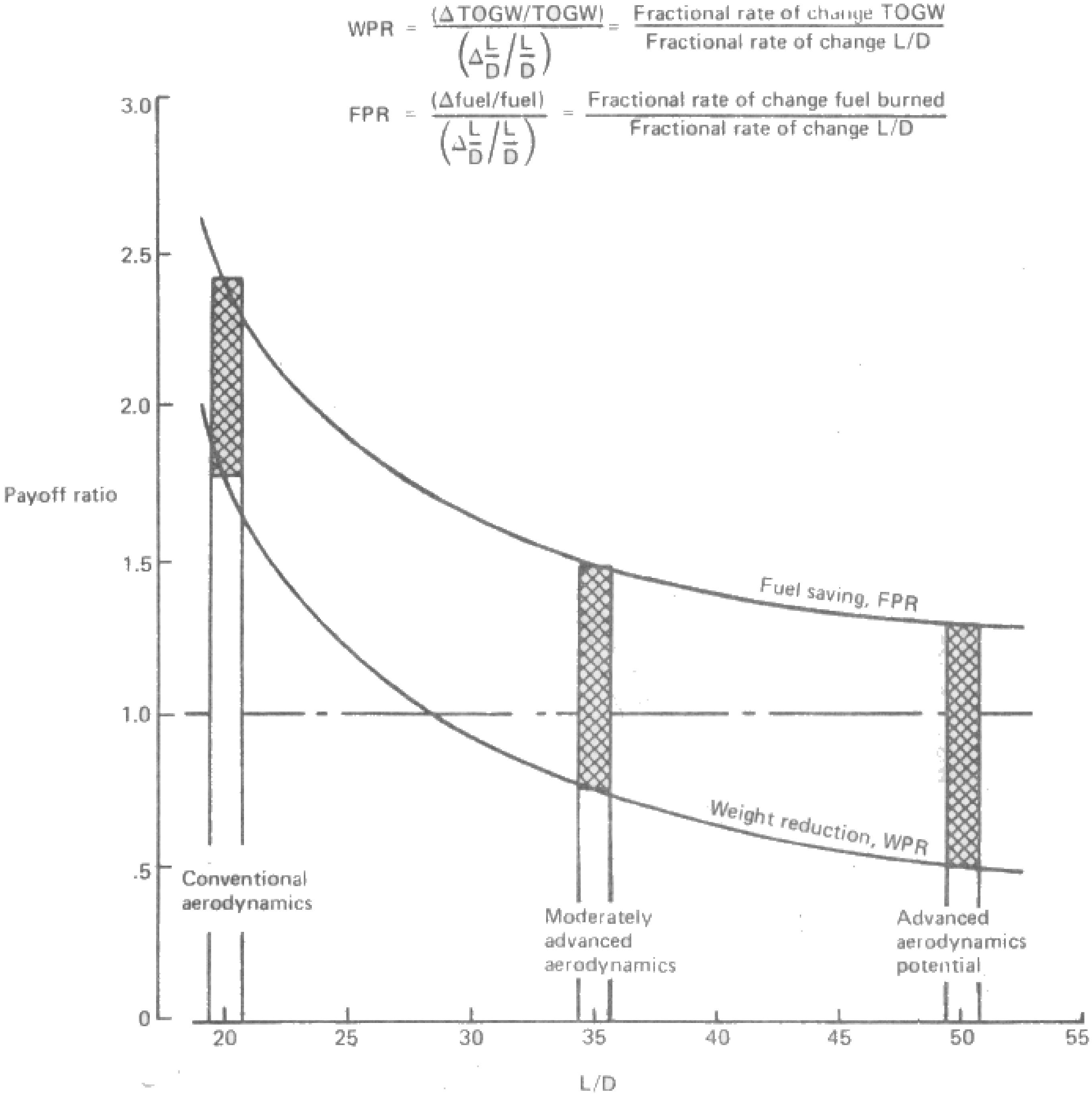


Figure 51.—Potential Aerodynamic Improvement Payoffs for the Long-Range Mission

- Advanced high-speed airfoils together with advanced wing aerodynamic design methodology including wing-body contouring to increase the critical Mach by 0.05 and reduce the wing sweep so that the trailing edge is straight

- Increased aspect ratio utilizing advanced structural materials and fuel burned as a principal optimization figure of merit

- Wingtip fins with a height equal to 10% of the wing semispan

- Minimum trim drag and reduced tail sizes associated with an advanced flight control stability augmentation system

- Laminar flow control on the wing and tail surfaces except for the TE control areas and turbulence wedge areas near component junctions

- Body drag reduction with either forebody injection plus aft-body suction or the use of compliant skins

The first four items are aerodynamic concepts that fundamentally reduce the induced drag (C_{D_I}) and the compressibility drag (C_{D_M}). The last two items primarily reduce the profile drag (C_{D_p}). In addition, both the first and fifth items offer the designer flexibility in developing an optimum arrangement.

Note that the LFC benefits must again be considered as a conservative appraisal, since complete laminarization of the trailing edge appears feasible with projected manufacturing technology improvements. This greatly improves the LFC benefits.

The drag and weight evaluation techniques used in the integrated configuration analyses were the preliminary design methods previously discussed. A total system weight penalty of 1.5 lb/ft^2 was allotted for LFC, based on the total laminarized wetted area (includes pumps and engines). Allowance of 1 lb/ft^2 of covered body wetted area was allotted for the compliant skins or for body BLC. The tip fin weights were estimated as the same weight for an AR increase producing the same aerodynamic benefit.

3.3 DESIGN SYNTHESIS PROCEDURE

The design synthesis procedure that was used to develop each of the study aircraft configurations consists of four steps.

STEP 1

The initial step was to define the preliminary configuration characteristics that included such general items as:

- Aerodynamic design features (e.g., tip fins, LFC, etc.)

- Wing planform characteristics and initial size

- Number of engines, engine cycle, and initial size
- Tail planform, arrangement, thickness, and initial sizes
- Estimated required TOGW
- Design guidelines and general technology assumptions

STEP 2

These estimated configurations characteristics, together with preliminary supporting aerodynamic, weight, propulsion, flight control, and performance evaluations, provided inputs for detailed configuration arrangement layouts.

STEP 3

The detailed design layouts defined the uncycled reference configuration. This reference configuration was then analyzed to determine the basic weight and L/D characteristics. Additional analyses were made to determine the effects of varying engine size, wing area, and gross weight to establish scaling rules to account for these changes.

STEP 4

The results of the reference configuration evaluations, along with the scaling rules, formed inputs used to size or cycle the airplane by determining gross weight, wing area, engine size, tail areas, and required fuel necessary to meet the design objectives.

The sized airplane configurations were then used for additional studies that included:

- Performance benefits without boundary layer drag reduction concepts
- Performance benefits with only the boundary layer drag reduction concepts
- Design range sensitivity study
- Design endurance sensitivity study
- Wing thickness study with LFC

3.4 CONFIGURATION DESCRIPTIONS

The conventional aerodynamic technology long-range airplane that was derived from the C-5A is shown in figure 52. Note that the fuselage is similar to the C-5A. The large wing area and the increased number of main gear tires reflect the design impact of the design range which leads to a large gross weight requirement.

The conventional technology high endurance airplane was derived from the long-range airplane layout and reflects the differences in mission objectives. The high endurance

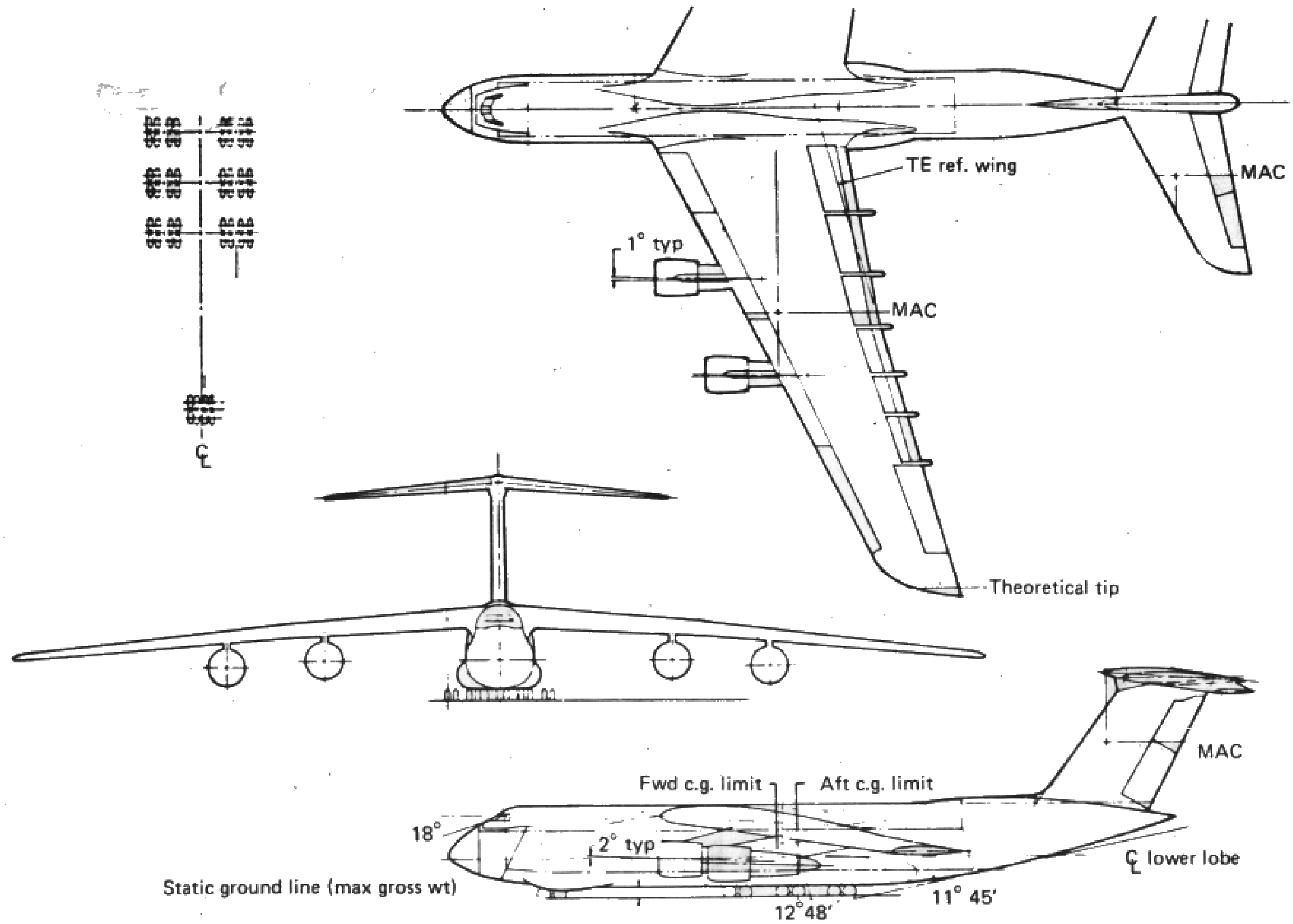


Figure 52.—General Arrangement of the Conventional Aerodynamic Technology Long-Range Airplane—Model 767-736

requirements dictated a slower cruise speed (approximately M = 0.65) to obtain higher L/D ratios. The slower speed allowed the wing sweep to be reduced from 25° to 8.5° with the structural span and wing area held constant. This resulted in an aerodynamic AR of 9.23—a 19% increase over the long-range airplane. The body arrangement of the long-range airplane was retained, providing for aft launching of missiles that could make up the payload of the high endurance airplane. Thus, the general arrangement (fig. 53) was obtained by holding the body size and shape, wing loading, thrust loading, and tail volume coefficients constant.

The design layout of the advanced aerodynamic technology long-range airplane incorporating the selected aerodynamic concepts (discussed in sec. 3.2) is shown in figure 54. Although the design speeds for the long-range and high endurance airplanes differ (Mach 0.75 and 0.65, respectively), the configuration definition of figure 54 incorporates the advanced aerodynamic concepts that have been selected for each mission. Consequently, this configuration layout was also used to evaluate the performance benefits of the advanced aerodynamic concepts for the high endurance mission.

3.5 CONFIGURATION PERFORMANCE AND ECONOMICS

Aerodynamic and weight analyses of each of these arrangements were made to provide the necessary data to size each configuration to meet the design mission objectives. The airplane size characteristics and performance are summarized in tables 8 and 9 for the long-range and the high endurance airplanes, respectively. The geometrical characteristics of the sized airplanes are contained in table 10. Group weight statements for each of these configurations are presented in table 11. Cruise drag polar comparisons are shown in figure 55.

Table 8. - Long-Range Airplane Characteristics and Performance

Payload = 250 000 lb
Range = 10 000 nmi
Mach = 0.75

	Conventional (model 767-736)	Advanced (model 767-740)
Takeoff gross weight, lb	1,665,000	970,000
Operating empty weight, lb	521,000	378,000
OEW/TOGW	0.313	0.390
Payload/TOGW	0.150	0.258
Wing area	13,430	7,820
Engine thrust rating		
SLST, lb	89,100	51,900
Number of engines/bypass ratio	4/8	4/8
Thrust to weight (T/W)	0.214	0.214
Wing loading (W/S)	124	124
L/D	21.2	40.1
Range factor	15,720	29,700
Productivity $\frac{\text{Mach x payload}}{\text{TOGW}}$	0.113	0.193
Block fuel, lb	835,500	308,000
Block fuel/lb payload	3.34	1.23

Table 9.—High Endurance Airplane Characteristics and Performance

Payload = 400 000 lb
Endurance = 24 hr
Radius = 250 nmi
Mach = 0.65

	Conventional (model 767-739)	Advanced (model 767-740E)
Takeoff gross weight, lb	1,703,000	1,217,000
Operating empty weight, lb	540,900	450,000
OEW/TOGW	0.318	0.370
Payload/TOGW	0.235	0.329
Wing area	13,730	9,810
Engine thrust rating		
SLST, lb	91,100	65,100
Number of engines/bypass ratio	4/8	4/8
Thrust to weight (T/W)	0.214	0.214
Wing loading (W/S)	124	124
L/D	23.9	44.8
Endurance factor	49.8	89.6
Productivity: $\frac{\text{Mach x payload}}{\text{TOGW}}$	0.153	0.214
Block fuel, lb	702,500	324,000
Block fuel/lb payload	1.76	0.81

The advanced aerodynamic configurations were also analyzed and sized with only the induced drag and compressibility drag reduction concepts and with only the boundary layer drag reduction concepts.

The TOGW breakdown (figs. 56 and 57) illustrate that the dramatic reductions in TOGW achieved with the use of advanced aerodynamic concepts are due primarily to the reductions in the required mission fuel. These results also show that the net benefits due to the induced drag reducing concepts are nearly equal to those of the boundary layer drag reduction concepts.

The takeoff gross weights and fuel requirements are cross-plotted versus the net L/D ratio for the sized airplanes (fig. 58) and as percentage improvements relative to the conventional airplanes (fig. 59). These results again illustrate the large initial rates of improvement with modest L/D increases. It should be noted that without LFC the objective levels of aerodynamic efficiency (discussed in sec. 3.2) could not be achieved.

Preliminary low-speed evaluations of the conventional long-range configuration had a TOFL to clear a 50-ft obstacle of 8000 ft with all engines operating. The conventional high endurance airplane had better low-speed aerodynamics because of the reduced wing sweep and increased span. The advanced aerodynamic technology airplanes were configured without LE devices to make the laminarization task easier. The lack of LE flaps resulted in a loss in $C_{L_{max}}$ that was compensated by a slightly higher increase in $C_{L_{max}}$ due to reduced wing sweep. In addition, the takeoff and landing L/D ratios are improved because of the higher aspect ratios. Hence, the advanced technology configurations also satisfied the low-speed performance constraints.

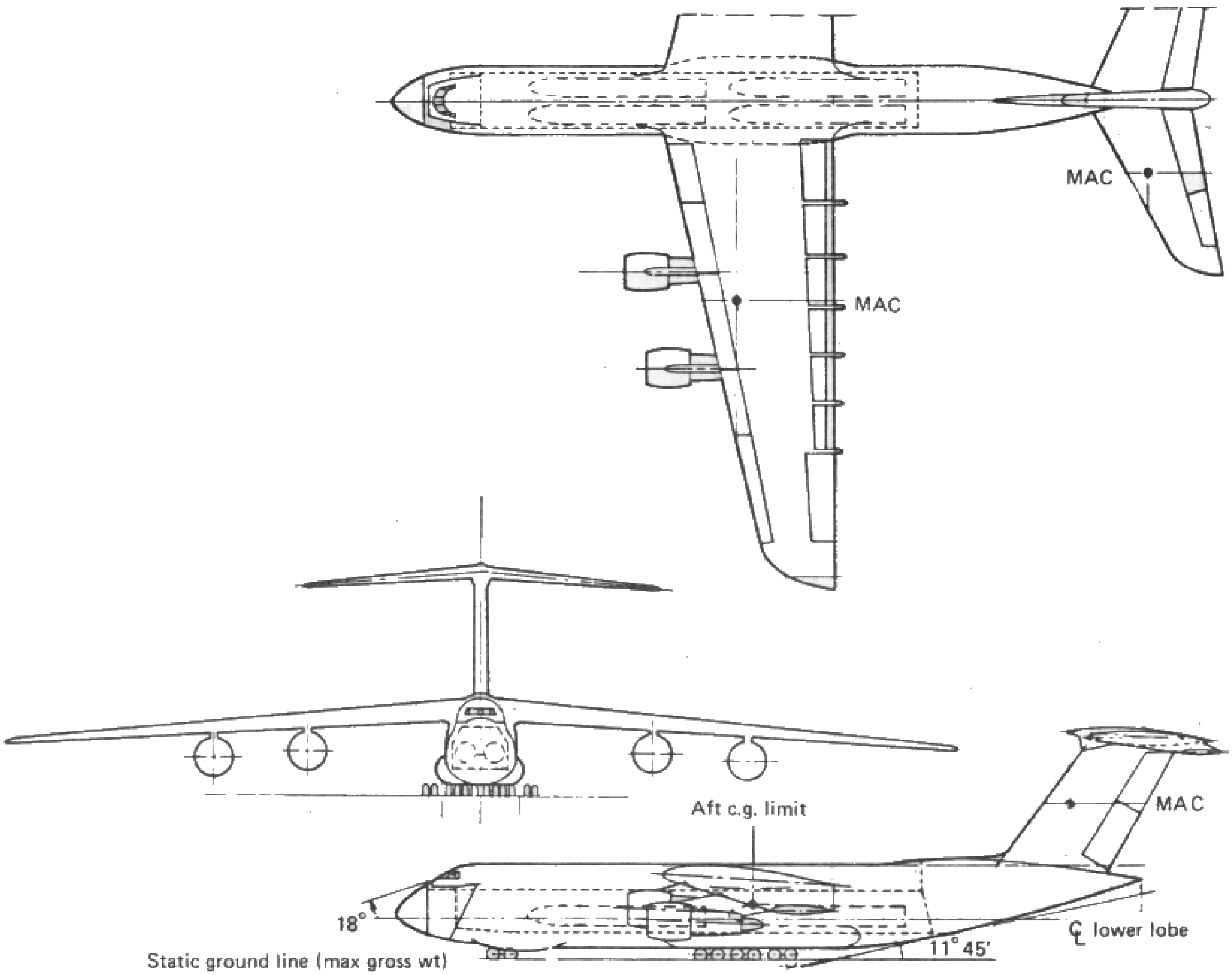


Figure 53.—General Arrangement of the Conventional Aerodynamic Technology High Endurance Airplane Model 767-739

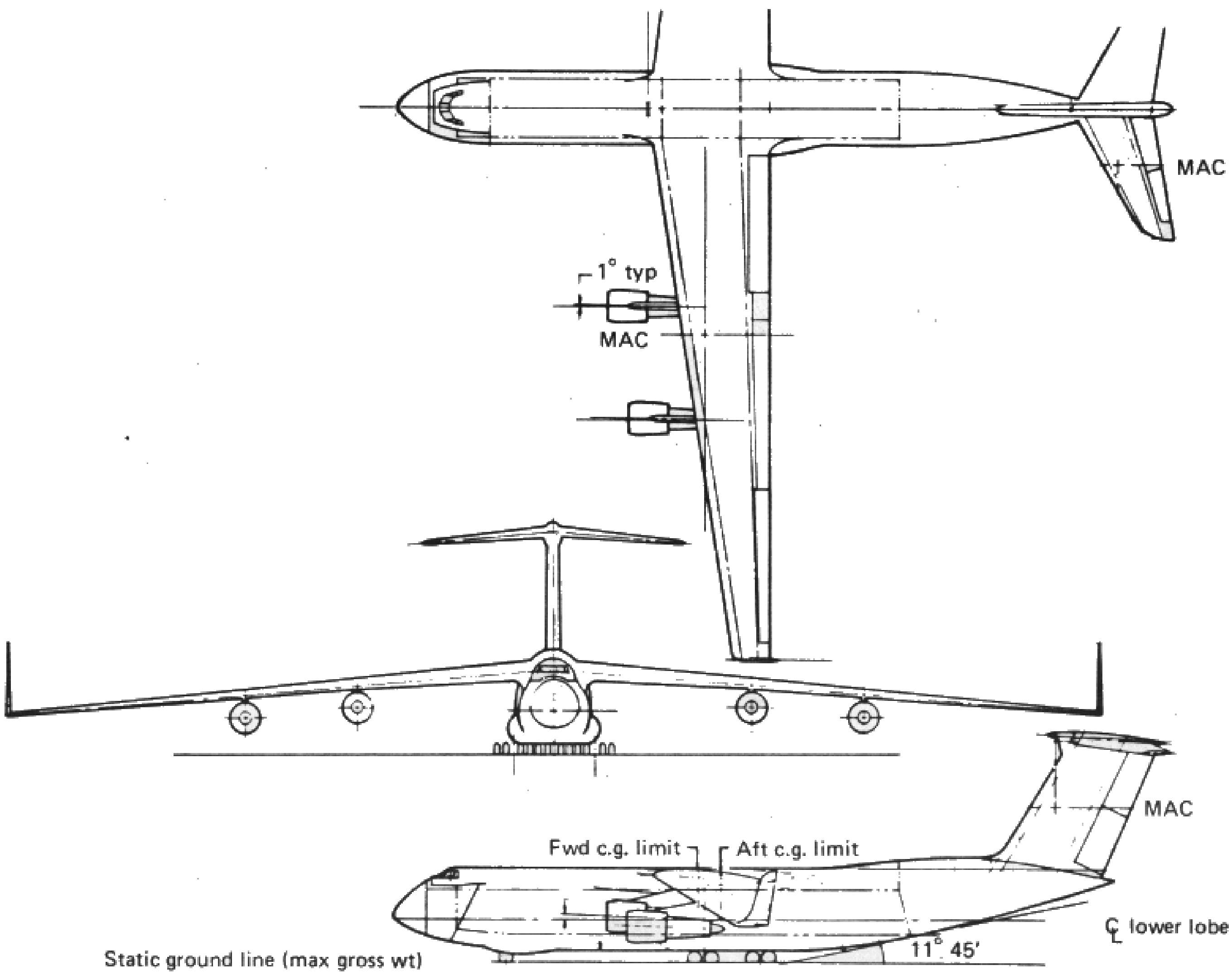


Figure 54.—General Arrangement for the Advanced Aerodynamic Technology Long-Range and High Endurance Airplanes—Models 767-700 and 767-740E

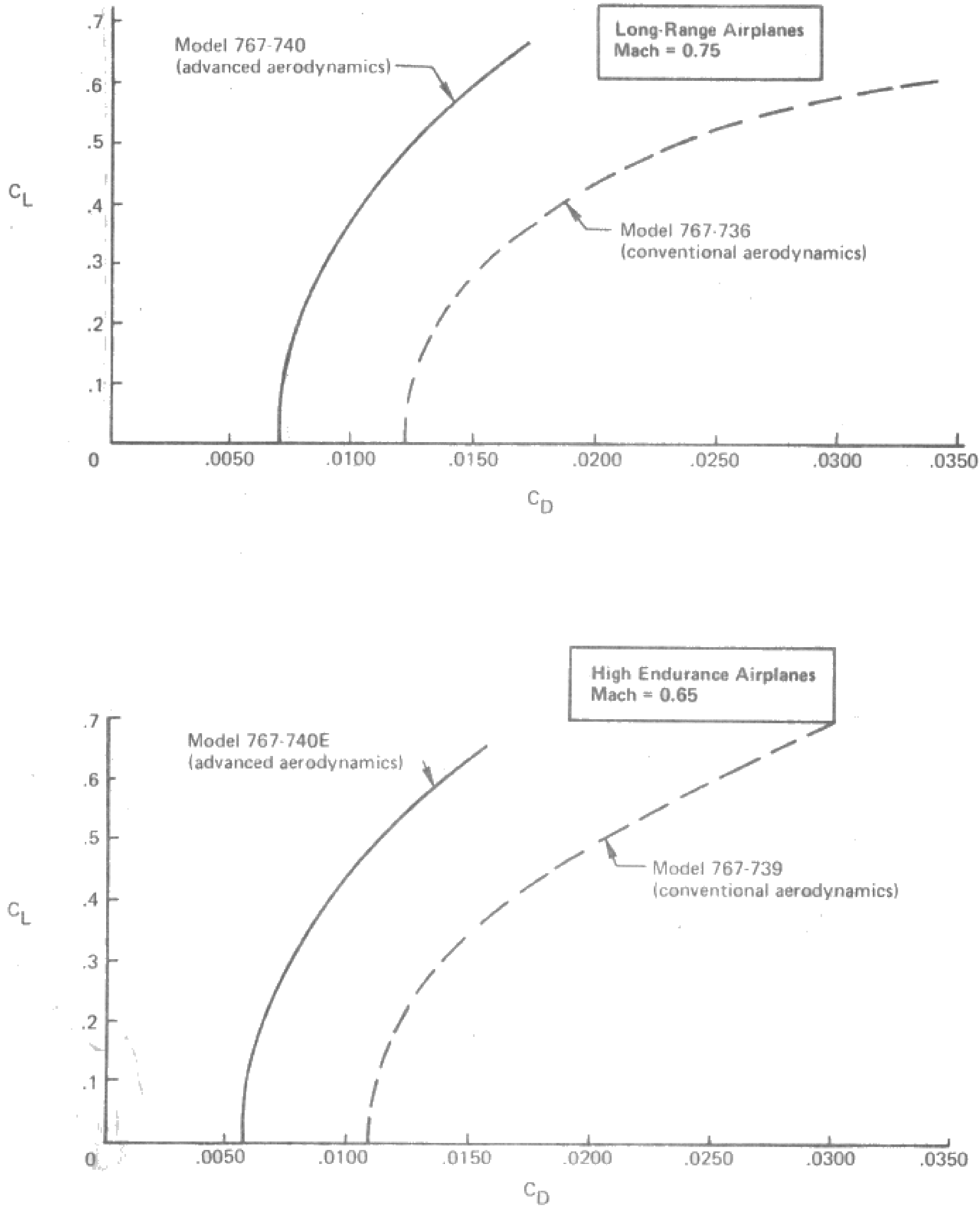


Figure 55.—Sized Airplanes Cruise Drag Polars

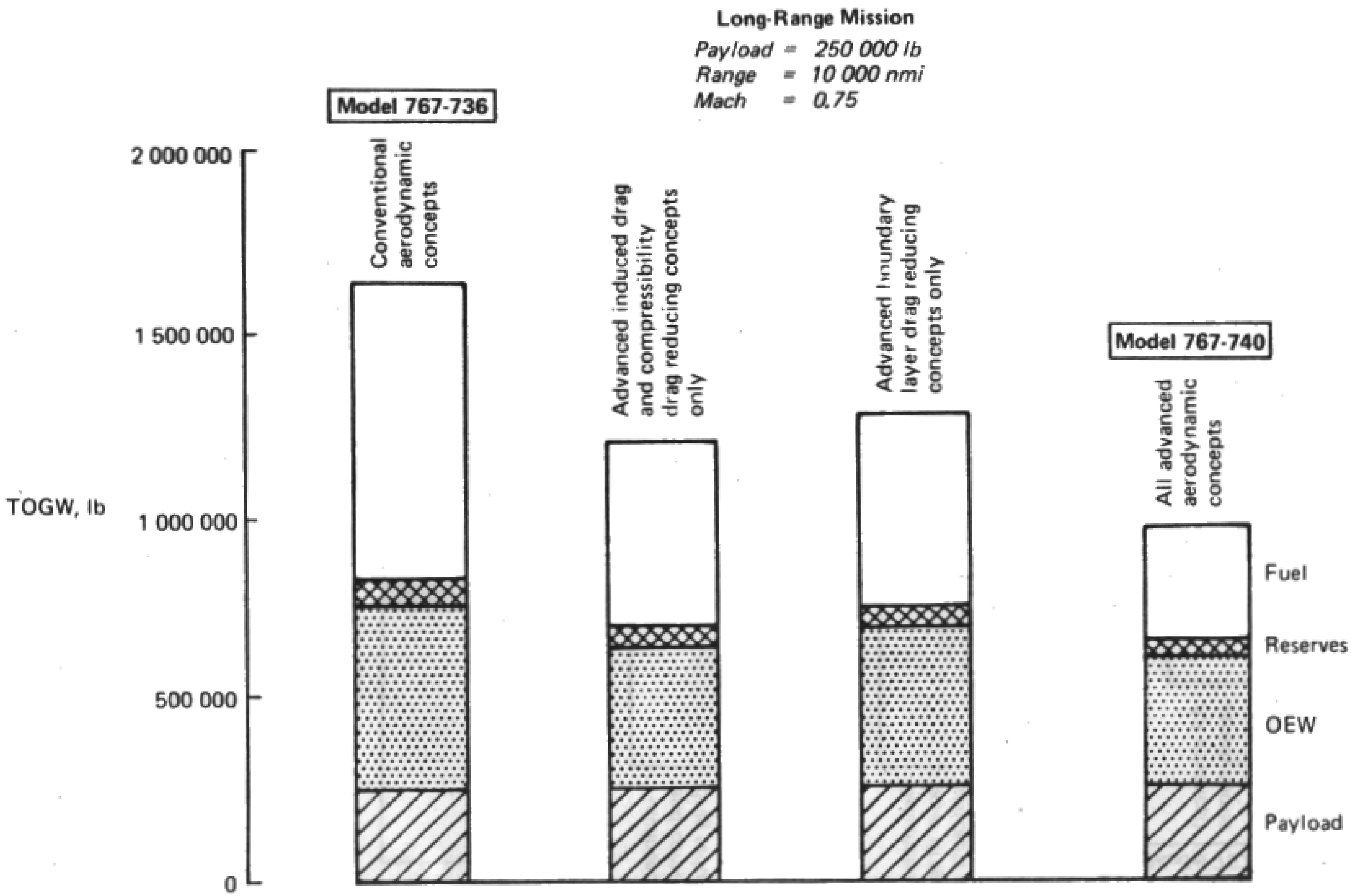


Figure 56.—Long-Range Airplanes Gross Weight Summary

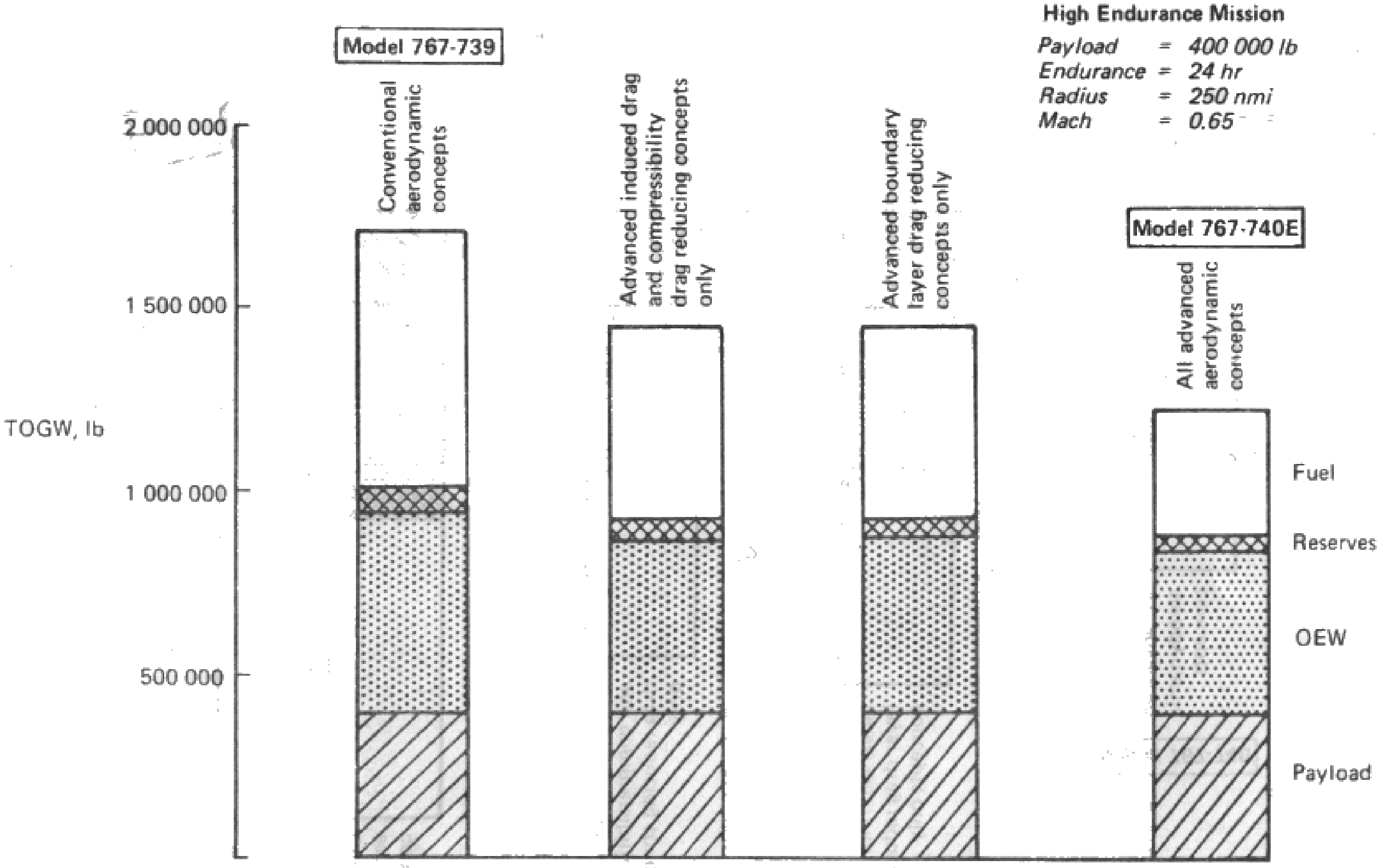


Figure 57.—High Endurance Airplanes Gross Weight Summary

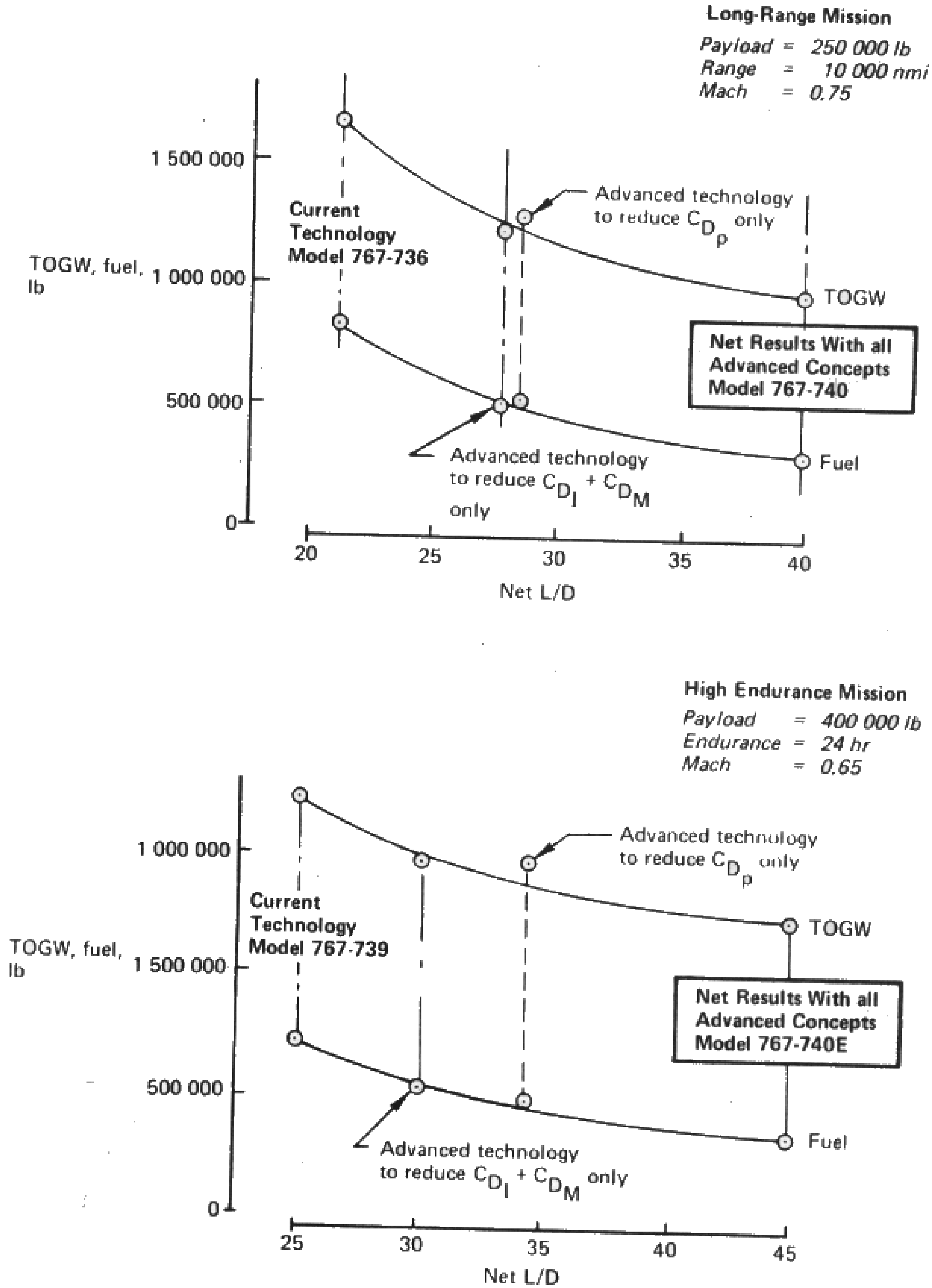


Figure 58.— Effect of Aerodynamic Technology Level on Study A/P Fuel and Weight

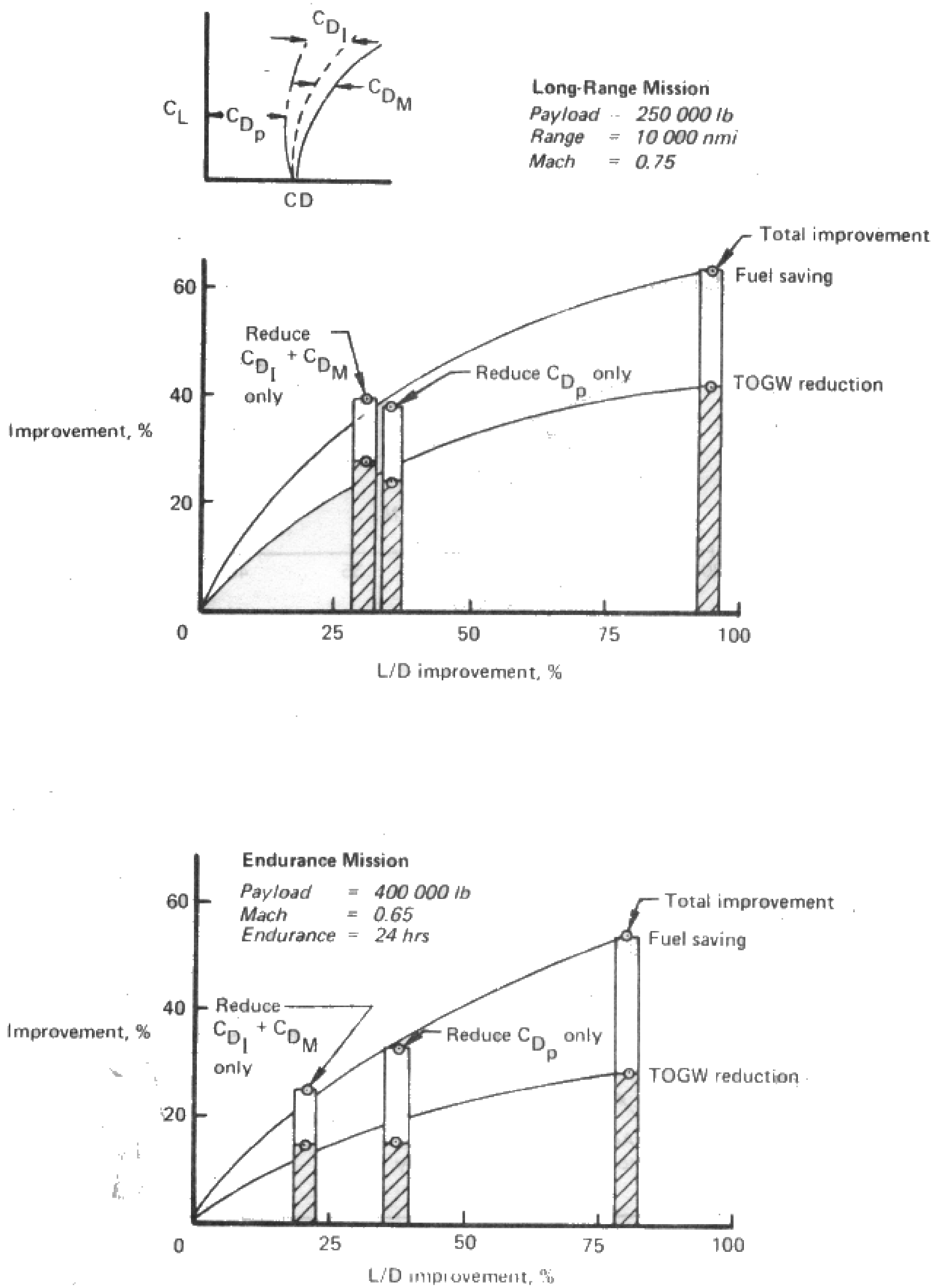


Figure 59.—Performance Benefits With L/D Improvements

Table 10. –Sized Airplane Design Characteristics

Item		Airplane model number 767-736	767-739	767-740	767-740E
Major design parameters	Payload, lb	250,000	400,000	250,000	400,000
	Range, nmi	10,000	--	10,000	–
	Endurance, hr	..	24	–	24
	Cruise Mach no.	0.75	0.65	0.75	0.65
	Aerodynamic technology	747–C-5A aerodynamics		Advanced aerodynamic concepts • High-speed airfoils • Increased aspect ratio • Wingtip fins • LFC (wings and tail) • Body BLC/compliant skin • Aft c.g./min trim drag	
Weights	TOGW, lb	1,665,000	1,703,000	970,000	1,217,000
	OEW, lb	521,000	540,900	378,000	450,000
	Fuel, lb	835,500	702,500	308,000	324,000
	Reserves, lb	58,500	59,600	34,000	43,000
Fuselage	Length, ft	244.4		230.6	
	Max diameter, in.	286.0			
Landing gear	Nose	(8) 49 x 17	(8) 56 x 16	(4) 56 x 16	
	Main	(36) 49 x 17	(48) 56 x 16	(24) 56 x 16	
	LOC, %, c_{ref}	28.4	30.6	38.2	
Wing	Area, ft^2	13,430	13,730	7,820	9,810
	AR	7.75	9.23	14.0	
	$\Lambda_{c/4}$, deg	25.0	8.5	6.6	
	Span, ft	322.6	356.0	330.9	370.6
	λ	0.371		0.30	
	Incidence, deg	3.5			
	Dihedral, deg	-5.0			
	MAC, ft	44.5	41.3	25.9	29.0
	t/c, root/tip	12.4%/11%	11.0%/9%	15.0%/10%	
Horizontal tail	Area, ft^2	2,628	2,491	1,188	1,669
	AR	4.74			
	$\Lambda_{c/4}$, deg	25.0			
	λ	0.37			
	t/c, %	10.5			
	MAC, ft	25.2	24.5	16.9	20.1
	Tail vol coeff	0.613	0.695	0.78	
Vertical tail / Tip fin	Area, ft^2	1,912/–	2,140/–	1,142/104	1,605/130
	AR	1.24/–		1.24/2.63	
	$\Lambda_{c/4}$, deg	34.9/–		30.0/15	
	λ	0.8/		0.8/0.6	
	t/c, %	13.0/–		13.0/6.0	
	MAC, ft	35.7	41.7	30.5	36.1
	Tail vol coeff	0.05/			
Propulsion	BPR	8.0			
	No./LOC	4/wing mounted			
	SLST, lb	89,100	91,100	51,900	65,100

Table 11.—Sized Airplane Weight Comparisons

Item	Configuration model number			
	767 736	767-739	767 740	767-740E
	lb	lb	lb	lb
Wing	177 800	191 050	111 000[a]	148 390[a]
Horizontal tail	19 670	19 570	9 850[b]	13 640[b]
Vertical tail	11 910	13 180	7 780[b]	10 780[b]
Body	115 130	116 540	110 410[c]	113 210[c]
Main gear	34 760	35 510	35 240	39 410
Nose gear	4 740	4 840	4 640	5 160
Nacelle and strut	15 870	16 350	9 230	11 430
Total structure	379 880	397 040	288 150	342 020
Engine	77 070	79 100	40 740	53 230
Engine accessories	1 060	1 080	620	770
Fuel system	5 560	5 690	3 240	4 060
Engine controls	410	420	240	300
Starting system	460	470	270	340
Thrust reverser	9 050	9 250	5 270	6 610
Total propulsion group	93 610	96 010	50 380	65 310
Auxiliary power unit	2 000	2 000	2 000	2 000
Instruments and nav equip	1 000	1 000	1 000	1 000
Surface controls	16 730	17 000	10 290	12 730
Hydraulic/pneumatic	4 520	4 590	2 920	3 680
Electrical	4 000	4 000	4 000	4 000
Avionics	3 900	3 900	3 900	3 900
Furnishings and equip	6 710	6 710	6 710	6 710
Air cond and anti-icing	3 620	3 620	3 620	3 620
Auxiliary gear	270	270	270	270
Total fixed equipment	42 750	43 090	34 710	37 910
Manufacturer's empty weight	516 240	536 140	373 240	445 240
Crew	1 290	1 290	1 290	1 290
Crew provisions	320	320	320	320
Oil and trapped oil	600	600	600	600
Unavailable fuel	800	800	800	800
Payload provisions	1 750	1 750	1 750	1 750
Total non-exp useful load	4 760	4 760	4 760	4 760
Operational empty weight	521 000	540 900	378 000	450 000
Payload	250 000	400 000	250 000	400 000
Fuel	835 500	702 500	308 000	324 000
Reserves	58 500	59 600	34 000	43 000
Takeoff gross weight	1 665 000	1 703 000	970 000	1 217 000

[a]Includes LFC systems weight and tip fin weight

[b]Includes LFC systems weight

[c]Includes body BLC/compliant skin weight

Primary factors that influence the economics of the advanced airplane compared with the conventional airplane are:

- Reduced airframe and engine weight
- Reduced fuel consumption
- Development costs for advanced concepts
- Increased manufacturing costs/lb
- Increased maintenance

Comparative weight and fuel consumption data have been identified in this study (tables 8 and 9). However at this point in time, the development, manufacturing, and maintenance costs cannot be accurately estimated. It has been suggested that a 10% increase for each of these factors (development, manufacturing, and maintenance) might be an appropriate starting point. More detailed system and configuration studies on the advanced concept airplane are needed to help identify more credible estimates. Therefore, it was judged inappropriate at this time to attempt to obtain any detailed systems costs. It should be mentioned, however, that data from this study are being supplied to the Rand Corporation for possible use in economic studies by that organization.

3.6 DESIGN RANGE AND ENDURANCE STUDIES

The effects of the design range or design endurance were investigated for both the conventional and for the advanced aerodynamic technology airplanes; first with only the aerodynamic concepts that reduce induced drag and compressibility drag, then with only those concepts that reduce boundary layer drag, and finally with all of the selected advanced aerodynamic concepts. These results are shown in figures 60 and 61. These data are also presented in figures 62 and 63 in the form of weight and fuel percentage improvements.

For the primary design missions, these results show that the induced drag and compressibility drag reduction items produce nearly the same benefits as the boundary layer drag reduction items. The boundary layer drag items produce greater improvements in L/D ratios but at the expense of a greater total systems weight penalty. For reduced endurance or lower design ranges, the boundary layer drag benefits decrease at a slightly faster rate. Again, this is the result of the additional systems weight.

The results shown in figures 60 through 63 dramatize the importance of reducing lift-dependent drag items as the profile drag is reduced. The increase in L/D with both groups of drag-reducing items exceeds the sum of the individual contributions. Consequently, the net improvements in fuel savings and gross weight reduction are nearly additive even in view of the diminishing payoff rate with large increases in L/D, previously discussed in section 3.2

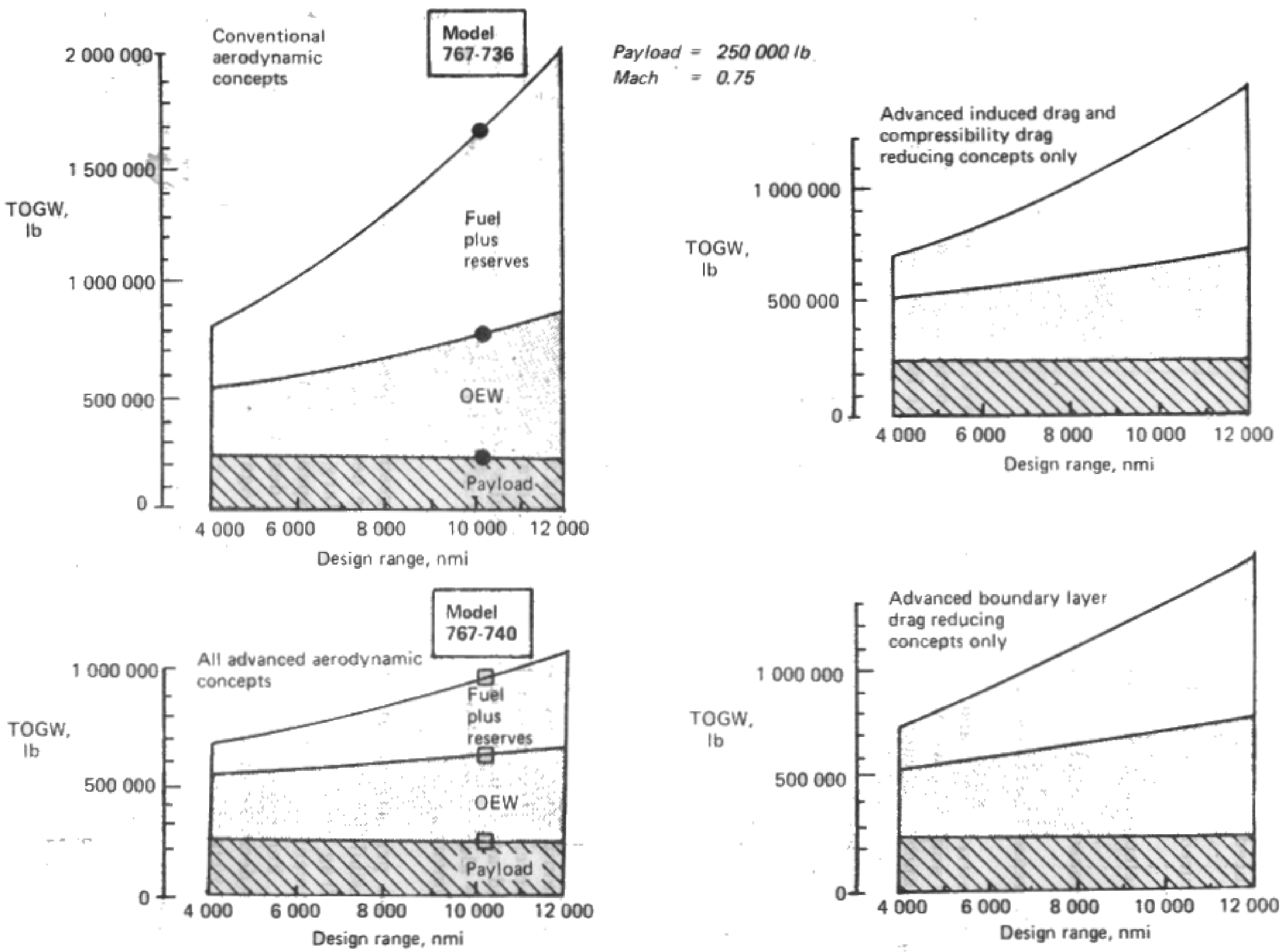


Figure 60.—Effect of Design Range on Fuel and Gross Weight

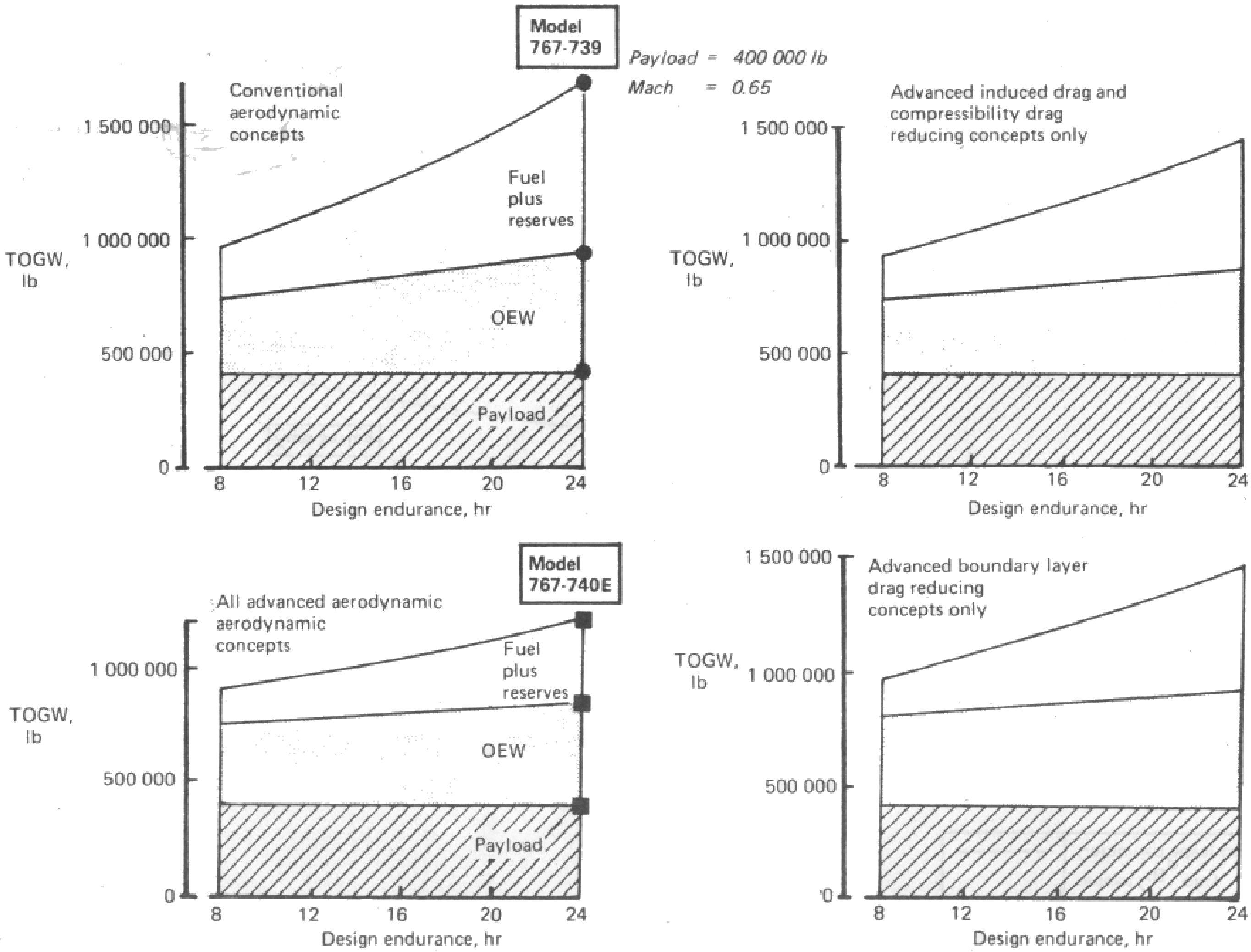


Figure 61.—Effect of Design Endurance on Fuel and Gross Weight

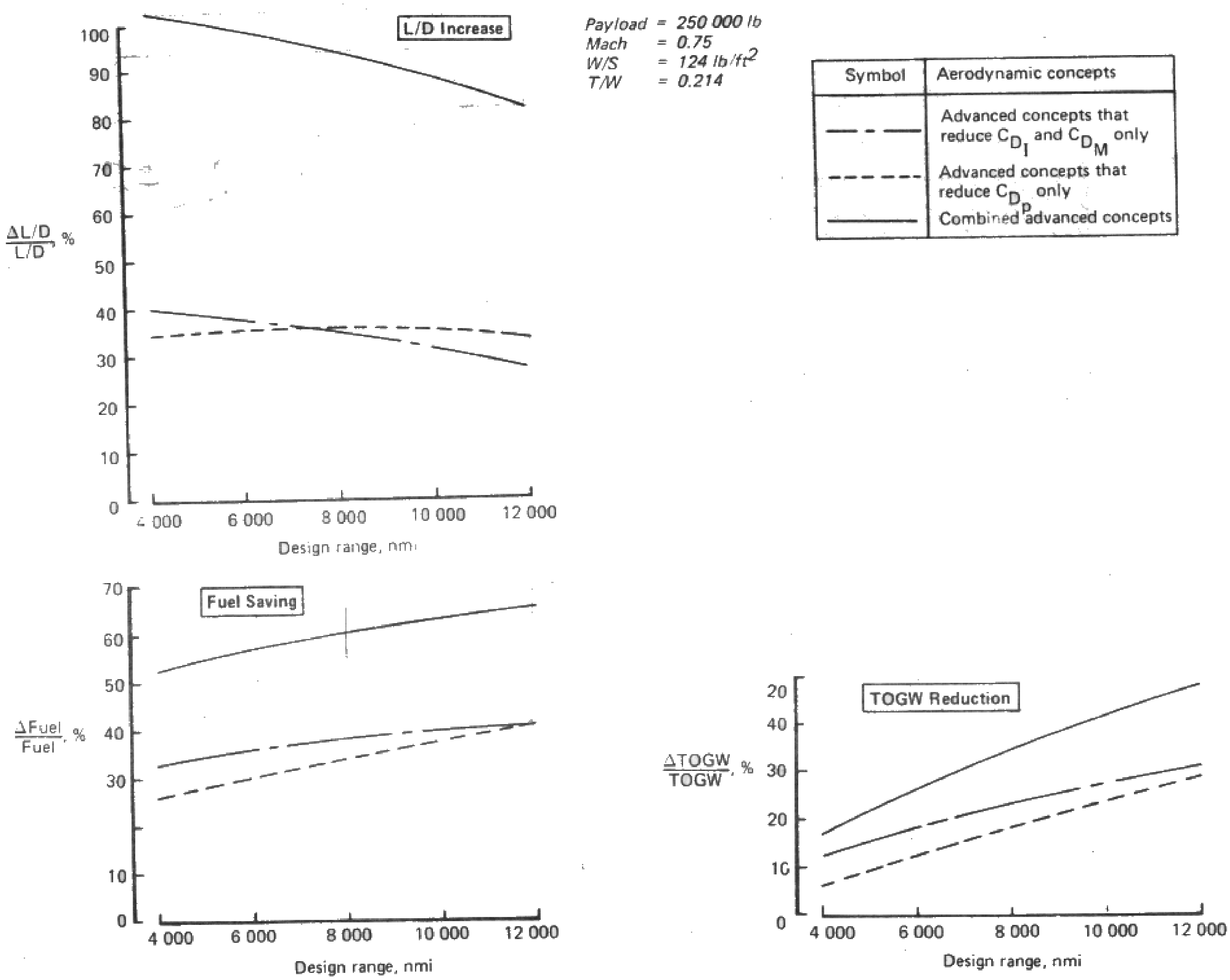


Figure 62.— Effect of Design Range on the Relative Performance Improvements

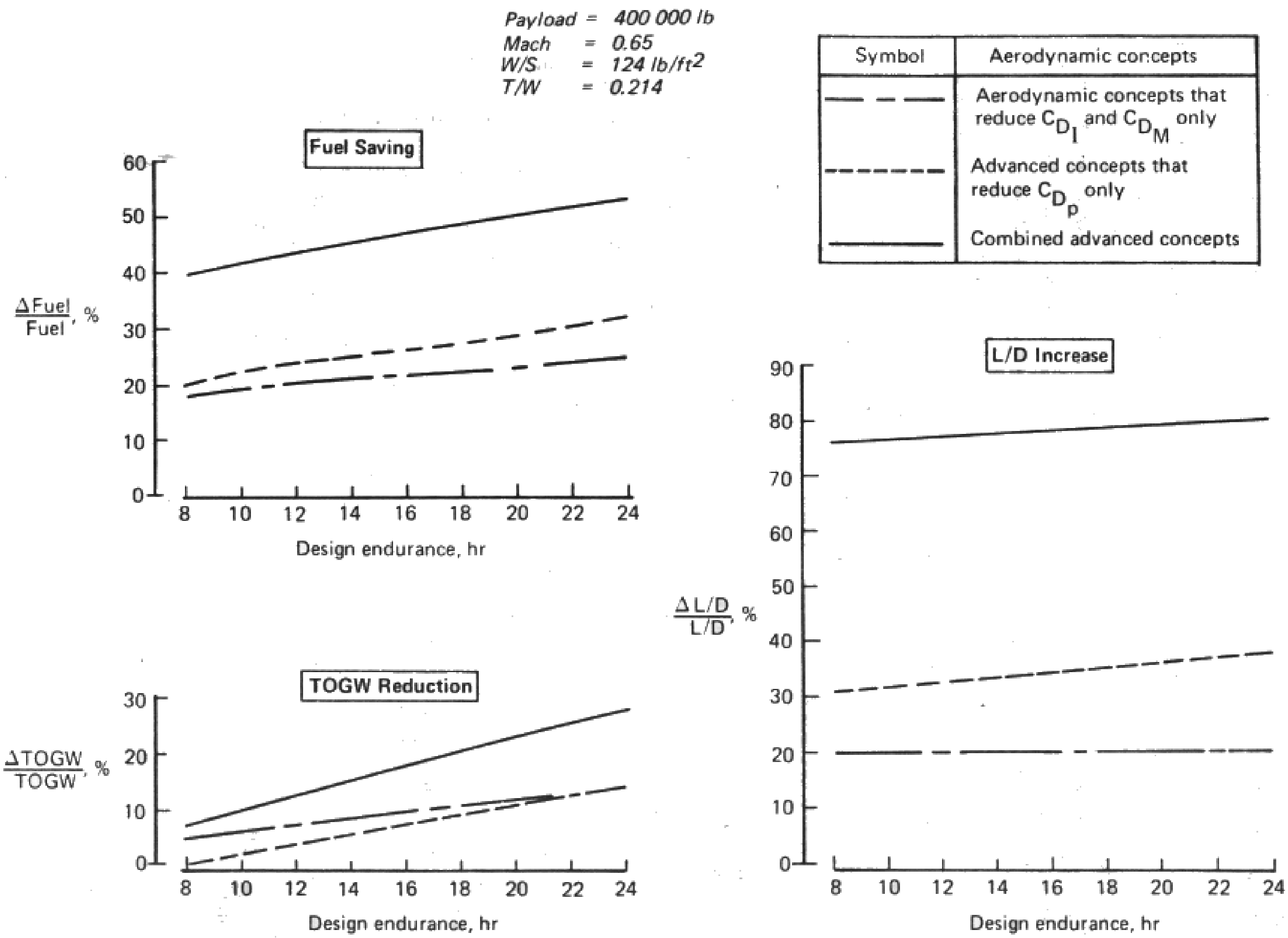


Figure 63.—Effect of Design Endurance on the Relative Performance Improvements

These results suggest a strong correlation between the aerodynamic improvement payoffs and the fuel/gross weight fraction. The greater the fuel requirements necessary to achieve the design mission, the more benefit the configuration will derive from aerodynamic efficiency. Continually improving the aerodynamic efficiency results in diminishing payoff returns because of the correspondingly smaller fuel/gross weight fractions.

3.7 WING THICKNESS STUDY

The advanced high-speed airfoil evaluation results (sec. 2.4.1) indicated that the fully turbulent flow profile drag limited the optimum wing outboard thickness ratios to less than 10%. However with LFC, the variation of wing profile drag with wing thickness is reduced. Hence, one might expect an LFC wing to favor high thickness ratios.

The effect of increasing the wing thickness of the advanced aerodynamic technology high endurance airplane (model 767-740E) was investigated. The results summarized in figure 64 show that the use of LFC does reduce the airplane sensitivity to wing thickness until the wing compressibility drag becomes important. This feature offers the designer flexibility in achieving the optimum balance between the aerodynamic and structural demands in the wing design process.

3.8 MILITARY TRANSPORT CONFIGURATION INTEGRATION CONCLUSIONS

Application of a compatible set of advanced aerodynamic concepts results in fuel savings of 63% and 54% for the long-range and high endurance missions, respectively. In addition, the airplane gross weights were also reduced by 42% and 28%, respectively. The net performance benefits achieved with boundary layer drag reduction concepts and the benefits obtained with the induced drag and compressibility drag reduction items were nearly equal. For maximum performance benefits, both of the aforementioned groups of drag-reducing items should be included. There is a strong correlation between the aerodynamic improvement payoff and the initial fuel/gross weight fraction. The greater the relative fuel requirements necessary to achieve the design mission, the greater the payoff for aerodynamic technology improvements. Initially, rather modest aerodynamic improvements produced large performance benefits. Continually improving the aerodynamic efficiency results in diminishing payoff returns. For maximum benefits, the lift-dependent drag items should be reduced as the profile drag is reduced. The increase in lift/drag with both groups of drag-reducing items exceeds the sum of the individual L/D improvements. Consequently, the net improvements in fuel savings and weight reduction are nearly additive.

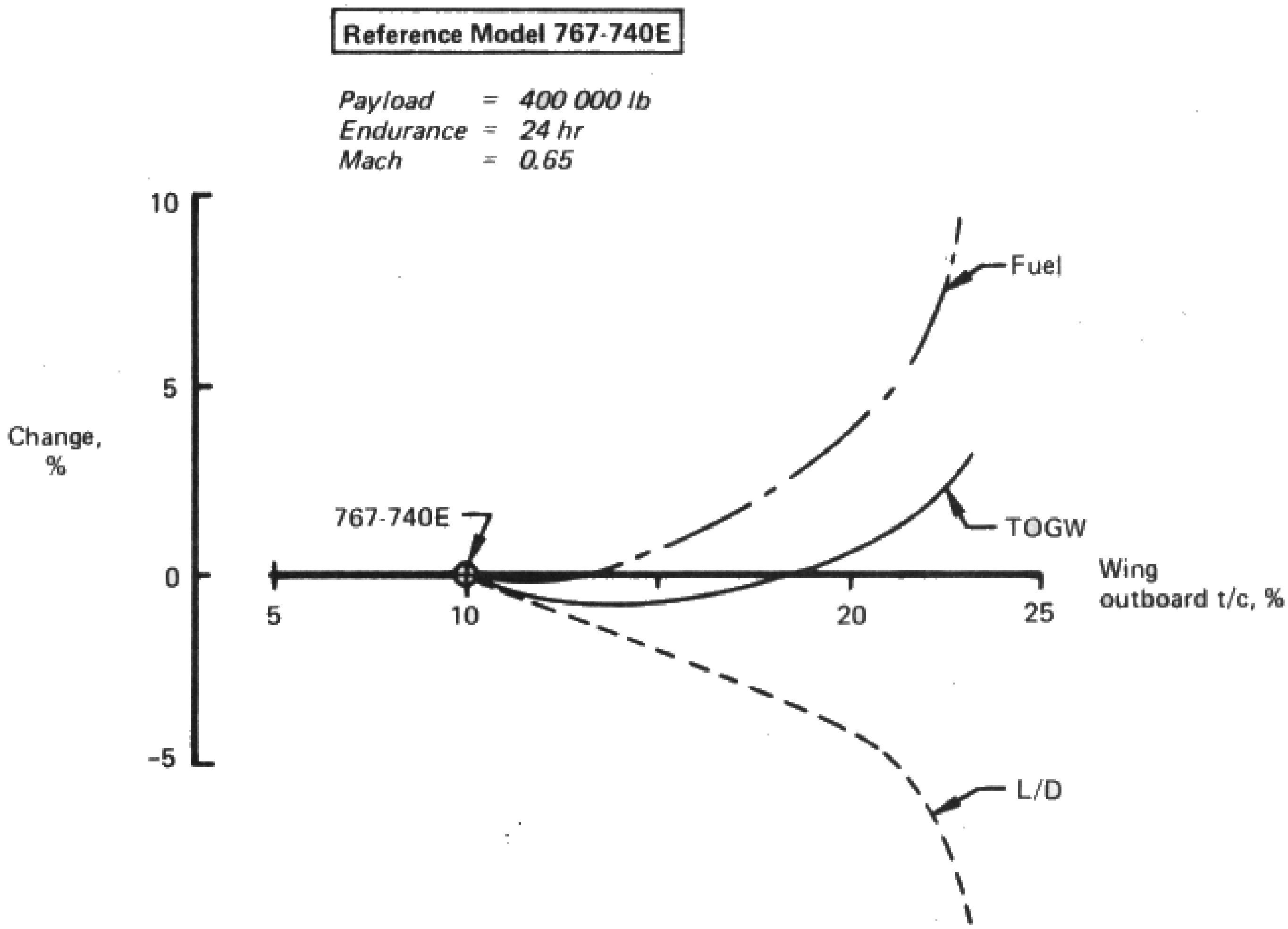


Figure 64.—Wing Thickness Study

4.0 CONCLUSIONS

The most significant conclusions of this study are:

- Laminar flow control offers the greatest performance benefit for both the large long-range and high endurance military airplanes.
- Fuel savings of 29% and gross weight reductions of 17% were identified with only 60% of the wing plus tail wetted area laminarized.
- Detailed designs on specific systems are necessary to identify fully the LFC potential.
- The advanced high-speed airfoils offer a high probability of success and were identified as the most compatible concept in support of other concepts.
- Advanced high-speed airfoils are desired for laminar flow applications and are required for natural laminar flow applications.
- With fuel consumption as a figure of merit, increases in wing aspect ratio are desirable, particularly with the application of advanced structural materials.
- Natural laminar flow airfoils offer short-term reduced benefits relative to LFC, particularly on smaller airplanes.
- The encouraging wind tunnel results and promising retrofit benefits of wingtip fins require detailed structural design and analyses to identify weight requirements.
- Because of limited existing knowledge and consistent data, compliant skins (body boundary layer control) offer promising but uncertain body drag reductions.
- Advanced aerodynamic design methods and broader experimental data offer large benefits in developing and applying advanced aerodynamic concepts.
- Application of a compatible set of advanced aerodynamic concepts results in fuel savings of 54% and 63% for high endurance and long-range missions, respectively. Additionally, the corresponding gross weights were reduced by 28% and 42%, respectively.
- There is a strong correlation between the aerodynamic improvement payoff and the initial fuel/gross weight fraction. The greater the initial fuel requirements, the greater the payoff for advanced aerodynamic technology concept applications.
- Initial, rather modest aerodynamic improvements produced large performance benefits. Continually improving the aerodynamic efficiency results in diminishing payoff returns.
- For maximum benefits, the lift-dependent drag items should be reduced as the profile drag is reduced. The increase in lift/drag with both groups of drag-reducing items exceeds the sum of the individual L/D improvements. Consequently, the net improvements in fuel savings and weight reduction are nearly additive.

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