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NASA Contractor Report 158930

Assessment of Variable Camber for Application to Transport Aircraft

Preliminary Design Department

BOEING COMMERCIAL AIRPLANE COMPANY
Seattle, Washington 98124

CONTRACT NAS1 - 15231
November 1980

National Aeronautics and
Space Administration

Langley Research Center
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1.0 SUMMARY

This study examined the potential attractiveness of varying the camber of transport aircraft wings while in flight to continuously optimize the lift-to-drag ratio and thereby reduce fuel usage and operating costs during all flight conditions. Most high-speed airplanes with high wing loadings change wing area and camber by using various mechanisms to extend leading- and trailing- edge flaps, slats, or both for low-speed takeoff and landing operations. The variable camber concept in this study incorporates shape-altering devices to deflect and smoothly recontour the leading and trailing edges of the wing during all stages of flight.

The study generally addressed three distinct facets of variable camber: the mechanical devices that provide the wing with the capability for variable geometry; the aerodynamic capability for various stages of flight (i.e., cruise, approach, and takeoff), and the capability for integrating with, and improving the characteristics of, transport aircraft configurations.

In this study, variable camber was applied to contemporary intercontinental and domestic transport configurations for which well-defined baseline design characteristics were available. Both the reference and variable-camber transports were conventional subsonic configurations defined for either intercontinental missions of 10 200 km (5500 nmi) or domestic missions of 3700 km (2000 nmi) and for payloads of 200 passengers.

To implement variable camber, simple, reliable, low-maintenance mechanisms were designed to independently deflect the wing leading and trailing edge surface areas to provide: (1) small deflections to optimize wing camber during climb, cruise, and descent, and (2) large deflections to provide high lift for takeoff and during final approach. The resulting, internally located devices can camber as much as the forward 25 percent and the aft 45 percent of the wing chord to closely match the contours of a family of "point-design" airfoils considered optimum for the flight conditions of a commercial transport. The limits on camber deflection (from normal flight) averaged 30 deg down for the leading edge and 15 deg up to 20 deg down for the trailing edge. The continuous skin of the leading edge was flexed by the variable camber mechanism to maintain a constant leading-edge radius over the range of deflections. On the trailing edge surface the overall length of the upper skin surface remained constant, and an overlapping seal on the lower surface allowed articulation. An alternate trailing edge was designed to provide variable camber during high-speed flight, but conventional double-slotted flaps for enhanced high lift at low speeds.

For the intercontinental mission, both the reference and the variable-camber airplanes were sized to approximately the same design point with relation to optimum gross weight versus fuel burned. The potential fuel saving for variable camber was 3.1 percent at maximum design mission range and 4.2 percent when evaluated on the weighted average airline route structure. The direct operating cost (DOC) benefits (using 1977 operational costs and fuel price) were slightly less than 2 percent for both the design mission and the weighted average route structure.

For the domestic mission, the initial variable-camber transport design required more wing area than the reference configuration to meet the 125-knot design approach speed because of limitations in stall lift coefficient, even with the outboard variable camber ailerons drooped. The larger wing resulted in a greater empty weight but also higher cruise lift-to-drag ratio, principally because of a 0.0006 reduction in excrescence drag and the greater wing area. The fuel saving was evaluated as 4.0 percent at design range; however, this reduced to 1.5 percent for the weighted average airline route structure. There was no DOC benefit at design range and a 1 percent penalty for the weighted average route structure.

The empty weight increment for the greater wing area of the initial variable-camber domestic airplane was large enough (2750 kg) to prompt consideration of a second configuration having sufficient high lift capability to be free of the 125 knot approach speed constraint. Therefore, the study was broadened to include an alternate hybrid trailing edge which provided variable camber at small deflections during cruise flight, and double-slotted flaps at large deflections for low speed flight conditions. The hybrid arrangement provided sufficient lift to eliminate the need for additional wing area over that of the reference aircraft. However, the excrescence drag reduction (a principal part of the variable camber benefit) dropped to 0.00015 so that the values of cruise lift-to-drag ratio were only slightly higher than those of the reference aircraft at lift coefficients within the normal cruise flight regime. Consequently, the hybrid arrangement produced a fuel saving of only 0.4 percent and incurred a slight DOC penalty at design range.

The potential benefits of variable camber were evaluated using the hypothesis that variable camber would enable wings to be designed with less drag at the design cruise condition than a fixed camber wing. Although some two-dimensional airfoil test data suggests that this may be possible, this hypothesis is not proven.

Based on this hypothesis, the study also showed that variable camber could allow a new design having less sweepback of the wing and provide even greater improvements in aerodynamic efficiency below the design cruise Mach number. For example, unsweeping the wing quarter-chord line of the domestic airplane from 30 deg to 25 deg, in combination with variable camber, could increase aerodynamic cruise efficiency by 7.5 percent at all Mach numbers. However, systematic variations of wing sweep, aspect ratio, taper ratio, and other configuration features were not evaluated in this study but should be addressed in any future evaluations of variable-camber airplanes.

Examination of variable camber on complete aircraft configurations was limited to applications for intercontinental and domestic versions of contemporary reference transport designs. The efforts directed toward both the variable camber devices and their aerodynamic capabilities consisted of parametric studies to provide information for subsequent design studies of the contemporary configurations. Therefore, general information necessary to define alternate transport configurations best suited for fully exploiting variable camber was limited. Wing size was allowed to vary from the reference design but planform shape and distribution of airfoil thickness ratio remained the same. Variable-camber devices were limited to the outboard 65 percent of the wing span with conventional high-lift devices retained over the thickened inboard sections configured for landing gear storage.

Based on this study, additional work in several areas is recommended:

1. Suitable theoretical and experimental investigations to evaluate the validity of the hypothesis on which the aerodynamic data are based.
2. With establishment of the validity of the aerodynamic hypothesis, new airplane design studies should be undertaken. These should include evaluations of wing design parameters such as sweep, thickness ratio, aspect ratio and taper ratio to help determine how best to exploit variable camber.
3. Development of excrescence drag data applicable to typical wing designs having a series of excrescences (gaps, forward or aft-facing steps, etc.), each experiencing the wakes of the upstream ones.

2.0 INTRODUCTION

Most aircraft today mechanically change their low-camber, high cruise speed wings into high-camber, low-speed wings for takeoff, landing, and other operations. To date, the methods used are characterized by leading-edge and trailing-edge slat and flap systems that, in general, move in large increments with associated undesirable steps and gaps in both the high-camber and low-camber positions. The result is an airfoil that is never quite optimum for every flight condition and an excrescence drag that is appreciable under all conditions.

A remarkable job of engineering has provided today's highly efficient civil transports with high ranges of speed and flight conditions. However, the spiraling cost of fuel requires renewed efforts to absolutely minimize the fuel consumed by these civil transports. In the area of camber-changing devices, structural and mechanical technology has advanced to where practical systems may be possible for changing the shape of an airfoil continuously and smoothly such that it is more nearly optimum for all flight conditions. The 747 leading-edge variable-camber Krueger flap system is an example of this technology wherein the camber of the flap changes from a flat surface when stowed to a curved airfoil when the flap is extended.

This report examines the potential advantages of replacing existing high-lift devices with devices capable of smoothly recontouring the leading- and trailing-edge surfaces in flight. This should enable the airplane to increase aerodynamic efficiency in all segments of flight, thus reducing fuel consumption and noise. The study emphasizes design and engineering analyses to determine the potential benefits and problems associated with variable-camber wings on domestic and intercontinental transports incorporating 1980-1982 technology. The objectives for this study were to:

- identify a variable camber concept with the potential to improve aircraft performance throughout all segments of the flight profile,

- assess potential variable-camber performance and economic benefits for transports entering airline service during 1982-1985,

- define technical uncertainties that would prevent industry from implementing the variable-camber concept and recommend research programs to remove such barriers.

3.0 SYMBOLS AND ABBREVIATIONS

AR	aspect ratio, b^2/S_{REF}
ATA	Air Transport Association
AVE	average
b	wing span
BL	buttock line
BLKF	block fuel
BPR	bypass ratio
c	airfoil chord
CAB	Civil Aeronautics Board
c_d	two-dimensional drag coefficient
C_D	drag coefficient
C_{D_p}	parasite drag coefficient
CG	center of gravity
c_ℓ	two-dimensional lift coefficient
C_L	lift coefficient
CLR	ratio of initial cruise lift coefficient capability to C_L for maximum lift/drag ratio
C_{L_S}	stall lift coefficient

$C_{L_{V_2}}$	lift coefficient at takeoff reference speed, V_2
c_n	normal-force coefficient
c_p	pressure coefficient
deg	degree
DOC	direct operating cost
E^3	Energy Efficient Engine Program (NASA)
EXCR	excrescence drag
FAR	Federal Aviation Regulation
FL	flight level
ICAC	initial cruise altitude capability
KEAS	knots equivalent airspeed
L/D	three-dimensional lift-to-drag ratio
LE	leading edge
$(\ell/d)_{MAX}$	maximum two-dimensional lift-to-drag ratio
LOWLAM	a computer program for determining low-speed aerodynamic characteristics
lb_f	pounds force
M	Mach number
MAC	mean aerodynamic chord

M_L	local Mach number
ML/D	Mach number times L/D
MTOW	maximum takeoff weight
MLW	maximum landing weight
MZFW	maximum zero fuel weight
OEW	operational empty weight
PASS	passengers
PD1	intermediate point-design baseline airfoil
PD2	low-camber airfoil
PD3	high-camber airfoil
rad	radian
RADEM	computer program for estimating high-speed aerodynamic characteristics
REF	reference airplane
R_N	Reynolds number
SAR	still air range
SFC	specific fuel consumption
SL	sea level
SLST	sea level static thrust
S_{REF}	reference wing area

STA	station
S_W	wing area
t/c	thickness-to-chord ratio
TE	trailing edge
TOFL	takeoff field length
TOGW	takeoff gross weight
TSLS	takeoff sea level static thrust
T/W	thrust-to-weight ratio
V_{APP}	approach speed
VC	variable camber
V_c	maximum operating cruise speed
V_S	FAR stall speed
V_∞	free-stream velocity
$\bar{V}_H$	horizontal tail volume coefficient
$\bar{V}_V$	vertical tail volume coefficient
W	weight
WL	water line
W/S	wing loading
x/c	chordwise station

x/c_{sep}	chordwise station at which separation occurs
W	wing angle of attack
Δ	increment
δ	deflection angle
δ_{AVE}	average deflection angle
δ_F	flap deflection
δ_{LE}	leading-edge deflection angle
δ_{TE}	trailing-edge deflection angle
η	semispan fraction
λ	taper ratio
$\Lambda_{c/4}$	sweep of quarter chord

4.0 VARIABLE-CAMBER CONCEPTS

The principal objective of the concept selection process was to investigate and propose variable-camber concepts that could potentially improve aircraft performance and still be economically practical. Preliminary mechanical and structural design studies were required to determine the feasibility and economic viability of the concept.

4.1 AERODYNAMIC CONCEPT SELECTION

The promise of variable camber lies in the potential ability to change an airfoil so as to simulate a variety of shapes. Since different airfoil shapes are required for optimum performance at low and high speeds, variable camber could provide the capability of continuously changing the camber of an airfoil to optimize the aerodynamic characteristics for any flight condition.

For this program, preliminary studies were made to determine high-speed aerodynamic performance possible with a practical variable-camber design. The performance was defined from experimental and analytical airfoil development studies previously conducted by The Boeing Company.

An advanced Boeing high-speed wing airfoil was selected for the reference configurations. This airfoil was developed by modifying a "point-design" high-speed airfoil (i.e., an airfoil optimized for a particular design normal-force coefficient and Mach number) to improve its off-design characteristics.

The original (unmodified) point-design airfoil was deficient in subcritical off-design characteristics in several regards: (1) it experienced significant drag creep and (2) it exhibited normal force curve breaks (commonly regarded as an indication of buffet onset) at relatively low normal force levels. The modifications were intended to delay the normal-force curve breaks to higher levels and to reduce or eliminate subcritical drag creep. As shown in Figure 1, these objectives were met, but only by reducing the drag-divergence Mach number. Thus, to achieve the same wing drag-divergence characteristic, the wing had to be slightly thinner, consequently heavier, than one based on the original point-design airfoil.

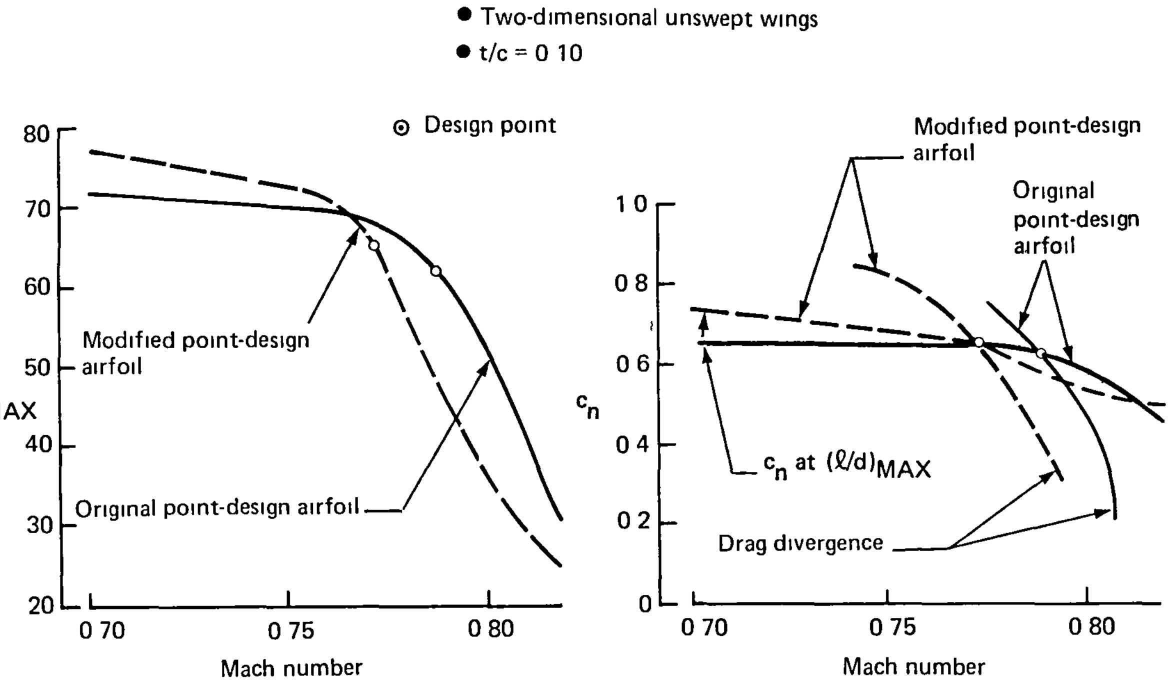


Figure 1. High-Speed Airfoil Aerodynamic Performance Comparison

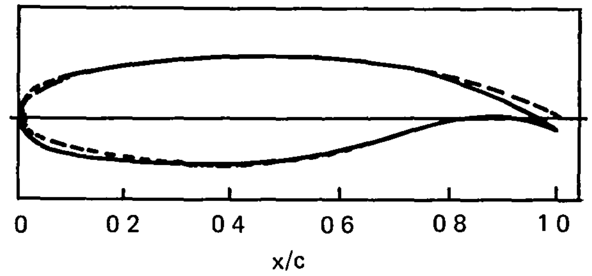
The pressure distribution of the original point-design airfoil is characteristic of an advanced high Mach design (i.e., "peaky" leading edge, low-crest super velocities, aft recovery, aft loading). This point-design airfoil is one of a family of three airfoils having different amounts of camber (fig. 2). The maximum L/D ratios of these three airfoils are plotted against Mach number in Figure 3. For this study, the optimum performance envelope for the variable-camber concept is defined as a line tangent to each maximum L/D curve, as shown in Figure 3.

The original point-design airfoil, having intermediate camber, was selected as the "basic" variable-camber airfoil (PD2 on fig. 3). The term "basic" is used to indicate that the leading- and trailing-edge portions are undeflected by the variable-camber mechanisms in this specific camber condition. As illustrated in Figure 4, the portions of the airfoil for which the camber can be varied are ahead of and behind the wing spars and are deflected on circular arcs. The desired airfoil characteristics defined in Section 5.2 indicate that the variable-camber leading-edge device could extend as far back as 25 percent of the wing chord, while the variable-camber trailing-edge device could extend as far forward as 55 percent of the wing chord without deviating appreciably from the airfoil shape desired.

• t/c = 0 10

Symbol	Airfoil	Camber	Design Mach	Design c_n
———	PD1	Intermediate	0 78	0 65
- - - - -	PD2	Low	0 82	0 49
— - - —	PD3	High	0 76	0 81

High-Speed Airfoil Shapes



Local Mach Number Distributions

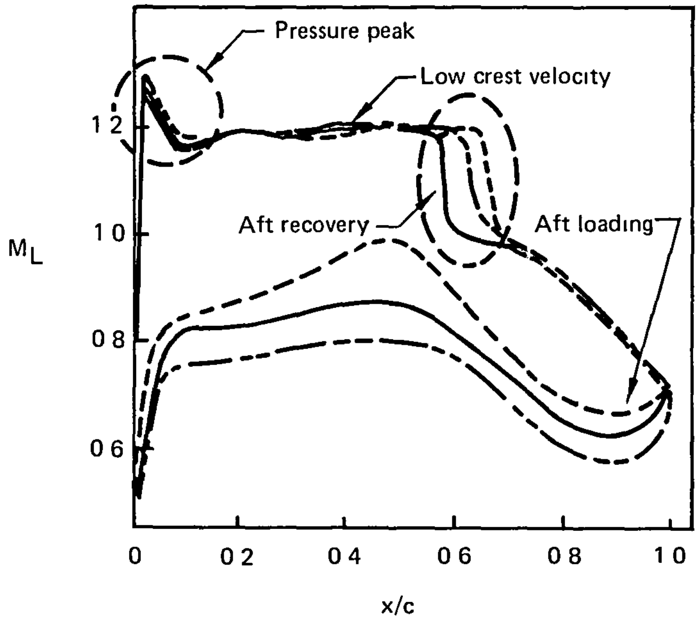


Figure 2. High-Speed Airfoil Point-Design Family

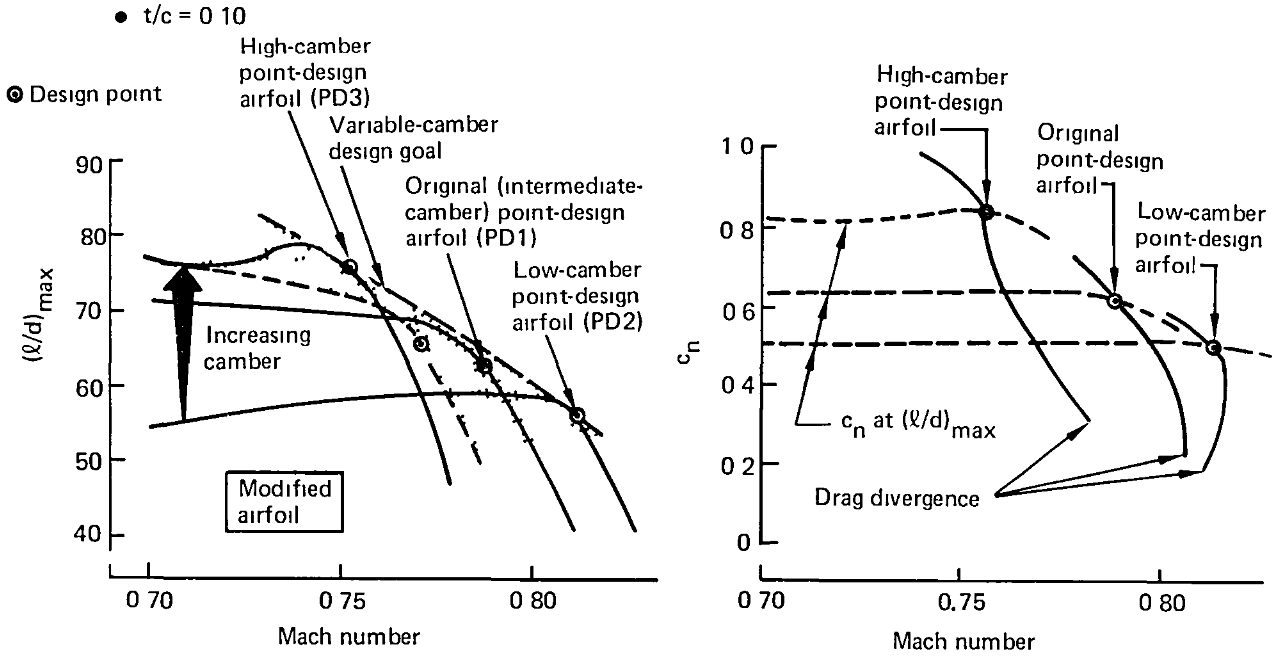
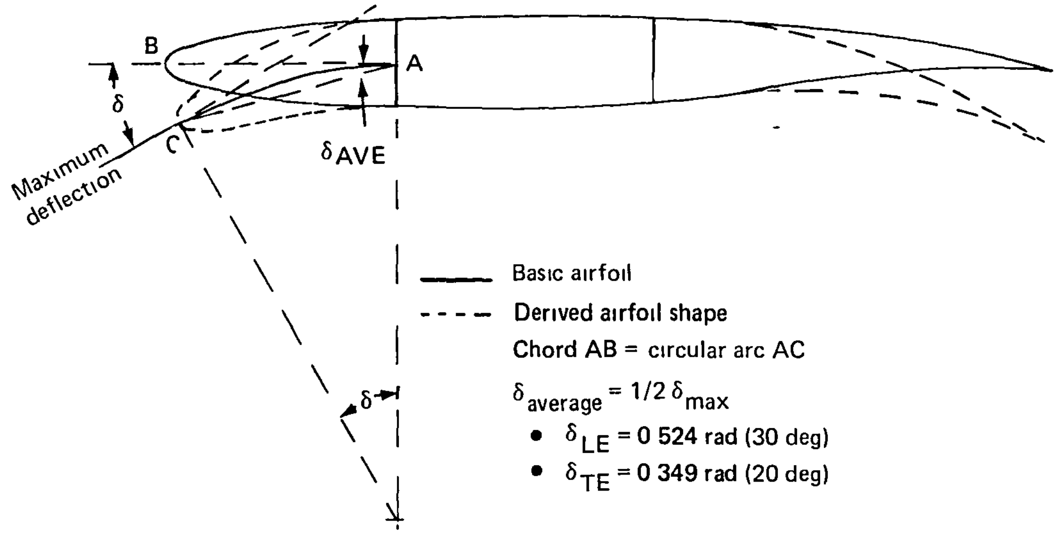


Figure 3. Variable-Camber High-Speed Aerodynamic Design Goal

The leading edge was required to change the airfoil camber from normal (zero deflection) to a maximum average deflection angle of 30 deg down. The trailing-edge requirements were to change the airfoil from normal flight to maximum average deflection angles of 15 deg up and 20 deg down. These requirements were compromises from an optimum design to satisfy the variable-camber requirements with a reasonably simple mechanism.

Because the actual flight characteristics of variable-camber devices are not fully understood, the "average" rather than the maximum surface deflection was used to estimate the low-speed flight performance. (When better analysis and/or wind tunnel test data are available, the low-speed performance characteristics can be better estimated.) The "average" deflection is defined as one-half of the maximum surface deflection as shown in Figure 4.

Airfoil Shape Deflections



Typical Low-Speed Deflections

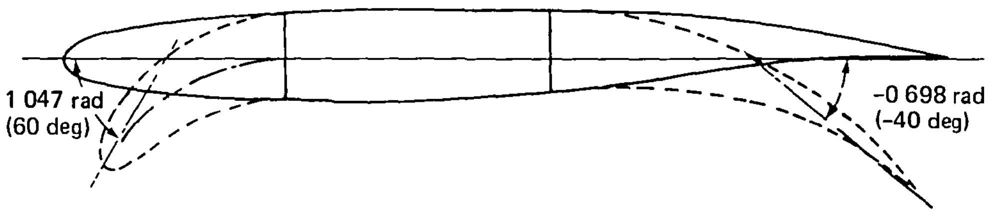


Figure 4. Scheme for Deriving Variable-Camber Airfoil Shapes

In the concept chosen for this study, the airfoil nose radius is essentially constant as the leading-edge is deflected. An alternative would be to increase the airfoil nose radius for leading-edge deflections representing the low-speed, high-lift configuration, but this should be achieved without increasing the design complexity of the system. The beneficial aerodynamic effect of increasing the nose radius was not assessed in this study.

Two-dimensional transonic flow analyses, including boundary layer effects, were made of both the low- and high-camber point-design airfoils and the corresponding variable-camber representations of these airfoils. Mach numbers ranging from M = 0.72 to 0.82 and lift coefficients (C_L) ranging from C_L = 0.55 to 0.8 were investigated for each airfoil. Pressure distribution and sonic-line comparisons, such as those in Figures 5 and 6, showed that the variable-camber representations of the low- and high-camber point-design airfoils were good.

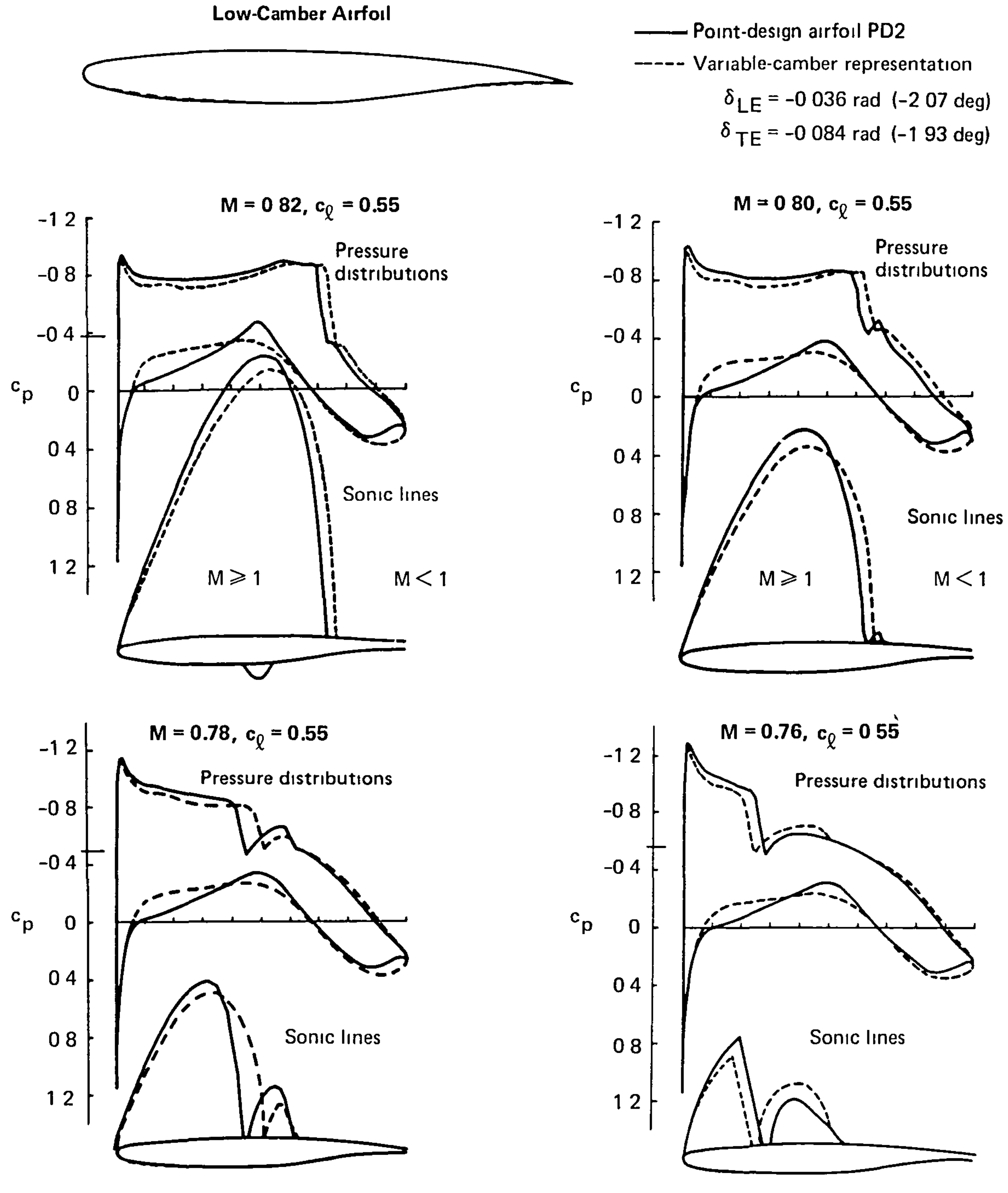


Figure 5. Variable-Camber Representation of Low-Camber Airfoil

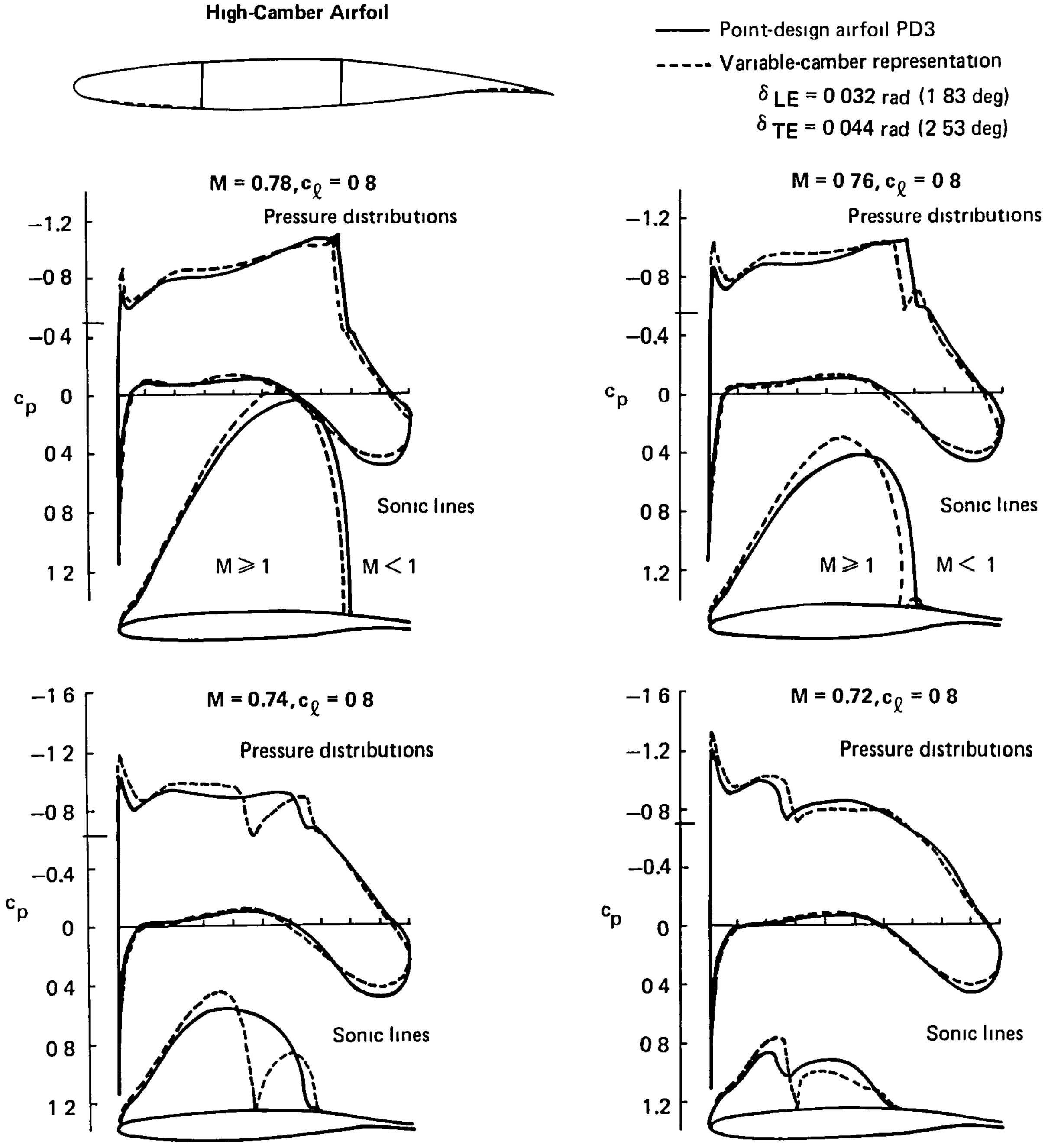


Figure 6. Variable-Camber Representation of High-Camber Airfoil

4.2 VARIABLE-CAMBER CONCEPTS

Variable-camber concepts available from earlier studies, including Reference 1, were examined for conformance to the design objectives established for this study and listed below:

- smooth, continuous airfoil surfaces for lower cruise drag
- a mechanism capable of deflections adequate to meet approach high-lift requirements
- lightweight structure and mechanisms
- adequate fuel volume in wing box
- high reliability and low maintenance

After preliminary evaluations, specific leading- and trailing-edge concepts were selected for further development as discussed in subsections 4.2.1 and 4.2.2.

4.2.1 LEADING-EDGE CONCEPT

An extremely efficient mechanism, an A-frame lying horizontally (fig. 7), was developed as the basic linkage for the leading-edge variable-camber concept. The upper leg is attached near the spar, and the lower leg is driven up and down with a rotary actuator arm located near the front spar. The upper and lower skins and the leading-edge radius are attached to the mechanism by spanwise stringers and short links. As the leading edge moves down, the upper surface becomes longer, forward and aft, while the lower surface becomes shorter. The overall length of the skin surface forward of the front spar remains the same without breaks or overlaps. The upper and lower surfaces are fiberglass, but the leading-edge radius is stainless steel or titanium for flexibility and erosion resistance. The lower surface contains a removable panel for inspection and maintenance, and a clearance hole is located in the mechanism supports for a hot-air anti-icing duct.

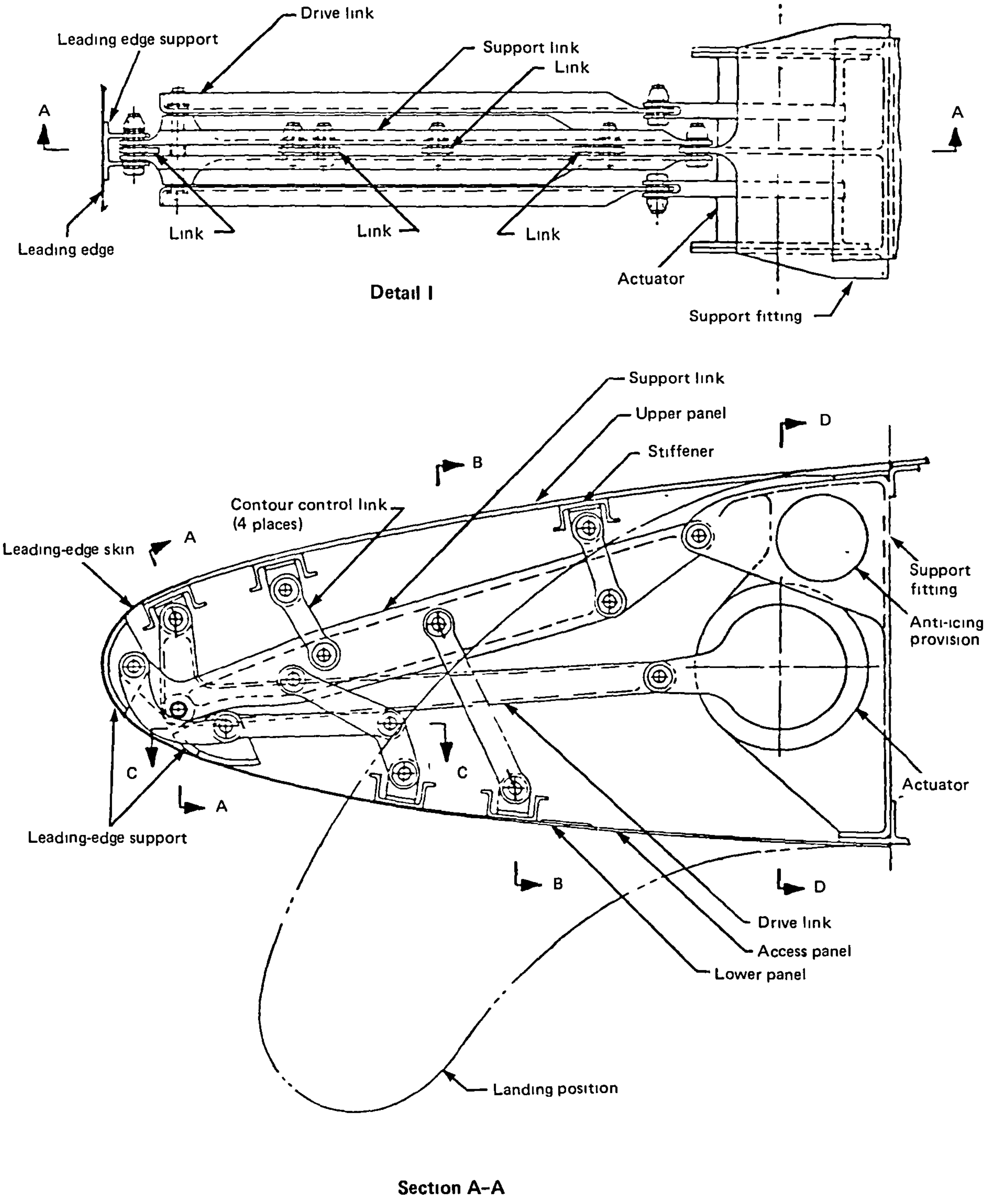


Figure 7. Variable-Camber Leading-Edge Concept

4.2.2 TRAILING-EDGE CONCEPT

The trailing-edge concept, shown in Figure 8, uses a basic mechanism of a four-bar linkage driven by a rotary actuator. The upper and lower fiberglass skins are attached to the four-bar linkages with spanwise stringers and short links. The trailing-edge wedge segment beyond the mechanism is honeycomb, and the upper surface is continuous. The lower surface has overlapping sealed surfaces to allow articulation of the mechanism. The lower panels are removable for inspection and maintenance.

As discussed in Section 6, the variable-camber domestic airplane was found to have insufficient lift capability to meet the approach speed requirement unless the wing area was greater than that of the domestic reference airplane. Consequently, to avoid increasing the wing area, a second domestic variable-camber airplane was studied with double-slotted, trailing-edge flaps to obtain higher approach C_L levels.

To attain the potential high-speed aerodynamic benefits of variable camber, the trailing edge must have variable camber with the double-slotted flaps retracted. To achieve variable-camber capability, the main flap (and nested aft flap) rotates about a pivot attached to the flap extension mechanism. The spoiler then follows both upward and downward deflections to provide a smooth upper surface.

4.2.3 DRIVE MECHANISMS

Two sets of mechanisms drive each flap segment with spanwise shafts connecting both mechanisms. All pivot points are self-aligning teflon-lined bearings to provide maintenance-free, lifetime durability and a close tolerance fit. During normal high-speed operation, the flaps are nested, and the spoiler is locked down by its actuation mechanism. The airfoil camber then is varied with an electromechanical actuator (section A-A, fig. 9) inside the main flap. Rotating the flap up forcibly deflects the spoiler (the base of the spoiler is held rigid by a spoiler mechanism), giving a smoothly contoured airfoil with decreasing camber. The spoiler and main flap mountings are designed so the maximum airfoil camber position is the fixed rest position with no pressure between the main flap and spoiler. Shown here with double-slotted flaps, this concept is also applicable to single-slotted or triple-slotted flaps.

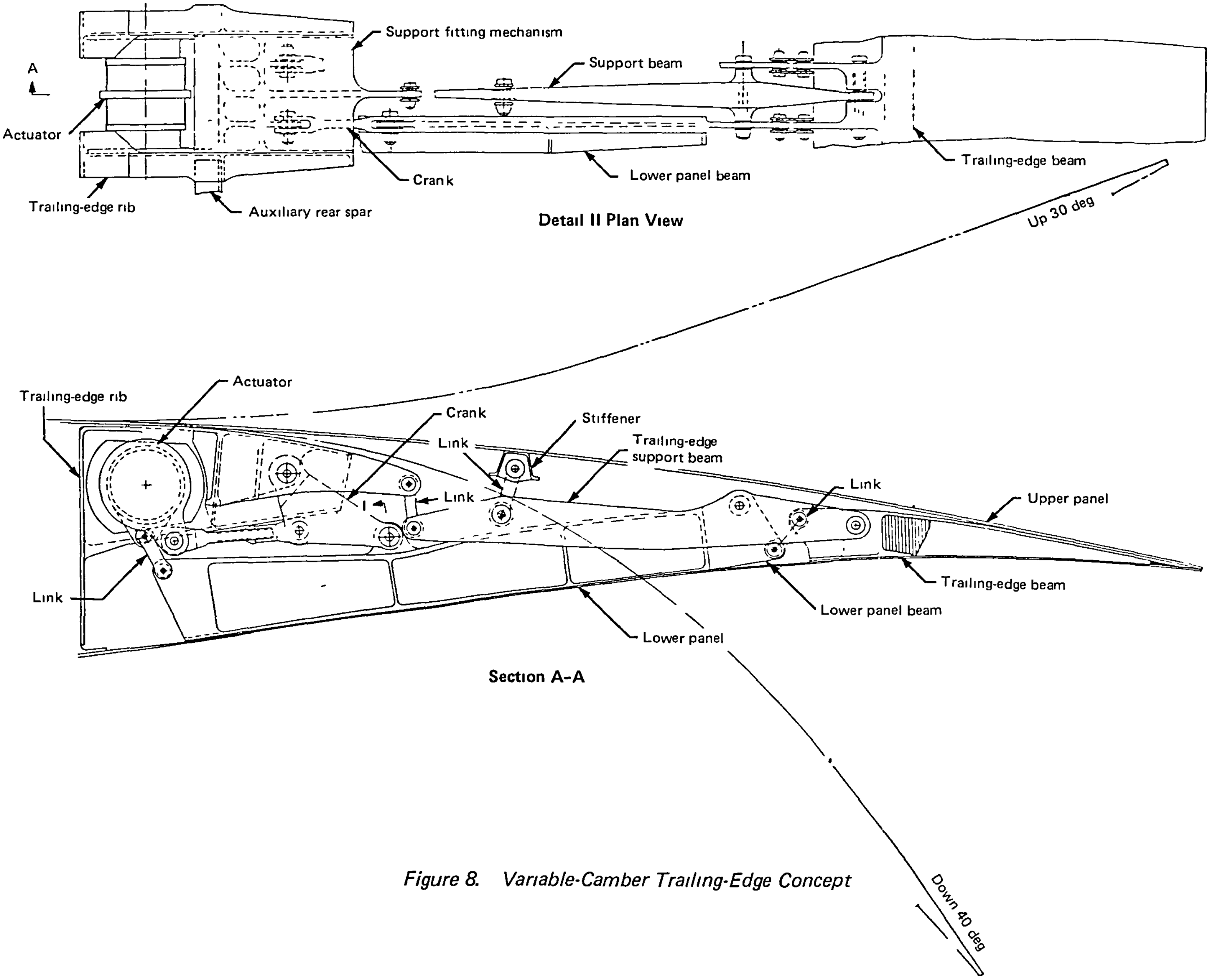


Figure 8. Variable-Camber Trailing-Edge Concept

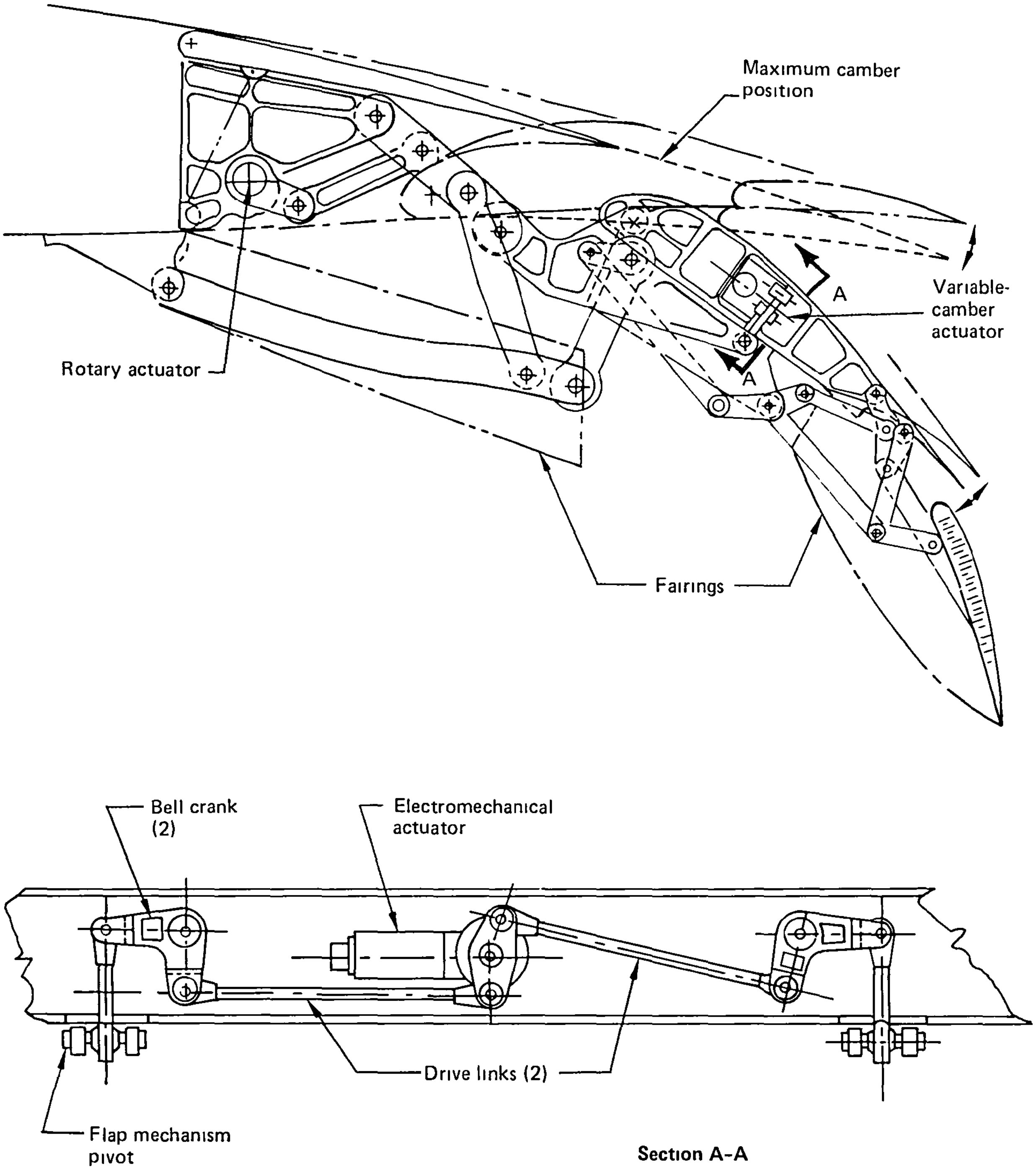


Figure 9. Double-Slotted Variable-Camber Flap

5.0 MISSION SELECTION AND CONFIGURATION DEFINITION

Mission requirements and configuration characteristics were selected to be representative of the next generation of commercial transports. Based upon examinations of available marketing information, future airplane markets are expected to be similar to current markets; i.e., similar sizes of airplanes flying familiar routes and schedules. This prediction is based on the premise that the air-traveling community in the 1980s will be about the same percentage of the total population as today's air travelers, with a small (4 to 6 percent) annual incremental growth. These data suggest a mid-1980s market for many replacement aircraft in the 180- to 220-passenger range, with either intercontinental- or domestic-range capability. The design missions (table 1) were selected for typical intercontinental (long-range) and domestic (medium-range) missions to demonstrate the benefits of variable camber. The ranges for these missions were 10 200 km (5500 nmi) and 3700 km (2000 nmi), respectively. Reference configurations developed for each mission served as the basis for assessing the potential benefits of variable camber.

5.1 INTERCONTINENTAL AND DOMESTIC COMMERCIAL TRANSPORTS--REFERENCE CONFIGURATIONS

Since the missions selected for this study coincided with those of the Reference 2 NASA Energy Efficient Engine (E^3) studies with well-defined baseline configurations, the same reference transport configurations were used for this study.

The development method used to design each study configuration is shown in Figure 10. The initial design data (step 1 on fig. 10) presented in the previous section were used to create two reference-configuration drawings (step 2) with enough detail for analysis of airplane weight, aerodynamic, and performance characteristics (step 3). During the interior-definition phase, the payload was determined to be 196 passengers on both configurations. These data then were used in the engine/airframe matching analyses (steps 4 and 5) to determine the best combination of engine size, wing size, fuel requirements, and gross weight necessary to achieve the design mission objectives.

Table 1. Design Missions for Typical Domestic and Intercontinental Airplanes

Mission	Intercontinental airplane		Domestic airplane	
Design range, km (nmi)	10 200	(5 500)	3 700	(2 000)
Passenger payload (15/85 mix)	200		200	
Cruise Mach	0.80		0.80	
TOFL, m (ft)	3 500	(11 500)	2 300	(7 500)
Initial cruise altitude, m (ft)	10 100	(33 000)	10 700	(35 000)
V_{APP} at mission landing weight, m/s (KEAS)	69.5	(135)	64.3	(125)

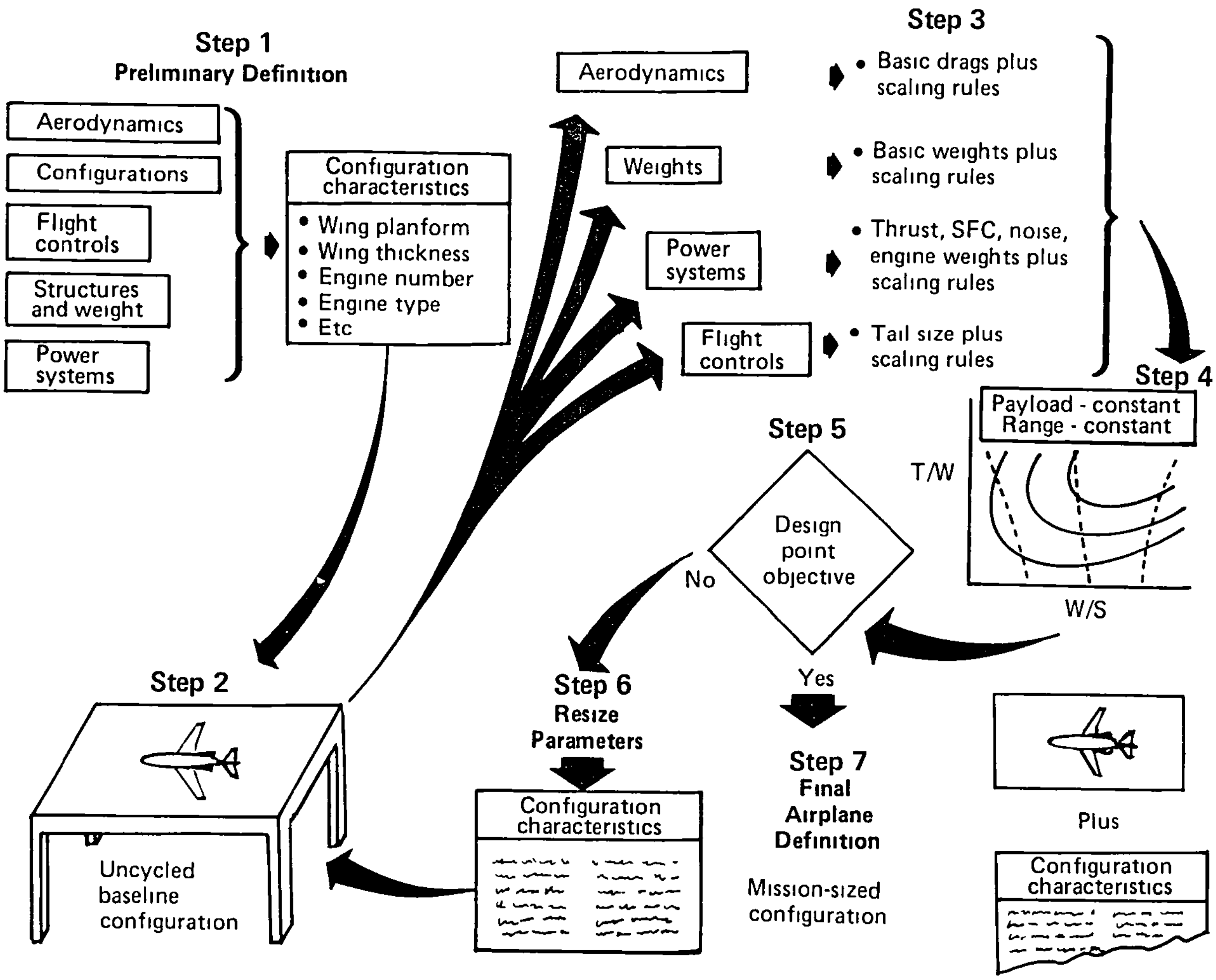


Figure 10 Design Development Method

The design selection charts for the reference airplanes are shown in Figures 11 and 12. This type of design chart parametrically shows the effect of thrust/weight ratio (T/W) and wing loading (W/S) on airplane gross weight and block fuel requirements. Performance characteristics, such as takeoff field length (TOFL), mission landing approach speed (V_{APP}), and initial cruise altitude capability (ICAC) are included. The ratios of the initial cruise C_L capability to the C_L for maximum lift/drag ratio (CLR) also are identified. Design mission constraints imposed on these charts separate the areas of acceptable and unacceptable configuration designs.

As shown in Figure 11, the final reference intercontinental airplane was selected by optimizing the gross weight along the initial altitude constraint line. The final design for the reference domestic airplane was selected by considering the trade between fuel burned and gross weight along the TOFL constraint line as shown in Figure 12. Three-view drawings of these airplanes are shown in Figures 13 and 14. The mission-sized airplane characteristics are summarized in Figure 15; a more detailed weight breakdown is given in Table 2. These reference airplanes are compared with the corresponding variable-camber airplanes in Section 7.

5.2 INTERCONTINENTAL AND DOMESTIC COMMERCIAL TRANSPORTS-- VARIABLE-CAMBER WINGS

The variable-camber configurations were developed from their respective reference configurations. Variable-camber leading- and trailing-edge devices were applied only to the outboard sections of span for several reasons. First, the wing thickness-to-chord ratio (t/c) increases rapidly over the inboard 30 percent of wing span to minimize the structure (and weight) required to carry wing bending loads. Incorporating variable-camber design into the leading edge in this region would involve bending thick double-curvature surfaces, which would greatly increase loads and complexity. Second, the landing gear beam extends aft of the rear spar in this region so that a variable-camber trailing-edge device would have to be limited to approximately 20 percent of wing chord. Third, the possible benefits of variable-camber wings are difficult to assess in this region of the wing where

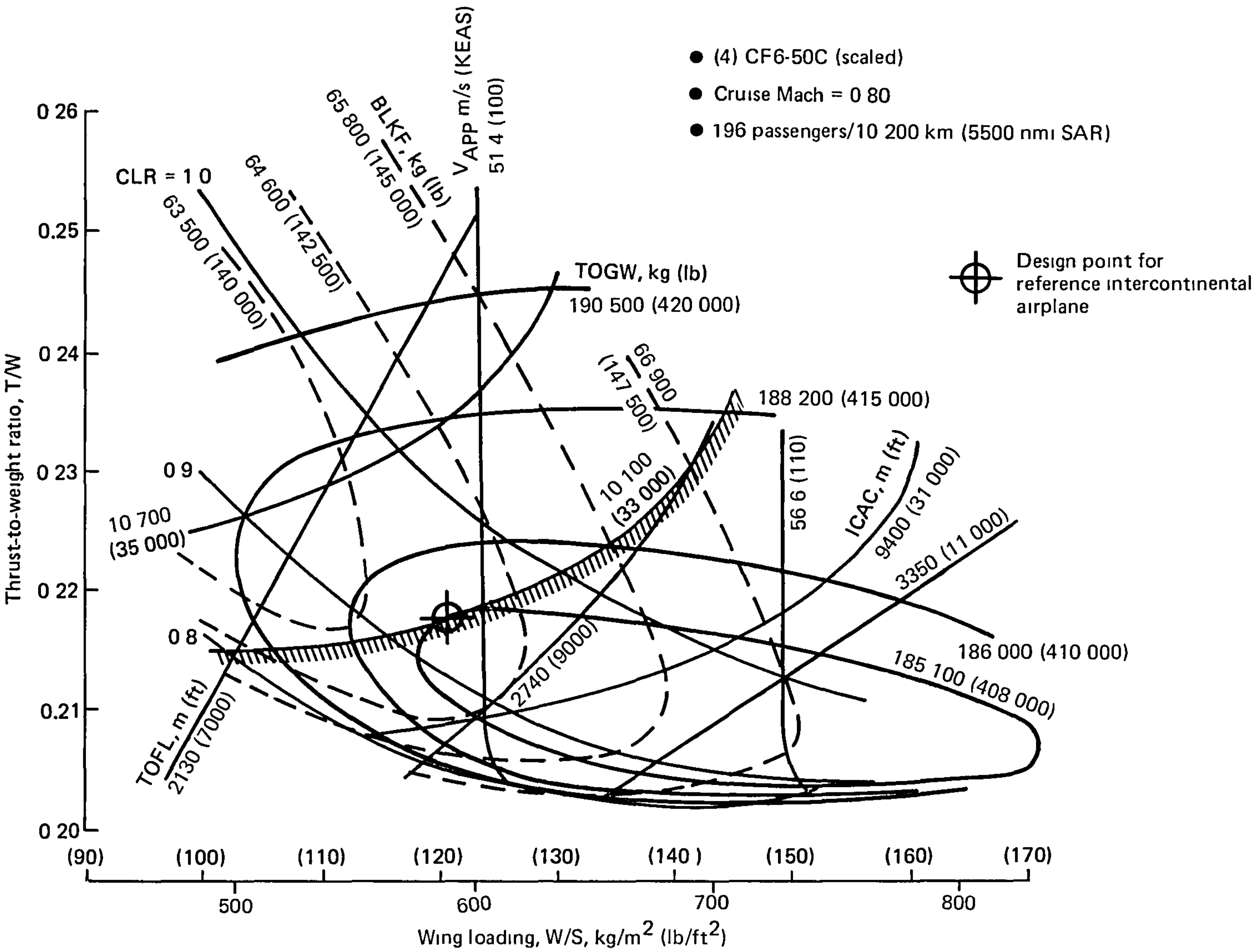


Figure 11. Reference Intercontinental Airplane Design Selection Chart

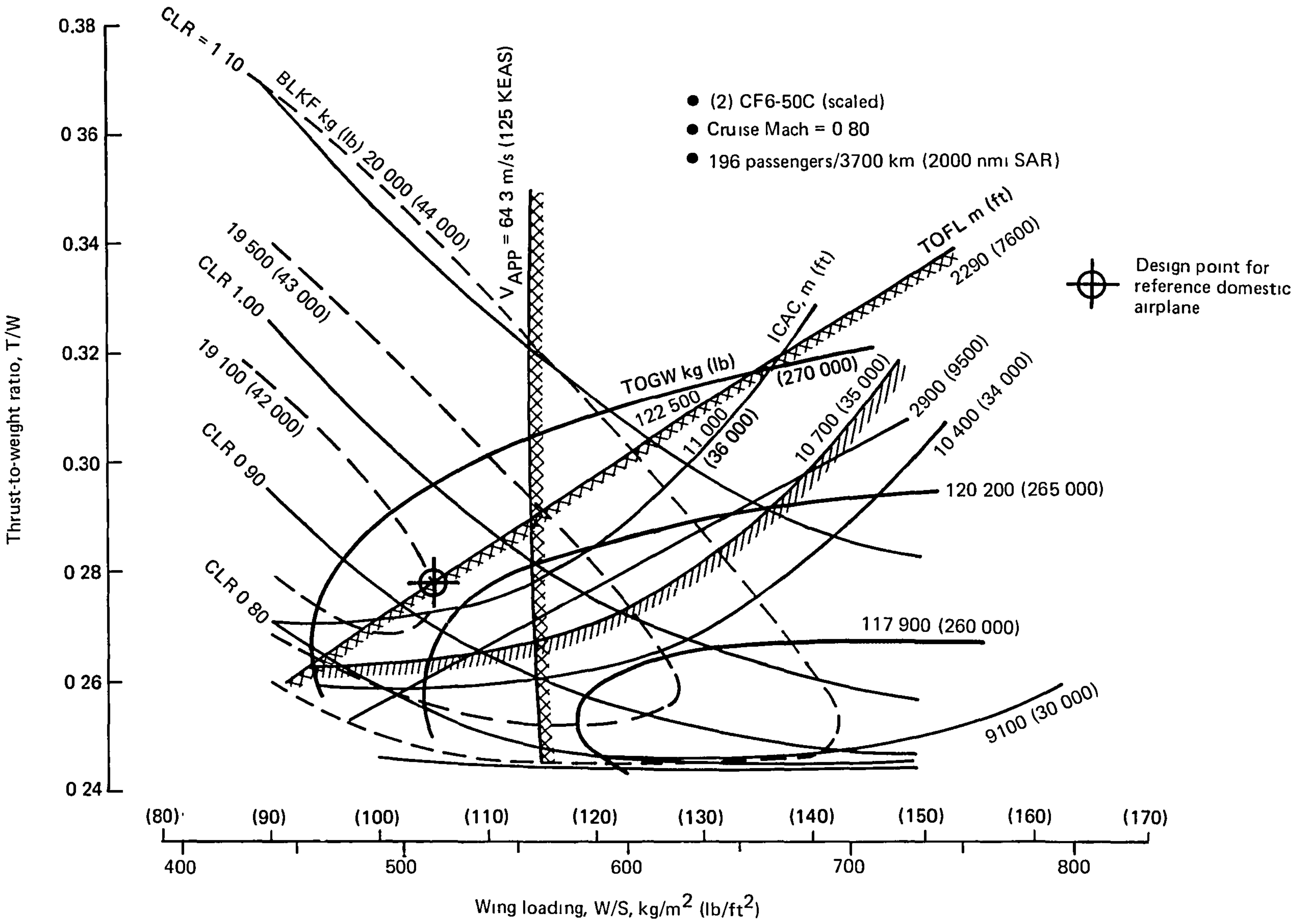
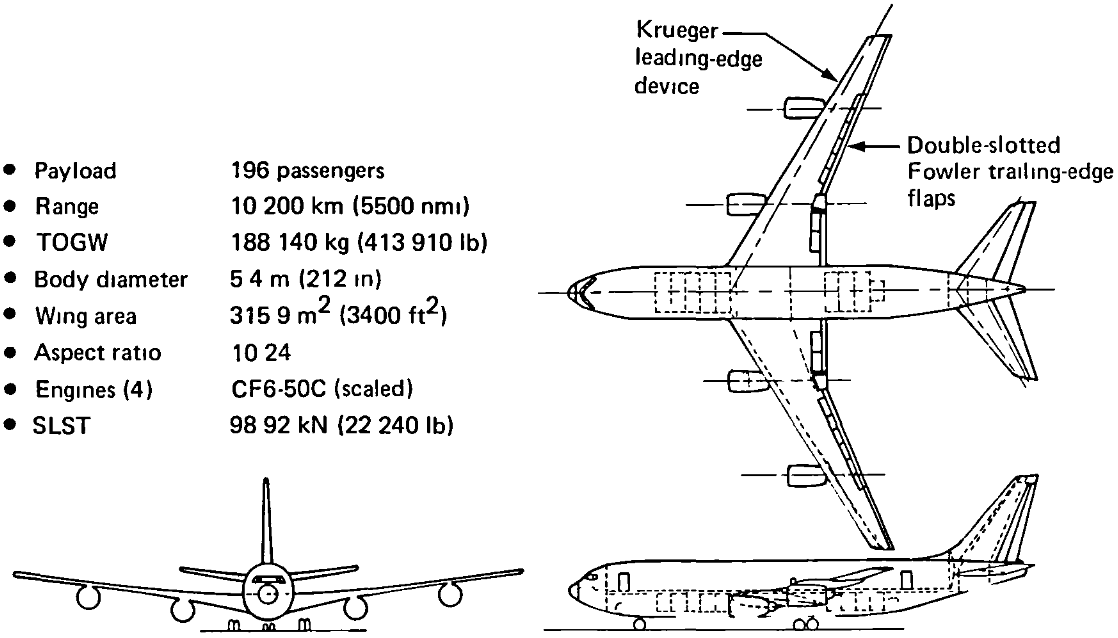
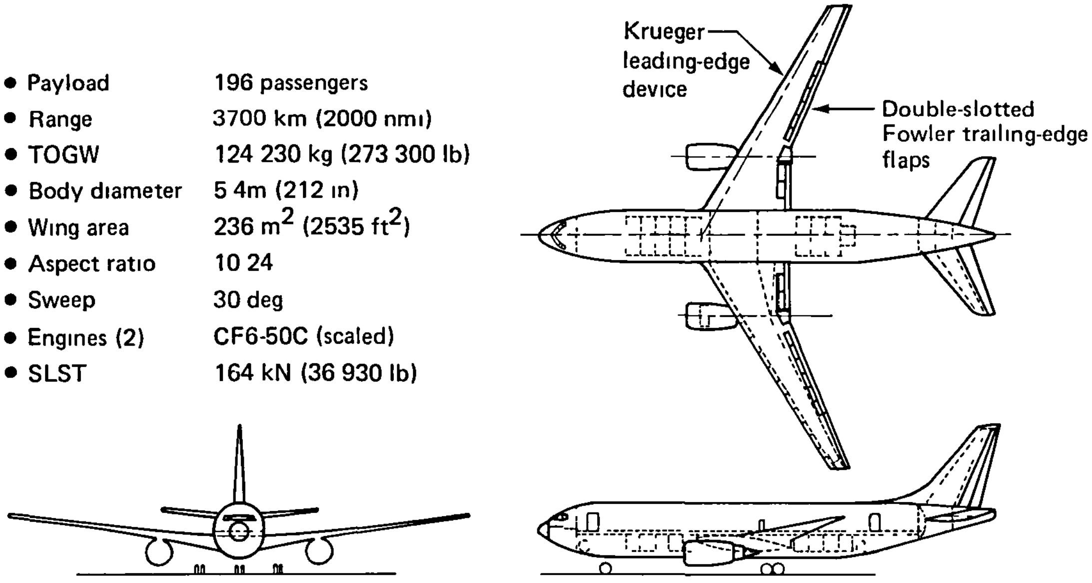


Figure 12. Reference Domestic Airplane Design Selection Chart



• Payload	196 passengers
• Range	10 200 km (5500 nmi)
• TOGW	188 140 kg (413 910 lb)
• Body diameter	5 4 m (212 in)
• Wing area	315 9 m^2 (3400 ft^2)
• Aspect ratio	10 24
• Engines (4)	CF6-50C (scaled)
• SLST	98 92 kN (22 240 lb)

Figure 13. Intercontinental Airplane Reference Configuration



• Payload	196 passengers
• Range	3700 km (2000 nmi)
• TOGW	124 230 kg (273 300 lb)
• Body diameter	5 4m (212 in)
• Wing area	236 m^2 (2535 ft^2)
• Aspect ratio	10 24
• Sweep	30 deg
• Engines (2)	CF6-50C (scaled)
• SLST	164 kN (36 930 lb)

Figure 14. Domestic Airplane Reference Configuration

Item		Intercontinental	Domestic
Design mission	Payload kg (lb)	196 Passengers 18 850 (41 550)	196 Passengers 18 230 (40 180)
	Range km (nmi)	10 200 (5500)	3700 (2000)
	Mach number	0 80	0 80
Wing type		Conventional	Conventional
Weights, kg (lb)	TOGW	187 750 (413 910)	123 970 (273 300)
	OEW	92 290 (203 470)	76 860 (169 450)
	Block fuel	66 750 (147 150)	20 740 (45 720)
Wing	Reference arêa, m^2 (ft^2)	315 9 (3400)	235 5 (2535)
	'W/S, Pa (lb/ft^2)	5840 (122)	5170 (108)
Engine	SLST, N (lb)	98 930 (22 240)	164 270 (36 930)
	T/W	0 2149	0 2703
	Type	CF6 50C	CF6 50C
	Number	4	2
	BPR	4 40	4 40

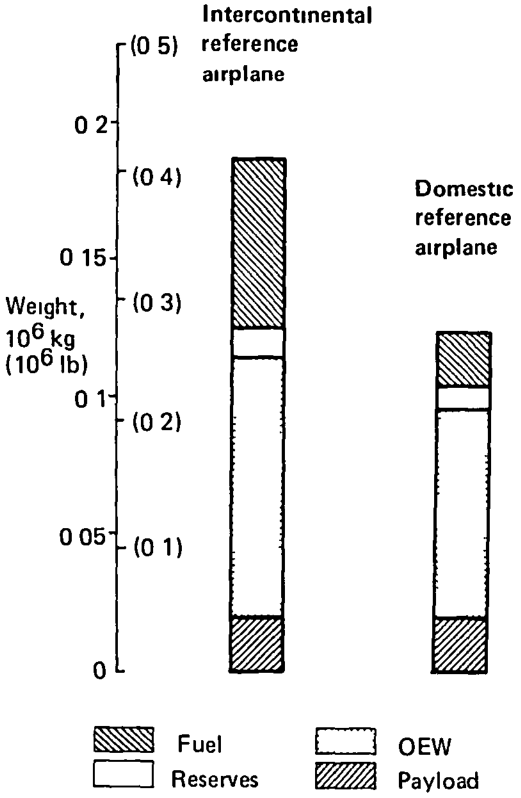


Figure 15. Sized Reference Airplane Characteristics

Table 2. Reference Airplane Weights

Item	Intercontinental airplane		Domestic airplane	
	kg	(lb)	kg	(lb)
Wing	24 030	(52 980)	16 660	(36 720)
Empennage	3 200	(7 050)	2 410	(5 320)
Body	17 110	(37 720)	16 050	(35 380)
Nacelle	4 620	(10 180)	4 020	(8 870)
Gear	7 340	(16 180)	6 440	(14 200)
Total structure	56 300	(124 110)	45 580	(100 490)
Propulsion system	7 700	(16 970)	6 760	(14 900)
Fixed equipment and options	20 040	(44 190)	19 350	(42 660)
Standard and operational items	8 250	(18 200)	5 170	(11 400)
OEW	92 290	(203 470)	76 860	(169 450)
MZFW	124 350	(274 140)	104 340	229 962
MLW	134 650	296 240	108 730	239 200
MTOW	187750	(413 910)	123 970	(273 300)

airfoil thickness distribution varies rapidly with spanwise location and where the flow is influenced by body interference effects. For these reasons, variable-camber devices were limited to the outboard 65 percent of the wing span, and conventional high-lift devices were used inboard next to the body.

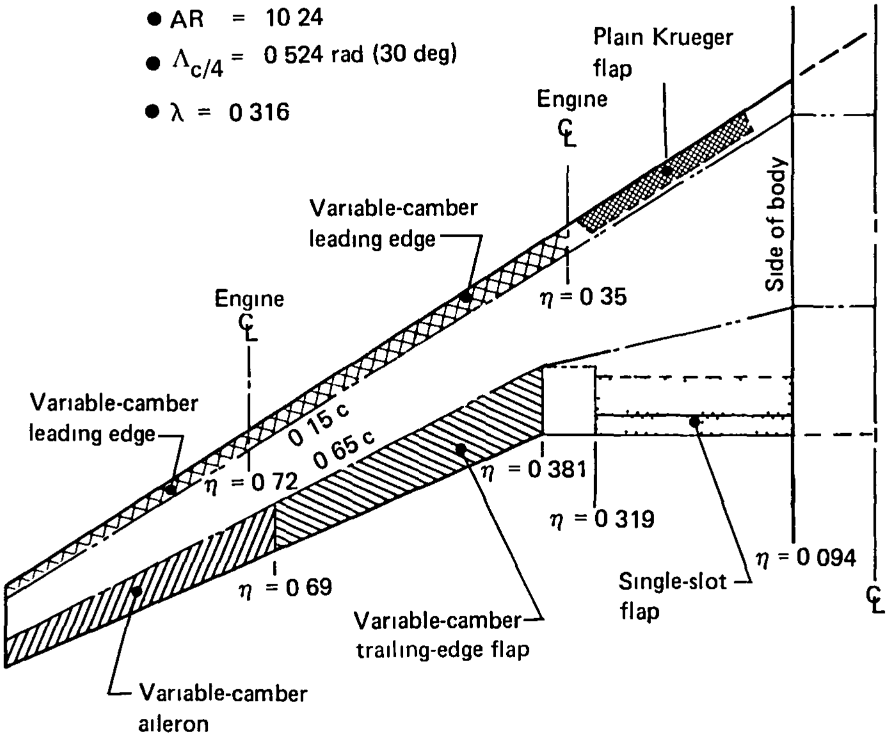
The same front spar location was retained for both the reference and variable-camber airplanes. The front spar is a constant distance from the leading edge (as contrasted to the constant-percent-chord spar used in the parametric studies). As with the reference airplane, a constant chord leading-edge device reduces production costs (through multiple use of leading-edge device parts) and increases stall protection for the outboard wing.

The rear spar is located on a constant-percent-chord line: 65 percent for the intercontinental airplane, and 60 percent for the domestic airplane. The rear spar location is identical for the intercontinental variable camber and reference airplanes, but the rear spar of the domestic variable-camber airplane was moved forward 5 percent to enhance high-lift capability. The resultant wing planforms are shown in Figure 16.

As discussed in Section 6, the domestic airplane required more wing area than the conventionally-flapped airplane to meet the 125 kn approach speed. Therefore, a second domestic airplane was configured with a double-slotted trailing-edge flap to meet the low-speed requirement and with a wing area identical to that of the reference domestic airplane. The first and second domestic variable-camber airplanes have been designated A and B, respectively.

The variable-camber airplanes (intercontinental, domestic airplanes A and B) are shown on Figures 17, 18, and 19, respectively. The initial 0.524 rad (30 deg) wing sweep of all the airplanes was retained because of the uncertainty of the weight penalty as the wing was unswept, even though aerodynamic trade studies indicate potential performance benefits. The overall effect of sweep on a variable-camber airplane can be quantified only with a comprehensive optimization study incorporating Mach number, wing thickness, camber, and twist distributions, plus a detailed aeroelastic analysis for reduced sweep. Such a developmental effort was not addressed in this study. The sizing constraints and objectives were the same as those described in Section 4. The

Intercontinental Airplane



Domestic Airplane

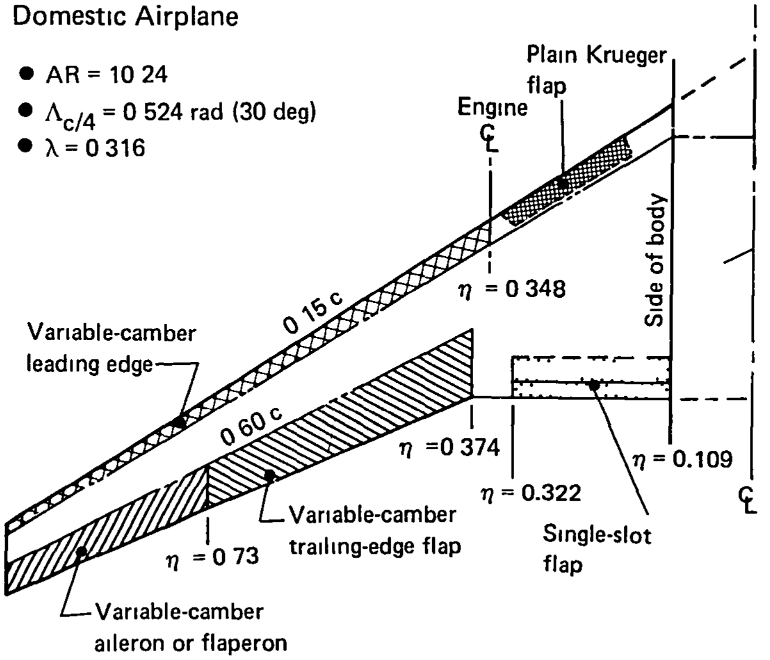
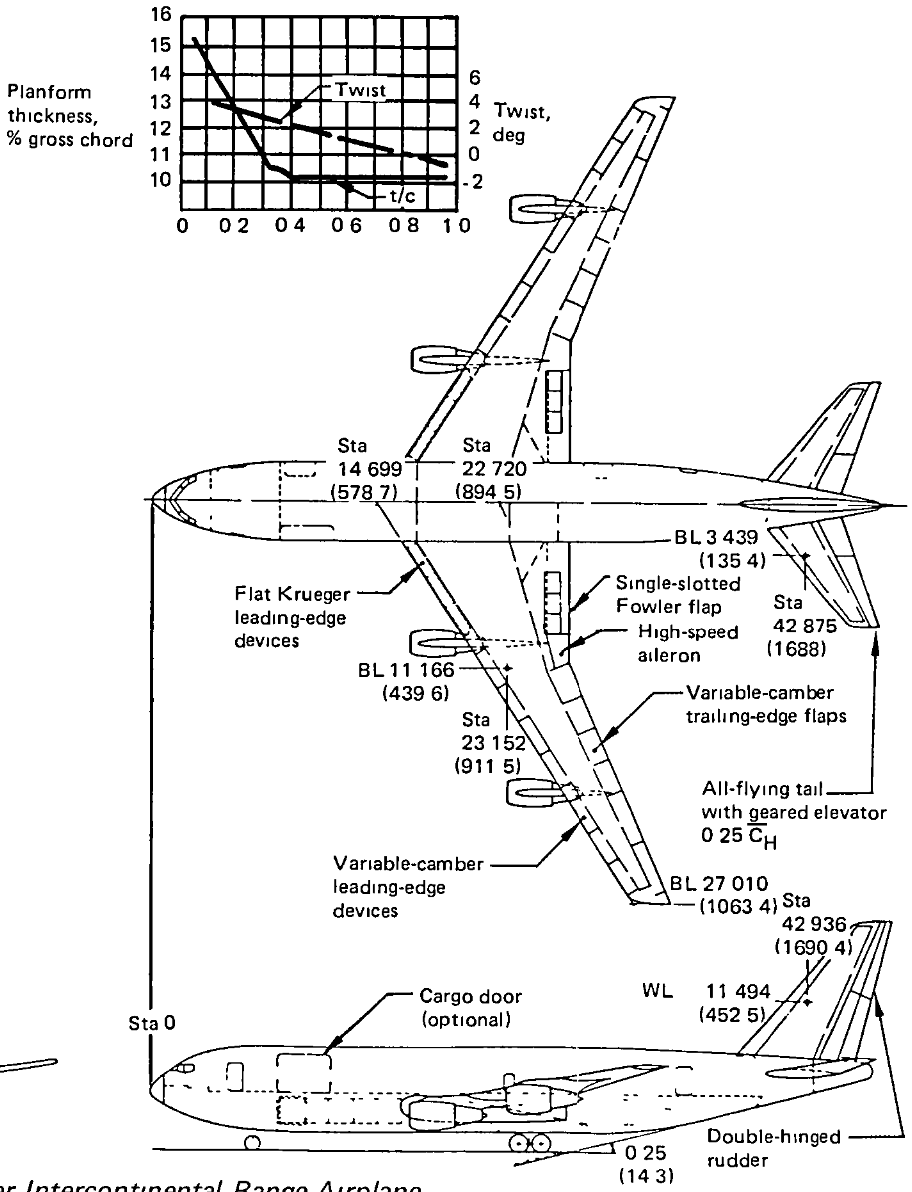


Figure 16. Variable-Camber Airplane High-Lift Systems

Long range				
Weights	TOGW	Payload	OEW	
kg (lb)	181 290 (399 700)	196 passengers	90 830 (200 200)	
Surfaces	Wing	Horizontal	Vertical	
Area m^2 (ft^2)	285 1 (3068 8)	67 2 (723 33)	45 1 (485 45)	
Aspect ratio AR	10 24	4	1 8	
Taper ratio	0 3154	0 35	0 30	
LE sweep rad (deg)	0 524 (30)	0 611 (35)	0 611 (35)	
Incidence rad (deg)	0 079 SOB (4 53)	–	–	
Dihedral rad (deg)	0 131 (7 5)	0 122 (7 0)	–	
t/c %	15 root 10 3 tip	11 root 9 tip	11 5 root 8 5 tip	
MAC (C_{ref}) m (in)	5 752 (226 57)	4 432 (174 49)	5 486 (216 0)	
Span m (in)	54 032 (2127 2)	16 393 (645 40)	9 007 (354 6)	
Tail arm m (in)	–	20 462 (805 60)	20 196 (795 12)	
Tail vol coeff V	–	0 819	0 050	
Body	Length, m (in)	Max dia, m (in)		
	47 55 (1877 05)	5 38 (212)		
Powerplants	Number	Type	SLST	BPR
	4	CF6 50C	95 3 kN (21 420 lb)	4 3
Landing gear	Nose	Main		
	(2) 37x14	(8) 49x19	€	



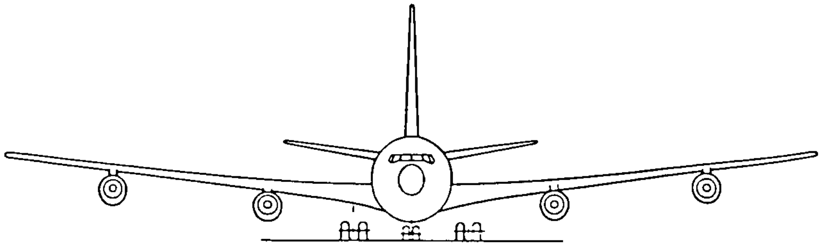
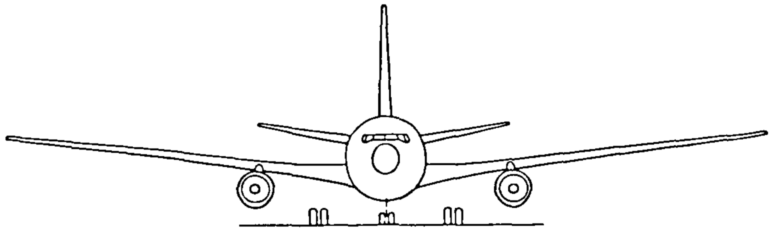


Figure 17. Variable-Camber Intercontinental Range Airplane

Weights kg (lb)	TOGW	Payload	OEW	
	125 900 (277 500)	196 passengers	79 600 (175 500)	
Surfaces	Wing	Horizontal	Vertical	
Area m^2 (ft^2)	252 1 (2713 6)	54 6 (587 7)	37 7 (405 8)	
Aspect ratio AR	10 24	4	1 8	
Taper ratio λ	0 3158	0 35	0 30	
LE seeep rad (deg)	0 524 (30)	0 611 (35)	0 611 (35)	
Incidence rad (deg)	0 079 (4 53)	–	–	
Dihedral rad (deg)	0 131 (7 5)	0 122 (7 0)	–	
t/c %	15 root 10 3 tip	11 root 9 tip	11 5 root 8 5 tip	
MAC (C_{ref}) m (in)	5 444 (214 33)	3 978 (156 6)	5 020 (197 64)	
Span m (in)	50 807 (2000 3)	14 772 (581 57)	8 240 (324 4)	
Tail arm m (in)	–	20 461 (805 55)	20 199 (795 236)	
Tail vol coeff	–	0 819	0 059	
Body	Length m (in)	Max dia, m (in)		
	47 549 (1872)	5 385 (212)		
Powerplants	Number	Type	SLST	BPR
	2	CF6 50C	170 1 kN (38 240 lb)	4 3
Landing gear	Nose	Main		
	(2) 37x14	(8) 49x19		



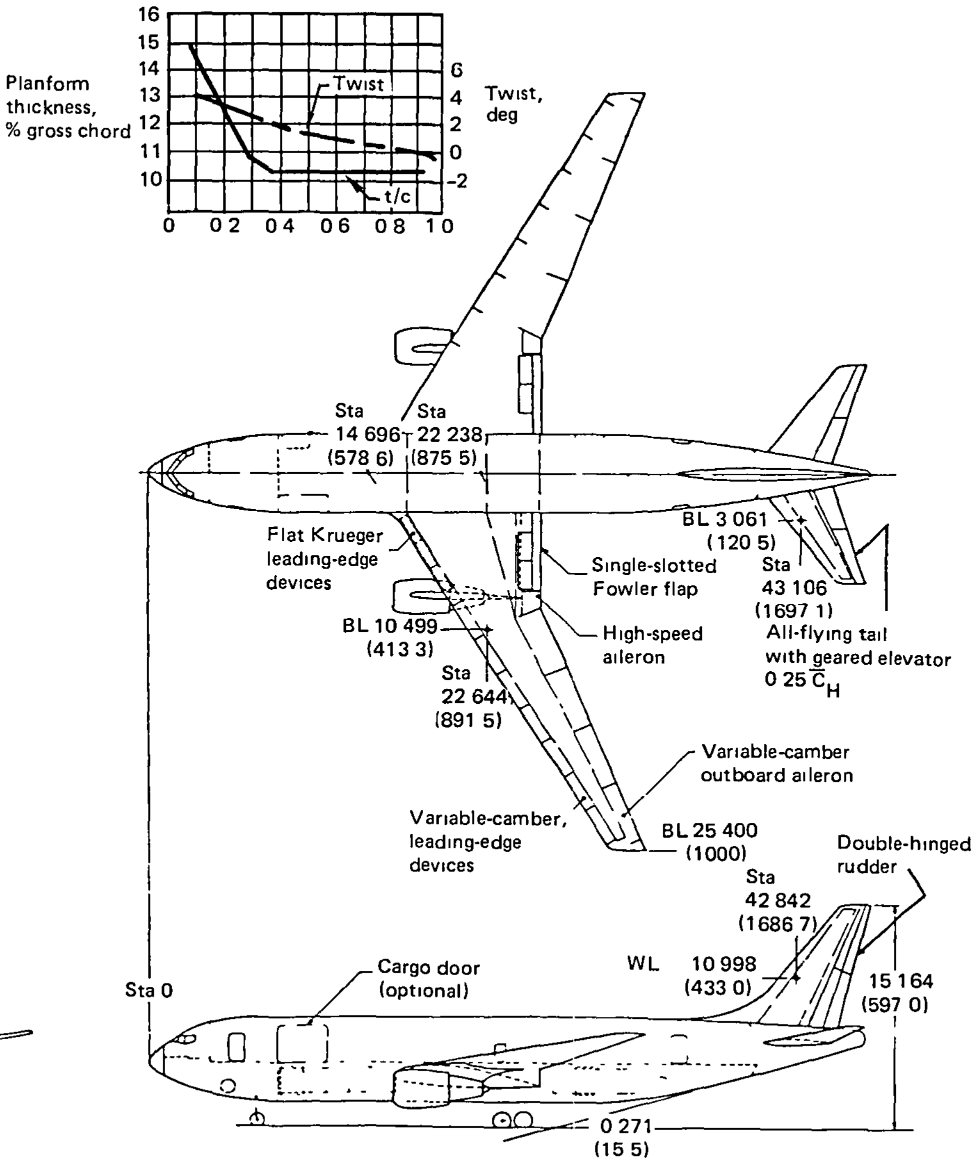
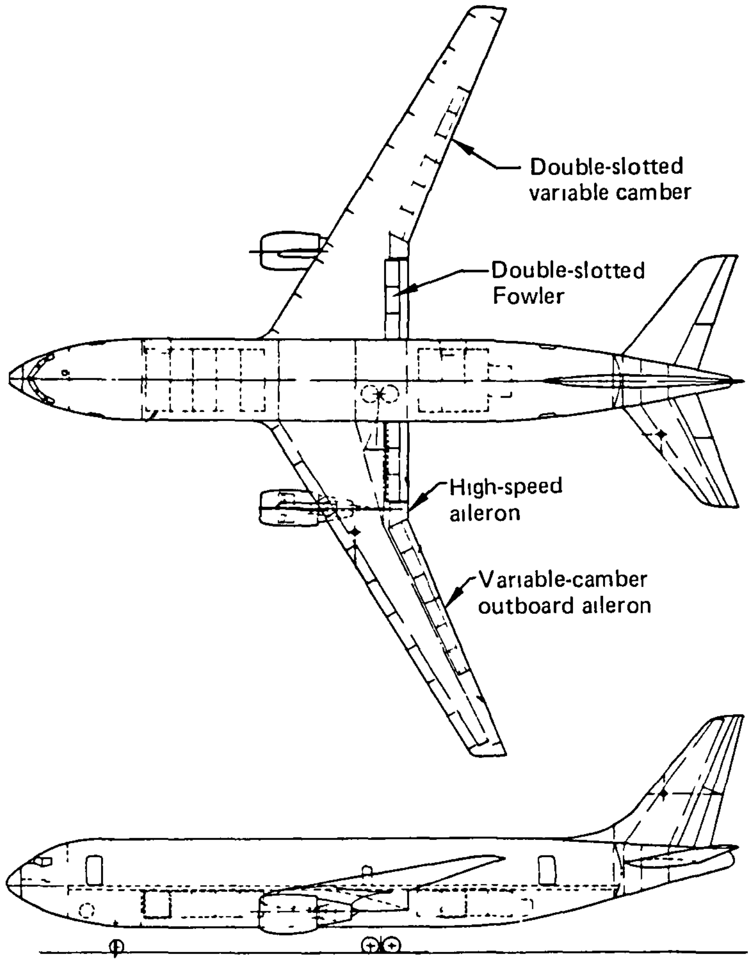


Figure 18. Variable-Camber Domestic Airplane A

Weights kg (lb)	TOGW	Payload	OEW	
	124 120 (273 700)	196 passengers	77 160 (170 140)	
Surfaces	Wing	Horizontal	Vertical	
Area m^2 (ft^2)	236.0 (2540)	51 7 (557)	36 1 (389)	
Aspect ratio AR	10 24	4	1 8	
Taper ratio λ	0 3158	0 35	0 30	
LE sweep rad (deg)	0 524 (30)	0 611 (35)	0 611 (35)	
Incidence rad (deg)	0 079 (4.53)	–	–	
Dihedral rad (deg)	0 131 (7 5)	0 122 (7 0)	–	
t/C %	15 root 10 3 tip	11 root 9 tip	11 5 root 8 5 tip	
MAC (C_{ref}) m (in)	5.232 (206.0)	3 873 (152 5)	4 910 (193 3)	
Span m (in)	49 15 (1935)	14 38 (566)	8.08 (318)	
Tail arm m (in)	–	20 5 (808)	20 3 (798)	
Tail vol coeff	–	0 86	0 063	
Body	Length m (in)	Max dia, m (in)		
	47 549 (1872)	5 385 (212)		
Powerplants	Number	Type	SLST	BPR
	2	CF6 50C	164 3 (36 940)	4 3
Landing gear	Nose	Main	LOC C_{ref}	
	(2) 37x14	(8) 49x19	57 9	



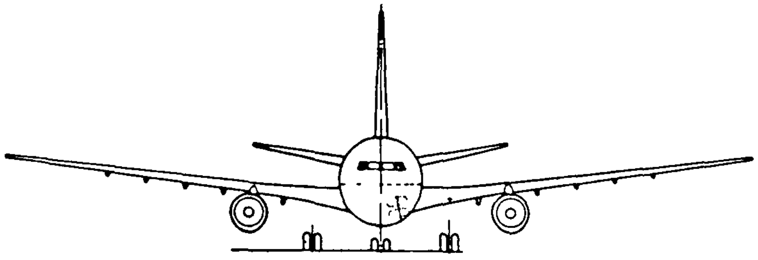


Figure 19. Variable-Camber Domestic Airplane B (Hybrid Variable Camber)

design selection charts and airplane design points for the intercontinental airplane are shown in Figure 20; the design selection charts for variable-camber domestic airplanes A and B are shown in Figures 21 and 22. The variable-camber intercontinental airplane was constrained by ICAC alone, as was the reference airplane. Both the reference and the variable-camber intercontinental airplanes were sized to approximately the same design point with relation to optimum gross weight versus fuel burned; therefore, they should provide a good basis for evaluating the merits of variable camber.

As noted before, domestic airplane A required a larger wing than the reference airplane because of the 125-knot design approach speed. Although this moved the design point toward minimum block fuel (fig. 21) it also required increased takeoff gross weight and, therefore, would tend to have a slightly higher DOC than if unconstrained by approach speed. Variable-camber domestic airplane B, which had double-slotted flaps, was not constrained by approach speed and so was sized close to the same design point as the reference airplane.

Comparisons between the reference and variable-camber airplanes are detailed in Section 7.

The selection of design points for the variable-camber airplane represents a compromise between minimum block fuel (BLKF) and minimum takeoff gross weight (TOGW). Previous studies indicate that the minimum direct operating cost (DOC) lies close to the minimum TOGW rather than minimum BLKF. However, minimum DOC will move toward minimum BLKF as progressively higher fuel prices are considered. This was not a significant effect over the range of fuel price considered in this study. As noted before, each variable-camber airplane is constrained by one of the mission requirements: ICAC for the intercontinental, approach speed for domestic airplane A. The variable-camber domestic airplane B, having double-slotted trailing-edge flaps and outboard flaperons, does not require increased wing area like domestic airplane A.

Figure 23 compares the domestic airplane B with the reference domestic airplane. Both are sized by the TOFL requirement of 2290m, SL 29°C (7500 ft, SL 84°F) and by a trade between minimum BLKF and TOGW. As seen in the

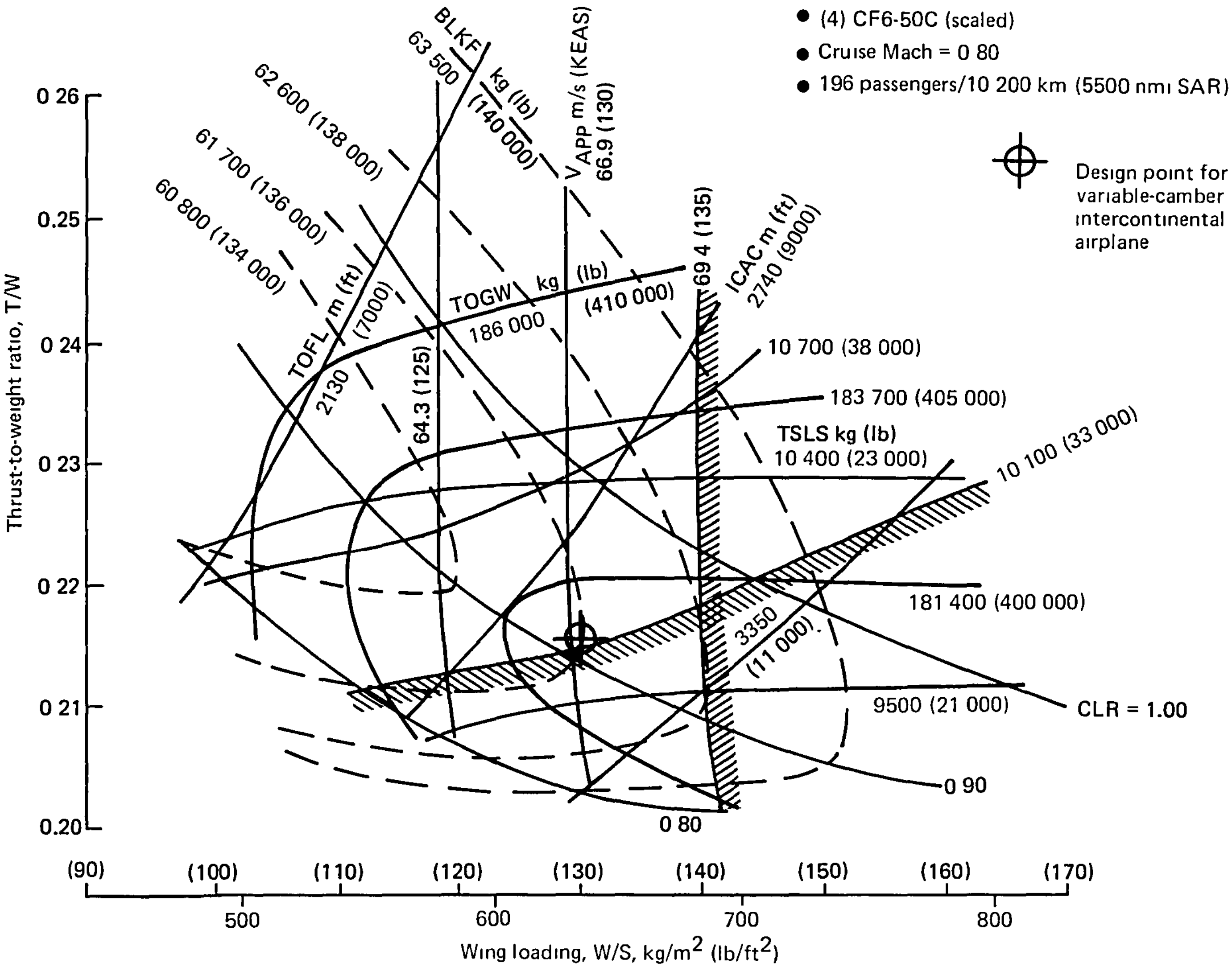


Figure 20 Variable-Camber Intercontinental Airplane Design Selection Chart

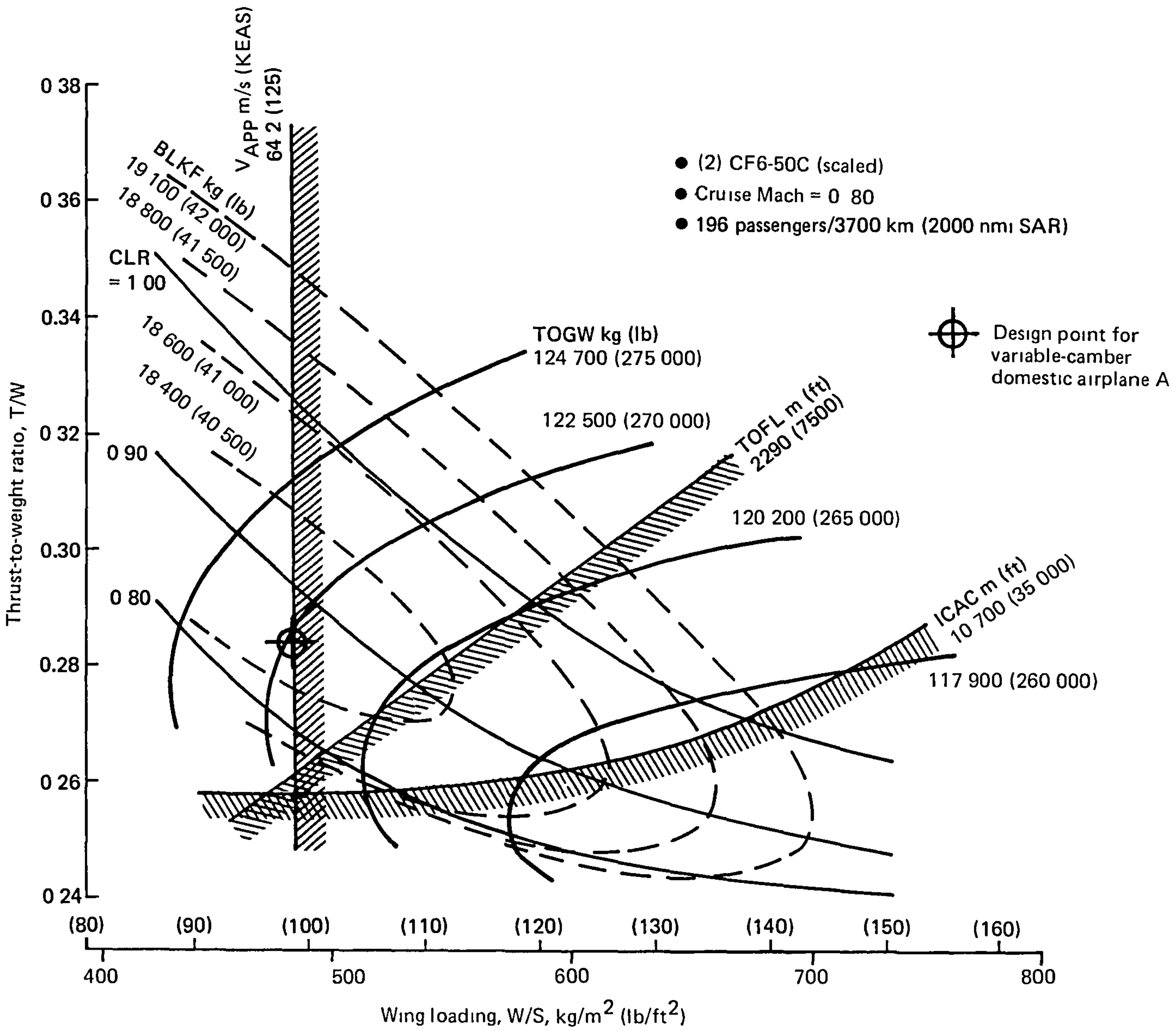


Figure 21. Variable-Camber Domestic Airplane A Design Selection Chart

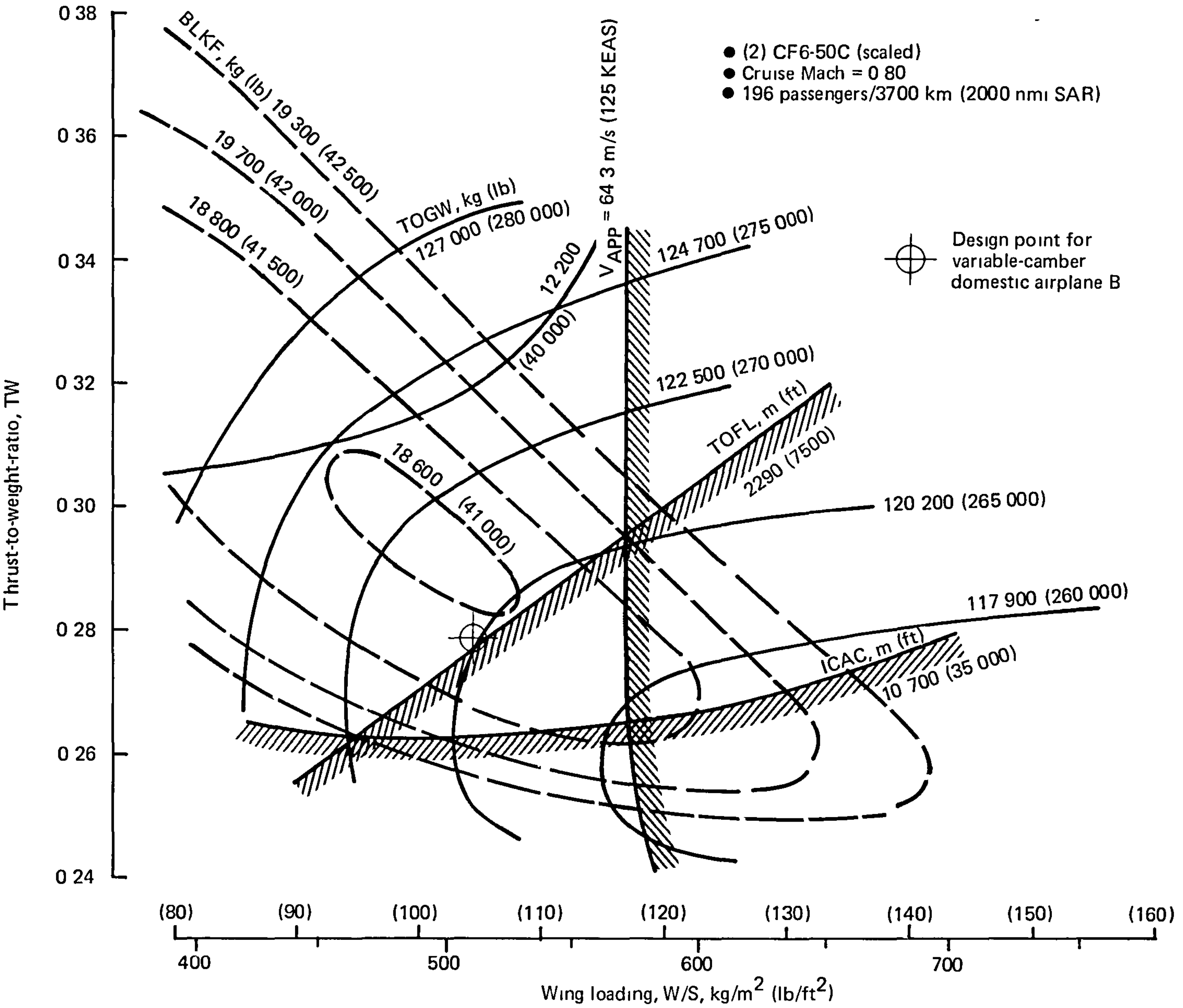


Figure 22. Variable-Camber Domestic Airplane B Design Selection Chart

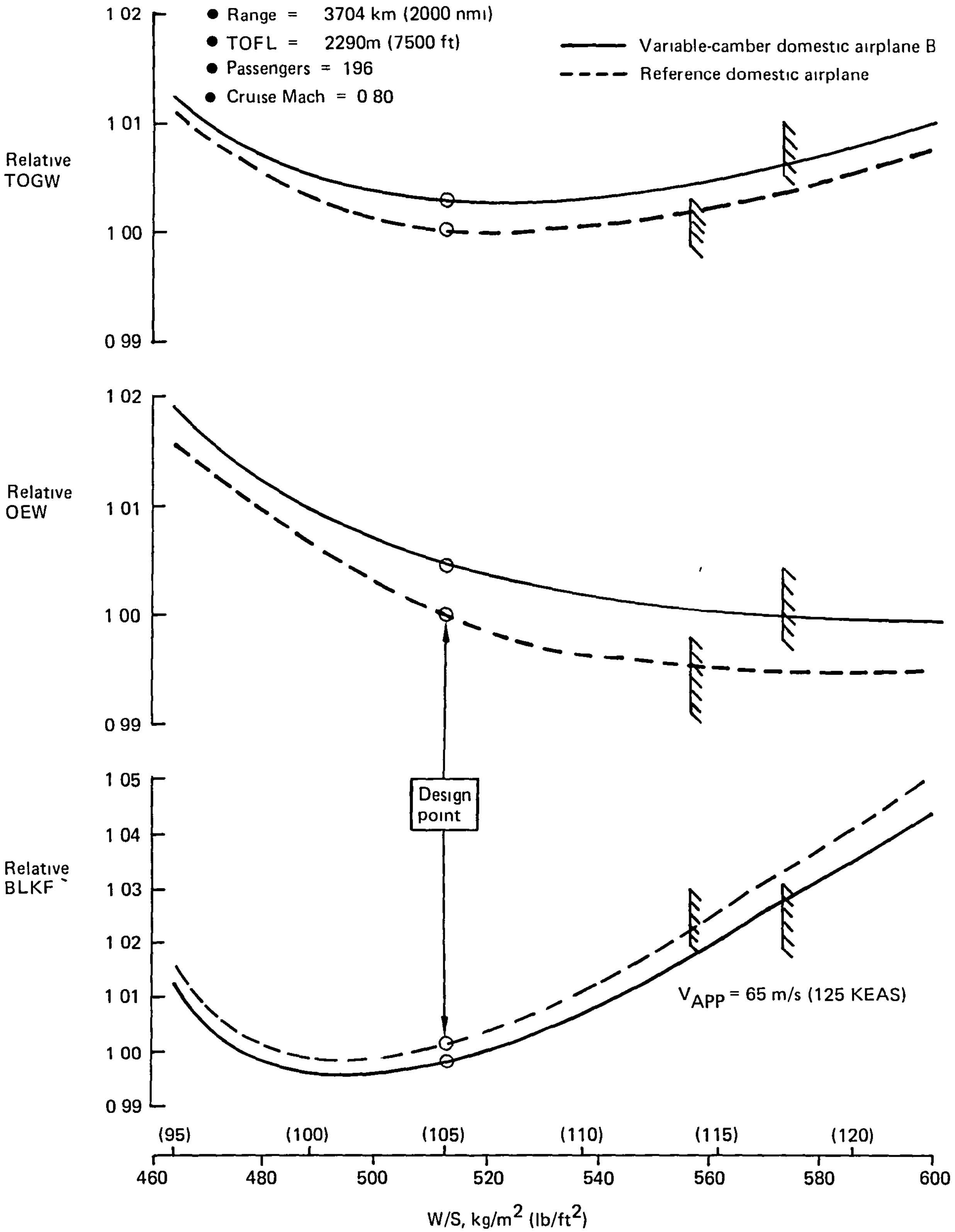


Figure 23. Variable-Camber Domestic Airplane B Design Selection

figure, approach speed is not a constraint. The domestic variable-camber airplane is slightly heavier but, having a higher cruise L/D, uses slightly less block fuel than the reference airplane. Weight summaries for the variable-camber airplanes are included in Table 3.

Table 3. Variable-Camber Airplane Weights

Item	Intercontinental airplane		Domestic airplane A		Domestic airplane B	
	kg	(lb)	kg	(lb)	kg	(lb)
Wing	23 160	(51 070)	18 800	(41 440)	16 950	(37 360)
Empennage	3 070	(6 770)	2 560	(5 640)	2 420	(5 330)
Body	16 990	(37 460)	16 110	(35 510)	16 060	(35 390)
Landing gear	7 240	(15 950)	6 490	(14 320)	6 450	(14 220)
Nacelle and strut	4 460	(9 820)	4 150	(9 160)	4 020	(8 870)
Total structure	54 920	(121 070)	48 110	(106 070)	45 900	(101 170)
Propulsion system	7 380	(16 280)	7 020	(15 470)	6 760	(14 900)
Fixed equipment and options	20 080	(44 270)	19 300	(42 540)	19 360	(42 670)
Standard and operational items	8 260	(18 200)	5 170	(11 400)	5 170	(11 400)
OEW	90 640	(199 820)	79 600	(175 480)	77 160	(170 140)
MZFW	122 690	(270 490)	107 070	(235 990)	101 300	(223 260)
MLW	131 610	(289 550)	109 860	(241 690)	100 400	(238 980)
MTOW	183 840	(405 290)	125 640	(276 980)	124 120	(273 700)

6.0 AERODYNAMIC ANALYSES

This section describes the analyses required to define the study data bases and to size and define the study airplanes. Section 6.1 describes the aerodynamic data bases and the theoretical methods used to supplement them. Section 6.2 summarizes the aerodynamic analyses of the variable-camber airplanes. Section 6.3 contains the weights analyses used for both reference and variable-camber airplanes. Sections 6.5 and 6.6 describe the wing planform studies performed to assist in the variable-camber airplane design, as well as the sensitivity studies used to relate a configuration change that affected drag and/or weight to the overall airplane performance or economics.

6.1 AERODYNAMIC DATA BASE

An aerodynamic data base was required to help select the variable-camber concepts and to predict the effects of changing the airfoil shape, flight attitude, or speed on aerodynamic characteristics. The aerodynamic data base for this study consisted of two parts:

- A low-speed data base to predict aerodynamic characteristics of the aircraft configurations with the high-lift systems deployed. These data and methods were used to predict the aerodynamic characteristics of the study configurations during takeoff, climbout, approach, and landing.

- A high-speed data base to predict the aerodynamic characteristics of the aircraft configurations for the remaining portions of the flight envelope including climb, cruise, descent, and hold.

Central to each data base system are computerized methods for developing three-dimensional wing aerodynamic characteristics from two-dimensional airfoil aerodynamic data. The basic aerodynamic data base uses extensive Boeing experimental and analytical studies of various airfoil, wing design, high-lift systems, and previous variable-camber investigations.

6.1.1 LOW-SPEED DATA BASE

The low-speed aerodynamic data base design and analysis methods are summarized in Figure 24. Low-speed aerodynamic characteristics of the study configurations were estimated using a computerized method (LOWLAM) developed by Boeing to evaluate preliminary design configurations for which no wind tunnel or flight test data exist. LOWLAM predicts full-scale airplane aerodynamic characteristics from an internal aerodynamic data base that may be supplemented by additional specific data. The internal data base consists of flight data for existing Boeing airplanes (models 727, 737, and 747) and results of other flight and wind-tunnel tests.

The LOWLAM data base is applicable to conventional, mechanical, high-lift systems consisting of either plain and/or cambered flaps and/or slots on the wing leading edge and slotted flaps on the wing trailing edge. These conventional leading- and trailing-edge devices extend in the chordwise direction when deflected. Figures 25 and 26 show results from an example application of the LOWLAM program to predict the low-speed aerodynamic characteristics of a 747 wind-tunnel model.

For this study, the LOWLAM aerodynamic data base was expanded to include data for sealed leading- and trailing-edge high-lift devices to represent the variable-camber configurations. Variable-camber leading-edge data were developed from three-dimensional flight-test and wind-tunnel data on configurations with sealed leading-edge devices.

Data necessary to evaluate the trailing-edge contribution to the low-speed aerodynamic characteristics of the variable-camber airfoils were developed using a multielement airfoil program and the separated wake analysis program described in Reference 3. Candidate variable-camber airfoils were analyzed at fixed angles of attack using the multielement airfoil program to establish the airfoil section properties. Section maximum lift coefficients ($c_{\ell_{MAX}}$) were calculated using the separated wake analysis program. Typical numerical results of these analyses, shown in Figure 27, include separated wake profiles calculated for two typical angles of attack. Also shown in Figure 27 are the resulting calculated section lift increments due to trailing-edge deflection and the section $c_{\ell_{MAX}}$ increment used to generate three-dimensional wing characteristics.

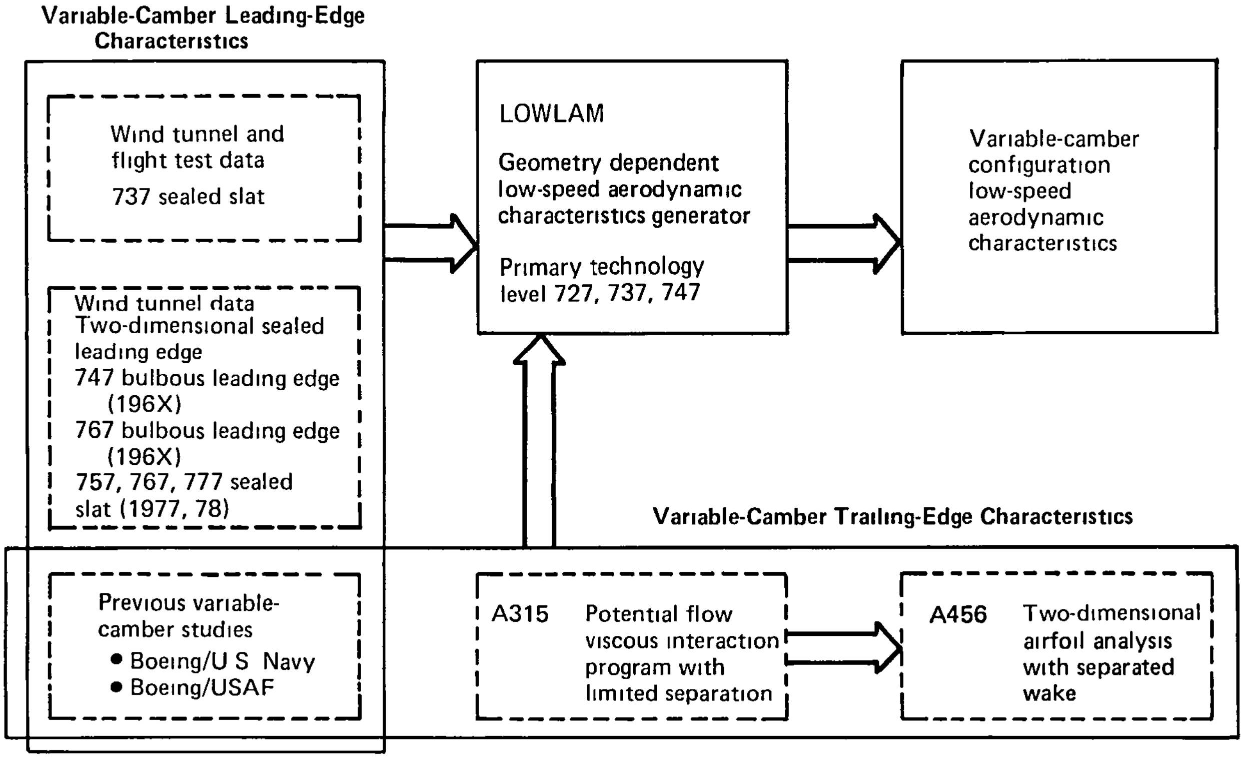


Figure 24. Low-Speed Aerodynamic Data Base/Design/Analysis Methods

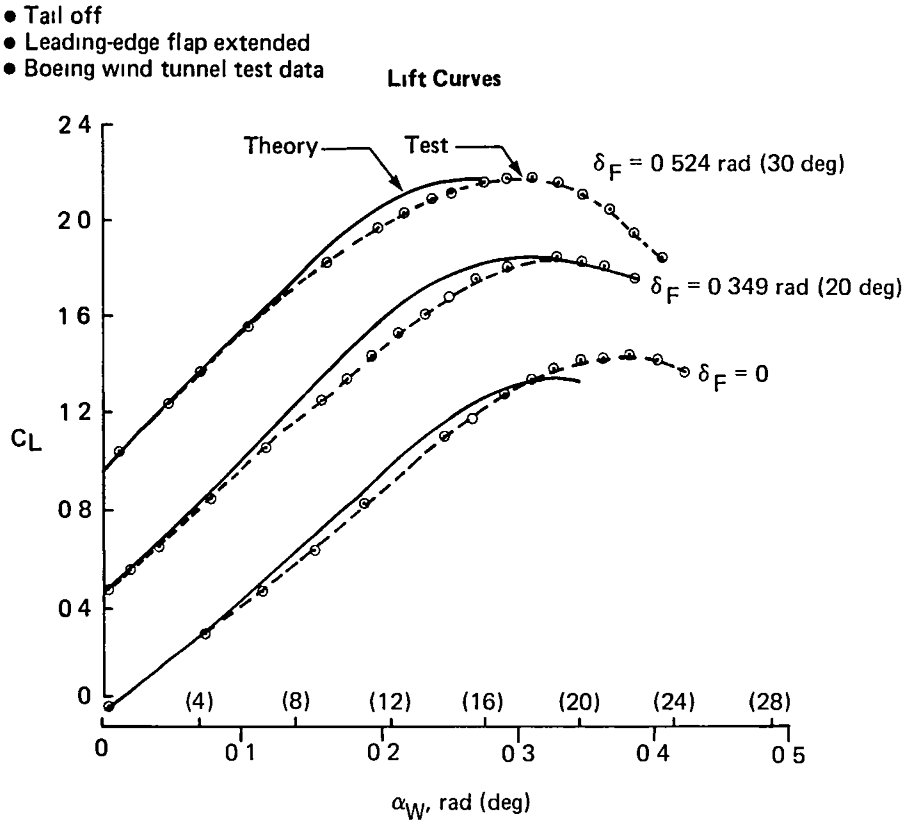


Figure 25. LOWLAM Lift Curve Comparison (747-100)

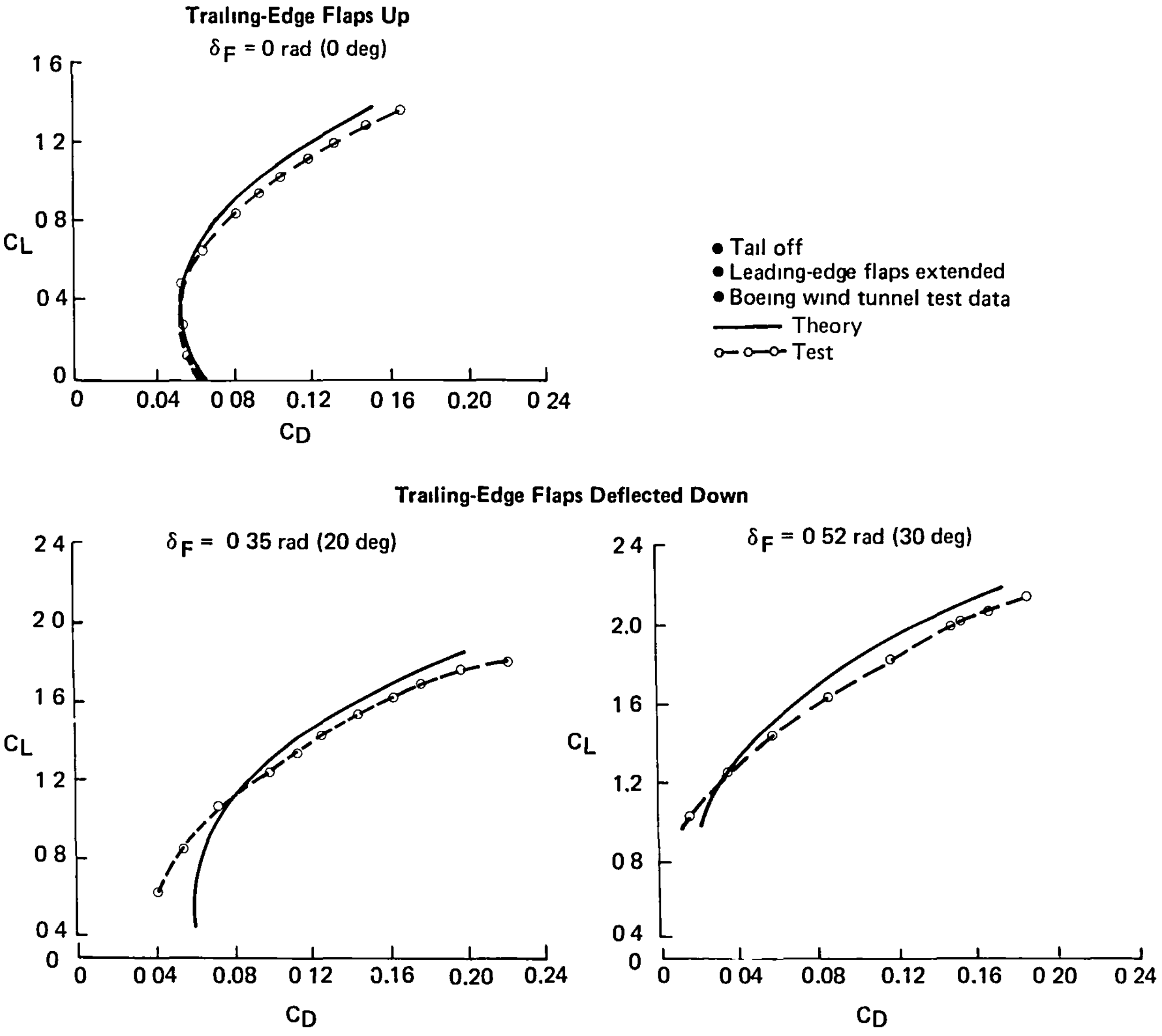
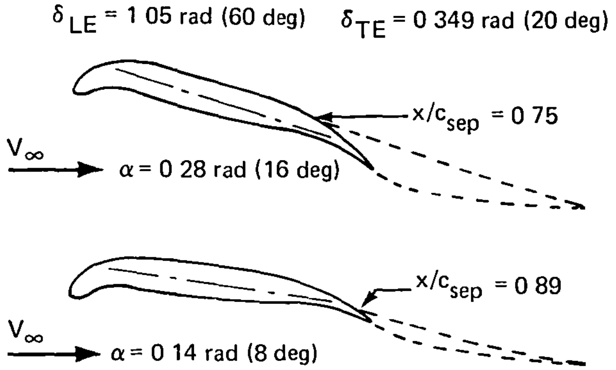
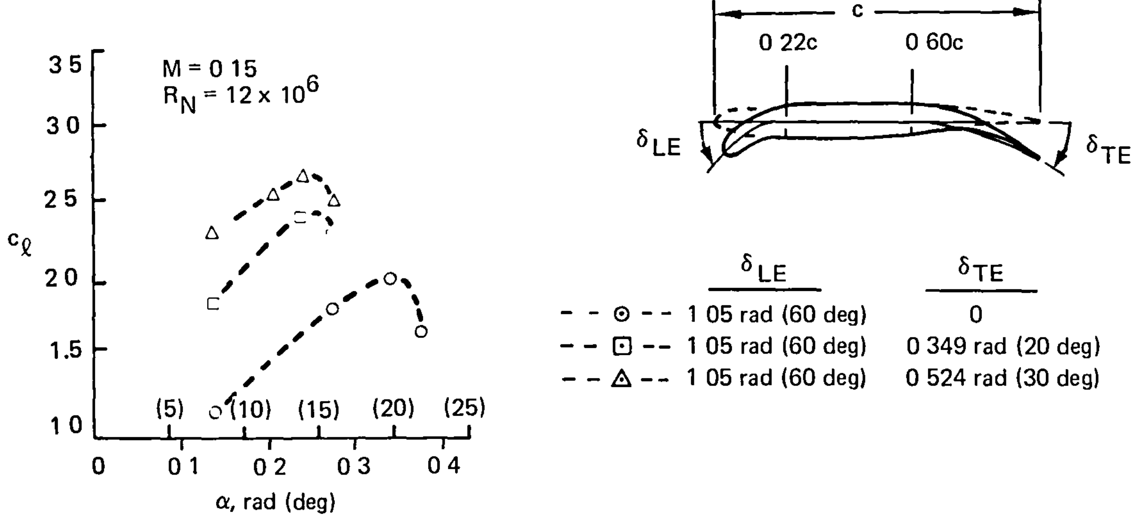


Figure 26. LOWLAM Drag Polar Comparison (747-100)

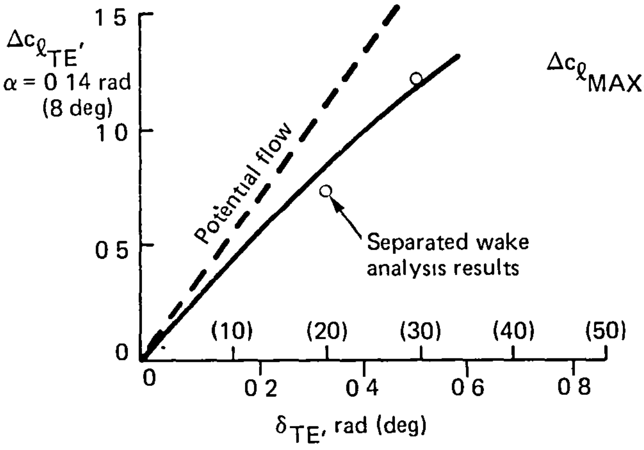
Separated Wake Profiles



Lift Coefficient Prediction



Trailing-Edge Flap Lift Increment



Trailing-Edge Flap Contribution

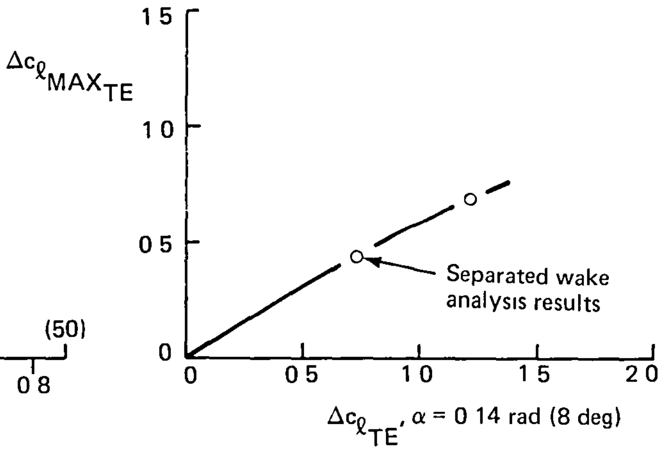


Figure 27. Separated Wake Airfoil Analyses

6.1.2 HIGH-SPEED DATA BASE

The high-speed aerodynamic data base analysis methods are summarized in Figure 28. A high-speed aerodynamic analysis method (RADEM) was used to predict three-dimensional wing aerodynamic characteristics from two-dimensional wind tunnel data on Boeing-developed airfoils. The internal data base of RADEM was supplemented by additional sets of analytical/experimental airfoil data for this study. Figure 29 shows how well RADEM can predict the aerodynamic characteristics of the 747 airplane and of an advanced-technology wing/body design.

The aerodynamic comparisons in Figures 5 and 6 show that the shapes of the derived variable-camber airfoils closely resemble the design objective family of point-design airfoils. Therefore, the wind tunnel data for the family of point-design airfoils were used to construct the aerodynamic characteristics of the variable-camber airplanes. The variable-camber wings can change shape as either cruise speed or lift coefficient changes. Thus, the drag polars are envelope polars representing an entire family of drag polars. These drag polars are compared to the reference airplane polars in Figure 30.

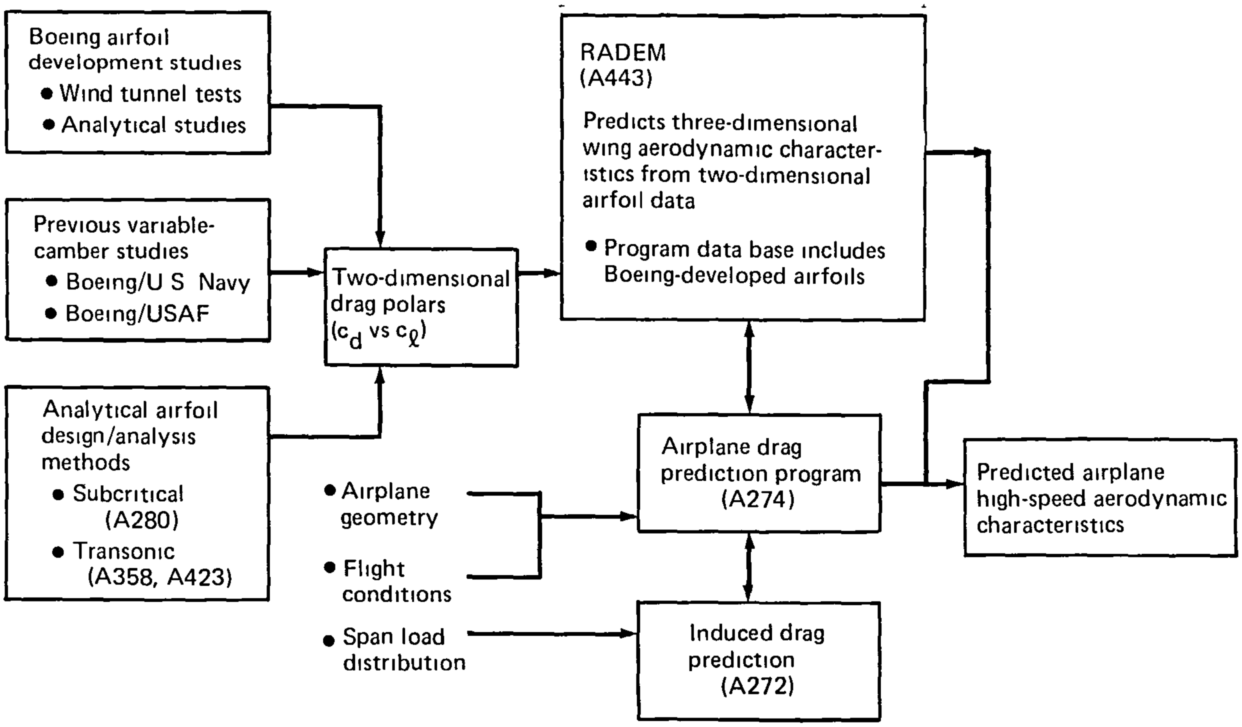
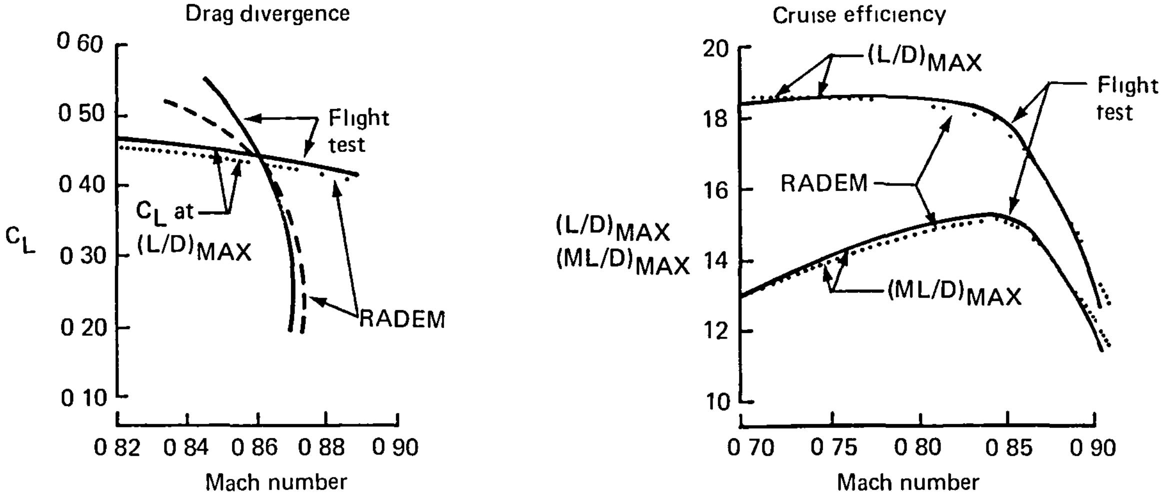


Figure 28. High-Speed Aerodynamic Analysis Methods

747 Full-Scale Airplane



Advanced Technology Wing/Body Configuration

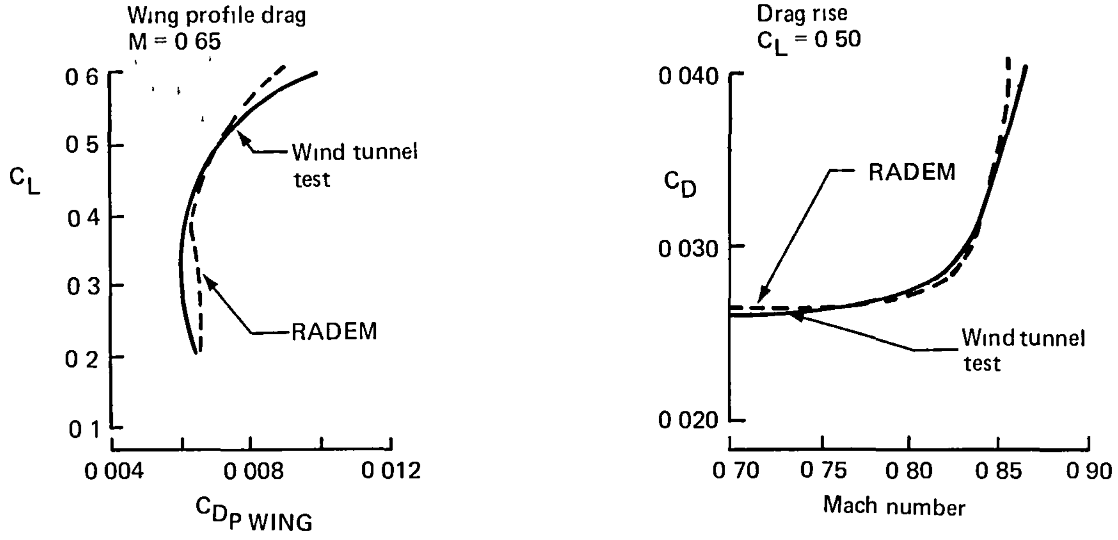


Figure 29. RADEM Program Test/Theory Comparisons

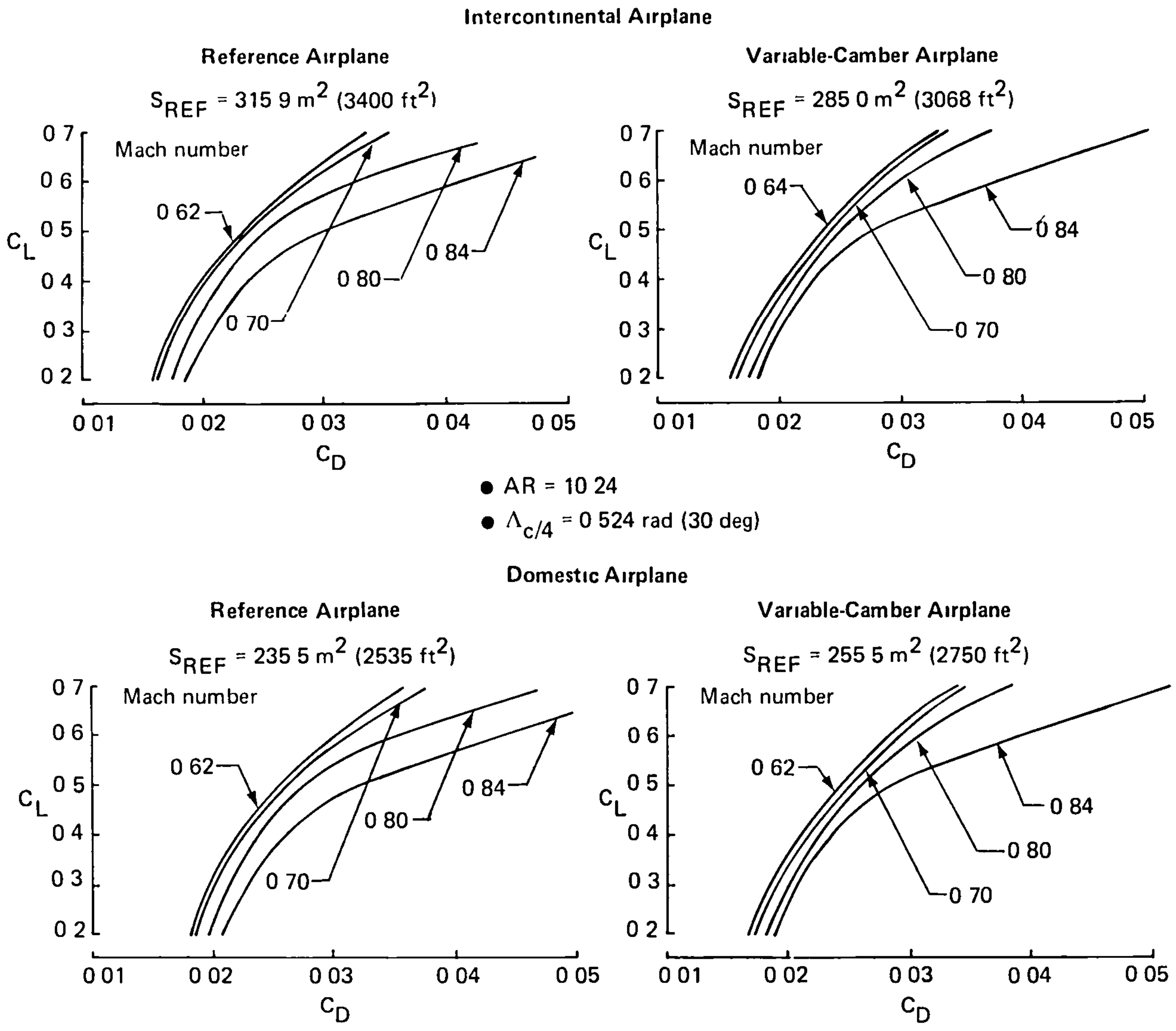


Figure 30. Domestic and Intercontinental Airplanes High-Speed Drag Polars

At speeds lower than Mach 0.7, the variable-camber airplane required more camber than available with the three point-design Boeing airfoils shown in Figure 3. Therefore, the experimental airfoil data were extended to higher camber shapes by theoretical calculations of the aerodynamic characteristics of existing family and higher camber airfoils. The increments in the theoretical lift-and-drag caused by additional camber were applied to the experimental data for the base variable-camber airfoil to extend the data base. This procedure was substantiated by comparing the predicted drag polar for point-design airfoil PD3 to the corresponding test data (see fig. 31). Figure 31 shows predicted drag polars for increased camber and the envelope polar used to simulate the variable-camber airfoil for that particular Mach number.

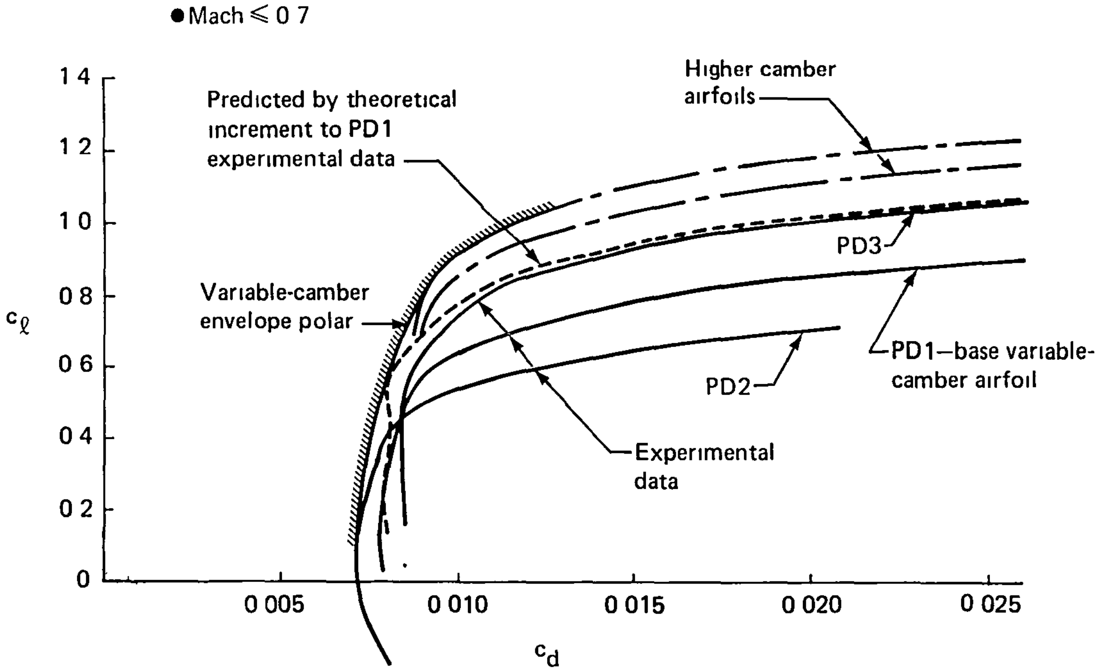
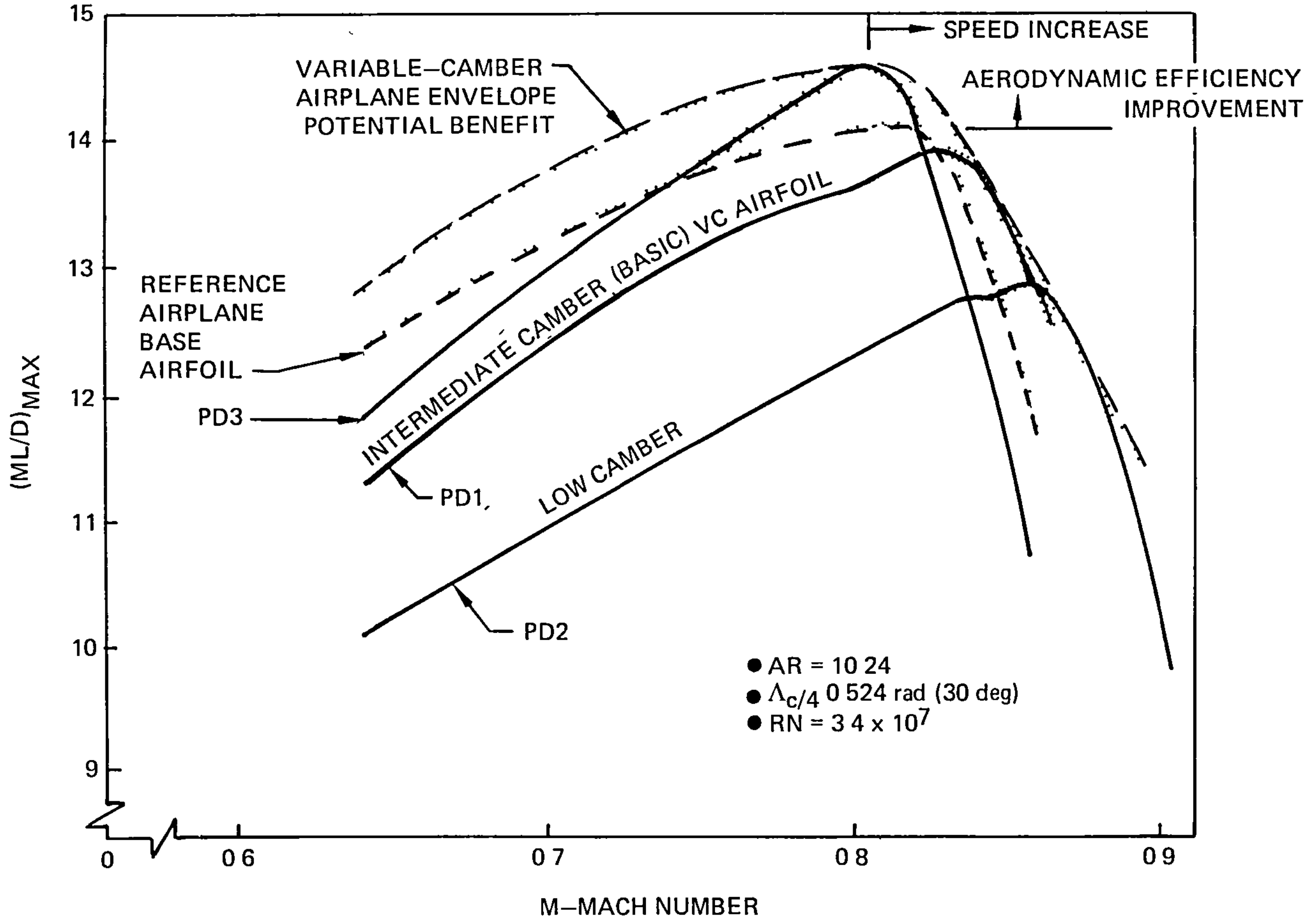


Figure 31. Predicted Incompressible Drag Polars for Airfoil Camber Changes

6.2 AERODYNAMIC ANALYSES

6.2.1 HIGH-SPEED DRAG ANALYSES

Using the data base developed as discussed above, the lift/drag ratios were calculated for the domestic airplane with the reference wing and the variable-camber wing having the same area. The resulting airplane $(ML/D)_{MAX}$ values for several airfoils are shown in Figure 32. The variable-camber wing increased the L/D at the design Mach number (0.8) by approximately 3.5 percent. The maximum lift/drag ratio of the variable-camber wing occurred at a slightly higher lift coefficient than for the reference wing. These initial evaluations did not include excrescence drag reductions from the reduced number of steps, fairings, and gaps for the variable-camber airplane. The final aerodynamic evaluations of the variable-camber airplanes did include estimates for these reductions.



NOTE REDUCTIONS IN EXCRESCENCE DRAG WERE NOT INCLUDED IN THESE PRELIMINARY VARIABLE-CAMBER ESTIMATES

Figure 32 Domestic Variable-Camber Airplane Preliminary Lift/Drag Ratios

6.2.2 LOW-SPEED AERODYNAMIC ANALYSES

Low-speed aerodynamic design objectives were identical for the variable-camber airplanes and the reference airplanes (see figs. 11 and 12). The initial high-lift systems for the variable-camber airplanes, as shown in Figure 16, included:

- a plain Krueger leading-edge flap and a single-slotted trailing-edge flap between the engine and the side-of-body
- a variable-camber leading-edge outboard of the planform break
- a variable-camber trailing-edge flap from the engine to the outboard aileron (approximately 70-percent semi-span)
- a variable-camber outboard aileron

The preliminary low-speed evaluations shown in Figure 33 indicate that the variable-camber intercontinental airplane can meet the high-lift requirements.

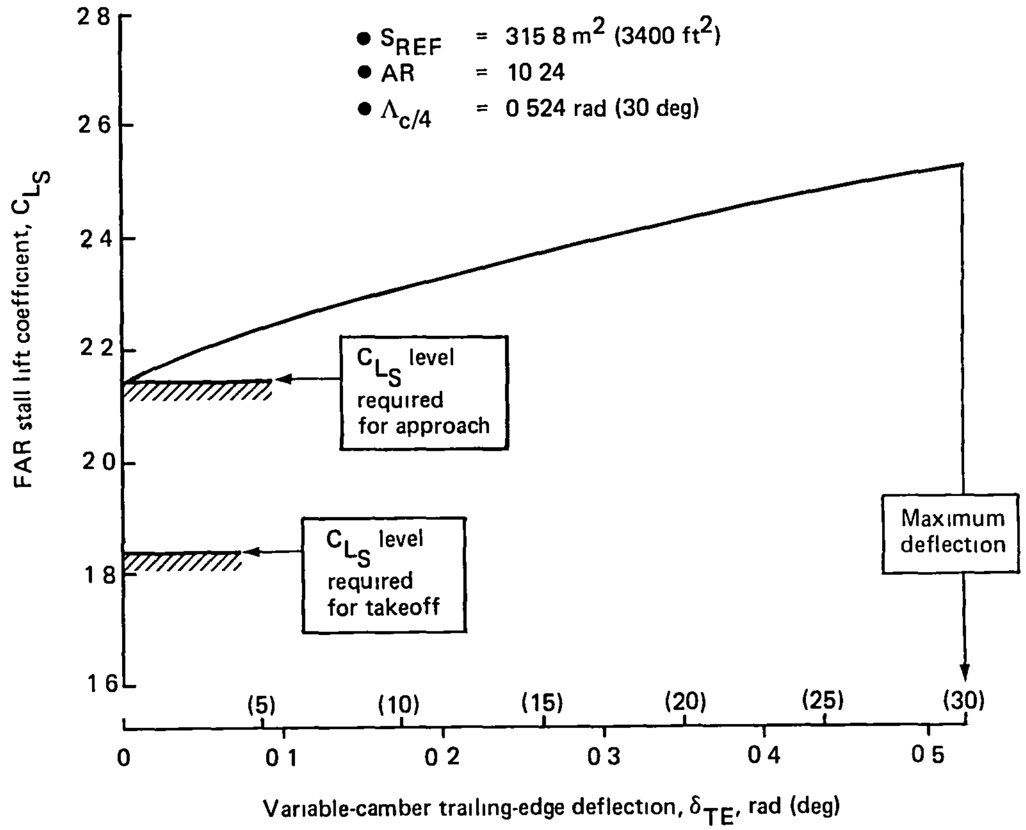


Figure 33. Intercontinental Variable-Camber Airplane High-Lift Capability

The high lift obtainable for the variable-camber domestic airplane A was calculated as 14 percent less than required for the same wing loading with the reference airplane. Consequently, the outboard variable-camber aileron was drooped, increasing the high-lift capability approximately 5 percent. These preliminary results, shown in Figure 34, indicated that the variable-camber domestic airplane A would need additional wing area to meet the approach speed requirements.

Because of the concern that the increased wing weight (because of added area) could negate part of the potential fuel saving of the variable-camber domestic airplane, an alternate domestic configuration (airplane B) was defined with double-slotted trailing-edge flaps at both the inboard and outboard locations, allowing for variable camber with flaps retracted to preserve the potential aerodynamic benefits in high-speed flight. The drooped aileron feature of domestic airplane A was retained. The double-slotted flap system for domestic airplane B requires the addition of both spoilers and flap mechanism fairings, which increase the excrescence drag by $\Delta C_D = 0.00045$. The drag level and polar shape benefits for variable camber were assumed the same for this configuration.

Low-speed lift and drag characteristics of variable-camber domestic airplane B were obtained using LOWLAM and methods described in Section 6.2.1. The double-slotted trailing-edge flaps were accounted for by adding inputs selected from wind tunnel tests of a similar wing with double-slotted flaps.

The low-speed L/D envelopes for both variable-camber domestic airplanes and the reference airplane are shown in Figure 35. The takeoff envelopes are formed by the low-speed characteristics of all possible takeoff flap settings (i.e., from zero to full flaps) at any speed equal to or greater than 1.2 V_s. For landing approach, the envelopes correspond to speeds equal to or greater than 1.3 V_s.

The takeoff curves of the figure show that at $C_L = 1.5$ (corresponding to a sea level takeoff) and below, the variable-camber airplanes have better L/D than the conventionally-flapped reference airplane. This occurs because the variable-camber leading edges have lower profile drag and the drooped ailerons

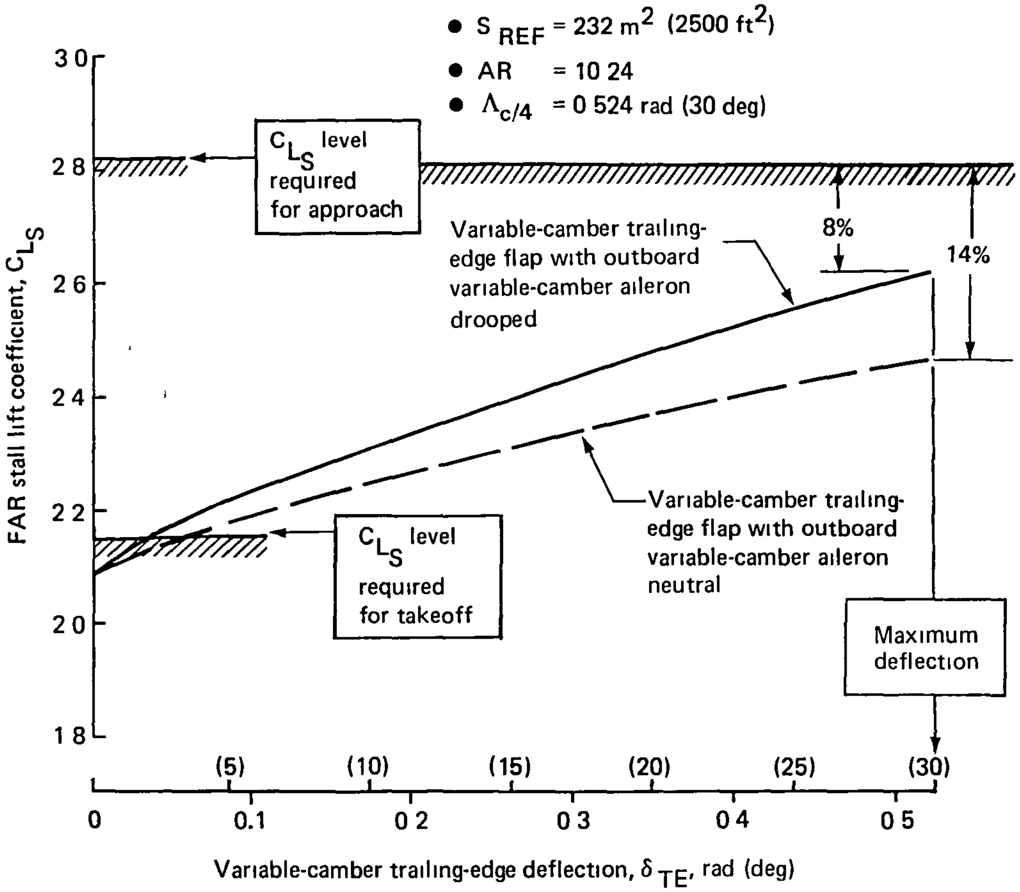


Figure 34. Domestic Variable-Camber Airplane A High-Lift Capability

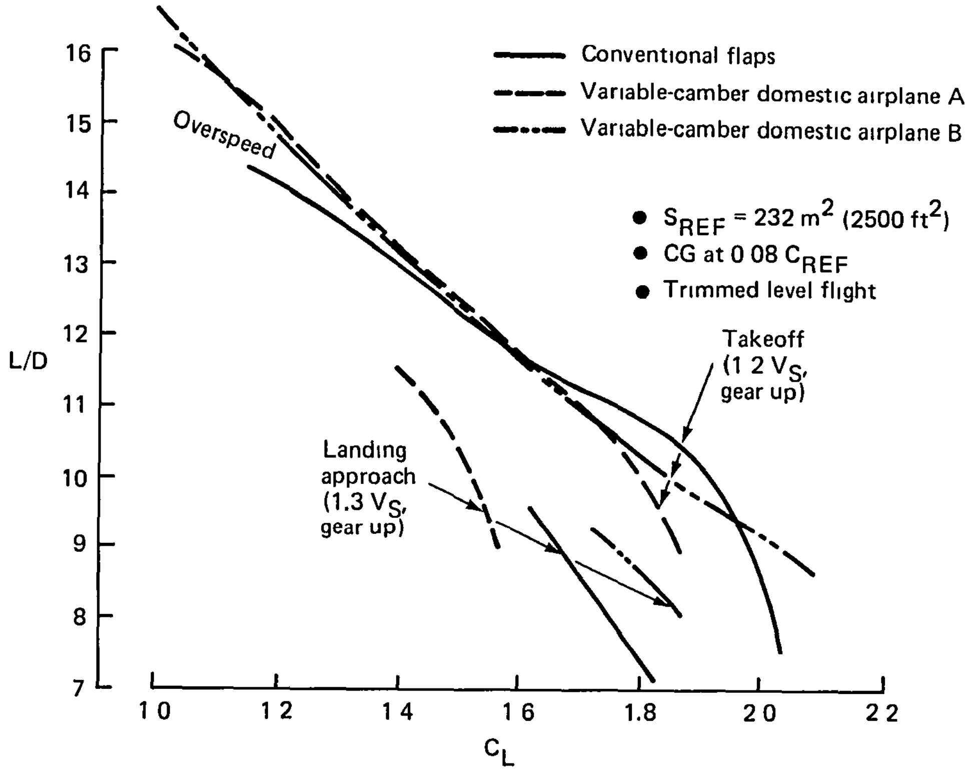
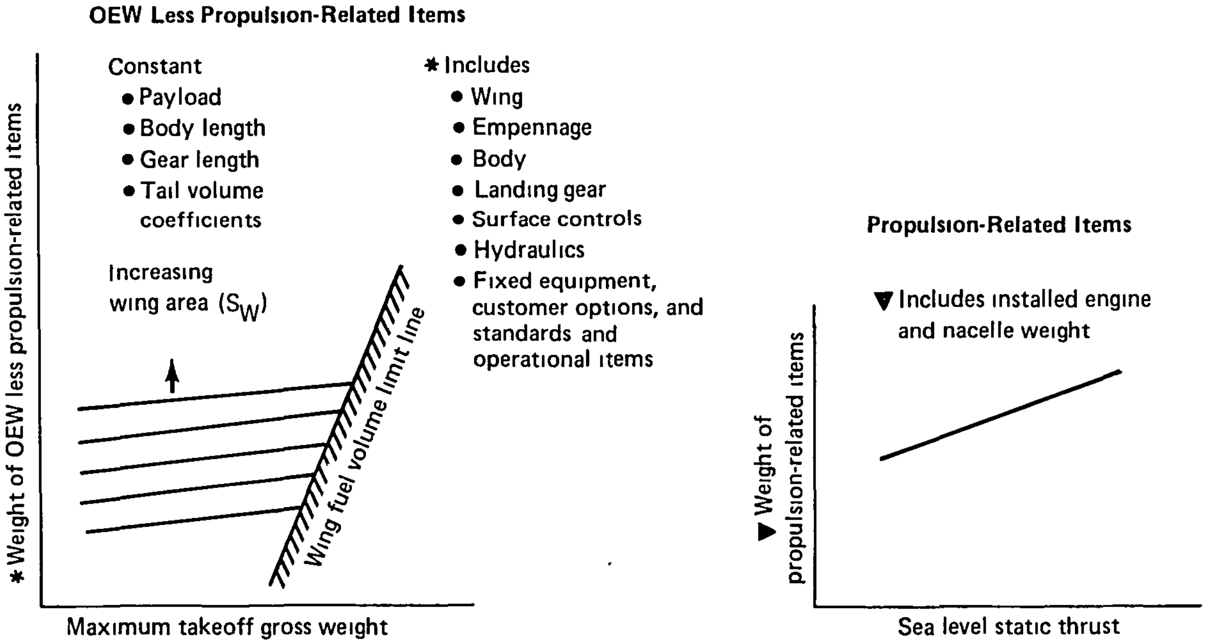


Figure 35. Domestic Airplane Low-Speed Aerodynamics

reduce induced drag at these conditions. The reference airplane required neither sealed leading-edge devices nor drooped ailerons to meet the design mission requirements. However, if the design missions required takeoff from a high, hot airfield such as Denver, sealed leading-edge devices and drooped ailerons would also be desirable for the reference airplane.

6.3 WEIGHT ANALYSIS

The effects of changes in design parameters (e.g., gross weight, wing area, and engine thrust) on component weights can be expressed in terms of partial derivatives as shown in Figure 36. These weight sensitivities were developed individually for the various airplanes because of different configuration characteristics, thus enabling the development of a consistent set of airplane operational empty weights (OEW) as inputs to mission sizing analyses.



$$dW = \overbrace{\frac{\partial W}{\partial MTOGW} dMTOGW + \frac{\partial W}{\partial S} dS}^{\ast\text{ OEW less propulsion-related items}} + \overbrace{\frac{\partial W}{\partial SLST} dSLST}^{\blacktriangledown\text{Propulsion-related items}}$$

Figure 36. Parametric Representation of the Weight-Scaling Data

Because a constant payload was maintained throughout the study, the primary weight effects of variations in gross weight, wing area, and engine thrust were limited to the airplane structure, surface controls, and propulsion-related items. Payload-related weight (e.g., fixed equipment, customer options, standard and operations items) remained unchanged.

Weights estimated for both the reference and variable-camber airplanes were identical except for the flap systems. The weights were derived from in-house study airplanes designed for the same time period, but they included adjusted configuration differences such as wing area, gross weight, and engine location.

An indepth weight evaluation of the variable-camber flap concept was not made because the design and structural sizing were not defined in detail. To account for additional mechanism complexities, the variable-camber flap weight was increased 20 percent relative to conventional flaps. This increment was based upon results of previous variable-camber studies and Boeing experience with variable-camber flap systems. This approach is consistent with the objective of this study to evaluate the feasibility of the variable-camber concept, rather than to establish detailed design characteristics.

6.4 FLIGHT CONTROL ANALYSIS

Conventional current technology margins were used for sizing the horizontal and vertical tails of the study airplanes. These were: 6-percent aft-flight limit for approach conditions, 3-percent static margins at cruise, and zero static margins at dive. All study airplanes used an "all-flying" horizontal tail with geared elevator and double-hinged rudder.

6.5 WEIGHT AND DRAG SENSITIVITIES

Detailed mission analyses were made of the reference intercontinental and domestic airplanes to determine the effects of additional drag or weight changes on the fuel requirements of these airplanes. The results of these sensitivity studies are shown in Figures 37 and 38.

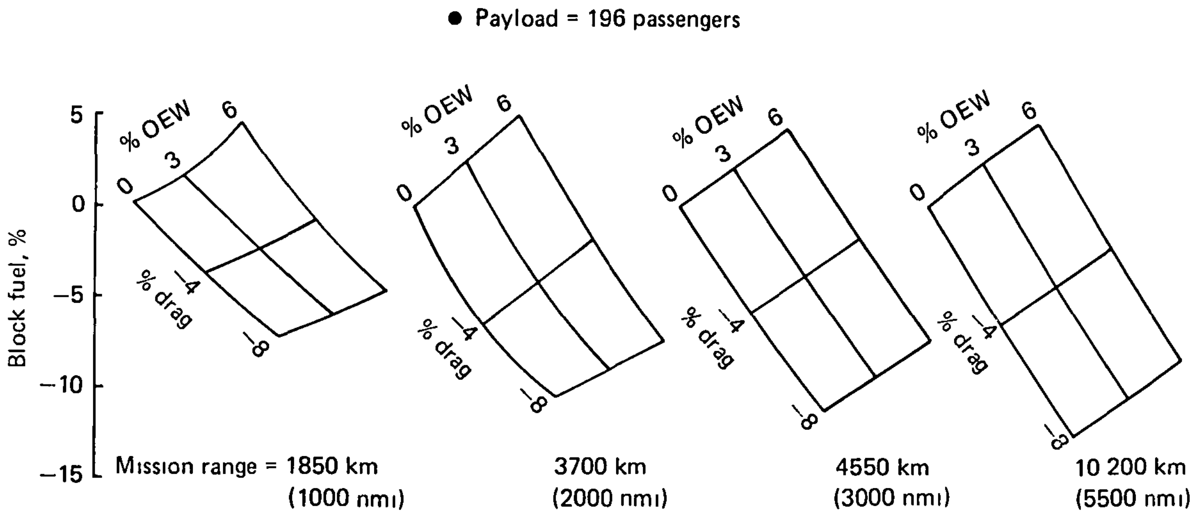


Figure 37 Intercontinental Airplane Sensitivity to Δ Weight and Δ Drag

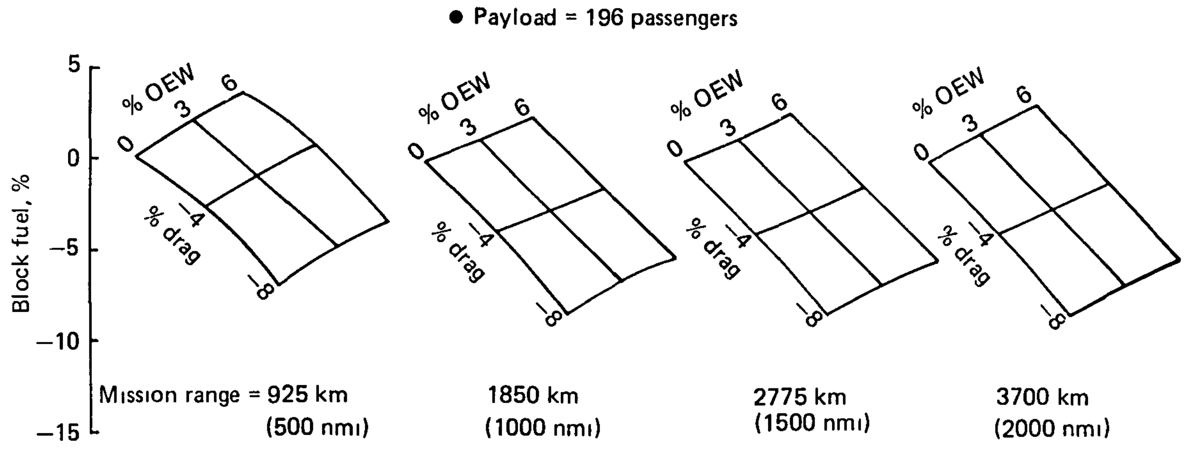


Figure 38 Domestic Airplane Sensitivity to Δ Weight and Δ Drag

The effects of weight and drag differences on block time are insignificant for both intercontinental and domestic airplanes. The intercontinental airplane shows the effect of changing weight to be approximately constant for all ranges, whereas changing drag has an increasing effect on block fuel at longer mission ranges. The domestic airplane sensitivities show that weight and drag have approximately the same percentage effect on block fuel at ranges of 900 to 3700 km (500 to 2000 nmi) with full payload.

The sensitivities of DOC to changes in OEW, block fuel, block time, and fuel costs also were calculated. The airplane DOC sensitivities at the average stage length are listed in Table 4. At different ranges, DOC sensitivities for both configurations varied negligibly. The relative DOCs were calculated based on the 1977 update to the 1967 American Transport Association (ATA) cost formulas discussed in Section 7. Each parameter listed in Table 4 was changed independently in the DOC equation to calculate DOC sensitivities. The OEW sensitivities were developed using general formulas for airframe maintenance costs as a function of airframe weight. This method of obtaining the percentage changes in DOC associated with percentage changes in OEW is considered a reasonable representation of airplane sensitivities.

Table 4. DOC Sensitivities

Parameter, Δ%		ΔDOC, %
Fuel cost	+5	+1.4
OEW	+5	+1.5
BLKF	+5	+1.5
Block time	+5	+2.0

6.6 PARAMETRIC ANALYSIS

Several wing-planform trade studies were conducted to determine suitable configurations for the variable-camber airplanes. These studies are described in the following subsections.

6.6.1 WING-SPAR LOCATION TRADES

The reference airplanes have the front and rear wing spars located at 15- and 65-percent chord, respectively. Although moving the spars to 20- and 60-percent chord would not significantly change wing-box weight, bending load intensities would increase, requiring thicker structural material gages. High-lift devices, whether conventional or variable camber, would tend to get heavier as the wing-box chordwise size decreased.

The intercontinental variable-camber airplane retained the same spar locations as the reference airplane. The wing configuration selected for the domestic variable-camber airplanes retained the same front spar location as the reference airplane (15-percent chord), while the rear spar was moved forward to 60-percent chord. Changes in spar location affected the weights of the leading- and trailing-edge areas. Therefore, these weight effects were accounted for during evaluation of the variable-camber airplanes.

6.6.2 WING SWEEP STUDY

Because lower sweep angles result in higher achievable stall lift coefficients, the reduced sweep for the domestic variable-camber configuration was briefly studied to determine how much the approach capability could be improved before the cruise L/D fell below that for the reference domestic airplane.

The preliminary ML/D comparisons shown in Figure 32 indicate that the variable-camber airfoil concept offers either a higher cruise speed or a decrease in sweep relative to the reference wing design. Accordingly, a wing quarter-chord sweep reduction from 0.524 rad (30 deg) to 0.436 rad (25 deg) was determined to result in essentially the same cruise L/D as the reference airplane. Maintaining a constant structural span as the wing sweep was reduced increased the aerodynamic aspect ratio from 10.24 to 11.22. Maintaining a constant wing thickness along the mid-chord line increased the streamwise wing t/c from 0.109 to 0.114 percent.

The L/Ds of the variable-camber wing with reduced sweep and of the higher sweep variable-camber wing are compared with the reference wing in Figure 39. As noted, the reduced-sweep variable-camber wing had approximately the same maximum L/D at the design Mach number ($M = 0.8$). However, the reduced wing sweep nearly doubled (from 4 to 7.5 percent) the aerodynamic benefit of variable camber at the lower off-design Mach numbers. The favorable effect of reduced excrescence drag was not included here.

The reduced wing sweep also increased the low-speed lift capability of the variable-camber wing by approximately 5 percent. This is important for the domestic mission where the cruise-sized variable-camber wing had difficulty meeting approach speed constraints at optimum-cruise wing loadings. The increased high-lift capability of the wing with less sweep would reduce the wing area required for the domestic variable-camber airplane.

A preliminary analysis was made to determine the effect of unsweeping on wing weight. The results obtained using theoretical aerodynamic loads for both wings indicated a possible increase of 5 percent in wing-box weight for equal wing areas. Weight changes on leading and trailing edges were not evaluated, and the weight analysis did not include a flutter evaluation.

Configuration	Sweep	AR	t/c
Reference airplane	0 524 rad (30 deg)	10 24	0 109
Variable-camber airplane			
Reduced-sweep variable-camber airplane	0 436 rad (25 deg)	11 22	0 114

$S_{REF} = 232\ m^2\ (2500\ ft^2)$

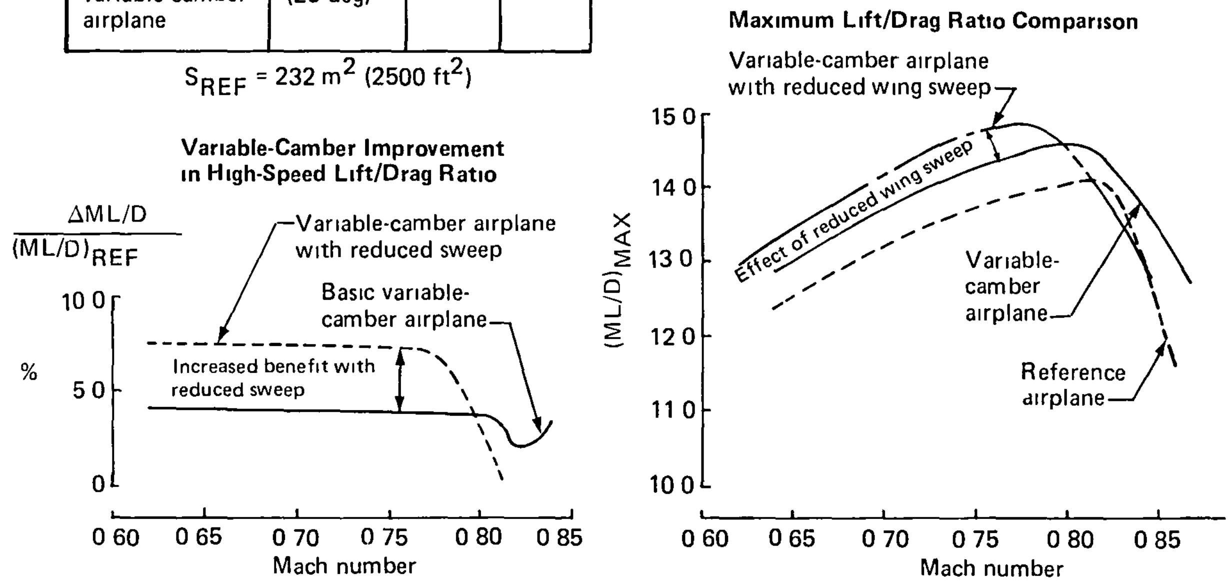


Figure 39. Effect of Reduced Wing Sweep on Domestic Variable-Camber Airplane A High-Speed Lift/Drag Ratios

The results shown in Figure 39 suggest that the domestic variable-camber airplane could significantly benefit from reducing wing sweep, but optimizing wing sweep would require detailed aerodynamic, weight, and performance trade studies beyond the scope of this study.

7.0 COMPARISON OF VARIABLE-CAMBER AND REFERENCE CONFIGURATIONS

7.1 INTRODUCTION

In this section, the drag, performance, and economics of the variable-camber airplanes are compared with the corresponding data for the reference airplanes. The performance data were developed from detailed mission analyses after the configurations were parametrically sized for required missions.

7.2 DRAG COMPARISONS

Cruise drag polars for the sized variable-camber airplanes are compared with those for the sized reference airplanes in Figure 40. Corresponding L/Ds are shown as functions of lift coefficient in Figure 41.

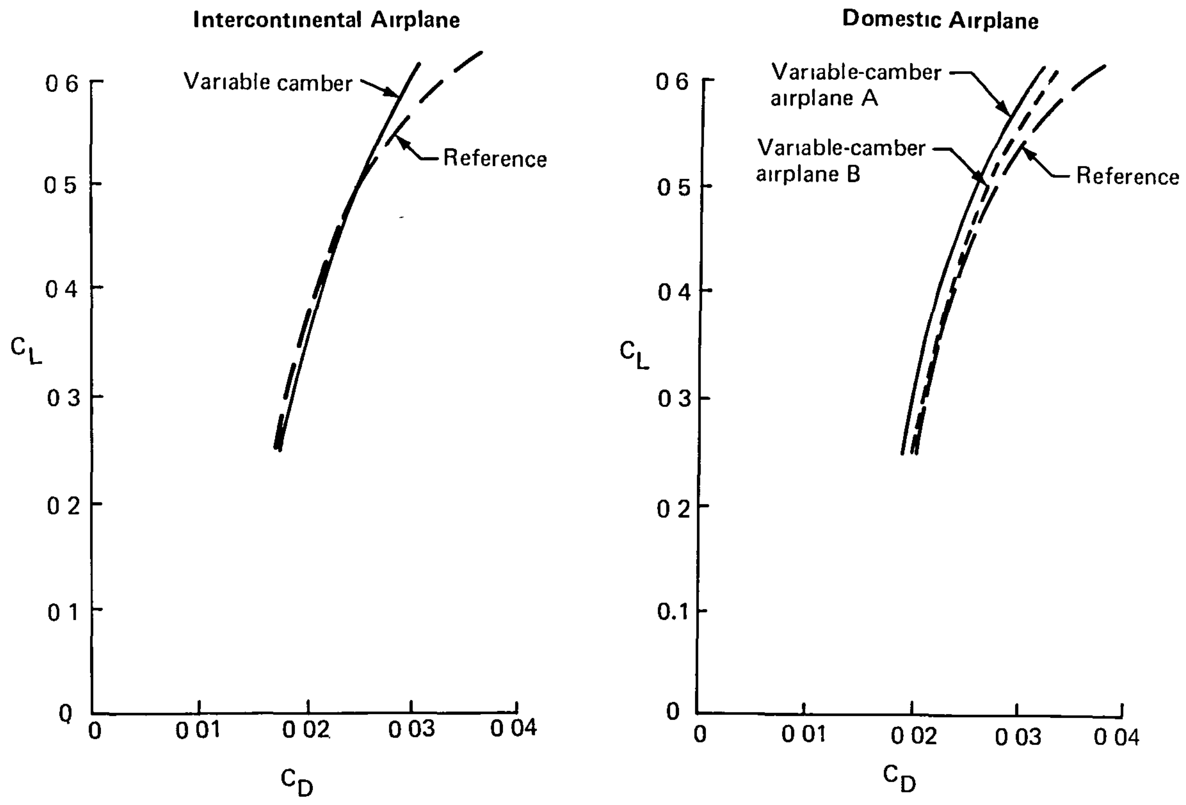


Figure 40. Sized Airplane Drag Polar Comparisons, Mach = 0.8

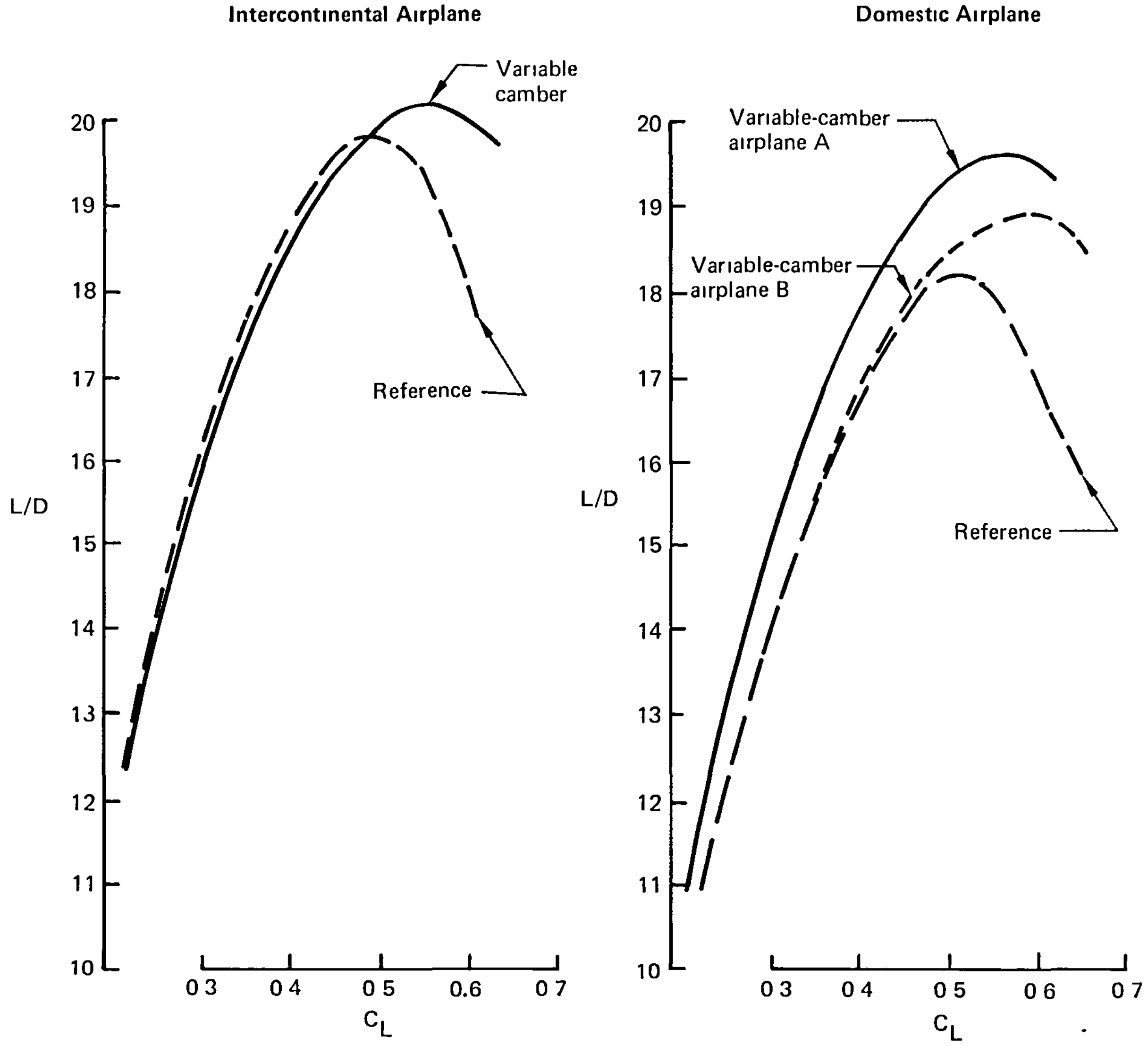


Figure 41. Aerodynamic Efficiencies, Mach = 0.8

When sized, the variable-camber intercontinental airplane required less wing area than the reference airplane. As a result, drag coefficient values for the variable-camber airplane are higher than for the reference airplane over much of the polar (fig. 40). Consequently, the variable-camber airplane has a higher L/D only when its C_L for $(L/D)_{MAX}$ is approached (fig. 41).

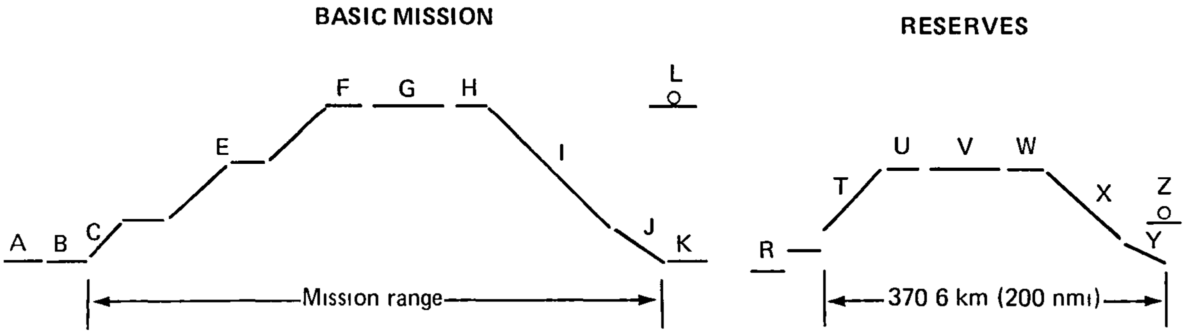
By contrast, the variable-camber domestic airplane A has greater wing area than the reference domestic airplane and, therefore, lower drag and better L/D over most of the useful (for cruise) range of lift coefficients. Variable-camber domestic airplane B, having approximately the same wing area as the reference domestic airplane, has a smaller L/D improvement than variable-camber domestic airplane A.

7.3 PERFORMANCE COMPARISONS AND CHARACTERISTICS

Following the airplane sizing studies (discussed in Section 5), gross weight and fuel requirements were established from detailed mission analyses.

7.3.1 MISSION ANALYSES

The detailed mission analyses followed the flight profile illustrated in Figure 42. During cruise (segment G, fig. 42) the airplane operates at the initial cruise altitude until it is both possible and advantageous to step climb an altitude increment of 1200m (4000 ft).



Mission	Segment	Comments	Mission	Segment	Comments
A	Taxi out	9 min at idle thrust	L	Reserves Extended cruise	Fuel flow x time at optimum Mach, end of cruise altitude 1 hr for medium range airplane, 10% trip time for international airplane
B	Takeoff	1 min at takeoff thrust			
C	Climbout	Accelerate to climb at V_c			
E	Climb	U S climb rules	R	Missed approach	2 min at takeoff thrust
F	Accelerate	Accelerate at constant altitude			
G	Cruise	Constant altitude or step cruise	T	Climb	U S climb rules
H	Decelerate	Decelerate at constant altitude	U	Accelerate	Accelerate constant altitude
I	Descent	U S descent	V	Cruise	Constant altitude cruise
J	Approach	0 052 rad (3 deg) glide slope	W	Decelerate	Decelerate at constant altitude
K	Taxi in	5 min at idle thrust	X	Descent	U S descent
			Y	Approach	
			Z	Hold	Fuel flow [457m (1500 ft), 30 min]

Figure 42. Flight Profile for Detailed Mission Analysis

A step climb is permitted when these conditions are satisfied:

- The rate of climb available is equal to or greater than 1.5 m/sec (300 ft/min) at rated maximum climb thrust and 0.5 m/sec (100 ft/min) at rated maximum continuous thrust.

- Greater range can be obtained by stepping up to the higher altitude.

Long-range flights may include several step climbs, provided these two conditions are met.

The initial cruise altitude for the mission analyses is the highest odd-numbered flight level (FL) for which the airplane can satisfy the rate-of-climb requirements defined above. Flight levels are specified for air transport operations in thousands of feet; thus, FL35 is equivalent to 10 670m (35 000 ft).

Because detailed evaluation showed the intercontinental airplane was not quite capable of meeting the climb requirements at 10 060m (33 000 ft) for which it was sized, the initial cruise altitude was 9 450m (31 000 ft).

Figure 43 shows the relative distributions of block fuel, reserves, operating weight, and payload for the intercontinental airplane operated at design range. The variable-camber intercontinental airplane required 3.1 percent less block fuel than the reference intercontinental airplane. Figure 44, which also includes block fuel reduction as a function of range, shows the relative effects of variable-camber drag improvements, excrescence drag reduction, wing size, and OEW differences at design range. Figure 45 presents fuel usage, calculated by major mission segment, as a function of range for the variable-camber intercontinental airplane.

The reference domestic airplane and variable-camber domestic airplane B commenced cruise at 10 670m (35 000 ft). Variable-camber domestic airplane A was sized at a higher T/W and, therefore, could initiate cruise at 11 280m (37 000 ft). Initial results of the detailed mission analysis for variable-camber domestic airplanes A and B showed block fuel savings of 4.0 and 0.4 percent, respectively. The larger saving for the domestic airplane A is primarily attributable to its lower excrescence drag and relatively larger wing area (lower wing loading) and the associated improvements in cruise L/D.

Design mission	Payload, kg (lb) Range, km (nmi) Mach number	196 passengers 18 850 (41 550) 10 200 (5500) 0.80	
Airplane		Reference airplane	Variable camber airplane
Weights, kg (lb)	TOGW	187 750 (413 910)	183 840 (405 290)
	OEW	92 290 (203 470)	90 640 (199 820)
	Block fuel	66 750 (147 150)	64 650 (142 530)
Wing	Reference area, m^2 (ft^2)	315.9 (3400)	285 0 (3068)
	W/S, N/m^2 (lb/ft^2)	5840 (122)	6320 (132)
Engine	SLST, N (lb)	98 930 (22 240)	95 280 (21 420)
	T/W	0 2149	0 2114
	Type	CF6-50C	
	Number	4	
	BPR	4 40	

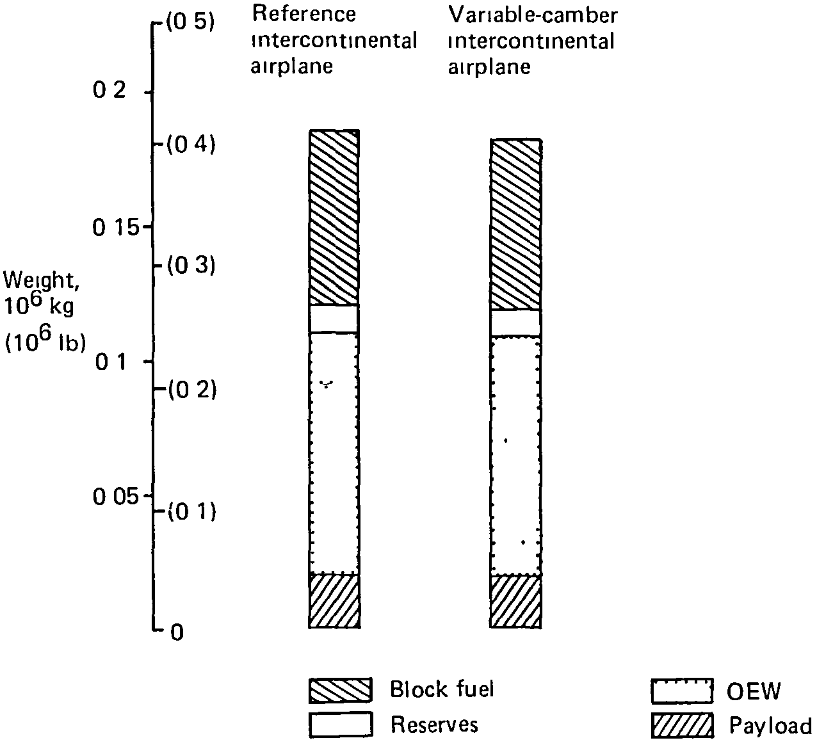


Figure 43. Sized Intercontinental Airplane Gross Weight Comparisons

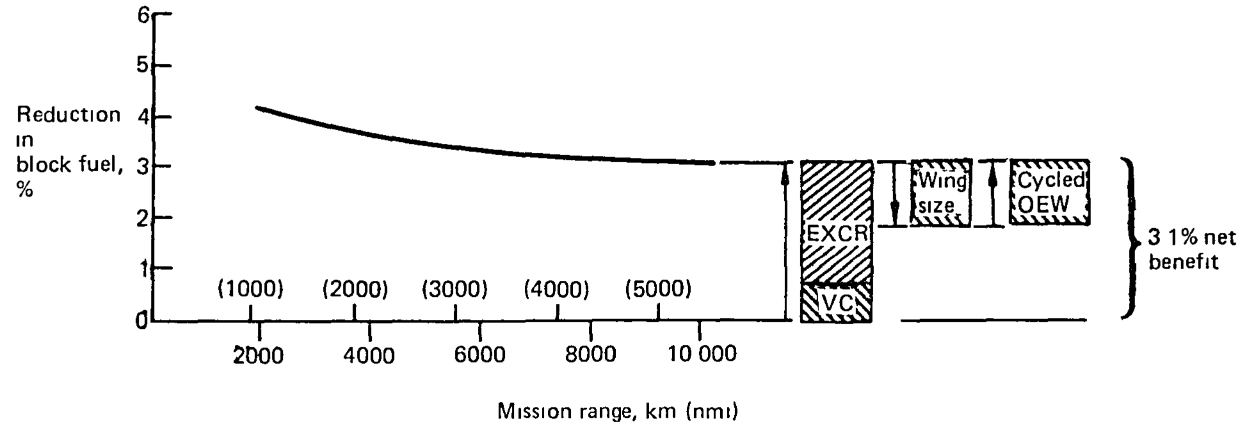


Figure 44. Block Fuel Reduction for Variable-Camber Intercontinental Airplane

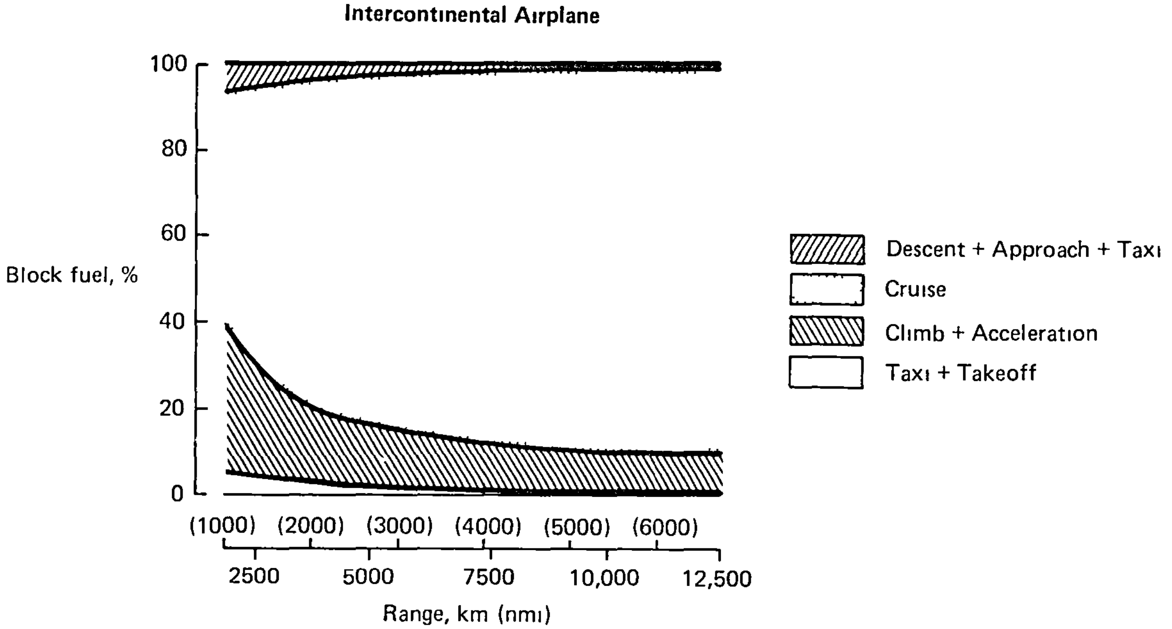


Figure 45. Airplane Fuel Usage—Variable-Camber Intercontinental Airplane

The additional weight of the larger wing does, however, reduce potential block fuel savings. Variable-camber domestic airplane B was sized at the same wing loading and T/W as the reference airplane (fig. 23). Both airplanes operate at lift coefficients below those for cruise $(L/D)_{MAX}$, so that the block fuel saving for variable camber is principally due to the excrescence drag reduction rather than improvements in drag polar shape. The block fuel benefits were also reduced by the higher OEW associated with the variable-camber features of domestic airplane B.

In summary, block fuel, reserves, operating weight, and payload for the domestic airplanes are presented in Figure 46. Figure 47 shows the variation in block fuel reduction with range and indicates the relative effects of variable-camber drag improvement, excrescence drag, and OEW differences at design range. Fuel usage of the domestic airplane, presented in Figure 48, also indicates the relative portions of block fuel for the major mission segments.

7.3.2 ALTERNATE MISSION ANALYSIS

The use of several example missions and associated sets of specific sizing constraints in a study of this type does not guarantee that the results will procuce a general evaluation of the potential benefits for applying a technology such as variable camber. In other words, the results apply to the specific mission studies and constraints used--not in every possible situation. Gaining a broader understanding of benefits potentially available requires developing an appreciation for how some of the "fixed" parameters influence the study results.

Accordingly, a short study for variable-camber domestic airplane B was undertaken to investigate the effects of cruise procedure and engine-rated thrust level on performance benefits potentially available from variable camber. Engine thrust rating (engine size) was allowed to vary up to +20 percent. The cruise procedures evaluated included:

- step-cruise, 10 670m (35 000 ft) through 11 890m (39 000 ft)
- constant-altitude cruise at initial cruise altitude capability
- climbing cruise at best cruise altitude

		Reference	Variable-camber A	Variable-camber B
Design mission		196 passengers		
	Payload, kg (lb)	18 230 (40 180)		
	Range, km (nmi)	3710 (2000)		
	Mach number	0 80		
Airplane		Reference	Variable-camber A	Variable-camber B
Weights, kg (lb)	TOGW	123 970 (273 300)	125 640 (276 980)	124 120 (273 700)
	OEW	76 850 (169 450)	79 600 (175 480)	77 160 (170 140)
	Block fuel	20 740 (45 720)	19 900 (43 880)	20 640 (45 520)
Wing	Reference area, m^2 (ft^2)	235 5 (2535)	255 5 (2750)	236 0 (2540)
	W/S, N/m^2 (lb/ft^2)	5170 (108)	4840 (101)	5170 (108)
Engine	SLST, N (lb)	164 270 (36 930)	170 100 (38 240)	164 310 (36 940)
	T/W	0 2703	0 2751	0 270
	Type	CF6-50C		
	Number	2		
	BPR	4 40		

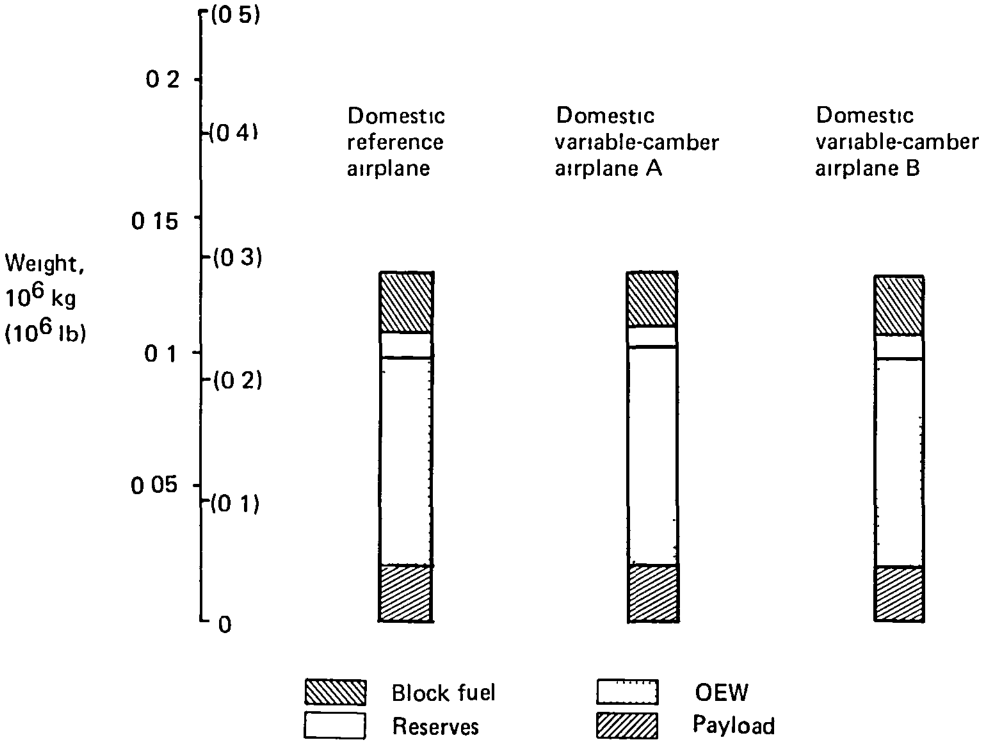
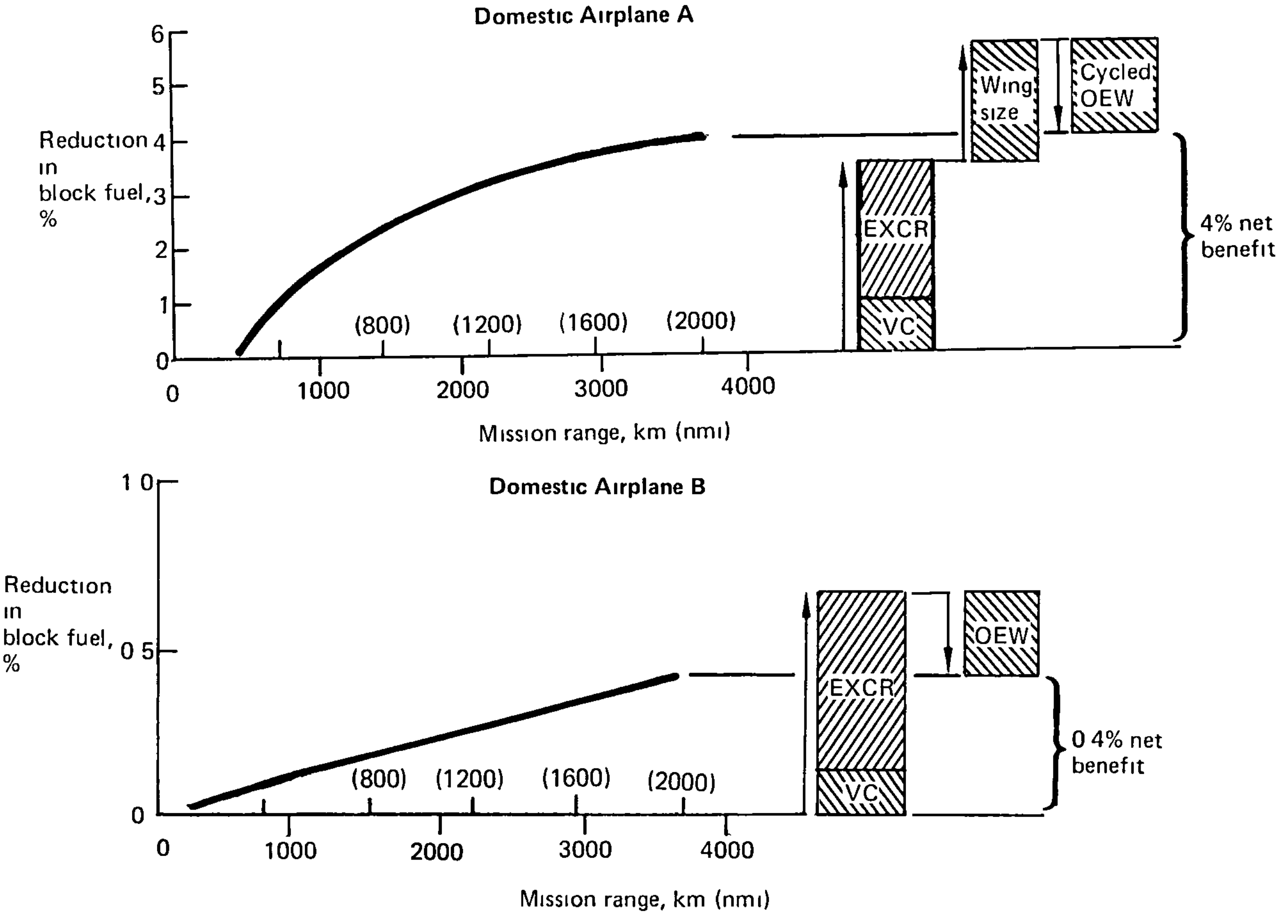


Figure 46. Sized Domestic Airplane Gross Weight Comparisons


Domestic Airplane A

Domestic Airplane B

Figure 47. Block Fuel Reduction for Variable-Camber Domestic Airplanes

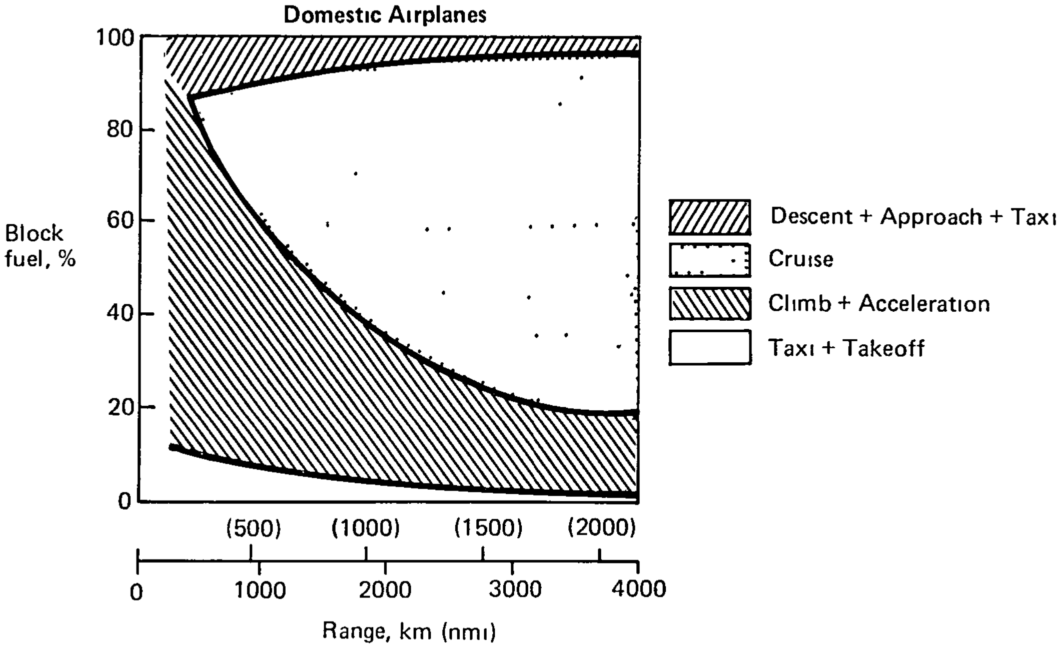

Domestic Airplanes

Figure 48. Airplane Fuel Usage—Variable-Camber Domestic Airplanes

The study results are included in Figures 49, 50, and 51. The summary of results presented in Figure 52 shows that the climbing cruise procedure produced the greatest block fuel reduction, 2.4 percent; constant altitude at ICAC, 1.6 percent reduction; and step-cruise, 0.4 percent reduction. It was also found that the variable camber fuel benefit increased slightly at a higher wing loading but the block fuel was greater than at the domestic airplane B design point. These block fuel reductions fall short of the aerodynamic improvements indicated in Figure 41 principally because of the OEW increment for variable camber and the greater drags and weights for the higher thrust ratings. With no increase in engine thrust ratings, block fuel reductions of 1.8, 0.6, and 0.4 percent are obtained for climbing cruise, constant altitude cruise at ICAC, and step-cruise operations, respectively (fig. 53).

This study indicates that the variable-camber domestic airplane B could potentially reduce block fuel by 2.4 percent with a climbing cruise procedure and a thrust rating 5 percent higher than that for which it was sized. The block fuel saving drops to 1.8 percent at the "sized" thrust rating. These figures represent the block fuel reductions potentially attainable for the domestic airplane B when an air traffic control system capable of handling climbing cruise air transport operations becomes available. Until then, air transport operations will continue in the constant altitude/step-cruise mode. Therefore, the principal study results are based on step-cruise procedures at odd-numbered flight levels.

7.4 AIRLINE ROUTE STRUCTURE

In actual practice, airplanes are seldom used at their design ranges. The complexity of airline route structures and schedules requires that a given type of airplane be assigned to operate over many different stage lengths. Since the fuel benefits of variable-camber airplanes vary with range, it is appropriate to consider the net result of operations over the entire distribution of flights for which the airplanes might be used.

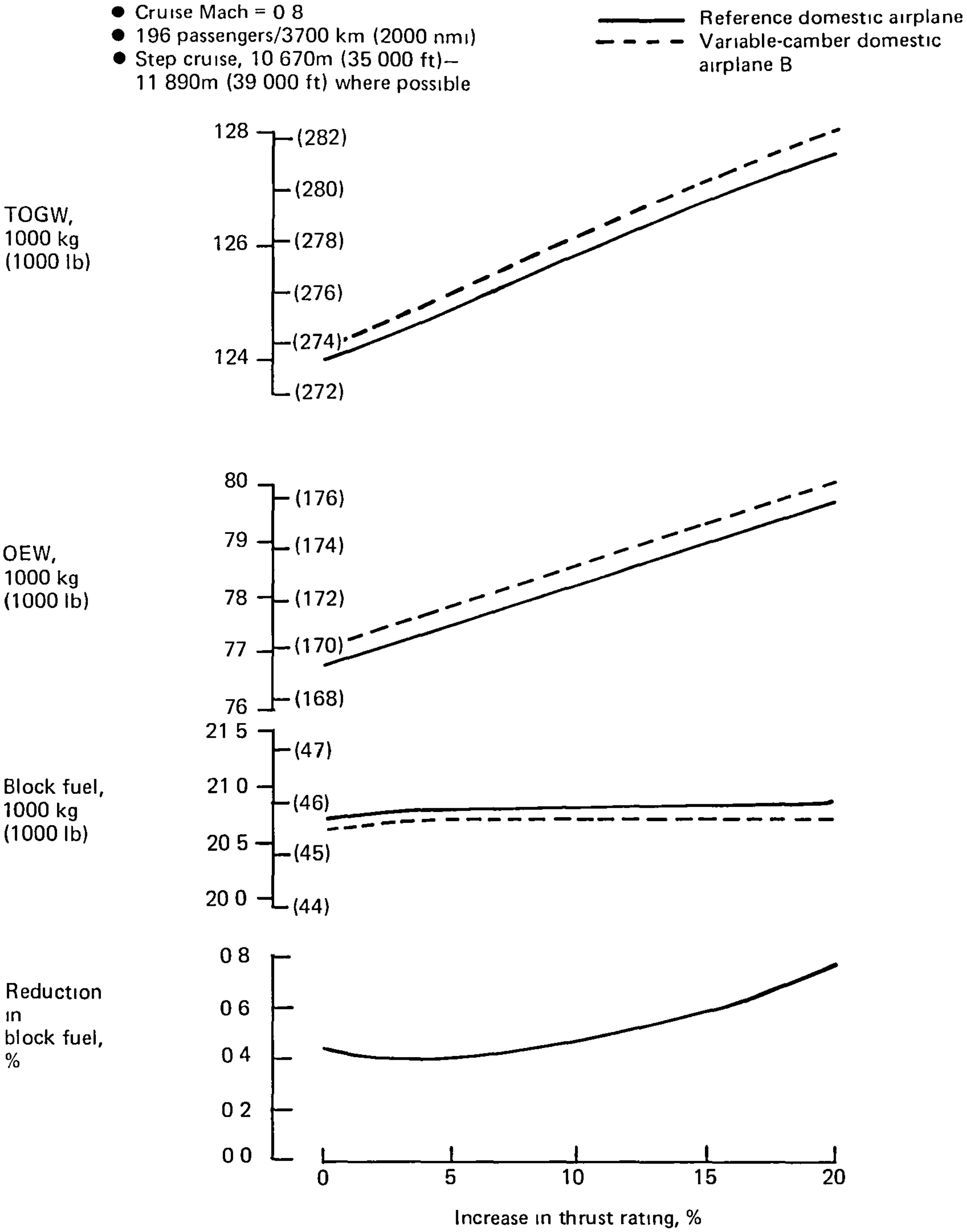


Figure 49. Effect of Engine Thrust Rating, Step-Cruise Procedure, FL35-FL39

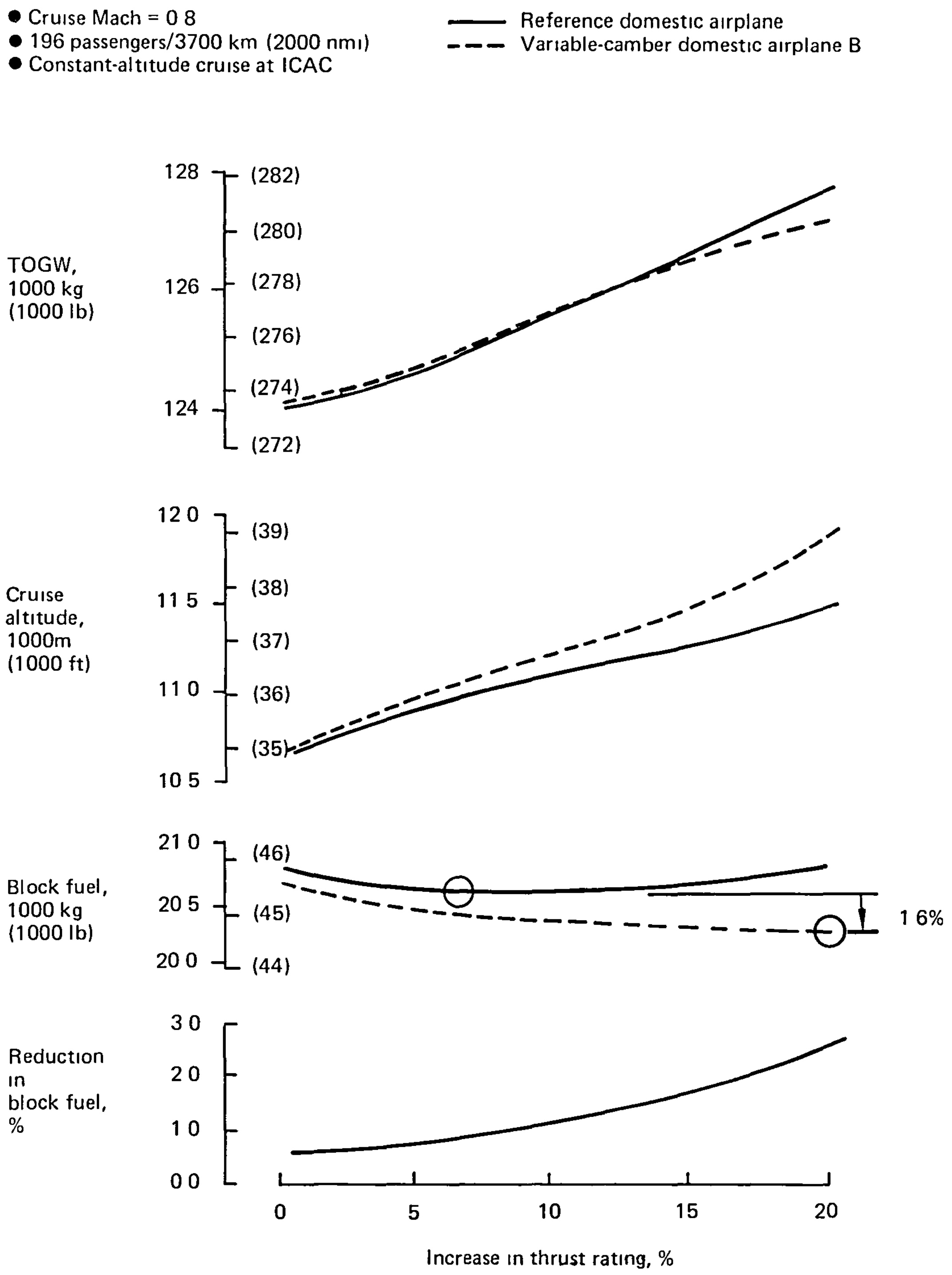


Figure 50. Effect of Engine Thrust Rating, Constant Altitude Cruise at ICAC

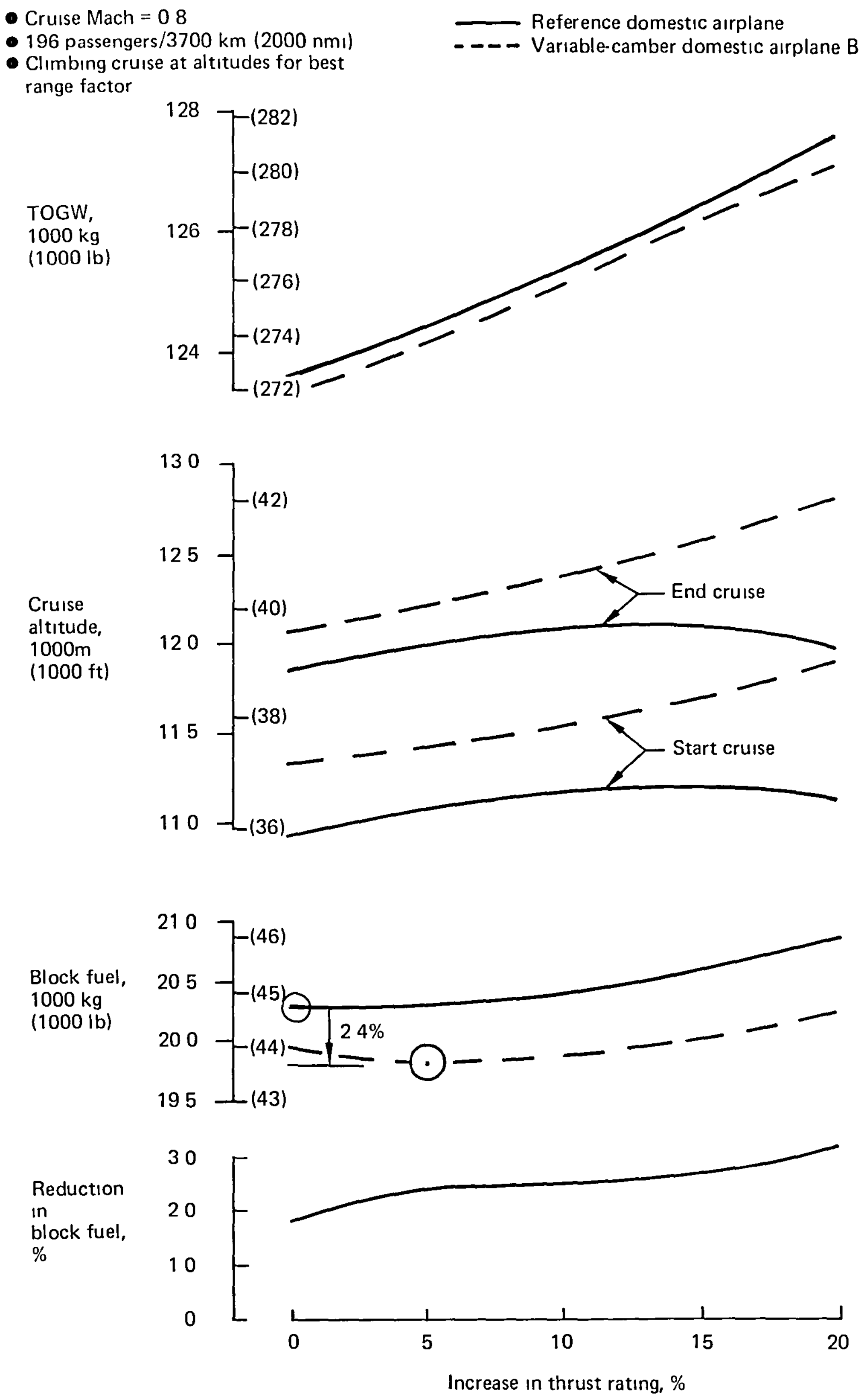
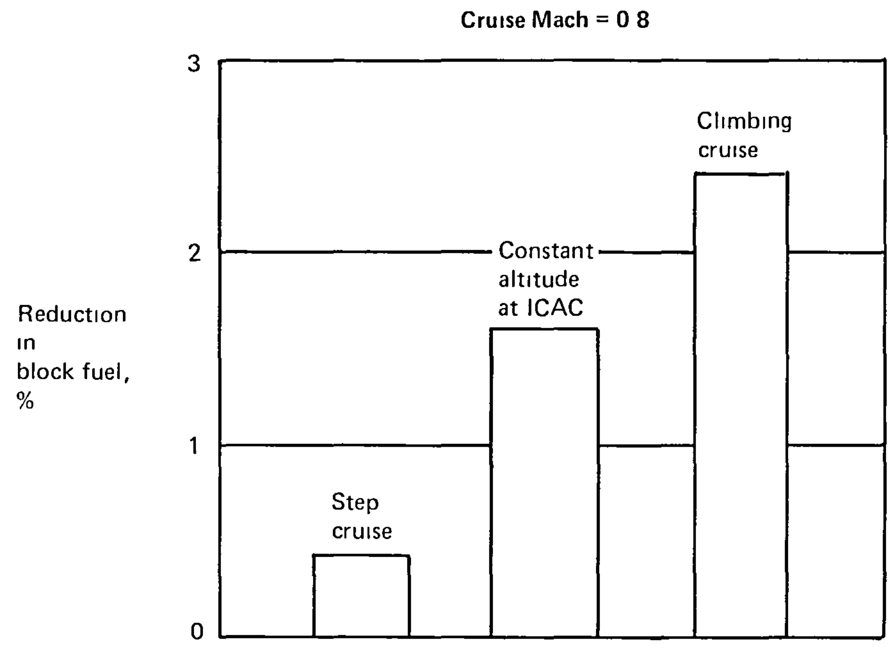


Figure 51 Effect of Engine Thrust Rating, Best Range Climbing Cruise



Relative thrust rating for minimum block fuel			
Reference	0%	+6.5%	0%
Variable camber	0%	+20%	+5%

Figure 52. Effect of Cruise Procedure at Thrust Rating For Minumum Block Fuel—Variable-Camber Domestic Airplane B

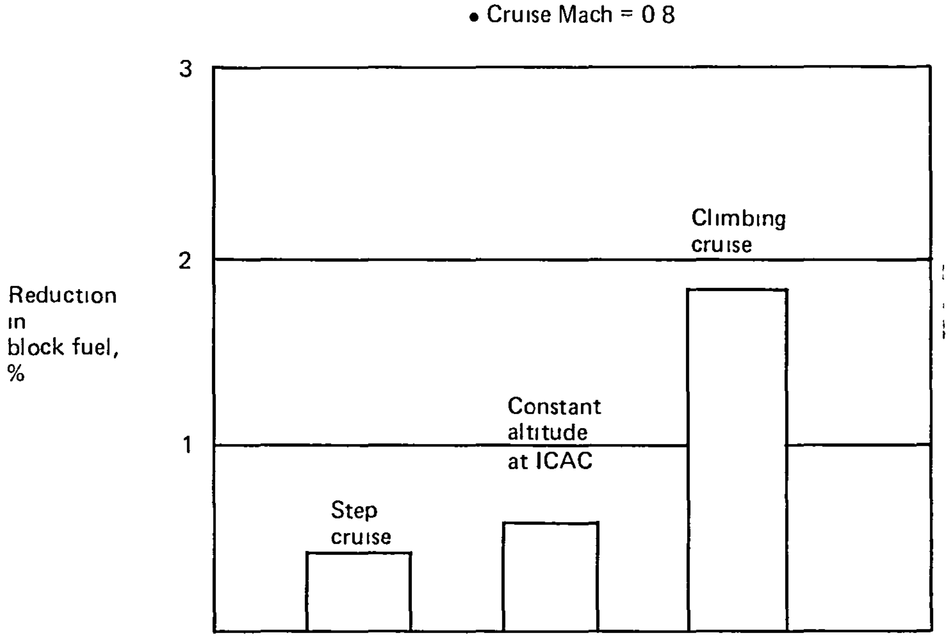


Figure 53. Effect of Cruise Procedure With Constant Thrust Ratings—Variable-Camber Domestic Airplane B

The distributions for both the intercontinental and domestic airplanes have average (mean) ranges of slightly more than one-third their design ranges, with a large proportion of flights at the shorter ranges. For domestic airplane A, this distribution means that the fuel savings at design range and average range would exceed the 1.5-percent saving experienced by operating over a typical route structure. However, fuel efficiency for the variable-camber intercontinental airplane, compared with the reference airplane, increases with decreasing range. Therefore, the fuel saving of 4.2 percent over a typical route structure would exceed the savings at the design range and the average range. The comparative fuel efficiencies of the variable-camber airplanes are listed in Table 5.

Table 5. Fuel Efficiencies

Airplane model	Fuel saving, %
● Intercontinental airplane	
• Design range, 10 200 km (5500 nmi)	-3.1
• Average range, 3700 km (2000 nmi)	-3.6
• Weighted average route structure	-4.2
● Domestic airplane A	
• Design range, 3700 km (2000 nmi)	-4.0
• Average range, 1170 km (640 nmi)	-1.9
• Weighted average route structure	-1.5
● Domestic airplane B	
• Design range, 3700 km (2000 nmi)	-0.4

7.5 ECONOMIC ANALYSIS

The objectives of the economic analyses were to: (1) determine the cost of manufacture and price to an airline for both the reference and variable-camber airplane configurations, and (2) incorporate these prices into an operating cost analysis to evaluate the relative economic benefits of variable-camber devices.

7.5.1 AIRPLANE COSTING AND PRICING

A standard costing method was used to evaluate the conventional portions of each airplane; determining the relative complexity of variable-camber devices was also considered in this method. For each airplane configuration, costs were then estimated for these elements:

- engineering hours
- developmental hours
- tooling hours
- production hours
- production material
- purchased equipment
- flight test
- engines
- labor and overhead rates

Costs were assessed for the conventional airplanes. The costs associated with the leading- and trailing-edge surfaces to be replaced by the variable-camber devices were isolated. The complexity of the variable-camber devices was estimated from design data comparisons, and the costs of the leading- and trailing-edge surfaces were adjusted appropriately. Commercial pricing incorporated the effects of program schedule, costs, receipts, and expenditures to establish a price that would yield a reasonable return on the manufacturer's investment.

7.5.2 OPERATING COST METHODS

Boeing operating-cost methods evolved from formulas published in 1967 by the Air Transport Association (ATA). Changes in airplane technology and in the airline operating environment, however, have made these ATA formulas obsolete. Although the basic formula structure has been retained, many changes have been made. Computerized data reporting and refined analytical techniques have sophisticated estimation of operating costs and other economic parameters.

These methods are intended primarily for economic comparison of airplanes and may be applied to any commercial-transport-type airplane carrying passengers, cargo, or both. The formulas have been updated for 1977, using data for U.S. airlines operating turbofan- and turboprop-powered airplanes. The data base consists of costs reported on the Civil Aeronautics Board (CAB) Form 41, with some engine maintenance cost data supplied by the engine manufacturers.

Consistent with the 1967 ATA formulas, the DOC method included maintenance formulas for computing airframe maintenance as a function of airframe weight and for computing engine maintenance as a function of flight time and thrust.

These maintenance formulas are now intended only to be used in parametric studies where individual maintenance estimates are not feasible for all incremental configurations. The OEW sensitivity analysis for this study used these maintenance formulas.

A refinement to the maintenance formulas was used whenever a specific configuration was defined. Maintenance costs were compiled on a subsystem basis, complying with ATA Specification 100. In forecasting maintenance costs for new airplanes, subsystems were compared against known subsystems, and cost adjustments were estimated to reflect new technologies. This approach was used for the airplanes considered in this study.

7.5.2.1 Engine Maintenance

Maintenance costs for the scaled study engines were estimated by factoring the maintenance costs that would be expected for a full-scale CF6-50C engine. Maintenance costs were reduced for lower gross weights (shorter ranges with lower fuel load) where the engines could be operated at derated thrust levels. Based upon estimated T/Ws, the required thrust was calculated at various flight lengths. A percent derate from maximum thrust was then determined, based upon empirical data, to establish the material dollar per flight hour and labor manhours per flight hour for the specific flight length (block time) being analyzed.

7.5.2.2 Airframe Maintenance

Variable-camber airplane maintenance was estimated using the basic ATA equations with adjustments to reflect anticipated higher maintenance costs associated with the variable-camber system. The major factors that contributed to the increased maintenance costs for ATA System 27 were:

- Leading Edge--A variable-camber wing has approximately the same number of links and joints as a curved 747-type Krueger flap, so complexity is comparable. However, accessibility for variable-camber maintenance is more difficult.

- Trailing Edge--The inboard flap on the variable-camber intercontinental airplane and domestic airplane A is single-slotted versus the double-slotted flap of the reference airplanes. Maintenance on variable-camber airplanes is estimated to be less than for the reference airplanes. However, the variable-camber trailing-edge system on the outboard wing is more complex than the conventional hinged aileron it replaces.

- Flexible Skin Fatigue Life--The skin selected for variable-camber application was a fiberglass epoxy sheet similar to what is currently employed in the flexible portion of the curved 747-type Krueger flap. Although the 747 panels have been tested for essentially infinite fatigue life, the range of deflections is less than required in the proposed variable-camber system.

These specific maintenance items, combined with the fact that the variable-camber system is actuated during all segments of the flight (rather than just takeoff and landing), results in higher estimated maintenance costs for the variable-camber system versus conventional leading- and trailing-edge devices.

The impact of the variable-camber devices on total airframe maintenance costs was small because (1) the leading- and trailing-edge devices account for only part of the ATA System 27 (flight controls) cost, and (2) as a whole, ATA System 27 comprises a relatively small portion of total airframe costs.

7.5.3 AIRPLANE DIRECT OPERATING COSTS

As the last step in the economic analyses, the DOCs for the variable-camber intercontinental airplane and domestic airplane A are compared as functions of range (fig. 54 and 55); all DOC data are for full payload. The shapes of the relative DOC curves follow the relative block-fuel curves shown in Figures 44 and 47. The relative values of DOCs are functions of block-fuel cost savings and changes in airplane depreciation and maintenance costs (airplane price and maintenance costs generally follow changes in airplane OEW and engine thrust).

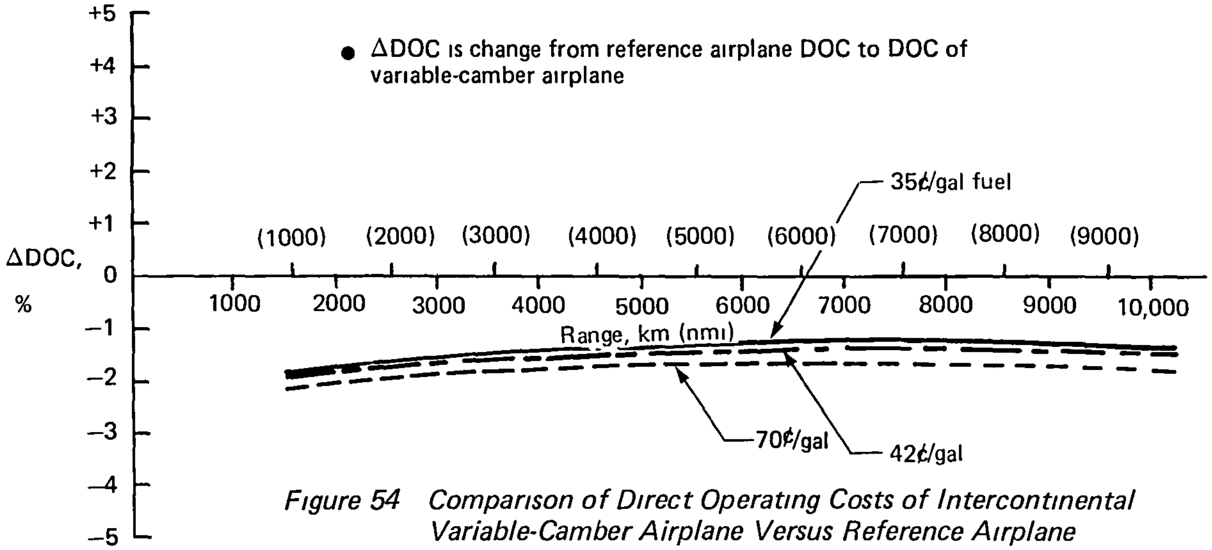


Figure 54 Comparison of Direct Operating Costs of Intercontinental Variable-Camber Airplane Versus Reference Airplane

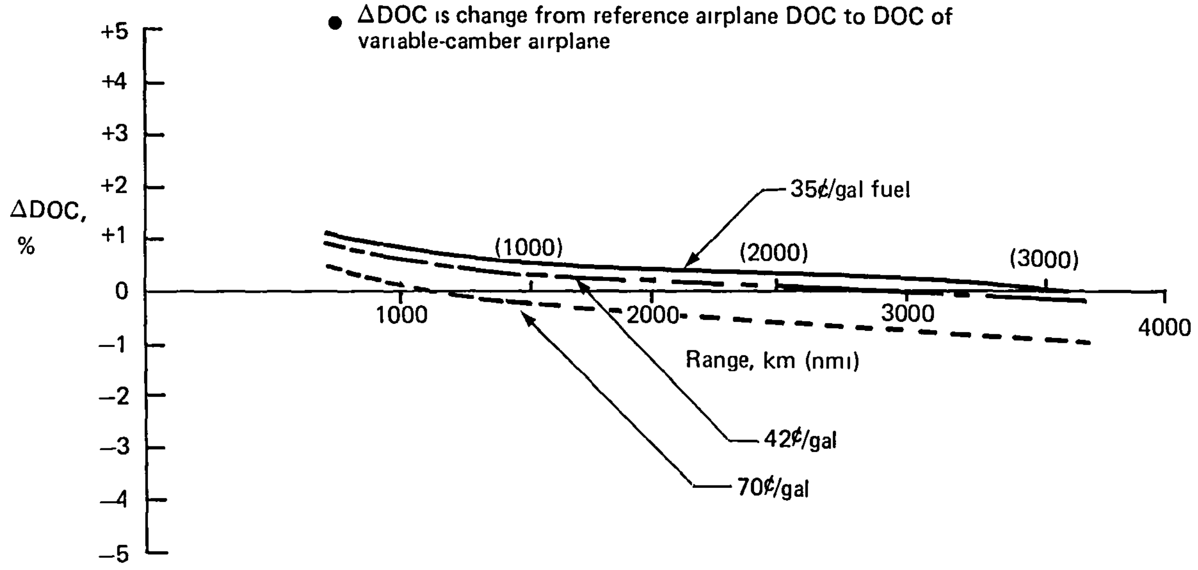


Figure 55 Comparison of Direct Operating Costs of Domestic Variable-Camber Airplane Versus Reference Airplane

Table 6 compares the relative DOCs, as a function of fuel cost, at design range, at average stage length, and for the weighted airline route system. The distribution of DOC elements for an average stage length mission is shown in Figure 56. The differences between the variable-camber and respective reference airplane cost elements are small.

Table 6. Direct Operating Costs Comparisons at Specific Ranges

Variable-camber airplane and range	Direct operating cost (DOC) % change from reference airplane		
	Fuel 35¢/gal	Fuel 42¢/gal	Fuel 70¢/gal
Intercontinental airplane			
Design range	-1.3	-1.5	-1.8
Average stage length	-1.5	-1.6	-2.1
Weighted airline route system	-1.2	-1.4	-1.7
Domestic airplane A			
Design range	+0.1	-0.2	-0.9
Average stage length	+0.7	+0.5	0
Weighted airline route system	+1.0	+0.8	+0.4
Domestic airplane B			
Design range	+0.1	+0.1	+0.1

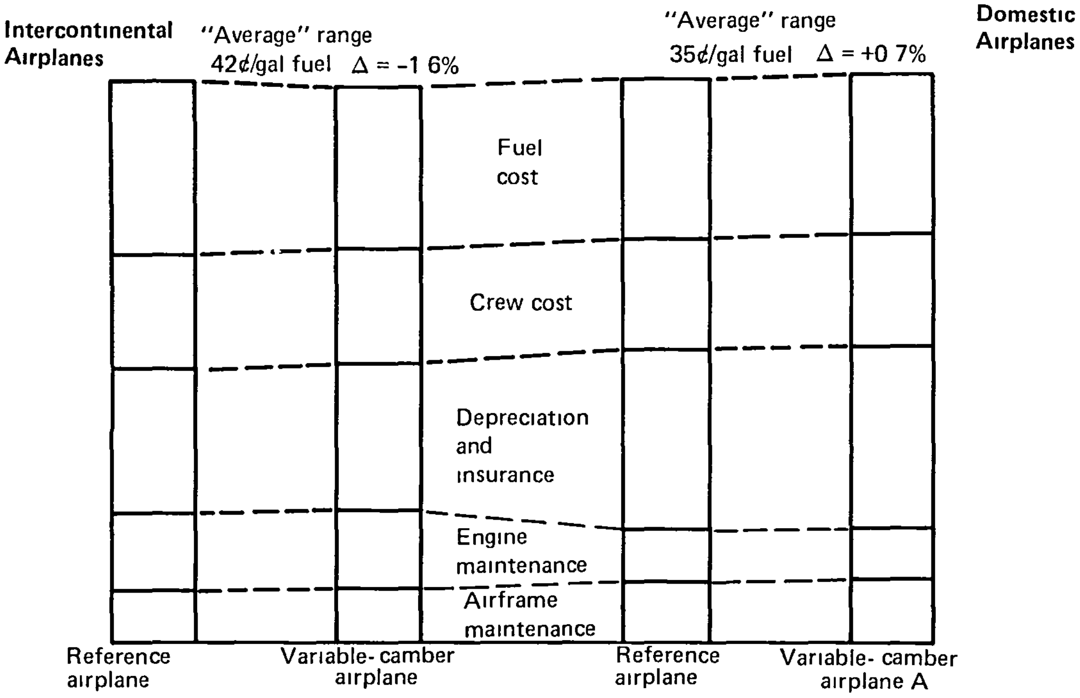


Figure 56 Direct Operating Costs Distribution

8.0 CONCLUDING REMARKS

This study has been carried out to assess variable camber for transport aircraft. Smoothly contoured variable camber was shown to be potentially useful by providing good aerodynamic efficiency over a range of lift coefficients within a wide speed range.

Variable camber was applied to contemporary intercontinental and domestic transport configurations for which well-defined baseline design characteristics were available. Both the reference and variable-camber transports were conventional subsonic configurations defined for either intercontinental missions of 10 200 km (5500 nmi) or domestic missions of 3700 km (2000 nmi) and for payloads of 200 passengers.

8.1 STUDY RESULTS

To implement variable camber, simple, reliable, low-maintenance mechanisms were designed to independently deflect the wing leading and trailing edge surface areas to provide: (1) small deflections to optimize wing camber during climb, cruise, and descent, and (2) large deflections to provide high lift for takeoff and during final approach. The resulting, internally located devices can camber as much as the forward 25 percent and the aft 45 percent of the wing chord to closely match the contours of a family of "point-design" airfoils considered optimum for the flight conditions of a commercial transport. The limits on camber deflection (from normal flight) averaged 30 deg down for the leading edge and 15 deg up to 20 deg down for the trailing edge. The continuous skin of the leading edge was flexed by the variable camber mechanism to maintain a constant leading-edge radius over the range of deflections. On the trailing edge surface the overall length of the upper skin surface remained constant, and an overlapping seal on the lower surface allowed articulation. An alternate trailing edge was designed to provide variable camber during high-speed flight, but conventional double-slotted flaps for enhanced high lift at low speeds.

For the intercontinental mission, both the reference and the variable-camber airplanes were sized to approximately the same design point with relation to optimum gross weight versus fuel burned. The potential fuel saving for variable camber was 3.1 percent at maximum design mission range and 4.2 percent when evaluated on the weighted average airline route structure. The direct operating cost (DOC) benefits (using 1977 operational costs and fuel price) were slightly less than 2 percent for both the design mission and the weighted average route structure.

For the domestic mission, the initial variable-camber transport design required more wing area than the reference configuration to meet the 125-knot design approach speed because of limitations in stall lift coefficient, even with the outboard variable camber ailerons drooped. The larger wing resulted in a greater empty weight but also higher cruise lift-to-drag ratio, principally because of a 0.0006 reduction in excrescence drag and the greater wing area. The fuel saving was evaluated as 4.0 percent at design range; however, this reduced to 1.5 percent for the weighted average airline route structure. There was no DOC benefit at design range and a 1 percent penalty for the weighted average route structure.

The empty weight increment for the greater wing area of the initial variable-camber domestic airplane was large enough (2750 kg) to prompt consideration of a second configuration having sufficient high lift capability to be free of the 125 knot approach speed constraint. Therefore, the study was broadened to include an alternate hybrid trailing edge which provided variable camber at small deflections during cruise flight, and double-slotted flaps at large deflections for low speed flight conditions. The hybrid arrangement provided sufficient lift to eliminate the need for additional wing area over that of the reference aircraft. However, the excrescence drag reduction (a principal part of the variable camber benefit) dropped to 0.00015 so that the values of cruise lift-to-drag ratio were only slightly higher than those of the reference aircraft at lift coefficients within the normal cruise flight regime. Consequently, the hybrid arrangement produced a fuel saving of only 0.4 percent and incurred a slight DOC penalty at design range.

8.2 TECHNICAL UNCERTAINTIES AND STUDY LIMITATIONS

The principal technical uncertainties barring immediate implementation of variable camber in air transport applications are aerodynamic, although there are also a number of potential problem areas in structural design and design integration.

A key assumption of this study follows a traditional swept wing design maxim that the high speed aerodynamic characteristics of a well-designed three-dimensional wing reflect the characteristics of the airfoil sections comprising the outboard 60 to 70 percent of it. The resulting hypothesis attributes to the wing the favorable aerodynamic lift and drag characteristics demonstrated with two-dimensional variable camber airfoils. At high speeds, near or below the cruise Mach number, the use of additional camber to attain higher lift coefficients before the onset of buffet is proven and accepted. However, at the design cruise lift coefficient and Mach number the use of camber as a design variable to improve cruise L/D over that attainable with a fixed geometry outboard wing has not been proven.

For this study, it was assumed that high speed polar shape and compressibility drag improvements could be attained without incorporating variable camber in the inboard part of the wing. Because of the compound curvature in the leading edge region of the inboard wing, mechanizing a variable-camber concept here is difficult. From an aerodynamic standpoint, a smooth transition from the variable-camber outboard wing to the inboard wing is probably required; however, the requirements for variable camber on the inboard wing are not determined at the present.

Significant portions of the fuel savings potential are attributable to reductions in excrescence drag as contrasted with the polar shape and compressibility drag improvements assumed for variable camber. Gaps or joints such as those for the leading edge Krueger flap and spoiler hinge line are among the excrescences which can be eliminated with incorporation of variable camber. Nevertheless, spanwise segmenting of both the leading- and trailing edges will be required to accommodate wing spanwise bending throughout the flight envelope. (No excrescence drag has been included to account for the gaps or joints between adjacent segments.)

Although several mechanical design concepts appear suitable for incorporating variable camber, there are several other major structural and design integration uncertainties in its application to transport aircraft. These include:

- Deflection Logic and Rate Requirements--The degree to which variable camber should be automated, particularly during high-speed flight, is highly uncertain. Elastic response characteristics of the leading- and trailing-edge portions of the wing may encourage flutter, and high deflection rates may be required to suppress the elastic modes. Also, a "short-period" variable-camber deflection scheme may be necessary for acceptable aircraft handling qualities and characteristics, especially near the boundaries of the flight envelope.

- Fatigue--Whether or not reasonable life expectancy can be anticipated for variable-camber surfaces greatly depends on how they are used.

- Segment Seals and Joints--As noted before, spanwise segmenting of the leading- and trailing-edge variable-camber surfaces is required to accommodate spanwise bending of the wing. Therefore, some design innovation may be required to effectively seal adjacent segments and capitalize on the reduced excrescence drag that can substantially contribute to potential fuel saving.

Based on the aerodynamic hypothesis noted above, the study also showed that variable camber could allow a new design having less sweepback of the wing and provide even greater improvements in aerodynamic efficiency below the design cruise Mach number. For example, unsweeping the wing quarter-chord line of the domestic airplane from 30 deg to 25 deg, in combination with variable camber, could increase aerodynamic cruise efficiency by 7.5 percent at all Mach numbers. However, systematic variations of wing sweep, aspect ratio, taper ratio, and other configuration features were not evaluated in this study but should be addressed in any future evaluations of variable-camber airplanes.

Examination of variable camber on complete aircraft configurations was limited to applications for intercontinental and domestic versions of contemporary reference transport designs. The efforts directed toward both the variable camber devices and their aerodynamic capabilities consisted of parametric studies to provide information for subsequent design studies of the contemporary configurations. Therefore, general information necessary to define alternate transport configurations best suited for fully exploiting variable camber was limited. Wing size was allowed to vary from the reference design but planform shape and distribution of airfoil thickness ratio remained the same. Variable-camber devices were limited to the outboard 65 percent of the wing span with conventional high-lift devices retained over the thickened inboard sections configured for landing gear storage.

Notwithstanding the uncertainties discussed above, variable camber may offer some significant advantages to the transport airplane designer and builder. For example, a set of trailing-edge variable camber surfaces can perform the functions which normally require an aileron, a set of spoilers and one or more Fowler flaps on the conventional transport airplane. Moreover, the potential versatility of variable camber may make the implementation of Active Control Technology for wing load alleviation, gust load alleviation, and elastic mode suppression simpler to accomplish.

8.3 RECOMMENDATIONS

Several areas which are key to implementing variable camber for improving the fuel efficiency of transport airplanes were identified and are recommended for additional effort:

1. The aerodynamic analysis used in this study included the hypothesis that the high-speed characteristics of a well, designed, swept (three-dimensional) wing reflect the characteristics of its two-dimensional airfoil sections comprising the outboard 60 to 70 percent. Although evidence exists to support this hypothesis, undebatable proof is not available. Investigations of this hypothesis with suitable theoretical and experimental programs are therefore recommended.

2. With establishment of the validity of the aerodynamic hypothesis, new airplane design studies should be undertaken. These should include evaluations of wing design parameters such as sweep, thickness ratio, aspect ratio and taper ratio to help determine how best to exploit variable camber.

3. Significant portions of the potential fuel savings are attributable to reductions in excrescence drag, contrasted with the polar shape and

compressibility drag improvements assumed for variable camber. Gaps or joints such as those for the leading-edge Krueger flap and spoiler hinge-line are among the excrescences that variable camber can eliminate.

Currently available excrescence drag data generally deal with single protuberances (gaps, forward- or aft-facing steps, etc.) but typical wing designs produce a series of excrescences, each experiencing the wakes of the upstream ones. Systematic investigations to enable meaningful evaluations of downstream excrescences are therefore recommended.

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15 Supplementary Notes

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16 Abstract

This study was conducted to determine the potential benefits of variable camber for commercial transport airplanes designed for intercontinental and domestic missions. During the study a variable camber concept was developed and incorporated into airplanes designed for the two missions. Benefits were evaluated by comparing the mission performance and direct operating costs for the variable camber airplanes with those for reference airplanes designed for the same missions but having fixed geometry high speed wings. Several technical uncertainties associated with implementing variable camber are discussed and recommendations for future research effort and studies are presented.

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