NASA Contractor Report 3519

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project

Final Act Configuration Evaluation

Staff of Boeing Commercial Airplane Company

CONTRACT NAS1-15325
FEBRUARY 1982

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Final Act Configuration Evaluation

Staff of Boeing Commercial Airplane Company
Boeing Commercial Airplane Company
Seattle, Washington

Prepared for
Langley Research Center
under Contract NAS1-15325

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1982

FOREWORD

This document constitutes the final report of the Final ACT Configuration Evaluation, which was performed as task 4.2.3.4 of Contract NAS1-15325.

The NASA Technical Monitor for this task was D. B. Middleton of the Energy Efficient Transport Project Office at Langley Research Center.

The work was accomplished within the Preliminary Design Department of the Vice President–Engineering organization of the Boeing Commercial Airplane Company. Assistance in economic analysis was obtained from the Vice President–Strategic Planning organization of the Boeing Commercial Airplane Company. Key contractor personnel who contributed were:

G. W. Hanks	Program Manager
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C. C. Flora	Task Manager (Final ACT Evaluation)
K.A.B. Macdonald	Reliability and Cost Analysis
M. T. McIntosh	Structures Technology
R. B. Snodgrass	Economic Analysis
J. S. Kautzky	Economic Analysis

During this study, principal measurements and calculations were made in customary units and were converted to Standard International units for this document.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

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1.0 SUMMARY

This report presents the results of an evaluation of the reliability, economics, and technical risk of the Final ACT Configuration. This configuration is the end product of the configuration development tasks of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project. The objective of this work was to determine the effect on fuel efficiency and economics of designing a 200-passenger, medium-range commercial transport airplane to take maximum practical advantage of Active Controls Technology (ACT).

The reference configuration, referred to as the Conventional Baseline Configuration, was a modern, state-of-the-art transport airplane. It was balanced for conventional longitudinal stability margins and had a wing aspect ratio of 8.7.

The Final ACT Configuration took advantage of ACT to allow balance at a more aft center-of-gravity range and with a smaller horizontal tail area and also to minimize the wing structural weight penalty resulting from increasing the wing aspect ratio to 12. Relative to the Baseline Configuration, the Final ACT Configuration used 10% less block fuel at design range, of which 6.5% is attributed to ACT and 3.5% to the increase in wing span.

An economic evaluation of the Final ACT Configuration was performed using standard Boeing 1980 domestic cost methods. The results indicated an incremental return on investment of approximately 25% for the Final ACT Configuration at a fuel price of \$0.26/ℓ (\$1.00/gal).

Reliability analyses showed that the ACT functions could be mechanized without significant adverse effect on dispatch reliability. The system also met the hardware reliability requirement for extremely remote probability of failures that results in loss of function; i.e., less than 1×10^{-9} per 1-hr flight for the crucial pitch stabilization function. However, the prediction methodology available does not account for the probability of software error or other possible generic fault causes.

The airplane performance benefits identified by the IAAC Project are the result of a degree of dependence on control system function that is well beyond that of any currently certified commercial airplane. Commitment to commercial application will require additional development and testing, both laboratory and flight, to remove technical risks identified in this study. These risks are principally in the areas of system tolerance of software faults and in control surface effectiveness for large-amplitude and high-frequency surface deflections.

2.0 INTRODUCTION

Although active controls have had limited application in several commercial transports, those applications typically were made either to overcome an unanticipated difficulty or to add capability to the airplane. A considerable body of evidence suggests that the greatest benefit from applying ACT to a transport airplane will result from incorporating ACT early in the design process. Although this evidence strongly indicates a benefit, it lacks verification; there have been no commercial transport airplanes where significant applications of ACT were incorporated into the initial design.

The principal objective of the IAAC Project, therefore, was to assess the benefits associated with design of a commercial ACT transport. During development of this benefit assessment, certain technical risks became clear. This led to the second objective of the IAAC Project, which was to identify technical risk areas and to recommend appropriate test and development programs. The final objective—to pursue resolution of these risk areas to the maximum possible extent within project resource limitations—is the focus of the current IAAC Project work because the potential benefit is significant.

2.1 IAAC PROJECT

The IAAC Project comprises three major elements, as discussed in Reference 1 and shown in Figure 1. The first, Configuration/ACT System Design and Evaluation, addressed design of an ACT transport, to specific design requirements and objectives (DRO), in sufficient detail to clearly identify the performance and economic benefits associated with the use of ACT. This airplane design incorporated all beneficial ACT systems, with current technology implementation assumed, which yielded a performance and economic improvement.

In parallel, work was initiated on the second major element, Advanced Technology ACT Control System Definition, to identify potential improvements through use of optimal control law synthesis techniques and/or advanced technology components for the implementation of ACT systems.

Further details of the Wing Planform Study results and the Final ACT Configuration characteristics are contained in the IAAC Wing Planform Study and Final Configuration Selection final report (ref 2).

Following the benefits assessment, work will begin on the final major element, Test and Evaluation, to reduce selected real or perceived technical risks associated with implementation of ACT.

2.2 TECHNICAL APPROACH

The configuration development activity leading to the definition of the Final ACT Configuration has been discussed extensively in References 2 and 3. Details of the major configurations developed and a summary of their performance characteristics are given in Section 4.0.

A modern Conventional Baseline Configuration, without any significant application of ACT, was developed as a yardstick against which the benefits of ACT could be measured. The Conventional Baseline Configuration is illustrated in Figure 2, and its detailed characteristics are given in Reference 4. This reference airplane configuration also established the design mission for the ACT configurations. The technology of the ACT airplanes designed under this project was fixed at the level established by the baseline, except for ACT.

Airplane configuration design work proceeded under the assumption that any beneficial ACT function could be implemented with appropriate reliability and availability. The

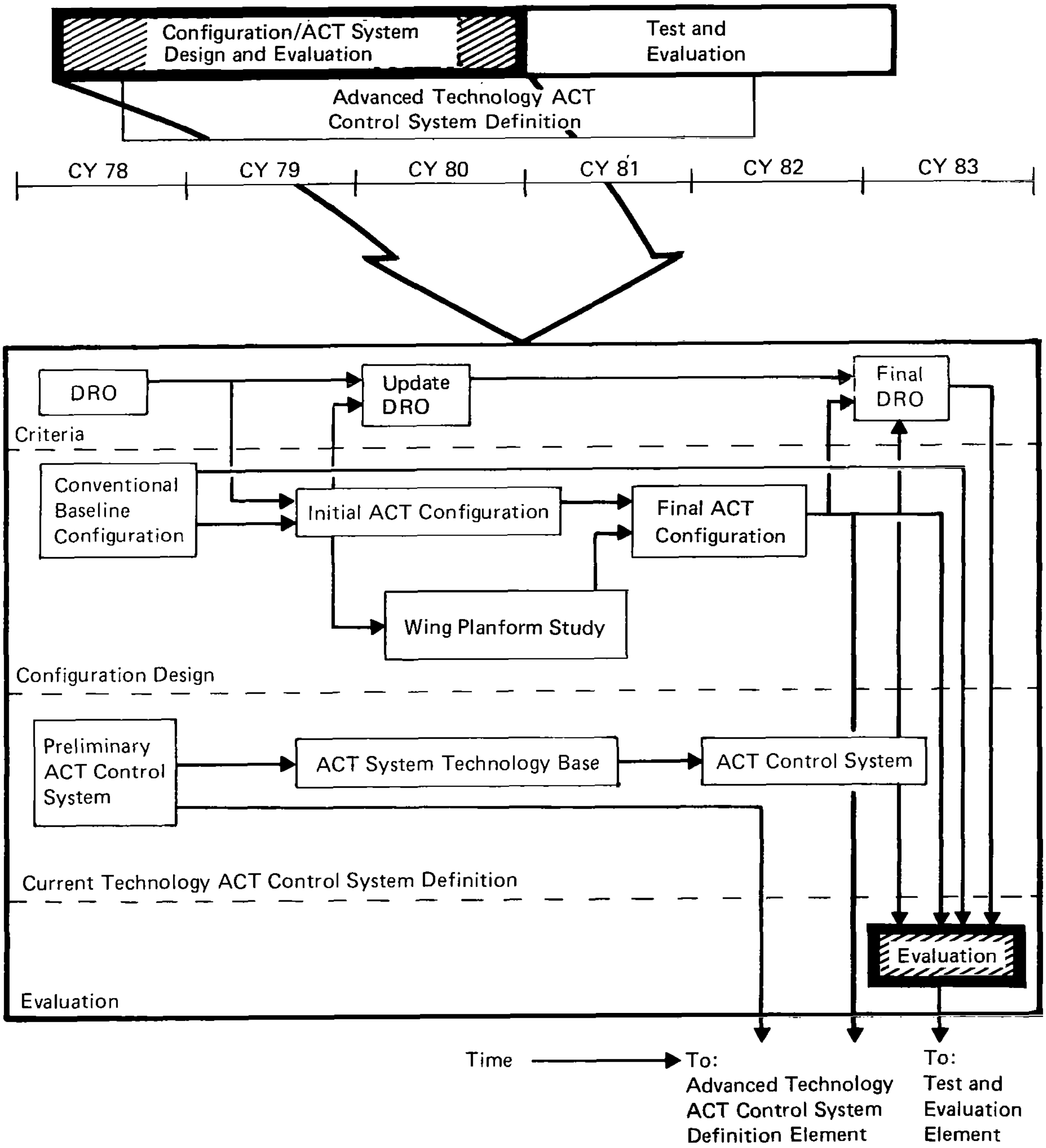


Figure 1. Relationship of Final ACT Evaluation Task to the Overall IAAC Project

Current Technology ACT Control System Definition Task proceeded in parallel to determine a suitable low-technical-risk implementation.

The configuration design has proceeded through the Initial ACT Configuration, the Wing Planform Study, and the Final ACT Configuration tasks, as shown in Figure 1. Figure 3 shows the Initial ACT Configuration; Figure 4 depicts the Final ACT Configuration. As shown in the performance summary in Section 4.0, the Final ACT Configuration has substantial improvements in fuel economy over the Conventional Baseline Configuration. The objectives of the Final ACT Evaluation Task reported herein are to determine what the resulting economic benefits to the airline operator would be and to evaluate the technical risks in designing the airplane and systems to meet the reliability requirements.

3.0 SYMBOLS AND ABBREVIATIONS

This section contains three subsections: Airplane Model Numbers, General Abbreviations, and Symbols. Each subsection is arranged in alphabetical order.

3.1 AIRPLANE MODEL NUMBERS

768-102	Conventional Baseline Configuration
768-103	Initial ACT Configuration
768-104	Study configuration, AR 12, Λ = 31.5 deg
768-105	Study configuration, AR 10, Λ = 31.5 deg
768-106	Study configuration, AR 10, Λ = 26.5 deg
768-107	Final ACT Configuration

3.2 GENERAL ABBREVIATIONS

ac	alternating current
app	appendix
AAL	angle-of-attack limiter (limiting)
ACT	Active Controls Technology
APB	auxiliary power breaker
APU	auxiliary power unit
AR	aspect ratio (based on trapezoidal wing planform area)
ASM	available seat-mile
ASN	assigned serial number
brkr	breaker
BBL	body buttock line
BOS	Logan International Airport (Boston)
BPCU	bus power control unit
BS	body station
BTB	bus tie breaker
BWI	Baltimore-Washington International Airport

BWL	body water line
cg	center of gravity
cm	centimeter
C	Celsius
CARE	computer-aided reliability estimates
CARSRA	computer-aided redundant system reliability analysis
CB	circuit breaker
CPU	central processing unit
CY	calendar year
C_L	lift coefficient
dc	direct current
deg	degree
DADC	digital air data computer
DOC	direct operating cost
DRO	design requirements and objectives
EWR	Newark International Airport (New Jersey)
f	function
fig.	figure
ft	feet
F	Fahrenheit
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FH	flight hour
FMC	flutter-mode control
FTREE	fault tree computer program
gal	gallon

GCB	generator circuit breaker
GCU	generator control unit
GLA	gust-load alleviation
hr	hour
in	inch
IAAC	Integrated Application of Active Controls Technology to an Advanced Subsonic Transport Project
IDG	integrated drive generator
INS	inertial navigation system
I/O	input/output
IRS	inertial reference system
JFK	John F. Kennedy International Airport (New York)
kg	kilogram
km	kilometer
kn	knot
kVA	kilovoltampere
K	thousand
lb	pound
LAS	lateral/directional-augmented stability
L/D	lift/drag
LD-(2,3,4)	lower deck containers (various sizes)
LE	leading edge
LRU	line replaceable unit
LSI	large-scale integration
LVDT	linear variable differential transformer
ℓ	liter
m	meter

min	minute
M	million
MAC	mean aerodynamic chord
MCDP	maintenance control and display panel
MEL	Minimum Equipment List
MIA	Miami International Airport
MIL-HDBK	military handbook
MLW	maximum design landing weight
MTBF	mean time between failures
nmi	nautical mile
N	newton
N/A	not applicable
Ni-cad	nickel-cadmium
OEW	operational empty weight
pwr	power
PAS	pitch-augmented stability
PCU	power control unit
PHL	Philadelphia International Airport
q	dynamic pressure
Q	body axis pitch rate
QPA	quantity per airplane
ref	reference
RADC	Rome Air Development Center
ROI	return on investment
ROM	read-only memory
sec	section

S/C	short circuit
SLST	sea-level static thrust
SOB	side of body
SSFD	signal selection and failure detection
STA	station
t/c	thickness-to-chord ratio
TE	trailing edge
TOGW	takeoff gross weight
TP	tangent point
TPA	Tampa International Airport
T-R	transformer-rectifier
V	voter
WL	water line
WLA	wing-load alleviation
yr	year

3.3 SYMBOLS

α	angle of attack
Δ	change in quantity
λ	failure rate
Λ	sweep
Σ	summation

4.0 CONFIGURATION DEVELOPMENT AND PERFORMANCE SUMMARY

4.1 CONFIGURATIONS

The following subsections briefly describe the three configurations developed in greatest detail during the IAAC Project.

4.1.1 CONVENTIONAL BASELINE CONFIGURATION (MODEL 768-102)

The Conventional Baseline Configuration is a modern, twin-engined, medium-range, turbofan-powered transport airplane. It has a passenger capacity of 197 in the standard mixed-class interior arrangement and a design range with maximum payload of approximately 3700 km (2000 nmi).

The principal characteristics of this airplane design are shown in Figure 2. Additional description, technical data, and analysis results are given in Reference 4.

4.1.2 INITIAL ACT CONFIGURATION (MODEL 768-103)

The Initial ACT Configuration was evolved from the Baseline Configuration with the constraints that both the wing planform and the airplane size (i.e., the maximum takeoff weight) remain unchanged. The resulting airplane uses pitch-augmented stability (PAS) and angle-of-attack limiting (AAL) and also incorporates detail changes in the main landing gear design to achieve a more aft balance range and reduced horizontal tail size with resulting improvements in trim and wetted area drag. Wing trailing-edge surfaces were reconfigured for load alleviation and structural mode stabilization, which allowed structural weight reductions in the wing.

The principal characteristics of the Initial ACT Configuration are shown in Figure 3. Additional description, technical data, and analysis are contained in Reference 3.

4.1.3 FINAL ACT CONFIGURATION (MODEL 768-107)

Recognition of the aerodynamic efficiency improvements possible by increasing the wing span and the potential of active control for reducing the structural weight penalties usually associated with such increased span led to the Wing Planform Study. Three configurations (Models 768-104, -105, and -106) with increased span were investigated. This investigation resulted in selection of the Final ACT Configuration with a wing aspect ratio of 12 as the most fuel-efficient design within the study constraints. The aspect-ratio 12 study configuration (Model 768-104) and the Final ACT Configuration (Model 768-107) are geometrically identical.

The principal characteristics of the Final ACT Configuration are shown in Figure 4. Reference 2 contains details of the Wing Planform Study and selection of the Final ACT Configuration.

4.2 PERFORMANCE SUMMARY

Figures 5 through 10 develop a comparison of the parameters determining fuel efficiency for the configurations investigated in the Wing Planform Study.

Geometry:

Body cross section, m (in)			
Shape	Vertical double lobe		
Maximum width	5.292 (198.00)		
Maximum height	5.410 (213.00)		
Landing gear	Nose	Main	
Type	Dual	Truck	
Location, m (in)	6.896 (271.50)	56% MAC	
Spacing, m (in)	0.609 (24)	1.143 x 1.422 (45 x 56)	
Tire size, m	0.939 x 0.330 -0.406	1.092 x 0.393 - 0.508	
(in)	(37 x 13-16)	(43 x 15.5-20)	
Oleo stroke, m (in)	0.381 (15)	0.457 (18)	
Aerodynamic surfaces	Wing	Vertical tail	Horizontal tail
Area, m^2 (ft^2)	256.3 (2759)[a]	57.4 (618)	57.6 (620)
Aspect ratio	8.71[a]	0.67	4.00
Taper ratio	0.267[a]	0.700	0.400
Sweep at c/4, deg	31.5[a]	55.0	35.0
Incidence, SOB, deg	3.8[a]	–	–
Dihedral, deg	6.0[a]	–	–
Root t/c, percent	15.1	12.0	11.0
Tip t/c, percent	10.3	12.0	9.0
Root chord, m (in)	8.567 (337.30)[a]	10.888 (428.69)	5.421 (213.45)
Tip chord, m (in)	2.286 (90.00)[a]	7.622 (300.08)	2.168 (85.37)
MAC, m (in)	6.031 (237.47)[a]	9.351 (368.17)	4.027 (158.55)
Span, m (in)	47.244 (1860.00)[a]	6.201 (244.14)	15.179 (597.61)
Tail arm, m (in)	–	19.972 (786.30)	27.134 (1068.30)
Tail arm, coefficient[b]	–	0.088	0.942

Engine toe-in angle—1 deg to a BBL

Nacelle incidence—2.625 deg to a BWL

Wing upper surface at side of body rib at WL 4.940m (194.5 in)

[a] Trapezoid geometry quoted: aero reference area = 275.1 m^2 (2961 ft^2)

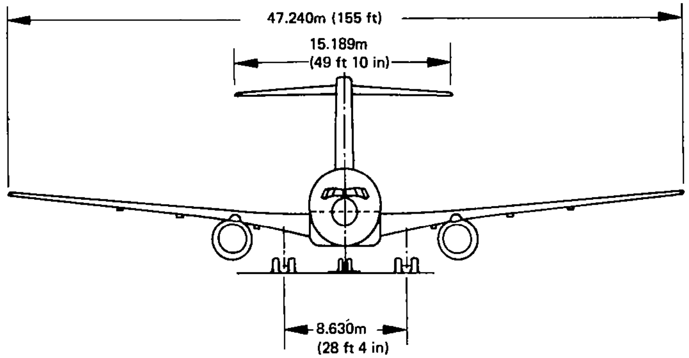
[b] Based on aero reference area

Passenger accommodations:	Passengers	Abreast	Pitch
First class	18	6	0.965m (38 in)
Tourist	179	7	0.864m (34 in)

Cargo and baggage, m^3 (ft^3):			
Containers	22 LD-2	or	11 LD-3
Forward	40.78 (1440)		26.85 (948)
Aft	33.98 (1200)		22.37 (790)
Bulk cargo (aft only)	11.33 (400)		11.33 (400)
Total	86.09 (3040)		60.55 (2138)

Weights, kg (lb):	
TOGW	122 470 kg (270 000 lb)
OEW	78 300 kg (172 610 lb)
MLW	112 570 kg (248 160 lb)

Propulsion: Two CF6-6D2



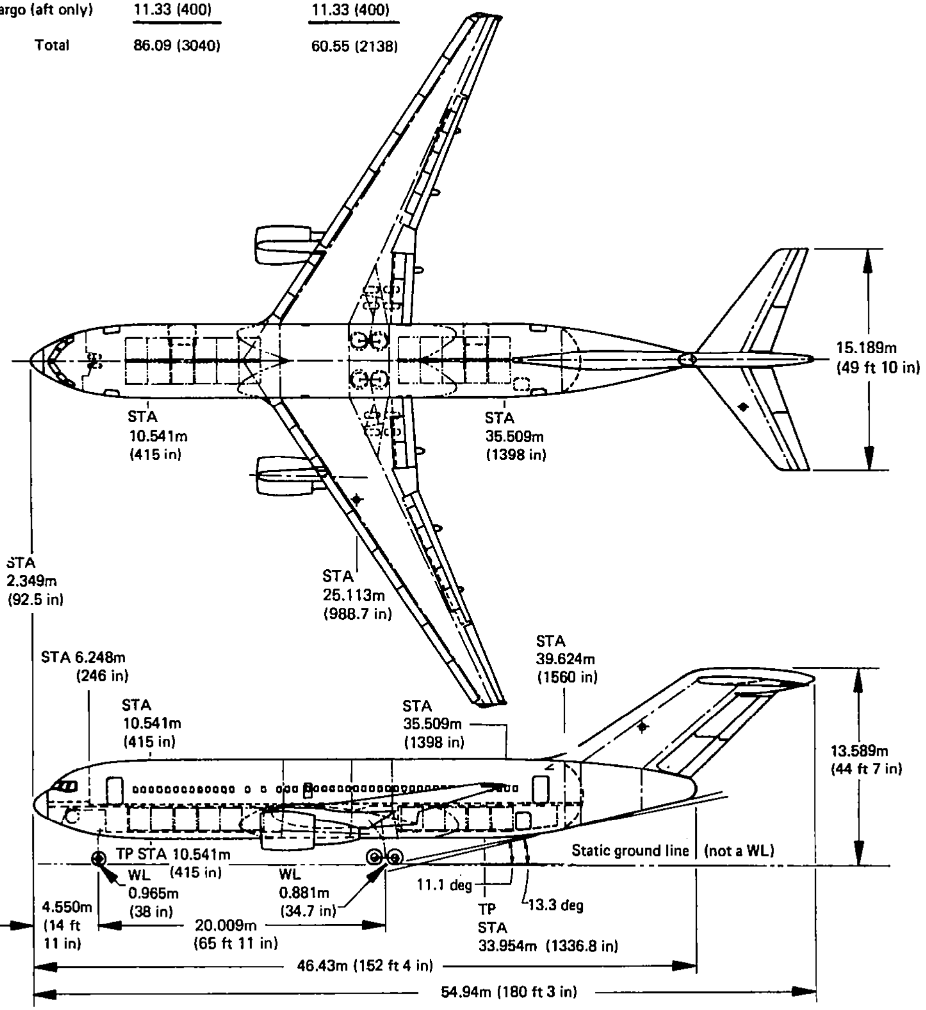


Figure 2. Conventional Baseline Configuration (Model 768-102)

Geometry:

Body cross section, m (in)			
Shape	Vertical double lobe		
Maximum width	5.029 (198.00)		
Maximum height	5.410 (213.00)		
Landing gear	Nose	Main	
Type	Dual	Truck	
Location, m (in)	BS 6.896 (271.50)	64.7% MAC	
Spacing, m (in)	0.609 (24)	1.143 x 1.422 (45 x 56)	
Tire size, m (in)	0.939 x 0.330-0.406 (37 x 13-16)	1.092 x 0.393-0.508 (43 x 15.5-20)	
Oleo stroke, m (in)	0.381 (15)	0.508 (20)	
Aerodynamic surfaces	Wing	Vertical tail	Horizontal tail
Area, m^2 (ft^2)	256.3 (2759)[a]	54.0 (581)	32.0 (344)
Aspect ratio	8.71[a]	0.67	4.00
Taper ratio	0.267[a]	0.700	0.400
Sweep at c/4, deg	31.5[a]	55.0	35.0
Incidence, SOB, deg	3.8[a]	–	–
Dihedral, deg	6.0[a]	–	-3.0
Root t/c, percent	15.1	12.0	11.0
Tip t/c, percent	10.3	12.0	9.0
Root chord, m (in)	8.567 (337.30)[a]	10.558 (415.74)	4.038 (158.98)
Tip chord, m (in)	2.286 (90.0)[a]	7.392 (291.01)	1.615 (63.59)
MAC, m (in)	6.031 (237.47)[a]	9.070 (357.07)	3.000 (118.10)
Span, m (in)	47.244 (1860.0)	6.014 (236.76)	11.306 (445.13)
Tail arm, m (in)	–	21.679 (853.50)	28.633 (1127.28)
Tail volume coefficient[b]		0.090	0.551

Engine toe-in angle = 1 deg to a BBL
Nacelle incidence = 2.625 deg to a BWL
Wing upper surface at SOB rib at WL 4.940m (194.5 in)

[a] Trapezoid geometry quoted: aero reference area = 275.1 m^2 (2961 ft^2)

[b] Based on aero reference area

Passenger accommodations:	Passengers	Abreast	Pitch
First class	18	6	0.965m (38 in)
Tourist	179	7	0.864m (34 in)

Cargo and baggage, m^3 (ft^3):			
Containers	22 LD-2	or	11 LD-3
Forward	33.98 (1200)		22.37 (790)
Aft	40.78 (1440)		26.85 (948)
Bulk cargo (aft only)	11.33 (400)		11.33 (400)
Total	86.09 (3040)		60.55 (2138)

Weights, kg (lb):	
TOGW	122 470 (270 000)
OEW	77 370 (170 560)
MLW	111 640 (246 110)

Propulsion: Two CF6-6D2

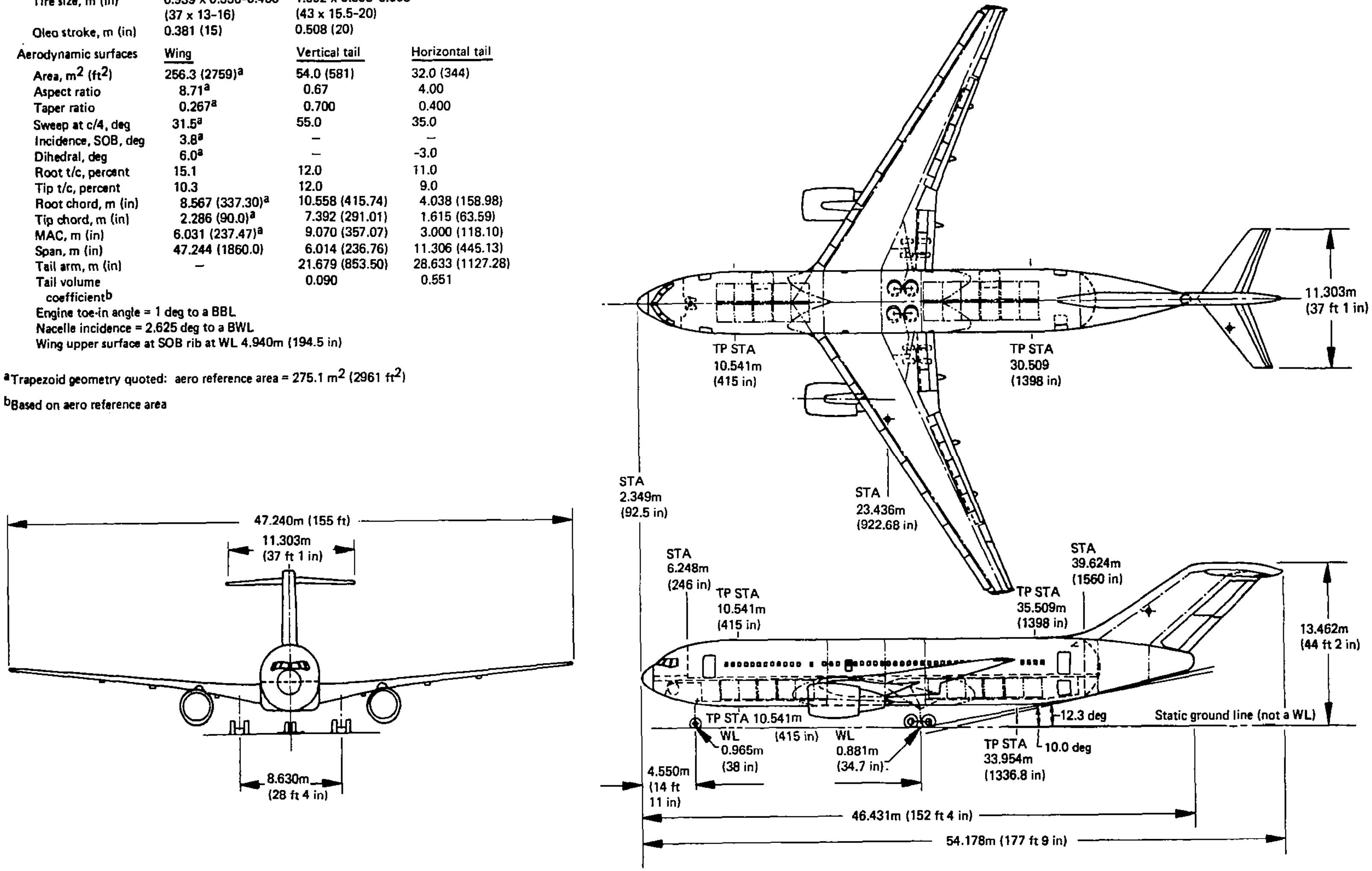


Figure 3. Initial ACT Configuration (Model 768-103)

Geometry:

Body cross section, m (in)

Shape	Vertical double lobe
Maximum width m (in)	5.029 (198.0)
Maximum height, m (in)	5.410 (213.0)

Landing gear	Nose	Main
Type	Dual	Truck
Location, m (in)	BS 6.896 (271.50)	72.4% MAC
Spacing, m (in)	0.610 (24)	1.143 x 1.422 (45 x 56)
Tire size, m (in)	0.940 x 0.330-0.406 (37 x 13-16)	1.092 x 0.394-0.508 (43 x 15.5-20)
Oleo stroke, m (in)	0.381 (15)	0.508 (20)

Aerodynamic surfaces	Wing	Vertical tail	Horizontal tail
Area, m^2 (ft^2)	226.8 (2441)[a]	56.6 (609)	32.0 (344)
Aspect ratio	12.03[a]	0.67	4.00
Taper ratio	0.267[a]	0.700	0.400
Sweep at c/4, deg	31.5[a]	55.0	35.0
Incidence, SOB, deg	3.8[a]	–	–
Dihedral, deg	6.0[a]	–	-3.0
Root t/c, percent	15.1	12.0	11.0
Tip t/c, percent	10.3	12.0	9.0
Root chord, m (in)	6.855 (269.89)[a]	10.811 (425.64)	4.038 (158.98)
Tip chord, m (in)	1.830 (72.06)	7.568 (297.94)	1.615 (63.59)
MAC, m (in)	4.827 (190.05)[a]	9.285 (365.57)	3.000 (118.10)
Span, m (in)	52.222 (2056)	6.157 (242.40)	11.291 (444.53)
Tail arm, m (in)	–	21.534 (847.78)	28.709 (1130.27)
Tail volume coefficient[b]	–	0.085	0.689

Engine toe-in angle = 1 deg to a BBL

Nacelle incidence = 2.625 deg to a BWL

Wing upper surface at SOB rib at BWL 4.953m (195 in)

[a] Trapezoid geometry quoted: aero reference area = 275.8 m^2 (2969 ft^2)

[b] Based on aero reference area

Passenger accommodations:	Passengers	Abreast	Pitch
First class	18	6	0.965m (38 in)
Tourist	179	7	0.864m (34 in)

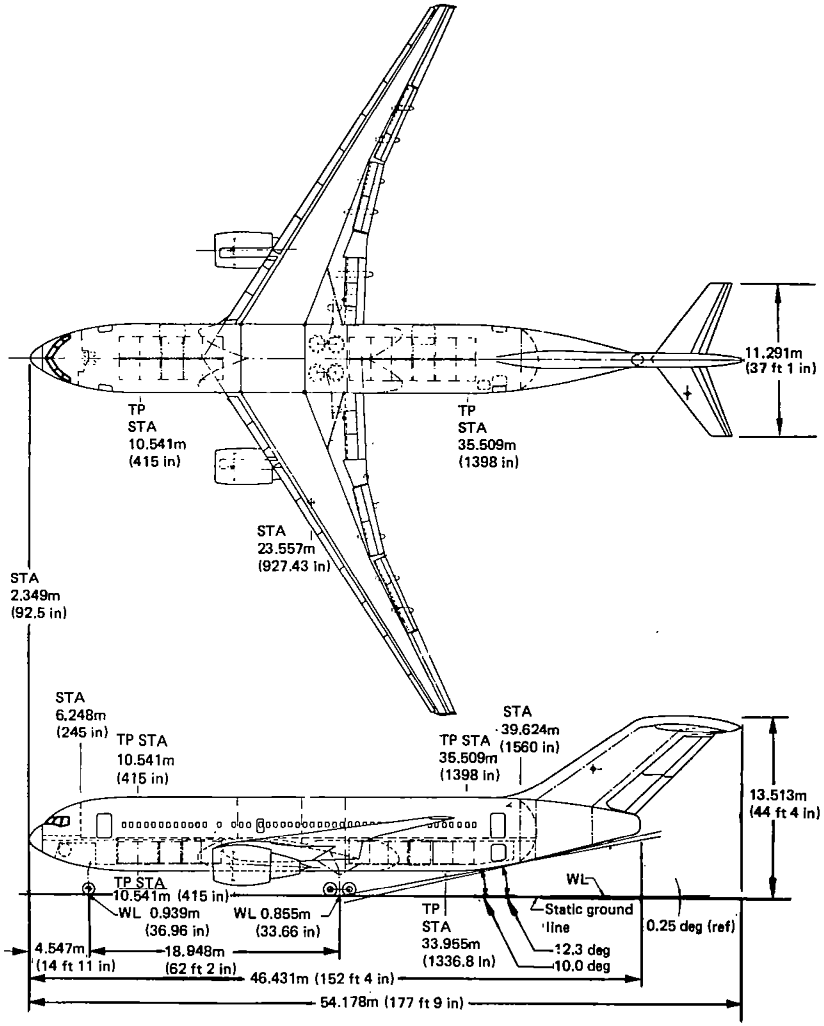
Cargo and baggage, m^3 (ft^3):

Containers	22 LD-2 or	11 LD-3 or	11 LD-4
Forward	33.98 (1200)	22.37 (790)	27.61 (975)
Aft	40.78 (1440)	26.85 (948)	33.13 (1170)
Bulk cargo (aft only)	11.33 (400)	11.33 (400)	11.33 (400)
Total	86.09 (3040)	60.55 (2138)	72.07 (2545)

Weights, kg (lb):

TOGW	121 580 (268 040)
OEW	79 890 (176 120)
MLW	114 160 (251 670)

Propulsion: Two CF6-6D2



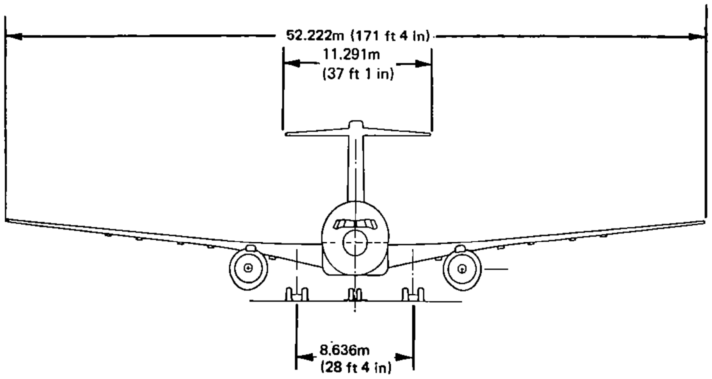


Figure 4. Final ACT Configuration (Model 768-107)

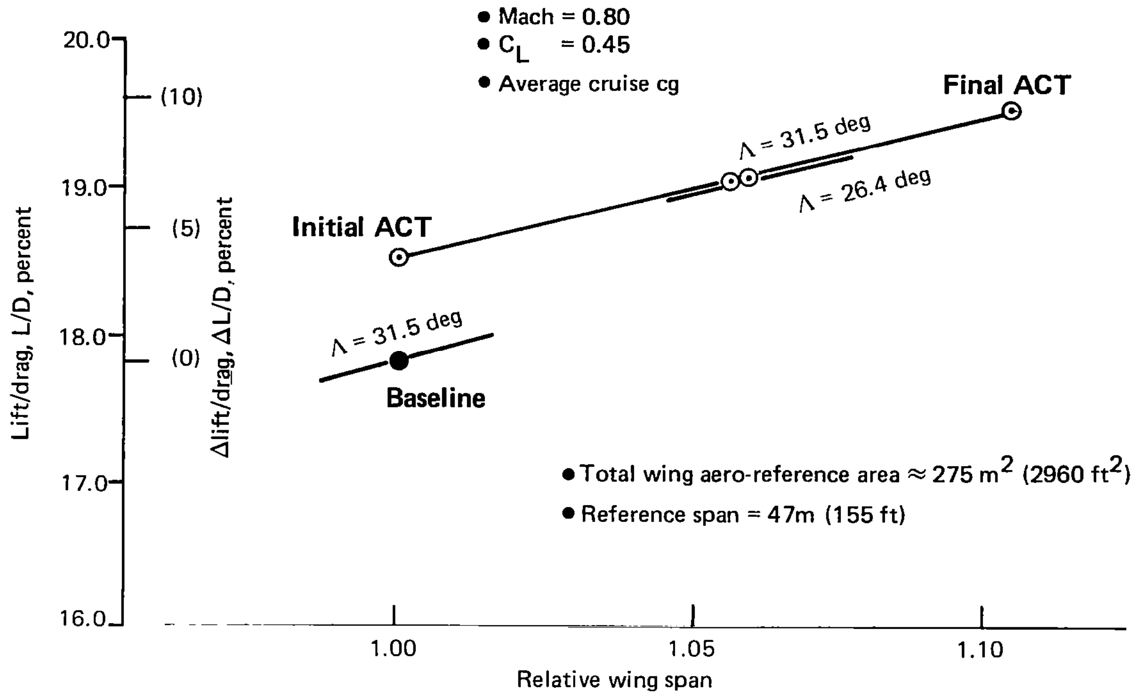


Figure 5. Effect of Wing Span on Cruise Lift/Drag

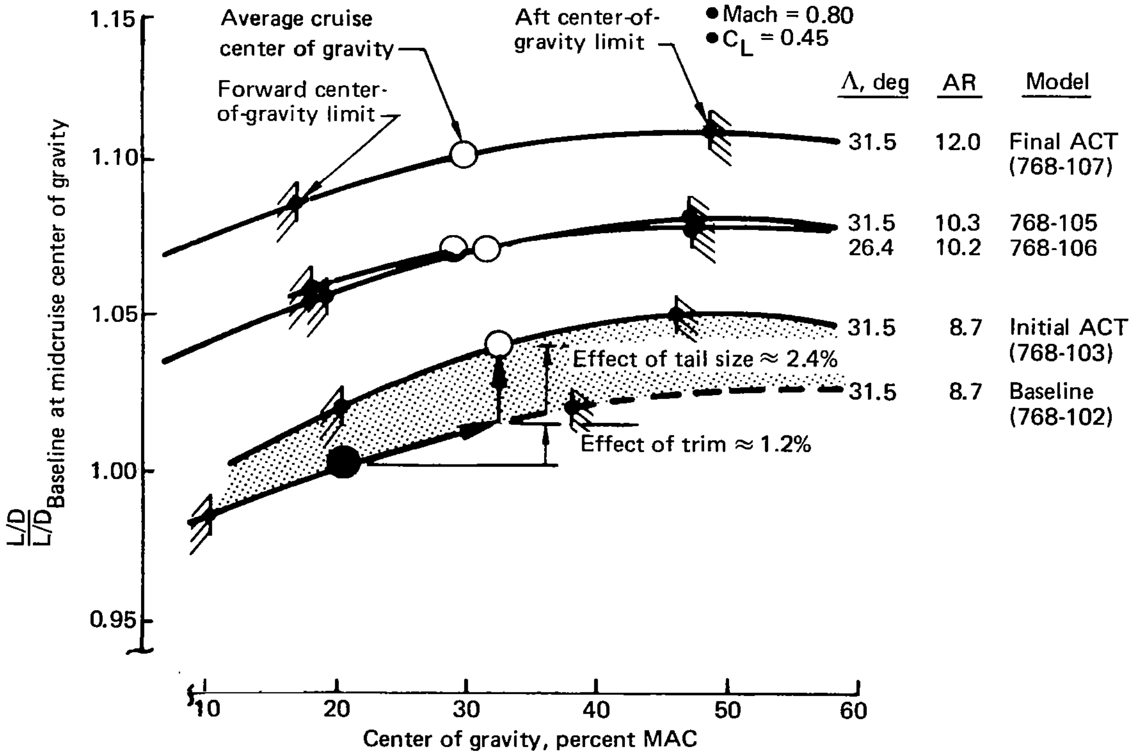


Figure 6. Relative Cruise Efficiency

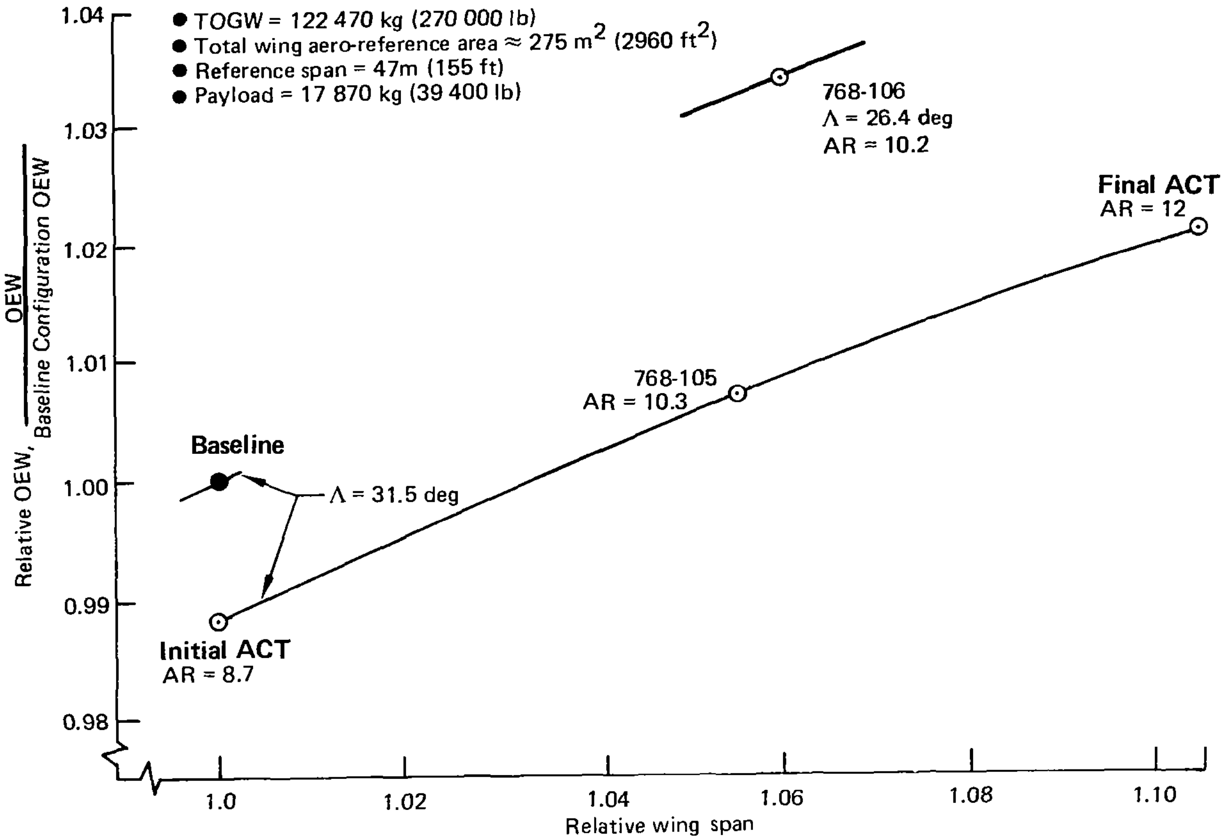


Figure 7. Relative Weights

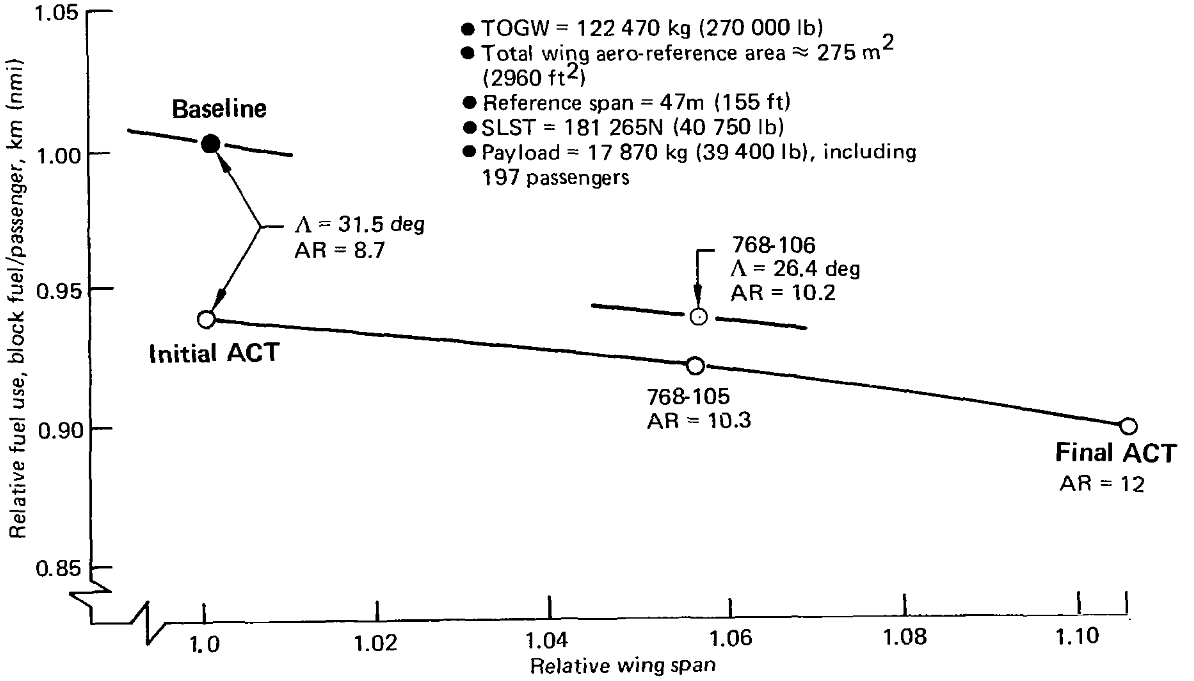


Figure 8. Relative Fuel Usage

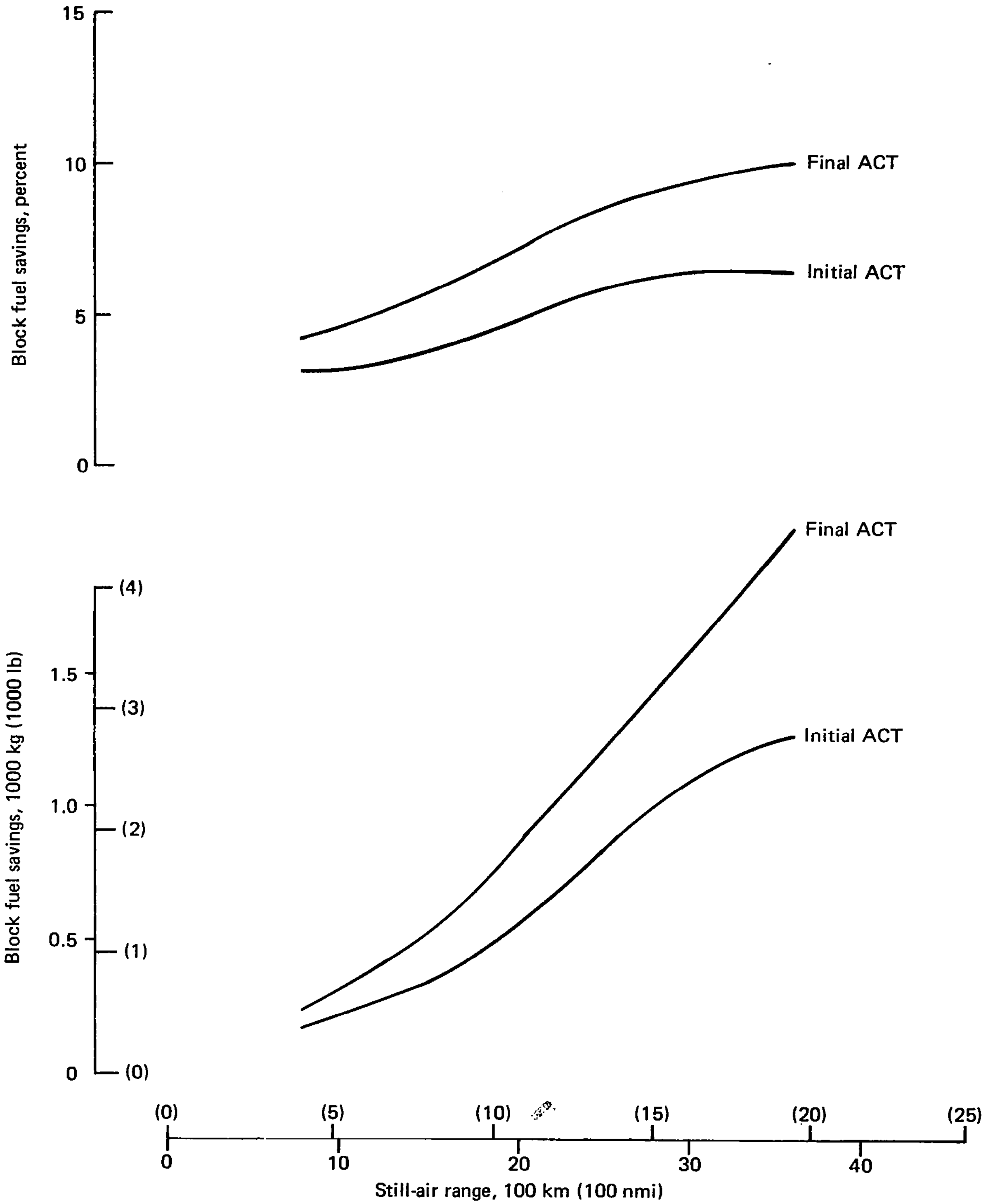


Figure 9. Block Fuel Savings of Final ACT and Initial ACT Relative to Conventional Baseline Configuration

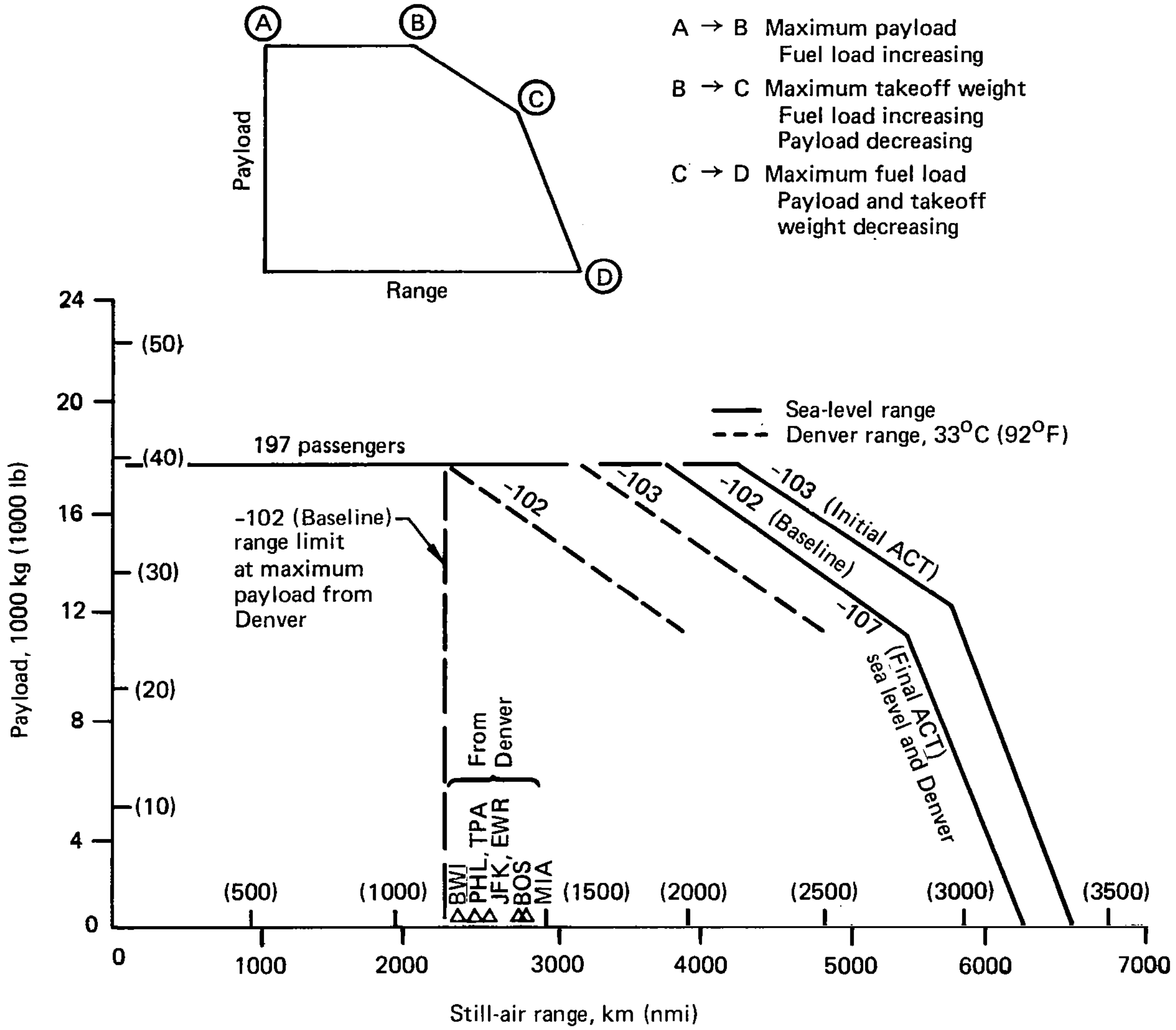


Figure 10. Payload Versus Range—Sea-Level and Denver Altitudes, Models 768-102, -103, and -107

Figure 5 shows the trend in aerodynamic efficiency (lift/drag [L/D]) with increasing span, with the Final ACT Configuration having approximately 10% increased cruise L/D over the Baseline Configuration. Data points are shown for the intermediate configurations of the planform study—768-105 and 768-106. The effect of sweep angle on L/D is negligible over the range studied. The Initial ACT Configuration, with the same wing planform as the Baseline, has nearly 4% improvement in L/D relative to the Baseline. This is due to the rebalance and reduced horizontal tail size made possible by ACT, as shown in Figure 6. This figure plots cruise L/D as a function of center-of-gravity position for the configurations studied. L/D values are normalized to that of the Baseline Configuration at its average cruise center of gravity. Of the 10% improvement shown by the Final ACT Configuration, about 4% is due to the rebalance and reduction in tail size and the remaining 6% due directly to increased span.

The adverse effect of span increase is increased structural weight required, principally in the wing primary structural box. Figure 7 shows that the Final ACT Configuration operational empty weight (OEW) is about 2% greater than the Baseline OEW. The effect of wing-load alleviation (WLA) is indicated by the relative positions of the Initial ACT and Baseline Configurations on this plot. Figure 7 also shows the large weight penalty for the reduced-sweep configuration studied. This weight penalty is due to the wing thickness reduction required to maintain the same cruise Mach number.

Figure 8 shows the net effect of aerodynamics and structural weight changes on fuel efficiency. The aerodynamic and weight increments from the Baseline Configuration are favorable and result in about a 6% reduction in fuel burn relative to the Baseline Configuration. The Final ACT, with its better aerodynamic efficiency offsetting its weight increase, shows approximately 10% improvement in fuel efficiency relative to the Baseline.

Fuel burn was compared at the maximum range, where the aerodynamic improvements in cruise L/D have greatest effect. At shorter ranges the relative improvements are smaller, as shown in Figure 9, which gives block fuel savings, both absolute and in percentage, relative to the Baseline Configuration for the Initial and Final ACT Configurations. Fuel savings are significant, and the Final ACT Configuration maintains its superiority at all ranges.

Figure 10 shows payload versus range for the Baseline, Initial ACT, and Final ACT Configurations; the format of these curves is explained in the inset. For sea-level takeoff conditions, the Final ACT Configuration has been resized to achieve the same range with maximum payload as the Baseline. The Initial ACT, which was not resized, shows greater range at maximum payload. For high-altitude airports, typified by the Denver conditions shown, the Baseline and Initial ACT Configurations have reduced maximum takeoff weights due to climb performance limitations, which result in reduced range capability. The Baseline Configuration does not have range capability from Denver to reach the indicated east coast destinations with maximum payload. The Final ACT Configuration, due to its increased span, has no climb performance limitations at Denver conditions and thus maintains full payload-range capability.

5.0 RELIABILITY EVALUATION

The reliability evaluation presented here is limited to the ACT system. As described elsewhere, the Baseline and Final ACT Configurations have similar system configurations, with the exception of ACT.

The Final ACT control system is described fully in Reference 2 and shown schematically in Figure 11. Four central frame-synchronized digital computers control all ACT functions, which are:

- The quadruply redundant essential PAS function, which stabilizes the short-period pitch mode by driving three secondary actuators that position the main elevator power control unit servovalves, based on a simple fixed-gain control law. The only sensor input required is pitch rate, which is obtained from the three inertial reference units and from a single, dedicated pitch-rate sensor. Level 3 handling qualities are thus provided. The equivalent of quadruple actuation redundancy is obtained by modeling the secondary actuator in each computer so that after two failures a single actuator and model will provide control.
- The triply redundant full PAS function, which stabilizes both the short-period and the phugoid instability by adding triply redundant airspeed signals to the essential PAS to provide level 1 handling.
- The triply redundant WLA function, which uses vertical acceleration at the airplane center of gravity to reduce maneuver-caused wing bending moments by deflecting the outer ailerons upward. To prevent this aileron movement from destabilizing the short-period and phugoid pitching modes, WLA cross feeds to the PAS secondary actuators.
- The AAL function, which uses a dual-redundant stick pusher to overcome normal pilot elevator control force and thus prevents the airplane from entering deep stall. It uses triple angle-of-attack signals modified by pitch rate to provide protection in abrupt stall entry maneuvers.

The four central computers communicate with one another over dedicated data buses, which facilitates selection of the best sensor and actuator command and enables faulty components to be temporarily or permanently switched out. Such faults are recorded at the component level for future ground maintenance. Actuator outputs are force series summed with the pilot or autopilot control signals.

5.1 FAILURE CRITICALITY

The safety impact of failure of any ACT function depends on its necessity for continued safe flight or its function criticality level, defined as follows:

- Flight Crucial—Complete loss of function results in an immediate, unconditional hazard to safe and continued flight.
- Flight Critical—Complete loss of function results in a potential hazard to safe, continued flight, but appropriate flight crew action can avert the hazard.

- Non-Flight Critical—Complete loss of function may result in increased crew workload or passenger discomfort but does not result in a hazard to safe, continued flight.

- Dispatch Critical—Function is required for dispatch.

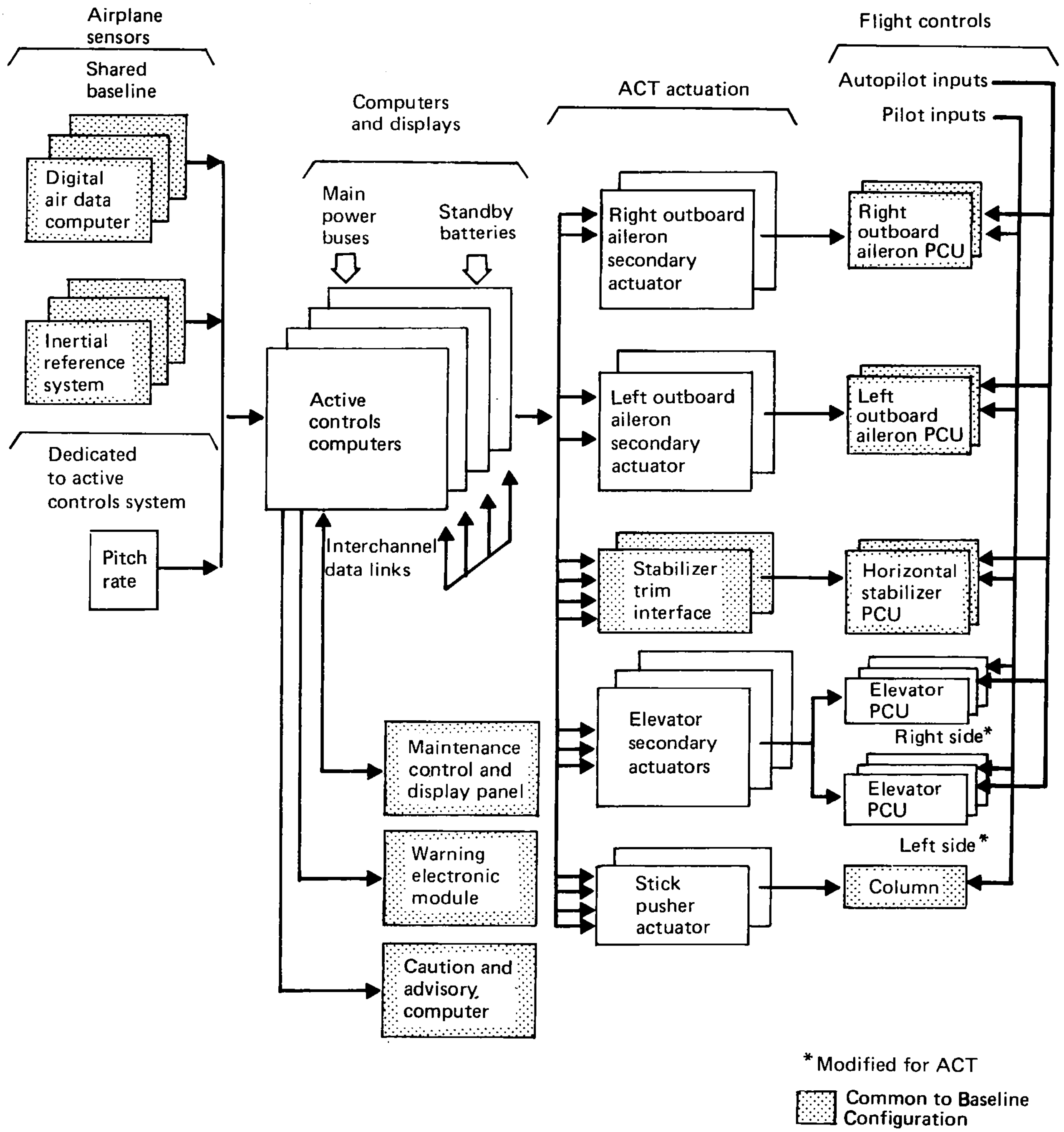


Figure 11. Final ACT System Architecture

5.2 IMPACT OF ACT FUNCTION LOSS ON FLIGHT SCHEDULE AND DISPATCH

Failures of the ACT system may delay or cancel airplane dispatch, or restrict flight, or necessitate diversion to another airport, depending upon the nature of the system failure.

The assumed airplane performance capability when ACT functions are partially or completely inoperative is described as follows:

- Essential PAS Loss—The airplane will be lost if essential PAS is lost in the air. If the function is lost on the ground, the airplane cannot be dispatched until the system is repaired. The pilot will divert to the nearest suitable airport when the system is one failure away from loss of essential PAS.

- Full PAS Loss—The airplane must be operated within a restricted flight envelope when the static stability augmentation of full PAS is lost. If the function is inoperative on the ground, the airplane can be dispatched into a restricted flight envelope.

- LAS (Yaw Damper) Loss—The airplane must be operated within a restricted flight envelope when lateral/directional-augmented stability (LAS) is lost in the air. If the function is totally inoperative on the ground, the airplane cannot be dispatched because LAS is required for limiting structural loads; however, the airplane can be dispatched into a restricted flight envelope with one channel of the LAS inoperative.

- AAL Loss—The airplane can continue a normal flight schedule after AAL is lost in the air, because such loss does not degrade airplane handling qualities within the operational flight envelope. However, the pilot will be informed of system status and will continue the flight with special caution. If AAL is inoperative on the ground, the airplane cannot be dispatched because of loss of safety margin. Inadvertent operation of the stick pusher could be catastrophic under some flight conditions and therefore must be as equally remote in probability as failure of a crucial function.

- Concurrent Loss of WLA, Yaw Damper, and Full PAS—Because the concurrent loss of WLA, yaw damper, and full PAS impacts handling qualities and at the same time reduces structural margins, the flight crew will divert to the nearest airfield when the system is one failure away from this condition.

5.3 RELIABILITY REQUIREMENTS

Reliability requirements for the Final ACT Configuration are based on Figure 1 of Reference 5, reproduced herein as Figure 12. Full compliance with all the "consequence of failure conditions" will finally depend on a detailed assessment of handling characteristics after function failures, which is not possible at this stage of design. To establish reasonable reliability requirements, the effects of failures described in Subsection 5.2 have been used in conjunction with Figure 12 to establish the failure probability requirements shown in Table 1.

5.4 ASSUMPTIONS OF RELIABILITY ANALYSIS

- Software reliability is assumed equal to 1.0.

- All equipment is assumed serviceable prior to each flight.

- A minimum of two operating channels is required for success.
- Coverage (probability of successful transfer) from quadruple to triple and from triple to dual is assumed equal to 1.0.

5.5 FLIGHT SCHEDULE RELIABILITY PREDICTION

Using the fault trees described in Appendix C and the failure rates listed in Appendix B, in conjunction with the fault tree (FTREE) computer program (appendix A), enabled prediction of the function failure rates shown in Table 2.

Comparison of the first and last column in the table shows that the Final ACT Configuration, including flap position indication as backup to the digital air data computer (DADC), meets all reliability requirements.

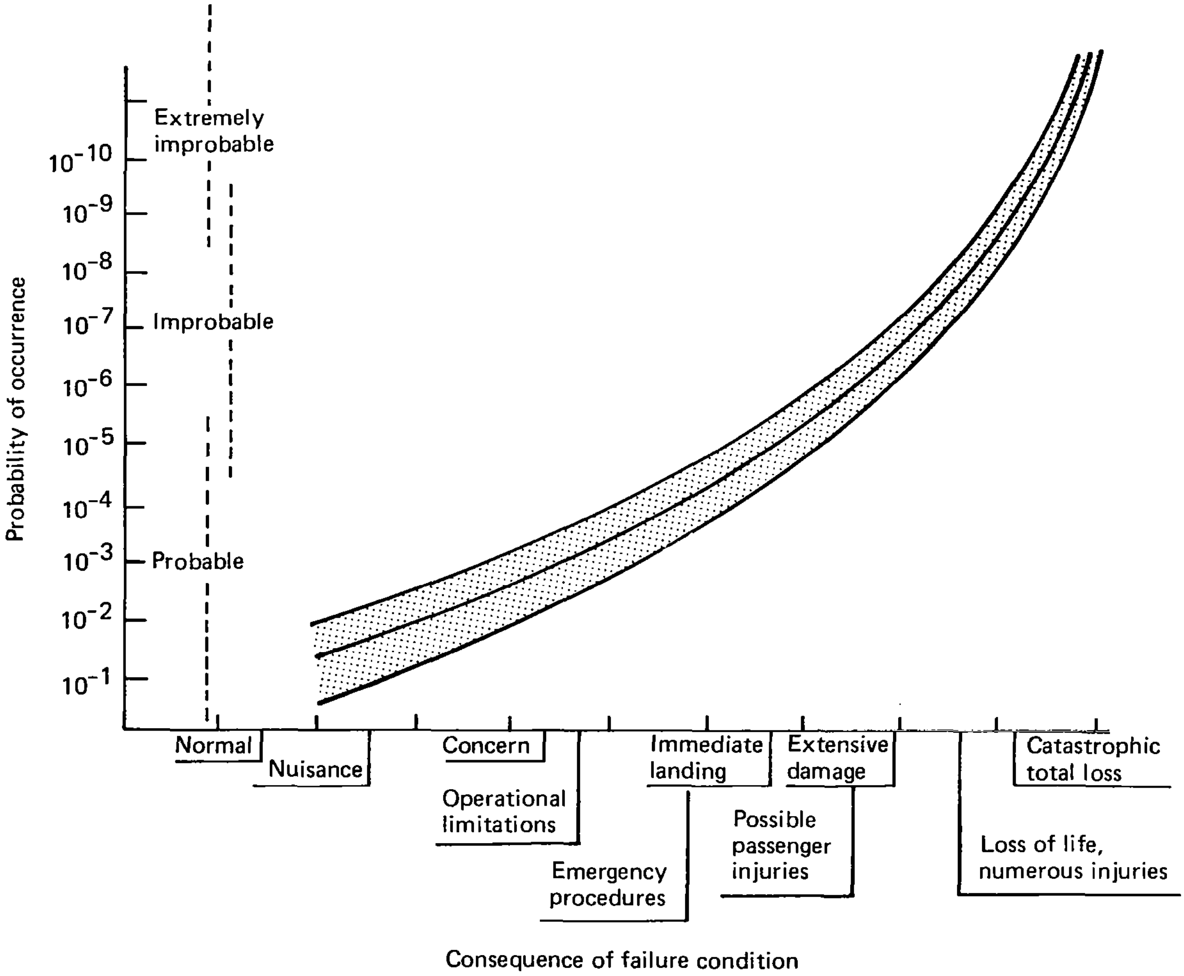


Figure 12. Relationship Between the Consequence of Failure and the Probability of Occurrence

Table 1. Failure Probability Requirements and Criticality of ACT Functions

Failure	Criticality	Probability of failure during 1-hr flight	Flight crew action required on loss of function
Essential PAS	Crucial	$< 1 \times 10^{-9}$	None, aircraft is lost
Full PAS	Critical	$< 1 \times 10^{-5}$	Reduce speed
AAL			
Failure to operate	Critical	$< 1 \times 10^{-5}$	Proceed with added care
Inadvertent operation	Crucial	$< 1 \times 10^{-9}$	Disconnect and override stick pusher
WLA	Critical	$< 1 \times 10^{-5}$	None
One failure away from concurrent loss of full PAS, yaw damper, and WLA	Critical	$< 1 \times 10^{-5}$	Divert to nearest airfield

The ACT airplane must meet dispatch requirements as follows:

a. Airplane schedule reliability must be at least 98.7%. Not more than 5% of the unreliability shall be attributable to ACT system failure.

b. The airplane shall be dispatchable with any one ACT system component failed.

Table 2. Predicted or Required Probability of Failure Events (1-hr Flight)

Event	Flap position gain schedule backup			Requirement (see table 1)
	With	Without[c]	With, but without partitioning	
Essential PAS failure	9.0×10^{-12}	9.0×10^{-12}	3.49×10^{-10}	1×10^{-9}
Full PAS failure	1.1×10^{-7}	1.1×10^{-7}	1.67×10^{-7}	1×10^{-5}
WLA failure	1.7×10^{-7}	2.1×10^{-7}	1.21×10^{-5}	1×10^{-5}
AAL failure	2.3×10^{-7}	2.3×10^{-7}	4.26×10^{-7}	1×10^{-5}
(Yaw damper failure)[a]	3.0×10^{-7}	3.0×10^{-7}	1.63×10^{-6} (LAS)	NA
Any of the above	6.9×10^{-7}	6.9×10^{-7}	NA	NA
Probability of retreat to restricted envelope (full PAS one failure away)	5.70×10^{-4}	5.70×10^{-4}	7.08×10^{-4}	10^{-3}
Probability of diversion due to being one failure away from loss of essential PAS	1.44×10^{-7}	1.44×10^{-7}	1.327×10^{-6}	1×10^{-5}
Probability of diversion from one failure away from loss of the set (full PAS x WLA x yaw damper)[b]	3.18×10^{-7}	1.27×10^{-4}	7.1×10^{-4}	1×10^{-5}
Probability of diversion from all causes	4.30×10^{-7}	1.28×10^{-4}	7.1×10^{-4}	1×10^{-5}
Probability of inadvertent AAL actuation	4.00×10^{-10}	4.00×10^{-10}	–	1×10^{-9}

[a] The yaw damper is part of the Baseline Airplane, hence its failures are not chargeable to the ACT program, but, for comparison with other systems, the probabilities including that system are provided.

[b] Diversion is the result of being one failure away from loss of crucial PAS (very low probability) or one failure away from loss of the set (full PAS x WLA x yaw damper). Although the yaw damper is part of the Baseline Airplane, it must be included in this calculation.

[c] Based on closest equivalent current technology Integrated System (ref 6).

Comparison of column 1 with column 3 (table 2) shows the benefit derived from partitioning the active control computer, the DADC, and the inertial reference system (IRS). Crucial PAS failure goes from 3.49×10^{-10} to 9×10^{-12} and smaller, but significant improvements are apparent in other functions. The need for such partitioning was shown by the FTREE run of an earlier system configuration (see table 3) of component ranking for impact on a top failure event probability. This showed that loss of full PAS, LAS, and WLA in the current technology Integrated System, reported in Reference 6, would cause a diversion. The "unreliability" column is the assumed failure rate of the component, the "delta probability" is the impact of the component on the top event, and the "top probability" shows what the failure probability of the top event would be if the component reliability were set equal to 1.0.

The preceding predictions are based on the assumptions of Subsection 5.4. These assumptions are known to be optimistic in the design of crucial digital flight hardware because both software failure (error) and coverage failure have finite nonzero probability of occurrence. More sophisticated reliability models such as the computer-aided reliability estimation (CARE III) model being developed by Raytheon have better capability to properly model digital computers driving highly complex, critical flight control systems. The Boeing fault tree model (ref 6, app B, subsec B.2.0) can list and predict the independent probability of each minterm. It appears that this information can be used in a reliability model such as CARE III to account for latent failures and degrading coverage. However, no results of such advanced reliability studies are available at this time.

Table 3. Component Sensitivity to Full Pitch-Augmented Stability, Lateral/Directional-Augmented Stability, and Wing-Load Alleviation Loss Causing Diversion in Current Technology Integrated System

IAAC sensitivities of multiple occurring events to top event 377					
Component names	Event	Unreliability	Delta probability	Top probability	Rank
Computer B	28	1.510×10^{-4}	7.12×10^{-8}	9.579×10^{-8}	1
Computer A	27	1.510×10^{-4}	7.12×10^{-8}	9.579×10^{-8}	2
Computer D	30	1.510×10^{-4}	7.12×10^{-8}	9.579×10^{-8}	3
Sensor, air data C (DADC)	50	8.500×10^{-5}	4.01×10^{-8}	1.269×10^{-7}	4
Sensor, air data B (DADC)	49	8.500×10^{-5}	4.01×10^{-8}	1.269×10^{-7}	5
Sensor, air data A (DADC)	48	8.500×10^{-5}	4.01×10^{-8}	1.269×10^{-7}	6
Computer C	29	1.510×10^{-4}	4.00×10^{-12}	1.670×10^{-7}	7
Power hydraulic A (landing gear)	31	8.700×10^{-5}	2.00×10^{-12}	1.670×10^{-7}	8
Elevator, actuator B	21	3.860×10^{-5}	1.00×10^{-12}	1.670×10^{-7}	9
Elevator, actuator A	20	3.860×10^{-5}	1.00×10^{-12}	1.670×10^{-7}	10
Power, hydraulic B	32	1.400×10^{-5}	3.00×10^{-13}	1.670×10^{-7}	11

Note: See Reference 6 for further data on current technology Integrated System.

The reinitialization capability designed into the current system will provide the answer to many of the transient hardware and software problems of present digital computers. Approximately 90% of computer failures are not traceable to hardware defects (ref 7), and the impact of such interruptions on ACT operability may be alleviated by rapid, automatic recovery from temporary faults.

5.6 DISPATCH RELIABILITY

Prediction of dispatch reliability (the probability that the airplane may be dispatched without delay in excess of 15 min) can be made by either of two methods:

- By an analysis based on the probability of a required ACT function being made inoperable by failure of a component
- By comparing delay rates experienced in commercial service, resulting from the failure of components, that are similar to the ACT components both in function and dispatch requirements

Although the FTREE program can compute the probability, as in Table 2, that an airplane would be in an undispatchable condition upon landing, the program cannot assess the impact of the time required to troubleshoot, repair, or replace, nor does it account for the different maintenance time available at a through-stop, a turnaround, or an overnight. All of these data and much more are required to determine whether there will be a dispatch delay, but such data are not readily available.

The second method requires extensive actual airline experience data on the number and duration of delays charged to particular components similar to ACT hardware in both function and Minimum Equipment List (MEL) requirements. The MEL identifies those components that can be inoperable without precluding dispatch. Previous experience has shown that only the second method provides accurate predictions, and it is therefore used here.

A simplifying assumption used in the calculations was that if any component is part of a redundant set, not all of which is needed for dispatch, it does not contribute significantly to dispatch delays or cancellations. This assumption is valid because the probability of two failures is much lower than that of a single failure.

These calculations cover only the increment in dispatch delays and cancellations produced by incorporating the ACT system into the Baseline Airplane.

Table 4 shows the ACT component to be analyzed and then lists hardware currently in airline service chosen to approximate the ACT component, the airplane type in which it is used, and the actual delay and cancellation rates experienced. The following correction factors are used as indicated in the table:

- Number Per Airplane—The ratio of the number of components in the ACT airplane to the number of similar components in the airplane in service.
- Flight Length Factor—The ratio of 1 hr, assumed as the ACT airplane duration, to the average flight duration of the inservice airplane.

Table 4. Dispatch Reliability Prediction

			A	B	C	D	E	F	G= A·B·C·D	H= A·B·C·E	J= A·B·C·F	
Number and name of part added to (or deleted from) Baseline Configuration	Comparison airplane	Comparison part assigned serial numbers and part names	Number per airplane factor	Flight-length factor	Removal rate factor	Comparison airplane (per 1000 departures)			ACT airplane (per 1000 departures)			Remarks
						Interruptions	Delay-hours	Cancellations	Interruptions	Delay-hours	Cancellations	
Three elevator secondary actuators	747	27-31-675-051 elevator PCU	3/4	0.36	0.91	0.0277	0.095	0.0	0.0068	0.023	0.0	No MEL dispatch with a secondary actuator inoperative
Two elevator power control units (PCU) (reduction)	747	27-31-675-051 elevator PCU	-2/4	0.36	0.91	0.0277	0.095	0.0	(0.0045)	(0.016)	0.0	No MEL dispatch without all PCUs
Angle-of-attack limiting system	727	27-32-xxx (shaker) 32-43-xxx (pneumatics) Selected components	2/1	1.0	1.0	0.0149	0.0069	0.0021	0.030	0.014	0.0042	No MEL dispatch without all parts
ACT additional hydraulic lines	727	27-21-280-191 rudder hydraulic hoses	2/1	1.0	1.0	0.0021	0.0094	0.0	0.0042	0.019	0.0	Increased likelihood of hydraulic leaks
Inertial reference system (IRS)	747	34-49-692-021 INS navigational unit minus navigational computer	3/3	0.36	0.565	0.4115	0.3212	0.0	0.084	0.062	0.0	No MEL dispatch without IRS
Dedicated (analog) pitch-rate sensor	747	34-49-692-021 INS navigational unit minus navigational computer	1/3	0.36	0.007	0.4115	0.3212	0.0	0.00035	0.00027	0.0	No MEL dispatch without dedicated pitch-rate sensor
Four ACT computers	DC-10	34-12-130-011 digital air data computer	4/2	0.58	1.1	0.116	0.097	0.0	0.148	0.124	0.0	No MEL dispatch without all ACT computers
Digital air data computer (DADC)	DC-10	34-12-130-001 digital air data computer	3/2	0.58	1.0	0.116	0.097	0.0	0.101	0.084	0.0	No MEL dispatch* without all DADCs

*When DADC is backed up with flap position, it is possible to dispatch with one DADC inoperative.

		G	H	J
Not including DADC (i.e., assuming flap position backup for DADC)	LRU totals	0.268	0.227	0.0042
	ACT system totals (1.3 x LRU totals)	0.349	0.295	0.0055
Including DADC (i.e., assuming no flap position backup for DADC)	LRU totals	0.369	0.311	0.0042
	ACT system totals (1.3 x LRU totals)	0.480	0.405	0.0055

- Removal Rate Factor—The ratio of anticipated removal rate of an ACT component to the experienced removal rate of an inservice component. This value may be estimated by the ratio of failure rates.

It is noteworthy that the airlines do not count a delay if the airplane is dispatched under flight restriction unless the dispatch is delayed beyond 15 min. The sum of the interruption rates for each of the listed components represents the line replaceable unit (LRU) total; i.e., the total interruptions traceable to the particular ACT LRUs. Experience has shown that total airplane interruptions for an automatic flight control system are about 1.3 times as great as the sum of all interruptions traceable to particular LRUs because of interface problems. Therefore, the ACT system totals are computed as 1.3 times the LRU totals.

Table 5 lists the components that contribute most to dispatch delays under various MEL assumptions. The bottom two lines show why flap position sensing was provided to back up DADC q (dynamic pressure for gain scheduling) in the Final ACT Configuration. The delay rate allowed under the DRO for the Baseline Airplane was 1.3%. The ACT system is not to add more than 5% to that. Thus, the allowable limit is 0.65 delay per thousand departures (5% of 1.3% of 1000). The Final ACT System meets this objective. The Final ACT System does not, however, meet the objective that the airplane be dispatchable with any one ACT component inoperative. The loss of one ACT computer precludes dispatch because it degrades the essential PAS function below the 1 x 10^{-9} requirement.

Table 5. Significant Contributors to Dispatch Delays

Component	Delays per 1000 FH*		Minimum equipment list requirements
IRS (without computer)	0.084		Dispatch not permitted with IRS failed
Four ACT computers	0.148		All four computers required for dispatch
Digital air data computers	0.101		All three DADCs required for dispatch
Other LRUs	0.036		
LRU total	0.369	Including DADC delays when there is no flap position backup	
LRU total	0.268		ACT does not require DADC for dispatch, because flap position backs up DADC for gain scheduling

*Final ACT meets dispatch requirements of <0.65 delay per 1000 FH.

6.0 ECONOMIC EVALUATION

The economic evaluation consists of two subsections: Subsection 6.1, a detailed estimate of maintenance-related cost increments, and Subsection 6.2, an evaluation of the impact of Initial ACT (768-103) and Final ACT (768-107) Configurations on airline economics relative to the Baseline Configuration (768-102).

6.1 ESTIMATION OF FIRST COST AND MAINTENANCE COST INCREMENTS

Estimates of first cost and maintenance cost increments, attributable to Final ACT Configuration changes from the Baseline Configuration, are tabulated in Table 6 (1980 dollars). Initial ACT is included for comparison.

6.1.1 INCREMENTAL AIRPLANE COST

It was desired to explore the difference in airplane cost between the Initial ACT and the Final ACT Configurations because both incorporated the Integrated System, and the primary difference, both in performance (fuel burn) and configuration, was the change from an aspect ratio (AR) 8.71 wing to an AR 12.03 wing. Aspect ratios quoted are based on reference trapezoidal planform area. The cost increment of the Initial ACT Configuration relative to the Baseline Configuration was detailed in Reference 3 and is summarized in Table 6. The cost increment between the Initial ACT and Final ACT Configurations reflected the weight changes shown in Table 7.

Wing planform and surface changes between the Initial and Final ACT Configurations are seen by comparing Figures 13 and 14. The following description gives details, which were also used to estimate the cost increment:

- Flutter-mode control (FMC) is not used; therefore, the outboard aileron is no longer split, and the two FMC actuators and their associated wiring and hydraulic connections (two hydraulic systems per actuator) are deleted.
- An outboard single-slot, trailing-edge flap is added to the outboard wing, and the outboard flap torque tube is extended to drive it through two rotary actuators.

Table 6. Incremental Price and Maintenance Cost (1980 Dollars)

Parameter incremented (relative to Baseline Configuration, 768-102)	1980 dollars	
	Initial ACT	Final ACT
Purchase cost per airplane	300 000	600 000
Maintenance manual cost per 30-airplane fleet	24 800	24 800
Test equipment cost per 30-airplane fleet	26 600	26 600
Spare inventory initial cost per 30-airplane fleet	295 500	295 500
Maintenance cost per airplane flight hour	5.48	5.31
Departure delay and cancellation cost per airplane flight hour	1.03	0.41

Table 7. Weight Changes Between Initial ACT and Final ACT

	Weight Δ 768-107 from 768-103, kg (lb)
Wing aspect ratio increased from 8.71 to 12.03 (trapezoidal) and area decreased from 256.3 m^2 (2759 ft^2) to 226.8 m^2 (2441 ft^2)	+2384 (+5255)
Vertical tail area increased from 54.0 m^2 (581 ft^2) to 56.6 m^2 (609 ft^2)	+127 (+280)
Body weight increased because of increased tail loads	+150 (+330)
Main landing gear weight increased because of increased gear loads	+41 (+90)
Nose landing gear weight increased because of increased gear loads	+14 (+30)
Outboard reserve tank deleted	
Fuel system weight decrease	-45 (-100)
Wing structure weight decrease	-14 (-30)
Unusable fuel weight decrease	-45 (-100)
FMC system deleted	-43 (-95)
Split outboard aileron eliminated; wing structure weight decrease	-45 (-100)
Total weight increment	+2522 (+5560)

Operational empty weight:	79 887 kg (176 120 lb) 768-107 Final ACT	77 365 kg (170 560 lb) 768-103 Initial ACT

- One outboard leading-edge slat is added to the outboard wing on each side. Two rotary actuators per side are added to drive each added slat, and the outer slat torque tube on each side is extended to drive these geared rotary hinges.

- Twelve wing accelerometers and associated wiring are deleted from the wing tips.

The ACT functions implemented in the Final ACT Configuration were PAS, WLA using the outboard aileron, and AAL.

First Cost and Maintenance Cost of Final ACT Computers—It was postulated initially that because the Final ACT was somewhat simpler than the Initial ACT in that FMC and gust-load alleviation (GLA) were not used, some reduction in first cost and maintenance cost and some improvements in reliability might be obtainable from computer simplification. This postulate is examined below.

The Final ACT control system is the Integrated System with certain modifications due to deletion of certain functions. The FMC and GLA functions have been deleted, leading to the following modifications:

- FMC accelerometers deleted

- GLA accelerometers deleted

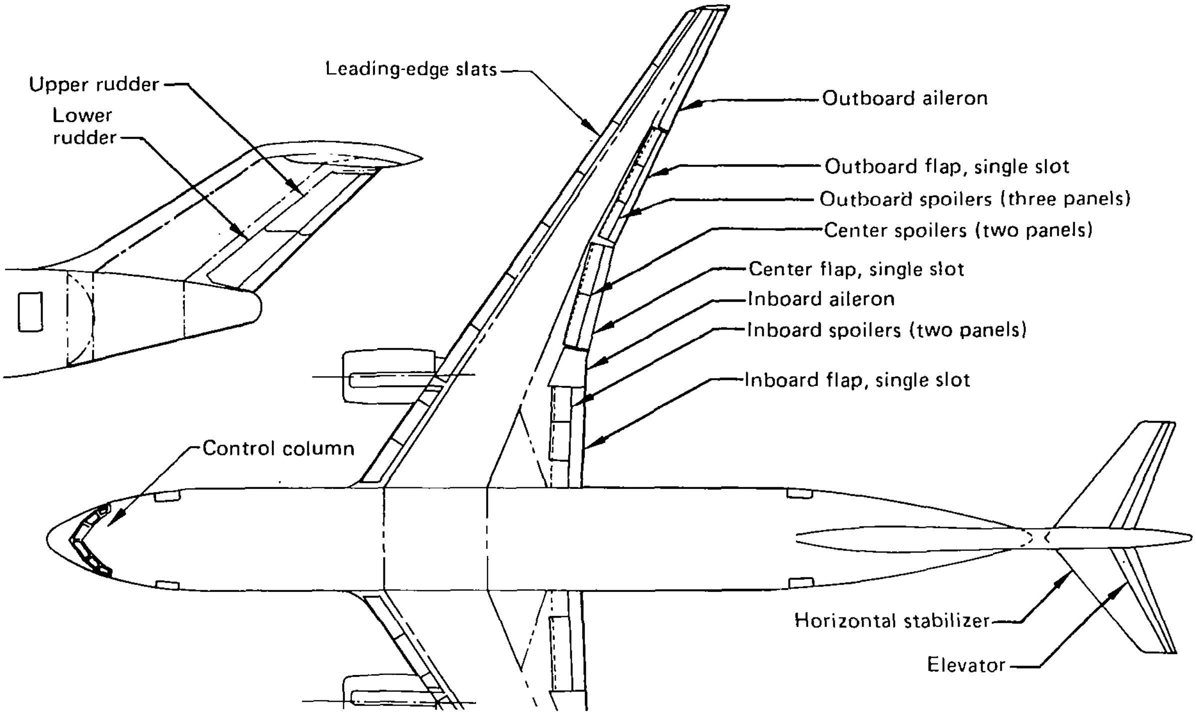


Figure 13. Flight Control Surfaces—Final ACT (768-107)

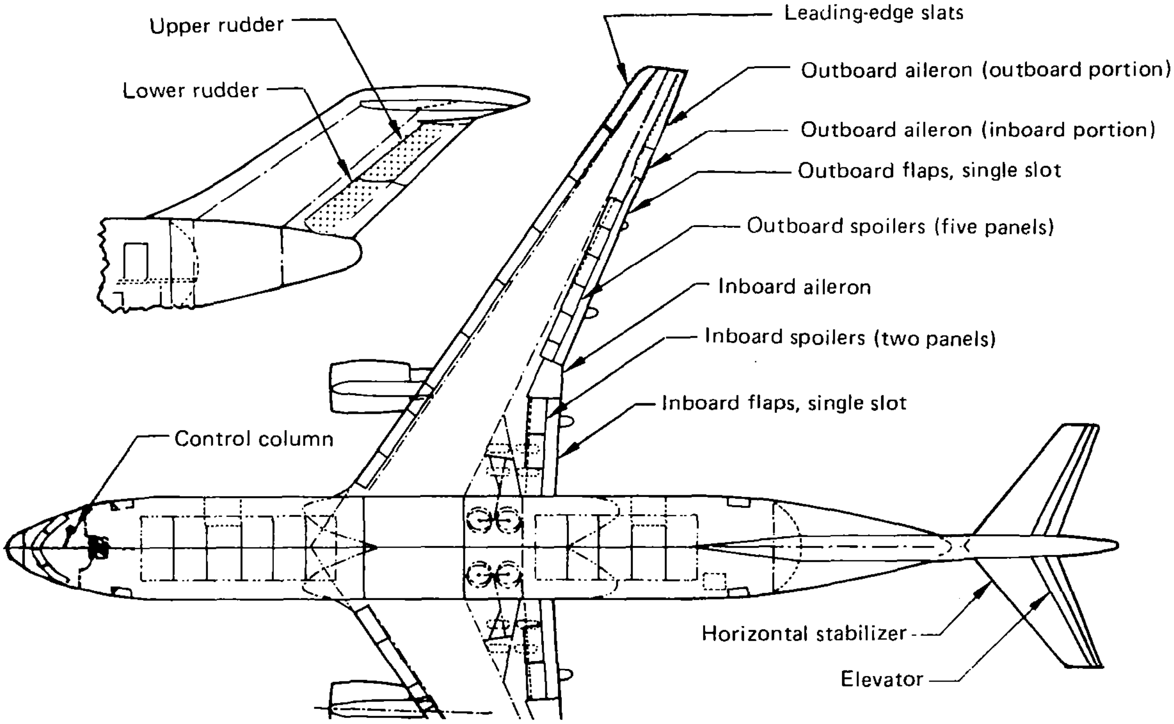


Figure 14. Flight Control Surfaces—Initial ACT (768-103)

- Inboard flaperons and servos deleted
- Outboard flaperons and servos deleted
- Split outboard aileron replaced with a single surface, and outboard aileron inner-segment servos deleted

These modifications allow some simplification of the Integrated System computers, primarily in the input/output (I/O) and servodrive sections, and reduction of memory required. Table 8 shows I/O and servodrive requirements for the Integrated System and Final ACT System. As can be seen from the table, the number of analog inputs and outputs is reduced by approximately 50%, with servoelectronics reduced by 60%. The number of discrete outputs is reduced by approximately 40%, and the number of discrete voters (servo shutdown logic and AAL voters) is reduced by 55%. Based upon circuits used in the General Electric MCP-701A, this leads to elimination of approximately one 23- by 18-cm (9- by 7-in) card for the I/O and servoelectronics. An additional card may be saved by deleting the six servo shutdown logic voters, if these are constructed from discrete parts. If a custom large-scale integration (LSI) chip is used for the voters, these could be put on a single board for the Integrated System computer, rather than the two required for discrete part construction. The requirement for separation of the servo logic from the rest of the computer would prevent the elimination of any boards, but parts cost would be reduced 55% for the LSI version.

Table 9 lists the estimated memory for the Integrated System and Final ACT System. The table shows a reduced requirement for the Final ACT System: 25K compared to 32K for the Integrated System. This reduction in memory would have some impact on reliability but very little on cost; both computers would undoubtedly be provided with space for at least 32K of read-only memory (ROM), and parts savings would be small for memory, particularly if large, modern ROMs were used.

Differences between the computers for the Integrated System and Final ACT System are relatively minor except for a significant reduction in discrete voter logic. If off-the-shelf computers, modified for ACT, are used, it is likely that the same computer would be offered for both systems. The Final ACT System computer would have slightly better reliability due to fewer parts required, but this difference would be small.

It was therefore concluded that no change in Initial ACT computer cost, maintenance cost, or reliability was justified at this time.

6.1.2 MAINTENANCE MANUAL COST FOR 30-AIRPLANE FLEET

Maintenance manual cost was based on typical autopilot cost prorated for increasing electronic complexity. Because of the reasoning expressed earlier (First Cost and Maintenance Cost of Final ACT Computers), the same cost was assumed for both Initial and Final ACT.

6.1.3 INCREMENTAL TEST EQUIPMENT COST FOR 30-AIRPLANE FLEET

Incremental test equipment cost assumed that the airline would already possess the basic digital test equipment for the remainder of the digital electronic suite. Thus, the cost increment was based on the cost of additional adapters and test software required for ACT, and because of the reasons given earlier the same cost was assumed for both Initial and Final ACT.

Table 8. Input/Output and Servodrive Requirements for Integrated and Final ACT Systems

I/O or servodrive	Integrated System		Final ACT System	
Discrete inputs	Air/ground logic	2	Air/ground logic	2
	Test initiate	3	Test initiate	3
	Electric power monitor	4	Electric power monitor	4
	Hydraulic pressure monitor	3	Hydraulic pressure monitor	3
	Pneumatic pressure	2	Pneumatic pressure	2
	Solenoid (AAL) valve position	4	Solenoid (AAL) valve position	4
	Dump valve position	2	Dump valve position	2
	Slat position	3	Slat position	3
	Actuator fail (P-H)	4		
	Total	27	Total	23
Analog inputs	Dedicated pitch rate	1	Dedicated pitch rate	1
	Column force	1	Column force	1
	Dynamic pressure	1	Dynamic pressure	1
	Cg acceleration	1	Cg acceleration	1
	Stabilizer position	1	Stabilizer position	1
	Flap position	1	Flap position	1
	Servo position	10	Servo position	4
	Servo spool position	4	Servo spool position	4
	Servo current	2		
	FMC acceleration	2		
	GLA acceleration	2		
	Total	26	Total	14
Digital inputs	IRS	1	IRS	1
	DADC	1	DADC	1
	Maintenance/display	1	Maintenance/display	1
	Cross channel	3	Cross channel	3
	Total	6	Total	6
Discrete outputs	Warning displays	12	Warning displays	8
	Self-test	6	Self-test	6
	Stick-pusher activate	1	Stick-pusher activate	1
	Stabilizer drive	2	Stabilizer drive	2
	Shutdown actuator—servo failure	40	Shutdown actuator—servo	16
	Shutdown actuator—computer failure	24	Shutdown actuator—computer failure	16
	Total	85	Total	49
Analog outputs	Elevator position command	1	Elevator position command	1
	Rudder position command	1	Rudder position command	1
	Outpoard aileron outer segment position command	1	Outboard aileron outer segment position command	1
	Outboard aileron inner segment position command	1		
	Outboard flaperon position command	1		
	Inboard flaperon position command	1		
	Total	6	Total	3
Digital outputs	Cross channel	1	Cross channel	1
	MCDP	1	MCDP	1
	Caution/warning	1	Caution/Warning	1
	Total	3	Total	3

Table 8. Input/Output and Servodrive Requirements for Integrated and Final ACT Systems (Concluded)

I/O or servodrive	Integrated System		Final ACT System	
Discrete voter logic				
Servo shutdown logic	Elevator	1	Elevator	1
	Rudder	1	Rudder	1
	Outboard aileron outer segment, left	1	Outboard aileron, left	1
	Outboard aileron outer segment, right	1	Outboard aileron, right	1
	Outboard aileron inner segment, left	1		
	Outboard aileron inner segment, right	1		
	Outboard flaperon, left	1		
	Outboard flaperon, right	1		
	Inboard flaperon, left	1		
	Inboard flaperon, right	1		
AAL voter	AAL voter	1	AAL voter	1
	Total	11	Total	5
Servodrives	Elevator	1	Elevator	1
	Rudder	1	Rudder	1
	Outboard aileron outer segment, left	1	Outboard aileron, left	1
	Outboard aileron outer segment, right	1	Outboard aileron, right	1
	Outboard aileron inner segment, left	1		
	Outboard aileron inner segment right	1		
	Outboard flaperon, left	1		
	Outboard flaperon, right	1		
	Inboard flaperon, left	1		
	Inboard flaperon, right	1		
	Total	10	Total	4

6.1.4 INCREMENTAL SPARES INVENTORY INITIAL PURCHASE COST FOR 30-AIRPLANE FLEET

Incremental spares inventory initial purchase cost was affected primarily by the higher cost, higher-removal-rate electronic equipment; therefore, the same cost was assumed for Initial and Final ACT.

6.1.5 MAINTENANCE COST PER FLIGHT HOUR

Maintenance cost per flight hour was calculated based on past experience and recent predictions at the significant LRU level, as shown in Table 10. Compared to Initial ACT, reductions were due to deletion of the wing-mounted accelerometers and elimination of the FMC actuators. An increase was caused by the addition of the one leading-edge and one trailing-edge device on each wing, for a net decrease as shown in Table 6. The additional maintenance cost for ACT is less than that for a current autopilot system because the rate gyros that account for up to 70% of the maintenance cost of current systems are eliminated. Vertical reference and rate data are provided by the IRSs, which are part of the baseline aircraft navigation system.

Table 9. Memory Estimates for Integrated and Final ACT Systems

Software module	Integrated System, words	Final ACT System, words
Real-time control		
Real-time executive	900	900
Foreground tasks		
Synchronization	600	600
Multirate scheduler	200	150
SSFD	1 000	800
Control laws	1 200	900
Output monitor	400	200
Servomonitor	400	160
Background tasks		
Flight crew interface	6 000	4 500
In-flight tests	200	200
Maintenance support	2 000	1 500
Ground operations		
Test executive	1 200	1 200
Preflight tests		
Computer self-test	4 000	4 000
System monitor test	800	800
End-to-end tests	1 000	600
Maintenance test	1 000	450
Total	20 900	16 960
Minimum with 50% growth allowance	31 350	25 440

6.1.6 INCREMENTAL DELAY AND CANCELLATION COST PER FLIGHT HOUR

The decrease shown in Table 6 is due to the addition of flap position backup to the DADC for gain scheduling, which enables dispatch with the DADC down (see table 4).

6.2 ECONOMICS

An economic assessment of the Final ACT Configuration (768-107) was performed to provide direct operating cost (DOC) and return on investment (ROI) data on the configuration relative to the Baseline Configuration (768-102) and the Initial ACT Configuration (768-103). Return on investment is given in the following results as incremental ROI, defined as the return on the incremental investment for the ACT configurations, calculated by the formula shown in Table 13.

6.2.1 METHODS AND DATA

The methodology and assumptions used in the analysis are summarized in Tables 11 through 13. Each airplane configuration was analyzed at two ranges, 926 and 1852 km (500 and 1000 nmi), using two fuel prices: \$0.26/ℓ (\$1.00/gal) and \$0.36/ℓ (\$1.35/gal). The current 1980 domestic price of fuel is \$0.26/ℓ (\$1.00/gal); \$0.36/ℓ (\$1.35/gal) represents a

Table 10. Prediction of Maintenance Cost per 1000 Flight Hours—Final ACT

Nomenclature	[a] QPA	Reference ASN [b]	Direct [c] maintenance cost—78 $	Total [c] maintenance cost—78 $	Remarks
Dedicated pitch-rate sensor	1	N/A	2.64	5.28	Based on workshop experience
High-lift devices	4	747 ATA 27 and 57	348.14	696.29	747 LE and TE transmission and flap mechanisms
Computer	4	N/A	940.88	1881.76	Significant component estimate
Preflight and maintenance test panel	1	N/A	137.63	275.26	Significant component estimate
Secondary actuator	9	27-21-675-021	284.65	608.06	727 rudder actuator used as baseline
Stick pusher pneumatic actuator	2	78-34-008-001	4.40	10.03	Based on 727 thrust reverser actuator
Stick pusher pressure transmitter	2	32-43-556-021	4.04	8.73	Based on 727 pneumatic brake pressure transmitter
Stick pusher solenoid valve	2	30-44-576-201	2.01	4.24	Based on 747 window washer solenoid valve
Stick pusher pneumatic regulator	2	29-03-418-011	21.16	44.39	Based on 727 hydraulic reservoir regulator
Stick pusher pneumatic accumulator	2	32-43-064-011	8.24	17.85	Based on 727 pneumatic brake accumulator
Stick pusher relief valve	2	N/A	0	0	Simple pneumatic relief valve—no maintenance cost
Stick pusher pressure gage	2	32-43-284-031	1.44	3.12	Based on 727 pneumatic brake pressure indicator
Stick pusher pressure switch	2	21-33-522-041	0	0	Based on 727 pressure warning system
Stick pusher dump valve	2	32-43-576-211	12.10	27.33	Based on 727 pneumatic brake control valve
Ni-cad battery	1	N/A	—	170.99	Estimate prorated to 0.6649 removal rate
Battery charger	1	24-32-104-011	6.89	15.98	Based on 727
T-R unit	2	24-32-104-011	1.66	3.37	Based on 727
Static inverter	4	24-22-294-011	28.00	58.34	Factor of 10 applied to 747 inverter for continuous duty
Transformer	4	—	0	0	
Delete four elevator control units	-4	27-31-675-051	-172.40	-344.80	Based on United Airlines 747 1977 data
Add additional hydraulic lines and hoses	—	27-31-312-101	10.90	29.16	Based on 727 elevator multiplied by 3

[a] Quantity per airplane

[b] Boeing identifier

[c] Dollars per 1000 FH

Total of $3515.33 for 768-107

Factor total by 1.28* = $4499.62 per 1000 FH (1978 $)

768-107 ACT System total = $4499.62 x 1.182 =
$5318.55 (1980 $)

*Accounts for maintenance costs not covered by LRU reporting.

predicted 1987 price in constant 1980 dollars. Detailed DOC, incremental ROI, and incremental payback results are presented in Tables 14 and 15 for each configuration. The following discussion will focus on the results at 926 km (500 nmi) (see table 14). The results at 1852 km (1000 nmi) would be more favorable for the Initial and Final ACT Configurations because of the greater proportion of the flight spent in cruise, where fuel burn reduction is larger.

The major economic benefit derived from the Final ACT Configuration is fuel savings, approximately $217 000/airplane/yr at $0.26/ℓ ($1.00/gal). Fuel consumption decreases approximately 5%, from 32.2 kg (71.0 lb) per seat for the Baseline Airplane to 30.7 kg (67.6 lb) per seat for the Final ACT Airplane (table 16). This savings works out to an incremental ROI of 25.1%.

Table 11. Direct Operating Cost Elements

Crew cost = f (TOGW, cruise speed, mission type)
Fuel = Fuel burn and fuel price specified
Airframe maintenance = Specified (Boeing)
Engine maintenance = Specified (engine manufacturer)
Burden = f (maintenance labor)
Depreciation = f (useful life, residual value, utilization, initial price, spares price)
Insurance = f (initial flyaway price)
Σ (of above elements) = DOC per trip
Utilization = f (block time)

Table 12. Return-on-Investment Analysis Ground Rules

Constant 1980 dollars

15 years' useful life

46% tax rate

Sum of years' digits depreciation schedule: 10 years to 10% residual value

10% investment tax credit taken over 3 years

926- and 1852-km (500- and 1000-nmi) range, domestic rules

2200-trips/yr utilization at 926 km (500 nmi)
1400-trips/yr utilization at 1852 km (1000 nmi)

Fuel price: $0.26/ℓ ($1.00/gal) basic, $0.36/ℓ ($1.35/gal) alternative (1987 fuel price in 1980 dollars)
Δ yield*: +8% for $0.36/ℓ ($1.35/gal)

65% passenger load factor

*Δ yield is incremental revenue per passenger mile.

Table 13. Incremental Return-on-Investment Method

$$\text{Net present value (NPV)} = -I + \sum_{n=1}^{\text{useful life}} (C_{IN}-C_{OUT})/(1+r)^n$$

When NPV = 0, r = incremental ROI = discount rate

Incremental cash outflows

- Airplane price (I)
- Insurance (C_{OUT})

Incremental cash inflows (annual)

- Cash operating cost savings (C_{IN}):
  - Fuel
  - Maintenance

Adjustments for depreciation tax effects and investment tax credit are included

Table 14. Active Controls Economic Summary—926 km (500 nmi), Domestic Rules (1980 Dollars)

Airplane configuration	Baseline (768-102)		Initial ACT (768-103)		Final ACT (768-107)	
Fuel price, \$/ℓ (\$/gal)	0.26 (1.00)	0.36 (1.35)	0.26 (1.00)	0.36 (1.35)	0.26 (1.00)	0.36 (1.35)
DOC, \$M/yr	9.97	11.56	9.84	11.39	9.78	11.30
Fuel	4.56	6.15	4.40	5.95	4.34	5.86
Crew	1.57	1.57	1.57	1.57	1.57	1.57
Insurance	0.16	0.16	0.16	0.16	0.16	0.16
Engine labor	0.11	0.11	0.11	0.11	0.11	0.11
Engine material	0.40	0.40	0.39	0.39	0.38	0.38
Airframe labor	0.21	0.21	0.22	0.22	0.22	0.22
Airframe material	0.19	0.19	0.19	0.19	0.19	0.19
Burden	0.65	0.65	0.66	0.66	0.65	0.65
Depreciation	2.12	2.12	2.14	2.14	2.16	2.16
Incremental after-tax ROI, percent	–	–	31.0	41.4	25.1	32.8
Incremental payback period, year			2.08	1.51	2.60	1.95

Table 15. Active Controls Economic Summary—1852 km (1000 nmi), Domestic Rules (1980 Dollars)

Airplane configuration	Baseline (768-102)		Initial ACT (768-103)		Final ACT (768-107)	
Fuel price, \$/ℓ (\$/gal)	0.26 (1.00)	0.36 (1.35)	0.26 (1.00)	0.36 (1.35)	0.26 (1.00)	0.36 (1.35)
DOC, \$M/yr	10.56	12.30	10.36	12.02	10.24	11.85
Fuel	4.95	6.69	4.72	6.38	4.61	6.22
Crew	1.87	1.87	1.87	1.87	1.87	1.87
Insurance	0.16	0.16	0.16	0.16	0.16	0.16
Engine labor	0.11	0.11	0.11	0.11	0.10	0.10
Engine material	0.38	0.38	0.37	0.37	0.36	0.36
Airframe labor	0.20	0.20	0.20	0.20	0.20	0.20
Airframe material	0.16	0.16	0.17	0.17	0.17	0.17
Burden	0.61	0.61	0.62	0.62	0.61	0.61
Depreciation	2.12	2.12	2.14	2.14	2.16	2.16
Incremental after-tax ROI, percent	—	—	45.5	60.6	37.8	49.3
Incremental payback period, year			1.37	1.00	1.68	1.25

Table 16. Airplane Economic Summary—1980 Domestic Rules and \$0.26/ℓ (\$1.00/gal) Fuel

Airplane	Engines	Maximum TOGW, kg (lb)	Number of seats	Still-air range, km (nmi)	Price, \$M	925-km (500-nmi) long-range cruise			
						Fuel, kg/seat (lb/seat)	\$/mi*	¢/ASM	Airplane incremental ROI
Baseline (768-102)	CF6-6D2	122 470 (270 000)	197	3589 (1938)	Base	32.2 (71.0)	7.885	4.003	—
Initial ACT (768-103)	CF6-6D2	122 470 (270 000)	197	4065 (2195)	+0.3	31.1 (68.6)	7.782	3.950	31.0
Final ACT (768-107)	CF6-6D2	121 581 (268 040)	197	3589 (1938)	+0.6	30.7 (67.6)	7.728	3.923	25.1

*Statute mile.

Another factor that affects the rate of return of the ACT configurations is the incremental price for each airplane. Figure 15 presents the sensitivity of incremental ROI to changes in incremental price for both the Initial ACT Configuration and Final ACT Configuration. A price increase of $100 000 for the Final ACT Airplane would result in a 3.5% decrease in incremental ROI to approximately 21.6%. Likewise, a $100 000 decrease in price from the study price of $600 000 would translate into a 4.7% increase in incremental ROI.

In addition to obtaining the data presented in Tables 14 and 15, an analysis was conducted to determine the potential revenue benefit of the greater payload and range capability of the Final ACT Configuration over the Baseline Configuration at high-altitude airports. Denver was chosen as the example for this analysis. Itineraries were identified that potentially would require offloading out of Denver for the Baseline Airplane. The probability of offload situations was determined, and the expected revenue loss due to offloading was calculated. The expected revenue loss is $8000/airplane/yr for the Baseline Airplane in a 30-airplane fleet. Airlines are believed to place a higher value on the cost of offloads, and this is estimated to be $20 000/airplane/yr for this example. The cost of offloads appears low because very few of the flights of a 30-airplane fleet are involved. As shown in Figure 10, the Final ACT Airplane has full range capability out of Denver. This then is a potential revenue gain for the Final ACT Airplane, which would have no offload situations out of Denver. This revenue gain for the Final ACT Airplane would change the results in Tables 14 and 15 very little.

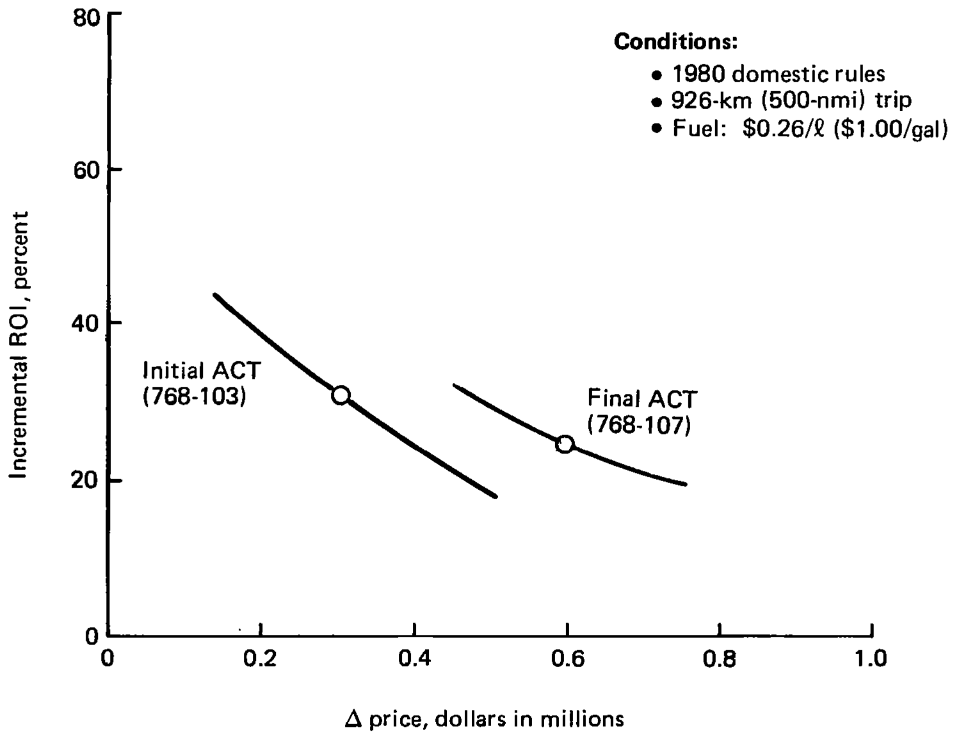


Figure 15. Effect of Price on Incremental Return on Investment

6.2.2 EVALUATIONS AND CONCLUSIONS

Evaluation of Initial ACT (768-103)—The addition of active controls to the Baseline Airplane, relocation of the wing, and reduction in horizontal tail size increased maximum range 13% for the same gross weight and reduced fuel burned by 3% for a 926-km (500-nmi) trip. Because the airplane study price increased less than 1% from the Baseline and direct operating costs decreased 1%, incremental ROI was approximately 31%. This option is clearly profitable.

Evaluation of Final ACT (768-107)—Sizing the airplane for the baseline range with active controls and a high-aspect-ratio wing provided a 5% savings in block fuel for a 926-km (500-nmi) trip, a 2% reduction in DOC, and approximately a 25% incremental ROI at the study price increase of less than 2% above the Baseline Airplane. This option provided the least fuel burned and lowest DOC. The superiority of the high-aspect-ratio wing is more evident at ranges above 1100 km (600 nmi).

Conclusions—As shown in Table 16, both the Initial ACT and Final ACT Configurations appear to be acceptable investments for an airline. The Initial ACT Configuration gives an excellent incremental return on the relatively modest additional investment of $300 000 per airplane. The investment of a further $300 000 per airplane for the Final ACT produces a slightly smaller incremental ROI but should be attractive because of better high-altitude-field performance, less fuel burned, and lower DOC.

One potential operational consideration is the effect of the increased span of the Final ACT Configuration on airport gate availability. An informal study of one major terminal indicated that about 7% fewer gates would be available to the 768-107 than the 768-102 or 768-103. The economic consequences of this have not been quantified.

7.0 TECHNICAL RISK ASSESSMENT

7.1 RISK CATEGORIZATION

A technical risk assessment of the Final ACT Configuration has been made. Risks have been categorized as either (1) risks that existing design and analysis methods deal with inadequately or (2) concerns that can be handled by existing methodology but that require technical effort beyond that expended thus far in the IAAC Project.

These technical risks and concerns are to be understood as those existing **now**, relative to the ability to proceed with the design, development, certification, and introduction into commercial service of a new transport airplane incorporating ACT as a basic component of its design.

7.2 RISK IDENTIFICATION

Risk assessments for the technology areas of significant importance to the conclusions of the IAAC Project are described in the following subsections. Where a category 1 risk is identified, required development activity or design alternatives are described briefly. Category 1 risks and recommended development activities are discussed in Subsection 7.3 and summarized in Table 17.

7.2.1 AERODYNAMICS

No category 1 technical risks are identified.

In category 2, the high aspect ratio and taper ratio of the Final ACT Configuration wing require higher outboard wing section lift coefficients, relative to the Baseline Configuration, to maintain cruise lift coefficient and span load distribution. This may

Table 17. Recommended Development Activities

Technical risk item	Development activity required	Recommendations
WLA control surface aerodynamic effectiveness	Improved unsteady aerodynamic methods for control surfaces	Continue development of computational fluid dynamics for unsteady flows, with viscous effects
• Large deflections • Unsteady aerodynamics	Improved data base for control surface effectiveness and hinge moments on modern airfoil sections and at high Mach number and Reynolds number	Develop experimental data base on generalized trailing-edge surfaces for correlation with improved computational methods
Crucial systems Inability to prove system reliability considering— • Software error • Latent and pattern failures • Other common mode failures	System architectures tolerant of common mode failures • Dissimilar redundancy • Monitoring • Hardware and software • Inline and cross channel Software verification and validation methods development	Develop several competing architectures (in addition to IAAC planned work) to laboratory demonstration of flight-qualified hardware and software; flight demonstration of at least one Selected System (preferably more than one)

result in reduced buffet margin and increased pitchup tendency. In addition, the reduced chord length available for outboard leading-edge flaps may make satisfactory low-speed stall characteristics more difficult to achieve. It should be noted that active control pitch stabilization allows the configuration to tolerate more pitchup than a conventional configuration.

A detailed wing development, using analytical and wind tunnel methods, is required to resolve these issues. This is a normal development activity for a new airplane configuration.

7.2.2 STRUCTURES

Category 1 risks identified are:

- Aerodynamic control surface effectiveness for WLA
- WLA system response including saturation effects

Effectiveness of the WLA system is critically dependent on the aerodynamic effectiveness of the wing control surfaces. IAAC studies and the 747 WLA demonstrator flight program have shown that to maximize the benefits of active control systems, the limits of control authority (actuator rate limits and control surface deflection limits) will be fully exploited. Thus, during flight test of a new design, little margin will be available to recover from an overly optimistic prediction. Simple changes to sensor location or control law parameters cannot offset a basic deficiency in aerodynamic authority or actuator rate.

Surface effectiveness at large deflections, for the Mach number and angle-of-attack ranges critical for wing loads, is affected by separated flow regions and thus is sensitive to Reynolds number and is not well predicted by available theoretical methods. High Reynolds number wind tunnel pressure and force data supported by theoretical analysis and correlation with flight data are required to provide adequate information for low-frequency applications, such as maneuver-load alleviation or low-frequency GLA.

Flutter suppression and GLA system requirements tend to be sensitive to configuration variables and to be most complex for large, low-load-factor airplanes such as large transports. Uncertainties in the prediction of incremental airloads due to complex structural vibrations and control surface oscillations are the principal concerns.

For this reason, scaled dynamic wind tunnel models have been used extensively in the past to verify flutter margins in the design of large aircraft without ACT. However, subscale modeling of active controls systems adds considerable complication to dynamic models. Accordingly, such models can be used mainly to substantiate analysis methods and to measure aeroelastic transfer functions. It is necessary to continue the development of computational fluid dynamics for unsteady flow, with viscous effects included, in order to increase confidence in analytical methods to the level required for design decisions involving flight-critical ACT applications. Full-scale flight demonstration of analytical prediction capability is also required to attain that level of confidence.

Active control for load reduction and airframe stabilization is affected by nonlinearities due to high angle of attack, and the WLA control surface response and resulting load relief are affected by control surface actuation hinge-moment and rate limits. This implies (1) knowledge of high angle-of-attack characteristics and surface hinge moments to an accuracy not usually attainable in wind tunnel testing or (2) conservative system designs to avoid saturation effects, which could significantly reduce WLA effectiveness or result in overshoot or divergence in maneuvering at minimum airframe stability conditions. A development effort is needed to improve computational methods for control surfaces, both for steady and nonsteady aerodynamics including viscosity effects, and extensive correlation with experimental data is required.

Category 2 technical concerns are as follows:

The increased wing span and reduced outboard structural box depth increase wing weight and reduce outboard stiffness. This results in reduced effectiveness of the outboard aileron as a WLA surface and more critical outboard wing flutter and dynamic gust response. Detailed aeroelastic analysis is required to establish design trades between wing structural material requirements and control surface size. There may be a payoff for additional load relief surfaces (flaperons), but a detailed trade study and data from high-speed wind tunnel tests would be required for verification.

7.2.3 FLIGHT CONTROL SYSTEMS

Category 1 technical risks identified are:

- Software Reliability—For the essential PAS function, the Final ACT System uses quadruply redundant hardware, but the hardware design and software are common to all channels. To meet reliability requirements, the probability of an error in the software, which results in loss of the crucial function, must be less than 10^{-9}. Current validation and verification methods do not provide assurance of such low error probability.

- Latent Failure—Reliability analyses were performed assuming no undetected faults at takeoff. However, current built-in test provides only about 95% coverage. Reference 8 also shows that only about 50% of gate level faults are detected by cross-channel monitoring. The presence of latent (undetected) failure seriously affects the reliability assumptions made, particularly with regard to exposure time and probability of simultaneous failures.

- Pattern Failures—LSI circuits are particularly susceptible to manufacturing errors, which may be repeated from chip to chip and which when not detected can lead to failures when the circuits are presented with certain patterns of data or instructions. This could cause a simultaneous failure of redundant hardware, with potentially catastrophic results. Methods of testing for, predicting, and preventing these types of failures are not well developed at this time.

Thus a single set of digital computers of any level of hardware channel redundancy, using common hardware and software, does not appear to be capable of meeting reliability goals, particularly those for a crucial function. Potential solutions to this dilemma are:

- Use dissimilar hardware and software for each channel of the multichannel redundant system; i.e., what might be termed "massive dissimilarity."

- Use dissimilarity with switching; i.e., switch between the normal system and a dissimilar backup system upon detection of anomalous behavior of the normal system.

- Use dissimilarity with limited-authority normal system; i.e., the dissimilar backup system functions all the time and has full authority. Normal system inputs are superimposed on the backup system through a hardware limiter. Common mode faults in the normal system are limited to acceptable values by the hardware limiters.

- Eliminate crucial system requirements by imposing a minimum unaugmented airframe stability criterion.

The feasibility of the massive dissimilarity approach has not been established. It appears that it would impose significant development cost, equipment purchase cost, and logistic penalties, because software maintenance and update cost is a major element in life cycle cost.

Dissimilarity with switching raises a number of problems that are unresolved at the present time. The switching algorithms, redundancy level of switching hardware, protection against latent failures in the switching device, and methods for ensuring that the switching mechanisms are free of common mode failures need to be established.

Dissimilarity with the limited-authority normal system eliminates the need for the switching monitor. It may, however, impose a performance penalty because, by definition, normal system outputs are of limited amplitude such that any common mode failure in the normal system is hardware limited to safe values.

The backup systems in the previous two systems could be either analog or digital. However, a digital backup system again raises the problem of common mode fault due to software. This might be avoided by dissimilar software and digital hardware in each channel of the backup system. Since the backup system is comparatively simple, hardware and software dissimilarity would pose far fewer problems in the backup system than in the massive dissimilarity approach.

Common mode failures in digital systems can be caused by software design coding errors and software specification errors. Hence, the dissimilarity must also be applied to software specification and design to eliminate the risk of common mode failures.

Imposing minimum unaugmented airframe stability requirements will eliminate the need for a crucial system. Nevertheless, some type of augmentation system is needed. Unless the authority of this system can be reduced to a level where a hardover failure can be tolerated, the requirement to eliminate the common mode failure risk remains.

A well-defined and well-executed laboratory test plan is necessary to verify that all system elements work as expected and to demonstrate failure survivability for any failure not shown to be extremely improbable. Failure conditions not demonstrated to be survivable will require an intensive, rigorous examination to justify classification as extremely improbable.

Current and projected future work under the IAAC Project contract is directed toward resolving these control system risk areas. A control system architecture will be defined that is tolerant of common mode failures. System design and component procurement for laboratory testing will be pursued. Current architecture studies tend toward either the dissimilarity with switching or the dissimilarity with limited-authority normal system approaches previously discussed.

Additional development is required to establish the most cost-effective system that meets the requirements for reliability and dispatchability. It is probably necessary to have several competing systems developed to at least laboratory demonstration level. In particular, projected reductions in hardware costs and potential improvements in software design and verification methodology may make the "massive dissimilarity" approach more feasible.

In addition to the category 1 risk areas, category 2 concerns were expressed about the following aspects of the system:

- Cross-Channel Data Transfer—Failure of the cross-channel data buses could lead to shutdown of the digital system. These buses must be designed with careful attention to such factors as electromagnetic interference and lightning to prevent simultaneous loss of all cross-channel data.
- Crew Communication—The problem of what information to present to the crew and the manner in which this information is to be transmitted and displayed require further detailed consideration.
- Dissimilar Pitch-Rate Sensors—The system defined for the Final ACT Airplane uses four pitch-rate signals: three from the IRSs plus one from an additional pitch-rate sensor. This may lead to problems in comparison of data due to differing dynamic characteristics of the sensors and potentially reduced reliability due to nuisance trips of the fault detector. Four identical pitch-rate sensors dedicated to the backup system will be investigated and may be the preferred configuration.
- Dissimilar Redundancy—The system mixes dual, triple, and quadruple redundancy, which leads to complex redundancy management and complex software. Careful attention to initializing and indexing is necessary to be certain that all computers function properly in any channel.

7.3 RECOMMENDED DEVELOPMENT ACTIVITIES

The following subsections describe development activities recommended to alleviate the category 1 risks identified in the structures and flight controls areas.

7.3.1 STRUCTURES

The recommended activities are as follows:

- A specific flight test program on a subsonic transport airplane with advanced airfoil sections to measure aerodynamic characteristics of outboard control surfaces, including hinge moments, section aerodynamic properties, and oscillatory aerodynamic characteristics, in the Mach number and deflection ranges of interest for WLA. Wing internal loads and external surface pressures should be instrumented.
- These flight test results be correlated with analytical predictions based on doublet lattice and kernel function unsteady aerodynamic methods.
- The preceding results be correlated at zero frequency with wind tunnel pressure data on a model of the flight-tested aerodynamic configuration.

The foregoing activities probably can be accomplished most efficiently by contracting with the airplane manufacturer for the flight test, including data reduction, and for the wind tunnel model construction.. Wind tunnel testing should be planned for a Government facility with the largest Reynolds number capability in the Mach number range of interest. The analytical work could be done either inhouse by NASA or contracted. A combination of NASA inhouse and contracted work would likely achieve the most efficient information exchange.

A rough estimate of timing and cost for this work is as follows:

- Flight test (including data analysis):
  1 year $1.5 to $2.0 million
- Wind tunnel test:
  9 months $500 000 to $750 000, assuming contracted model construction and facility costs
- Analytical work:
  1 year $250 000 to $400 000

The wind tunnel test might be eliminated, or the model design and construction costs reduced, if an adequate wind tunnel pressure model and test data exist for the flight test configuration.

7.3.2 FLIGHT CONTROLS

The planned work to completion of the IAAC Project will develop one system architecture through the beginning of laboratory evaluation. This work should be continued to complete system laboratory evaluation and flight test evaluation.

In addition, further research on competing architectures is required. At least one alternate architecture should be developed through laboratory evaluation. Supporting research in software verification, validation, configuration control, and monitoring schemes is also required.

A rough estimate of timing and cost for this work is as follows:

- Complete laboratory and flight evaluation of the IAAC system:
  2 years $6 to $10 million
- Alternate architecture development and laboratory evaluation:
  3 years $3 to $4 million
- Supporting research:
  3 years $750 000 to $1 million

8.0 CONCLUDING REMARKS

The configuration design and evaluation activities of the IAAC Project have resulted in definition of the Final ACT Configuration. This airplane configuration achieves a fuel savings of 10% at its design range. At a fuel cost of \$0.26/ℓ (\$1.00/gal), the airplane yields an incremental ROI to the operator of 25% relative to the Conventional Baseline Configuration at 925-km (500-nmi) range. Analysis shows that the ACT functions required for these performance and economic improvements can be provided with satisfactory dispatch and flight reliability. In achieving this performance the technical risks are chiefly in the areas of aerodynamic effectiveness of the WLA control surfaces and software reliability. The system described and analyzed has multiple redundant hardware but has common software in all channels. Evidence and opinion available at present indicate that flight-crucial functions (whose failure probability must be demonstrated to be extremely remote; i.e., less than 1×10^{-9} per 1-hr flight) require hardware and software dissimilar redundancy. Further control system development under the IAAC Project will be directed toward defining a system that is tolerant of software error and other common mode failures in performing flight-crucial functions.

It is recommended that further NASA research be directed toward development of systems for flight-crucial functions that can demonstrate tolerance of common mode failures. Research is also required to develop an adequate data base for WLA control surface design.

9.0 REFERENCES

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APPENDIX A: RELIABILITY ANALYSIS METHODS

COMPUTER-AIDED REDUNDANT SYSTEM RELIABILITY ANALYSIS

Initial reliability predictions concerning the system adopted for Final ACT, in which all active control functions are performed by four central computers operating in parallel and communicating with one another via digital data buses resident in the computers, were performed using the Boeing-developed computer-aided redundant system reliability analysis (CARSRA) computer program (ref A-1). This analysis, as shown in Tables A-1 and A-2, indicated that a four-channel system would meet the crucial reliability requirement, but a triple-channel system would not (ref A-2).

Subsequently, a detailed reanalysis was made using a fault tree approach because of the following limitations of the CARSRA method:

- Equal reliability of similar modules in each channel is a poor assumption because power bus and hydraulic supply reliabilities vary.
- There is a very limited capability to handle unequal sensor reliability.
- CARSRA does not portray system logic as clearly as the FTREE computer program.
- CARSRA does not rank LRUs by contribution to total system failure probability.
- CARSRA does not print out minterms and their probabilities for use in establishing built-in test requirements.

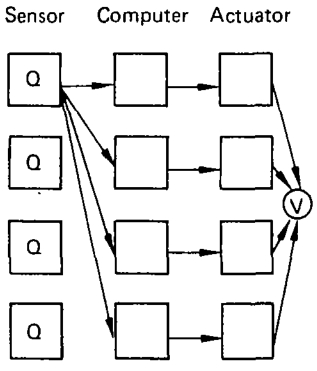
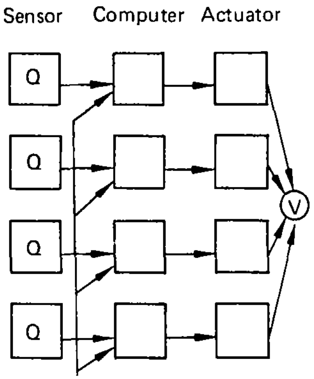
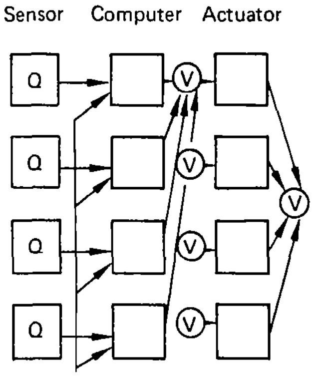
FAULT TREE

Reliability predictions for the Final ACT Configuration were made using the Boeing-developed FTREE computer model, which has the following capabilities:

- Direct access via local interactive terminal with capability to accept:
    - 1000 events
    - 1000 gates
    - 100 multiple occurring events

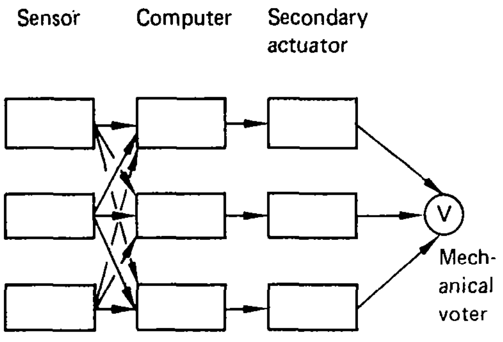
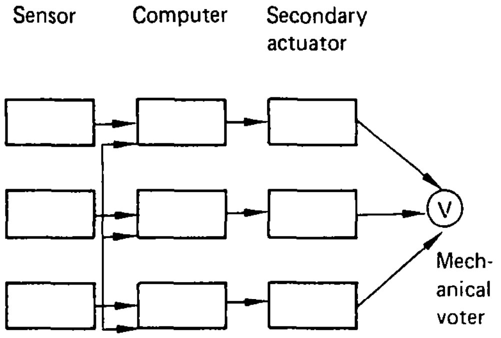
- Output printout
    - Failure probability at each gate
    - Identification of minterms and the failure probability of each
    - Impact of specified events on the top event or system failure probability

Table A-1. Quadruple-Channel System Configuration Comparison of Failure Probability

Case	Description of case	Configuration 1	Configuration 2	Configuration 3
				
A	4 IRS Q sensors, $\lambda = 263$ 4 computers, $\lambda = 250$ 4 mechanical, actuators λ (includes hydraulics) = 56.6	1.87×10^{-10}	5.92×10^{-10}	5.47×10^{-10}
B	Like A, except 3 mechanical actuators and a mathematical model, $\lambda = 0$	1.48×10^{-10}	5.53×10^{-10}	5.42×10^{-10}
C	Like B, except 3 IRS-based Q sensors, $\lambda = 263$, and 1 dedicated Q sensor, $\lambda = 73$	9.52×10^{-11}	3.51×10^{-10} Selected configuration	3.4×10^{-10}
D	Like C, except all Q from dedicated sensors	7.56×10^{-11}	8.13×10^{-11}	7.12×10^{-11}
E	Like D, except a different computer, $\lambda = 167$	2.49×10^{-11}	2.75×10^{-11}	2.4×10^{-11}

Notes:
1. Figures indicate essential PAS probability of failure rate per 1-hr flight.
2. V is voter.
3. λ = failure rate of component per 10^6 flight hours.

Table A-2. Three-Channel Configuration Comparison of Failure Probability

Requirements:	3 actuators + 1 mathematical model		2 actuators + 1 mathematical model	
At least 2 At least 2 At least 2	Case A: 3 IRS Q sensors 3 computers 3 hardware actuators 1 mathematical model	Case B: 3 dedicated Q sensors 3 computers 3 hardware actuators 1 mathematical model	Case C: 3 IRS Q sensors 3 computers 2 hardware actuators 1 mathematical model	Case D: 3 dedicated Q sensors 3 computers 2 hardware actuators 1 mathematical model
 Configuration 5	3.95×10^{-7}	1.88×10^{-7}	3.98×10^{-7}	1.91×10^{-7}
 Configuration 6	7.89×10^{-7}	1.99×10^{-7}	8.34×10^{-7}	2.44×10^{-7}

REFERENCES

A-1 Bjurman, B. E., G. M. Jenkins, C. J. Maereliez, K. L. McClellan, and J. E. Templeman. Airborne Advanced Reconfigurable Computer System. NASA CR-145024, 1976.

A-2 Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Initial ACT Configuration Design Study. NASA CR-159249, Boeing Commercial Airplane Company, July 1980.

APPENDIX B: RELIABILITY DATA

Reliability of the individual ACT functions and of combinations of those functions depends upon the failure rate of the component and upon the system configuration. The preferred source for reliability data was experience with the components in commercial service. If that information was not available, the manufacturer's quoted failure rate or an analysis by subcomponents from MIL-HDBK-217 was used. Values used and their sources are listed in Tables B-1 and B-2.

Electric Power System Reliability—The electric power system has been designed especially to provide an extremely low probability of loss of all four active control electric channels or of individual channels. Each channel is supported from both an airplane dc bus and a battery. No two channels have the same two sources. The airplane dc buses support each other and are themselves powered from ac buses that have multiple sources of supply. A fault tree illustrating the failure paths necessary to produce channel

Table B-1. Failure Rates of ACT Components

System elements	Mean time between failures, FH	Failure rate per 10^6 FH	Data source
ACT secondary actuator by parts			
Power piston and servovalve	6.25×10^5	1.6	NAS1-14742
T-valve	10^5	10.0	Boeing data
LVDT servovalve	1.43×10^5	7.0	NASA CR-145271
LVDT power piston	1.43×10^5	7.0	NASA CR-145271
Solenoid bypass valve	1.66×10^5	6.0	Boeing data
Total secondary actuator	31 600	31.6	Sum of above
Single-wire segment	5.00×10^6	0.2	Boeing data
Connectors			
10-pin stanchion connector (for essential PAS)	11.00×10^6	0.09	MIL-HDBK-217B
20-pin stanchion	7.14×10^6	0.14	MIL-HDBK-217B
10-pin production break (uninhabited environment)	5.09×10^6	0.196	MIL-HDBK-217B
20-pin production break (uninhabited environment)	3.29×10^6	0.304	MIL-HDBK-217B
200-pin rack-and-panel computer connector	2.78×10^5	3.6	MIL-HDBK-217B
Secondary actuator mechanical voter	—	0	Multiple mechanical failures required to cause malfunctions
Hydraulic power			
A	11 500	87.0	Boeing data
B	71 400	14.0	Boeing data
C	71 400	14.0	Boeing data
Pneumatic power (for AAL)	—	64.6	(Two, each supplied from separate gas cylinders) Boeing data
Electric power per channel	—	0.001	Boeing estimate

Table B-1. Failure Rates of ACT Components (Concluded)

System elements	Mean time between failures, FH	Failure rate per 10^6 FH	Data source
Actuator, secondary, outboard aileron	27 900	35.9*	Boeing data
Actuator, secondary, elevator	25 900	38.6*	Boeing data
Actuator, secondary, rudder	26 700	37.4*	Boeing data
Actuator, stick pusher	20 000	50.0*	Boeing data on similar 727 thrust reverser actuator
Actuator, stick shaker	10^6	1.0	727 experience
Computer, primary (see table C-2 for breakdown)	6 620	151.0*	Vendor data
Computer, management	6 620	151.0*	Vendor data
Digital air data computer (DADC) (see table C-2 for breakdown)	11 765	85.0*	Vendor MTBF
Sensor, inertial reference system	2 392	418.0*	Vendor MTBF
Sensor, angle of attack (used with DADC, see table C-2)	15 400	65.0	727 experience
Sensor, flap position (LVDT)	91 000	11.0*	NASA CR-145271
Sensor, wheel position (LVDT)	91 000	11.0*	NASA CR-145271
Valve, solenoid, stick pusher	65 400	15.3*	Boeing data

*Including connections and wires.

failure is shown in Figures B-1 and B-2. Input events shown in double circles are sets of components combined to simplify the drawing. Figure B-2 shows components of these sets, and Table B-3 lists failure rates used for the components. Analysis of the fault tree by the FTREE program yielded the failure rates in Table B-4 for several different takeoff conditions. It should be understood that when failure rates such as 10^{-14} or 10^{-16} appear, they represent only less than 10^{-10}. The numbers shown are presented for comparison but should not be interpreted as absolute values.

The electric power system enters into the ACT system in many places and in very involved ways. To consider this dependency when calculating the ACT function failure probabilities would have been extremely costly in time and computer use. Because failure rates are small, the electric power system does not contribute significantly to the ACT failure rate. Accordingly, electric power failure rates were not entered into the fault trees.

Table B-2. Partitioning of Failure Rates

Line replaceable unit and its component functions	Failures per 10^6 FH	Mean time between failures, FH
ACT computer	151.0	6 622
CPU and memory	31.8	31 450
Crucial input/output	14.1	87 640
Noncrucial input/output	65.4	15 290
Common parts	39.6	25 252
DADC (note 1)	85.0	11 765
Sensor, α (including vane)	38.0	26 316
Sensor, q (including pitot)	24.3	46 152
DADC common parts	18.1	55 250
Sensor, air data, remaining parts	42.5	23 530
IRS (note 2)	418.0	2 392
Sensor, Q (pitch rate)	20.4	49 020
Sensor, normal acceleration	31.7	31 550
Inertial reference, common parts	31.0	32 260
Remaining parts (includes other rate channels, accelerometers, computation)	129.0	7 752

Notes:

1. Components of DADC do not include external sensor parts, such as α vane and pitot tube, in addition to DADC parts.
2. The entire IRS includes many parts never used by ACT.

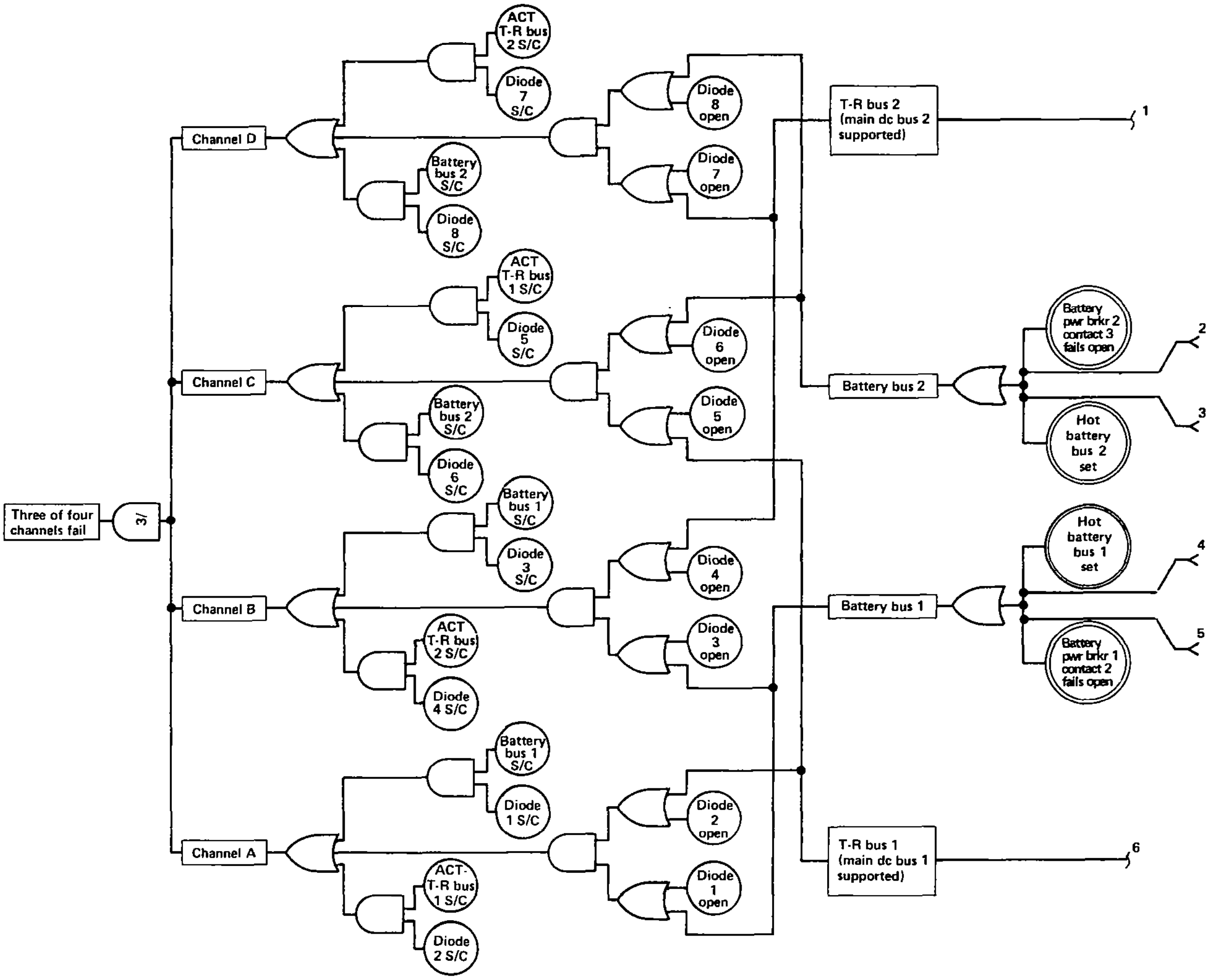


Figure B-1. Fault Tree for Electric System

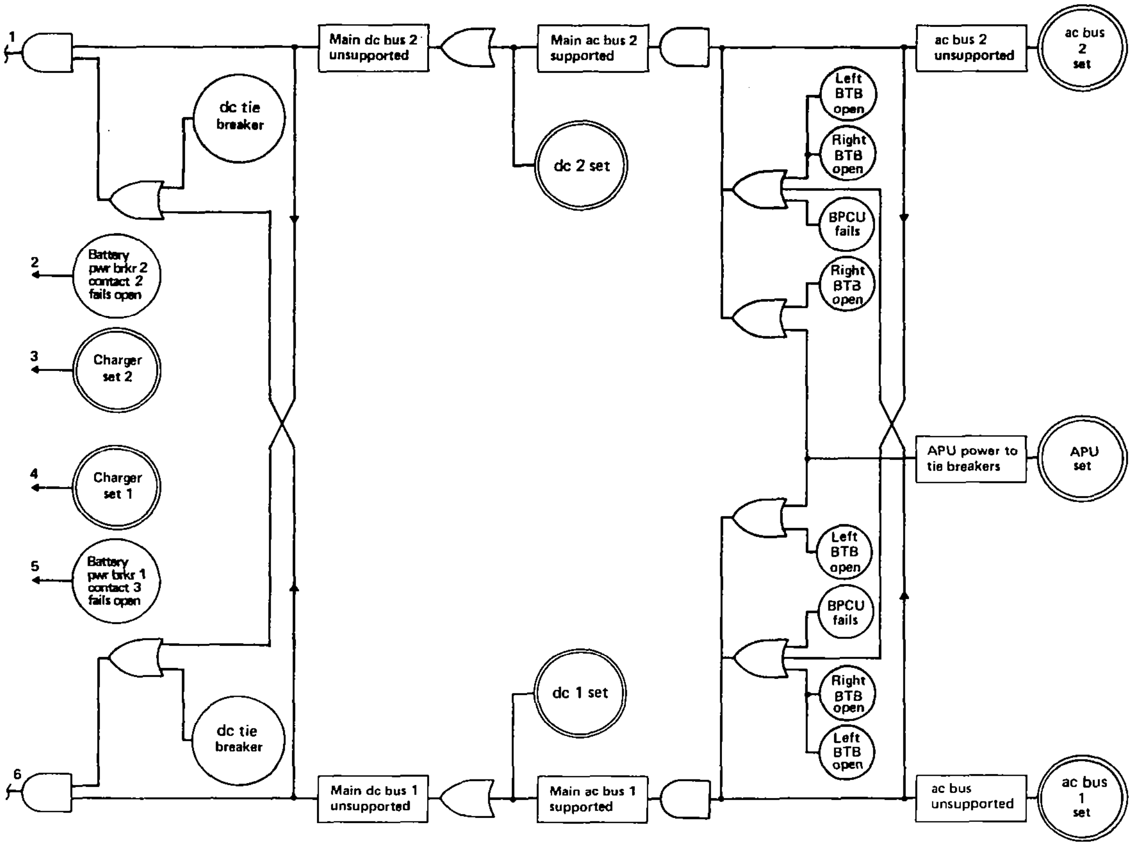


Figure B-1. Fault Tree for Electric System (Concluded)

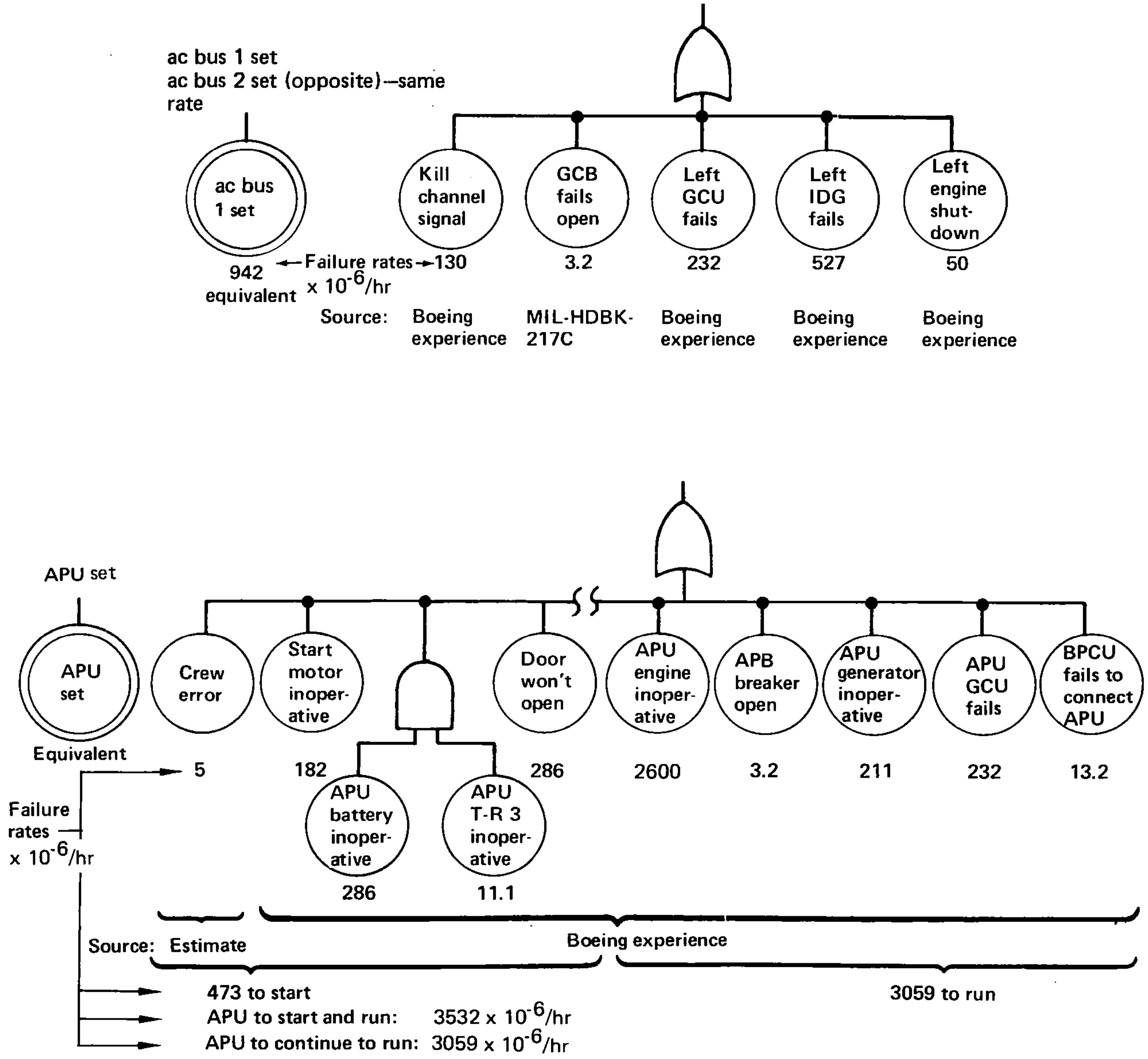


Figure B-2. Sets of Components Reducible to One Component

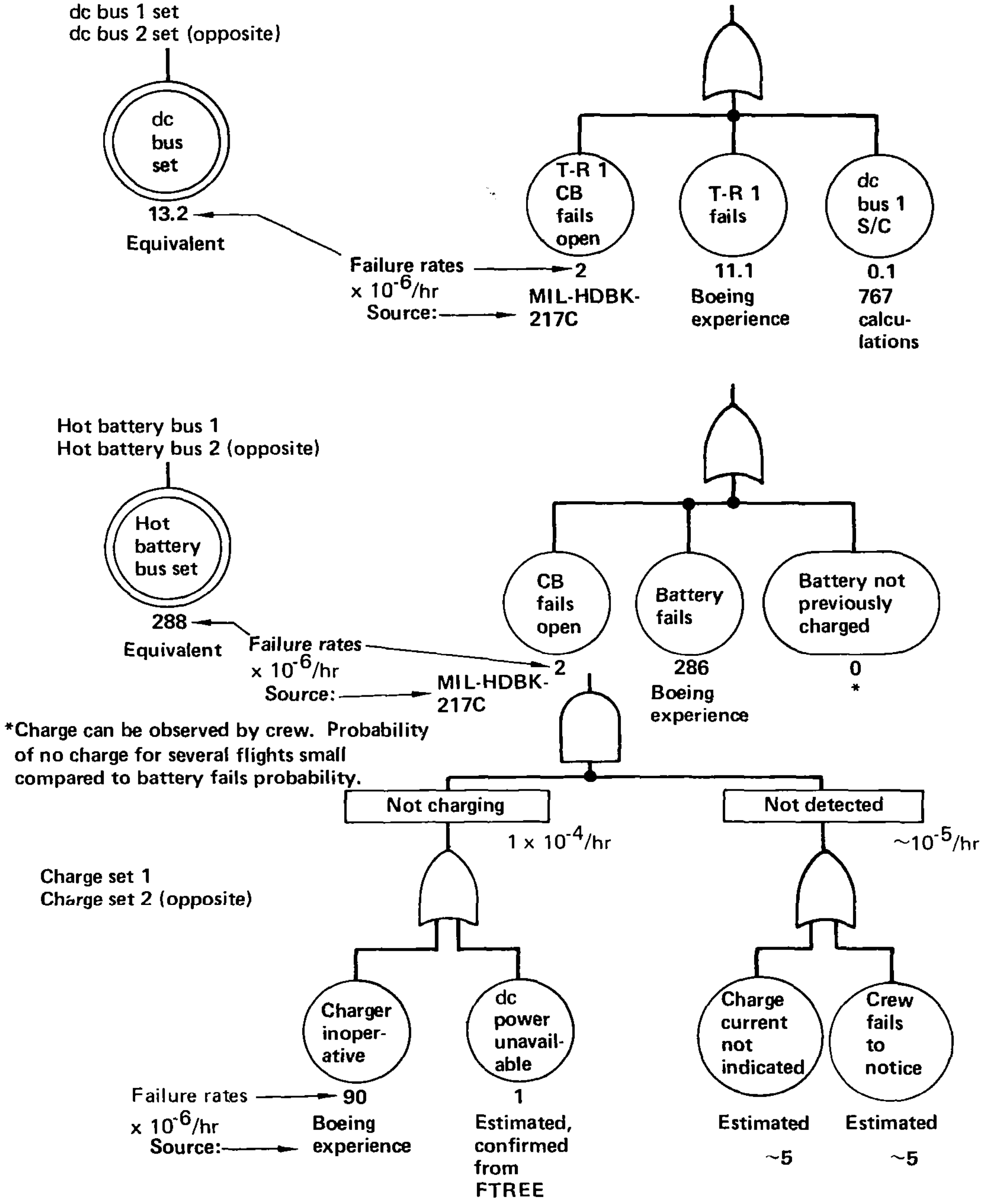


Figure B-2. Sets of Components Reducible to One Component (Concluded)

Table B-3. Electric Power System Component Failure Rates

Failure probability (x 10^{-6}/hr)	Source of failure rate	Name of event
942.0	See Figure B-2, ac bus set	ac bus 1 set
942.0	See Figure B-2, ac bus set	ac bus 2 set
3532.0	See Figure B-2, APU set	Auxiliary power unit—fails to start and run
3059.0	See Figure B-2, APU set	Auxiliary power unit—fails to continue to run
40.0	Boeing experience and Rome Air Development Center (RADC)	Over 90-kVA load, switch to one generator, excess not shed
3.2	Boeing experience and RADC	Left bus tie breaker—fails open
3.2	Boeing experience and RADC	Right bus tie breaker—fails open
93.0	Boeing calculation	Bus power control unit—all failure modes
13.2	See dc bus set	dc bus 1 set
13.2	See dc bus set	dc bus 2 set
3.2	Boeing experience and RADC	dc tie breaker—fails open
288.0	See Figure B-2, hot battery 2 set	Hot battery bus 1 set
288.0	See Figure B-2, hot battery 2 set	Hot battery bus 2 set
3.2	Boeing experience and RADC	Battery power breaker 1 contact 3—fails open
3.2	Boeing experience and RADC	Battery power breaker 1 contact 2—fails open
3.2	Boeing experience and RADC	Battery power breaker 2 contact 3—fails open
0.2	Boeing experience and RADC	Battery power breaker 2 contact 3—fails open
1.0	MIL-217—all modes	Computer power input diode 1—fails open
1.0	MIL-217—all modes	Computer power input diode 2—fails open
1.0	MIL-217—all modes	Computer power input diode 3—fails open
1.0	MIL-217—all modes	Computer power input diode 4—fails open
1.0	MIL-217—all modes	Computer power input diode 5—fails open
1.0	MIL-217—all modes	Computer power input diode 6—fails open
1.0	MIL-217—all modes	Computer power input diode 7—fails open
1.0	MIL-217—all modes	Computer power input diode 8—fails open
0.1	Boeing estimate	ACT T-R bus 1—short circuit to ground
0.1	Boeing estimate	ACT T-R bus 2—short circuit to ground
0.1	Boeing estimate	Battery bus 1—short circuit to ground
0.1	Boeing estimate	Battery bus 2—short circuit to ground
1.0	MIL-217C—all modes	Computer power input diode 1—short circuit across junction
1.0	MIL-217C—all modes	Computer power input diode 2—short circuit across junction
1.0	MIL-217C—all modes	Computer power input diode 3—short circuit across junction
1.0	MIL-217C—all modes	Computer power input diode 4—short circuit across junction
1.0	MIL-217C—all modes	Computer power input diode 5—short circuit across junction
1.0	MIL-217C—all modes	Computer power input diode 6—short circuit across junction
1.0	MIL-217C—all modes	Computer power input diode 7—short circuit across junction
1.0	MIL-217C—all modes	Computer power input diode 8—short circuit across junction
1.0	Arbitrary value to examine sensitivity	(Probability the charger failed in previous flights and was not noticed by crew)
1.0	Arbitrary value to examine sensitivity	

Table B-4. Electric System Failure Probabilities (1-hr Flight)

Takeoff condition	Probability of all ac channels inoperative (i. e., probability of being dependent upon battery alone)	Probability of one channel inoperative	Probability of three of four ACT channels inoperative (system failure)
Two engine-driven systems on line and APU operable but not running	3.3×10^{-9}	2.97×10^{-10}	2.91×10^{-16}
Two engine-driven systems on line and APU inoperable	—	4.63×10^{-10}	4.95×10^{-14}
No. 2 engine-driven system and APU on line; other engine-driven system inoperable	—	8.35×10^{-10}	1.6×10^{-13}

APPENDIX C: ACT FUNCTION FAULT TREES

The fault trees used to model the ACT functions are described here. Figure C-1 is the essential PAS fault tree. The OR gate at the top of the tree feeds the event "essential PAS fault." If any of the three inputs to this gate is positive (indicating a fault), the output indicates a fault; namely, that essential PAS is inoperative. The event "actuating fault" is the output of an AND gate fed by three OR gates, which implies that all three OR gates must give a failed condition for an actuating fault to occur. In this case the two-channel minimum requirement is satisfied by comparing actuator output with a mathematical model resident in all computers. Each of the three actuation OR gates is fed by one of the three crucial ACT secondary actuators, and its associated hydraulic system, and by the appropriate computer parts that control the actuator. Any of the events feeding an OR gate will, on failure, cause the loss of a single actuator.

The "sensor fault" event is the output of an OR gate fed by a "pitch-rate sensing" fault or a "servo position sensing fault." There are four linear variable differential transformers (LVDT) sensing servo position, even though there are only three actuators, because an extra LVDT senses the position of the summing linkage. The failure of three out of four of the LVDTs or their associated electronics results in a sensor fault because degradation below two operating channels is not allowed.

The "pitch-rate sensing fault" is fed by the body axis pitch-rate (Q) analog parts from each of the three IRSs, including the associated ACT computer electronics, and also by the analog signal from a single dedicated Q sensor. Three of four failures are required for Q sensor failure because at least two channels are again required for success.

The "computing fault" event is fed by failures in any one of the four ACT computer central processing unit (CPU) memories or common parts that control, monitor, and provide actuator modeling. Three of four failures are required to fail the system. It will be observed that "ACT computer common part" failure is a multiple occurring event that feeds every lower level gate of the "essential PAS" fault tree. This illustrates the usefulness of FTREE in handling dependencies and multiple occurring events.

The full PAS fault tree, shown in Figure C-2, combines the functions of essential (or short period) PAS and static or speed stability augmentation PAS and is similar in structure. The sensors depend upon the computers to accept their signals. Partitioning of computer failure rates permits including only those parts of the computer that are required to be operable to receive the sensor inputs. Under dynamic pressure (q) sensing fault, the DADCs have also been partitioned into the q parts and those common parts (power supplies, cooling, structure) that are required to provide a q output. A failure is not charged for other failed parts. The additional function, gain scheduling, is backed up by an alternative, the flap position switch, so that both must have produced a fault input to the gain scheduling fault AND gate to get a fault output. These backup functions appear in several of the ACT functions and result in the backed-up function being virtually infallible. Certain parts of the ACT computers are of overriding importance because all sensors and actuators depend on the ACT computers for communication to the rest of the system. In this tree the ACT computers, subfunctions of the DADC, and the IRS are all multiple occurring events.

The AAL (stick pusher and stick shaker) fault trees, shown in Figures C-3 and C-4, follow the same pattern. Stick pusher actuation is complicated by the need to ensure against inadvertent actuation. Each actuator is precluded from operating unless two solenoid valves open, so both valves and one power source are combined in an OR gate; thus failure of any one could produce actuator failure, but both actuators would have to fail to produce AAL actuation failure.

The probability of being required to divert during a 1-hr flight is the probability of being one failure away from the loss of essential PAS or one failure away from loss of all of the set (full PAS and LAS and WLA).

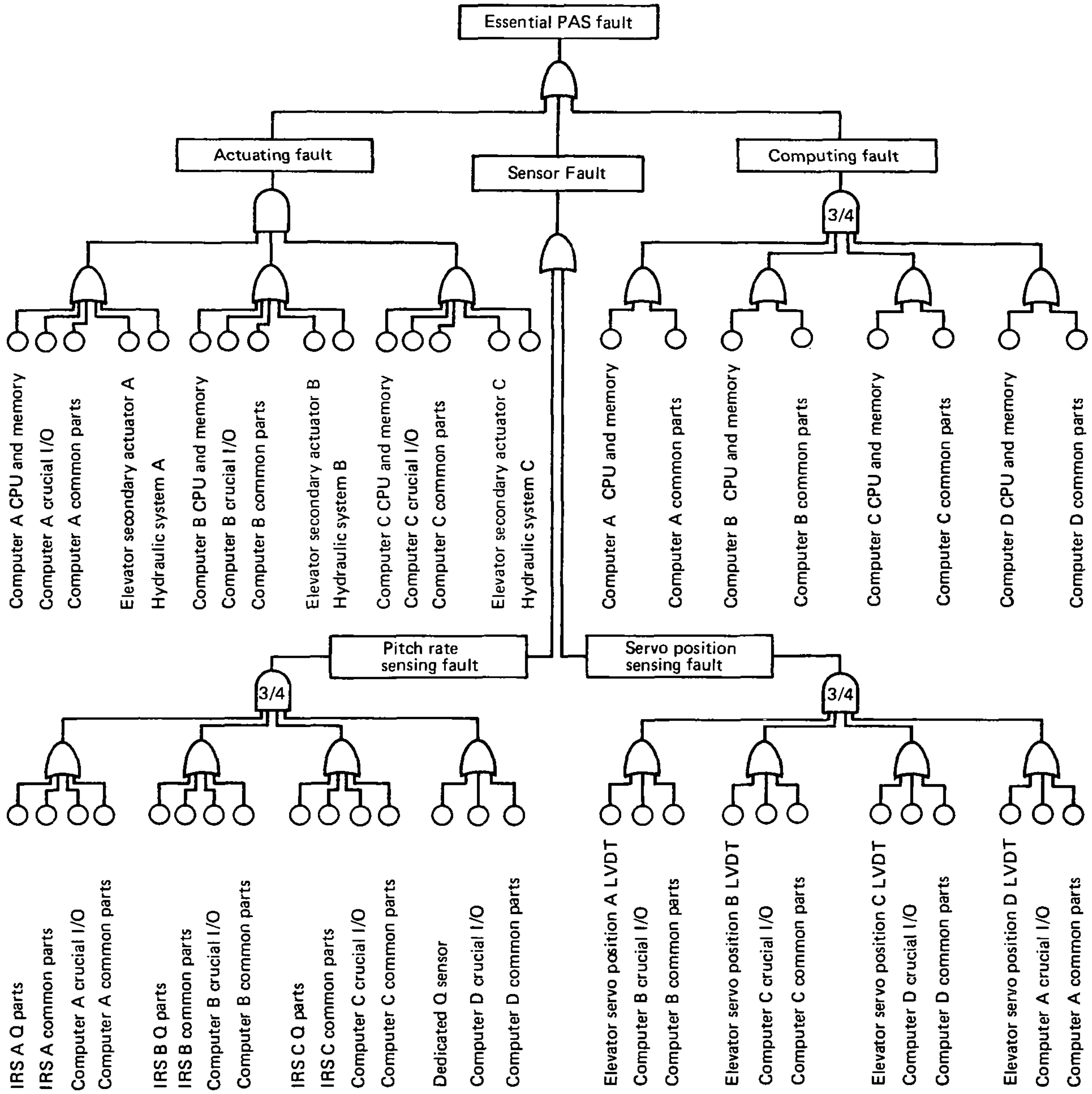


Figure C-1. Essential Pitch-Augmented Stability Fault Tree

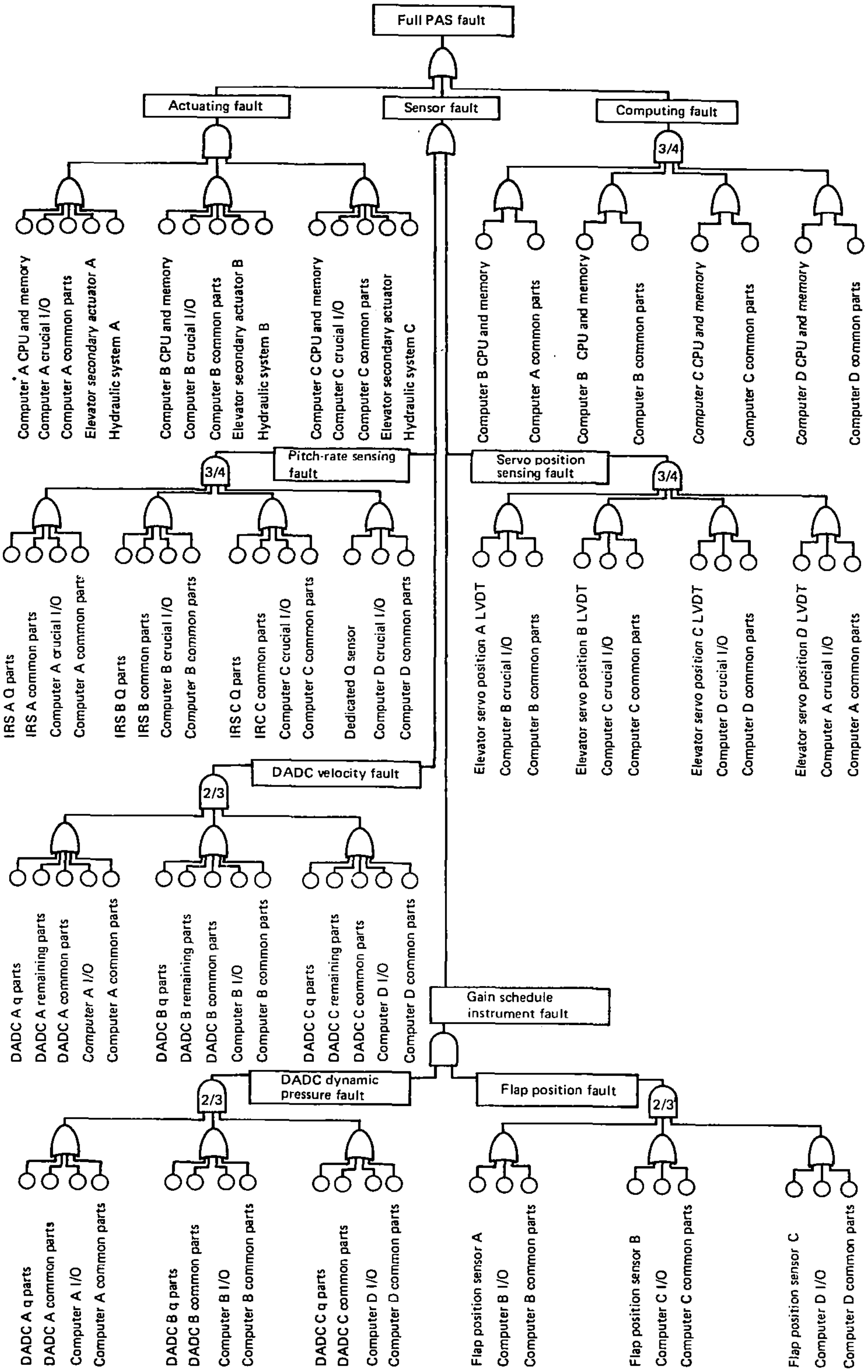


Figure C-2. Full Pitch-Augmented Stability Fault Tree

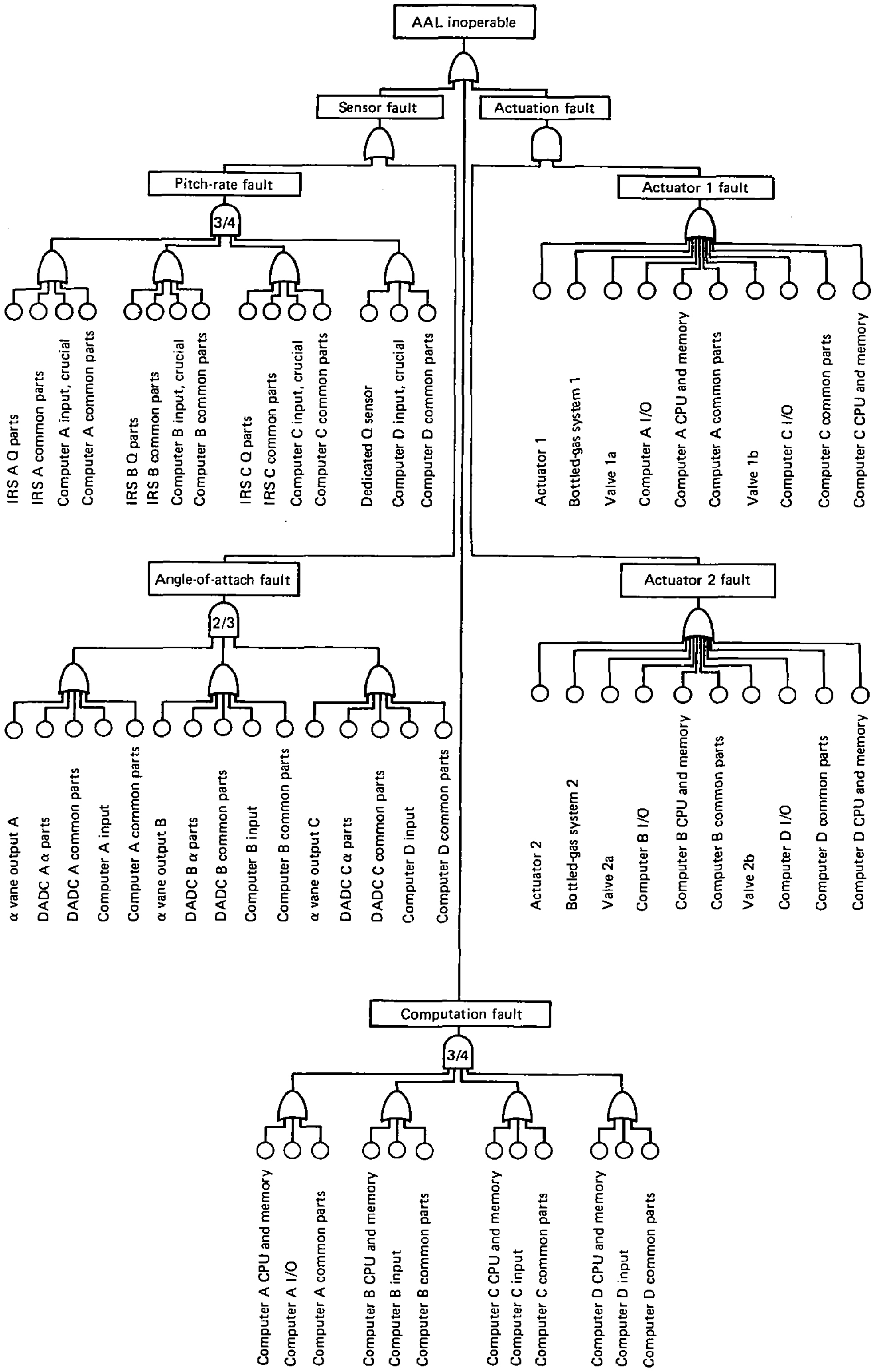
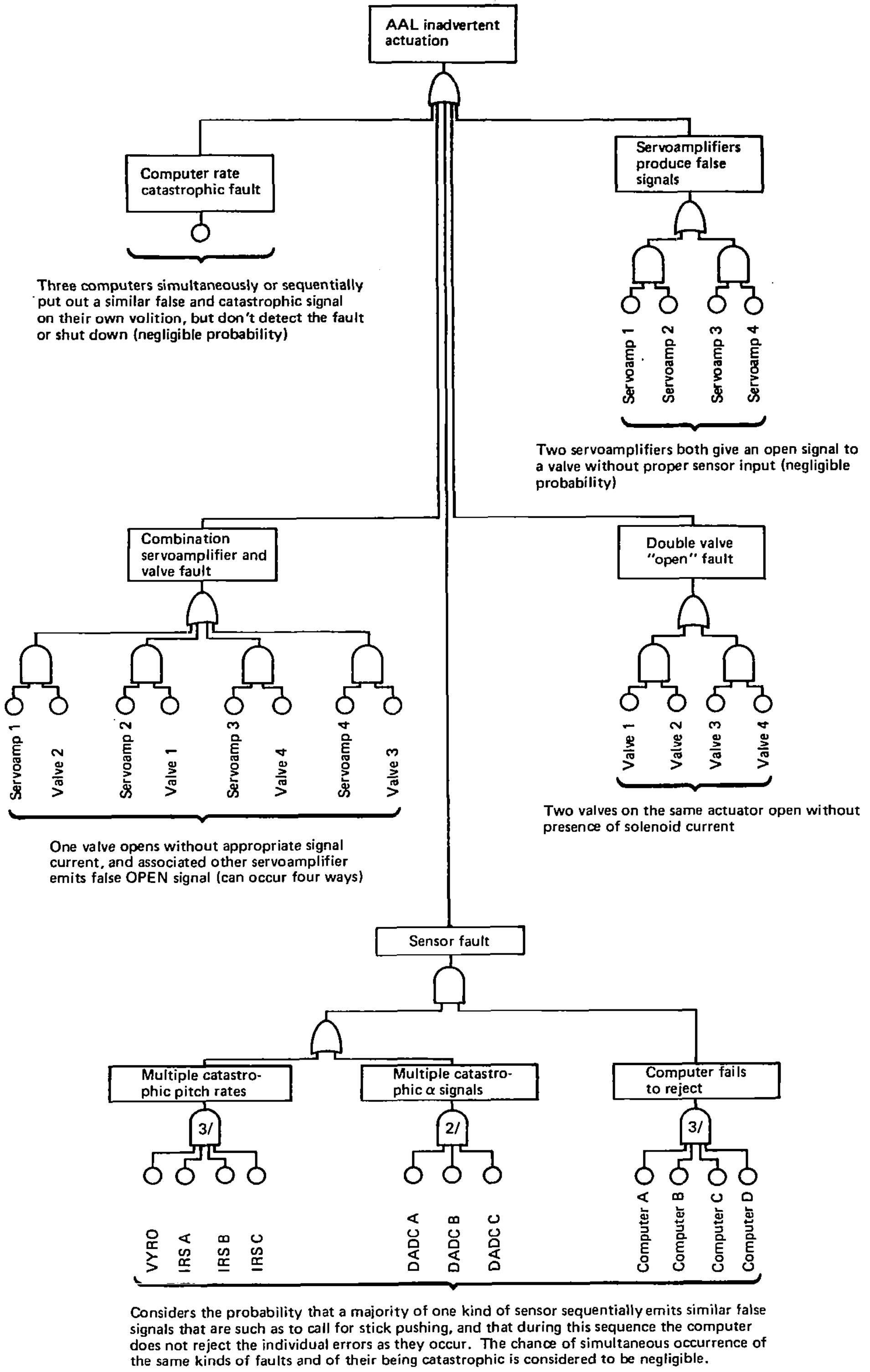


Figure C-3. Angle-of-Attack Limiter Inoperable Fault Tree



Three computers simultaneously or sequentially put out a similar false and catastrophic signal on their own volition, but don't detect the fault or shut down (negligible probability)

Two servoamplifiers both give an open signal to a valve without proper sensor input (negligible probability)

One valve opens without appropriate signal current, and associated other servoamplifier emits false OPEN signal (can occur four ways)

Two valves on the same actuator open without presence of solenoid current

Considers the probability that a majority of one kind of sensor sequentially emits similar false signals that are such as to call for stick pushing, and that during this sequence the computer does not reject the individual errors as they occur. The chance of simultaneous occurrence of the same kinds of faults and of their being catastrophic is considered to be negligible.

Figure C-4. Angle-of-Attack Limiter Inadvertent Operation Fault Tree

This is predicted by combining the relevant fault trees into one tree and changing the number of components required to produce a failed condition at the appropriate gates. The FTREE computer program will then take account of all dependencies and multiple occurring events.

Figure C-4 predicts the probability of inadvertent stick pusher actuation. In this case, failure in the sensors is not passive but produces a false signal that calls for actuation when it is not required. Failure in the actuation consists of actuation in the absence of a computer input signal calling for actuation. The computer fault consists of a computer output, in the absence of the appropriate sensor inputs, that the program and the rest of the computers fail to detect and deactivate. Commercial aircraft experience provided almost no data from which to calculate rates for such failure modes; therefore, conservative estimates were made. This fault tree, having an entirely different set of failure mode input events, cannot be combined with the rest of the ACT function fault trees to find the probability of joint failures.

1. Report No. NASA CR-3519	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) TECHNOLOGY TO AN ADVANCED SUBSONIC TRANSPORT PROJECT—FINAL ACT CONFIGURATION EVALUATION		5. Report Date February 1982
		6. Performing Organization Code
7. Author(s) Staff of Boeing Commercial Airplane Company Preliminary Design Department		8. Performing Organization Report No. D6-49356
		10. Work Unit No.
9. Performing Organization Name and Address Boeing Commercial Airplane Company P. O. Box 3707 Seattle, Washington 98124		11. Contract or Grant No. NAS1-15325
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Contractor Report Oct. 1980 to April 1981
		14. Sponsoring Agency Code

15. Supplementary Notes

Langley Technical Monitor: D. B. Middleton
Final Report

16. Abstract

This report summarizes the Final ACT Configuration Evaluation Task of the Integrated Application of Active Controls (IAAC) Technology Project within the Energy Efficient Transport Program. The Final ACT Configuration, through application of Active Controls Technology (ACT) in combination with increased wing span, exhibits significant performance improvements over the Conventional Baseline Configuration. At the design range for these configurations, 3590 km (1938 nmi), the block fuel used is 10% less for the Final ACT Configuration, with significant reductions in fuel usage at all operational ranges. Results of this improved fuel usage and additional system and airframe costs and complexity required to achieve it have been analyzed to determine its economic effects. For a 926-km (500-nmi) mission, the incremental return on investment (i.e., the return on the additional investment required for the Final ACT Configuration over the Baseline) is nearly 25% at 1980 fuel prices. For longer range missions or increased fuel prices, the return is greater.

This report also identifies the technical risks encountered in the Final ACT Configuration design and the research and development effort required to reduce these risks to levels acceptable for commercial airplane design.

17. Key Words (Suggested by Author(s)) IAAC, Final ACT Configuration, Economics, Reliability, Technical Risk, Energy Efficient Transport Program, Active Controls Technology, Aircraft		18. Distribution Statement FEDD Distribution Subject Category 05	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 87	22. Price

Available: NASA's Industrial Applications Centers

NASA-Langley, 1982