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LOW-WING-LOADING STOL TRANSPORT RIDE SMOOTHING FEASIBILITY STUDY FINAL REPORT

The Boeing Company
Wichita, Kansas

January 1971

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LOW-WING-LOADING STOL TRANSPORT RIDE SMOOTHING FEASIBILITY STUDY

FINAL REPORT

D3-8514-2

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THE BOEING COMPANY
WICHITA DIVISION - WICHITA, KANSAS 67210

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MODEL STOL Transport CONTRACT NAS1-10410

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PROGRAM OBJECTIVE

This document presents results of an analytical study conducted by the Wichita Division of The Boeing Company for the Langley Research Center, National Aeronautics and Space Administration, under Contract NAS1-10410. The primary objective of the study was to determine the feasibility of providing satisfactory ride qualities using modern controls technology on a high performance, low-wing-loading STOL aircraft. The aircraft configuration was designed to be competitive with present high speed jet aircraft economics and block times and to meet proposed noise requirements.

Gust alleviation is not a new concept as indicated by the references shown in the bibliography. During the late 1930's and 1940's, NACA personnel conducted analyses, wind tunnel tests and flight tests of gust alleviation systems and flight demonstrated acceleration reductions of up to 60 percent.[1]

Advances in electronic and hydraulic actuation hardware indicate that mechanization of a satisfactory ride smoothing system is now a realizable goal with current technology. This study was conducted to synthesize such a system for a high performance, low-wing-loading STOL aircraft.

1. Hunter, Paul A., Kraft, Christopher C. Jr., and Alford, William L., ""A Flight Investigation of an Automatic Gust - Alleviation System in a Transport Airplane", NACA TN D-532, dated 1961.

PROGRAM OBJECTIVE

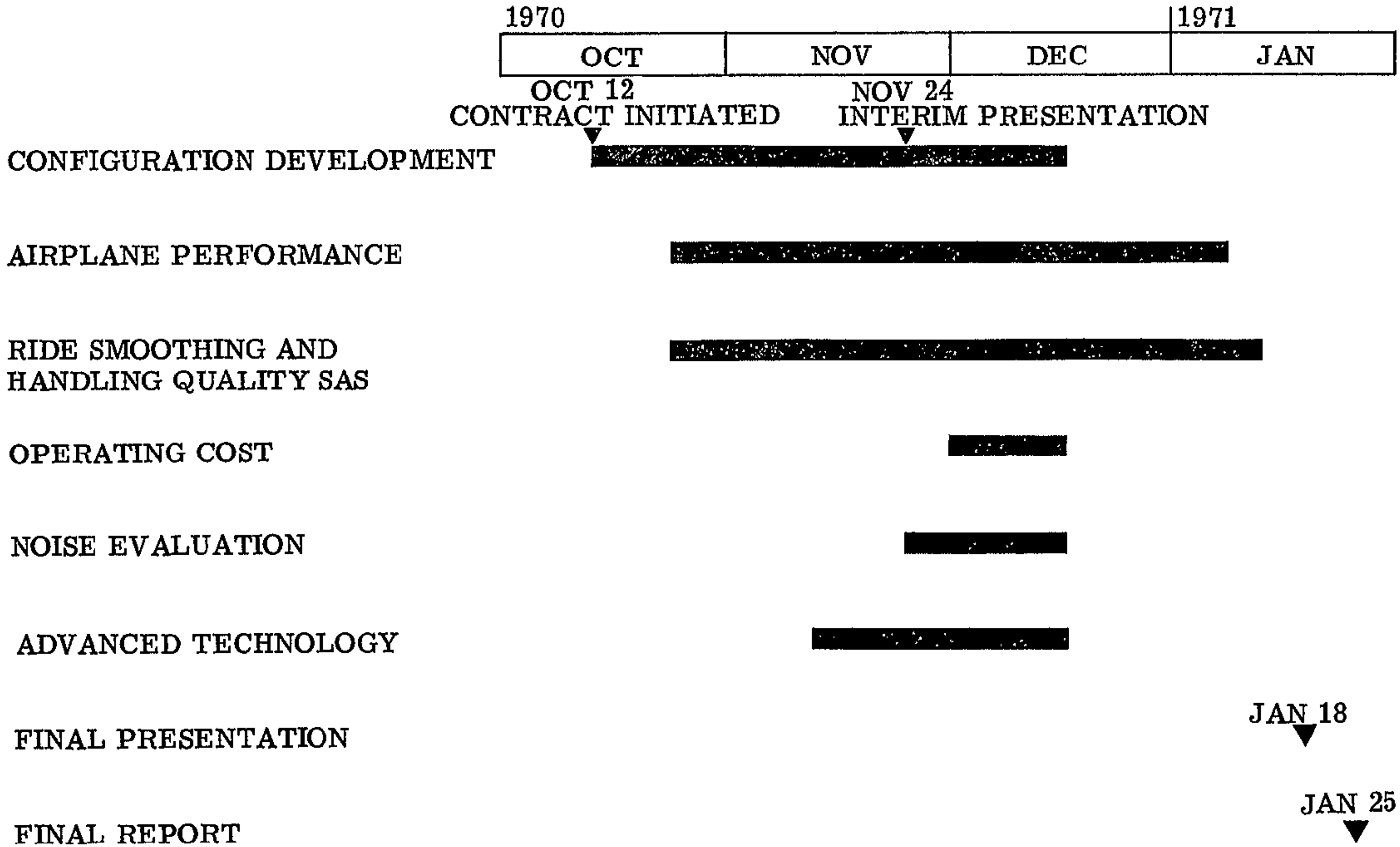
DETERMINE FEASIBILITY OF PROVIDING SATISFACTORY RIDE QUALITIES USING MODERN CONTROLS TECHNOLOGY ON A HIGH PERFORMANCE LOW-WING-LOADING STOL AIRCRAFT

IG710043-21

PROGRAM SCHEDULE

A configuration was developed to provide a vehicle for the ride smoothing system synthesis. Performance analyses were conducted to assess significant airplane capabilities. In addition, operating costs, noise, application of advanced composite structure and Prop-Fan propulsion were assessed.

PROGRAM SCHEDULE



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CONCLUSIONS

Within the limitations outlined in this document, conclusions of this study are shown on this chart. Principal limitations were rigid body dynamics, linear aerodynamics and linear control systems analyses.

CONCLUSIONS

A LOW-WING-LOADING STOL AIRCRAFT WITH RIDE SMOOTHING SAS PROVIDES

- SATISFACTORY RIDE QUALITIES
- COMPETITIVE HIGH SPEED PERFORMANCE

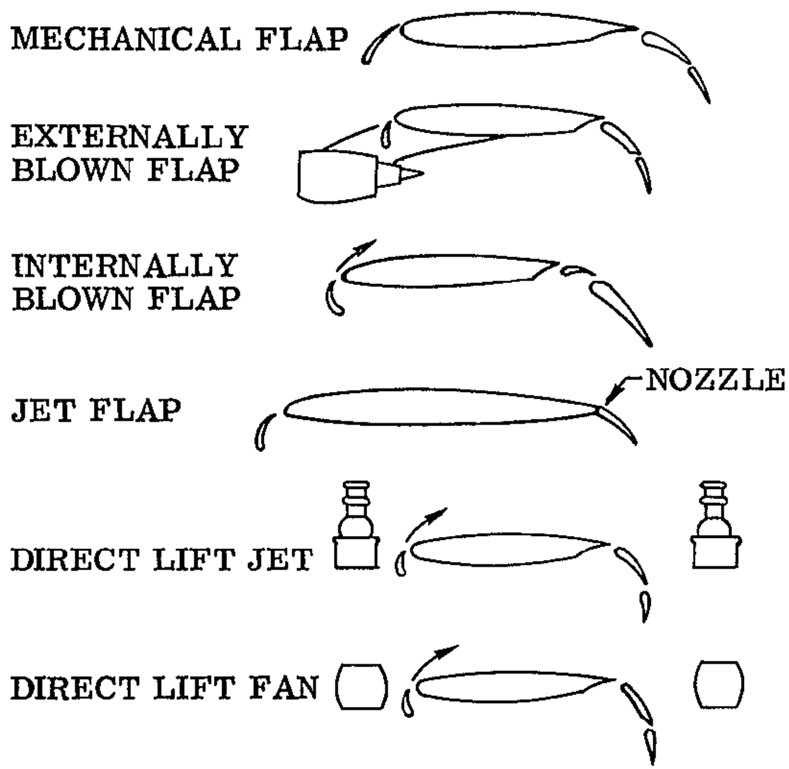
1G710043-40

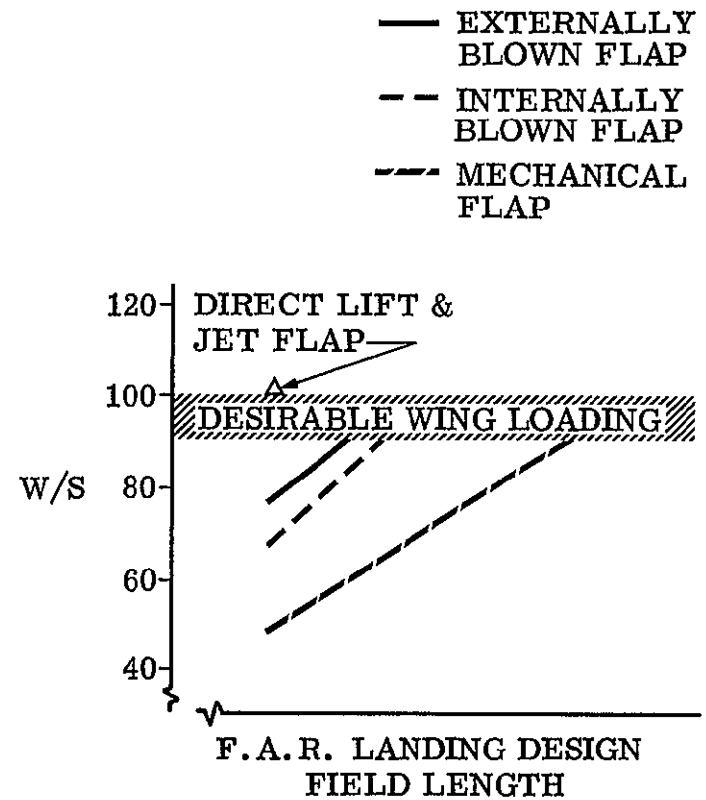
STOL DESIGN CONCEPTS

High cruise speeds have been a goal of most commercial STOL studies. This requirement, with a desire for high cruise efficiencies and passenger ride comfort, has resulted in airplanes designed with high-wing-loadings. To achieve STOL capability, these configurations rely on complicated auxiliary propulsive systems or augmented lift systems which must be carried throughout the mission for use on takeoff and landing only. These designs are sensitive to propulsion system failures which affect safety of flight in most cases.

The low-wing-loading concept relies on the flight control system to provide satisfactory ride and accepts some reduction in efficiency during high speed cruise. This STOL capability is provided with simple, flight proven, aerodynamic concepts.

STOL DESIGN CONCEPTS





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LOW-WING-LOADING STOL CONCEPT

The engine thrust required for takeoff is less for lower wing loadings. Since none of the lift is provided by the propulsion system, a propulsion system failure will not cause a sudden loss of lift. The low thrust requirement also reduces the takeoff and sideline noise and since less fuel is required for takeoff, airport pollution is reduced.

Low-wing-loading causes a larger than necessary wing for cruise which reduces cruise efficiency.

At comparable speeds, low-wing-loading airplane are more gust responsive than high-wing loading airplanes. To provide acceptable passenger ride comfort, a ride smoothing control system is required. A system failure in a turbulent environment would require a slower speed to maintain satisfactory comfort.

LOW-WING-LOADING STOL CONCEPT

- ADVANTAGES
  - RELIABLE - SIMPLE - STATE-OF-THE-ART ALL MECHANICAL FLAP SYSTEM
  - RELATIVELY LOW THRUST TO WEIGHT
  - LIFT NOT AFFECTED BY PROPULSION SYSTEM FAILURE
  - ECOLOGICAL BENEFITS ~ NOISE AND POLLUTION

- DISADVANTAGES
  - REDUCED EFFICIENCY AT HIGH SPEED CRUISE
  - POOR PASSENGER COMFORT AT HIGH SPEEDS WITHOUT RIDE SMOOTHING SAS

IG710043-18

DESIGN OBJECTIVES

The design objectives shown opposite were established to provide a framework for sizing the vehicle.

DESIGN OBJECTIVES

• PAYLOAD	130 PASSENGERS (18 FIRST CLASS AND 112 ECONOMY CLASS)
• FAR FIELD LENGTH	2000 FEET
• CRUISE MACH NUMBER	0.8 (APPROX.)
• UNREFUELED RANGE	750 N. MI. (3 EQUAL 250 N. MI. SEGMENTS)

IG710043-17

ASSUMPTIONS

The fuselage of the Boeing Model 751 was used for these studies. This aircraft was the Boeing configuration submitted in response to the requirements of Eastern Air Lines.[2] The Model 751 was a high wing loading configuration which used four auxiliary lift engines for high acceleration and deceleration to provide it with STOL capability. The configuration also used a small amount of leading edge blowing for flow attachment.

The lower than usual aspect ratio of six was selected since a high aspect ratio would result in a large span for the large area and the reduced lift curve slope somewhat improves the ride. Also, this configuration cruises at low lift coefficients where drag due to lift is not important to cruise efficiency.

By utilizing supercritical wing technology, the sweep of the flap hinge line can be zero for maximum flap effectiveness while maintaining high critical Mach numbers for cruise.

Estimated engine performance was based on projected 1975 technology which included increased turbine temperatures (2900°R) and compressor pressure ratios of 24.

The operating rules for certification type analysis were based on Tentative Airworthiness Standards.[3]

2. Operational Requirements and Guidelines For V/STOL Systems, Eastern Engineering Report No. E-482, August 12, 1969.

3. Tentative Airworthiness Standards For Powered Lift Transport Category Aircraft, D.O.T., F.A.A., Flight Standards Service, Washington, D.C., August 1970.

ASSUMPTIONS

- BOEING MODEL 751 FUSELAGE
- ASPECT RATIO = 6.0
- TAPER RATIO = .4
- SWEEP OF TRAILING EDGE FLAP HINGE LINE = 0 DEGREES
- DOUBLE SLOTTED FULL SPAN TRAILING EDGE FLAP WITH MATCHED LEADING EDGE FLAP
- 1975 ENGINE TECHNOLOGY
- SUPERCRITICAL WING TECHNOLOGY
- OPERATING RULES PER TENTATIVE AIRWORTHINESS STANDARDS, PART XX

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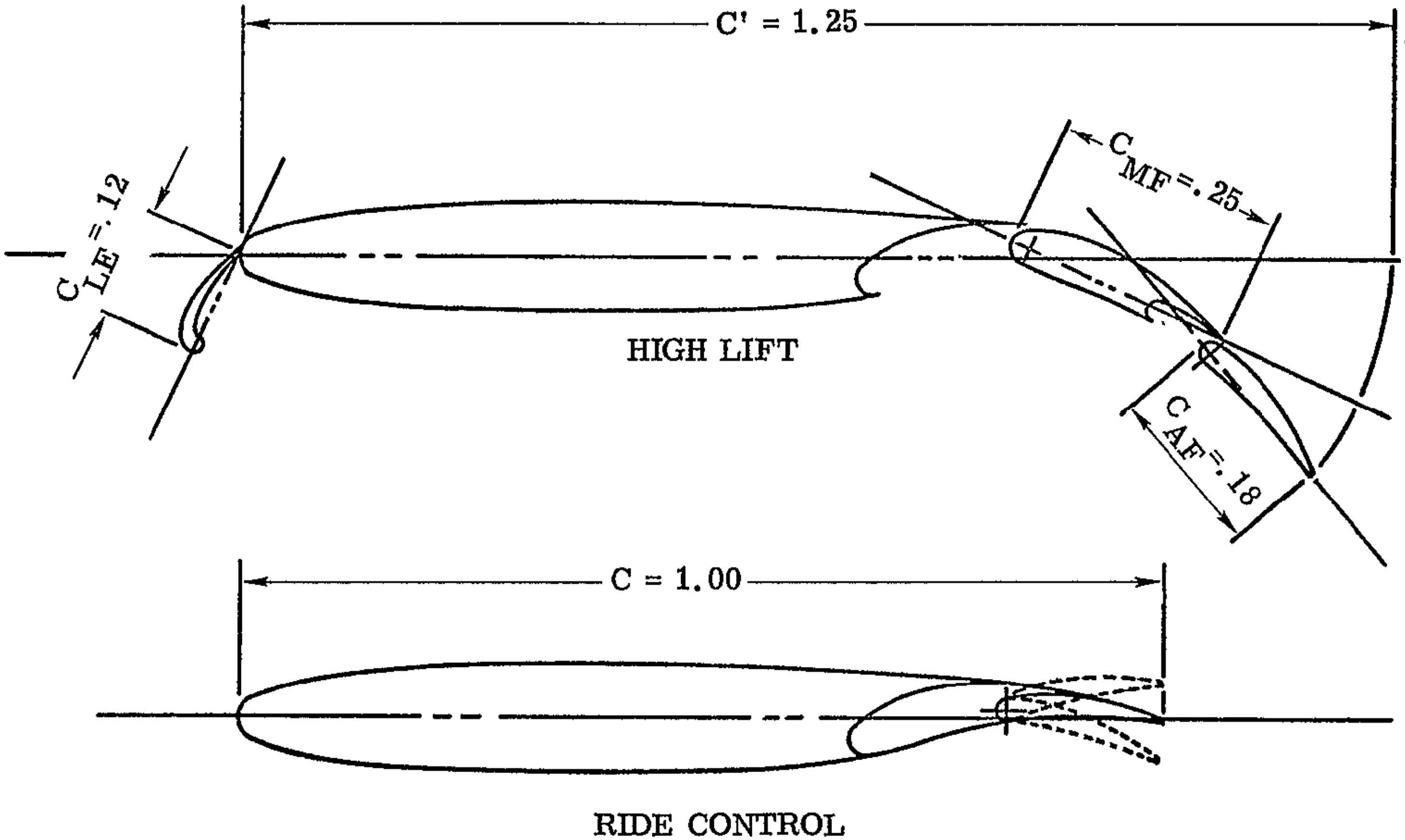
FLAP SYSTEM

The full span trailing edge flap is a dual purpose surface that performs as a conventional double slotted flap for takeoff and landing. The deflection for takeoff is 20° and for landing is 30°. The aft segment of the double slotted flap is provided with a high bandpass actuator for use by the ride smoothing control system. The estimated maximum authority required of the aft flap segment is ± 10° from its nominal position.

FLAP SYSTEM



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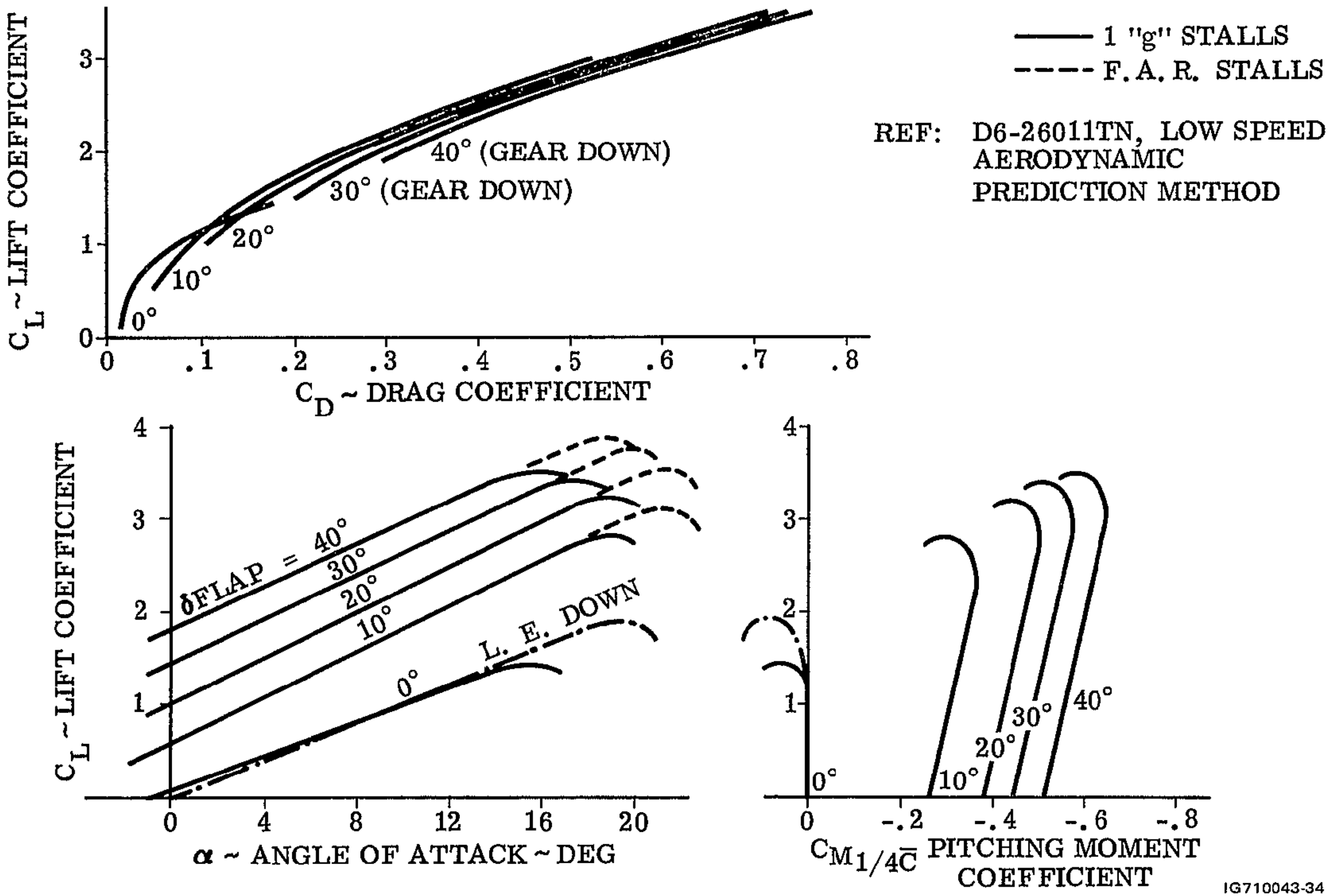
ESTIMATED LOW SPEED AERODYNAMIC CHARACTERISTICS

The low speed aerodynamic characteristics were estimated by Boeing methods.[4] This method has shown good agreement with flight test results of the Boeing 727, 737 and 747.

4. Boeing Document D6-26011TN, "Low Speed Aerodynamic Prediction Method", July 14, 1970.

ESTIMATED LOW SPEED AERODYNAMIC CHARACTERISTICS



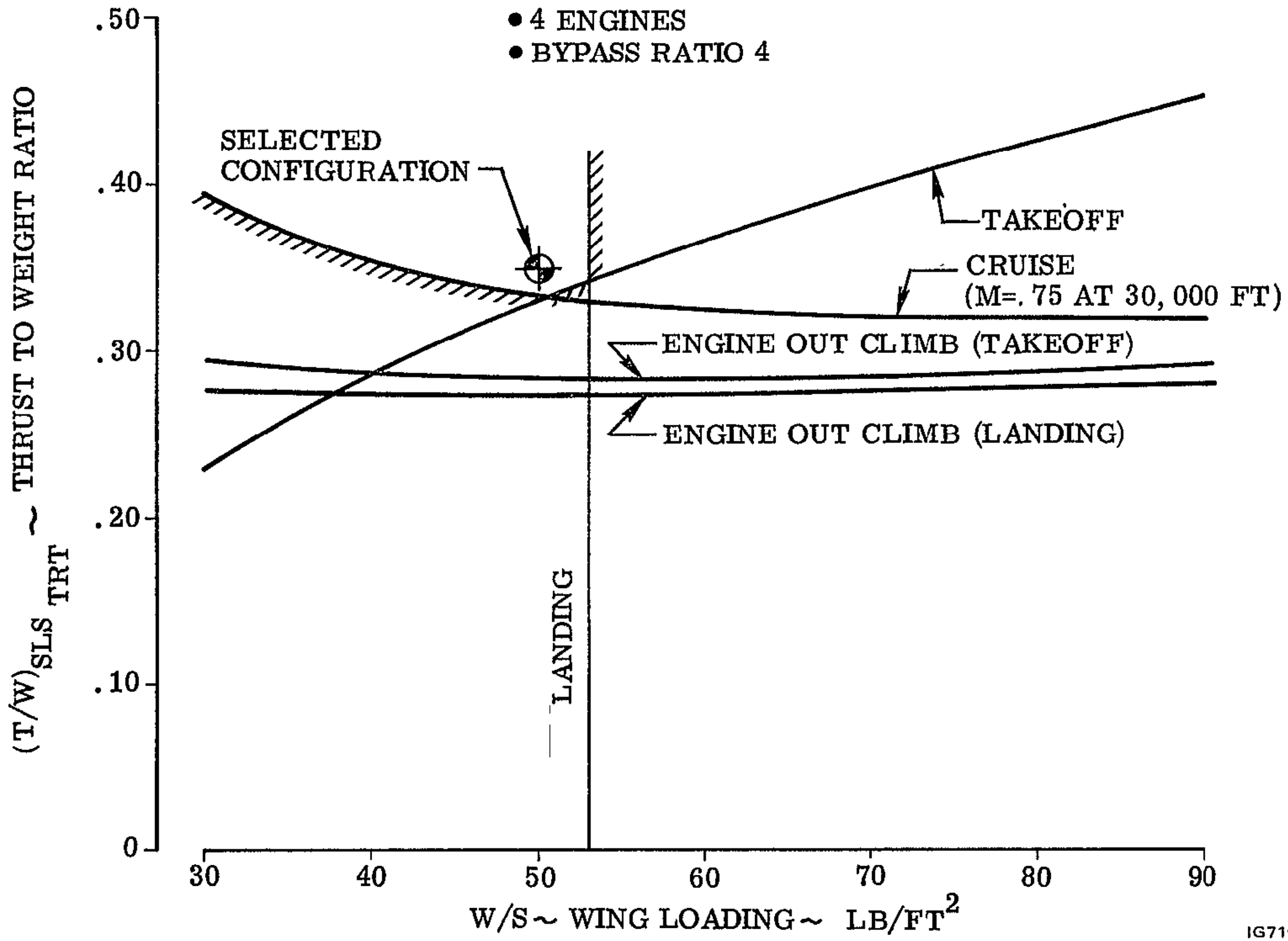
THRUST REQUIREMENT

A simple parametric study was performed to define the configuration which would satisfy the mission requirements and airworthiness standards.[3] A composite of these requirements is presented as a function of wing loading and thrust-to-weight ratio. The takeoff requirement is for a 2,000 ft. F.A.R. field length. The takeoff climb requirements and the balked landing requirements are established for the most critical engine inoperative.[3] The landing field length includes 67 percent conservatism. The cruise requirement is for a bypass ratio 4 turbofan engine (determined from sizing studies) at a Mach number of .75 at 30,000 ft. altitude.

The configuration selected for the ride quality studies had a $(T/W)_{SLS} = .35$ and a maximum gross weight wing loading of 50 lb/ft^2. This configuration has a good match between takeoff and cruise thrust requirements, which would not be the case for a higher cruise speed.

3. Tentative Airworthiness Standards For Powered Lift Transport Category Aircraft, D.O.T., F.A.A., Flight Standards Service, Washington, D.C., August 1970.

THRUST REQUIREMENT



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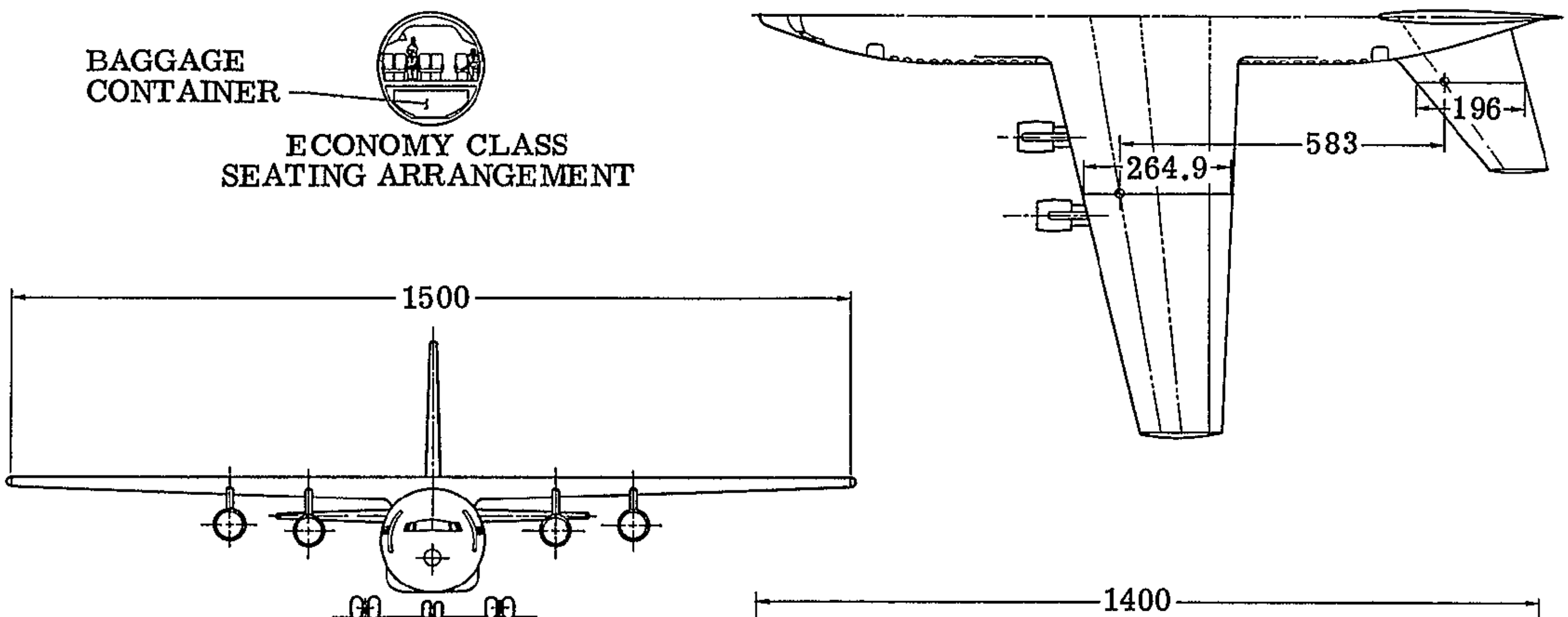
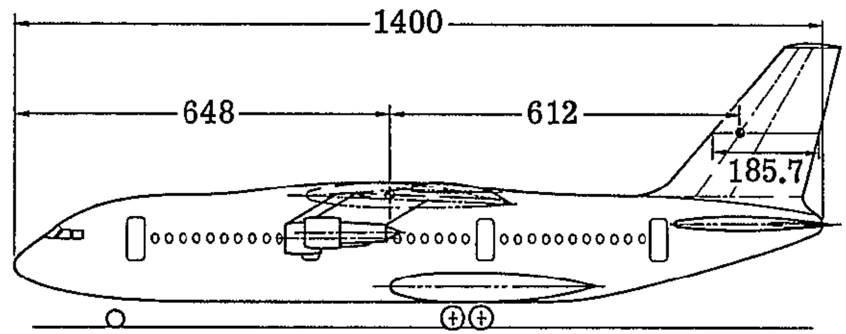
LOW-WING-LOADING STOL

The study airplane configuration is shown opposite. The fuselage represents current wide-body philosophy, incorporating a twin-aisle which aids rapid loading and unloading. The flight controls are conventional aerodynamic surfaces with minimum augmentation. The longitudinal controls are a .30c elevator for longitudinal control and a low-rate all movable stabilizer for trim. The directional axis is controlled by a large chord rudder on a conventional vertical tail. Lateral control is provided by wing mounted spoilers. The spoilers will also be used for landing roll airbrakes.

The high lift system is a full-span double-slotted trailing edge flap with a matched leading edge flap. The aft segment of the trailing edge flap will be used for the ride smoothing control system.

LOW-WING-LOADING STOL





WING

$S = 2600\ FT^2$

$b = 1500$ IN.

MAC = 264.9 IN.

$AR = 6$

$\lambda = .4$

$\Lambda_{.25c} = 9.71°$

IG710043 36

MISSION RULES

An unrefueled range of 750 n. mi. composed of three 250 n. mi. segments was chosen as the primary mission design objective. Airplanes sized for the primary mission were recycled to determine their size compatibility with a 1000 n. mi. alternate mission.

The airplanes were sized for the reserve requirements shown as distances A and B on the chart.[2,5] Distance A indicates a 1/2 hour continued cruise and descent to sea level followed by a missed approach. Distance B is 100 n. mi. composed of a climb to 10,000 ft., cruise and descent to an alternate field.

Takeoff and landing allowances were:

Taxi out time = 3 min.

Takeoff time = 1 min.

Landing time = 1 min.

Taxi in time = 3 min.

2. Operational Requirements and Guidelines for V/STOL Systems, Eastern Engineering Report No. E-482, August 12, 1969.

5. Boeing Document D6-24431-2, "Boeing Model 751 C/STOL Performance Report", November 18, 1969.

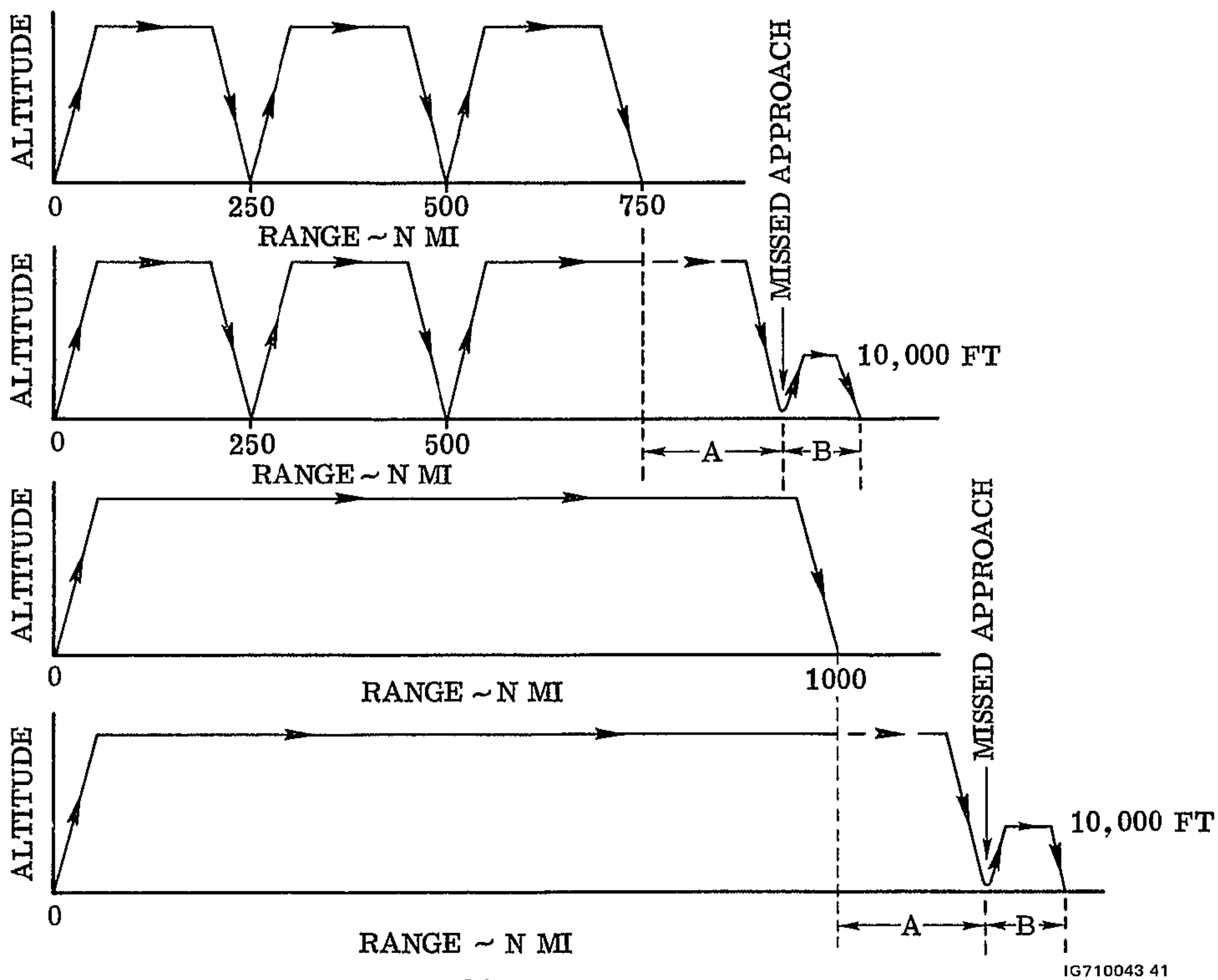
MISSION RULES

PRIMARY MISSION

PRIMARY MISSION RESERVES

ALTERNATE MISSION

ALTERNATE MISSION RESERVES

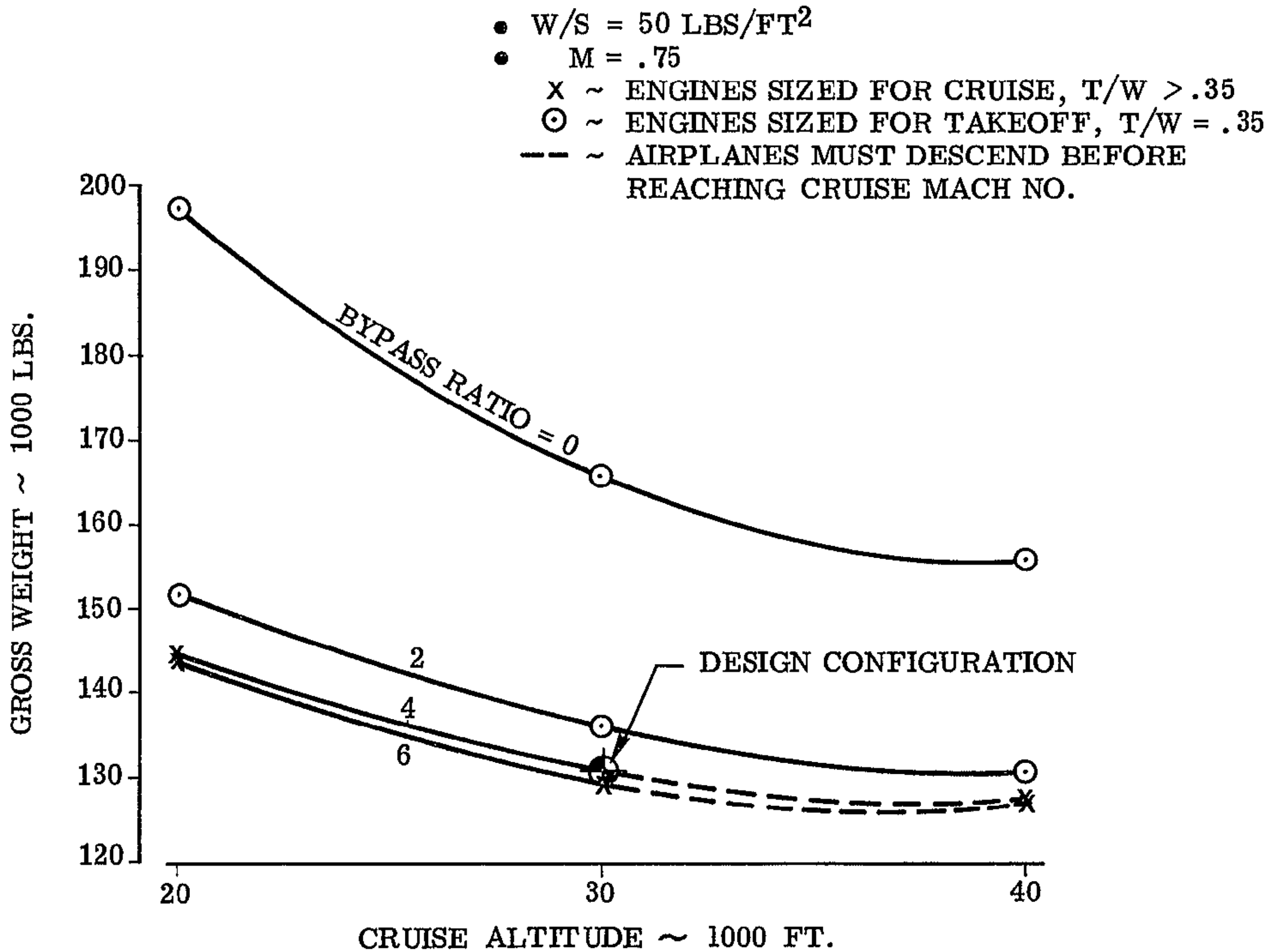


SIZING STUDY

As indicated in the chart, a cruise altitude of 30,000 feet for the selected design configuration results in the lightest airplane that can reach cruise Mach number with a T/W less than .35 when referenced to sea level static takeoff rated power.

For low bypass ratio engines, the engines are sized by the takeoff requirement. As bypass ratio is increased, the engines become sized by the cruise thrust requirement due to the thrust lapse-rate characteristics of the engine.

SIZING STUDY



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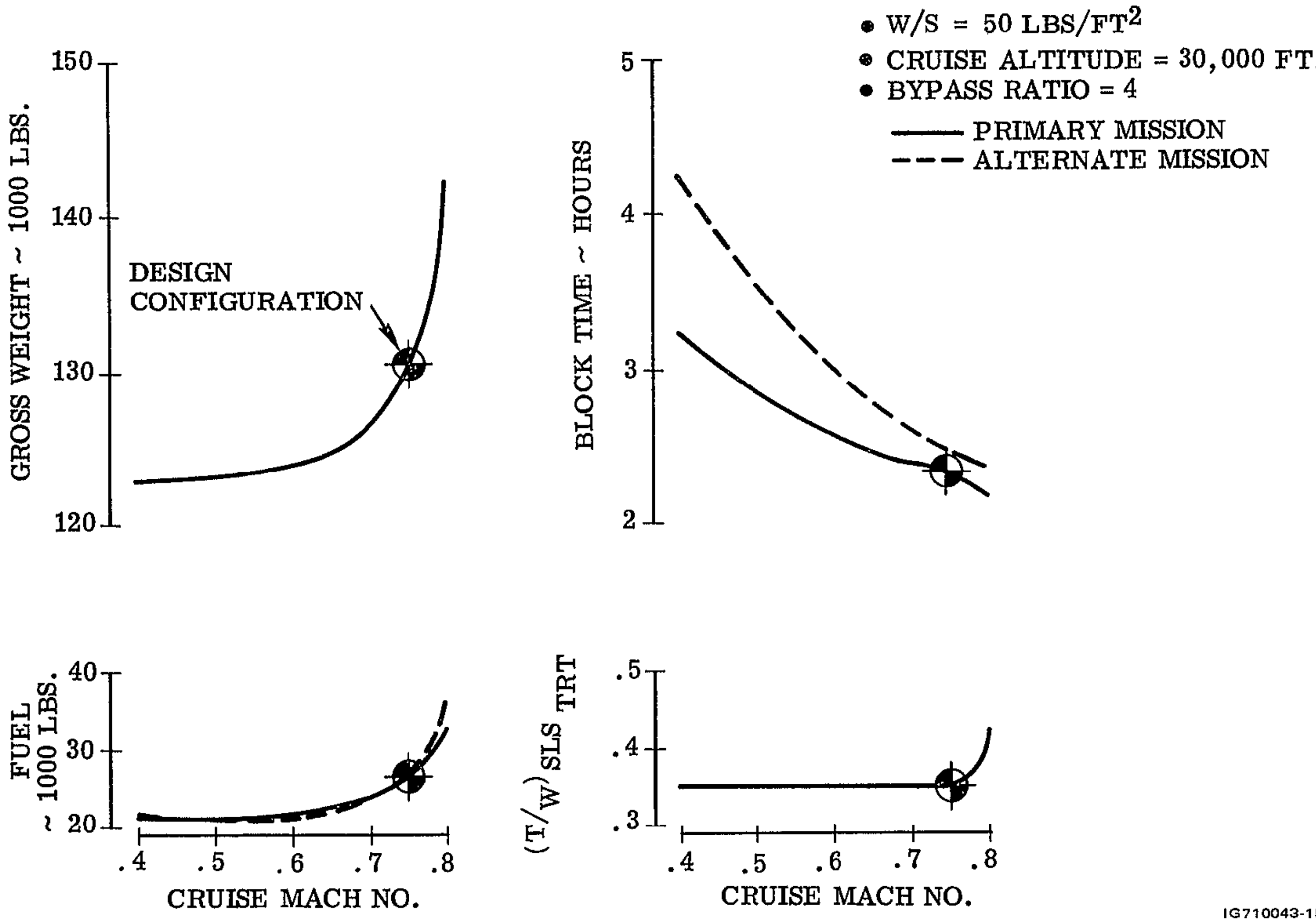
CONFIGURATION SENSITIVITY TO CRUISE MACH NUMBER

Above Mach .6, gross weight is extremely sensitive to cruise Mach number. The small block time advantage between Mach .7 and .75 may not be enough to merit the additional weight. A block time savings is indicated for cruise Mach numbers higher than .75. This is due to the lower climb times with the higher T/W required to fly faster than .75. However, it is questionable as to whether the resulting weight penalty would be economical. A more extensive configuration development could further refine the selected airplane by optimizing for economy.

CONFIGURATION SENSITIVITY TO CRUISE MACH NUMBER



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ECONOMIC CHARACTERISTICS

The Direct Operating Cost (DOC) of the STOL airplane is less than that of the 727-200 for trip distances less than 1,000 n. mi. This comparison is shown using ATA rules[6] for the 727-200 and the Eastern Air Lines DOC formula[2] for the STOL airplane. The costs were inflated to 1975 dollars.

The Boeing Model 751 DOC's, shown are estimated using the Eastern Air Lines DOC formula. However, time limitations prevented computing the Model 751 costs to 1975 dollars. If this effect were applied, the Model 751 costs would be increased.

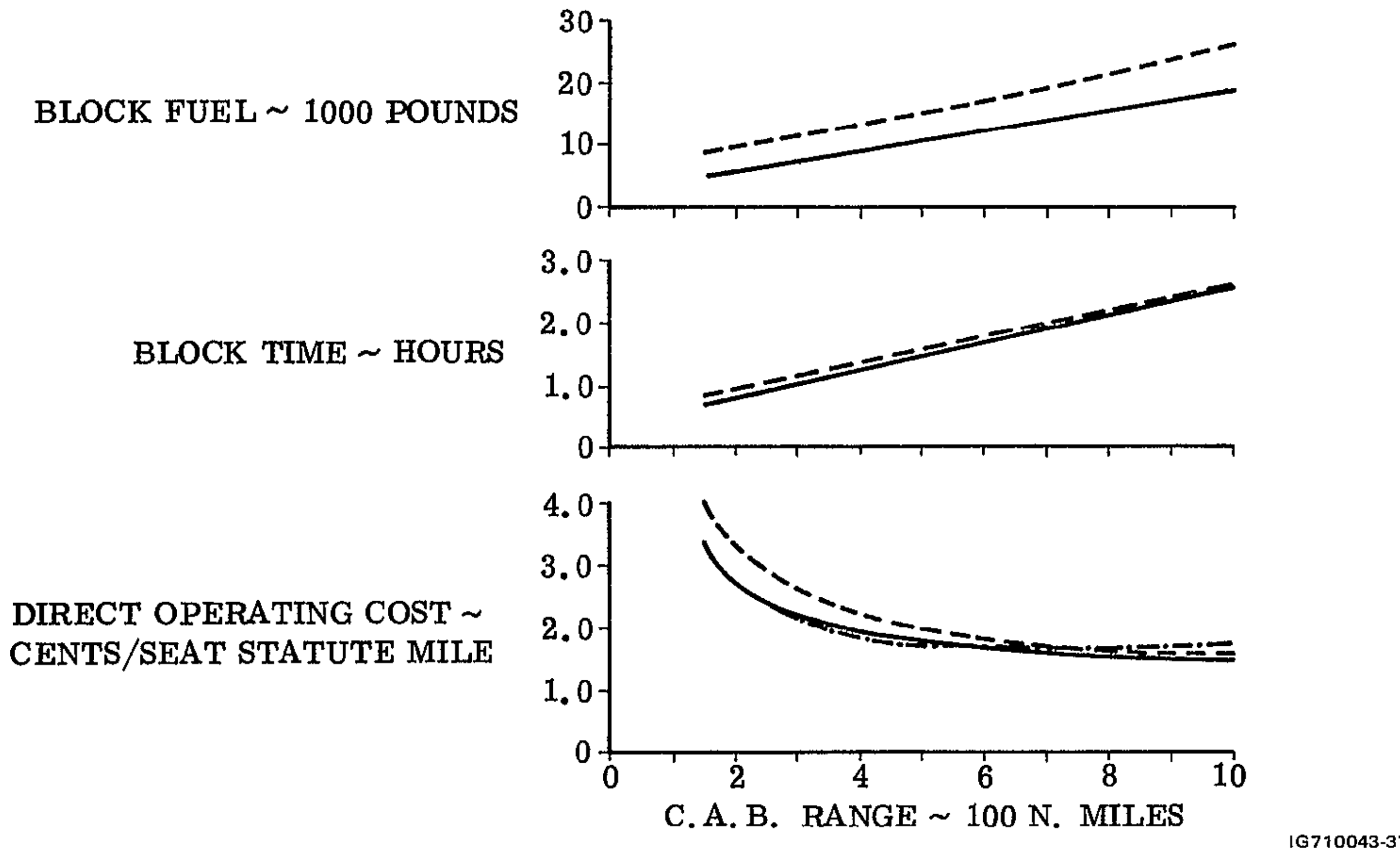
Since the data shown opposite are calculated for different rules, the conclusion is that the DOC of the low wing loading STOL airplane is "in the ball park" with DOC's of the other two vehicles.

2. Operational Requirements and Guidelines For V/STOL Systems, Eastern Engineering Report No. E-482, August 12, 1969.

6. Boeing Document ATN 70-007, "CAPATAR - Commercial Airplane Performance Using Air Transport Association Rules", December 11, 1970.

ECONOMIC CHARACTERISTICS

AIRPLANE	PASSENGERS	DOLLAR COST BASE	RULES
—— LOW W/S STOL	130	1975	EASTERN DOC FORMULA
---- 727-200	134	1975	ATA
-·-·- 751	130	1969	EASTERN DOC FORMULA

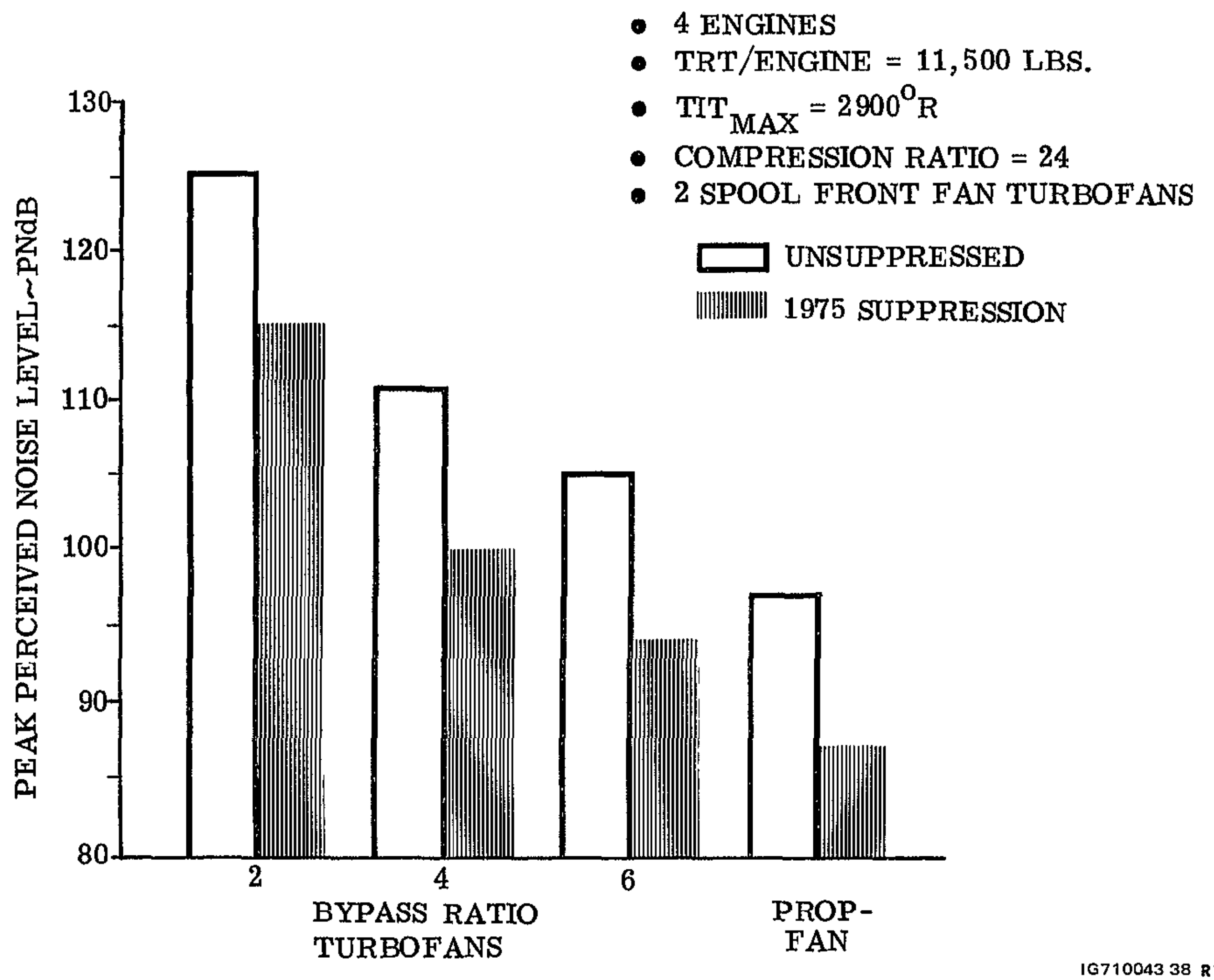


NOISE

The trend of today's advancements in engine technology is toward smaller, lighter and more efficient propulsion packages. Engines used for this study were assumed to be 1975 reflections of this trend which is advantageous from the engine efficiency standpoint but not necessarily compatible with minimum engine noise.

A critical point for STOL noise is the sideline. Data for 1,000 ft. sideline are shown opposite.

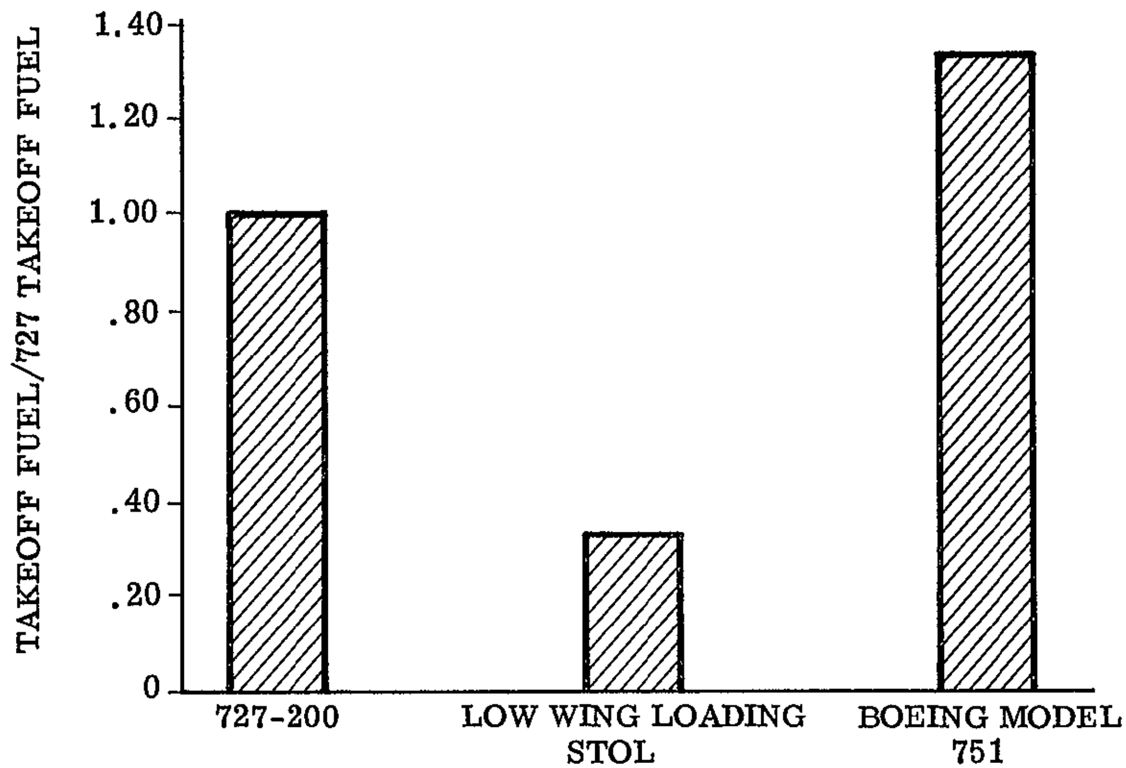
NOISE
(1000 FT. SIDELINE)



URBAN POLLUTION

The low-wing-loading STOL configuration with its relatively low thrust-to-weight will produce less pollution due to engine exhaust than other airplanes. The thrust-to-weight ratio of this configuration is approximately equal to present day jet transports. Because of the lower takeoff speeds, the total takeoff fuel is less. The takeoff time of the 727-200 is about 30 seconds compared to about 12 seconds for the low wing loading STOL configuration. A powered lift STOL configuration, such as the Boeing Model 751 with lift engines, has a total thrust to weight ratio of about .75 and a takeoff time of about 12 seconds. The data shown opposite reflect fuel burned from brakes release to clearing the 35 ft. obstacle.

URBAN POLLUTION



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ADVANCED TECHNOLOGY

To investigate the potential performance benefits possible through application of advanced composite structure technology, an estimate of the structural weight savings possible was predicted and an aircraft was sized to do the design mission. The primary structural weight of the wing, tails and fuselage was reduced one-eighth which reduced the gross weight approximately 7 percent.

For subsonic speed requirements (M = 0.7 to 0.8), the Hamilton Standard Prop-Fan concept offers potential performance improvements, and produces less noise than a comparable turbofan installation. A Prop-Fan configuration was determined using Hamilton Standard performance data.[7] The configuration has not been optimized for cruise altitude or Mach number and additional improvement may be possible.

A Prop-Fan configuration was also defined using composite structure technology.

7. Hamilton Standard, "Preliminary Prop-Fan Generalized Performance, Weight and Noise Data, Revision One", August 28, 1970.

ADVANCED TECHNOLOGY

	TURBOFAN BYPASS 4.0		PROP - FAN	
	CONVENTIONAL STRUCTURE	ADVANCED COMPOSITES	CONVENTIONAL STRUCTURE	ADVANCED COMPOSITES
STRUCTURE WEIGHT	44,000	37,500	43,000	37,000
PROPULSION WEIGHT	9,000	8,500	11,500	11,500
SYSTEMS, FIXED EQUIP. AND USEFUL LOAD	25,000	25,000	25,000	25,000
OPERATING WEIGHT EMPTY	78,000	71,000	79,500	72,500
PAYLOAD	26,000	26,000	26,000	26,000
FUEL	26,500	25,000	22,500	21,000
MAX. GROSS WEIGHT	130,500	122,000	128,000	119,500

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RIDE SMOOTHING SAS SYNTHESIS

The SAS synthesis consisted of three elements:

- o Ride quality criteria definition
- o Ride smoothing SAS conceptual trades
- o Performance benefits of the final configuration at three selected flight conditions

Results of the synthesis are shown on the following pages.

RIDE SMOOTHING SAS SYNTHESIS

MATHEMATICAL MODELS

Small perturbation, linear, rigid body equations of motion with six degrees of freedom were used in the airplane mathematical models.

Three flight conditions were selected to provide a reasonable variation of conditions within the STOL flight envelope. Wing loading was held constant at 46 lb/ft^2. A cruise condition was selected since a significant portion of flight time is spent at this condition. The most severe ride occurs at high speed descent, where the airplane is sensitive to turbulence. During landing approach with corresponding low dynamic pressure, large control surface deflections are required to produce aerodynamic forces and moments sufficient for ride smoothing purposes.

Random turbulence and discrete 1-cos gusts were used in the analyses to define surface rate and displacement limit effects. Random atmospheric turbulence was modeled with a Von Karman power spectral density function.

Four aerodynamic control surfaces were considered: full span trailing edge flap, elevator, spoiler and rudder. The 30 percent chord elevator and 18 percent chord rear segment of the full span, double slotted flap were used in the longitudinal SAS. The 40 percent chord rudder was used in the lateral SAS.

MATHEMATICAL MODELS

- AIRPLANE EQUATIONS OF MOTION - LINEAR, RIGID BODY, SMALL PERTURBATION, SIX DEGREES OF FREEDOM

- FLIGHT CONDITIONS

FLIGHT CONDITIONS	WEIGHT	ALTITUDE	MACH NO.	VELOCITY	WING LOADING
CRUISE	120,000 LBS	30,000 FT	.75	283 KCAS	46 LBS/FT^2
DESCENT	120,000 LBS	15,000 FT	.75	370 KCAS	46 LBS/FT^2
LANDING APPROACH	120,000 LBS	50 FT	.12	79 KCAS	46 LBS/FT^2

- ATMOSPHERIC RANDOM TURBULENCE - VON KARMAN POWER SPECTRAL DENSITY FUNCTION

- ATMOSPHERIC DISCRETE TURBULENCE - $V_g = 30\,(1 - \cos \omega t),\ 0 \le t \le \frac{2\pi}{\omega}$

- CONTROL SURFACES AVAILABLE - REAR SEGMENT OF FULL SPAN DOUBLE SLOTTED FLAPS
  - ELEVATOR
  - RUDDER
  - SPOILERS

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TURBULENCE LEVEL CRITERIA

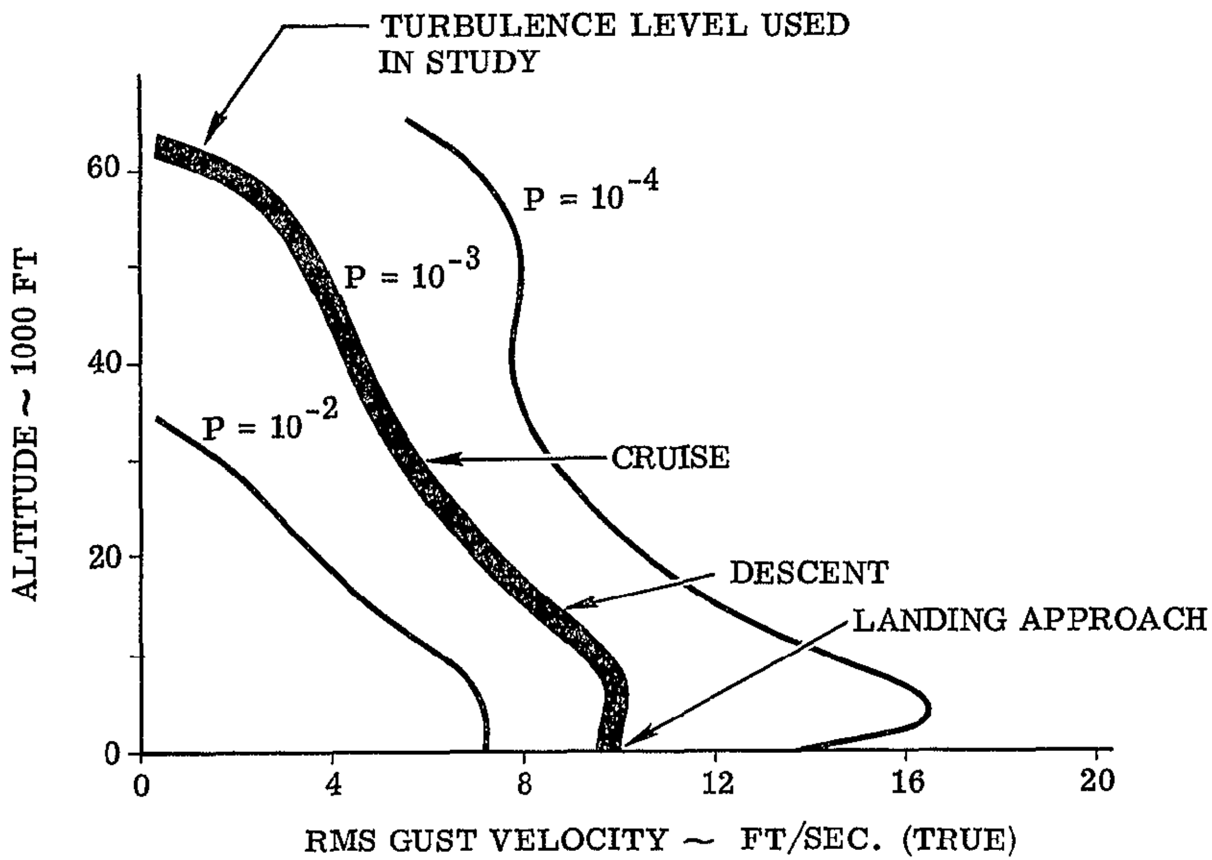
The probability of exceeding a specified RMS gust velocity varies as a function of altitude as shown by these constant exceedance probability curves.[8,9] An exceedance probability level of 10^{-3} was selected for this study. Corresponding RMS gust velocities for the selected cruise, descent, and landing approach conditions are 5.6, 8.2 and 9.8 ft/sec, respectively.

8. NACA TN-4332, "An Approach to the Problem of Estimating Severe and Repeated Gust Loads for Missile Operations", September 1958.

9. ASD-TR-61-235, "Optimum Fatigue Spectra", April 1962.

TURBULENCE LEVEL CRITERIA

- P ~ EXCEEDANCE PROBABILITY
- REFERENCES ~ NACA TN 4332
  ~ ASD - TR-61-235



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PASSENGER RIDE QUALITY CRITERIA AND PROBLEM

Criteria for determining STOL aircraft ride qualities were based on passenger compartment vertical and lateral linear accelerations. Based on results of SST ride quality moving base simulator tests[10] and a review of Boeing 727 and 720B commercial transport acceleration levels,[10,11] acceptable acceleration criteria for a 10^{-3} exceedance probability turbulence were set at 0.11 g's vertically and 0.055 g's laterally. The lateral acceleration criterion was set at one-half the vertical criterion since the SST tests indicated that, at rigid body frequencies, humans are approximately twice as sensitive to lateral oscillations as vertical oscillations.[10]

In general, the selected criteria are conservative and are less than acceleration levels of current commercial aircraft at comparable flight conditions and turbulence levels.

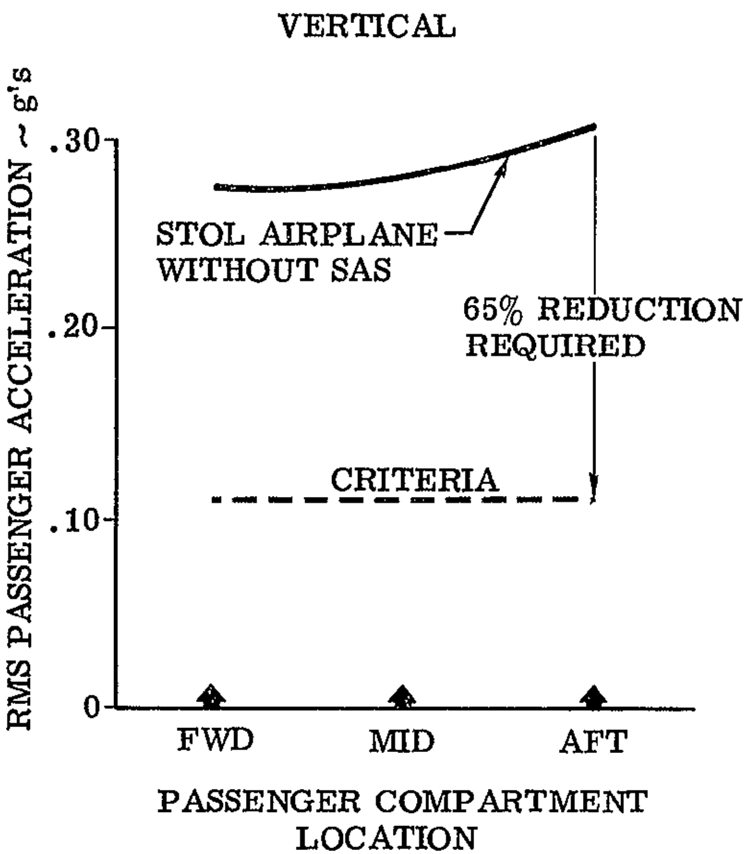
This chart illustrates the severity of the passenger ride problem at the high-speed descent condition. The aft passenger compartment requires vertical and lateral acceleration reductions of 65 and 47 percent, respectively, to meet the selected criteria.

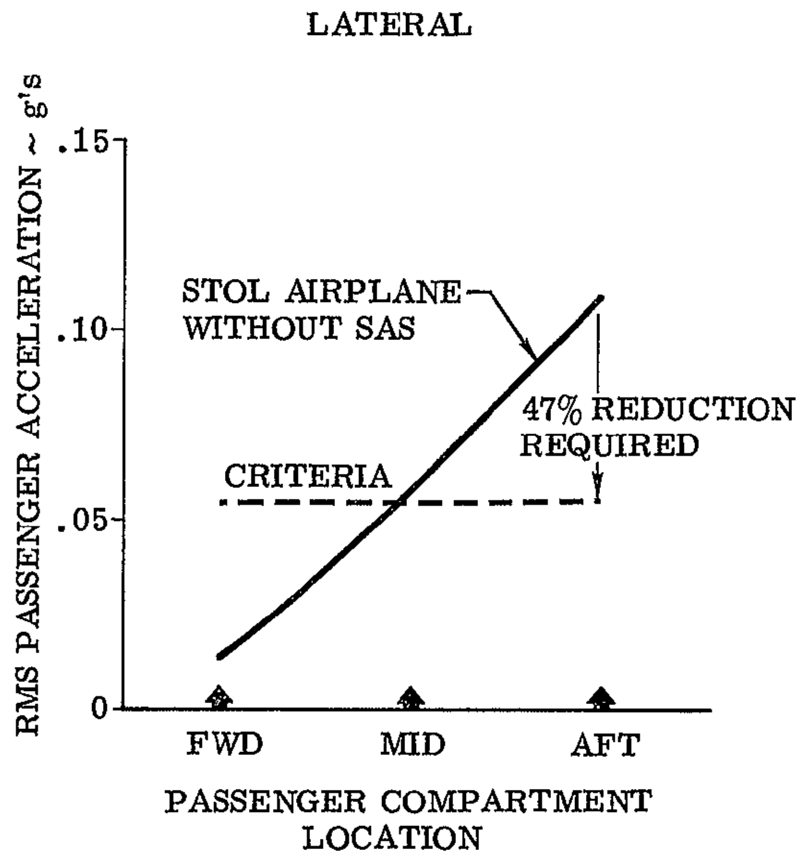
10. Boeing Document D3-7600-7, "Supersonic Transport Passenger Ride Quality Criteria Analysis Development and Validation Testing Results", February 1969.

11. Boeing Document D6-2575, Vol. I, "Development of a Power Spectral Gust Design Procedure for Civil Aircraft - Final Report", March 1965.

PASSENGER RIDE QUALITY CRITERIA AND PROBLEM

- LOW WEIGHT HIGH SPEED DESCENT CONDITION
- RMS GUST VELOCITY = 8.2 FT/SEC





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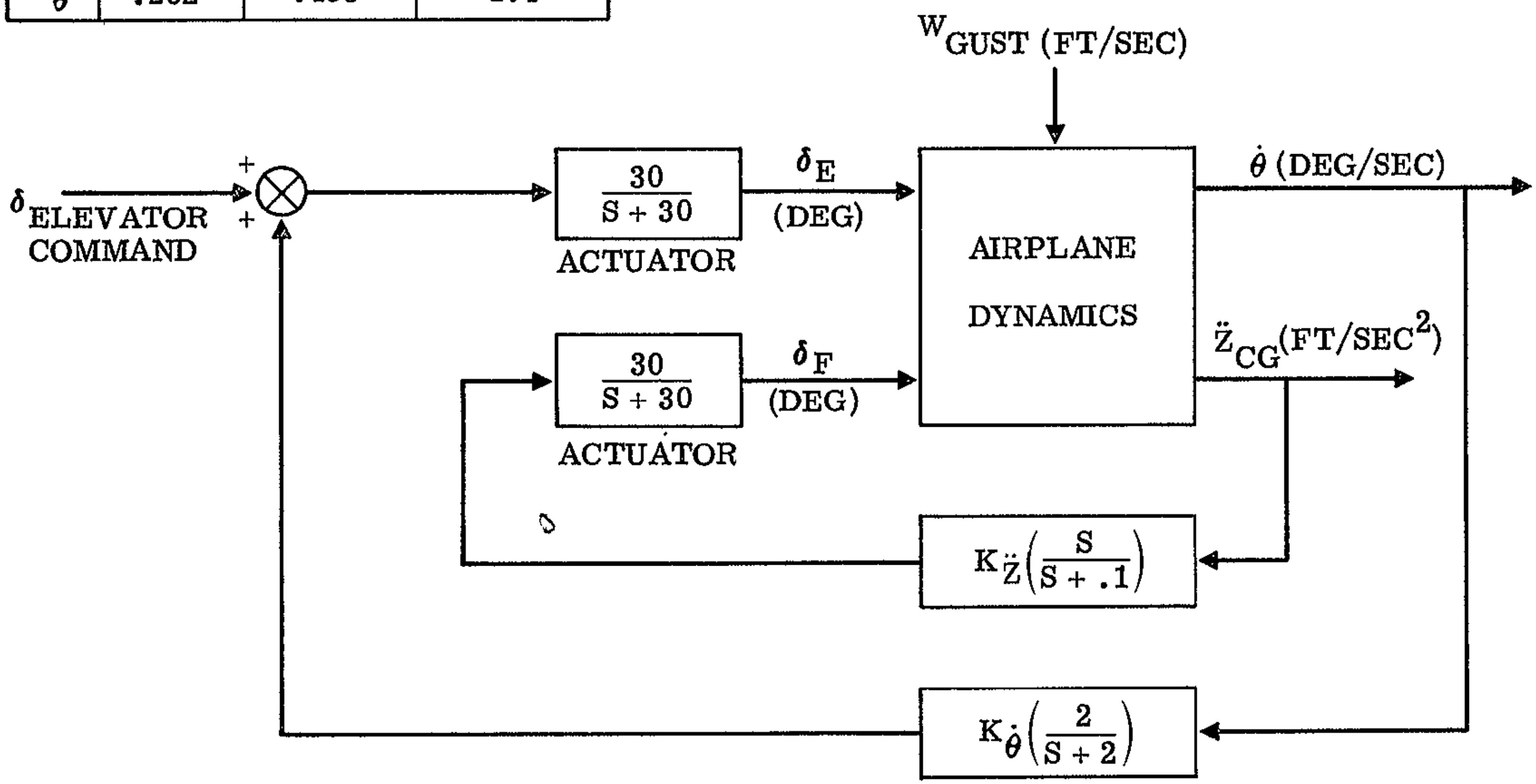
LONGITUDINAL STABILITY AUGMENTATION SYSTEM

The final longitudinal stability augmentation system (SAS) developed during the synthesis consists of two feedback loops: c.g. vertical acceleration driving the aft segment of the full span trailing edge flap, and pitch angular rate driving the elevator. The acceleration feedback provides ride smoothing, and the pitch rate feedback provides satisfactory handling qualities. A high-pass filter in the acceleration feedback improves phugoid mode stability and a low-pass filter in the elevator feedback provides proper phasing for handling qualities.

Although no attempt was made during this initial study to define gain scheduling requirements, it may be necessary to schedule gains as a function of flight condition.

LONGITUDINAL STABILITY AUGMENTATION SYSTEM

	CRUISE	DESCENT	LANDING APPROACH
$K_{\ddot{Z}}$	.25	.50	1.0
$K_{\dot{\theta}}$	.262	.435	1.4



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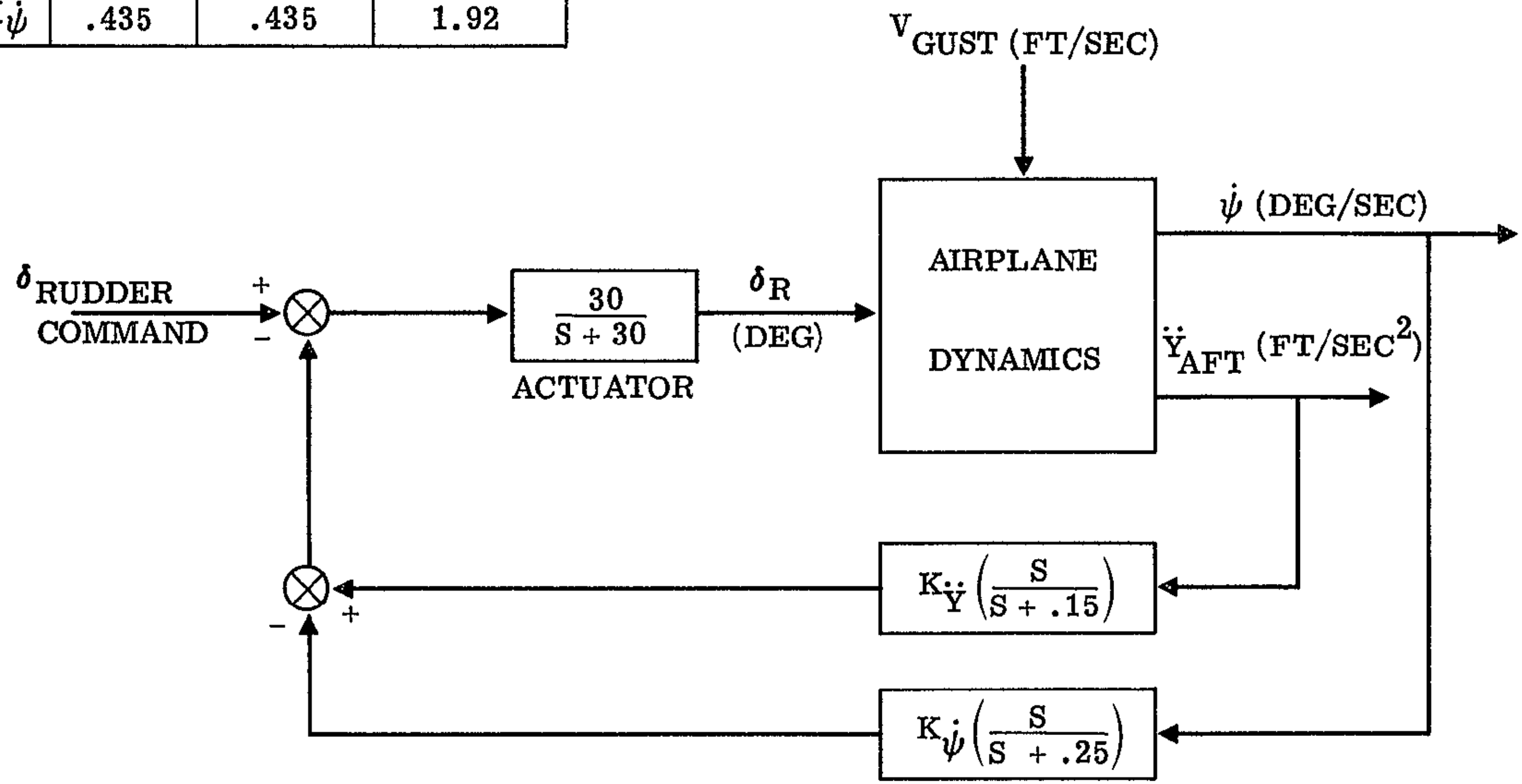
LATERAL STABILITY AUGMENTATION SYSTEM

During cruise and descent, the synthesized lateral stability augmentation system uses aft body lateral acceleration and yaw rate feedback signals driving the rudder to provide ride smoothing and satisfactory handling qualities. At landing approach, lateral acceleration feedback produces excessive spiral mode divergence and is, therefore, not used at this condition. A high-pass filter in the acceleration loop minimizes this effect at cruise and descent conditions. In the yaw rate loop a high-pass filter washes out steady state signals, providing satisfactory coordination during turns.

Although gain scheduling will probably be required, no attempt was made to establish gain scheduling requirements because of the limited scope of the study.

LATERAL STABILITY AUGMENTATION SYSTEM

	CRUISE	DESCENT	LANDING APPROACH
$K_{\ddot{Y}}$	.2	.2	0
$K_{\dot{\psi}}$	.435	.435	1.92



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PASSENGER RIDE QUALITY DURING CRUISE

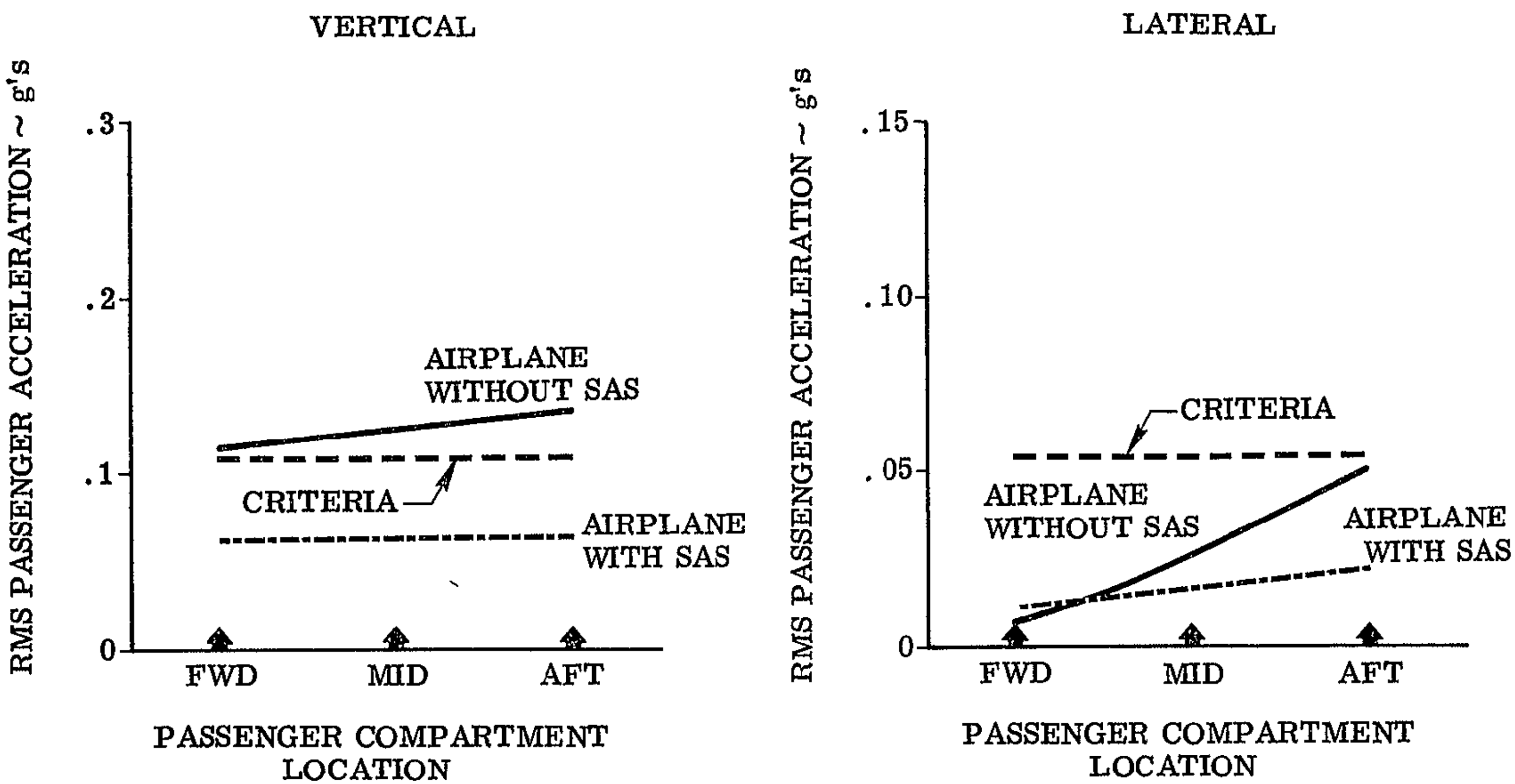
Passenger compartment vertical and lateral accelerations at the three selected flight conditions (cruise, descent and landing approach) are illustrated in the following three charts. Acceleration levels are for RMS gust velocities corresponding to an exceedance probability of 10^{-3}.

At the cruise condition,"airplane without SAS" vertical acceleration fails to meet the criteria, although the lateral acceleration criteria is met at all passenger compartment locations.

With the ride smoothing SAS, vertical and lateral acceleration criteria are met. RMS vertical accelerations are approximately 0.06 g's and RMS lateral accelerations range from 0.01 to 0.03 g's.

PASSENGER RIDE QUALITY DURING CRUISE

- RMS GUST VELOCITY = 5.7 FT/SEC



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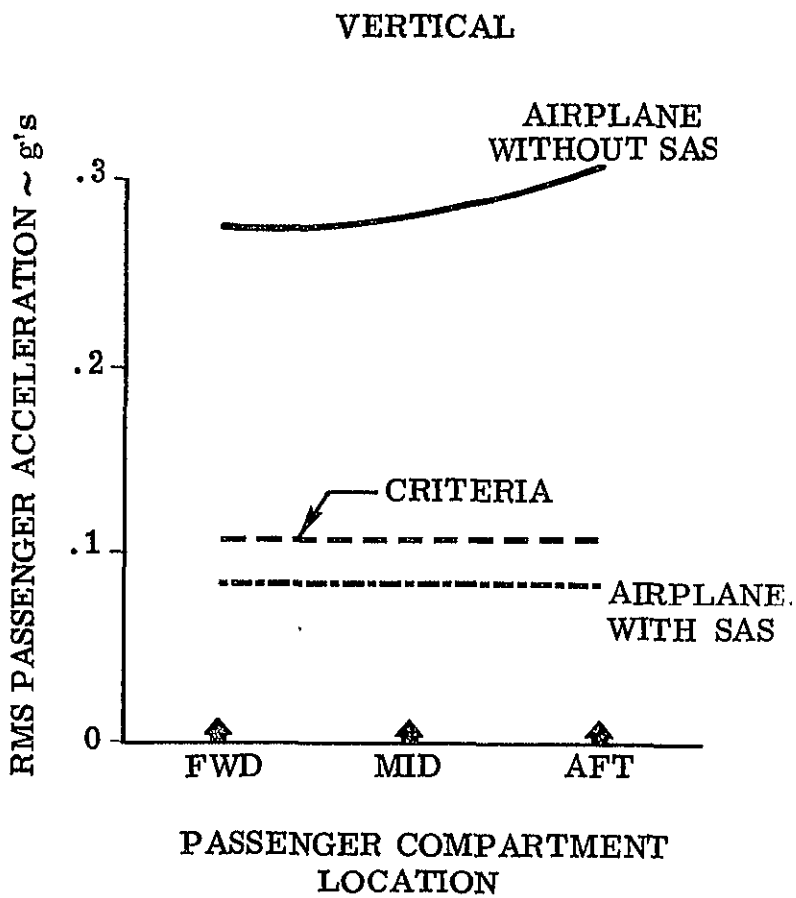
PASSENGER RIDE QUALITY DURING DESCENT

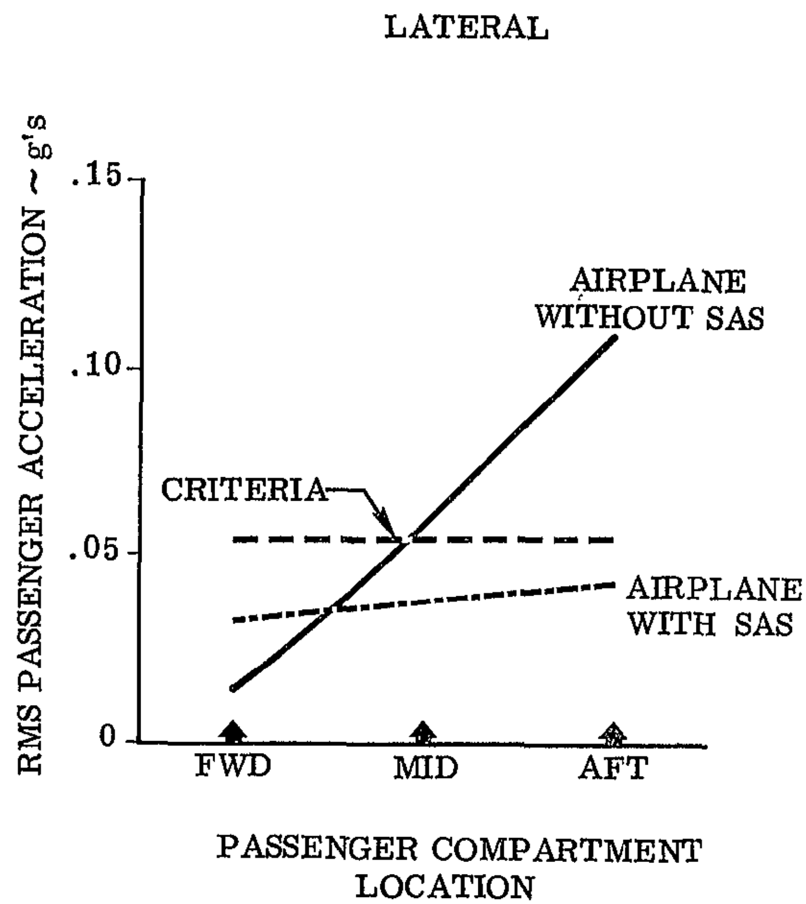
The high speed descent condition (370 KCAS at 15,000 feet) was selected for analysis because of the severity of the ride at this condition. With a gust velocity of 8.2 feet per second, the "airplane without SAS" has a c.g. RMS vertical acceleration of 0.28 g's and an aft body RMS lateral acceleration of 0.11 g's.

With the ride smoothing SAS, vertical and lateral accelerations meet the criteria at all passenger compartment locations.

PASSENGER RIDE QUALITY DURING DESCENT

- RMS GUST VELOCITY = 8.2 FT/SEC





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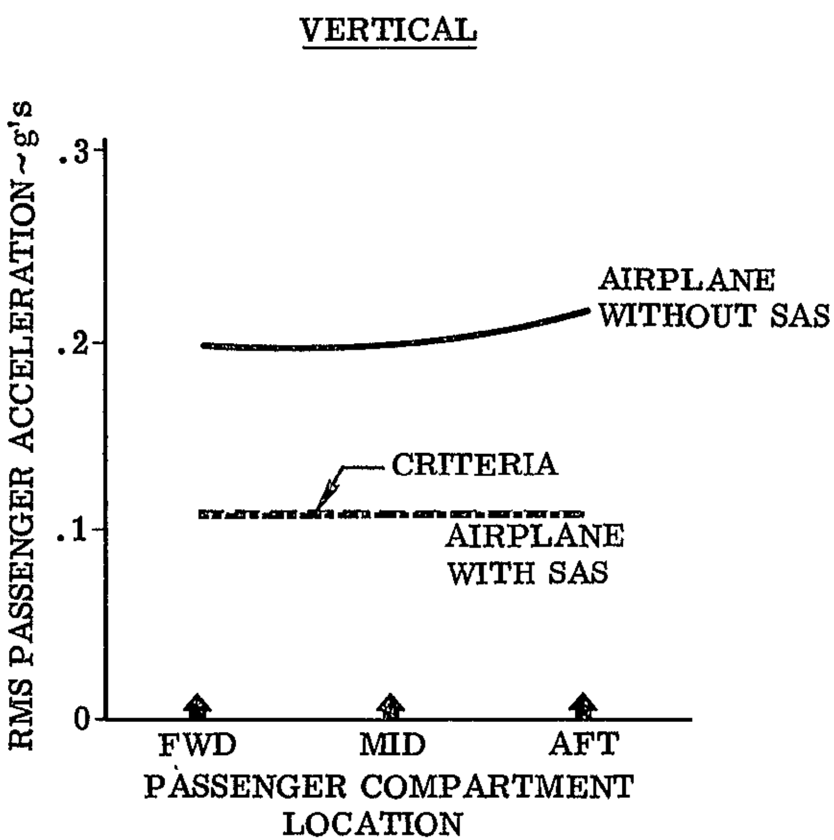
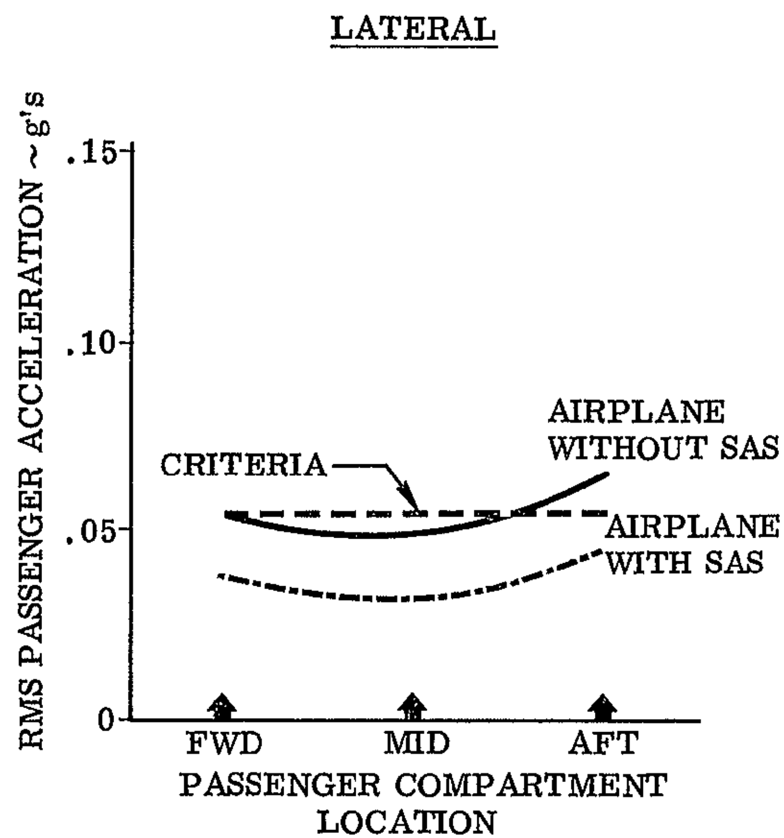
PASSENGER RIDE QUALITY DURING LANDING APPROACH

At the landing approach condition, the "airplane without SAS" aft passenger compartment has a RMS vertical acceleration of 0.22 g's and a RMS lateral acceleration of 0.067 g's. With the ride smoothing SAS, vertical and lateral accelerations are reduced to levels that meet the criteria.

PASSENGER RIDE QUALITY DURING LANDING APPROACH

- RMS GUST VELOCITY = 9.8 FT/SEC





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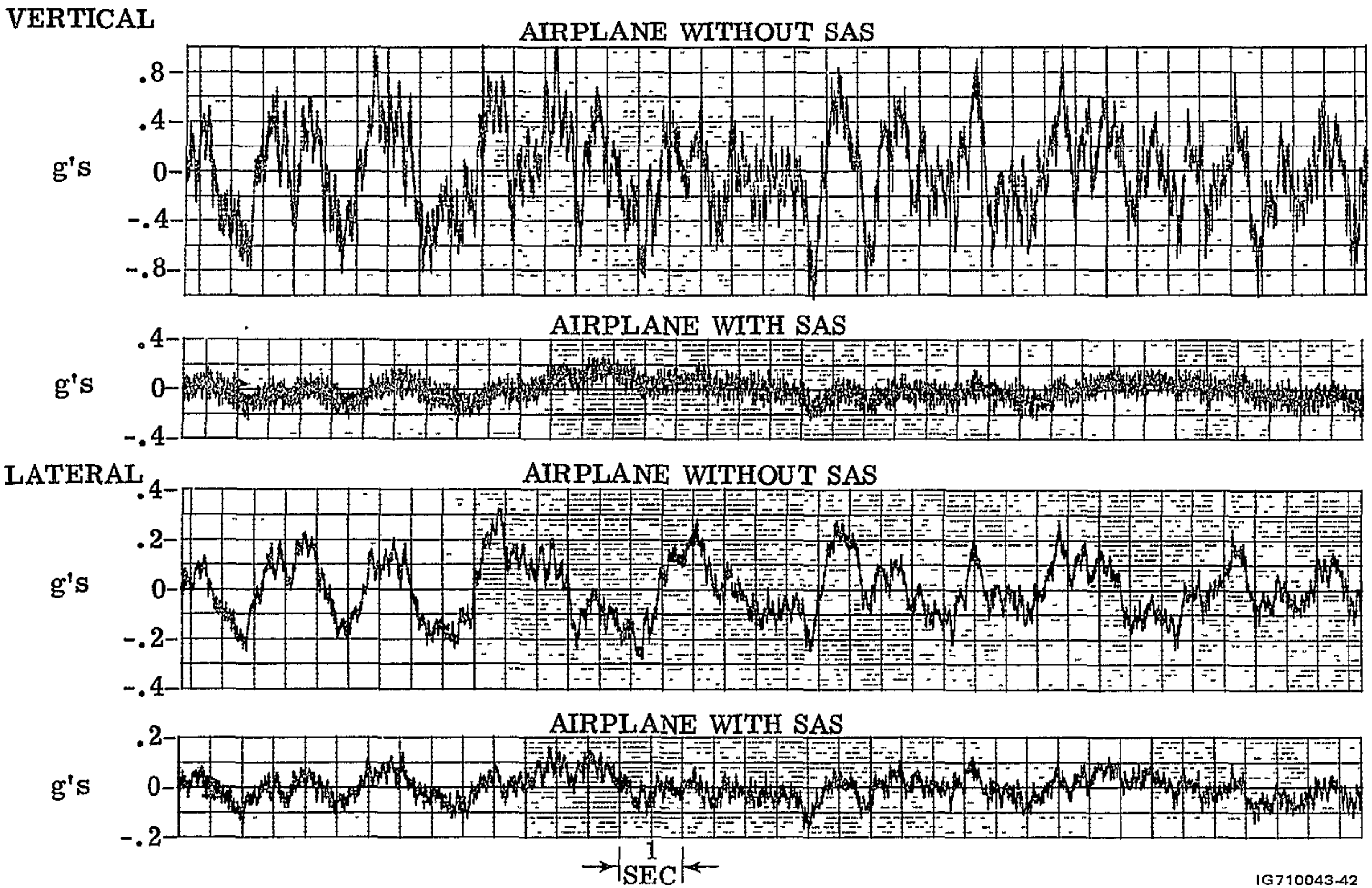
AFT PASSENGER ACCELERATION RESPONSE TO RANDOM TURBULENCE DURING DESCENT

This chart illustrates vertical and lateral acceleration time histories at the descent condition with and without the ride smoothing SAS in random vertical and lateral turbulence. At the descent condition, the SAS reduces RMS vertical acceleration levels 72 percent and RMS lateral acceleration levels 60 percent.

AFT PASSENGER ACCELERATION RESPONSE TO RANDOM TURBULENCE DURING DESCENT

• RMS GUST VELOCITY = 8.2 FT/SEC



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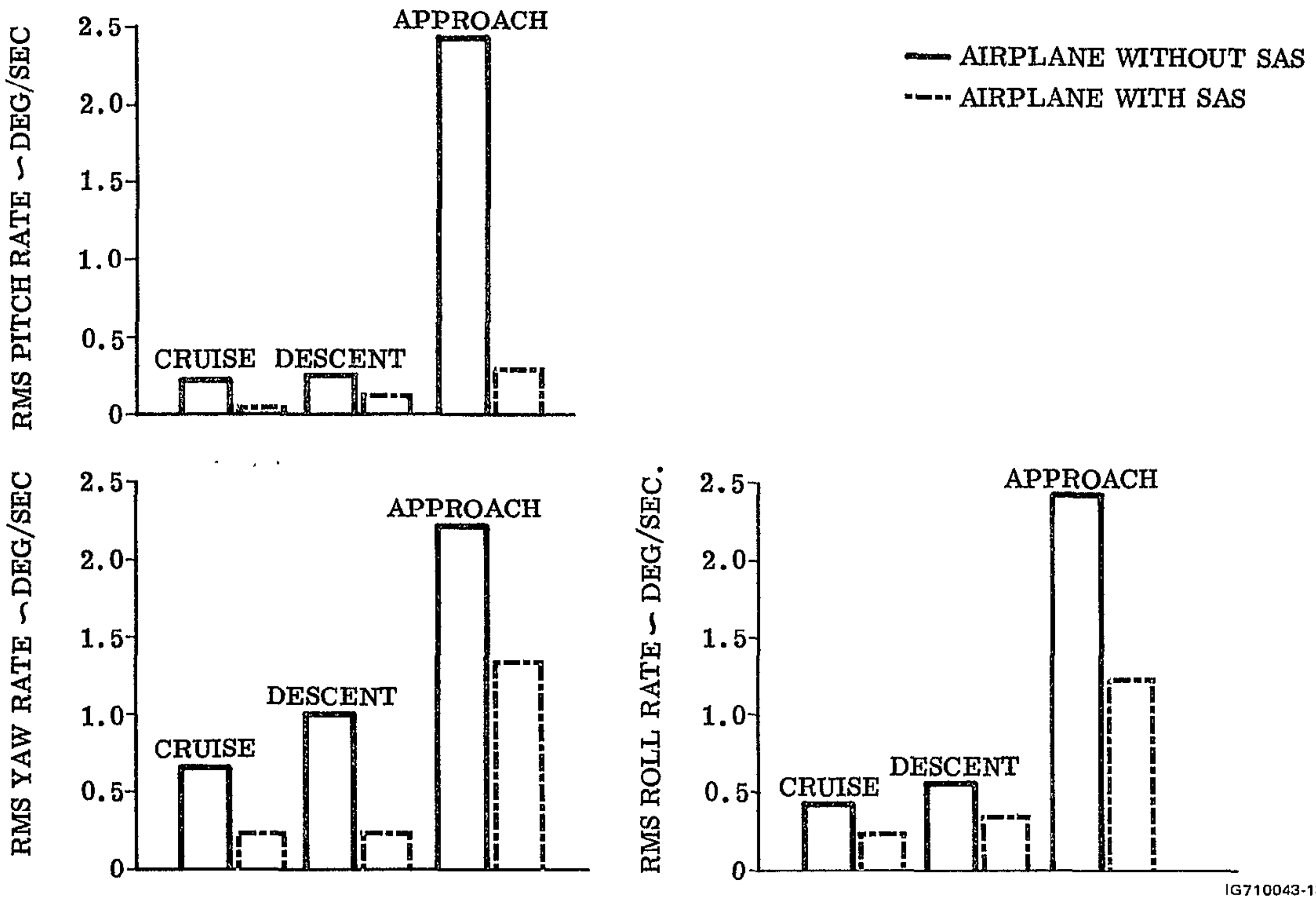
AIRPLANE ANGULAR RATES

Although the ride smoothing system was not designed to reduce airplane angular rates, it significantly reduces roll, pitch and yaw angular rates at the three flight conditions investigated.

AIRPLANE ANGULAR RATES

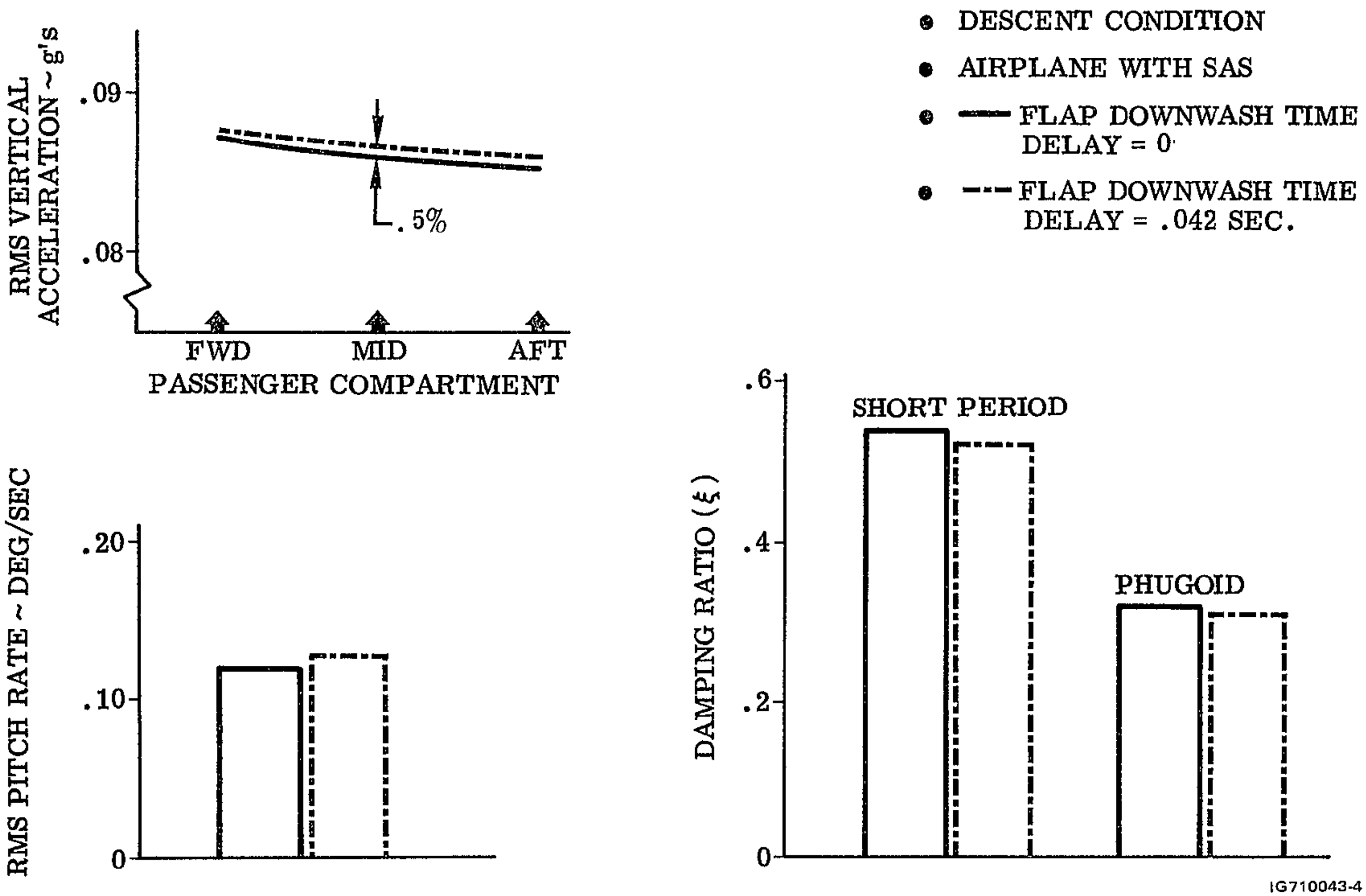


28

EFFECTS OF FLAP DOWNWASH TIME DELAY

To determine dynamic effects of flap downwash on the horizontal tail, a downwash time delay was included in the analysis using a second-order Padé time delay approximation. Effects were small at all flight conditions. At the descent condition, the time delay increases RMS vertical acceleration approximately 0.5 percent and RMS pitch rate 7.5 percent. The downwash time delay also has a slight destabilizing effect on the short period and phygoid modes.

EFFECTS OF FLAP DOWNWASH TIME DELAY



HANDLING QUALITIES

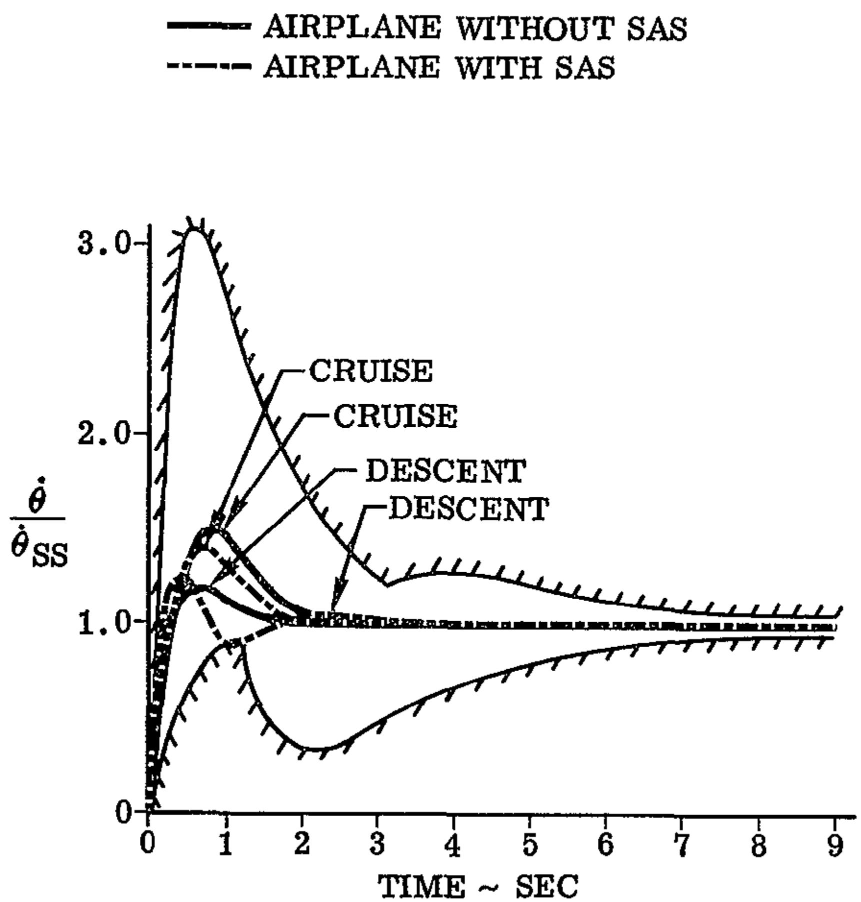
Longitudinal handling qualities were evaluated at the three flight conditions using airplane pitch rate response criteria contained in SST design requirements.[12] This chart illustrates typical longitudinal responses at the cruise and descent conditions. At all three conditions the "airplane without SAS" meets the criteria. Adding acceleration feedback for ride smoothing degraded airplane response. Therefore, pitch rate feedback was required for satisfactory longitudinal handling qualities.

Lateral handling qualities were evaluated based on rigid body characteristic root requirements contained in MIL-F-8785B(ASG) dated 7 August 1969. All lateral criteria are met except for spiral mode time-to-double-amplitude at the landing approach condition. The spiral mode time-to-double-amplitude at this condition is 8.2 seconds compared to a requirement of 20 seconds or greater. Future studies should consider the feasibility of using roll feedback to eliminate this handling qualities deficiency.

12. Boeing Document D6-6800-5, "Stability and Control, Flight Control, Hydraulic Systems and Related Criteria".

HANDLING QUALITIES

LONGITUDINAL



LATERAL

- CRITERIA (MIL-F-8785B)

FLIGHT CONDITION	DUTCH ROLL MODE DAMPING RATIO ξ	DUTCH ROLL MODE DAMPING FACTOR $\xi\omega_N$	ROLL MODE TIME CONSTANT (SEC)	SPIRAL MODE TIME TO DOUBLE AMPL. (SEC)
CRUISE	>.19	>.35	<1.4	>20
DESCENT	>.19	>.35	<1.4	>20
APPROACH	>.08	>.20	<1.0	>20

- AIRPLANE WITH SAS SATISFIES LATERAL HANDLING QUALITY CRITERIA EXCEPT DURING APPROACH THE SPIRAL MODE TIME TO DOUBLE = 8.2 SEC.

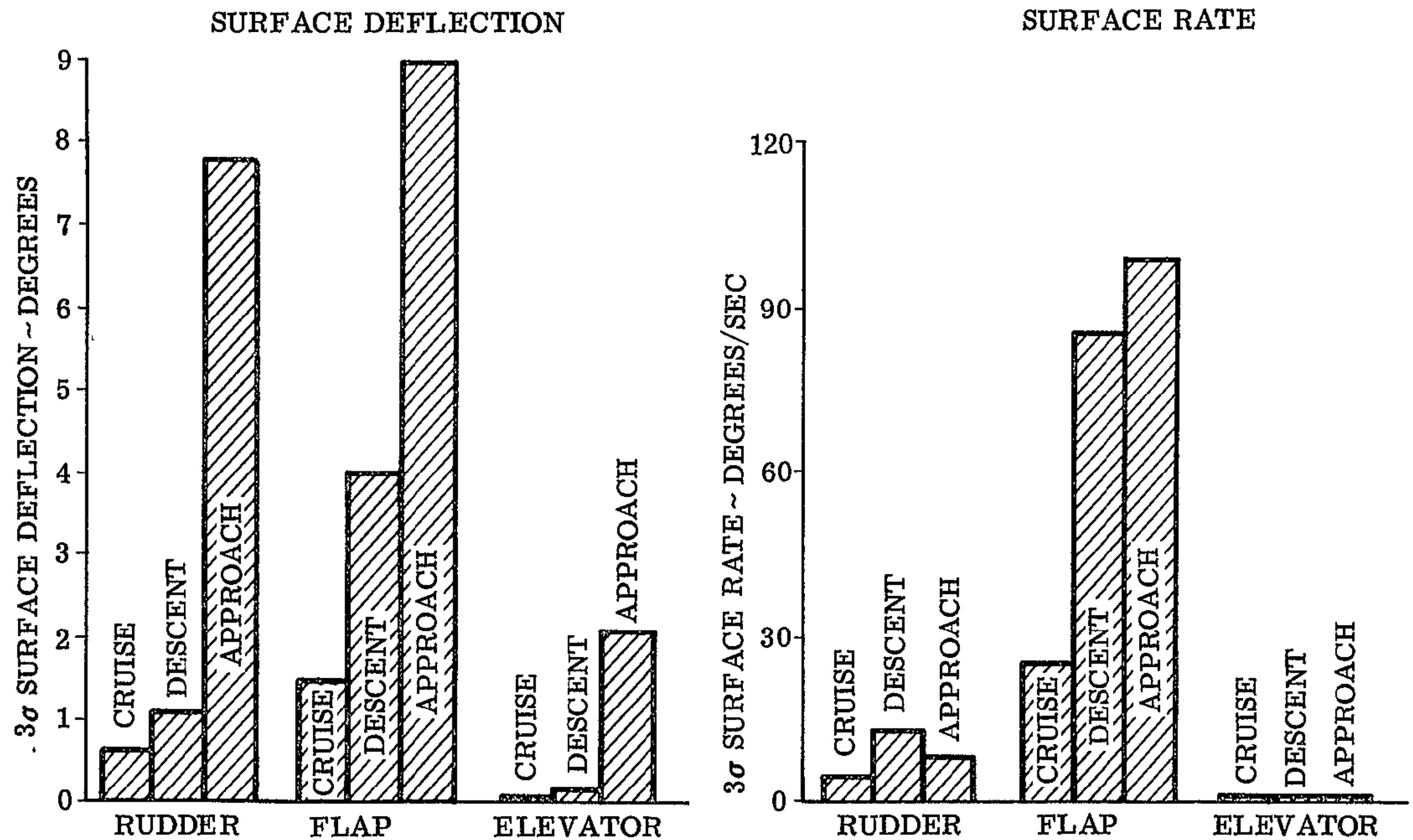
IG710043-8

SAS CONTROL SURFACE DEFLECTION AND RATE REQUIREMENTS

Three-sigma control surface deflection and rate requirements for a 10^{-3} exceedance probability turbulence level were determined for the three conditions. The approach condition requires maximum control surface deflection and rates. At this condition a flap deflection of ±9 degrees, a rudder deflection of ±8 degrees and a flap rate of 100 degrees/second are required.

These requirements are based on an actuator bandpass of 30 radians/second. As shown on the next chart, lowering the actuator bandpass reduces the rate requirement. Follow-on studies should consider trades of control surface deflection and rate requirements versus actuator bandpass to obtain maximum acceleration reductions with minimum control system complexity.

SAS CONTROL SURFACE DEFLECTION AND RATE REQUIREMENTS



IG710043-7

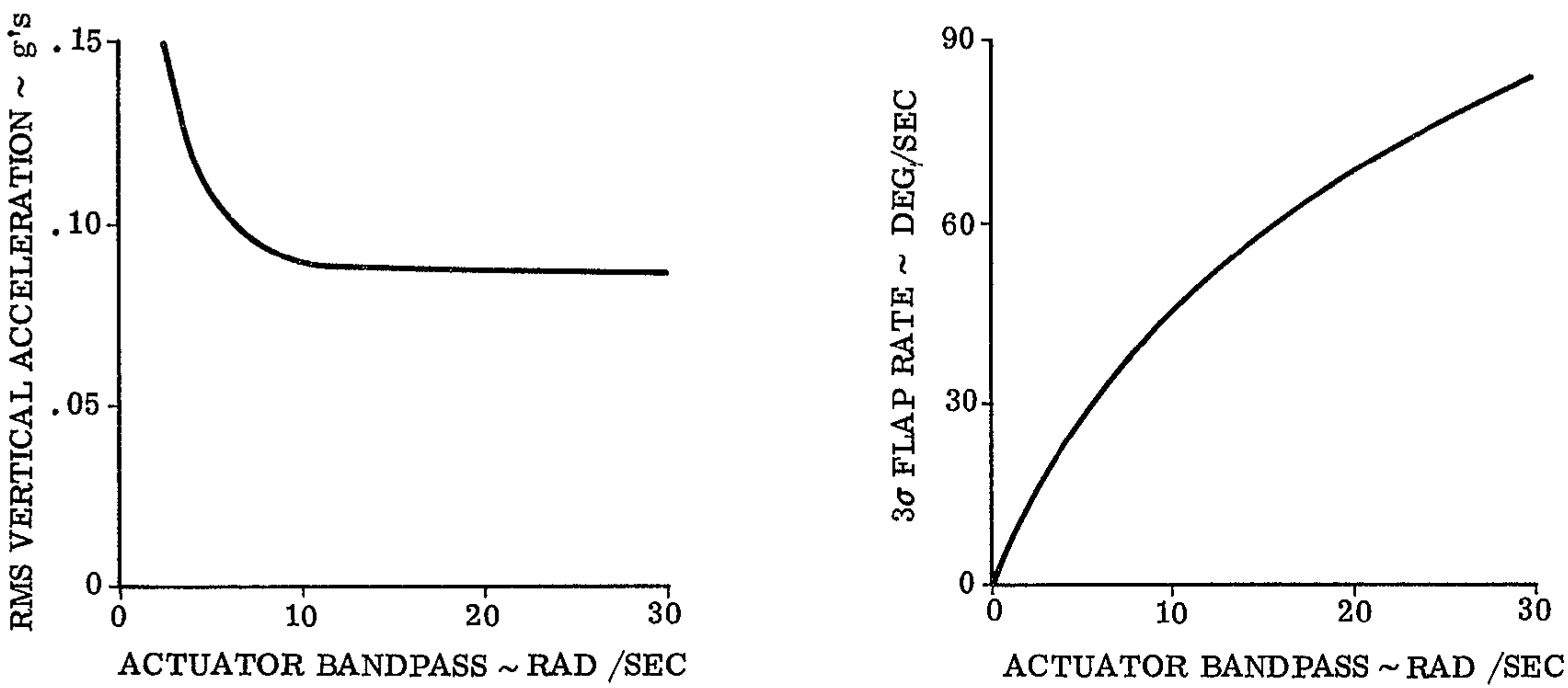
EFFECTS OF FLAP ACTUATION BANDPASS

Effects of flap actuator bandpass on midpassenger vertical acceleration and flap rate requirements were evaluated at the high speed descent condition. Based on this rigid body analysis, an actuator bandpass of 10 radians/second and a corresponding maximum flap actuator rate of 45 degrees/second provide satisfactory vertical acceleration reductions.

Further studies should consider trades of actuator bandpass and corresponding rates to minimize hydraulic power requirements and control system actuation complexity.

EFFECT OF FLAP ACTUATION BANDPASS

- DESCENT CONDITION
- RMS GUST VELOCITY = 8.2 FT /SEC



IG710043-28

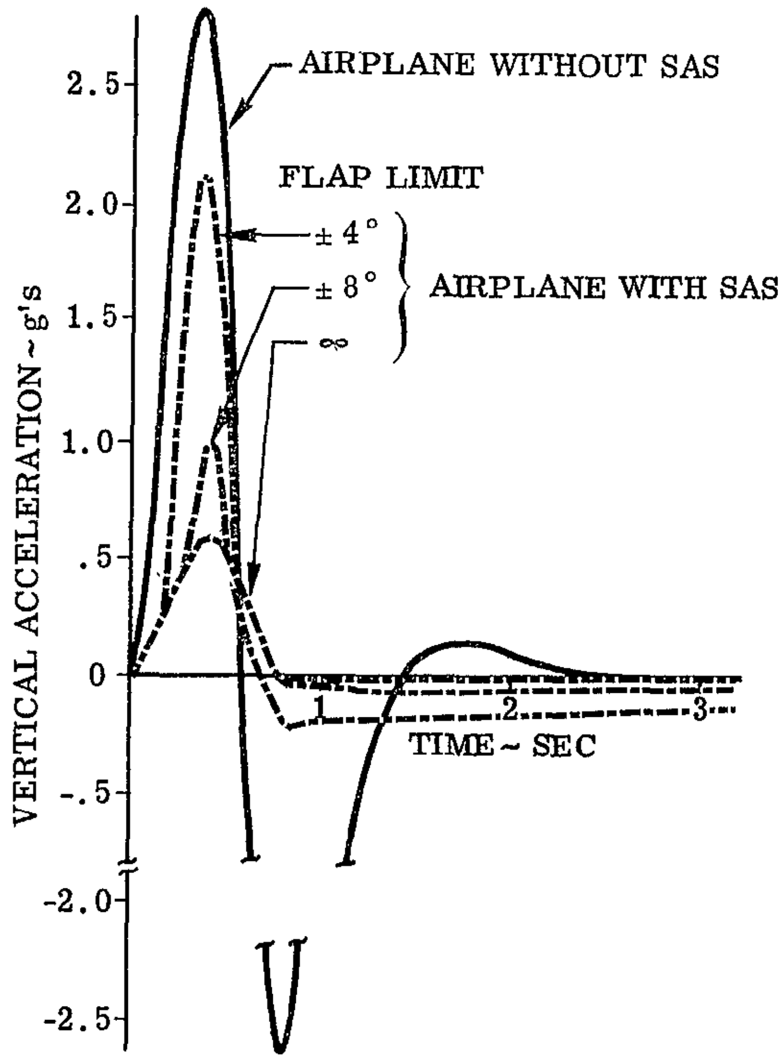
PASSENGER ACCELERATION RESPONSE TO 1-COS GUST

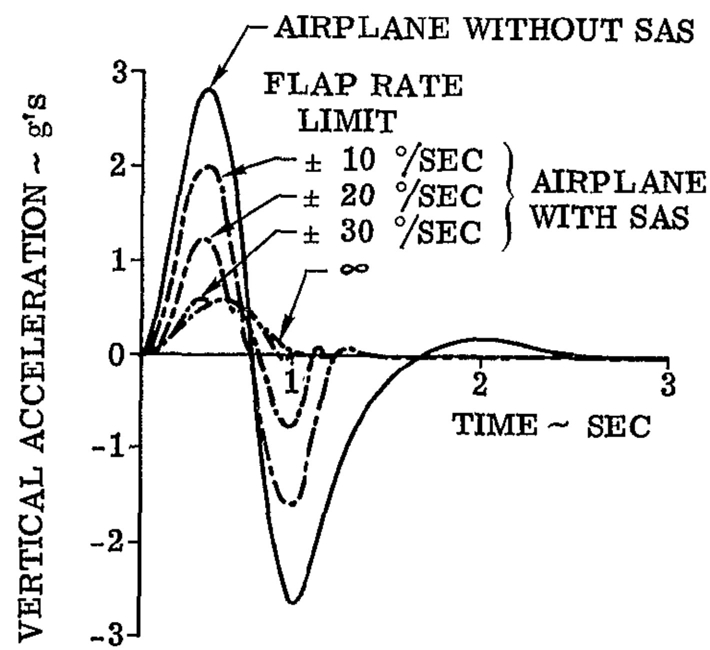
Effects of flap displacement and flap rate limits on acceleration reductions were determined at the descent condition for a 1-cos discrete gust with a peak velocity of 60 feet/second. Frequency of the gust was adjusted to provide maximum acceleration (2.8 g's) without the SAS.

With SAS, the peak acceleration is reduced to less than one g with flap displacements of ±10 degrees and flap rates of ±30 degrees/second.

PASSENGER ACCELERATION RESPONSE TO 1-COS GUST

- DESCENT CONDITION
- Wg = 30 (1-COS 7 t)
- C.G. PASSENGER LOCATION
- GUST FREQUENCY SELECTED FOR MAXIMUM "AIRPLANE WITHOUT SAS" POSITIVE ACCELERATION





IG710043-35

POTENTIAL PROBLEM AREAS

This study shows the feasibility of significantly reducing vertical and lateral accelerations of a low-wing-loading STOL airplane. However, the study was based on a linear analysis using a rigid body airplane mathematical model with an ideal single channel flap mechanization. Several areas not considered within this limited study could present potential problems.

Structural flexibility may make it difficult to reduce the accelerations to the extent indicated with a rigid body model. Adequate structural mode stability may limit system ride smoothing performance.

Control system nonlinearities during severe turbulence can cause excessive structural loading and reduced stability. Based on nonlinear analyses, design criteria must be defined to prevent this possibility.

This study assumed that the flap rear segment can be driven in retracted and extended positions. Potential problems associated with mechanizing a high response, aft segment full-span double-slotted flap should be considered. Related areas for study include redundancy, hydraulic power and flap segment requirements.

Although the primary objective of the SAS is to provide ride smoothing, handling qualities and maneuvering requirements must be satisfied within the airplane operational flight envelope. Compatibility of these two functions must be thoroughly analyzed.

POTENTIAL PROBLEM AREAS

- STRUCTURAL FLEXIBILITY EFFECTS
- CONTROL SYSTEM NONLINEAR CHARACTERISTICS IN SEVERE TURBULENCE
- FLAP ACTUATION SYSTEM MECHANICAL DESIGN
- RIDE SMOOTHING/HANDLING QUALITIES COMPATIBILITY

IG710043-19

SUMMARY

Conclusions of this limited study indicate that a low-wing-loading STOL aircraft with ride smoothing stability augmentation provides satisfactory ride qualities and competitive high speed performance.

Further studies should be conducted to analyze potential problem areas in depth and to obtain additional confidence in the concept.

SUMMARY

- RESULTS OF THIS LIMITED STUDY INDICATE THAT A LOW-WING-LOADING STOL AIRCRAFT WITH RIDE SMOOTHING SAS PROVIDES
    - SATISFACTORY RIDE QUALITIES
    - COMPETITIVE HIGH SPEED PERFORMANCE

- FURTHER STUDIES SHOULD BE CONDUCTED TO ANALYZE POTENTIAL PROBLEM AREAS IN DEPTH.

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