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APPLICABILITY OF NASA (ARC) TWO-SEGMENT APPROACH PROCEDURES TO BOEING AIRCRAFT

By Robert L. Allison

January 1974

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NASA Technical Monitor: Mr. Kenneth C. White
Ames Research Center
Moffett Field, California 14035

16. Abstract

This report presents the results of an engineering study to determine the feasibility of applying the NASA (ARC) two-segment approach procedures and avionics to the Boeing fleet of commercial jet transports. The specific procedures and avionics considered were those developed by United Airlines and Collins Radio for use in the UAL 727-200 line operational evaluation phase (May-October 1973) of the NASA two-segment approach program. This feasibility study does not include simulation or flight test and is concerned with the speed/path control and systems compatibility aspects of the procedures rather than the noise benefits.

Path performance data are provided for representative Boeing 707/727/737/747 passenger models. Thrust margin ($\Delta\gamma$) requirements for speed/path control are analyzed for still air and shearing tailwind conditions. The Collins avionics configuration and two alternate avionics configurations are reviewed for compatibility with existing systems. Certification of the two-segment equipment and possible effects on existing airplane certification are discussed. Operational restrictions on use of the procedures with current autothrottles and in icing or reported tailwind conditions are recommended. Using the NASA/UAL 727 procedures as a baseline, maximum upper glide slopes for representative 707/727/737/747 models are defined as a starting point for further study and/or flight evaluation programs.

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FOREWORD

This study was conducted under NASA contract NAS2-7561, administered by the Ames Research Center. Mr. Clark White was the NASA technical monitor.

The work was accomplished within the Technology Department of the Boeing Commercial Airplane Company, Seattle, Washington. Participating engineers were as follows:

R. L. Allison	Principal investigator
G. A. Chenkovich A. C. Marley	Flight controls (autopilot/flight director)
R. E. Buchholz	Aerodynamics
D. B. Swanson	Propulsion

This report has been reviewed and approved by:

F.C. Hall

F. C. Hall
Program Manager

WA Reinhart

W. A. Reinhart
Chief Engineer, Technology
707/727/737 Division

Paul L. Sandoz

P. L. Sandoz
Chief Engineer, Technology
747 Division

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APPLICABILITY OF NASA (ARC)

TWO-SEGMENT APPROACH PROCEDURES TO

BOEING AIRCRAFT

By Robert L. Allison

1.0 SUMMARY

The purpose of this feasibility study is to complement the NASA-Ames Research Center evaluation of two-segment approaches by making a preliminary determination of their applicability to the Boeing 707/727/737/747 fleet. This study did not include simulation, flight testing, or noise comparisons and considered only nominal airframe/engine characteristics for sea-level standard-day conditions, all engines operating. The results represent engineering judgments, based on static analyses, experience, and available data, and are intended for use by NASA in conducting studies and test programs. This report should not be interpreted as a final Boeing recommendation concerning procedures and systems to be introduced into airline service.

The NASA/UAL procedures used for the 727 line evaluation of two-segment glide slopes appear feasible for application to the Boeing fleet. However, the maximum upper glide slope angles recommended for representative passenger models are as follows:

- 707–5.5°
- 727–6°
- 737–5°
- 747–5.5°

Due to the reduced nominal power settings, the upper glide slopes listed above are not compatible with current autothrottles and are not recommended for use in icing conditions or when tailwinds are reported. These glide slopes and operational limitations are based on using the 707/727/737 reduced (certified) landing flap positions and the 747 maximum flap position, which is comparable to the reduced flap positions for the other models. The angles shown provide the same thrust margin from idle ($\Delta\gamma = -1.2^\circ$ for the minimum-weight case) for all models. The adequacy of this margin should be determined from NASA/UAL flight test results. Analyses of the thrust margin required for path control (still air) and for speed control in shearing tailwinds are presented herein. The latter shows that thrust margin requirements for a specified tailwind profile are proportional to the glide slope angle, being greater for a steep approach than for a normal ILS.

Restricting usage of two-segment approaches to nonicing, nontailwind conditions is not viewed as a disadvantage of two-segment glide slopes when compared to other noise-abatement approach techniques. In fact, one advantage of the NASA two-segment system, when compared to steeper ILS beams, is that current ILS glide slope angles and procedures remain available as a backup for use in adverse weather conditions.

The NASA concept for providing two-segment path guidance using the existing ILS and an airborne computer (with DME and altitude inputs) appears feasible for application to any jet transport. The avionics developed by Collins for the NASA/UAL 727 evaluation are generally compatible with the Boeing fleet and are expected to provide satisfactory flight director and single-channel autopilot performance to category II minimums. However, the Collins configuration uses the "altitude hold" mode of the existing autopilot/flight director; hence, it is not suitable for approaches to lower weather minimums with autoland (multichannel) systems. Several other areas of concern regarding fleet retrofit, monitoring, and autopilot/flight director certification were also noted in this study. Alternate configurations using already certified approach modes should be considered when defining hardware for large-scale fleet retrofit. Regardless of the configuration implemented, modifications to existing equipment are required but can be minimized by two-segment system input/output circuitry design.

Certification can be accomplished by either the operational method where individual airlines obtain supplemental type certificates applicable to their particular aircraft, or by the engineering method where the airframe manufacturer obtains type-certificate revisions applicable to all airlines. Either method will require flight testing, performance evaluation, and failure analyses, with the extent of the required program dependent on the avionics configuration selected.

The overall NASA/UAL/Collins effort is quite comprehensive and should provide valuable data concerning the operational suitability of two-segment approaches. When procedures and hardware are defined for fleetwide implementation, noise trades for the alternate flap settings should be conducted (i.e., increased flaps allow steeper upper segments but increase noise on the ILS), and further consideration should be given to nonstandard days, variations from nominal airframe/engine characteristics, alternate avionics configurations, monitoring, and to the compatibility (reliability, failure modes, flight checks) of DME facilities.

2.0 INTRODUCTION

2.1 BACKGROUND

The NASA-Ames Research Center has implemented a program to further develop and evaluate the operational feasibility of the two-segment landing approach as a means of reducing community noise near airports. The program includes the development and evaluation of avionics that will aid the pilot in making two-segment approaches. Flight evaluations have been completed for the Boeing 727 and are in progress for the DC-8. The 727 system requires a DME ground station collocated with the ILS glide slope transmitter, while the DC-8 system requires R-NAV capability.

The NASA program involves the participation of an engineering contractor (Collins Radio) to design and fabricate the avionics and an airline contractor (United Air Lines) to develop the procedures in a simulation study, to install the equipment in the evaluation aircraft, to conduct an engineering flight evaluation, and, finally, to conduct a line operational evaluation of the equipment and procedures. The 727 line evaluation was conducted during regularly scheduled passenger service using a UAL 727-200 flown by line pilots on the California-Oregon route.

This study complements the above program by making a preliminary determination of the applicability of the two-segment approach to the entire fleet of Boeing commercial jet transports. The aircraft of interest are the 707, 727, 737, and 747. This is a feasibility study and does not include simulation or flight test. The required tasks are:

- Task I—path performance analyses
- Task II—airplane systems review
- Task III—program review

2.2 OPERATIONAL CRITERIA

A general statement, sometimes made in discussions of noise-abatement approaches, is that it should be possible to use the same procedure* for all approaches, VFR or IFR. Provision of IFR capability is very desirable with respect to crew training and proficiency and need not adversely

*"Procedure" implies a total definition of all operational variables such as flap position, glide slope angle, etc.

affect the noise benefits. However, analyses of noise-abatement approach procedures show there are operational limitations associated with the noise reduction. These limitations result when the procedure reduces the approach thrust below the level required to provide a particular operational capability. In general, approach procedures that require less thrust than current ILS procedures will be quieter but will also be restricted to less severe tailwind/icing conditions. Autothrottle compatibility may also be affected.

Thus, if a single new procedure were developed to *replace* current ILS procedures, the potential noise benefits of the new procedure and the operational flexibility available with current ILS procedures would be compromised. Since gear/flap/speed schedules for the two-segment approach are very similar to normal ILS procedures, it appears preferable to specify upper-segment glide slope angles that will maximize noise benefits for the majority of approach conditions and to retain current ILS glide slopes for use in unusual weather conditions.

Consistent with the above rationale, the following operational criteria were defined for use in this study:

- Upper Glide Slope Angle: For purposes of this study, it is not necessary to use the same upper glide slope angle for all models. The glide slopes for each model should be the steepest considered feasible, with adequate margins provided for speed/path control. However, glide slopes steeper than 6° are not to be specified until feasibility is demonstrated by simulator or flight tests (beyond the scope of this study).

- Wind and Weather: Requirements for instrument approaches to category II minimums should be satisfied, except that the upper segment need not be compatible with icing or reported tailwind conditions. This assumes that normal ILS procedures will be retained for use in these weather conditions. While the upper-segment glide slope need not provide a margin for speed/path control in reported (sustained) tailwinds, sufficient margin should be provided to cope with random tail gusts likely to be encountered in turbulence.

- Autopilot Compatibility: The capability to fly coupled two-segment approaches to category II minimums is required. Compatibility with a category III autopilot (or a category II autopilot with autoland) is desirable.

- Autothrottle Compatibility: The ability to use autothrottles is desirable, particularly for the 747. However, the upper glide slope should not be reduced solely for the purpose of providing autothrottle compatibility.

2.3 UNITS OF MEASUREMENT

Calculations were made in the U.S. customary system of units and converted to SI units using conversion factors from reference 1. Both the U.S. customary and the SI units are shown on the data plots.

The maximum and minimum weight conditions are identified on the data plots by showing the airplane weight in pounds. The corresponding gravitational forces in newtons are listed in table I for reference:

TABLE I.—AIRPLANE WEIGHTS

Model	Flap position	Landing weights			
		Maximum		Minimum	
		1000 lb	1000 N	1000 lb	1000 N
707-300B (Adv)/C (JT3D-3B)	40 50	247	1098	160	712
727-200 (JT8D-9)	30 40	154.5 142.5	687 634	110	489
737-200 (JT8D-9)	30 40	103	458	66	294
747-200B (JT9D-7)	25 30	564	2509	380	1690

3.0 TASK I—PATH PERFORMANCE ANALYSES

This task involves presentation of thrust data, steady-state flightpath angle (γ) capabilities, approach speeds, and flap placards for representative passenger models of Boeing 707/727/737/747 aircraft and review of the 727 two-segment approach procedures defined by NASA/UAL for feasibility of application to the Boeing fleet.

Steady-state flightpath angle (γ) data are summarized on figure 1 for two power settings, at speeds ($1.3\ V_S + 15$) corresponding to the upper-segment glide slope speed selected by NASA/UAL for the 727 procedure. Since current autothrottle aft limits are set above engine idle, the path angle at the autothrottle aft limit would be shallower than for engine idle (sec. 3.2.3). Upper-segment glide slope capabilities (earth referenced) are less than the γ capabilities (referenced to the air mass) shown on figure 1, due to the margins necessary for speed/path control (sec. 3.3).

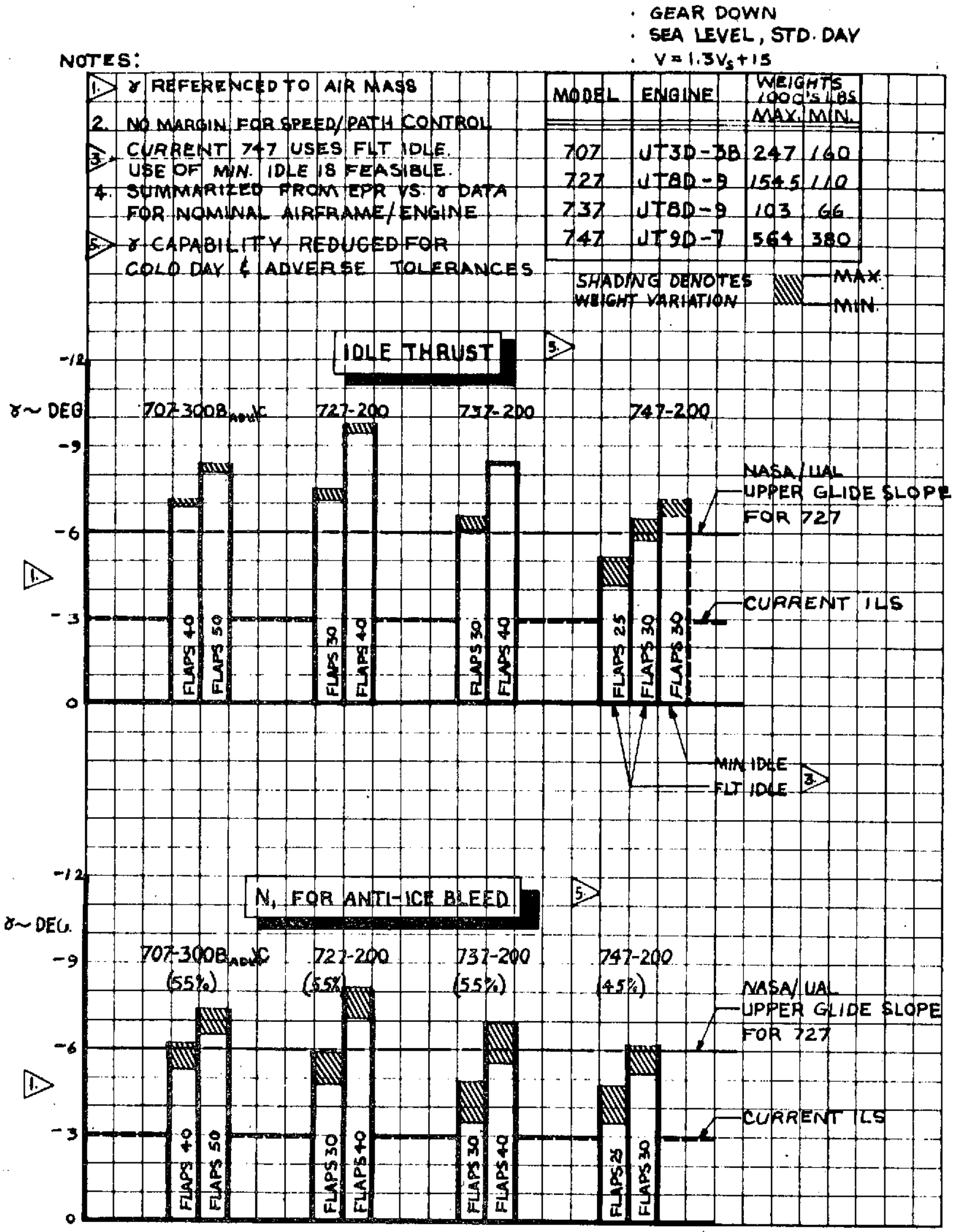

FIGURE 1.–TRIMMED FLIGHTPATH ANGLE (γ) FOR BOEING TRANSPORTS

The NASA/UAL two-segment approach procedures for the 727 are defined on figure 2. The 6° upper glide slope is flown with gear down using the minimum certified flap position (30), at a speed (V_{ref} + 15) slightly higher than the normal final approach speed. Transition to the ILS glide slope is begun at about 1000 ft of altitude and is completed above 500 ft. Speed is allowed to bleed down to the normal final approach speed, and thrust is advanced to the normal approach thrust during the transition. Thereafter, the approach is the same as for a normal ILS.

These procedures appear feasible for application to the Boeing fleet with the maximum upper glide slopes and operational limitations shown in figure 2. The glide slopes and operational limitations are based on the use of the reduced (certified) landing flap position for the 707/727/737. The maximum flap position was used for the 747 because the 747 landing configurations are relatively cleaner than for the other models; e.g., the 727 minimum certified landing flap position is the same as the 747 maximum flap position.

The upper glide slopes shown on figure 2 provide the same thrust margin from idle for all models. Shallower glide slopes would be required if based on the autothrottle aft limit or the minimum power setting for inlet anti-ice. At present, "flight idle" is used for 747 approaches; but it is feasible to use "minimum idle" if required for noise abatement. The other models (707/727/737) have no "flight idle" limit.

The adequacy of the thrust margin (equivalent to a $\Delta\gamma = -1.2°$ path modulation capability for the minimum-weight case) should be determined from NASA/UAL 727 flight test results. Analyses indicate that it should be sufficient for speed/path control under normal approach conditions, but that additional margin would be necessary for the tailwind profile considered.

3.1 THRUST DATA

Figures 3 through 6 present the throttle/EPR/thrust relationships for nominal JT3D-3B (707), JT8D-9 (727/737), and JT9D-7 (747) engines. These data are based on estimates for "nominal" engines and are valid, for purposes of this feasibility study, for the conditions shown on the plots. However, substantial variations from the nominal should be expected. Engine characteristics at low power settings (near idle) are not well defined because of considerable engine-to-engine variations and other factors. The relationship between EPR and power lever angle is particularly uncertain due to rigging tolerances and differences in the surge bleed valve operating points. Very little flight test data are available regarding the thrust/EPR/N_1 relationships at power settings below that required for a normal ILS approach.

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NOTE:

1. REDUCED (CERTIFIED) FLAP POSITIONS: FOR 707/727/737 MAX FOR 747
2. PROVIDES $\Delta\ \gamma = -1.2^{\circ}$ MARGIN FROM MIN. IDLE (AT MIN WEIGHT)
3. UPPER GLIDE SLOPES NOT COMPATIBLE WITH:
   - ICING CONDITIONS
   - REPORTED TAILWINDS
   - CURRENT AUTOTHROTTLES

MAXIMUM UPPER GLIDE SLOPES

	MODEL	FLAPS [1]	GEAR	MAX. ANGLE [2]
	707-300B ADV/C	40	DOWN	5.5
NASA/UAL →	727-200	30	↓	6
	737-200	30		5
	747-200	30		5.5

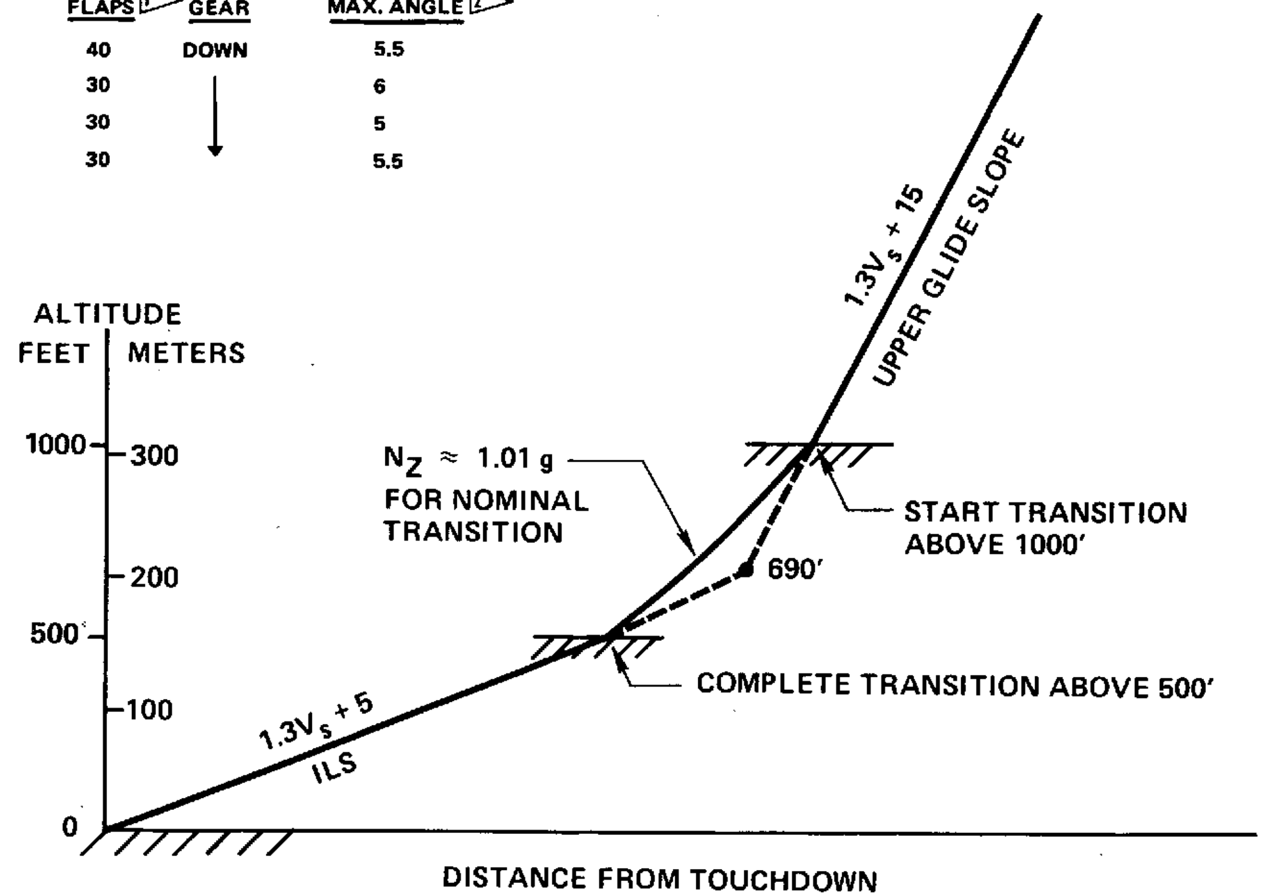


FIGURE 2.—APPLICATION OF NASA/UAL TWO-SEGMENT APPROACHES TO BOEING AIRCRAFT

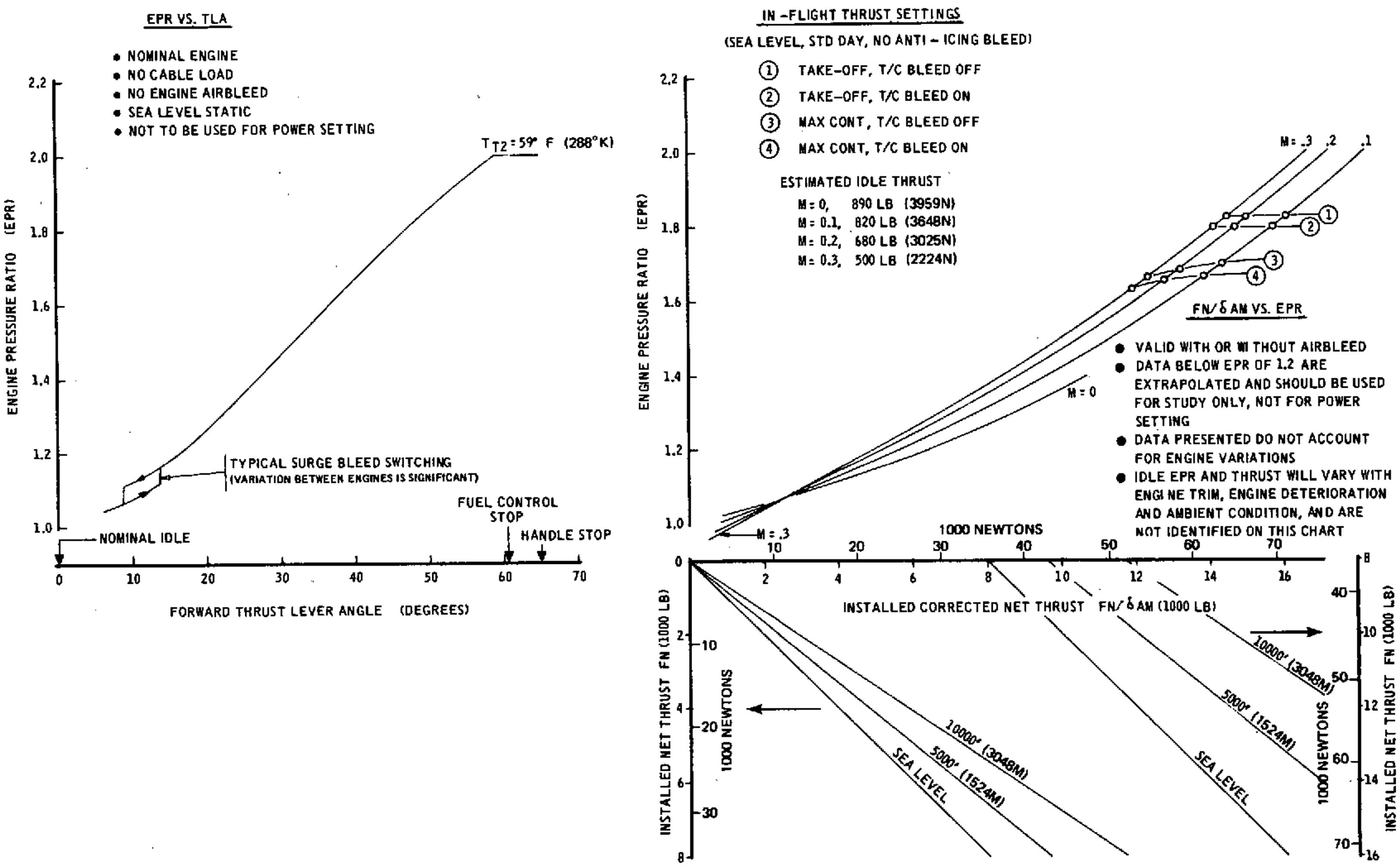


FIGURE 3.–NOMINAL ENGINE CHARACTERISTIC FOR LANDING APPROACH STUDY–707-320B/C AIRPLANE, JT3D-3B ENGINE

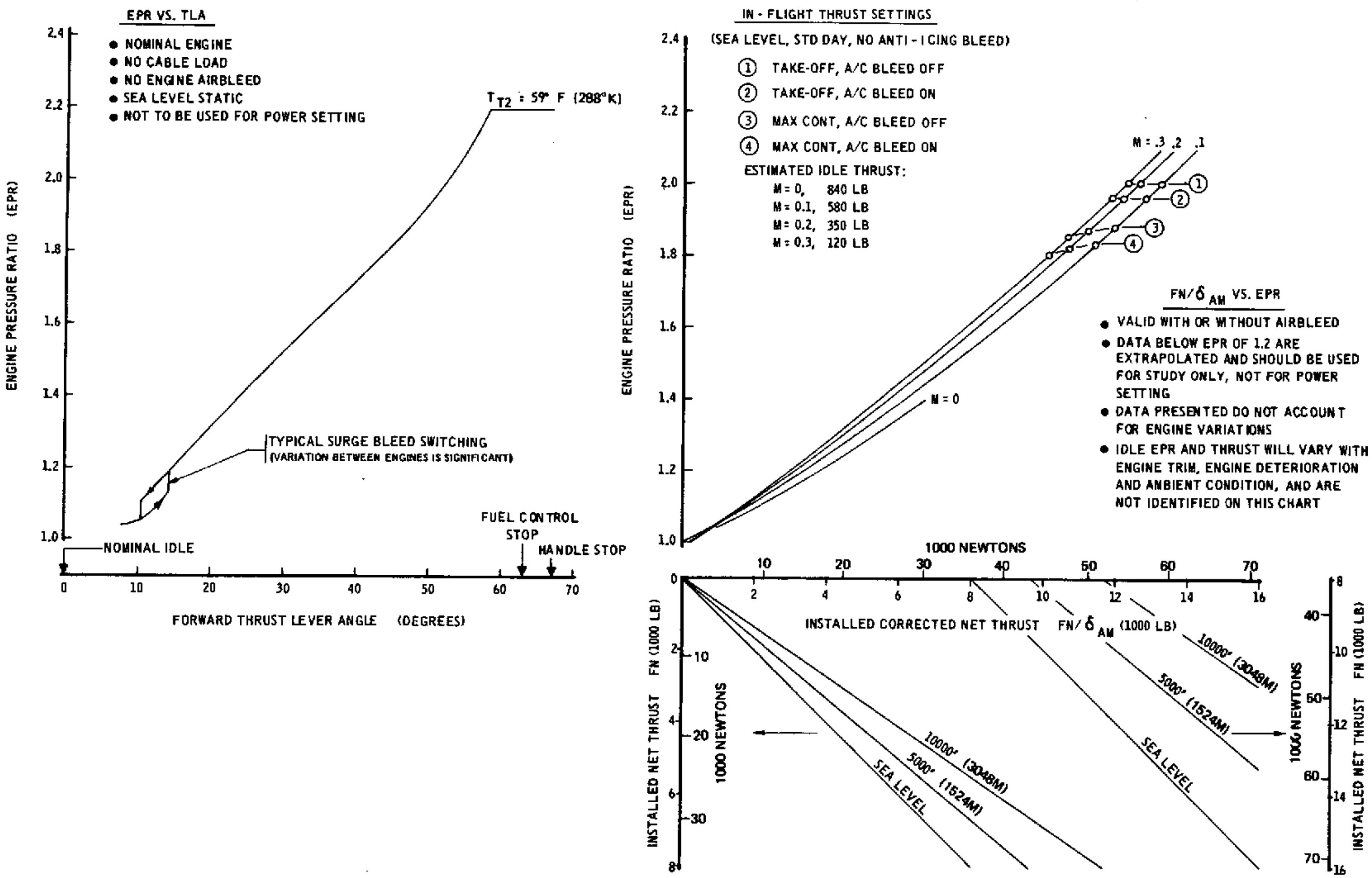


FIGURE 4.–NOMINAL ENGINE CHARACTERISTIC FOR LANDING APPROACH STUDY–727-200 AIRPLANE, JT8D-9 ENGINE

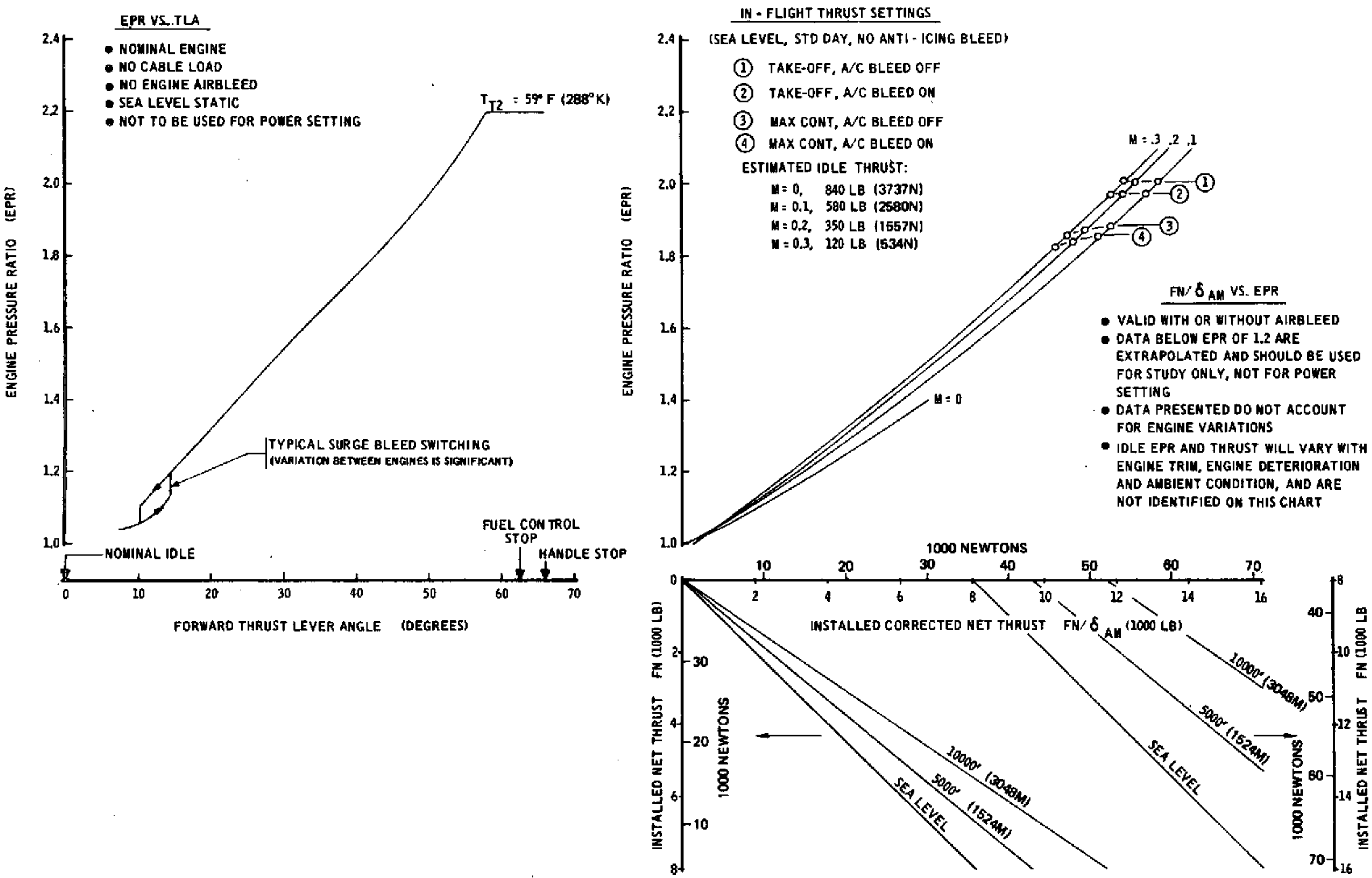


FIGURE 5.—NOMINAL ENGINE CHARACTERISTIC FOR LANDING APPROACH STUDY—737-200 AIRPLANE, JT8D-9 ENGINE

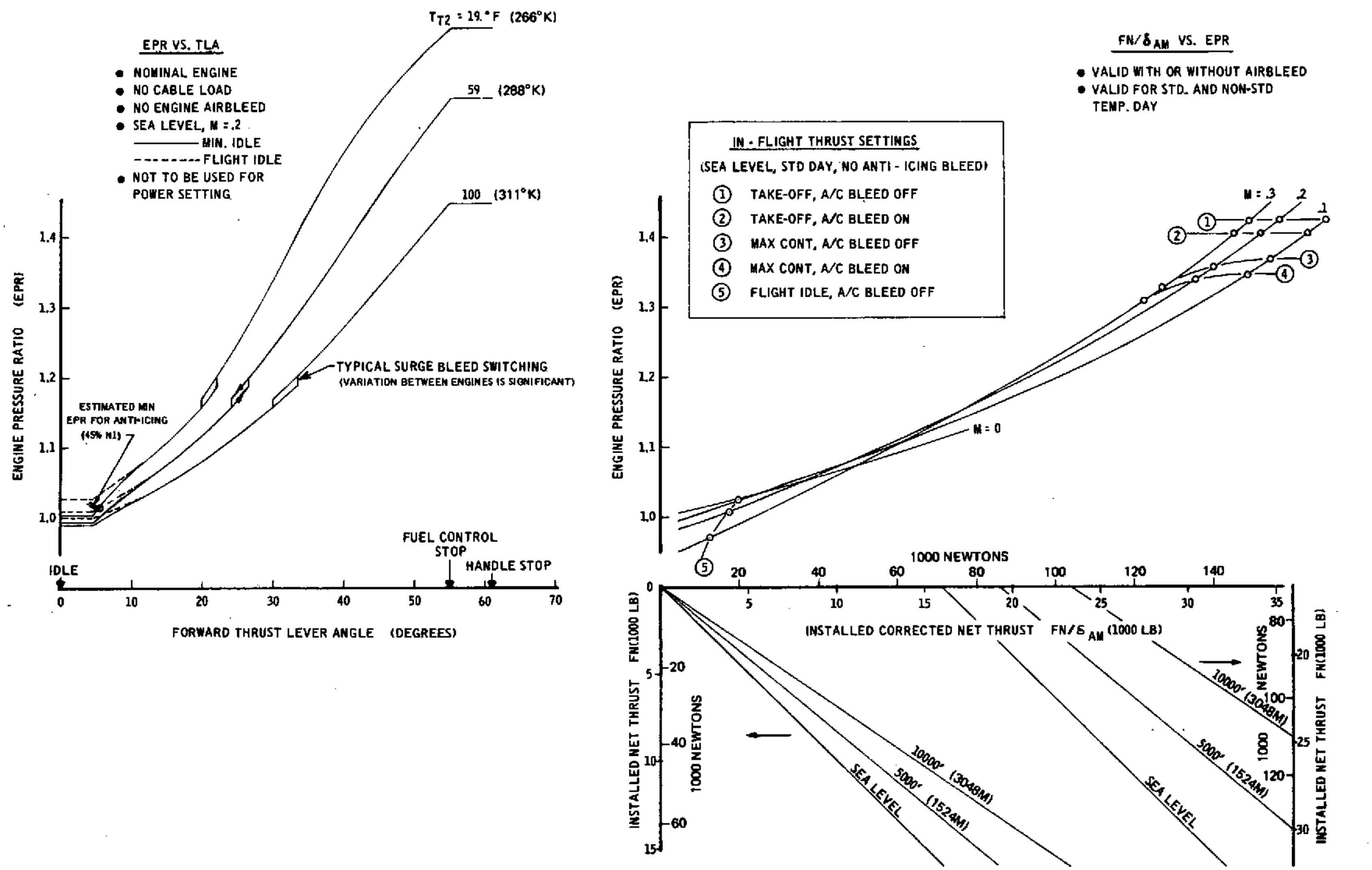


FIGURE 6.—NOMINAL ENGINE CHARACTERISTIC FOR LANDING APPROACH STUDY—747-200 AIRPLANE, JT9D-7 ENGINE

3.2 TRIMMED PATH PERFORMANCE

3.2.1 Data

Figures 7 through 14 show computed values of the trimmed flightpath angle (zero-wind glide slope) γ for the Boeing 707-300B Advanced/C, 727-200, 737-200 basic, and 747-200. The relationship between γ and EPR (nominal engine) is shown for each model with the gear down and the flaps in two landing positions. Each flap setting is shown at two weights. The larger weight is the current maximum certificated landing weight for the particular flap setting. The smaller weight is based on approximately the sum of the operating empty weight plus minimum fuel reserves with no allowance for payload.

3.2.2 Computation

For conventional airplanes in straight flight, the steady-state flightpath angle (γ) relative to the air mass is determined by the thrust-to-weight ratio (T/W), drag-to-lift ratio, (D/L), and inertial deceleration (dV/dt) in accordance with the following equation:

$$\underset{(\text{rad})}{\gamma} = T/W - D/L - \frac{1}{g}\frac{dV}{dt} \qquad (1)$$

The γ/EPR relationships were obtained by first computing the thrust (F_n) required for trim and then determining the corresponding EPR from the generalized thrust curves presented in section 3.1. The thrust required for trim was computed for a constant equivalent airspeed descent using the following equation:

$$F_n = W[D/L + \gamma(1 + 0.567\ M^2)]$$

where:

γ is negative for a descent

$0.567\ M^2$ results from the dV/dt term of equation (1)

The D/L data were obtained from certificated drag polars.

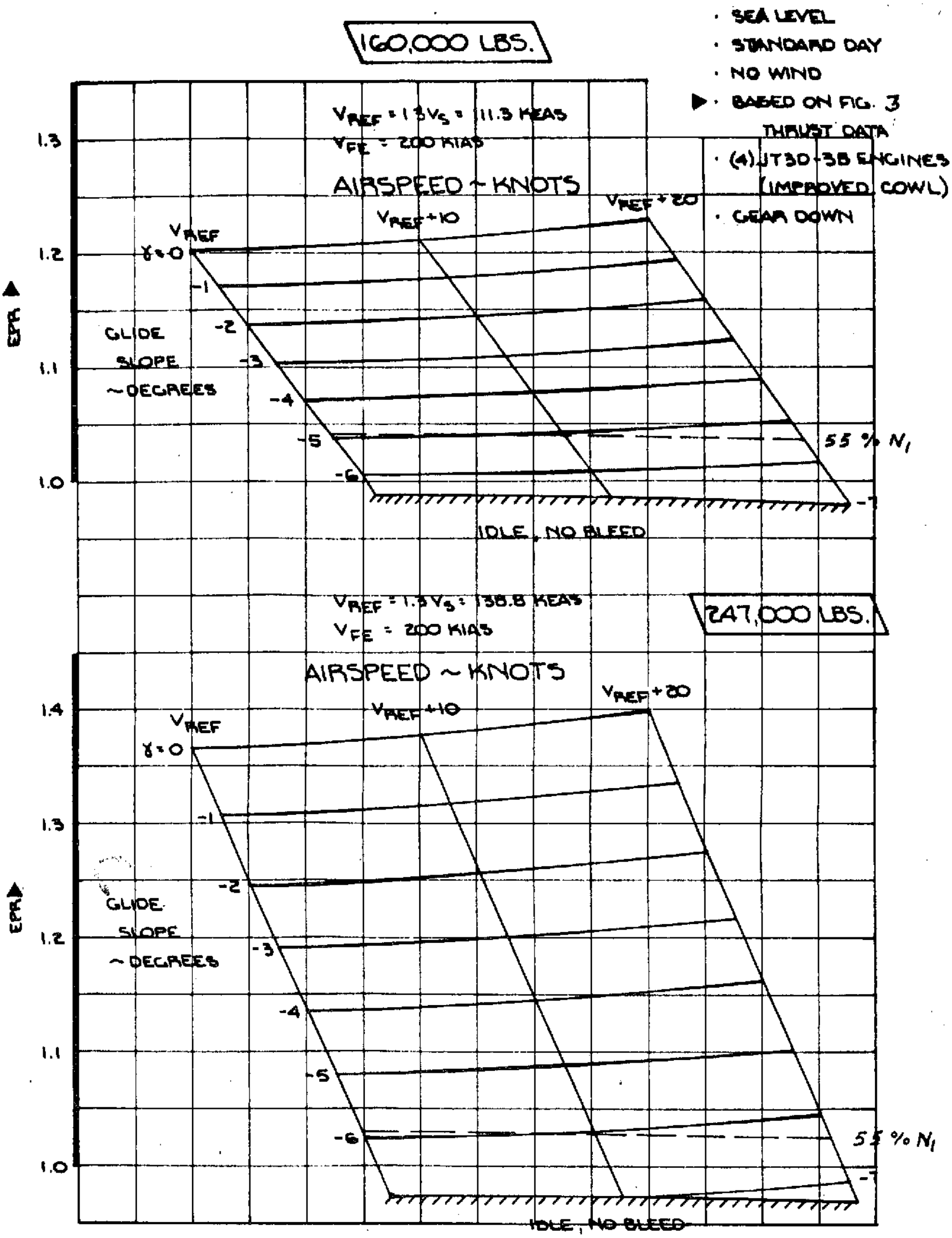


FIGURE 7.–COMPUTED APPROACH PATH, LANDING FLAPS 40–707-300B ADVANCED/C

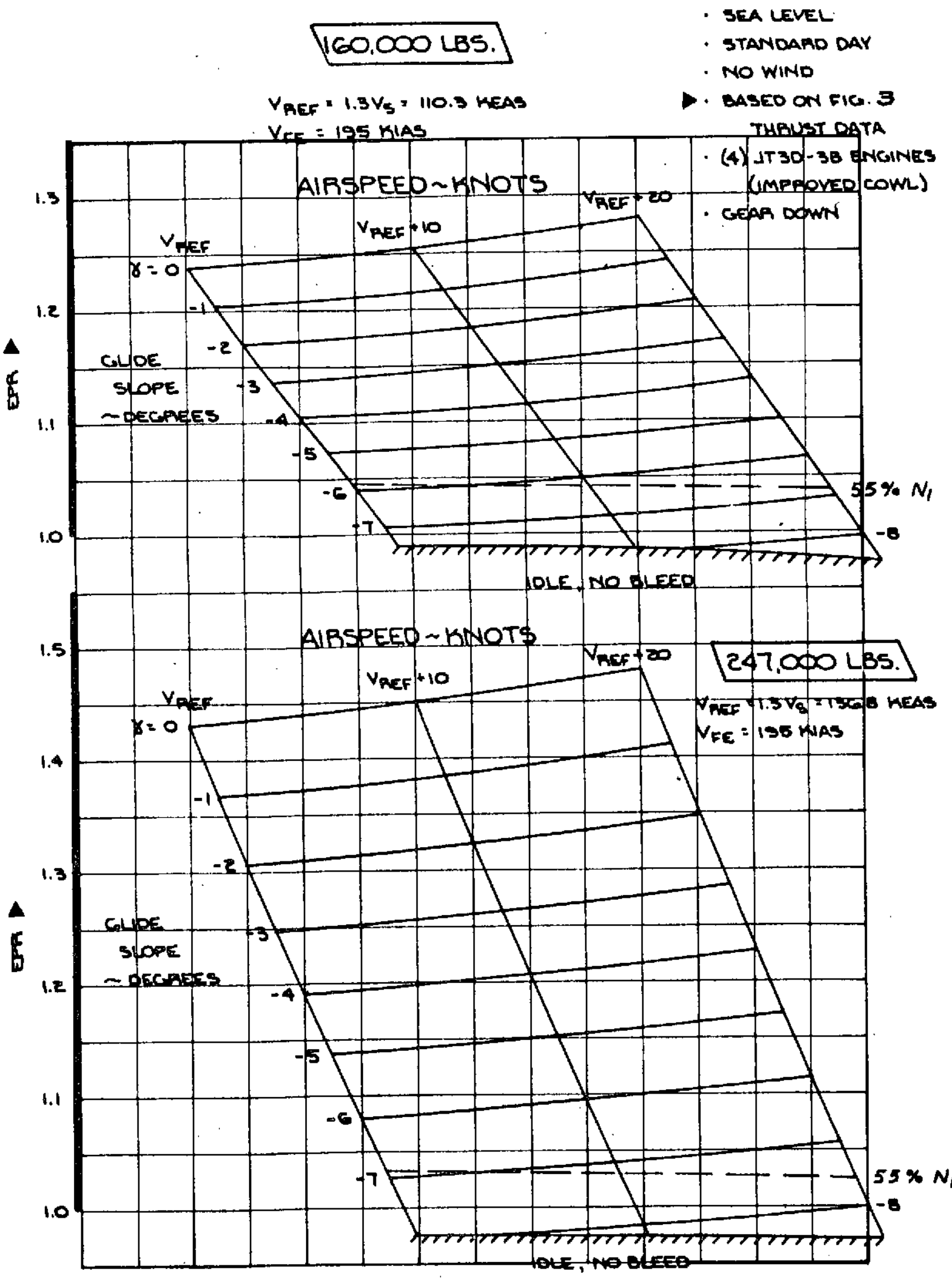


FIGURE 8.—COMPUTED APPROACH PATH, LANDING FLAPS 50—707-300B ADVANCED/C

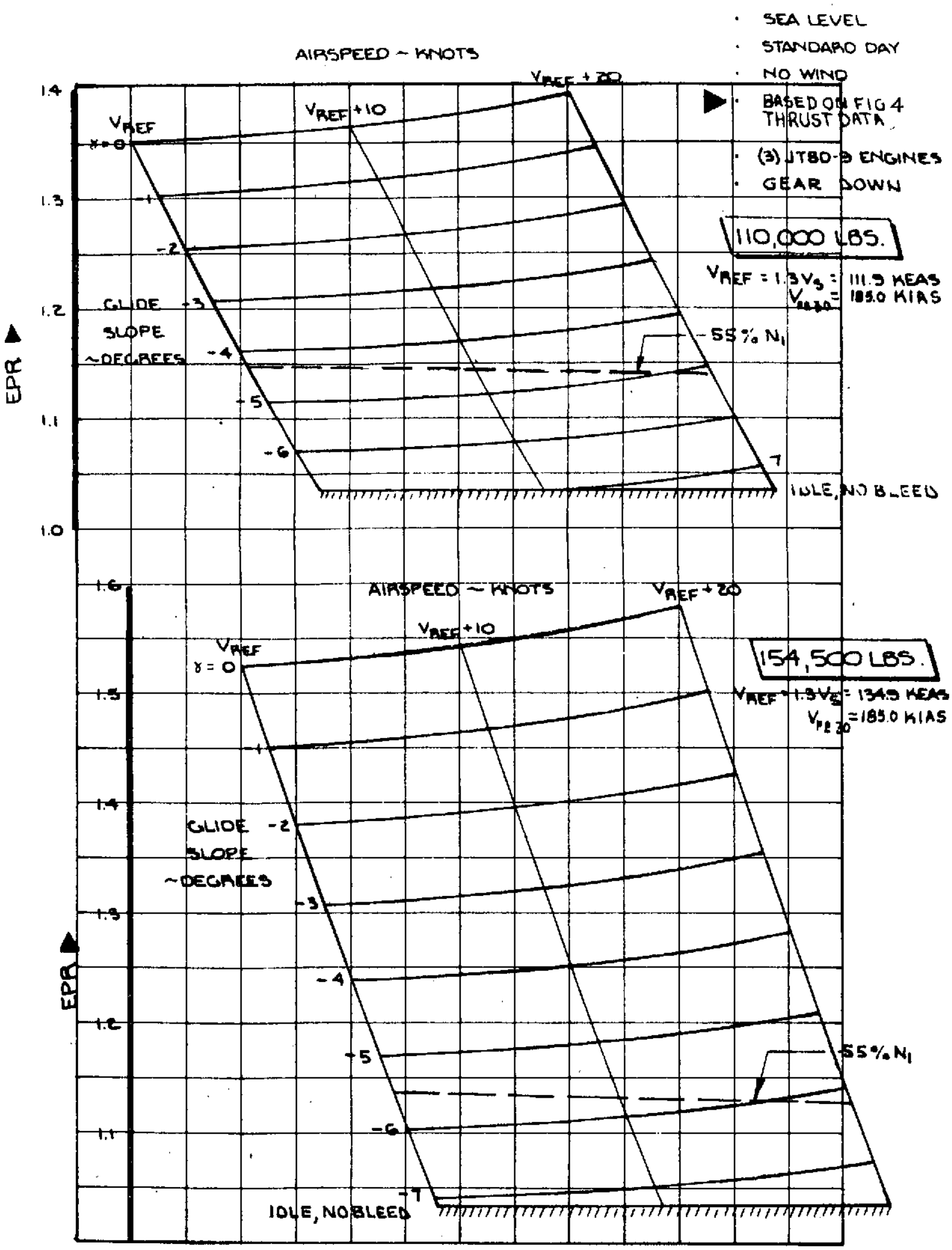


FIGURE 9.–COMPUTED APPROACH PATH, LANDING FLAPS 30–727-200

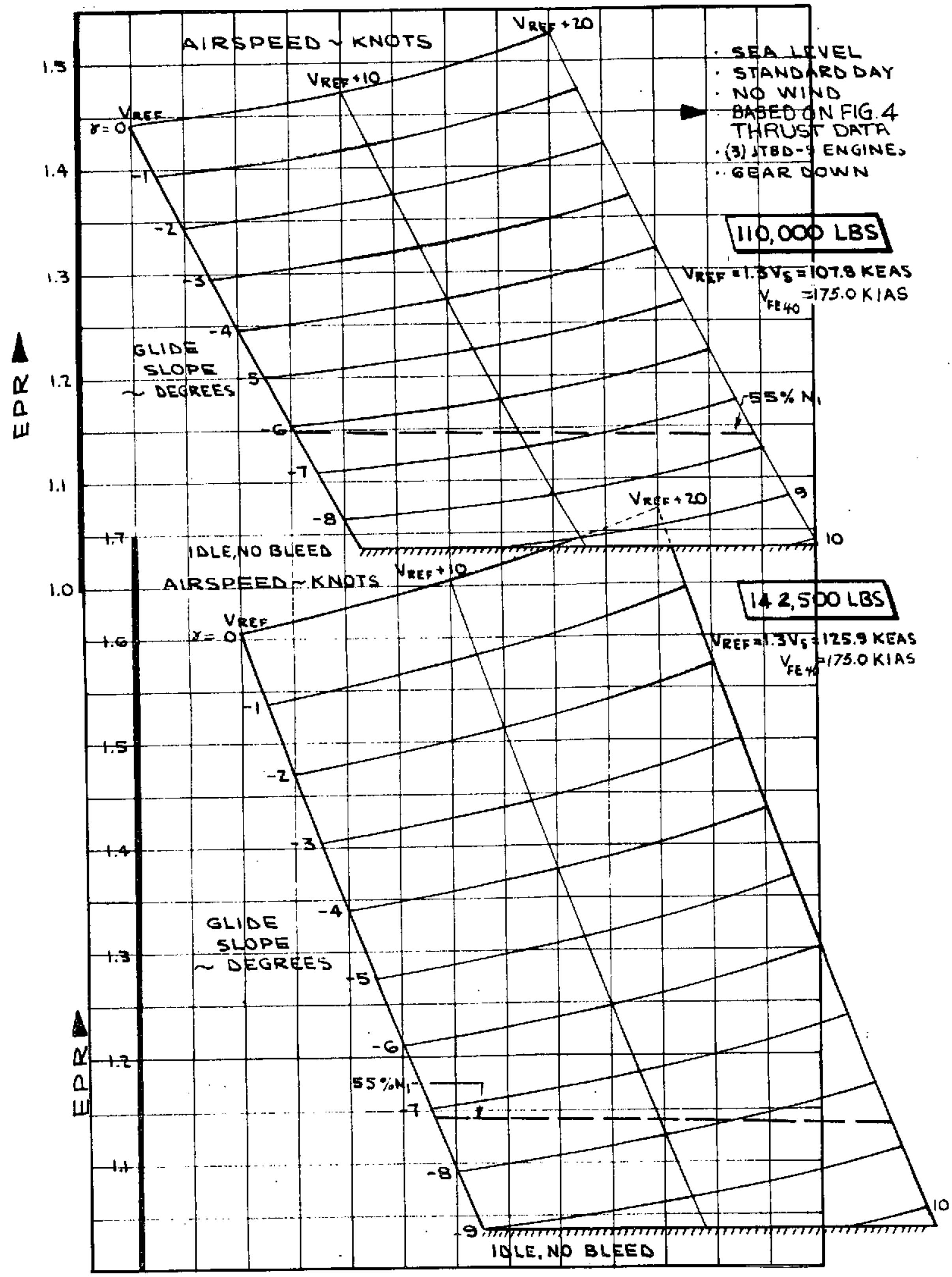


FIGURE 10.—COMPUTED APPROACH PATH, LANDING FLAPS 40—727-200

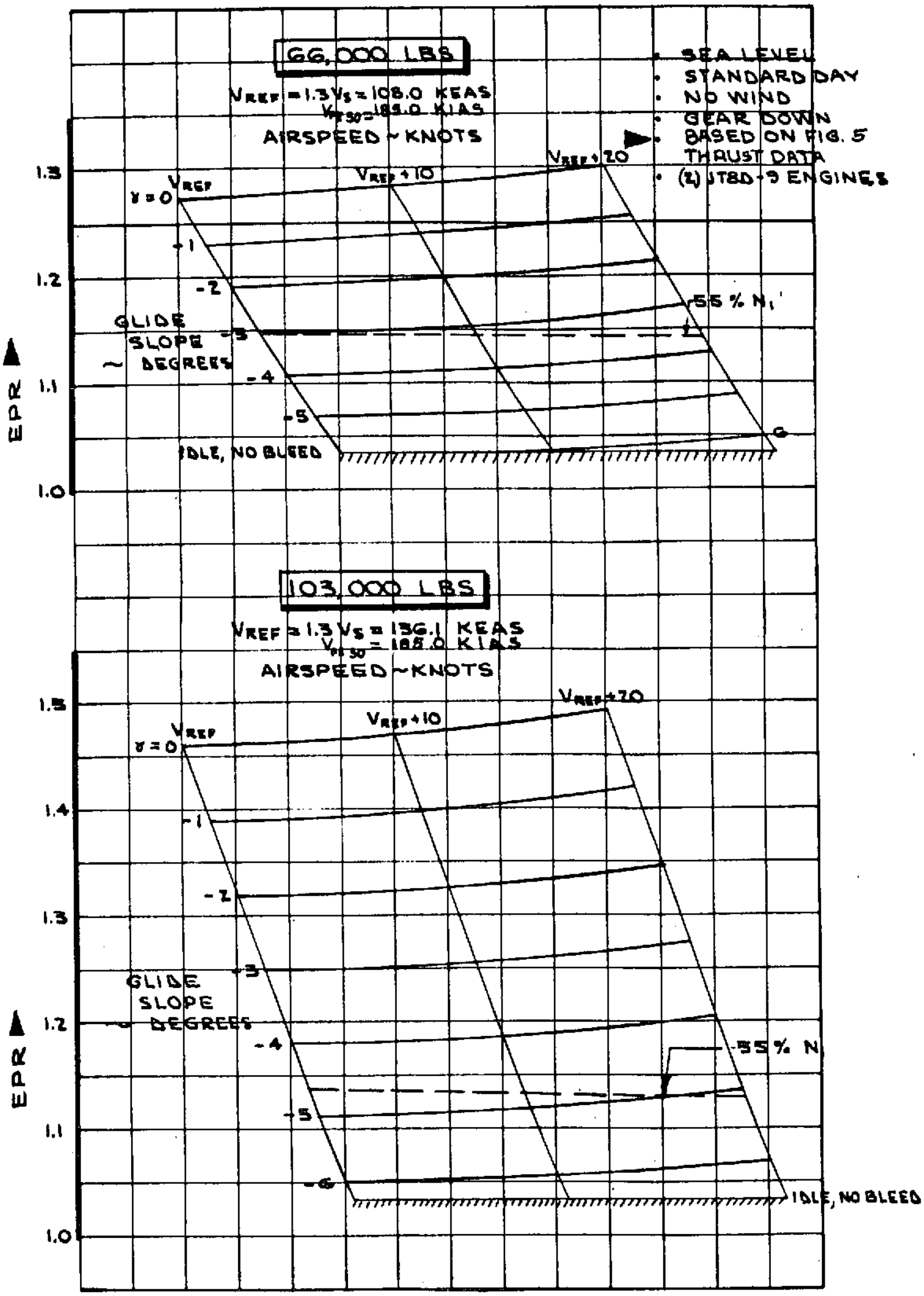


FIGURE 11.–COMPUTED APPROACH PATH, LANDING FLAPS 30–737-200 BASIC

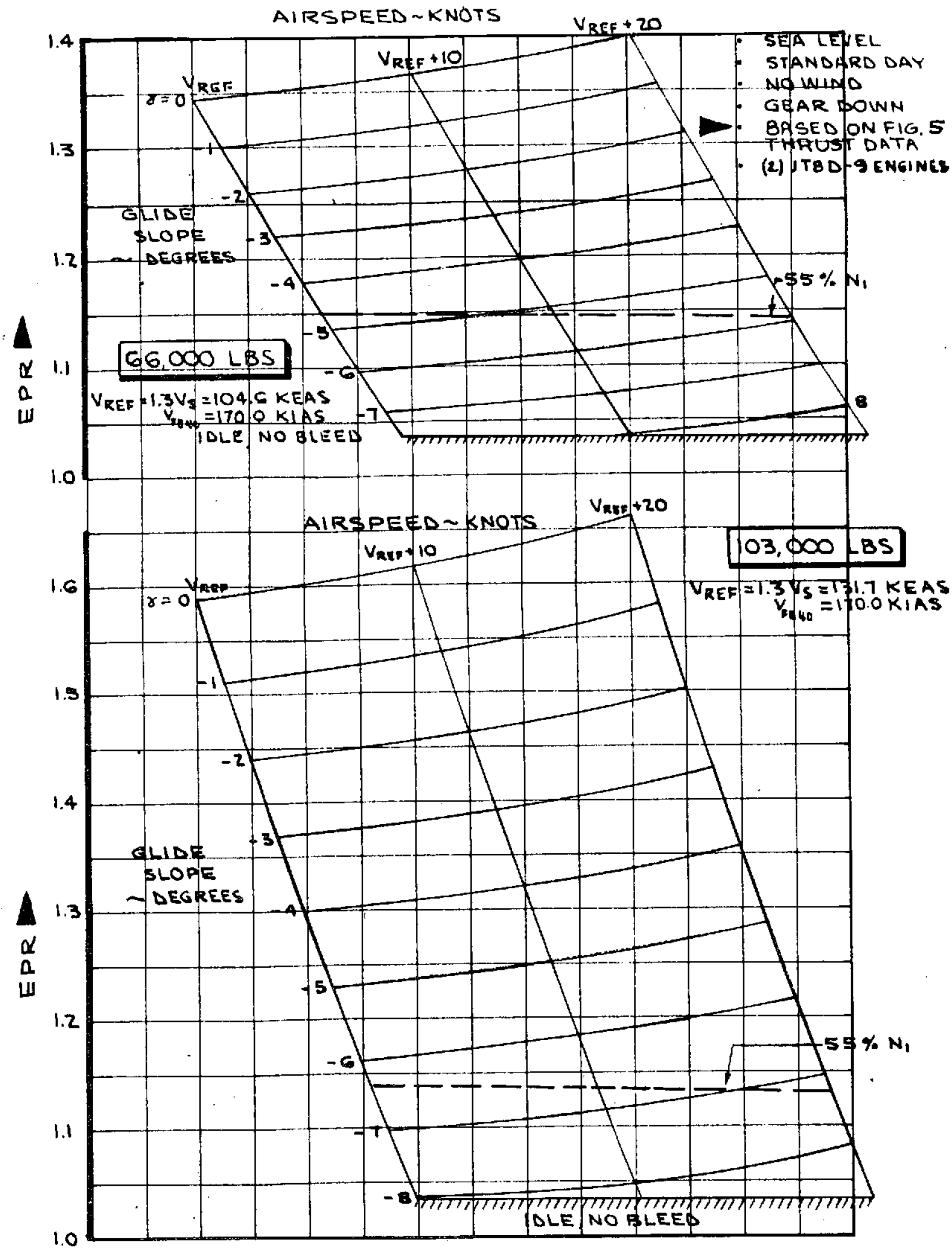


FIGURE 12.–COMPUTED APPROACH PATH, LANDING FLAPS 40–737-200 BASIC

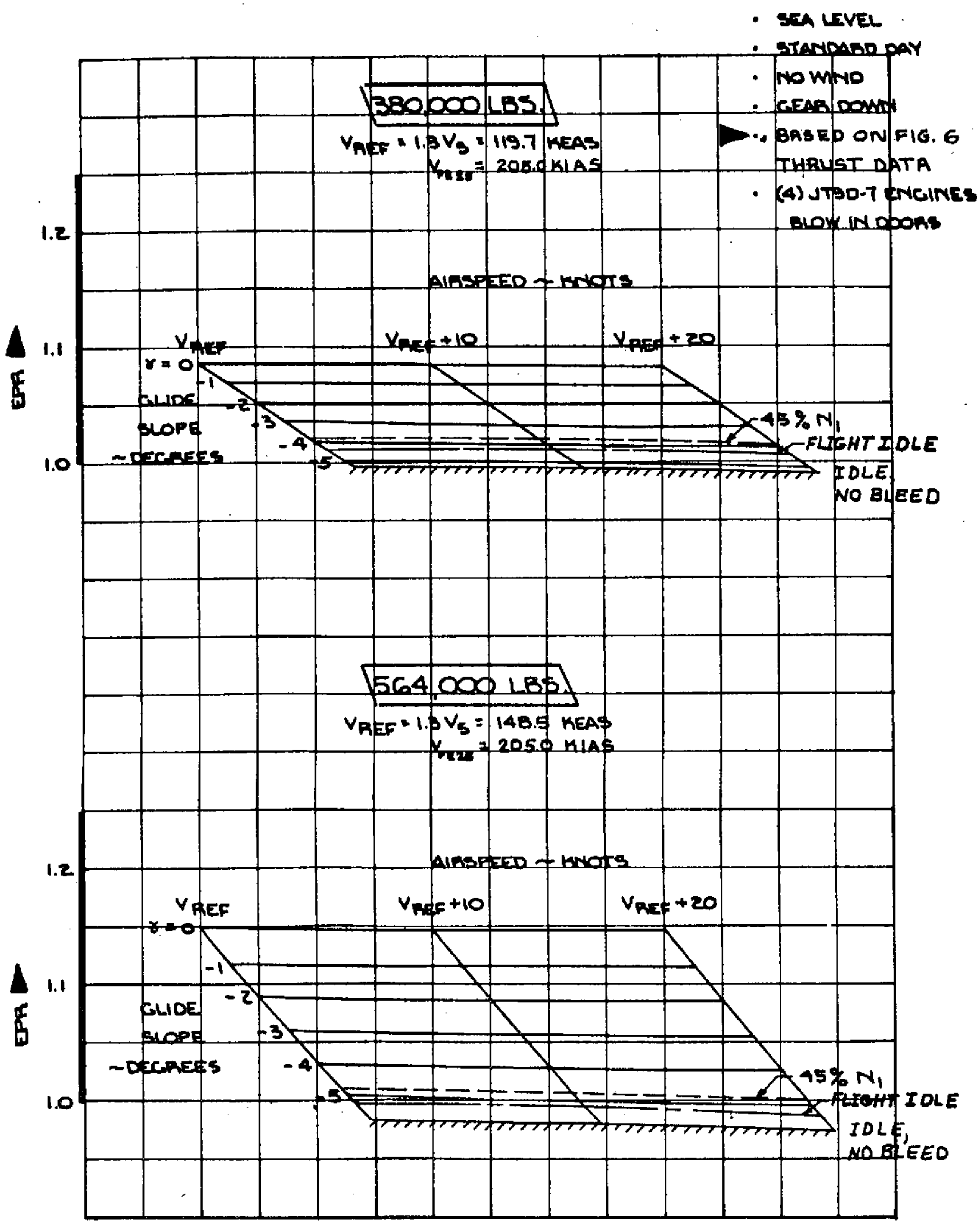


FIGURE 13.–COMPUTED APPROACH PATH, LANDING FLAPS 25–747-200 B

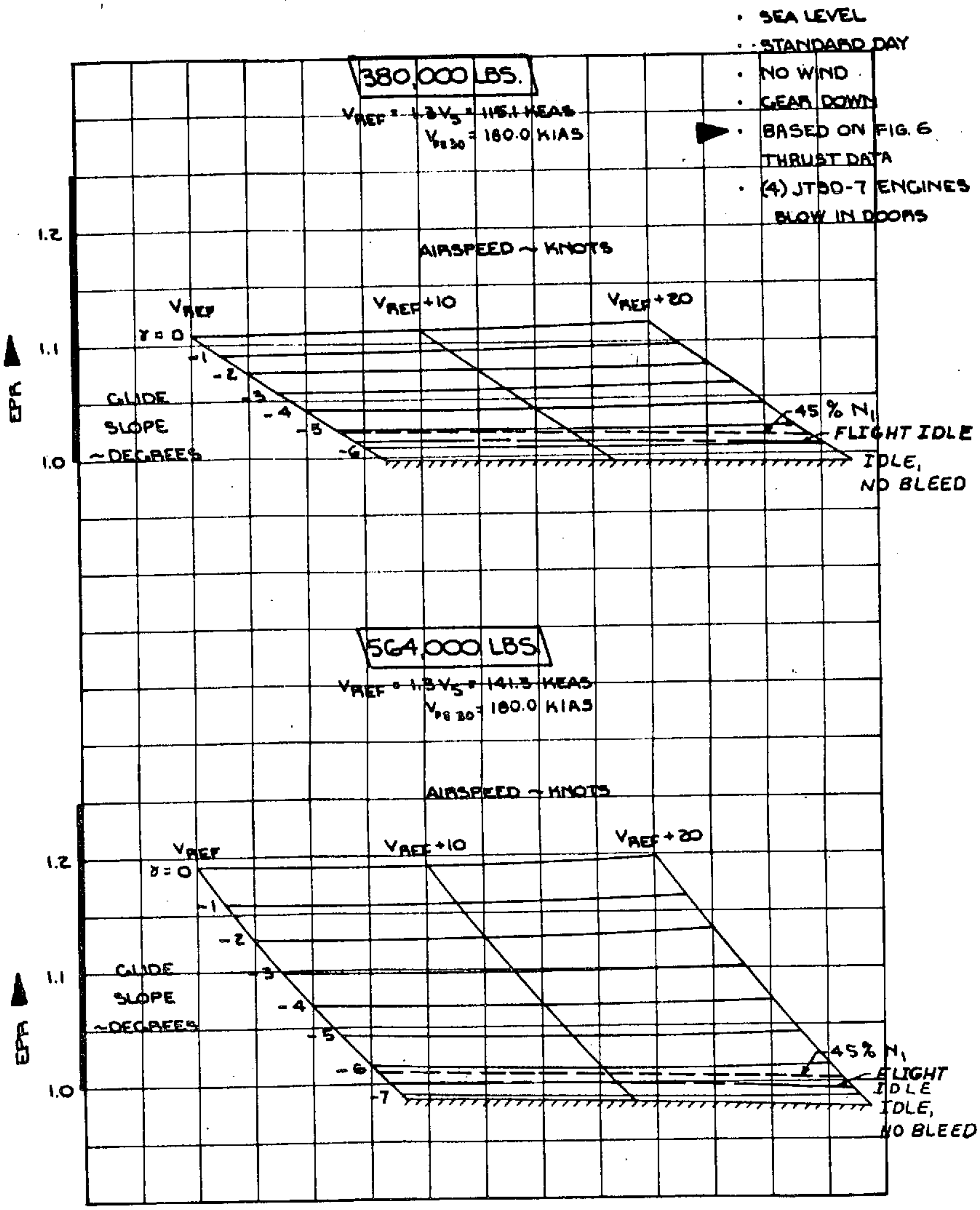


FIGURE 14.–COMPUTED APPROACH PATH, LANDING FLAPS 30–747-200 B

3.2.3 Limits

For a given weight (W) and drag-to-lift ratio (D/L), the steep glide slope capability is limited by the minimum attainable thrust. Two of the engine operating limits considered are indicated on the data plots. These are:

- Idle: Two idle limits are shown for the 747. For the current 747, the "flight idle" limit is activated when airborne with a flap position greater than 22 (normal for landing). However, it appears feasible to remove the "flight idle" limit if required for noise-abatement approaches. There is no separate "flight idle" limit for the 707/727/737.

- Anti-Ice: The flight manuals specify a minimum N_1 to be maintained in icing conditions to provide adequate bleed air temperature and quantity for engine inlet anti-ice. The dashed lines labeled as percentage N_1 show the approximate EPR associated with the minimum N_1 requirements. Anti-ice is not necessary at the ambient conditions for these plots, but the lines are shown to indicate the limits placed upon the glide slope obtainable if it is desired to maintain the specified N_1. For actual icing conditions (colder), the EPR corresponding to the specified N_1 is higher than the value shown. This further reduces the steep glide slope capability.

The trimmed γ capability corresponding to these two limits is summarized in figure 1 for a $V_{ref} + 15$ approach speed. It is important to note that the figure 1 data apply to nominal engines on a standard day with no margin for modulating thrust to control speed or path.

If autothrottles are used for speed control, a third limitation on minimum thrust must be considered. The autothrottle aft limit is set higher than engine idle for all models. Consequently, the trimmed path angle at the autothrottle aft limit will be shallower by the amount shown on figure 15. The figure 15 increments depend only on the change in T/W between the autothrottle and manual throttle limits, so they are approximately applicable to either flap position.

3.3 THRUST MARGINS

The upper glide slope angle should be shallower than the nominal trimmed idle-thrust γ capability of the airplane. This is desirable to provide an allowance for several factors including:

- Variations from nominal airframe/engine characteristics

- Nonstandard days

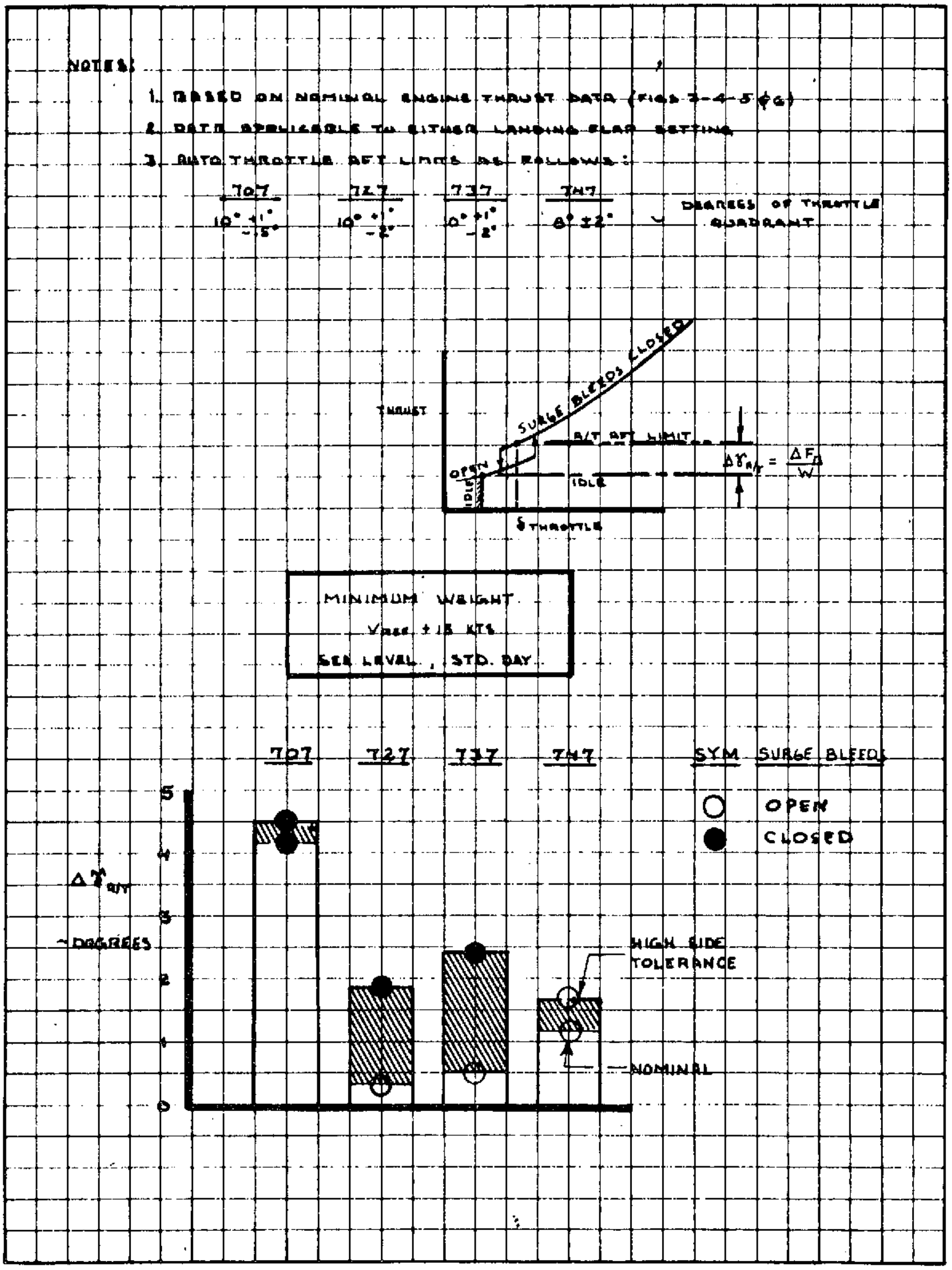


FIGURE 15.–REDUCTION IN γ CAPABILITY DUE TO AUTOTHROTTLE AFT LIMIT

- Tailwinds

- Path corrections.

It was agreed to conduct this feasibility study for nominal airplanes on standard days, so the first two factors have not been analyzed.

The thrust margins (from idle) required for speed control during path corrections and in shearing tailwind conditions are discussed below.

3.3.1 Path Corrections

Figure 16 illustrates the effect of the path modulation capability ($\Delta\gamma$) on the distance required to correct a one-dot deviation above glide slope. The $\Delta\gamma$ capability is the difference between the glide slope angle and the earth-referenced γ_E capability of the airplane. For a given glide slope angle, the $\Delta\gamma$ capability is increased by headwinds and decreased by tailwinds, as discussed below.

The ΔX distances on figure 16 show the distance traveled while correcting a one-dot deviation from the glide slope. The one-dot magnitude was selected arbitrarily, since the expected glideslope deviations for two-segment approaches were not available. A one-dot deviation is typical of the "window" defined for category II flight director certification. For the current NASA/UAL/Collins system, a one-dot deviation on the upper glide slope corresponds to a 250-ft altitude error (independent of X distance). The cutoff on the allowable distance is based on the assumption that a tracking error of this magnitude will probably occur only during glide slope capture (3500 ft for LAX); and that it should be possible to correct the error before reaching the start-transition altitude (1050 ft).

The idle thrust data on figure 1 show that the NASA/UAL procedure for the 727 (flaps 30 and 6° upper glide slope) provides a $\Delta\gamma = -1.2^\circ$ capability for still-air, minimum-weight conditions. Figure 16 indicates this will be satisfactory, particularly since:

- Some overspeed can be tolerated on the upper path (this increases the $\Delta\gamma$ capability due to the drag increase).

- The transition altitude is high enough to adjust to target speed prior to landing.

- Normally, the aircraft will be operating at heavier weights and in a headwind.

However, the adequacy of the $\Delta\gamma$ capability should be determined from a review of the operational flight test results.

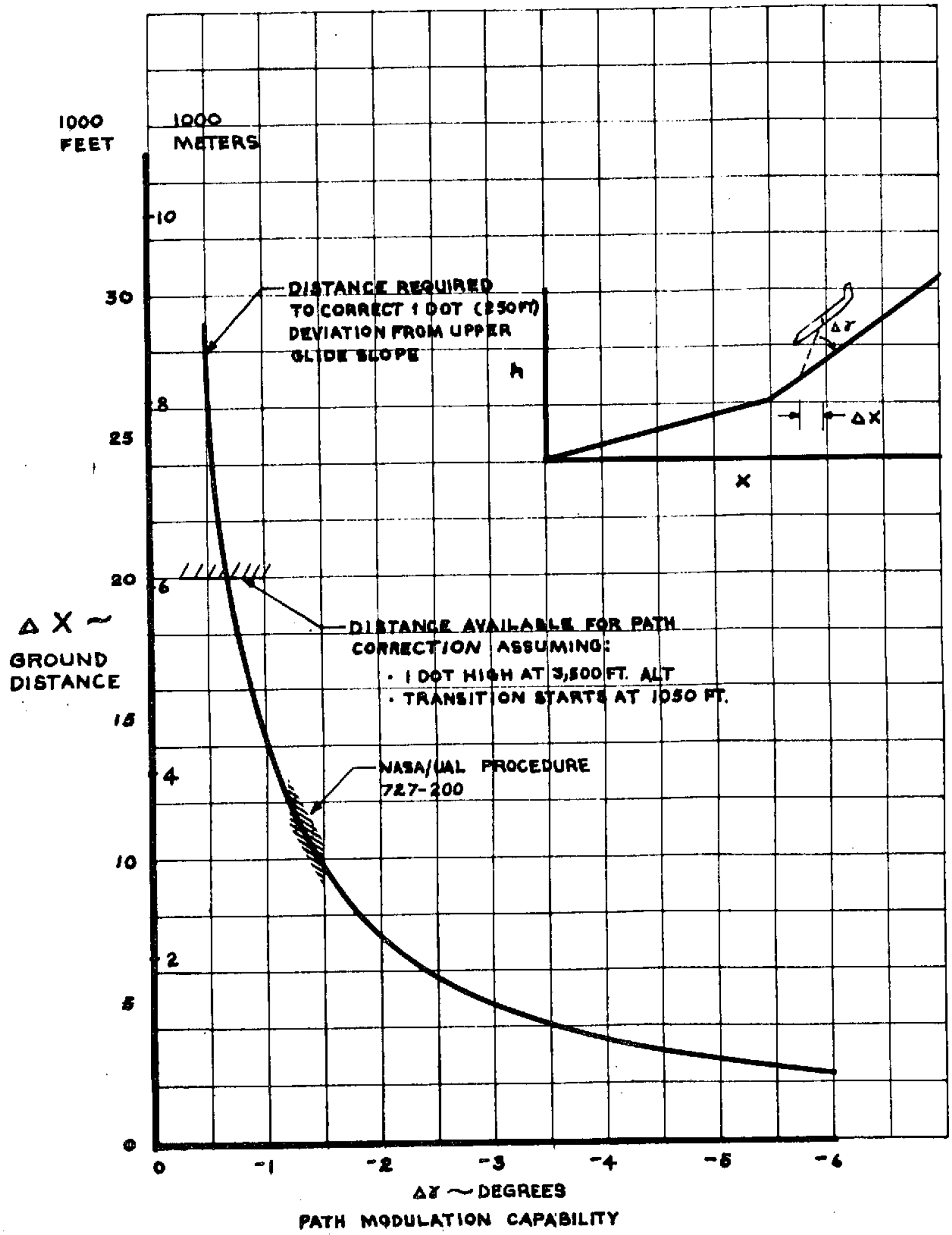


FIGURE 16.–GROUND DISTANCE REQUIRED TO CORRECT ONE DOT GLIDE SLOPE OFFSET

3.3.2 Tailwind (Also See Sec. 4.6)

The thrust margin required for speed/path control in a shearing tail wind was analyzed. An equation was developed that shows that the thrust margin required for speed control in a given tail wind is proportional to the glide slope angle, being greater for steeper glide slopes.

3.3.2.1 Derivation of Equation

The derivation of an equation for computing the thrust modulation required for speed control was suggested by reference 2, which pointed out that a shearing tailwind has two effects on thrust requirements.

1) Path Angle Effect: When tracking a glide slope in a tailwind, the flightpath angle (γ) relative to the air mass is steeper than the earth-referenced glide slope (γ_{earth}). The relationship between the two is a function of wind speed (V_w) and true airspeed (V_A) and can be derived from the small-angle approximation for sink rate (dh/dt)

$$dh/dt = \gamma V_A = \gamma_{earth} \underbrace{(V_A + V_w)}_{\text{(Ground speed)}}$$

$$\gamma = \gamma_{earth} \left[1 + \frac{V_w}{V_A} \right]$$

2) Deceleration Effect: An airplane flying in a tailwind is immersed in an air mass that is moving in the same direction as the airplane. If the air mass slows down, relative to the earth, then the airplane must slow down (ground speed) by the same amount to maintain constant airspeed. Since wind speed is usually considered to shear as a function of altitude (e.g., 4 kn per 100 ft) then the inertial deceleration required to maintain constant speed can be computed from:

$$dV/dt = dV_w/dh \times dh/dt$$

$$= \underset{\substack{\text{(Wind}\\\text{shear)}}}{dV_w/dh} \times \underset{\substack{\text{(Ground}\\\text{speed)}}}{V_G} \times \underset{\text{(Glide slope)}}{\gamma earth}$$

The above equations can be combined with equation (1) to obtain the difference in thrust required between still air and shearing tailwind conditions. This difference is given by:

$$\Delta T/W = \underset{\text{(rad)}}{\gamma_{\text{earth}}} \left[\frac{V_W}{V_A} + \frac{(1.69)^2}{g} (V_G) \frac{d\,V_W}{d\,h} \right] \begin{matrix}\text{(Speeds in knots)} \\ \text{(Altitude in feet)}\end{matrix} \qquad (2)$$

3.3.2.2 Data for 10-Kn Reported Tailwind

Figure 17 presents the thrust margin requirements that result from equation (2) for a tailwind profile based on a 10-kn reported wind with a severe shear corresponding to very stable (nonturbulent) atmospheric conditions. The wind speed is 35 kn at altitudes above 1500 ft.

The thrust margin $\Delta T/W$ is sometimes expressed in terms of the $\Delta\gamma$ capability (at constant speed) and is shown in that form on figure 17. Although the figure 17 data are expressed in terms of $\Delta\gamma$, the thrust margin is required for speed control on the glide slope, and no allowance for path tracking errors is included.

The data for the 3° path illustrate the relative magnitudes of the path angle and deceleration effects for the particular tailwind profile used in the study. It is seen that (for this wind profile) the path angle (wind velocity) effect predominates at higher altitudes, while the deceleration (wind shear) effect predominates closer to the ground at altitudes below the NASA/UAL transition height.

As seen from equation (2), the thrust margin required for a particular wind profile at a given altitude is proportional to γ_{earth}. The figure 17 data show that the thrust margin required for a 6° path exceeds the $\Delta\gamma = -1.2°$ margin provided by procedures defined on figure 2. Hence, the glide slopes shown on figure 2 would have to be reduced to provide compatibility with the tailwind profile used for this study. This is not recommended, however, for reasons discussed in section 4.6.1.

3.4 PROCEDURES REVIEW

The 727 two-segment glide slope procedure recommended by NASA/UAL for further evaluation by line pilots in revenue service is illustrated on figure 2. This procedure was reviewed for feasibility with respect to the approach path performance capability of the Boeing fleet, considering such factors as safety, stall margins, wind shear, engine response, FAR 25 requirements, ATC procedures, etc. Since terminal area maneuvering, upper glide slope capture, and ILS glide slope tracking below 500 ft are essentially the same as for normal ILS approaches, only the steep glide slope and transition phases are discussed.

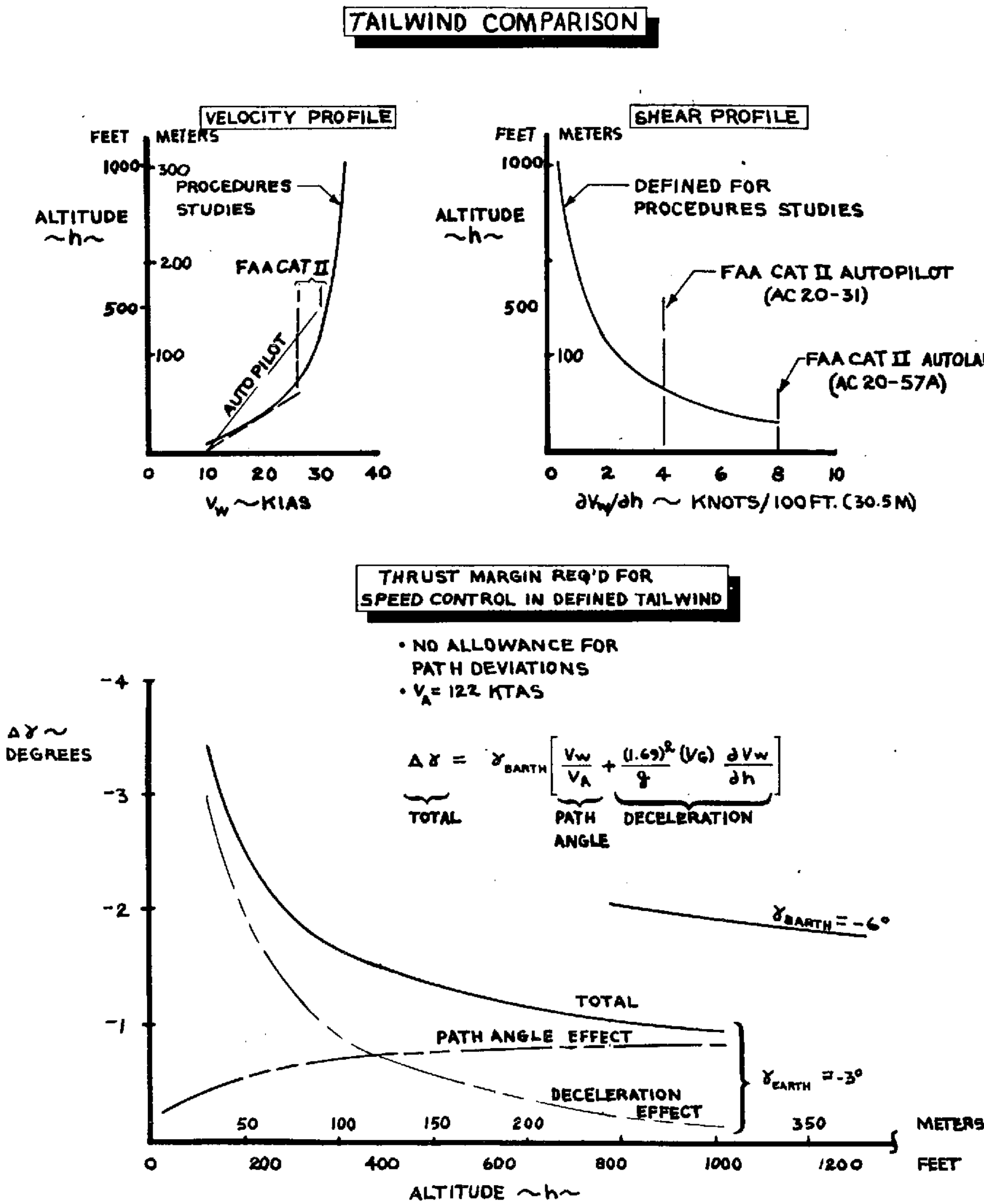


FIGURE 17.—ANALYSIS OF THRUST MODULATION IN SHEARING TAILWINDS

The aspects of the procedure discussed in sections 3.4.1 through 3.4.4 below, appear satisfactory for all Boeing models. The upper path angles depend on the model and operational criteria.

3.4.1 Gear

Gear extension during upper glide slope capture is consistent with normal ILS procedures and is recommended from a safety, pilot workload, and checklist compatibility point of view. The added drag, while contributing to aerodynamic noise, allows the use of steeper glide slopes.

3.4.2 Reduced Landing Flaps (Maximum Flaps for 747)

All Boeing models have at least two certified landing flap positions (the 737 has three). Use of the reduced flap position is satisfactory where field length permits. Some 707/727/747 operators have blocked the maximum flap position so that only the reduced setting is available to their pilots. The reduced flap setting reduces noise on the ILS glide slope but decreases the steep glide slope capability. Noise trades were not calculated in this study but should be considered before making a final recommendation regarding the flap position and path angle. The results of such a trade study would be highly dependent on the criteria used for evaluating noise. Since the certified landing configurations for the 747 are relatively cleaner than for the other models, maximum flaps were used to define the 747 glide slope, while reduced flaps were used for the 707/727/737.

3.4.3 Speeds

The two-segment approach speeds (V_{ref} + 15 upper segment, V_{ref} + 5 on ILS) appear to be safe and reasonable for flying the designated profile with all models. The nominal transition is a very gentle maneuver requiring a nominal load factor on the order of 1.01 g to accomplish a 3° change in path angle over a 30-sec time period. *If* speeds are maintained at or above the specified values, FAR 25 stall margins will be adequate. The 10-kn speed bleed during the transition is considered desirable (in spite of the trim change) because engine response is slow at power settings near idle. The extra 10 kn should allow the pilot to perform a smoother spoolup with less concern about speed undershoots.

3.4.4 Transition Altitude

The hazardous nature of operating turbojet aircraft at high sink rates and low power settings "close to the ground" has long been recognized. The difficult question of "how close is too close?" has been the subject of a number of simulator and flight evaluations. The altitudes selected by NASA/UAL appear reasonable and safe from an engineering point of view, if the pilots consistently track the beam. The UAL 727 on-line evaluation should provide useful data in this area.

Figure 18a shows the relationship of the NASA/UAL two-segment glide slope to the airport obstacle clearance plane specified by FAR 77.25. Figure 18b shows the altitude separation between the nominal profile and the highest allowable obstacle. Since there is adequate obstacle clearance, and since the transition allows about 30 sec for spoolup to normal approach power, the nominal profile is compatible with engine response characteristics. However, a potentially hazardous situation could develop if the pilot were distracted at the start-transition altitude since, timewise, the aircraft is about 30 sec above the obstacles if the high sink rate is maintained.

Approach and landing climb gradient certification under FAR 25 is discussed in section 4.6.1.

3.4.5 Upper Glide Slope Angles

Maximum glide slope angles for each model were selected in accordance with the operational criteria presented in section 2.0. The maximum glide slope angles provide a $\Delta\gamma = -1.2°$ path modulation capability relative to idle thrust for the nominal airframe/engine, at minimum weight, in still air, on a standard day, with minimum landing flaps (maximum flaps for 747), and at $V_{ref} + 15$. This is consistent with the NASA/UAL procedure for the 727. The recommended maximum upper glide slope angles and the corresponding flap positions and operational limitations are defined on figure 2.

Restricting use of two-segment approaches to nonicing, nontailwind conditions is not viewed as a disadvantage of two-segment glide slopes when compared to other noise-abatement approach techniques. In fact, one advantage of the NASA two-segment system, when compared to steeper ILS beams, is that current ILS glide slope angles and procedures remain available as a backup for use in adverse weather conditions. If it is determined that these operational limitations significantly detract from the usefulness of two-segment procedures, it is possible, though not recommended, to provide the required capability by reducing the upper path angle or using increased flaps (for customer aircraft so equipped).

4.0 TASK II—AIRPLANE SYSTEMS REVIEW

4.1 PURPOSE

The purpose of this task is to assess the adequacy of the autopilot, flight director, and other associated systems currently installed in Boeing aircraft for performing two-segment approaches. Emphasis is on equipment modification and recertification aspects. Consideration was limited to systems and procedures similar to those used for the UAL 727 line evaluation.

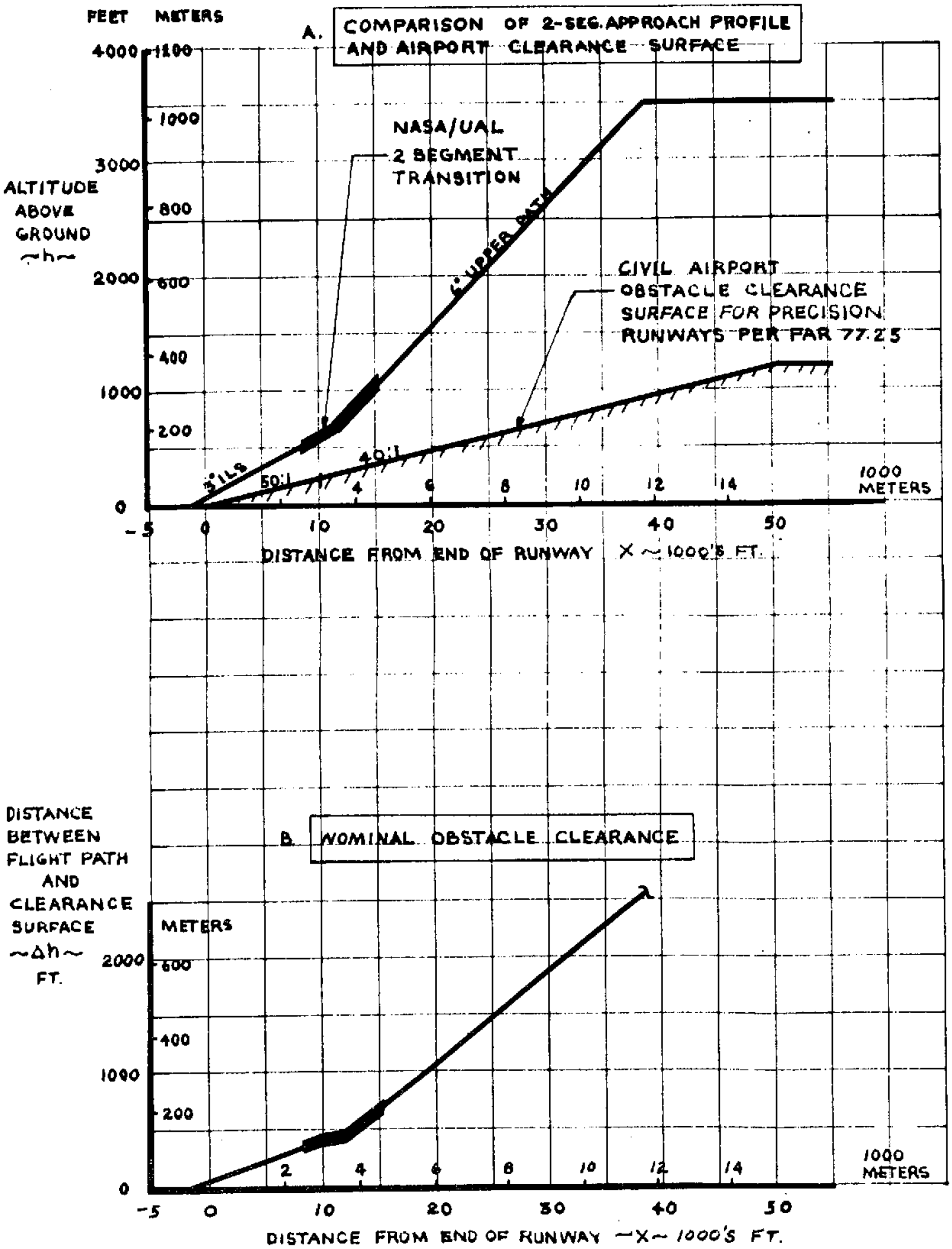


FIGURE 18.–OBSTACLE CLEARANCE FOR NASA/UAL TWO-SEGMENT APPROACH

4.2 NASA SYSTEM DESCRIPTION

The NASA two-segment approach system provides the capability to fly two-segment glide slopes, using either the flight director or autopilot, under VFR or IFR conditions. The normal ILS beam is used for lower segment guidance, while the upper path is computed by the airborne system.

The two-segment system developed by Collins Radio for the UAL 727 evaluation computes the upper path using DME range (DME ground station collocated with the ILS glide slope), field elevation (pilot input), and barometric altitude. Guidance and monitoring information are displayed to the pilot via the flight director (ADI), the horizontal situation indicator (HSI), and the approach progress display annunciator panel.

4.3 AVIONICS MECHANIZATION CONCEPTS

Detailed hardware mechanization of the two-segment control laws can be accomplished in several different ways while retaining the two-segment path reference concepts developed and evaluated by NASA/Collins/UAL. The extent of the fleet retrofit and certification program and the ability to use existing system capabilities (e.g., autoland) during two-segment approaches may depend on the mechanization concept selected. Consequently, two alternate avionics configurations were considered in this study, while using the UAL 727 installation as a baseline.

The three avionics configurations considered are outlined on figure 19. All three use the same path reference information as provided by the ILS beam and the existing Collins two-segment computer. The differences are in the method and degree of utilization of existing autopilot/flight director hardware. Configuration A (Collins unit) uses the "altitude hold" mode for the entire approach. Configuration B is the same as configuration A until the ILS beam is captured, at which point control is switched to the existing approach mode. Configuration C uses the "approach" mode for the entire approach.

Configuration A was implemented by Collins and has been successfully flight tested on the UAL 727. Installation of this unit in other Boeing models is feasible, based on control law similarity, although design differences will arise because of variations in ship's wiring and logic signal requirements. Interfacing with the various autopilot and flight director computers is facilitated by use of the "altitude hold" mode. This configuration appears suitable for conducting two-segment approaches to category II minimums and should not adversely affect current system certification

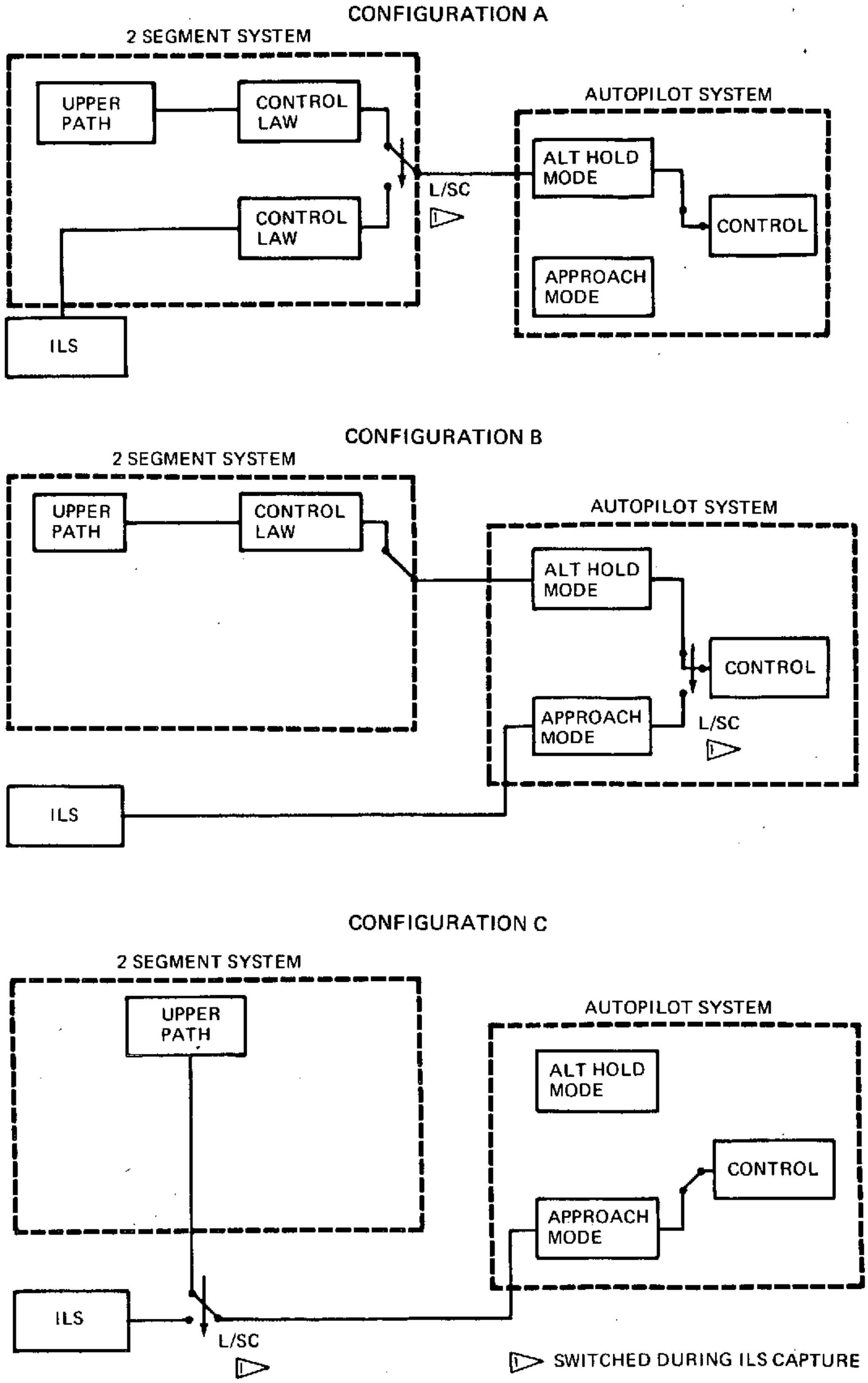


FIGURE 19.—COMPARISON OF TWO-SEGMENT AVIONICS CONFIGURATION

for normal ILS approaches. However, it does not use the existing "approach" mode hardware and prohibits the use of autoland** (multichannel) for two-segment operation on those airplanes so equipped.

The alternate configurations (B and C) take advantage of the existing "approach" mode hardware, which is already certified, and are compatible with autoland systems. This could permit two-segment computer commonality throughout the fleet, thereby eliminating the development of a separate set of hardware for autoland systems only. However, configurations B and C are more dependent than configuration A on individual autopilot and flight director system characteristics and may require more internal modifications to these existing systems.

It is premature to conclude which avionics configuration is preferable for fleet retrofit until detailed analyses (beyond the scope of this feasibility study) have been conducted. Customer requirements regarding avionics commonality and autoland capability, and the extent of the required certification effort, should be considered. Detailed configuration definition analyses prior to production are viewed as an essential part of a large-scale fleet retrofit program and could be conducted in a reasonably short time.

Design, operational, and certification considerations for the three mechanization concepts are summarized in table II. The following sections provide additional details and discussions of the avionics configurations considered.

4.3.1 Configuration A (Collins Unit)

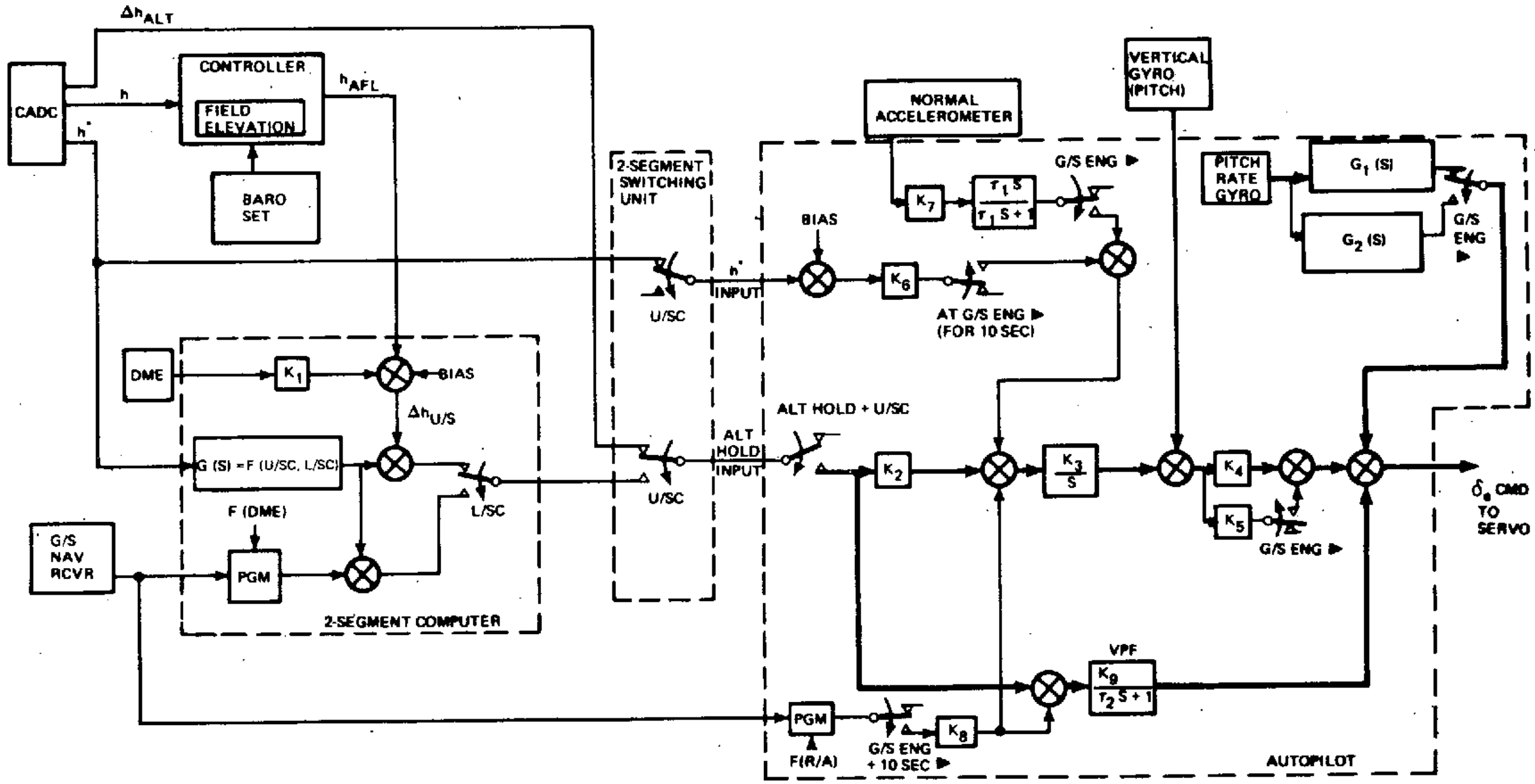
Figure 20 is a simplified block diagram illustrating how the existing Collins unit provides the capability for flying both the upper and lower segments through a typical (727) autopilot. The two-segment computer control signal is sent through an interface unit into the "altitude hold" mode of the autopilot. The "glide slope engage" relays are not activated. Upper-segment guidance is based on DME, field elevation, and barometric altitude. Lower-segment guidance is based on DME-programmed ILS glide slope deviation. Path damping for both segments is accomplished through "washed out" barometric altitude rate.

While compatible with category II systems, use of the Collins configuration for autoland operation would require a redesign of the autopilot "altitude hold" mode to provide multichannel capability. A multichannel system provides fail-passive or fail-operational capability, which is

**"Autoland" is used herein as a general term to include all systems approved for operation below category II minimums.

TABLE II.—CONFIGURATION DIFFERENCES

Configuration		Design considerations	Multichannel capability	Failure analysis	Performance analysis	Test program (conducted by manufacturer)
Letter	Description					
A	Existing Collins unit; controls entire approach with a command signal into the "altitude hold" mode	• Implements a new set of control laws • Requires sensor (CADC, DME, altimeter) modification	None	Required for complete approach, especially new hardware and sensors	Must prove that tracking meets Advisory Circular criteria throughout approach	• Approximately 80 approaches per aircraft type • Demonstrate performance to lower weather minima • Demonstrate system failures during lower segment tracking
B	Same as A for upper segment; control transferred to "approach" mode after lower segment capture	• Requires change in autopilot logic • Requires sensor (CADC, DME, altimeter) modification	Same as existing autopilot	Required for upper segment and transition only; existing analysis used for lower segment	Must prove that lower segment tracking not affected by transition	• Approximately 30 approaches per aircraft type • Lower segment already certified; must demonstrate that transition does not affect lower segment performance
C	Entire approach controlled via a steering signal through the "approach" mode	Same as B	Same as B	Same as B	Same as B	Same as B



NOTE:

1. ━ 727 AUTOPILOT SIGNAL PATHS UTILIZED
2. AUTOPILOT REMAINS IN ALT HOLD MODE
3. ▶ G/S ENG LOGIC NOT UTILIZED

FIGURE 20.—SIMPLIFIED TWO-SEGMENT SYSTEM—CONFIGURATION A

required for operation below category II minimums. Design consideration must be given to minimizing tracking errors between channels and to including such items as equalization, confidence testing, and fault detection.

4.3.2 Alternate Configurations (B and C)

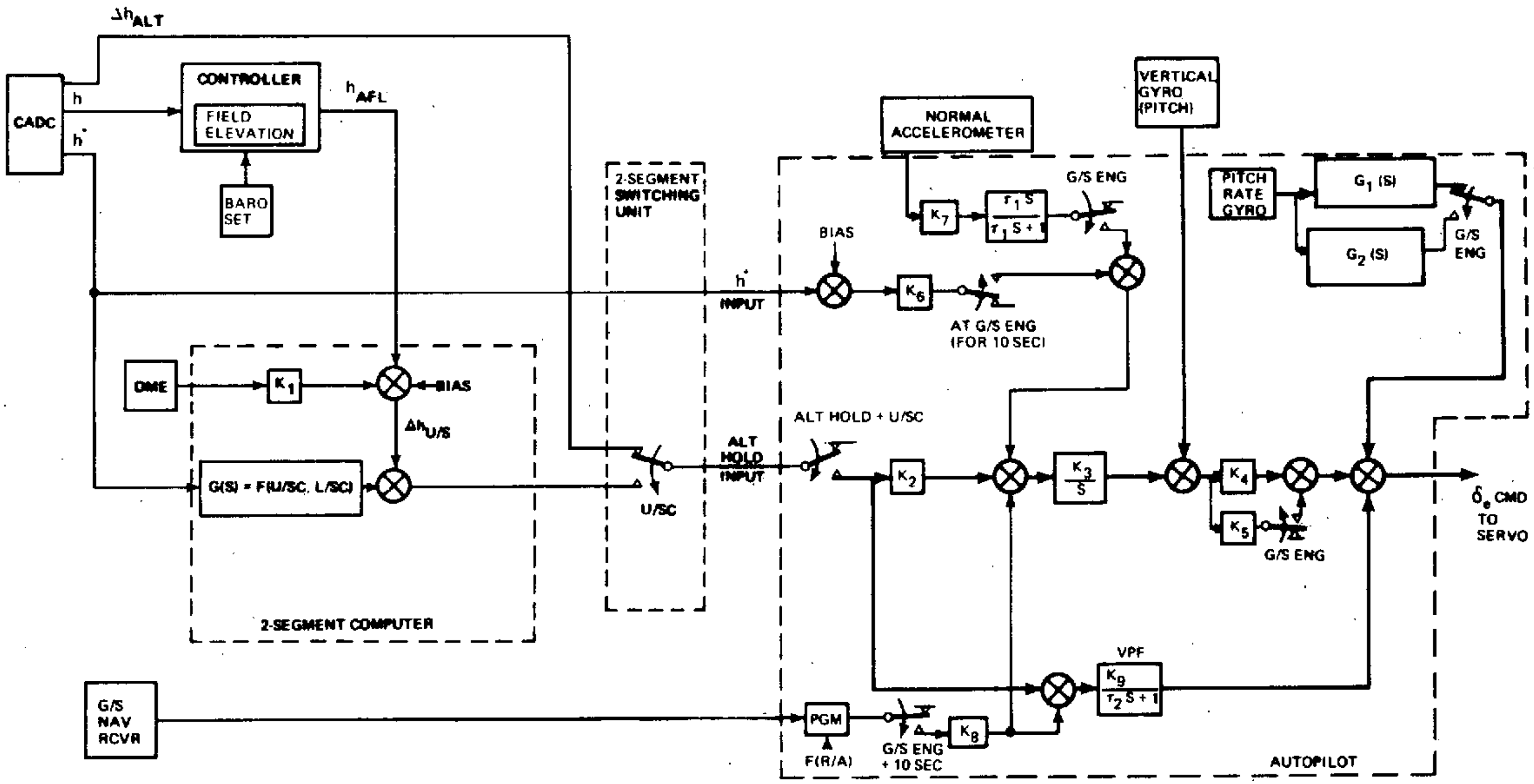
Two other techniques considered for mechanizing the two-segment approach hardware take advantage of the already certified approach modes and retain the autoland capability. Simplified block diagrams of these configurations (B and C) are presented as figures 21 and 22, respectively. Configuration B uses the Collins two-segment computer for upper-segment control and transition to the ILS through the "altitude hold" mode of the existing autopilot. However, upon reaching a prescribed ILS beam deviation, lower-segment control is transferred to the already certified approach mode. This transfer of control requires actuation of the several "glide slope engage" relays within the existing autopilot system at a low altitude.

Configuration C uses the existing approach mode during the entire two-segment approach and thus does not require autopilot mode switching during the transition. A steering signal generated within the two-segment computer (differs from the Collins unit) provides command information for upper-segment capture and track and for transition to the ILS. During the transition, the path reference signal source is switched from the two-segment computer to the normal ILS, while the autopilot remains in the approach mode. To use the approach mode on the upper segment, it is necessary to provide a signal (comparable to ILS beam capture) that will close the "glide slope engage" relays during upper-segment capture. Other logic signals may be required depending on the particular autopilot/flight director system characteristics.

4.4 ASSOCIATED EQUIPMENT

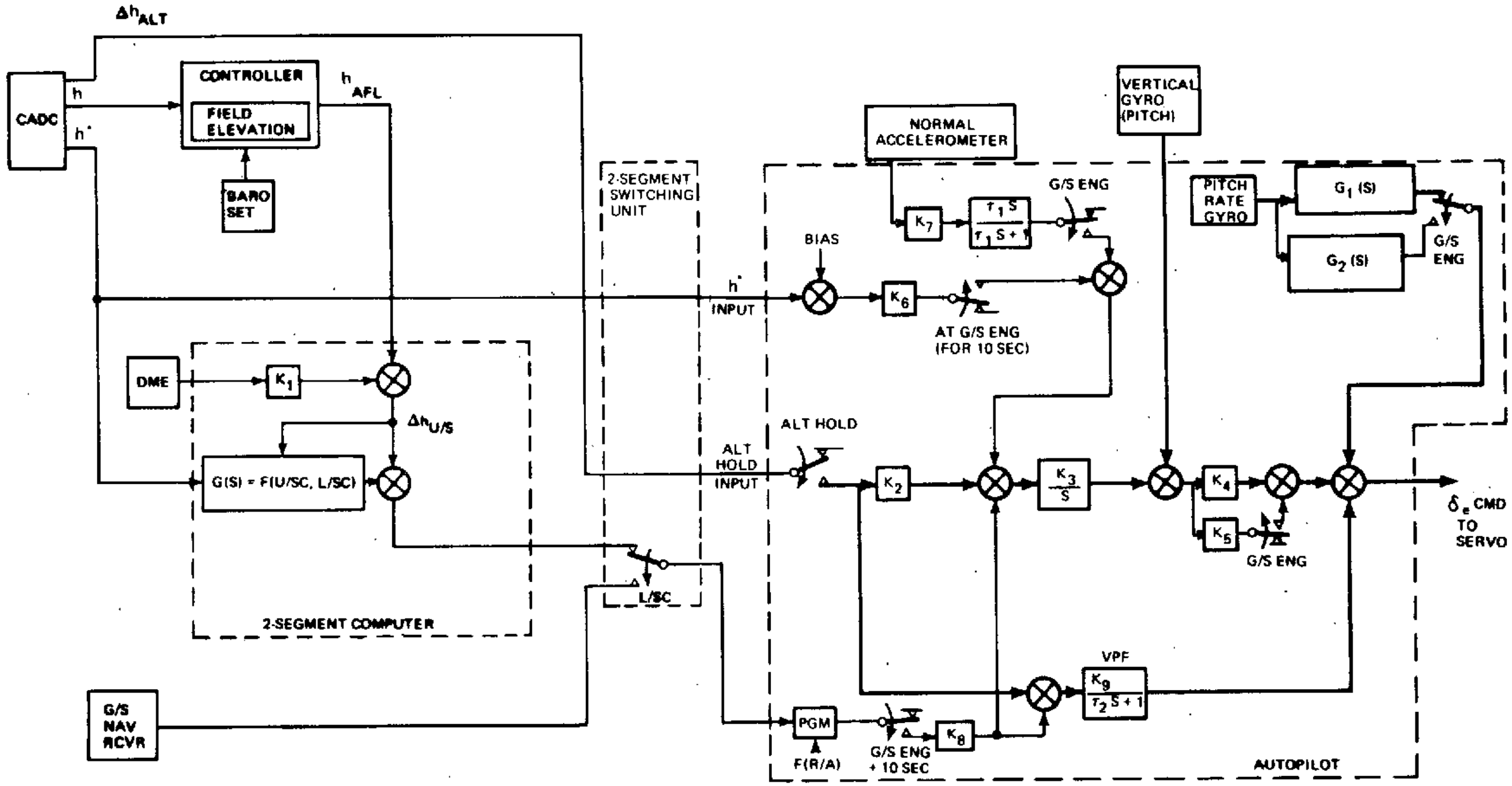
The following components are required for two-segment operation on a single-channel basis. In addition, this list contains their availability in Boeing aircraft.

VHF NAV RCVR	At least two are available in every aircraft; they are standardized on ARINC 547 characteristics.
Autopilot	Single-channel systems are used in a majority of the 707, 727, 737 fleet. Some 707s and 727s are provided with monitored or dual-channel systems. All 747s have at least dual-channel systems with, in some cases, triple channels.



NOTE:
1. G/S ENG. = LOWER SEGMENT CAPTURE (L/SC)

FIGURE 21.—SIMPLIFIED TWO-SEGMENT SYSTEM—CONFIGURATION B



NOTE:

1. G/S = UPPER SEGMENT CAPTURE (U/S C)

FIGURE 22.–SIMPLIFIED TWO-SEGMENT SYSTEM–CONFIGURATION C

Single-channel systems provide fail-safe operation down to category I or II minimums. Monitored and dual-channel systems provide fail-passive operation for autoland. Triple-channel systems provide for category IIIa fail-operational approaches.

"Altitude hold" mode and "approach" mode control laws are similar throughout the fleet. The 747 triple-channel approach equations are probably the most unique but also the most adaptable. Each individual system has its own peculiarities with respect to interfacing.

Autothrottle	Some of the fleet has provisions for or installation of the system; all 747s are equipped with autothrottles. Section 3.2.3 discusses the penalty, due to aft limit requirements, that will result from using current autothrottles during two-segment approaches.
Attitude source (vertical gyro or INS)	All aircraft are equipped with at least two attitude sources.
Radio altimeter	Majority of fleet has at least one system with provisions for a second. The autopilot and flight director systems use the radio altimeter output for gain programming, initiation of time-based programming, and logic trip points.
DME	Majority of domestic fleet uses two Collins 860E-2 DMEs, which are standardized on ARINC 521D. Boeing is in the process of standardizing new aircraft with ARINC 568, which provides the pulse-pair output needed for the Collins two-segment computer. A modification is available from Collins to provide the pulse-pair output on the 860E-2 DMEs.
CADC	Majority of the 727, 737, and 707 fleet uses either a single or dual Honeywell or Kollsman unit standardized on ARINC 545. The early 707s have either a KIFIS system or nothing at all. The 747 uses dual CADCs standardized on ARINC 565. Any modifications to the 747 CADC require an ARINC change. All of the CADC units have an ac synchro altitude output that is not compatible with the existing Collins unit.
Barometric altimeters	The Boeing fleet in general utilizes either a servopneumatic or electric barometric altimeter. Most have a barometric corrected altitude output that is

an ac signal. The altimeters on the 707, 727, and 737 have a barometrically corrected altitude output via a barometric potentiometer that is used mainly for cabin pressure control (both the captain's and first officer's units). The majority of the 747s have servopneumatic altimeters with a few customers having electric.

4.5 MODIFICATION REQUIREMENTS

Depending on the two-segment system configuration, several modifications will be required. These modifications, although not specifically defined, will occur within the autopilot and flight director computers in addition to the two-segment computer. Interfacing and aircraft wiring modifications will also be required to accommodate the new computers and customer variations. Development testing with the preproduction hardware will determine what modifications will be required for the production hardware. Since the transition to the 3° glide slope is slow and gentle, there appears to be no requirement for changes to the autopilot authority limit or auto-stab trim rates. The existing Collins unit requires a modification of the CADC and barometric altimeter to provide a linear altitude output. It would be more desirable for the Collins unit to be modified for acceptance of the present CADC signal. The addition of a second potentiometer to the barometric altimeter is dependent on available space and should be avoided.

4.6 CERTIFICATION PROGRAM

The NASA /Collins two-segment approach system was evaluated in West Coast passenger service by UAL. The Collins unit was installed in a 727-222 airplane, S/N 19913, equipped with an SP-50 autopilot. FAA approval for the installation was by supplemental type certificate (STC) SA 2679 WE, which permits use of the system during revenue flights on that particular aircraft to category I minimums. While approaches to category II minimums were not approved by the STC, it is expected that category II capability can be demonstrated by systems using this mechanization concept (configuration A).

Certification of additional installations could be obtained by the individual airlines using the STC method. An alternate method would be for the airframe manufacturer to obtain a revision to the basic type certificate. The main advantage is that the manufacturer could take into account the many system options and configurations in use by the airlines. The certification program should also consider possible limitations on the existing airplane certification resulting from the new operating procedures.

4.6.1 Existing Systems

Installation of the two-segment system will not affect existing certification for normal ILS approaches, provided the autopilot/flight director analyses are updated to show that safety has not been compromised. When the system is used to fly two-segment approaches, however, several possible limitations on current airplane certification must be considered. These include:

- FAR 25 Climb Gradients: Landing climb gradient certification under FAR 25 is based on the thrust attainable within 8 sec after the throttles have been advanced following a cutback to idle from approach power. When using the NASA/UAL two-segment approach procedure, transition to the normal ILS beam is completed above 500 ft (see sec. 3.4.4). Thus, it is expected that FAR 25 climb gradient certification will not be affected because normal approach power is established above decision altitudes, and the basic climb performance with reduced flap settings is better than with maximum flaps. However, if the two-segment procedure is interpreted by the FAA as reducing the "approach" power, then the landing climb gradient certification would be affected and redemonstration of engine acceleration would be required for the 707/727/737.

- Autothrottles: The trimmed power setting for the upper glide slope is below current autothrottle aft limits (for the procedures shown on figure 2). Consequently, current autothrottles cannot be certified for two-segment operation (unless shallower glide slopes and/or increased flap settings are used).

- Anti-Ice: The trimmed power setting for the upper glide slope is below currently published operating limits for the wing deice and engine inlet anti-icing systems. Certification of the two-segment approach system should be limited to nonicing conditions.

- Tailwinds: Tailwinds, particularly shearing tailwinds, require power reduction for airspeed control. Increasing the glide slope angle reduces the tailwind capability. As discussed in section 3.3.2, the upper glide slope could be reduced to provide adequate thrust margin (from idle) for speed control in a prescribed tailwind. This is not recommended, however, for several reasons:

    a) Wind profiles (velocity/shear) are not sufficiently well defined, in terms of probability of occurrence, to ensure an acceptable frequency of go-arounds.

    b) Decreasing the glide slope will reduce the noise benefits of the two-segment procedures for the vast majority of (nontailwind) approaches. A normal ILS could be flown in tailwinds.

c) The two-segment procedure requires operating the engines at low power settings where the engine acceleration is slower than for a normal approach. Tailwinds further reduce the power setting and require higher sink rates to track the glide slope. If the tailwind shear ceases abruptly, rapid engine acceleration (similar to that available during a normal approach) is required to avoid an underspeed.

Consequently, certification for two-segment operation in reported tailwind conditions is not recommended.

4.6.2 Two-segment System

The Collins unit does not use the existing autopilot/flight director approach mode. It is, in effect, a new approach mode and must be certified as such. The autopilot/flight director recertification procedure is described in the following sections.

4.6.2.1 Applicable Certification Criteria

System certification for lower weather minima operation is based on the requirements set forth in the FAA Advisory Circulars listed below.

Category I and II	AC 120-29
Category II	AC 20-31
Category II with autoland	AC 20-57A
Category IIIa	AC 120-28A

Advisory Circulary 120-29 sets forth the criteria for certifying the airborne system and ground facility to category I or II lower weather minimums. In addition, it presents such items as operational requirements, a maintenance program, systems performance requirements, and obstacle clearance criteria.

Advisory Circular 20-31 sets forth the criteria for certifying an airborne system to category II lower weather minimums. These same criteria are presented in AC 120-29, appendix 1. However, all Boeing category II certifications are based on AC 20-31 since the AC 120 series is primarily addressed to the air carrier.

Advisory Circular 20-57A sets forth the criteria for certifying a category II system with autoland capability. This includes performance requirements for the ILS facility and the touchdown dispersion requirements for the system. Also included is a description of the wind model to be used for simulation evaluation of the system.

Advisory Circular 120-28A sets forth the criteria for approval of category IIIa systems. It presents operational concepts, requirements for airports and ground facilities, pilot training and proficiency programs, operations procedures, maintenance programs, and the operations demonstration and data collection program. Airworthiness approval of the airborne system is based on the same requirements presented in AC 20-31 and AC 20-57A. The requirements for fault analyses and reliability studies are also an integral part of AC 120-28A.

Note: Standards and flight checks similar to those for category II or IIIa ILS facilities should be established for the DME stations to ensure reliability and accuracy.

4.6.2.2 Engineering Effort

Depending on the two-segment configuration, an engineering analysis must be conducted for the following items to provide an optimum and certifiable system.

- A simulation of the two-segment system for each aircraft model must be established for adequate evaluation of system performance and failure effects and to optimize the two-segment control laws.

- The interfacing required for compatibility between the system and the particular aircraft must be developed.

- Failure modes and effects analyses must be conducted to determine circuit changes and periodic test requirements.

- Test program procedures for laboratory testing, aircraft functional testing, and specific flight test conditions must be established.

4.6.2.3 Flight Test Program

The chosen configuration will require a development and certification test program. The certification will follow the guidelines established during previous certification programs. Table II denotes, in general, the type of certification program for each configuration. The program size is based on the particular configuration and the lower weather minima desired.

The program effort required for configuration A would include a performance evaluation, an extensive failure analysis, and a reliability analysis. Existing certification data used for previous performance substantiation would not be applicable to this configuration.

The program effort required for configurations B and C would include mainly an evaluation of the upper-segment control and transition to the lower segment. The evaluation would include performance aspects in addition to a failure analysis of the transition. Since the lower-segment control system is already certified for a particular lower weather minimum, no specific testing need be accomplished.

The number of approaches required for a test program is dependent on the particular configuration and on whether the program is conducted by the airplane manufacturer or by the individual airline. For example, if a category II certification is desired on a particular aircraft type with configuration A, the aircraft manufacturer could conduct a program of approximately 80 approaches using the engineering criteria, whereas an airline would be required (by AC 120-29) to conduct a minimum of 300. The 80 approaches include development and the opportunity to incorporate improvements and changes, while the 300 approaches are after a specific production system has been established.

The types of flight test conditions that would be required include a sampling of approaches in wind and variations in weight and center of gravity, etc., to evaluate system tracking ability and to substantiate computer results. Simulated faults, such as ramps and hardovers at various altitudes, would be required to evaluate system safety if the already certified conditions do not apply.

5.0 TASK III—PROGRAM REVIEW

This task involves review of the overall NASA two-segment approach evaluation program. The UAL and Collins progress reports were reviewed. The overall program appears to provide valuable data concerning the operational suitability of two-segment approaches. It is recommended that airspeed variations from V_{ref} and the number of times the maximum flap position was used to avoid overspeed/go-around be included in the flight evaluation documentation. These data, along with representative time histories, will be useful in substantiating that the desired approach speed margins are maintained and that the thrust margin ($\Delta\gamma = -1.2°$) used to define the upper glide slope angle for the Boeing fleet (fig. 2) is adequate when the procedure is used in an operational environment.

6.0 CONCLUSIONS AND RECOMMENDATIONS

1. The NASA/UAL approach procedures appear feasible for application to the Boeing fleet, with the maximum upper glide slopes and operational restrictions shown on figure 2. However, this study did not include simulation or flight test and did not consider nonstandard conditions, variations from nominal airframe/engine characteristics, or noise trades. Therefore, these procedures should be used as a starting point for further study or test programs but should not be interpreted as a final Boeing recommendation concerning procedures and systems to be introduced into airline service.

2. Normal ILS procedures should be retained for use in icing conditions or when tailwinds are reported.

3. With the exception of the autothrottles, autopilot, and flight director, existing airplane systems (e.g., flaps, trim, hydraulics, etc.) are compatible, without major modification, with the two-segment approach procedures defined on figure 2. The upper glide slope capability would be substantially reduced (due to the autothrottle aft limit) if compatibility with existing autothrottles is required. It should be noted that redemonstration of engine acceleration for FAR 25 climb gradient certification would be required for the 707/727/737 if the two-segment procedure results in a redefinition of "approach power" (see sec. 4.6).

4. The Collins avionics configuration (A) can be easily interfaced with the autopilot/flight director computers to provide single-channel category II capability, and the modifications required to the CADC and barometric altimeter systems could be minimized by redesign of the two-segment avionics input/output circuitry. However, Collins avionics configuration A is not compatible with autoland systems. The use of an alternate avionics configuration (e.g., configurations B or C) would be required to provide autoland capability. This may allow two-segment system commonality throughout the Boeing fleet and reduce the certification effort. Regardless of the avionics configuration, interfacing and wiring modifications will be required, which will differ between the various airplane models.

5. System implementation should include the development and certification of production hardware for each model, evaluation of DME stations to ensure that reliability and accuracy requirements are met, and possible additional certification requirements for ILS installations (for compatibility with the two-segment system). Regarding avionics certification, the airframe manufacturer could obtain a revision to the basic type certificate that covers, with a single test program, the wide variations in configurations among customers of a given model.

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