NASA CR-137907

APPLICATION OF NASA-ARC DELAYED FLAP APPROACH PROCEDURES TO BOEING 727 AIRPLANE

ROBERT L. ALLISON

February 1977

FINAL REPORT

Prepared under contract NAS2-8953

Boeing Commercial Airplane Company
P.O. Box 3707
Seattle, Washington 98124

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Ames Research Center
Moffitt Field, California

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-137907		

4. Title and Subtitle

Application of NASA-ARC Delayed Flap Approach Procedures to Boeing 727 Airplane

5. Report Date

February 1977

6. Performing Organization Code

7. Author(s)

Robert L. Allison

8. Performing Organization Report No.

D6-44380

9. Performing Organization Name and Address

Boeing Commercial Airplane Company
P.O. Box 3707
Seattle, Washington 98124

10. Work Unit No.

11. Contract or Grant No.

NAS 2-8953

12. Sponsoring Agency Name and Address

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, California 94035

13. Type of Report and Period Covered

Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

NASA Technical Monitor: Dr. John S. Bull, Guidance and Navigation Division

Boeing Program Manager: John P. Headlund, 707/727/737 Flight Controls Technology

16. Abstract

This report presents the results of an engineering and piloted simulator study to adapt a NASA-developed-approach energy management system (AEMS) concept to the B727. The AEMS concept was developed and flight tested on a CV-990 by the Ames Research Center (ARC). The purpose of the AEMS is to reduce approach time, fuel, and noise by providing computer-driven cockpit displays to assist the pilot in flying optimized delayed flap approach (DFA) procedures.

The Boeing study, reported herein, includes development of the DFA flight profiles, the AEMS airborne digital computer algorithm, and associated cockpit displays. Study ground rules and pertinent aerodynamic and noise trend data used in developing the flight profiles are presented. Approach time, fuel, and noise for the DFA are compared to several other types of procedures. The theory and operation of the AEMS, and compatibility with existing systems are discussed. Results of the piloted simulator studies, including recorded data for approaches flown with autopilot and with manual control are presented.

Detailed definition of the AEMS hardware and computer software requirements are presented separately in the preliminary avionic specification, NASA CR-137906. Estimated implementation costs are presented in NASA CR-151942.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
delayed flap approach energy management fuel conservation noise abatement operational procedures	Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified			

*For sale by the National Technical Information Service, Springfield, Virginia 22151

CONTENTS

Preceding page blank

APPLICATION OF NASA-ARC DELAYED FLAP APPROACH PROCEDURES TO BOEING 727 AIRPLANE

Robert L. Allison
Boeing Commercial Airplane Company

1.0 SUMMARY

Boeing has been participating in a NASA Ames Research Center (ARC) program to develop an approach energy management system (AEMS) concept and associated delayed flap approach (DFA) procedures for the Boeing 727. The purpose of the procedures is to reduce approach time, fuel, and community noise during routine airline operation. The AEMS consists of an airborne digital computer and cockpit displays that indicate when to manually set the flaps, gear, and throttles to follow the desired DFA profile. Configuration management rather than throttle modulation is used to control speed during the deceleration phase. A DME ground station collocated with the VASI or ILS glide slope is required.

The AEMS concept was developed and flight tested by the ARC on a CV-990. The objectives of the Boeing study were to adapt the NASA concept to the 727; to provide data regarding the time, fuel, and noise benefits; to assess systems compatibility and aircrew workload; and to prepare a preliminary avionic specification. No hardware development or flight testing were involved.

Flight profiles were developed that provide substantial benefits with reasonable initial approach speeds and with minimum pitch attitude variations during the deceleration. The preferred 727 DFA flight profile for nonicing conditions begins in a clean configuration at 220 kn. However, flaps 2 and reduced speeds can be used with little reduction in benefits, and the AEMS will adjust to any initial flap/speed combination that might be required in the operational environment. Thrust is reduced to near idle at a point determined by the AEMS. Flaps, gear, and thrust are sequenced as indicated by the displays to stabilize at a target altitude selected by the pilot. The AEMS compensates for wind and other operational variables to consistently hit the target. Minimum stabilization heights of 152 m (500 ft) for VFR conditions and 305 m (1000 ft) for IFR conditions are considered realistic.

Approach time, fuel, and noise were computed for several types of procedures in still air, headwind, and tailwind conditions. Relative to current ATA airline procedures, the DFA procedure for still air, VFR conditions reduces approach time by 2 min, fuel by 1420 N (320 lb) or more, and centerline noise (prior to the stabilization point) by 10 EPNdB untreated nacelles, 6 EPNdB for quiet nacelles. The reduction in the 90 EPNdB ground-level-noise contour is comparable to that provided by quiet nacelles.

With the 152-m (500-ft) stabilization altitude, pilot comments indicate the workload is higher than for current ILS procedures but reasonable, being comparable to an IFR non-precision approach. Glide slope and speed control were acceptable, and the landing check-list was completed above 152 m (500 ft).

The procedures are compatible with current systems. No modifications would be required to the current autopilot or flight director, except for installation of a fast/slow indicator. Current autopilot trim motor rates are adequate. Compatibility with icing conditions is provided by automatically selecting alternate flight profiles using higher power settings ($N_1 \geq 55\%$) when the inlet ANTI-ICE switch is activated. The profile compensates for wind velocity (computed onboard using DME ground speed) so there need be no operational restrictions on usage in tailwinds.

Assuming the required DME ground stations will be installed, the AEMS concept appears practical for application to the 727. However, no conclusions can be drawn by Boeing regarding acceptability to airlines for routine operational use. The data provided by this study can be used to assess the benefits and to obtain a preliminary estimate of the possible impact on pilot workload and air traffic control (ATC) procedures. Cost estimates for the avionics and ground facilities are reported separately.

If further development of the concept appears warranted, close coordination with ATC, the FAA, and the airlines, including simulator evaluations by airline pilots early in the program, is recommended. The algorithm should be modified to incorporate nonstandard day provisions and other improvements not included in this conceptual study. A complete detailed design cycle with airline and avionics vendor participation would be required prior to building flight hardware. Alternative mechanization approaches, and safety aspects such as the need for redundancy, failure detection, or independent speed monitoring should be pursued at that time.

2.0 INTRODUCTION

NASA-ARC is investigating the application of an AEMS concept to jet transport aircraft in order to increase the fuel conservation and noise abatement benefits attainable from DFA procedures. The resultant procedures are similar, in principle, to the Air Transport Association (ATA) noise abatement approach procedures described by reference 1. The ATA procedures suggest remaining in a clean configuration as long as possible, delaying final landing flap extension until about 305 m (1000 ft) above field elevation, using the lowest permissible landing flap setting, and stabilizing the final approach at not less than 152 m (500 ft) above field elevation. By providing precision energy management guidance, including compensation for winds, the AEMS allows more of the approach to be flown in a low drag configuration while still allowing stabilization above 152 m (500 ft). The AEMS concept was developed by ARC for the NASA CV-990 research airplane (as described in ref. 2) and has been flight demonstrated to a number of airline and industry pilots.

The purpose of this NASA/Boeing study is to determine applicability of the CV-990 concept to the 727 for possible introduction into routine airline service. Specific study objectives were to:

- Develop flight profiles, airborne computer algorithm, and cockpit display concepts for the 727 using the NASA CV-990 AEMS as a baseline
- Determine the time, fuel, and noise benefits
- Evaluate systems compatibility and Boeing pilot acceptance considering performance, crew workload, and safety
- Provide a preliminary avionic specification

The contract tasks are outlined in table 1. The work consisted of engineering analyses and fixed-base simulator studies with consideration limited to nominal 727-200/JT8D-9 characteristics (i.e., no system tolerances) for standard days only. Although this Boeing study program did not include flight testing, preliminary qualitative checks of the flight profiles were obtained on a no-cost, noninterference basis during other scheduled test flights.

Because this was a very austere program a feasibility study approach was adopted. The intent was to provide the scoping level information needed to determine whether further, more detailed development is warranted. Although there are a number of ways to implement the AEMS concept on the 727, time and budget constraints required that only one be selected for study. The selected concept was implemented on the simulator and developed only to the extent necessary to provide a representative working system suitable for evaluating flight profiles, pilot workload, fuel/noise benefits, and systems compatibility (autopilot, etc.). There was no time to investigate alternate concepts, to resolve detailed design questions, or to fully develop the computer logic necessary to cope with all situations that might occur during operational use.

Table 1.—Contract Tasks

1.	Develop 727 Engineering simulation at Boeing • Complete six DOF low-speed model, flaps 0 → 30 • Pitch and roll flight director/autopilot • Engine dynamics and fuel flow • Centerline noise—untreated and QN
2.	Validate simulation against flight data
3.	Develop flight profiles and computer algorithm • Criteria • Trend data (attitude/drag/noise) and computed profiles • FCT minicomputer (NOVA) development of algorithm • Simulator—EAI-8400 and VARIAN
4.	Engineering and pilot evaluation • Definition of current procedures • Fuel/noise comparisons • Hardware implementation concept • Simulation—safety, workload, FD/AP compatibility
5.	Specification • Computer • Displays

A majority of the contract time and effort went into the development phase, first to develop the basic airplane simulation and the AEMS algorithm concept, and then to implement and further develop the algorithm on the simulator. Consequently, the evaluation phase was quite limited and was oriented toward assuring that there were no major problem areas of a conceptual nature rather than evaluating hardware design details. Heavy reliance was placed on pilot and engineering judgment.

The preliminary AEMS avionic specification defines a baseline system for use in obtaining preliminary estimates of hardware implementation costs, and serves as a reference for further discussion and development. It should not, however, be interpreted as a final production specification for airline retrofit. A complete detailed design and evaluation cycle, involving the airlines and the avionic vendor, would be required before releasing such a specification.

3.0 SYMBOLS AND ABBREVIATIONS

ADI	attitude director indicator
AEMS	approach energy management system
AFCS	automatic flight control system
AGL	above ground level
ALPA	Airline Pilot's Association
AP	autopilot
APP	approach
ARB	Air Registration Board
ARC	Ames Research Center
ARINC	Aeronautical Radio, Incorporated (electronic equipment standards)
ATA	Air Transport Association
ATC	air traffic conrol
ATR	Austin Trumbull Radio (ARINC designation for electronic case sizes per ARINC spec 404A)
AVG	average
CADC	central air data computer
C_D	drag coefficient
c.g.	center of gravity
C_L	lift coefficient
D	drag
deg	degree
DFA	delayed flap approach
DME	distance measuring equipment
DOF	degrees of freedom
dot	GSE index mark on ADI
dV_G/dt	derivative of groundspeed with respect to time (longitudinal acceleration)
dV_G/dx	derivative of groundspeed with respect to distance
EAI-8400	computer used for piloted simulation
EPNdB	effective perceived noise, decibels
EPNL	effective perceived noise level
EPR	engine pressure ratio
FAA	Federal Aviation Administration
FAR	Federal Air Regulation

FCT	Boeing Flight Controls Technology Staff
FD/AP	Flight Director/Autopilot
F_n	net thrust
FORTRAN	computer language
FSAA	flight simulator for advanced aircraft (at ARC)
ft	feet
g	gravity
GS	glide slope
GSE	glide slope error (angular displacement from GS)
GW	gross weight, landing gross weight
h	altitude above field elevation
h_{IC}	initial value of altitude used in profile prediction
h_{min}	target altitude for stabilizing DFA
IC	initial conditions for profile calculations
IFR	instrument flight rules
ILS	instrument landing system
INOP	inoperative
IP	initial point—the desired point for generating the first flap command
IPGS	initial point glide slope
KCAS	knots, calibrated airspeed
KEAS	knots, equivalent airspeed
kn	knots
KTAS	knots, true airspeed
L	lift
lb	pound—the U.S. engineering unit for weight and force
LE	leading edge
m	meter
max	maximum
min	minimum, minute
N	newton—the SI unit for force (Throughout this document, airplane and fuel weights (gravity forces) are expressed in N where 1 lb = 4.448 N.)
NASA	National Aeronautics and Space Administration
NAVAIDS	navigational aids
nmi	nautical mile
NOVA	computer used for AEMS algorithm development

N_1	engine compressor speed (low pressure stages)
OM	outer marker
OPS	operations
QN	quiet nacelle
ref.	reference
rms	root mean square
RNAV	area navigation
RTAC	NASA Research and Technology Advisory Council
s	second
std	standard
V	speed
VARIAN	minicomputer used for AEMS algorithm development
VASI	visual approach slope indicator
VFR	visual flight rules
V_{CAS}	calibrated airspeed
V_E	equivalent airspeed
V_{final}	final approach speed
V_G	groundspeed
V_{IC}	initial value of speed for profile prediction
V_{MO}	maximum operating speed
$V_{placard}$	flap placard speed
V_{ref}	reference approach speed(1.3 V)
$V_{ref\,30}$	V_{ref} for flaps 30
V_T	true airspeed
$V_{W_{ref}}$	reference windspeed at tower height
V_W	windspeed; varies with altitude
X	horizontal distance from touchdown
X_{final}	target distance for stabilizing approach—derived within the computer from the pilot input h_{min}
X_{IC}	initial value of X for X - V profile prediction
$\Delta\theta$	pitch attitude variation
Δh	attitude deviation from GS—used in energy compensation
γ	flightpath angle
γ_{GS}	glide slope angle
γ_2	flightpath angle prior to GS capture

δ	atmospheric pressure ratio
θ	pitch attitude
σ_u	longitudinal turbulence rms velocity
σ_w	vertical turbulence rms velocity

4.0 CONCEPT

4.1 OVERVIEW

The concept of using the AEMS to assist the pilot in flying delayed flap approaches is outlined in figure 1.

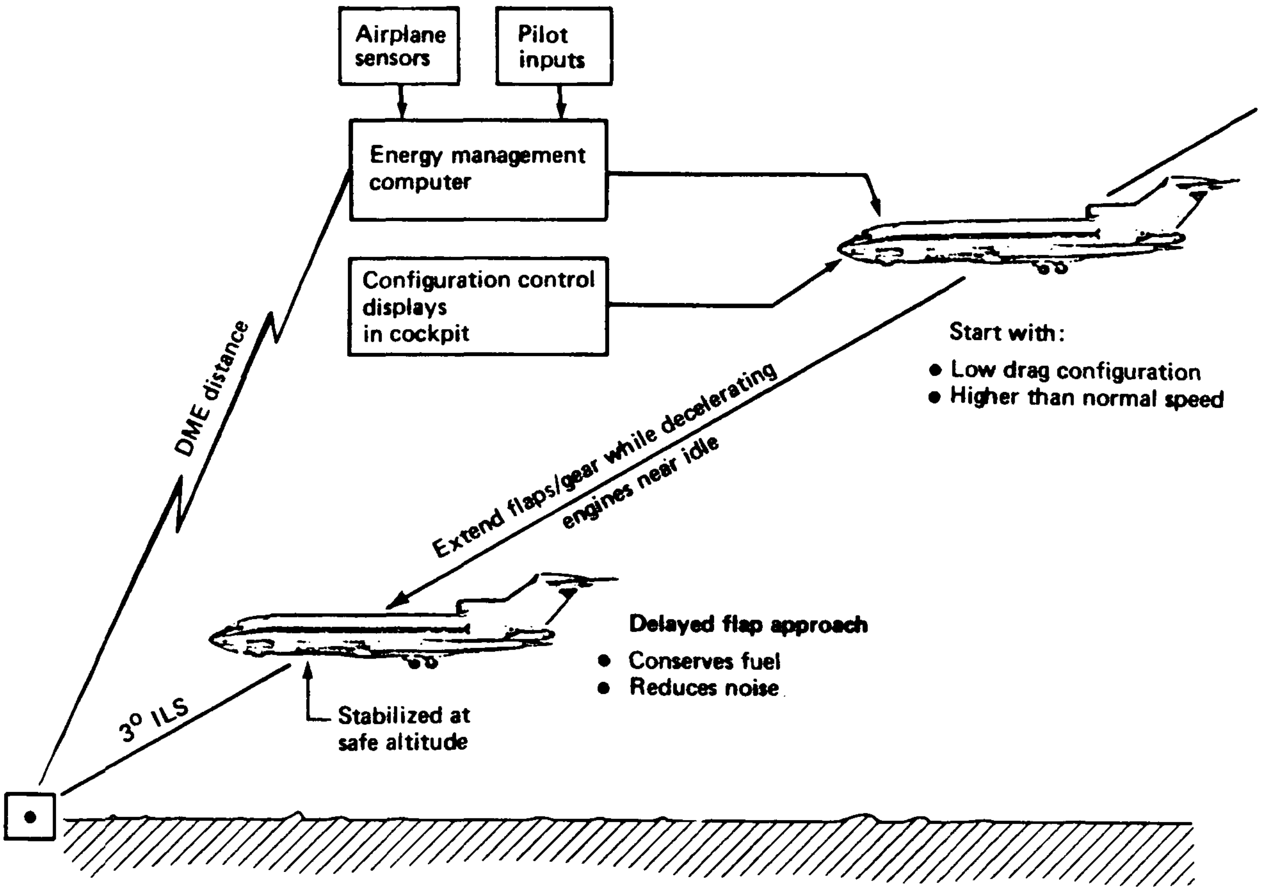


Figure 1.—727 AEMS Concept

4.1.1 PROCEDURE

The initial approach is flown in a low drag configuration at a speed considerably higher than the final approach speed. At the appropriate time, power is reduced to idle[1] and the flaps and gear are extended while decelerating to the final approach speed. The throttles are partially advanced to initiate engine acceleration prior to selecting final approach flaps and are further advanced to normal approach power as the final approach speed is reached. The configuration and power changes are scheduled so as to stabilize in the landing configuration at a target altitude above 152 m (500 ft), selected by the pilot. The remainder of the approach is conventional.

4.1.2 PURPOSE OF THE AEMS

Procedures of this type could be flown by experienced pilots using rule-of-thumb techniques that would not require additional equipment. However, the target altitude for stabilizing the approach would have to be higher to allow a margin for expected deviations. These deviations would result from the lack of precise range information in the cockpit and from the many operational variables such as wind, weight, initial approach speeds, glide slope (GS) capture altitudes, etc. Without energy management guidance, it would be impractical to expect a pilot to consistently hit a target altitude while following an optimized deceleration schedule in an operational environment. The purpose of the AEMS is to provide the equipment needed to make it operationally practical to use optimized delayed flap approach procedures in routine airline service.

4.1.3 FUNCTIONAL DESCRIPTION

The system employs computer-driven cockpit displays to assist the pilot in following optimized speed schedules and in consistently stabilizing at a minimum target altitude. An annunciator panel indicates the proper time to set throttles, flaps, and gear, while a fast/slow indicator on the attitude director indicator (ADI) displays energy deviations relative to the desired flight profile. The aircrew set the throttles and extend flaps and gear manually. The airplane is controlled in the normal manner, except configuration changes rather than throttle inputs are used to modulate energy during the deceleration phase. The AEMS is strictly an advisory system which can be used, ignored, or turned off at the discretion of the pilot.

4.2 EQUIPMENT

The 727 AEMS resulting from this study includes the following avionic components, which are defined by reference 3.

- Digital computer and interface equipment
- Control panel
- Annunciator panel

A fast/slow indicator on the ADI is used as an energy monitor. Installation of the avionics requires additional parts and wiring which would be supplied in an airplane retrofit kit. In addition to the airborne equipment, operational use of the AEMS requires a flightpath reference (ILS, VASI, or other) with collocated DME ground station.

---

[1] *Idle power was used for this feasibility study, which considered only standard day conditions. An engine pressure ratio (EPR) setting slightly above idle would be used in an operational system.*

4.2.1 AVIONICS

The AEMS avionic components and the required airplane sensor inputs are indicated schematically in figure 2. The proposed locations for the cockpit displays and the physical arrangements of the control panel and annunciator panel are shown in figures 3 and 4. These locations and arrangements are as defined in the preliminary avionic specification prepared as part of this study. The final configuration for an airline installation could be tailored to meet individual airline requirements. Simulation cockpit displays used during delayed flap procedures development are described in section 6.4.2.

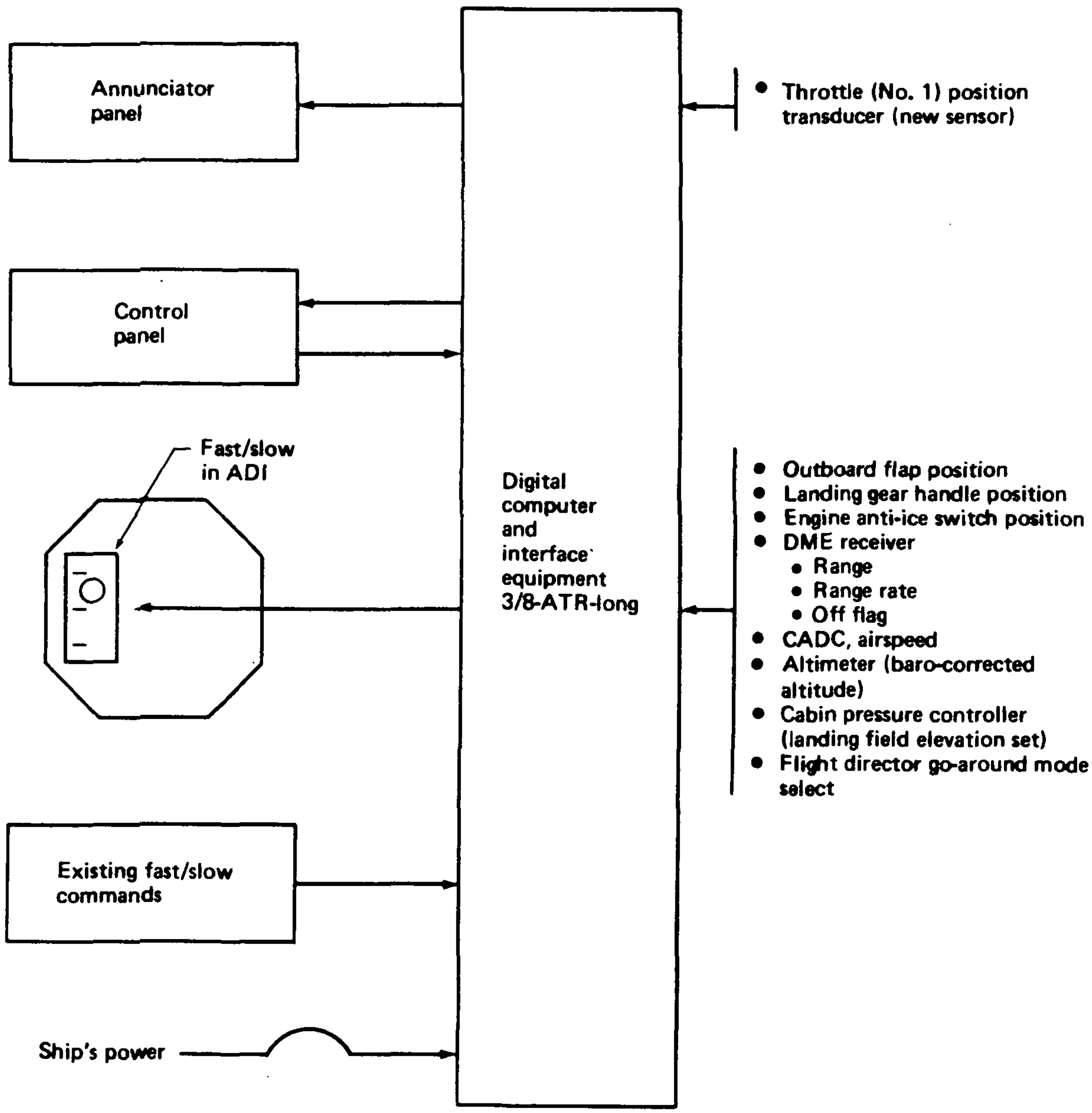


Figure 2.—727 AEMS Schematic

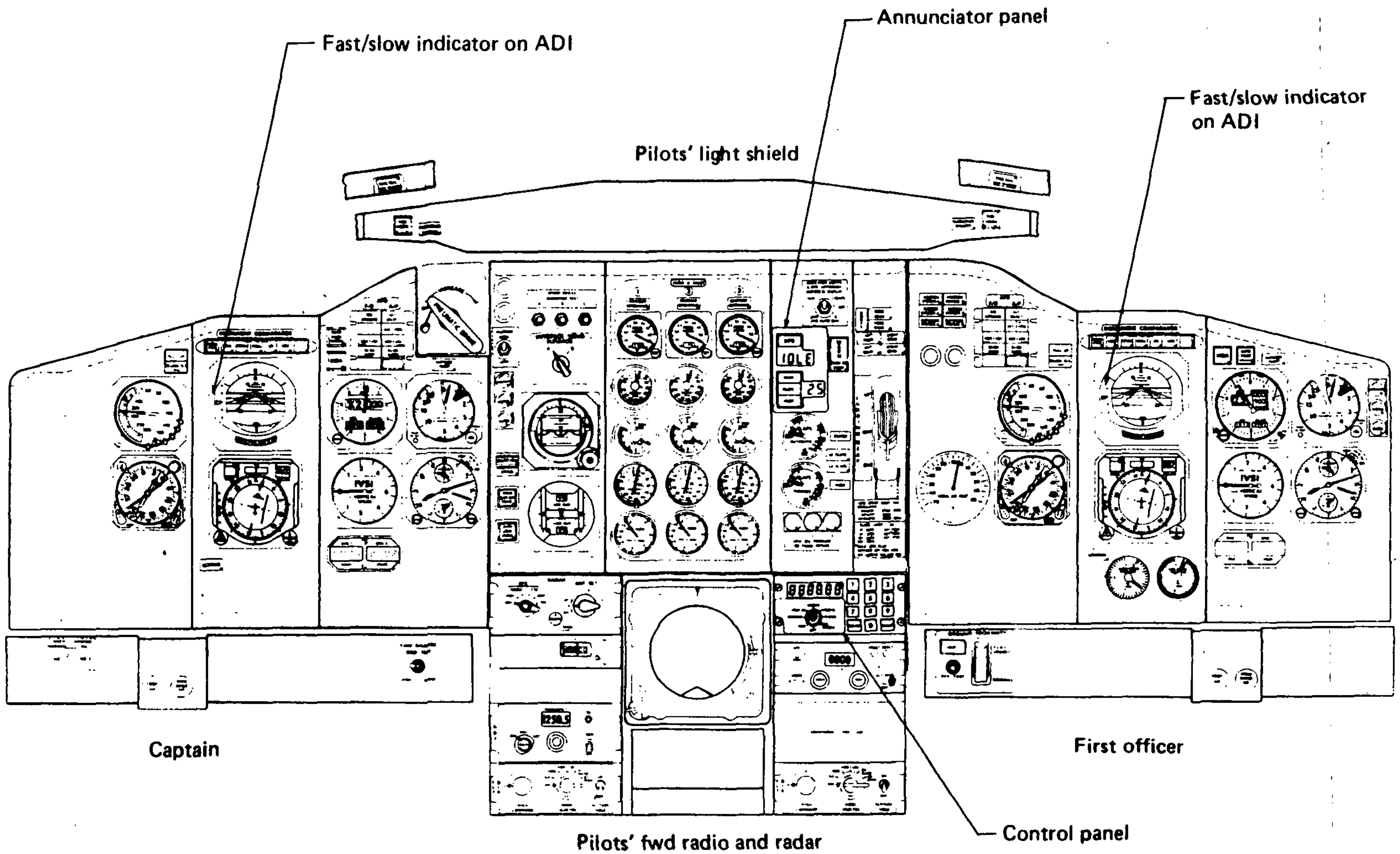
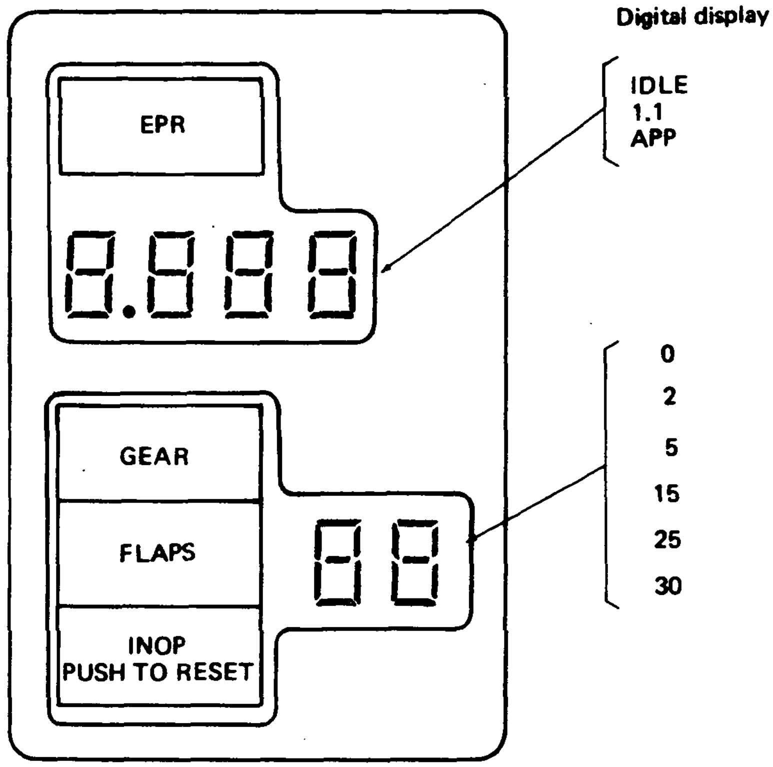
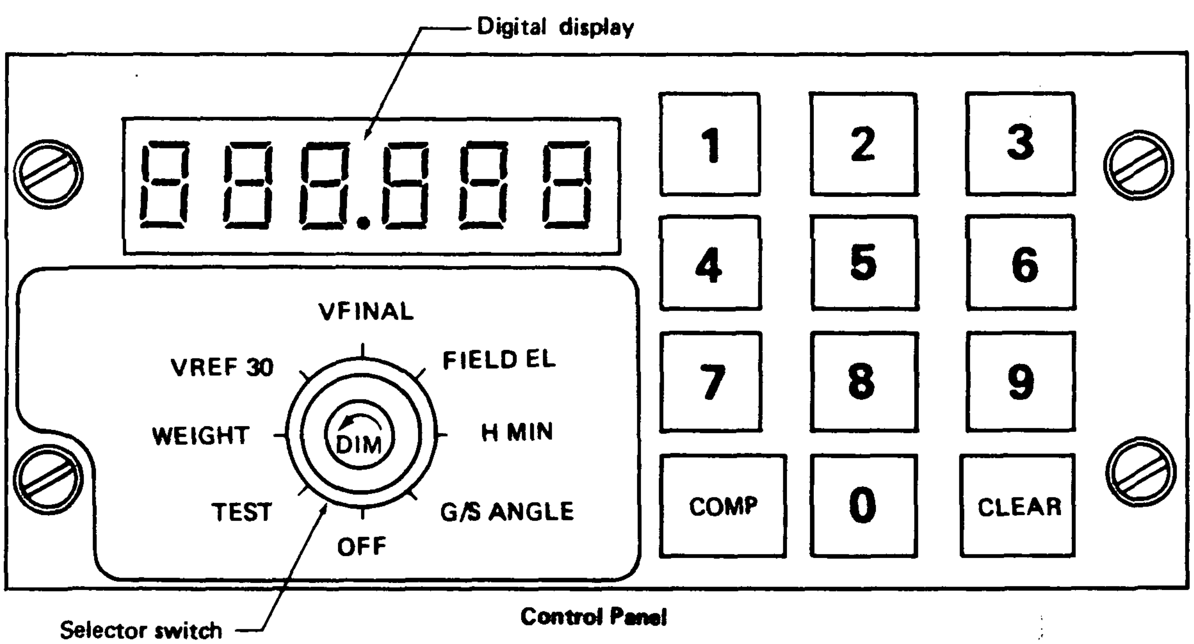


Figure 3.—727 AEMS Cockpit Displays



Annunciator Panel



Control Panel

Figure 4.—727 AEMS Annunciator and Control Panels

4.2.2 PATH GUIDANCE AND NAVIGATION

The AEMS avionics make no inputs to existing path guidance or navigation equipment. However, approach path guidance must be available to the pilot, and accurate values of groundspeed and distance from touchdown must be supplied continuously to the airborne computer.

The 727 AEMS concept is defined for use in airplanes not equipped with area navigation (RNAV) or inertial navigation systems. Consequently, a DME station, not currently available at most airports, is required adjacent to the aim point for each runway.

Although the computer algorithm contains energy compensation for deviations away from the intended glide slope, the pilot must maintain a nominal path reasonably close to the glide slope angle entered in the AEMS computer. The path reference can be provided by an ILS, a VASI, or any other system such as an airborne optical sight, which assists the pilot in maintaining a predetermined approach path.

4.3 COMPUTER ALGORITHM

The computer algorithm predicts speed versus distance profiles, which are continuously updated at least once per second, and uses the predicted profiles for generating the EPR, flap, and gear commands and the fast/slow indication. As indicated in figure 5, the computation and display concepts vary with approach phase.

4.3.1 PHASE I

In Phase I (initial approach), the computer first locates an initial point (IP) defined as the point at which the first flap command occurs on the desired deceleration profile. The computed profile follows a predetermined speed schedule for sequencing EPR, flaps, and gear and terminates at the altitude selected by the pilot for stabilizing in the landing configuration. The speed schedule is tailored to minimize pitch attitude variations on final approach and to maximize fuel/noise benefits. After locating the IP, the computer predicts a profile starting with the actual airplane position, speed, and configuration, and terminating at the IP distance. This portion of the prediction assumes that the throttles have just been retarded to idle and that the current flap configuration (e.g., clean) and idle power are maintained all the way to the IP with speed brakes retracted. The difference between the predicted speed and the desired speed at the IP is displayed on the fast/slow indicator. This assists the pilot in hitting the IP at the desired energy level. The EPR IDLE command is given on the annunciator panel when the predicted speed at the IP equals or exceeds the desired speed. The first flap command (normally FLAPS 2) is also generated using the Phase I logic.

4.3.2 PHASE II

After the first flap command has been generated, the computer switches to the Phase II logic. In Phase II, the complete profile is predicted starting with the actual airplane position,

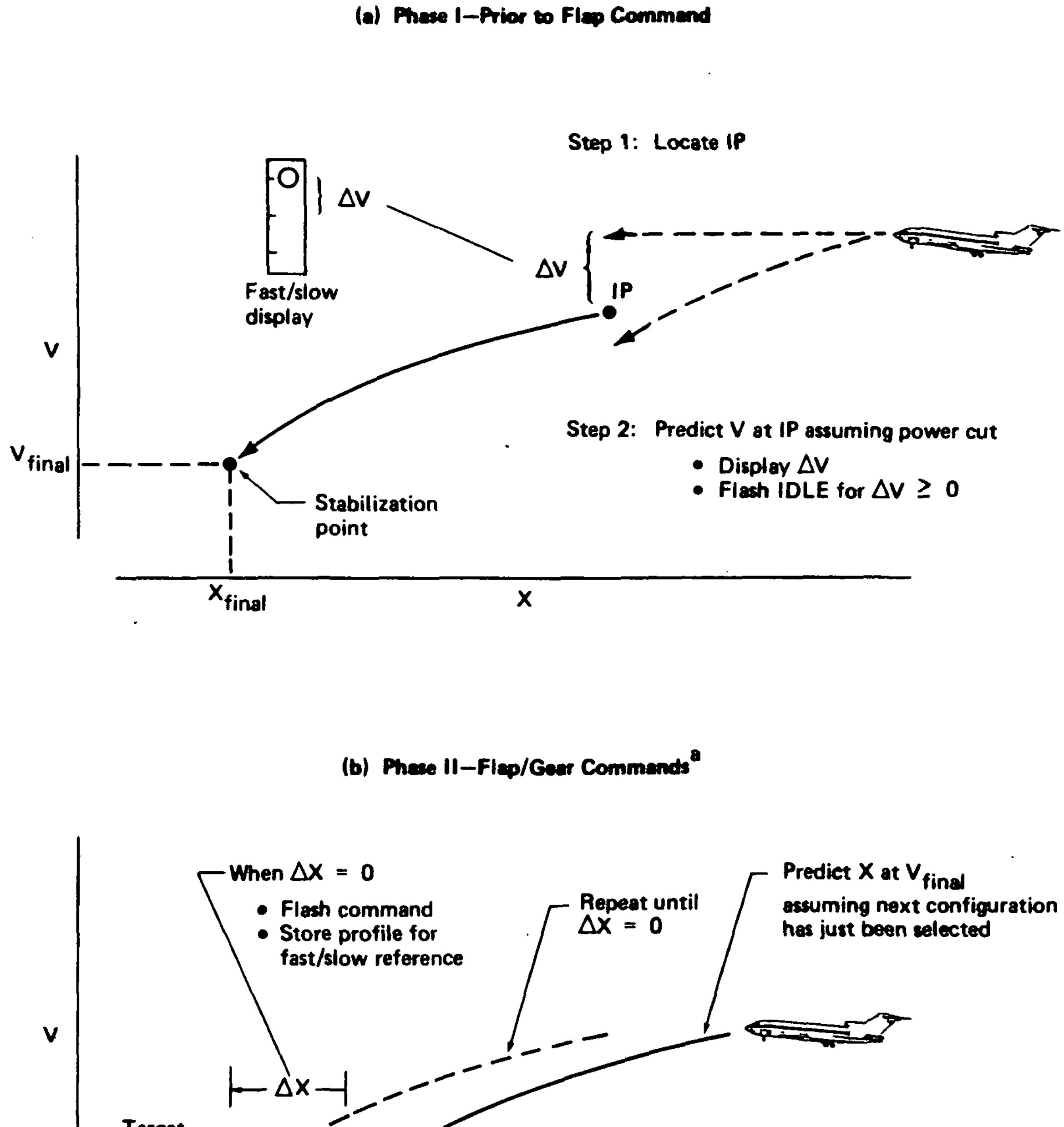


Figure 5.—Generation of Flap/Gear/Thrust Commands and Fast/Slow Display Using Onboard Computer Algorithm

speed, and configuration, and terminating at the final speed selected by the pilot. The prediction assumes that the next EPR, flap, or gear setting has just been selected. When the predicted profile terminates at or lower than the target altitude selected by the pilot, the assumed command is illuminated on the annunciator panel. At this instant, the predicted speed-versus-distance profile is stored in the computer memory for reference, and the computer begins predicting a new profile assuming the next EPR, flap or gear setting has just been selected. The fast/slow deviation is determined by entering the stored speed-versus-distance profile with the actual airplane distance (DME) to obtain the desired speed at that instant. After applying an energy correction to account for path deviations, the computer compares the actual speed to the (corrected) desired speed and displays the difference as an energy error on the fast/slow indicator. After the approach has been stabilized, the fast/slow display indicates energy deviations relative to the final approach speed and flight-path selected by the pilot.

4.3.3 PROFILE PREDICTION

The profile prediction is accomplished as outlined in figure 6. Deceleration is computed from the single-degree-of-freedom deceleration equation which assumes the airplane is in 1-g flight. The thrust and drag are computed from equations representing steady state engine thrust tables and trimmed drag polars. These equations are entered with EPR, flap, and gear settings that vary along the profile in accordance with stored speed schedules. Wind at flight altitude is derived from airspeed and DME groundspeed. The variation of wind along the computed profile is based on a typical shear model.

Numerical integration is used to compute the speed versus distance profile in small steps. Deceleration is integrated to obtain speed which is integrated to obtain distance. At each point along the profile, the updated airspeed is used to update the inputs (e.g., C_L) to the deceleration equation. The EPR, flaps, and gear are sequenced along the computed profile at the appropriate speeds. Thrust dynamics and flap/gear extension rates are represented in the prediction model.

4.3.4 ASSUMED PATH GEOMETRY

Prior to glide slope capture, the profiles are based on the two-segment path geometry indicated in figure 7. This geometry is used only for the speed-versus-distance predictions, and not for generating path guidance information. Since it is impossible to predict what path will actually be flown under operational conditions prior to glide slope capture, the geometry represents a guess as to what is likely to occur. If above the glide slope, it is assumed the glide slope will be intercepted at 305 m (1000 ft) of altitude. If below the glide slope, the assumed geometry depends on whether the airplane is above or below the IPGS (the point where the IP would be located if the entire deceleration occurred on the glide slope). Since the geometry is updated prior to each path prediction (at least once per second), the assumed geometry will tend to converge on the actual path being followed by the airplane.

(a) Basic Deceleration Equation

$$\frac{dV_G}{dt} = g\left[\frac{F_n}{W} - \frac{C_D}{C_L} - \gamma_{GS}\left(1 + \frac{V_W}{V_T}\right)\right]$$

- $\frac{dV_G}{dt}$: Deceleration relative to ground
- F_n: Stored[a] thrust tables
- W: Pilot input
- C_D: Stored drag[a] polars
- C_L: Computed along profile
- γ_{GS}: Pilot input
- V_W: Wind derived from ground speed (DME) and airspeed
- V_T: True airspeed computed along profile

[a]Profile prediction assumes EPR/flaps/gear sequenced per desired speed schedule.

(b) Speed/Distance Calculation

$$V_G = V_{G_{IC}} + \int \frac{dV_G}{dt}\,\Delta t$$

$$X = X_{IC} + \int V_G\,\Delta t$$

- $V_{G_{IC}}$, X_{IC}: from DME
- Δt: Variable time increment corresponding to 0.5-kn speed change

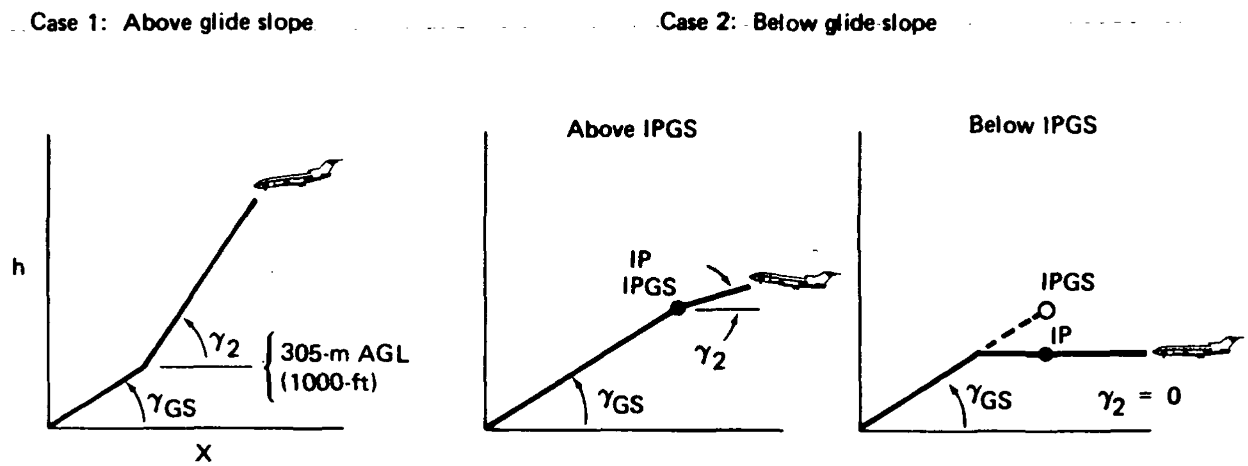
$$\Delta t = \frac{0.5}{\partial V/\partial t}$$

$$V_T = V_G - V_{wind}$$

- V_{wind}: ARB shear profile assumed for path predictions

Figure 6.—Profile Prediction Concept Using Onboard Computer

Initially Two-Segment Path



After GS Cap and FL2 Command—One-Segment Path + Energy Comp

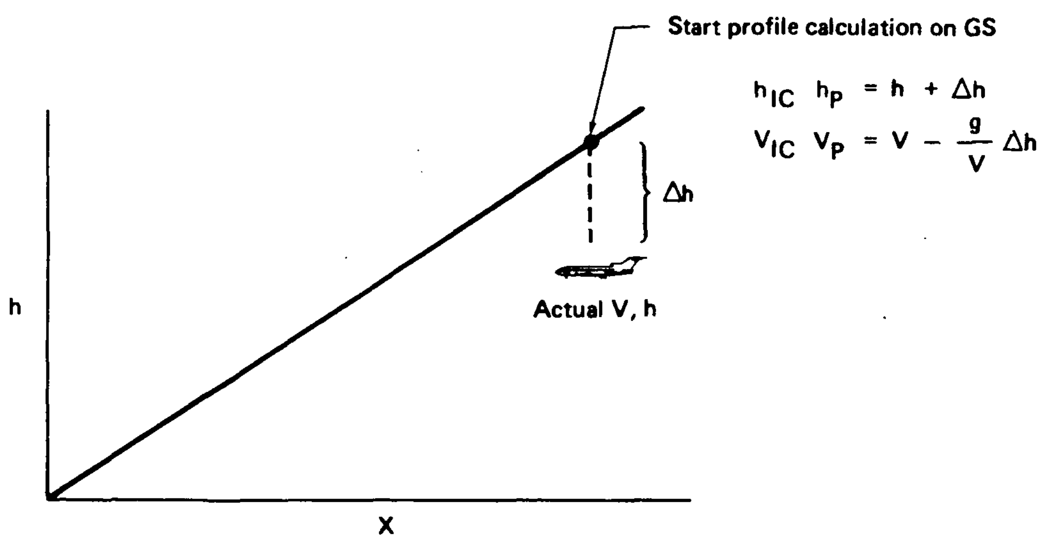


Figure 7.—Path Geometry Assumed for Profile Calculations—Not Used for Path Guidance

After the glide slope has been captured and flaps 2 commanded, the path is assumed to be the glide slope angle (γ_{GS}) entered into the computer by the pilot. The speed-versus-distance computation is initialized on the glide slope at the actual airplane distance, but with the speed adjusted to account for altitude deviations from the glide slope. This type of energy compensation (based on the phugoid approximation) was used by NASA in the CV-990 system.

4.4 OPERATION

As part of the descent checklist, the pilot sets up the AEMS computer using the selector switch and keyboard on the control panel (fig. 4). Actuating the TEST position checks operation of the displays. Turning the selector switch to the other positions displays default values which will be used by the computer if not modified by the pilot. An exception is the weight input that must be entered before each approach. Entry of the weight input places the computer in the standby mode.

After making the necessary inputs, the pilot leaves the computer in the standby mode until the runway DME station has been tuned and identified and a final approach course intercept angle of 30^{o} or less has been established. When energy management guidance is desired, the pilot actuates the COMPUTE switch.

Before displaying any guidance information, the computer first performs a confidence test to determine whether the operational interlocks have been cleared and that the system is functioning properly. If the confidence test is failed, the INOP light is illuminated on the annunciator panel, and a status message is displayed on the control panel to indicate the nature of the problem. If the confidence test is passed, the existing flap position will be displayed on the annunciator panel to indicate that the system is working. The aircrew then flies the approach using the displays to determine when to set power and to extend flaps and gear.

Normally, a slow indication will be displayed on the fast/slow indicator when the system is first turned on, indicating it is not yet time to cut power to idle. As the approach continues, the slow indication slowly approaches zero, at which point the EPR IDLE command is illuminated on the annunciator panel. If the pilot pulls the throttles to idle, the annunciator light will go out and the fast/slow indicator should remain centered. If the light is ignored, the indicator will continue to slowly move in the fast direction. When in a clean configuration, a fast indication beyond the first index mark on the fast/slow display indicates that airspeed will exceed the flap placard at the IP. In this case, idle power and speed brakes should be used if it is desired to continue the approach. When the indicator recenters from the fast direction, the speed brakes should be retracted so that the power can be left at idle.

As the approach progresses, commands will be generated on the annunciator panel in the following sequence: EPR IDLE, FLAPS 2, FLAPS 5, FLAPS 15, GEAR, FLAPS 25, EPR 1.1, FLAPS 30, EPR APP. The aircrew should set the throttles, flaps, and gear as soon as the annunciator light comes on. The appropriate light is extinguished when the AEMS sensors indicate that throttles have been set, flaps have started to move from the last position, or the gear is in transit. An exception is the digital display of flap position which remains illuminated at the last commanded setting until the final approach and landing flap position (FLAPS 30) is achieved. The throttle settings used to extinguish the EPR light are selected to give the approximate steady state EPR indicated. When advancing power, the pilot should readjust the throttles as required after the EPR has stabilized.

Prior to the FLAPS 2 command, the fast/slow indicator provides energy information based on predicted speed at the IP. After the FLAPS 2 command, the fast/slow display indicates deviations from a desired profile stored after the last flap or gear command. Since the stored profiles begin at existing flight conditions, the fast/slow indication will normally be centered after each flap or gear command. If the airplane energy level deviates from the stored profile, the fast/slow needle will indicate the deviation. Normally, the pilot need not take any corrective action other than to recheck that EPR, flaps, and gear are set properly. The command logic will advance or delay the next configuration change to get back on the energy schedule. A low energy situation would result in delaying the next flap or gear command, or could be corrected by adding power if necessary. If power is not added and energy gets too low to be compensated by delaying the next command, successive flap extensions will be commanded as speed approaches 1.3 V_S for the existing flap setting. In this case the approach will be stabilized at a higher altitude. The AEMS, when fully developed, should provide a clear-cut indication of a minimum energy limit, below which the pilot should add power. The present 727 AEMS computer algorithm is deficient in this regard, but this could be corrected in the next design cycle.

If an overspeed situation develops (after the first flap command) so that the approach cannot be stabilized at the target altitude using the above EPR, flap and gear sequence (even by extending flaps at the placard speeds), the INOP light will be flashed on the annunciator panel. A FAST message will also be displayed on the control panel, and the computer will automatically revert to the standby mode. The pilot may be able to complete an approach by extending the gear sooner. Logic for changing the gear sequence in overspeed situations could be added to the algorithm, if desired, in a subsequent development program.

To maximize the fuel and noise benefits, it is desirable to initiate the deceleration from a clean configuration. However, if it is necessary to extend flaps during the initial approach phase (e.g., ATC requests a speed reduction), the computer is programmed to reset itself to generate the remaining configuration commands in sequence. In other words, it provides guidance for optimizing as much of the approach as possible, starting from the existing conditions.

4.4.1 PILOT INPUTS

The pilot is required to enter WEIGHT for every approach. The computer determines VREF 30 from WEIGHT for display and check by the pilot. When the selector switch is turned to the other positions, a default value will be displayed as indicated in table 2. The

Table 2.—Pilot Inputs

Parameter	Definition	Default value
Weight	Airplane landing weight	—
VREF 30	1.3 V_s at flaps 30	For display only
VFINAL	Desired final approach speed	1.3 V_s + 5 kn
Field el	Runway elevation	As input from the cabin pressure controller
HMIN	Desired height above the runway for stabilizing at VFINAL with flaps 30	500 ft—the pilot can set a higher (but not a lower) value
GS angle	Glide slope angle	3°

default values will be used by the computer unless corrected by the pilot. When the airplane passes the threshold on a missed approach or touch-and-go landing, WEIGHT will be automatically reset to zero and the computer returned to the standby mode. The other parameters will be retained at the last approach values.

4.4.2 INTERLOCKS

Since the 727 AEMS can be used without an ILS glide slope, no beam interlocks are provided. The pilot actuates the COMPUTE switch manually when on a final approach course intercept heading. The computer will return to the standby mode and will not display the flap position when COMPUTE is actuated unless the following interlocks are cleared:

- DME signal reliable
- Range decreasing; i.e., inbound
- Range rate greater than 50 kn

The last item provides a gross check for reasonable airspeed, wind measurement, and intercept heading. For example, if the localizer were approached on a 90° intercept heading, the range rate interlock would prevent AEMS engagement until a shallower intercept angle was established.

4.4.3 SELF-TEST

The computer will perform limited self-tests before generating energy management information for display. However, it will not be possible to cover all possible sources of error, so the pilot will have to use his judgment to decide if the system is giving correct information on a given approach.

4.4.4 ICING CONDITIONS

When the engine anti-ice switch is turned on, the computer automatically selects an alternate schedule using EPR 1.2 rather than idle for the deceleration sequence. This maintains the engine compressor speed ($N_1 \geqslant 55\%$) required for operation of the anti-ice system. With this alternate schedule, the AEMS does not become operable until FLAPS 15 and gear have been extended. The resulting procedures would be quite similar to those currently flown by ATA airlines, and were not implemented in the AEMS computer for this feasibility study.

4.5 TYPICAL APPROACHES

The nominal profile computed by the onboard computer when locating the IP (FLAPS 2 command point) is shown in figure 8 for a typical landing weight of 578 000 N (130 000 lb). Operational speed limitations are shown for reference. The target altitude of 152 m (500 ft) is the minimum recommended for visual flight rules (VFR) operation. The pilot could select a higher altitude (e.g., for IFR) and/or a faster final approach speed (e.g., for headwinds and/or turbulence) if desired, and the profile would be adjusted accordingly.

A typical delayed flap approach profile recorded during a piloted simulator run is presented in figure 9, with the computed nominal profile from figure 8 overlayed for comparison. Although a glide slope capture altitude of 915 m (3000 ft) was used for this run, the profile computation is automatically adjusted to accommodate any capture altitude required for each individual approach as previously discussed (paragraph 4.3.4).

The same delayed flap procedure is compared in figure 10 to one of the current airline procedures used for the fuel/noise comparisons. The higher initial speed for the DFA procedure provides additional energy, relative to current airline procedures, which allows power to be reduced to idle for several miles. The AEMS concept uses drag modulation for energy control. Hence, the thrust modulation that is apparent for the current airline procedure is not necessary for the DFA approach until the target altitude is reached. This tends to offset the otherwise increased pilot workload, and would eliminate engine transient noise effects for part of the approach.

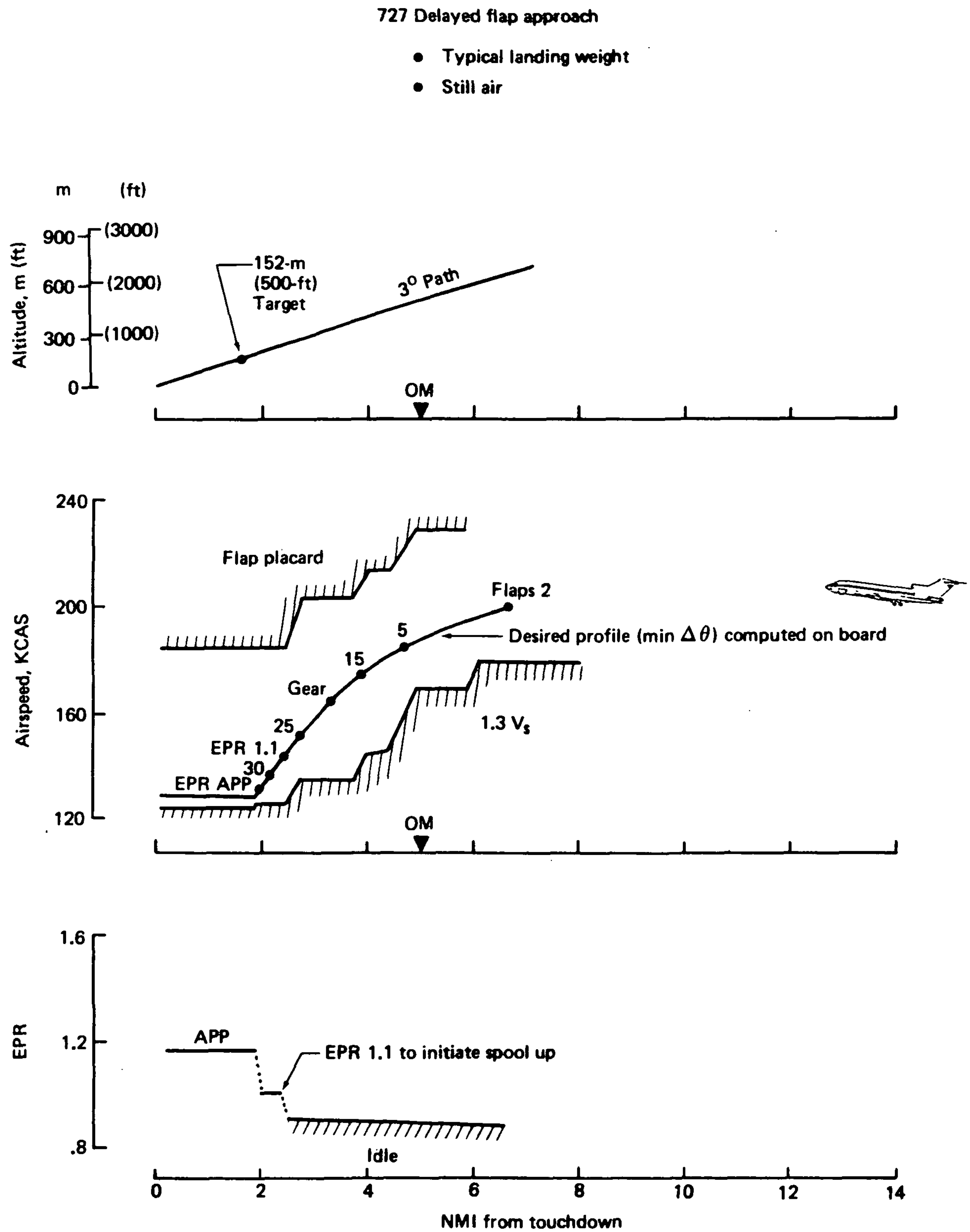


Figure 8.—Desired Deceleration Profile for 727 DFA

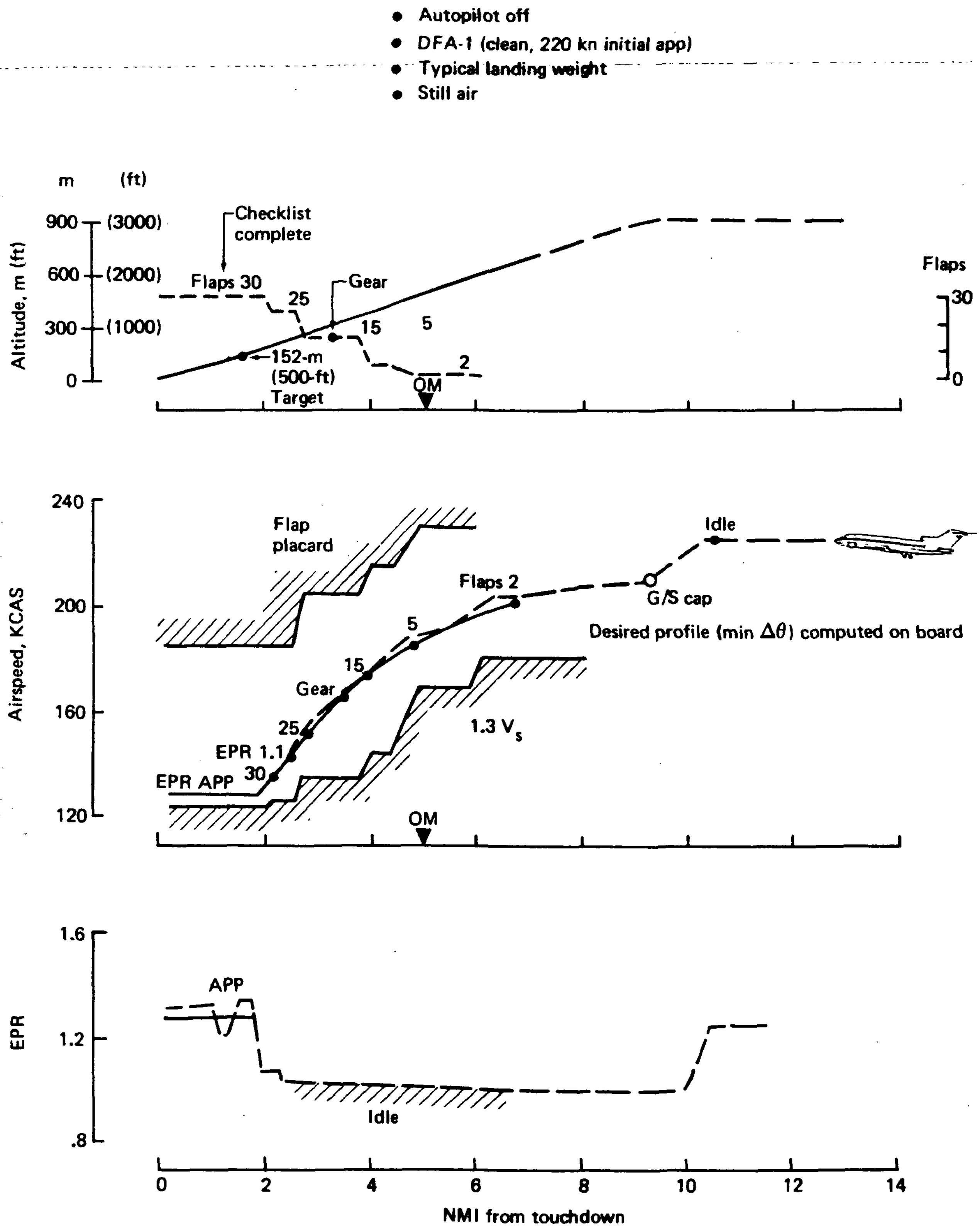


Figure 9.—Piloted Simulation Flight Profile for 727 DFA

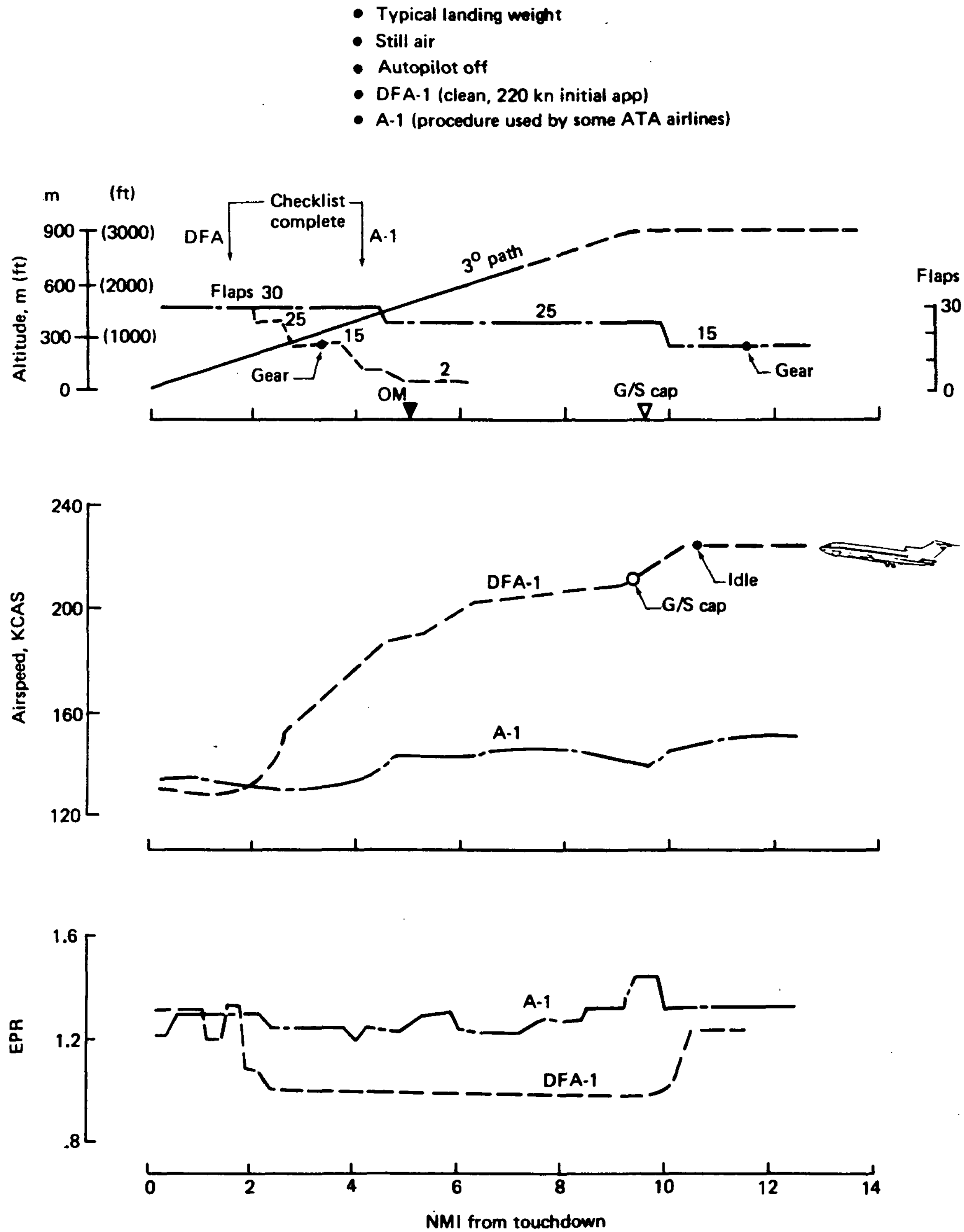


Figure 10.—Piloted Simulator Comparisons for DFA and Current Airline Procedures

5.0 BENEFITS

When jet transports were first introduced into airline service, stabilized approach procedures were adopted in the interest of safety and crew workload. With these procedures, the airplane was stabilized in the landing configuration shortly after glide slope capture. In that time period, glide slope intercept altitudes were typically 457 m (1500 ft) above the terrain. In response to the FAA "keep 'em high" program for reducing low altitude traffic congestion in terminal areas and the increased emphasis on noise abatement and fuel conservation in recent years, glide slope capture altitudes have been increased and various modifications to the stabilized approach procedures have been investigated. The primary reasons for developing the DFA procedures were to reduce approach fuel consumption and noise. By maintaining higher speeds until closer to the runway, the procedures also reduce total flight time.

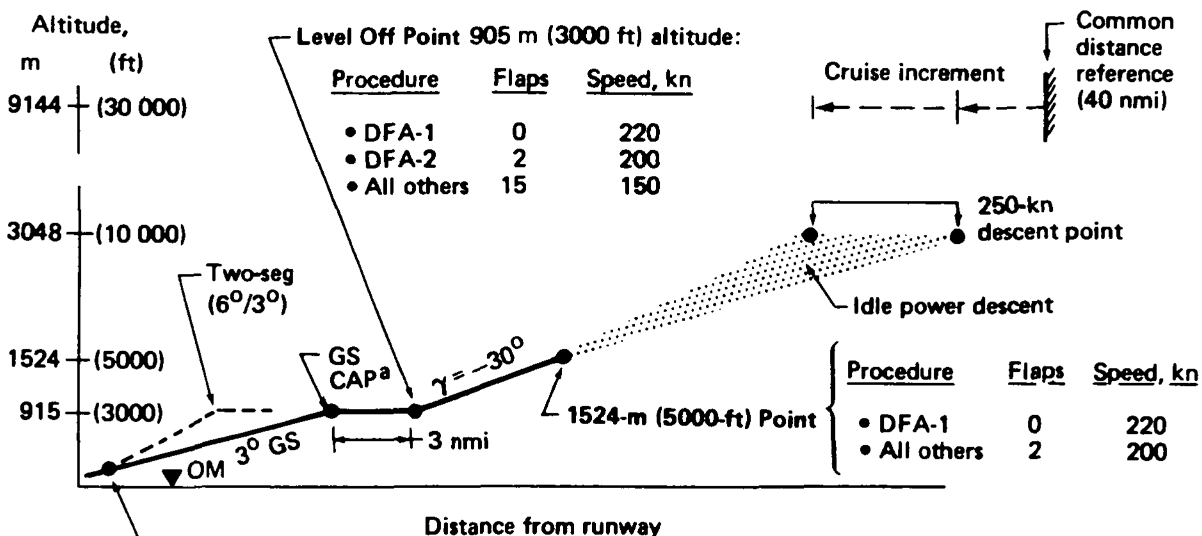
Evaluation of the potential benefits of the DFA procedure was an essential part of both the engineering and piloted simulator studies. Approach time, fuel, and noise were compared for a wide range of procedures and wind conditions, using an unpiloted digital computer routine that represents airplane performance along nominal preselected profiles. The unpiloted computer analyses provided an economical means to rapidly compare a large number of cases without introducing variations due to path tracking deviations, speed/thrust control, or pilot delays in making configuration changes. The unpiloted routine also facilitated starting the fuel comparisons at an altitude of 3048 m (10 000 ft), which would have been very time consuming on the piloted simulator. Piloted simulation data were then obtained for the engineering reference, A-1 and DFA-1 procedures for comparisons with the computed data to determine if any adjustments should be made to the unpiloted results to account for dynamic variations not represented in the unpiloted computer routine. Correlation between the two sets of data proved to be good, and therefore no adjustments were required.

Using the unpiloted computer routine, approach time, fuel, and noise were compared for the following procedures (illustrated in fig. 11 and further defined in paragraph 5.1):

- Engineering reference (Eng ref)
- Typical airline, type 1 (A-1)
- Typical airline, type 2 (A-2)
- Delayed flap, type 1 (DFA-1)
- Delayed flap, type 2 (DFA-2)
- Two segment (Two-seg)

- 727-200
- Flaps 30, landing

[a] Procedure	Intermediate approach configuration
• Eng ref	Stabilized at GS CAP, flaps 30, gear down
• A-1	Gear down, flaps 25, 140 kn at GS cap, flaps 30 at OM
• A-2	Gear up, flaps 15, 150 kn to 1 nmi from OM
• DFA-1, -2	See computed profiles
• Two-seg	Flaps 30, gear down at 6^{o} path capture



Final Approach, flaps 30, stabilized; speeds as follows:

Procedure	Final Approach (still air & tailwind)	Speed 30-kn headwind
• Eng ref, A-1, A-2	V_{ref} + 10	V_{ref} + 20
• DFA-1, DFA-2, Two-seg	V_{ref} + 5	V_{ref} + 20

Figure 11.—Flight Profiles for Benefits Comparisons

Data were computed for all of the procedures under the following conditions:

- Flaps 30 landing
- Average landing weight of 578 000-N (130 000-lb)
- Mid c.g.
- Standard day (except noise data for FAR 36 conditions)
- 3° ILS glide slope
- 915-m (3000-ft) glide slope intercept altitude
- 30-kn headwind, still air, 10-kn tailwind

The wind velocities are at 10-m (33-ft) tower height and increase with altitude (ARB shear profile). Data are shown for the two-segment procedure in still air and headwind conditions only since reference 4 recommends against use of the procedure in tailwinds.

Fuel and noise data were obtained from the piloted simulation runs for the Eng ref, A-1, and DFA-1 procedures to confirm the computed data.

5.1 PROCEDURES DEFINITIONS

5.1.1 TYPICAL AIRLINE PROCEDURES (A-1 AND A-2)

Before defining procedures for use in the benefits comparisons, a request for data was submitted to the ATA for transmittal to several major airlines. Detailed information was supplied by five airlines concerning typical speed/configuration/altitude/distance profiles for ILS approaches under VFR and IFR conditions. The principal difference between VFR and IFR procedures is that some airlines delay landing flap extension to a lower altitude for VFR; others use the same procedures for both. The airline data were reviewed in an attempt to define one typical procedure representative of all airlines for VFR operations. Because of variations between airlines, it was concluded that two general types of procedures should be shown. As defined for this study, the two types of procedures are identical except for the gear, flaps 25 and flaps 30 extension points, as follows:

Type	Gear/flaps 25	Flaps 30
A-1	At glide slope capture	At outer marker
A-2	1 nmi from outer marker	At 140 kn

These procedures are composites that do not exactly match the data submitted by any one airline. However, three of the five reported airline procedures are similar to A-1, while the other two are similar to A-2.

To provide a realistic comparison of fuel benefits, it was decided to include the terminal area descent phase as well as the final approach phase. The defined procedures begin at 3048-m (10 000-ft) altitude at the 250-kn maximum speed allowed by ATC. The descent to 1524 m (5000 ft) is made at idle power with a flightpath angle selected so as to pass through 1524 m (5000 ft) at 200 kn, at which point flaps 2 is selected.

The airline data indicated that an approximately constant descent angle is maintained from 1524 m (5000 ft) to capture the glide slope (from below) at a typical altitude of 915 m (3000 ft). To facilitate computations and simulator setup, a distinct level off at 915-m (3000-ft) altitude 3 nmi prior to glide slope intercept (about 12.5 nmi from touchdown) is shown for the defined procedure. Deceleration and flap sequencing during the descent from 1524 m (5000 ft) to 915 m (3000 ft) are defined to occur on a 3^{o} glide slope with flaps extended at the currently published approach maneuvering speeds and with power set so as to arrive at the level off point at flaps 15, 150 kn. Power is reset at the level off point to maintain flaps 15, 150 kn until approaching glide slope capture. With the A-1 procedure, gear and flaps 25 are extended during glide slope capture with flaps 30 delayed until outer marker (OM). With the A-2 procedure, the glide slope is captured in a gear up, flaps 15 configuration, with gear and flaps 25 extended 1 nmi from the outer marker, and flaps 30 selected at 140 kn. A final approach speed of V_{Ref} + 10 kn is defined for both procedures, as typical of routine airline practices for light wind conditions. For the 30-kn headwind case, V_{Ref} + 20 kn was used.

5.1.2 ENGINEERING REFERENCE PROCEDURE (ENG. REF.)

The engineering reference procedure is the same as the typical airline procedures, except the landing configuration and final approach speed are established during glide slope capture. This was the *stabilized approach* procedure formerly used with low glide slope capture altitudes. It is doubtful that any domestic airlines use this procedure with a 915-m (3000-ft) glide slope capture altitude. However, it is convenient as an engineering reference since a number of prior reports have shown noise data relative to such procedures. It is called an *engineering reference* procedure rather than a *stabilized approach* procedure because all current airline procedures comply with the stabilized approach concept in that they are stabilized at a safe altitude.

5.1.3 TWO-SEGMENT APPROACH (2-SEG)

The two-segment approach procedure is identical to the engineering reference procedure except that $6^{o}/3^{o}$ two-segment path geometry and final approach speeds defined by the NASA/UAL/Collins program are used. In computing data for the 30-kn headwind case, V_{Ref} + 20 kn was maintained on both the upper and lower segments.

The upper segment intercept altitude of 915 m (3000 ft) was selected to be the same as the ILS glide slope intercept altitude for the other procedures. It was assumed that ATC clearance restrictions determined the intercept altitude, and that these would be the same regardless of the final approach path geometry. The benefits of two-segment approaches relative to other types of procedures might vary as a function of the upper segment intercept altitude. However, this was not investigated.

Because of the two-segment path geometry, the final approach path intercept point is closer to the runway than for the other procedures. The 915-m (3000-ft) level off point and the 3048-m (10 000-ft) descent points are shifted accordingly.

5.1.4 DELAYED FLAP APPROACHES (DFA-1 AND DFA-2)

The two delayed flap procedures differ from each other only in the initial approach speed and configuration and the resulting difference in the power cut point. The DFA-2 procedure is the same as the typical airline procedures from 3048 m (10 000 ft) through 1524 m (5000 ft). However, 200 kn is then maintained with flaps 2 through glide slope capture. Power is cut to idle (on glide slope) when determined by the AEMS (varies with wind, weight, etc.) so as to decelerate and stabilize at the target altitude selected by the pilot.

The DFA-1 procedure maintains 220 kn (preferred) in a clean configuration through the level off at 915 m (3000 ft). Power is cut to idle sooner than for the DFA-1 procedure, and flaps 2 is selected at 200 kn. Thereafter, the approach is identical to DFA-2. Since the DFA-1 procedure requires less speed reduction during the descent from 3048 m (10 000 ft) to 1524 m (5000 ft), a slightly steeper descent angle is used. The 3048-m (10 000-ft) descent point is shifted accordingly.

The delayed flap approach speed is stabilized at the target altitude at V_{Ref} + 5 kn for still air or light wind conditions, and at V_{Ref} + 20 kn for the 30-kn headwind. A target altitude of 152 m (500 ft) was used as a baseline for comparing the DFA procedures against other procedures. In addition, the effects of variations in the target altitude also were computed for the DFA-1 procedures.

5.2 COMPUTED TIME AND FUEL COMPARISONS

The delayed flap approach procedures require a higher total airplane energy level on initial approach than the other procedures. To account for possible differences in the fuel burned prior to initial approach (in order to maintain the higher energy level) it was concluded that the most realistic reference point for computing fuel comparisons would be the 3048 m (10 000 ft) 250-kn descent point, adjusted to a common reference distance (40 nmi). While suitable for calculations, use of this reference point would be inconvenient for simulator and flight test evaluation. Therefore, data are also presented relative to other reference points along the profile.

The fuel consumption data in figure 12 and table 3 show the fuel required from the 250-kn descent point to the runway threshold, plus an additional increment computed at cruise conditions. The cruise increment makes up the difference in the descent and approach distance for the various procedures and wind conditions, so that all fuel comparisons are made for the same total ground distance of 40 nmi.

The effect on fuel consumption of parametric variations in the final approach stabilization target altitude is illustrated in figure 12 for the DFA-1 procedure in still air. The 152-m (500-ft) target altitude is used throughout this report when comparing the DFA procedures against other types of procedures. This is the minimum target altitude recommended for VFR conditions.

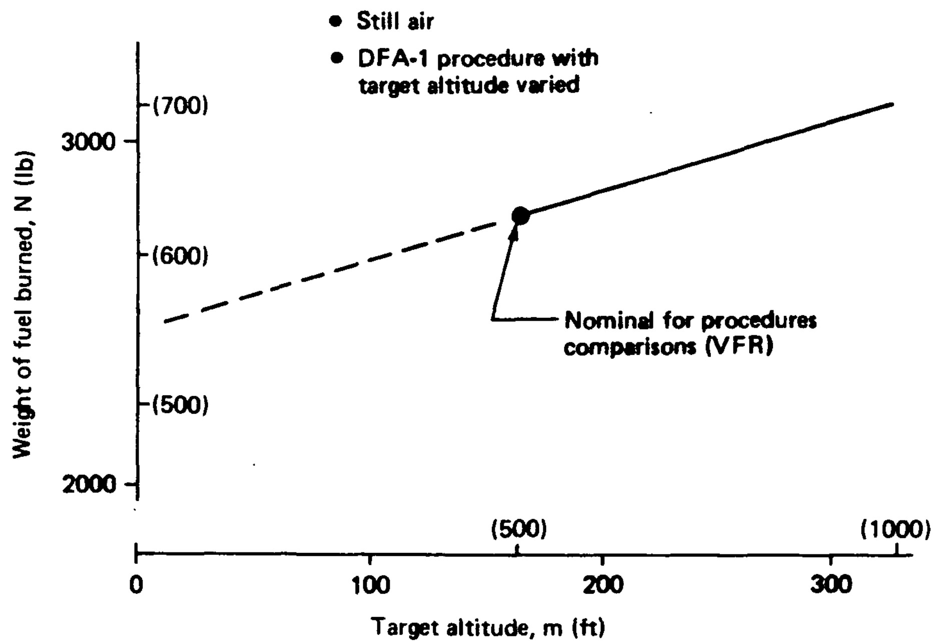


Figure 12.—Effect of Target Altitude On Fuel Burned

Elapsed time and fuel consumption for the various procedures in three wind conditions are compared in table 3. The delayed flap procedures require less time and fuel than any of the other procedures, particularly in strong headwinds. The AEMS delays initiation of flap sequencing in headwinds, so the cleaner configuration and associated higher speeds and lower power settings are maintained until closer to the runway.

Fuel comparisons are presented in table 4 relative to three other points along the defined 727 flight profiles. Approach time and fuel computed from the initial conditions specified by NASA ARC for comparison with their CV-990 flight data are presented in table 5. In computing data from the CV-990 reference, all procedures were initiated in a clean configuration with the same total energy, and all were allowed to decelerate in level flight at idle power until reaching the speed and configuration shown in figure 11 for level off at 915 m (3000 ft) prior to GS capture. Thereafter, the previously computed profiles were used.

Table 3.—Time and Fuel Comparisons from 250-kn Descent Point

- Data computed from 3048 m (10 000 ft) altitude, 250-kn point to threshold, with cruise increment to common (40-nmi) distance reference
- Wind given at 10-m (33-ft) tower height

Procedure		Weight of fuel burned		Elapsed time min:sec
		N	LB	
10-knot tailwind	Eng ref	4050	911	10:52
	A-1	3880	873	10:56
	A-2	3580	805	10:53
	DFA-1	2460	556	9:26
	DFA-2	2860	644	10:01
Still air	Eng ref	4700	1058	11:49
	A-1	4480	1009	11:55
	A-2	4150	934	11:52
	DFA-1	2725	614	9:58
	DFA-2	3210	723	10:35
	Two-Seg	3550	799	10:54
30-knot headwind	Eng ref	7700	1733	15:46
	A-1	7400	1662	15:45
	A-2	6910	1554	15:36
	DFA-1	3640	820	11:41
	DFA-2	4560	1029	12:45
	Two-Seg	5880	1322	14:00

Computed fuel profiles are shown in figure 13 for the various procedures in still air conditions. These data are useful in visualizing the effects of certain key features in the profile definition; e.g., stabilization height and level flight at 915 m (3000 ft).

The time and fuel benefits of the DFA-1 procedure relative to current ATA airline procedures (A-1 and A-2) and two-segment approach procedures are summarized in table 6. These estimated benefits are based on the data computed from the 250-kn descent point (table 3).

Table 4.—Fuel Comparisons for Alternative Reference Points

Note:

- Still air
- Computed along defined profile from reference point to threshold

Reference Point →	Weight of fuel burned from:					
	1524 m (5000 ft) descending		915 m (3000 ft) level off		915 m (3000 ft) GS capture	
Procedure	Newtons	Pounds	Newtons	Pounds	Newtons	Pounds
Eng ref	3720	839	3260	734	2520	569
A-1	3510	790	3040	685	2300	520
A-2	3170	714	2700	609	1970	444
DFA-1	1730	390	1350	305	1010	228
DFA-2	2240	504	1710	384	1160	262
Two-Seg	2300	518	1830	414	1110	250

Table 5.—Time and Fuel Comparisons from NASA Reference Point

- Still air
- Initial conditions:
  - 220 kn airspeed
  - 15 nmi from threshold
  - Level flight, 915 m (3000 ft) altitude
  - Clean configuration

Procedure	Weight of fuel burned		Elapsed time min:sec
	N	Lb	
Eng ref	3410	769	6:02
A-1	3200	720	5:53
A-2	2850	642	5:49
DFA-1	1720	388	4:41
DFA-2	2050	462	4:51
Two-Seg	2890	650	5:49

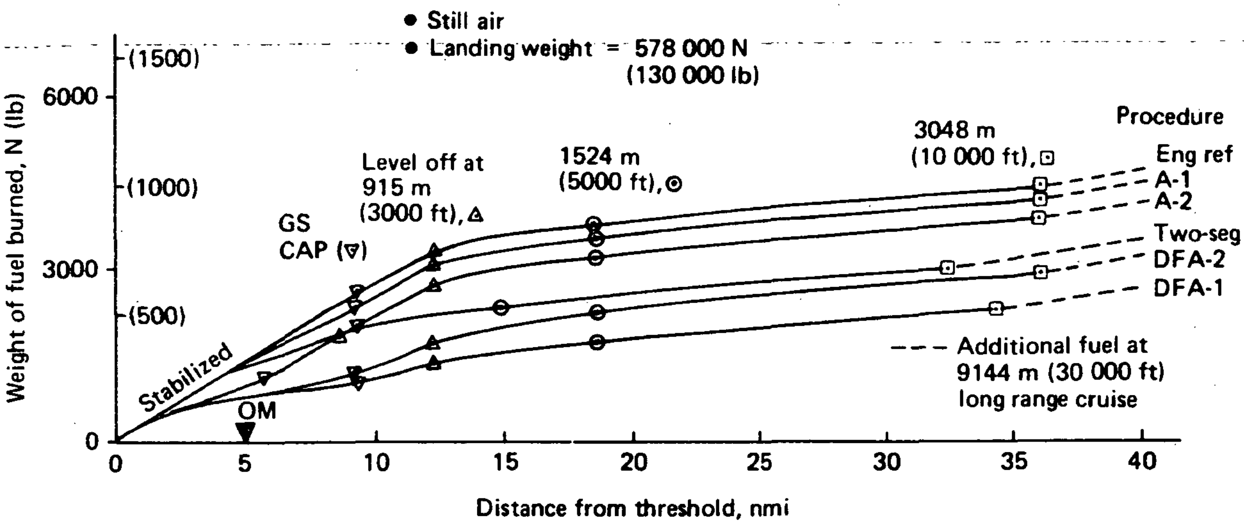


Figure 13.—Computed Fuel Profiles

Table 6.—Computed Time and Fuel Benefits of DFA-1 Procedure

	Benefits of DFA-1 procedure relative to baseline procedure					
	Time reduction, min:sec			Weight of fuel saved, N (lb)		
Baseline procedure	30-kn headwind	Still air	10-kn tailwind	30-kn headwind	Still air	10-kn tailwind
Current airline, A-1	4:04	1:57	1:30	3750 (842)	1750 (395)	1410 (317)
Current airline, A-2	3:55	1:54	1:27	3250 (734)	1420 (320)	1100 (249)
Two-Seg	2:19	:56	a	2230 (502)	820 (185)	a

[a] Two-seg approach should not be used in tailwinds.

Note: Benefits based on profiles beginning at 250 kn descent point with cruise increment (fig. 11)

5.3 COMPUTED NOISE DATA

The computed flight profiles were loaded into existing noise computation programs to obtain ground level 90-EPNdB contour areas and centerline noise plots. The noise data are for total airplane noise including the combined effects of airframe and engine noise as computed for FAR 36 ambient conditions.

The noise differences between still air, headwind, and tailwind conditions reflect only the differences in airspeed, configuration scheduling, and thrust levels resulting from the winds. While noise propagation may be influenced by winds, the noise computation programs available at the time of this study did not include such effects.

5.3.1 90 EPNdB CONTOURS

Computed 90 EPNdB contours (ground level) are compared in figure 14(a) for the delayed flap (DFA-1), two-segment, and current airline (A-1) procedures. The contour closure distance is similar for the DFA and. two-segment procedures, being much closer to the runway than for the current airline procedure. The relative areas enclosed within the contours are compared in figure 14(b), using the contour area for current airline procedures (the same for both A-1 and A-2)as a normalizing factor. With untreated nacelles, the 90 EPNdB contour area for the DFA procedures is about one-third that of the current airline procedures. The contour area for current airline procedures flown with quiet nacelles (QN) is about the same as for the DFA procedures flow with untreated nacelles. Due to the airframe noise contribution, nacelle treatment is less effective at the low power settings used with the DFA procedures. Conversely, the DFA procedures are less effective for airplanes equipped with quiet nacelles.

Noise contour area comparisons for all of the previously defined procedures are presented in figure 15 as computed for three wind conditions. In this figure, the 90 EPNdB contour area for the Eng ref procedure is used as a reference for normalizing the data. The results apply to untreated nacelles, except for the still air conditions where the effect of nacelle treatment is indicated by shading. The stabilization altitude for the DFA procedures is 152 m (500 ft).

In still air conditions, the two-segment approach procedure, which stabilizes on the 3^{o} glide slope at an altitude of 152 m (500 ft), offers benefits comparable to the delayed flap approach procedure with a 152-m (500-ft) target altitude. However, the two-segment procedure is less effective in headwinds. Reference 4 recommends against the use of the two-segment approach in tailwinds.

The effect of parametric variations in the DFA stabilization altitude on the 90 EPNdB contour area is illustrated in figure 16. Here again, the contour area for the Eng ref procedure in still air is used as a reference for normalizing the data. It is seen that the stabilization altitude has a powerful effect on the noise contour area for the DFA procedures. Comparison with the still air data in figure 15 shows that the DFA procedures provide some contour area reduction, relative to current airline procedures, even with a 305-m (1000-ft) stabilization altitude (both with untreated nacelles).

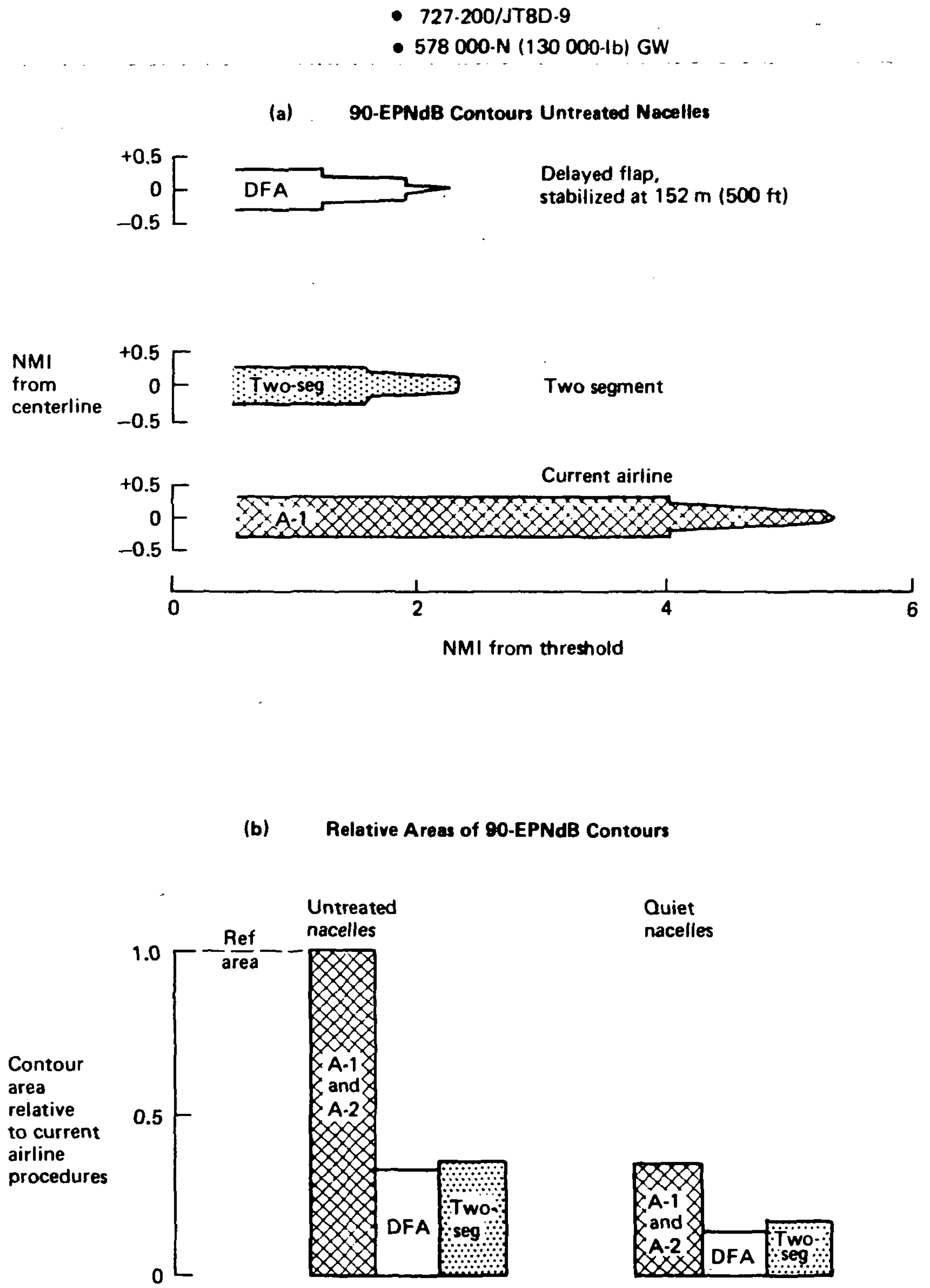


Figure 14.—Noise Contour Comparisons

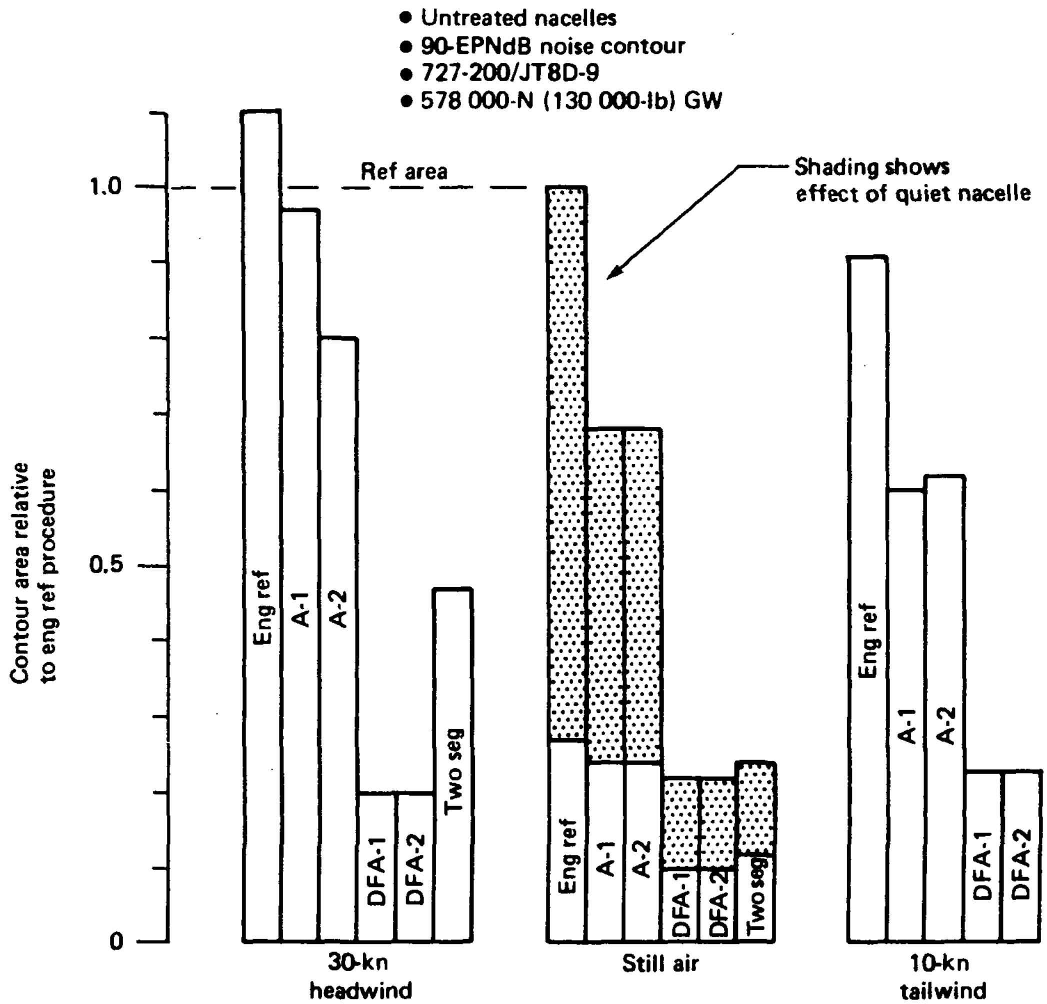


Figure 15.—Contour Area Comparisons for Three Wind Conditions

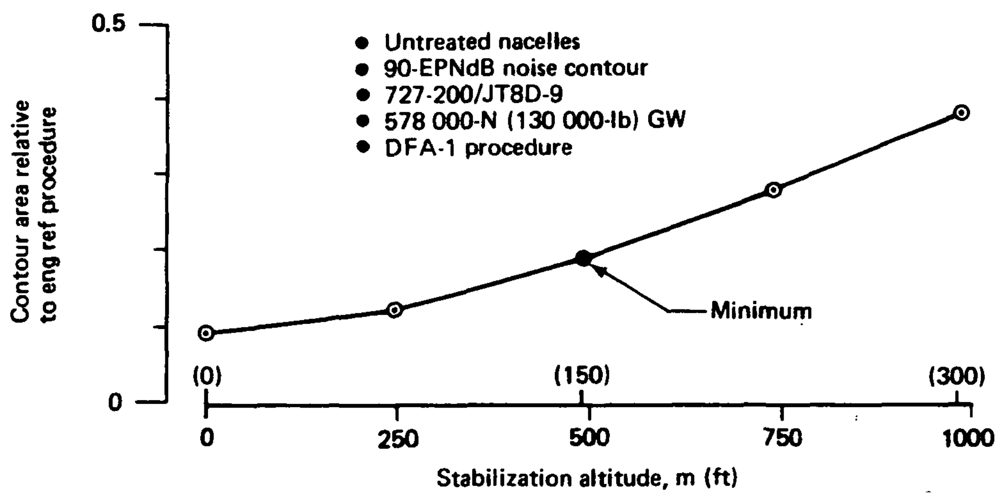


Figure 16.—Effect of DFA Stabilization Altitude on Contour Area, Still Air

5.3.2 CENTERLINE NOISE

Plots of computed noise levels directly under the flightpath are presented in figures 17 through 22. All except figure 19 apply to untreated nacelles. The Eng ref procedure is shown on all plots as an aid in visualizing the noise benefits of various procedures.

The noise plots begin at the 3000-ft level off point which is about 12 nmi from the threshold for all procedures except the two-segment (see fig. 10). Thrust, altitude, and speed are held constant for a distance of 3 nmi from this point for all procedures except DFA-1, which requires an earlier power cut. The glide slope intercept distance is about 9 nmi for the 3° ILS and about 6 nmi for the two segment.

The DFA-1 procedure is compared to the current airline procedures and engineering reference in figure 17. The different noise levels following glide slope capture reflect the different intermediate approach configurations.

Procedure	Gear	Flaps
Eng ref	Down	30
A-1	Down	25
A-2	Up	15
DFA-1	Up	0

The delayed flap and two-segment approach procedures are compared in figure 18. Power is cut to idle about 1 nmi prior to glide slope capture for DFA-1. The DFA-2 procedure requires a large thrust reduction to maintain constant speed during glide slope capture (at 9 nmi). The DFA-2 thrust later is cut to idle at about 6 nmi, which is the flaps 2 selection point for DFA-1. Thereafter the delayed flap procedures are identical. The two-segment approach is noisier in the 5.5- to 8.5-nmi range because the airplane is still in level flight (thrust set for flaps 15, gear up, 150 kn) awaiting upper segment capture. The two segment is a little noisier than the DFA in the 2- to 3-nmi range because of the slightly higher nominal thrust level. Since the two-segment procedure relies on thrust modulation for speed control, the upper path angle (6°) is established so as to require trimmed thrust levels above idle (thrust margin equivalent to about 1.5° $\Delta\gamma$). The lower thrust for the DFA offsets the altitude advantage of the two segment.

Figure 19 compares the same procedures as figures 17 and 18, but for airplanes equipped with quiet nacelles (QN).

Comparison of the two figures shows that the noise level for the idle power deceleration phase of the DFA procedure is nearly the same for untreated and quiet nacelles. This occurs due to the predominance of airframe noise when the engines are at idle. Following application of normal approach power, the quiet nacelle again becomes effective for the final

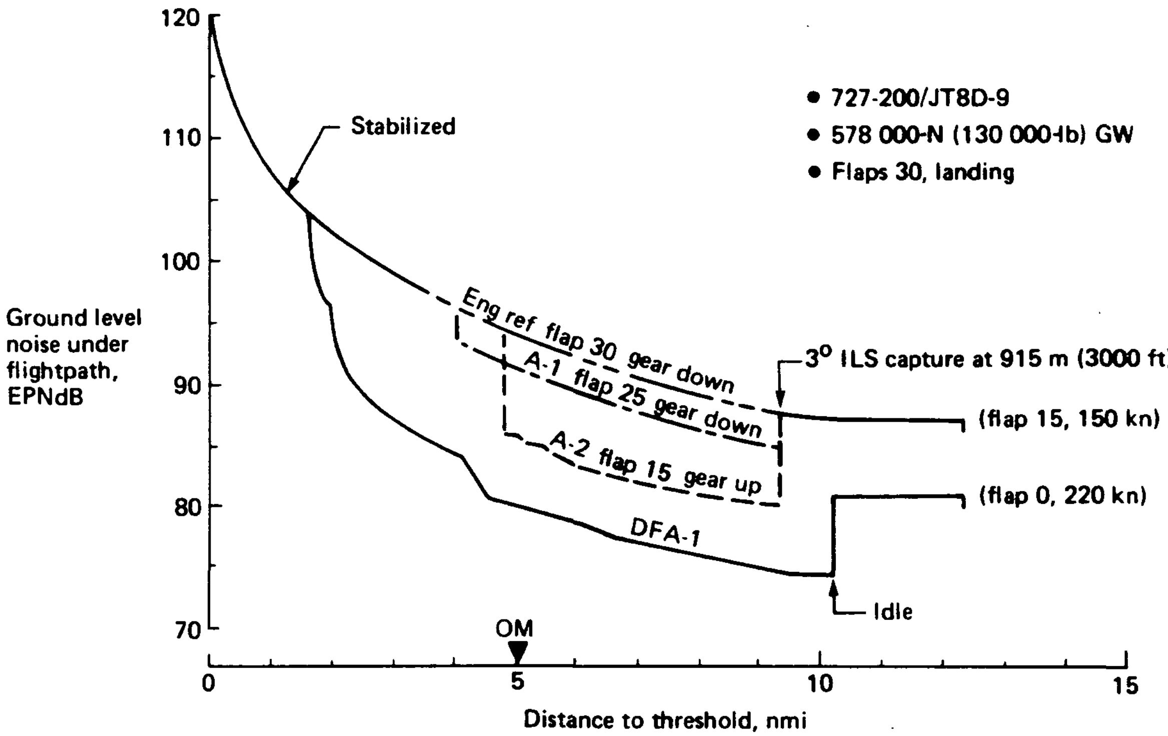


Figure 17.—Computed Centerline Noise for DFA-1, A-1, and A-2 Procedures, Untreated Nacelles, Still Air

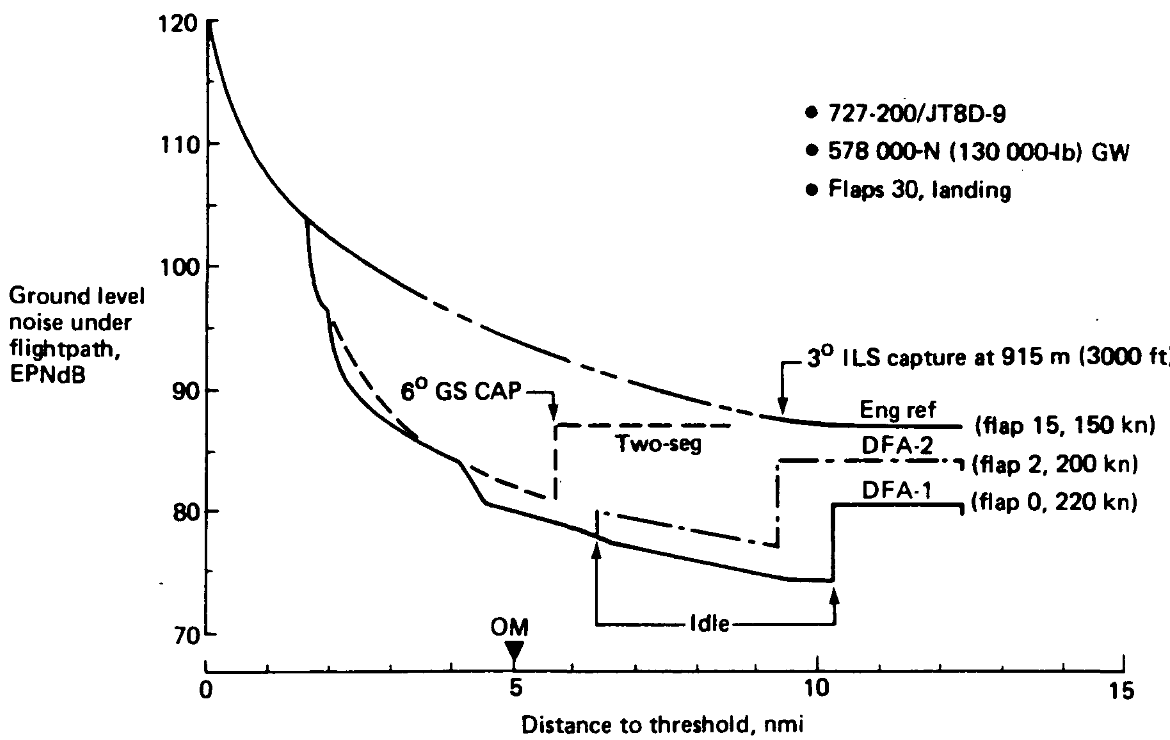


Figure 18.—Computed Centerline Noise for DFA-1, DFA-2, and Two-Seg Procedures, Untreated Nacelles, Still Air

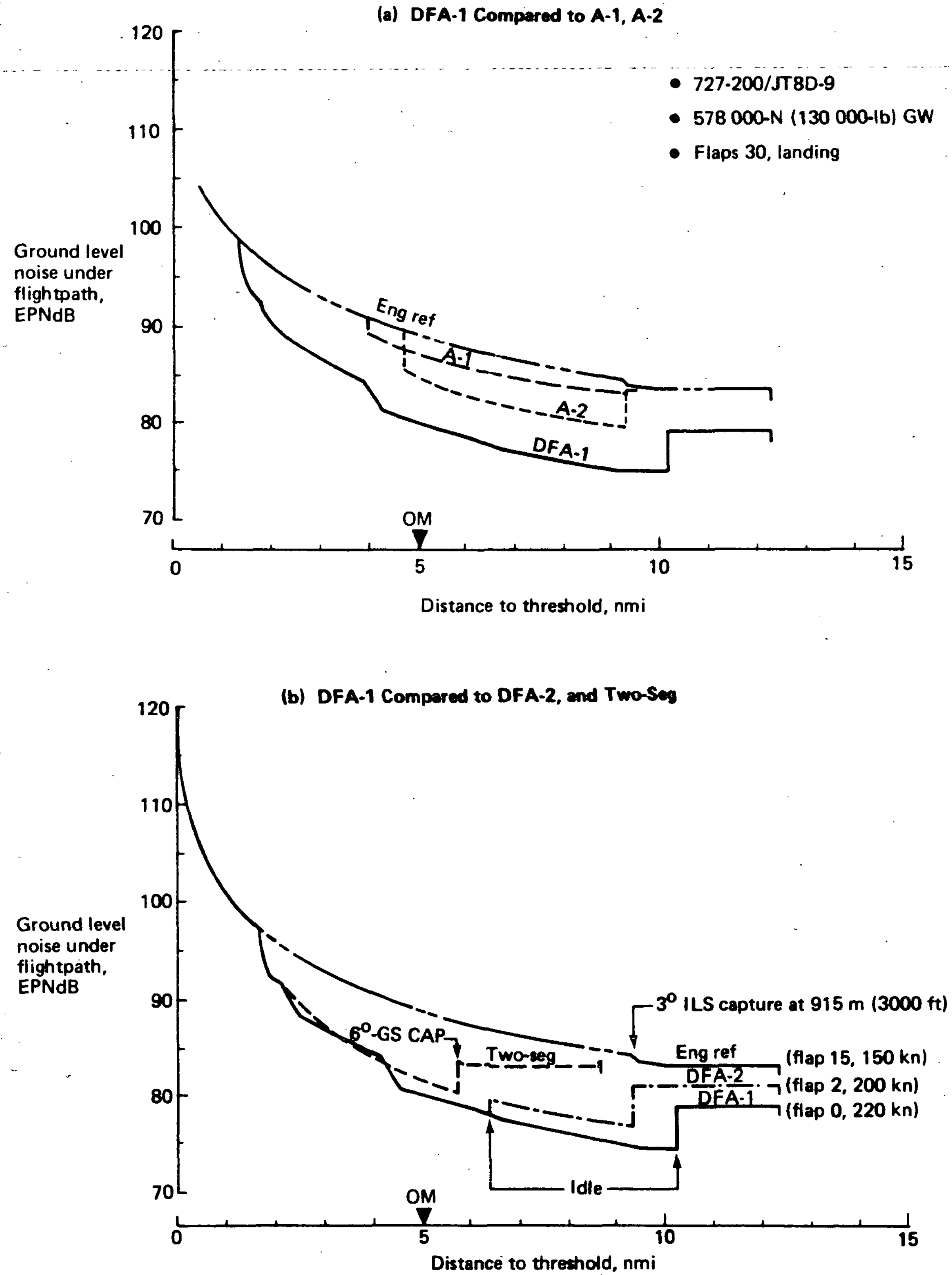


Figure 19.—Computed Centerline Noise Comparisons of Procedures, Quiet Nacelles, Still Air

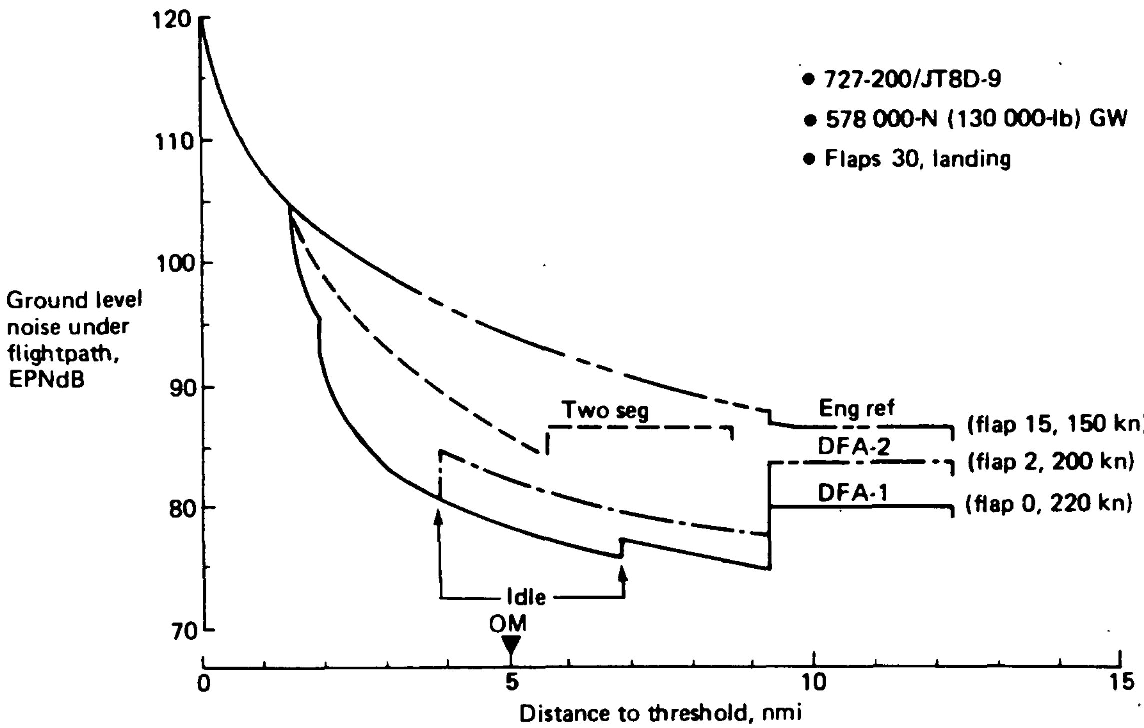


Figure 20.—Computed Centerline Noise for DFA-1, DFA-2, and Two-Seg Procedures, Untreated Nacelles, 30-kn Headwind

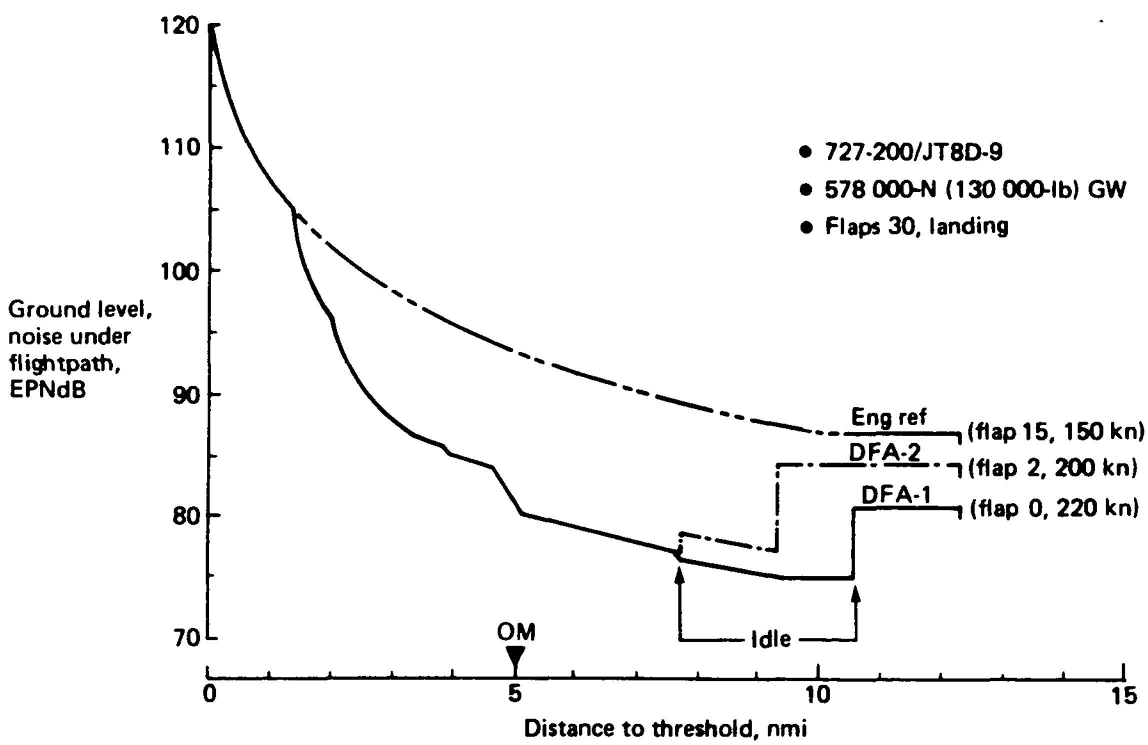


Figure 21.—Computed Centerline Noise for DFA-1 and DFA-2 Procedures, Untreated Nacelles, 10-kn Tailwind

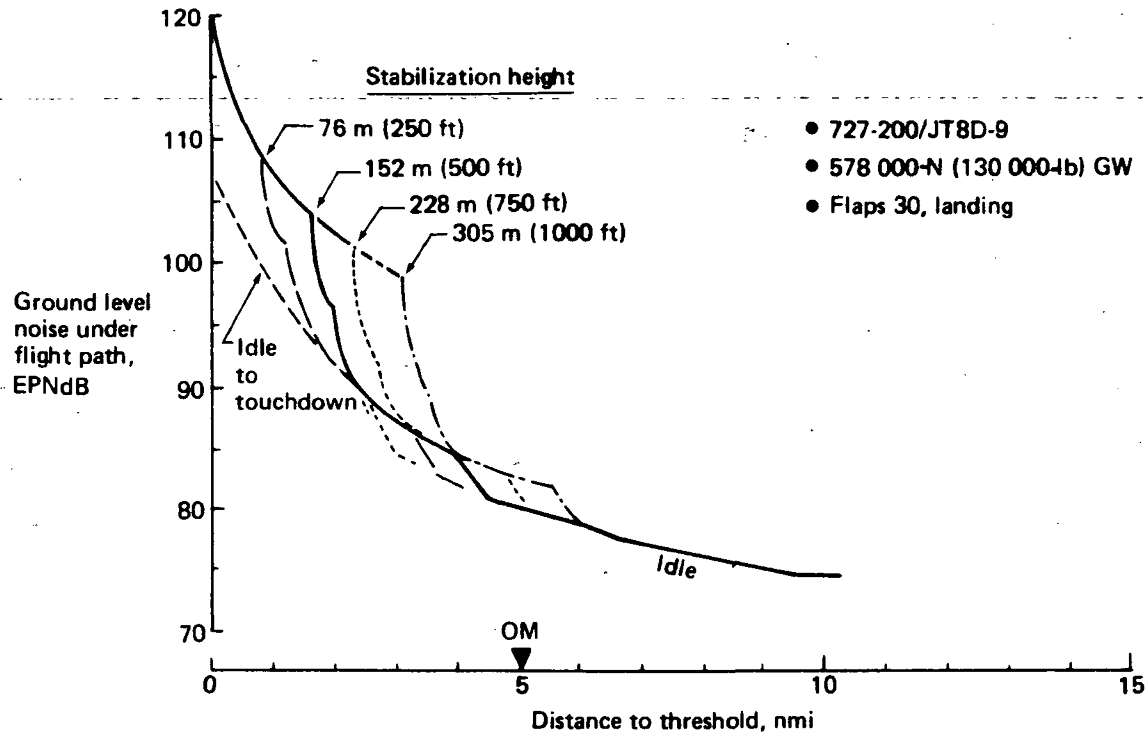


Figure 22.—Effect of Stabilization Height on Centerline Noise for DFA-1 Procedure, Untreated Nacelles, Still Air

approach phase from the stabilization point to touchdown. Since the quiet nacelles reduce centerline noise at normal approach power but have little effect at idle power, the DFA procedures provide less noise reduction for QN equipped airplanes. Conversely, when DFA procedures are used the extent of the community that would benefit from QN installation is reduced.

The effects of headwinds and tailwinds on centerline noise are illustrated in figures 20 and 21. The Eng ref and two-seg procedures require additional thrust (relative to still air thrust levels) to track the glide slope in a headwind. The DFA procedures also require higher thrust immediately after glide slope capture. However, the power cut to idle is delayed so as to retain the benefits of the procedure in the higher noise regions closer to the runway.

The preceding centerline noise data for the DFA procedures were based on a 152-m (500-ft) target altitude for stabilizing in the final approach configuration. The effect of stabilization height on centerline noise is illustrated in figure 22. These data were obtained for the DFA-1 procedure by parametrically shifting the target altitude to lower and higher altitudes. Also shown for reference is an idle power deceleration to touchdown. Stabilization altitudes below 152 m (500 ft) are not recommended for 727 operational use. In addition to increasing pilot workload, lower altitudes would result in gear extensions below 305 m (1000 ft) unless the DFA profile was modified, would probably require autopilot and/or flight director modifications; and could adversely affect go-around capability.

5.4 SIMULATOR COMPARISONS

The Eng ref, A-1, and DFA-1 procedures were flown on the simulator by two Boeing pilots to confirm the computed fuel and noise data. To minimize costs, the Eng ref procedure was spot-checked on one run only, and the remaining time was spent obtaining a number of runs for the A-1 and DFA-1 procedures in each of three wind conditions. About two-thirds of the runs were flown manually, with the autopilot used for the remainder. The autopilot had no effect on approach time and fuel. However, it appeared that the pilots were able to stabilize on the final approach speed with less throttle manipulation when flying on autopilot. This could result from the reduced path control workload which allows more concentration on power setting and speed control. Overshoot of the stabilized thrust level and the resulting engine transients could result in more annoying noise (than the computed nominal level) in the vicinity of the stabilization point. Hence, the autopilot might help in realizing the potential noise benefits of the procedure in addition to reducing pilot workload.

The simulator runs were initiated from trimmed level flight on localizer at the 915-m (3000-ft) altitude about 12.5 nmi from touchdown. The 915-m (3000-ft) altitude was maintained until capture of a 3° ILS glide slope which was tracked to the runway threshold in simulated IFR conditions. Elapsed time, computed fuel consumption, centerline noise, distance, and a number of flight parameters were recorded on magnetic tape during each run for subsequent analyses.

Approach time and fuel consumption from the simulator runs are plotted in figure 23 for comparison with computed values. There is very little scatter in the simulator results, and correlation with the computed data is good.

Centerline noise for the A-1 and DFA-1 procedures is compared in figure 24 for representative runs by one pilot. Additional runs for the DFA-1 procedure illustrating noise variations between the runs flown with manual and autopilot control are presented in figure 25. Additional simulator data for other flight parameters (e.g., speed, engine pressure ratio (EPR), etc.) are provided in section 7.0. Note that the touchdown point is used as the zero distance reference for the simulator data recordings, whereas the preceding computed centerline noise plots are referenced, by convention, to the runway threshold. The touchdown point is 0.2 nmi from the threshold.

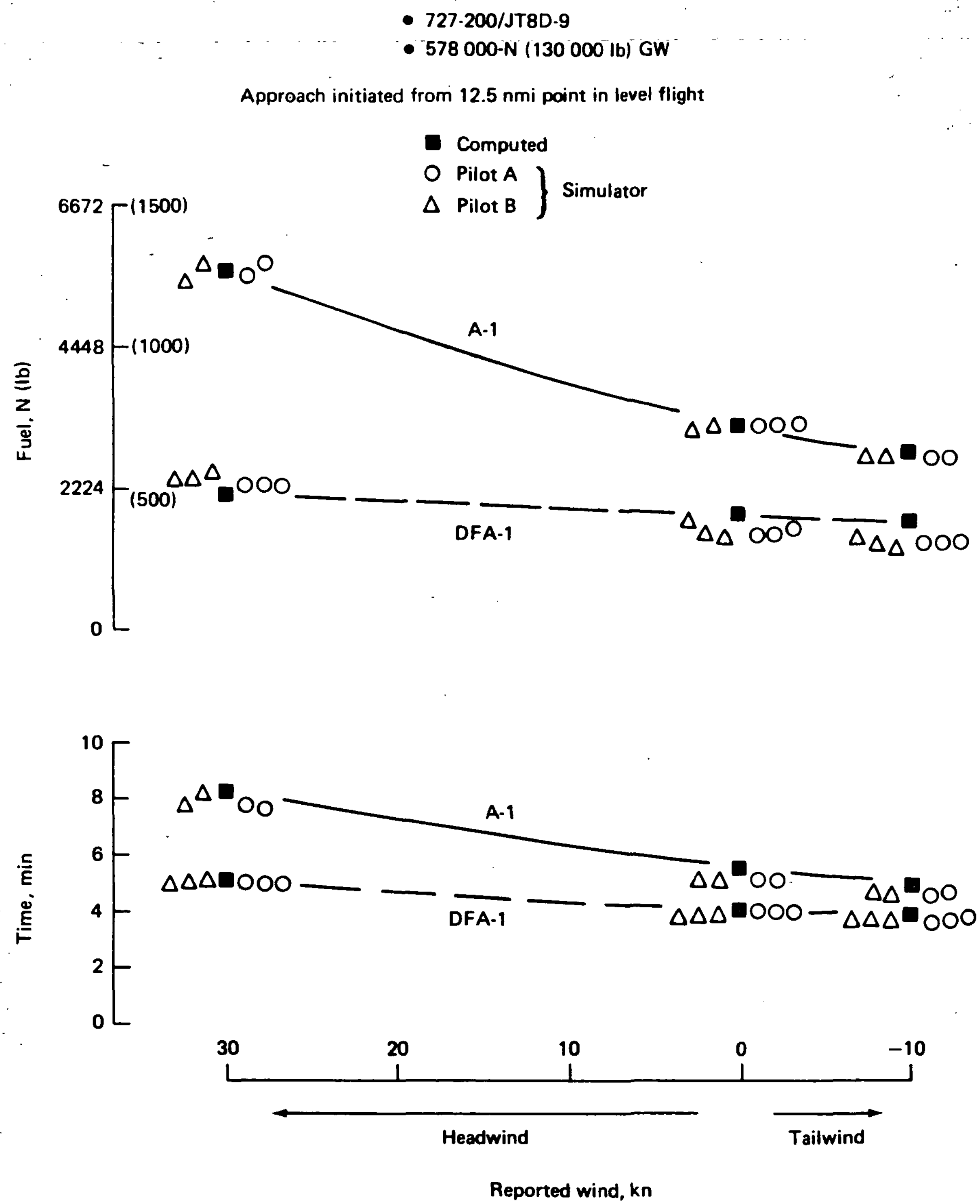


Figure 23.—Comparison of Simulator Results With Computed Fuel and Time Data

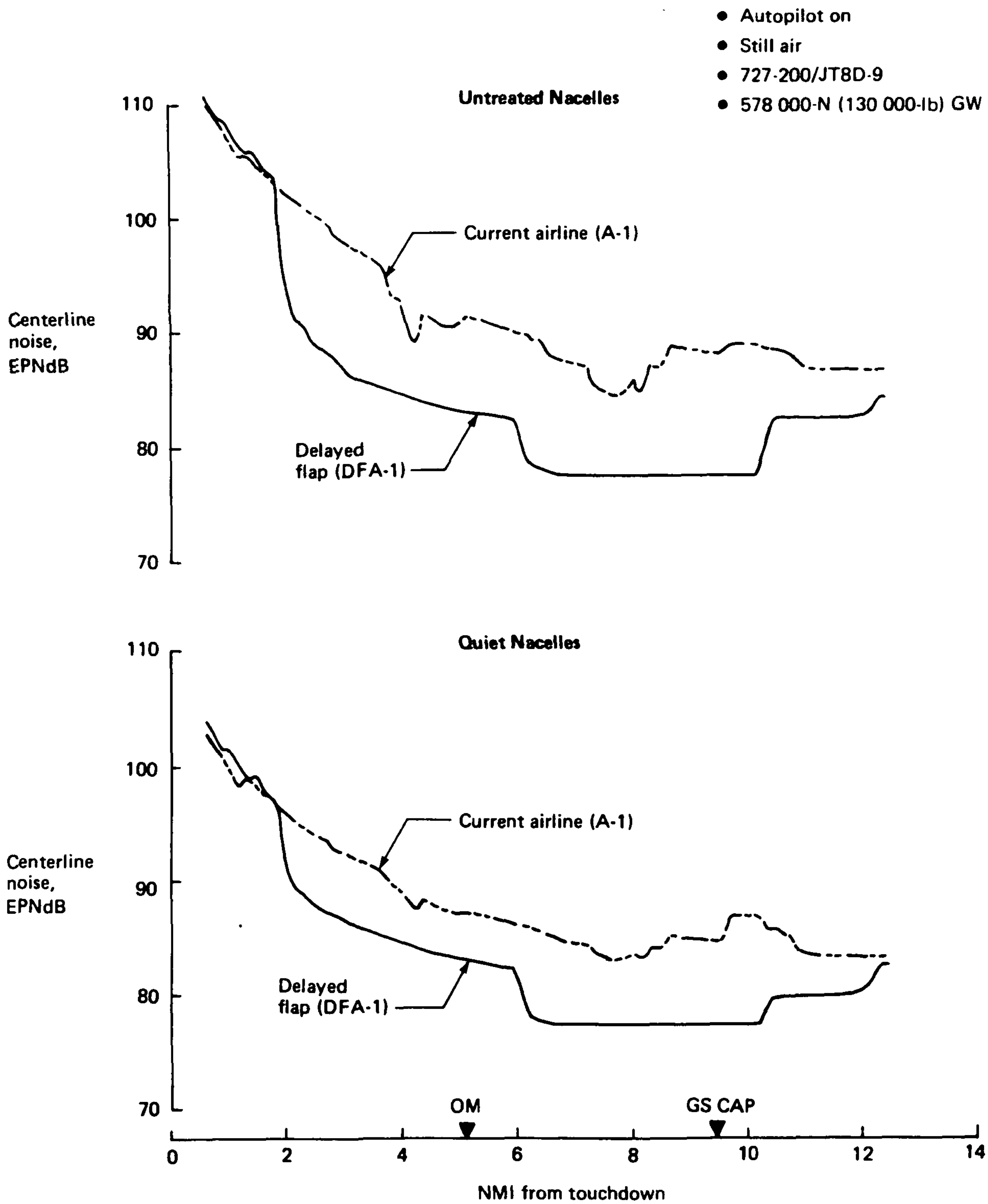


Figure 24.—Centerline Noise Comparisons from Piloted Simulation of A-1 and DFA-1 Procedures

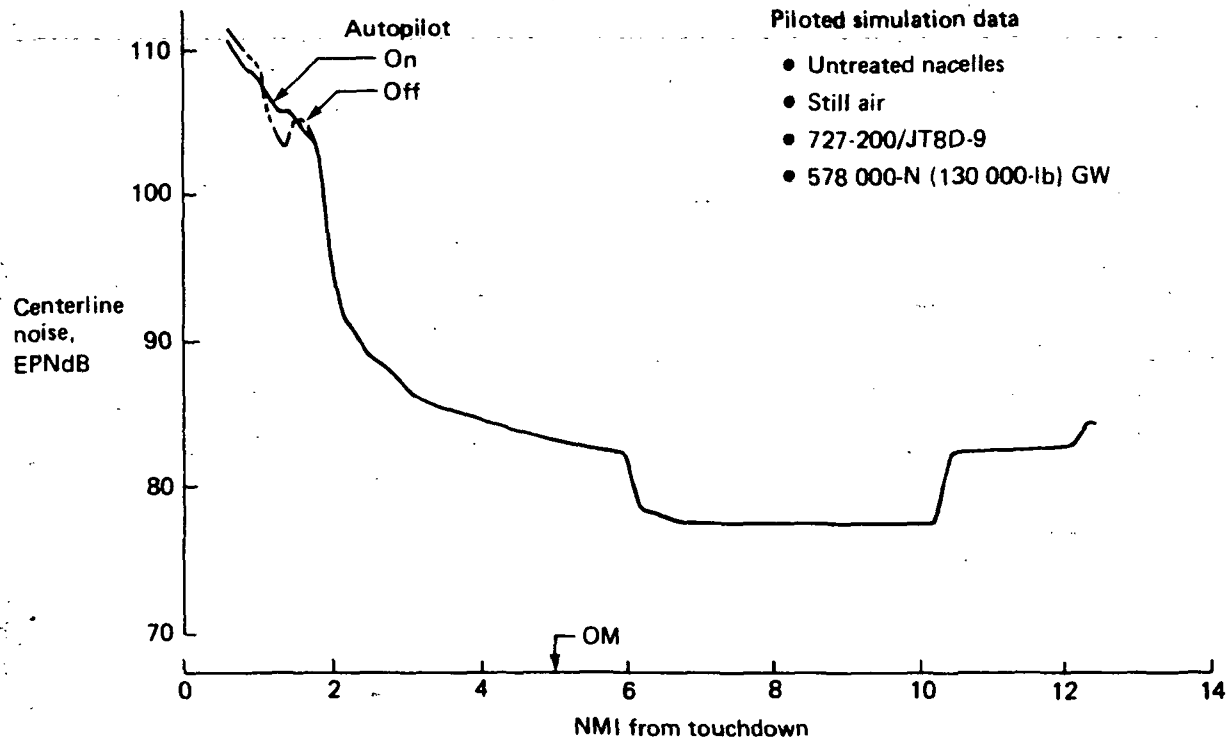


Figure 25. —Effect of Autopilot on Centerline Noise for DFA-1 Procedure

6.0 DEVELOPMENT

Application of the NASA CV-990 AEMS concept to the 727 required development of flight profiles and an airborne computer algorithm specifically tailored to 727 characteristics. In addition, it was necessary to develop and validate a fixed-base engineering simulation of the 727 airplane to be used for evaluating the algorithm and flight procedures.

6.1 CRITERIA

Before beginning detailed development of the 727 algorithm and flight profiles, the NASA CV-990 work was reviewed, the procedures were discussed with Boeing pilots and engineers, and preliminary criteria were established. The criteria were updated as the work progressed. The AEMS concept resulting from this study, as defined by reference 3, is intended to meet the final set of criteria outlined in table 7.

6.2 FLIGHT PROFILES

Considerable attention was given to selection of flight profiles that would maximize the fuel/noise benefits and yet be safe and acceptable to pilots. The development approach was to (1) select preliminary schedules based on review of operating limits, aerodynamic data, and noise trends, (2) use an unpiloted digital computer routine to check deceleration distances and refine the profiles, and (3) further refine the procedures on the simulator as required.

6.2.1 SPEED SCHEDULES

The speed schedules selected for the 727 delayed flap approach procedures evaluation are shown in tables 8 and 9. The airborne computer uses the equations and data shown in table 10 to calculate these speeds based on the weight and final approach speed selected by the pilot. Since much of the deceleration phase is flown at idle power, these schedules are not suitable for icing conditions that require $N_1 \geqslant 55\%$ for engine inlet anti-icing. When the inlet ANTI-ICING switch is turned on, interlock logic prevents engaging the AEMS compute mode until flaps 15 and gear have been extended. In addition, a minimum power setting of EPR 1.2 is used in lieu of the IDLE, EPR 1.1 schedule. The procedures for icing conditions would be similar to current ATA airline procedures and were not investigated in this study.

The speed schedules are used by the computer in predicting deceleration distances for the desired flight profile. The commands displayed to the pilot will occur at the speeds shown if the airplane decelerates exactly as predicted. The flap and gear commands are based on the distance prediction and may be given at higher or lower speeds if the actual profile starts to deviate from the prediction. The EPR commands are determined by speed only; thus, flaps and gear extension will always be in the same sequence, but will not always occur at the scheduled speeds. The EPR commands will always occur at the scheduled speeds, but sequencing with respect to the flaps and gear commands will vary.

Table 7.—AEMS Design Criteria

Required NAVAIDS	
• DME collocated with path reference	
• Path reference (VASI, ILS, or other)	
• ILS for simulator study	
Wind and weather	
• CAT II ceiling/visibility	
• Tailwinds to 10 kn	
• Compatible with inlet anti-icing (stabilized approach for wing deice)	
AFCS compatibility	
• Suitable for coupled ILS autopilot approaches	
• No change to autopilot/flight director	
• Autothrottles not required	
Thrust scheduling	
• Nonicing	Idle allowable to flaps 25; set EPR 1.1 prior to flaps 30; set final EPR prior to final speed
• Icing	$N_1 \geq 55\%$
• Thrust displays	ALERT light remains on until throttles are reset
Landing flaps—profiles based on flaps 30	
Configuration Scheduling	
• Stabilized	Above 152-m (500-ft) VFR; 305-m (1000-ft) IFR
• Gear down	Above 305 m (1000 ft)
Speed/path control—with normal pilot skills	
• ±1-dot deviation	
• Stay in trim. Be able to take hands off (or A/P disconnect) at 91 m (300 ft) and stay within ±5 kn/±2 dots at 61 m (200 ft)	
Speed/altitude constraints—current ATC and OPS manual, except:	
• Use 1.3 V_s reference for all flaps (plastic bugs set manually)	
• Stay 10 kn below placards	
• Stay on front side of drag curve	
Visibility and comfort $\theta < 5^o$, $dV/_{dt} < 2$ kn/s	

Table 8.—Speed Schedule for Winds to 10 kn

Command generated	Landing weight calibrated airspeed, kn		
	GW = 488 000 N (110 000 lb)	GW = 578 000 N (130 000 lb)	GW = 686 000 N (154 500 lb)
Flaps 2	188	200	215
Flaps 5	170	185	203
Flaps 15	160	174	191
Gear	151	165	181
Flaps 25	139	152	167
EPR 1.1	130	143	159
Flaps 30	122	134	147
APP EPR	120	131	144
a	117	128	140

[a]Final approach speed, (V_{ref} + 5 kn) no command

Table 9.—Speed Schedule for 30-kn Headwind

Command generated	Landing weight calibrated airspeed, kn		
	GW = 488 000 N (110 000 lb)	GW = 578 000 N (130 000 lb)	GW = 686 000 N (154 500 lb)
Flaps 2	188	200	215
Flaps 5	170	185	203
Flaps 15	160	174	191
Gear down	156	170	186
EPR 1.1	155	169	185
Flap 25	143	155	170
Flap 30	136	148	162
APP EPR	135	147	160
a	132	143	155

[a]Final approach speed (V_{ref} + 20 kn) no command

Table 10.—Speed Schedule Computation Concept

Equations

$V_{APP} = V_{ref} + 5$—computed from weight (GW)

$V_{COMMAND} = V_{NOMINAL} + K_{GW} (GW - 130\,000) + K_V (V_{FINAL} - V_{APP})$

(pilot inputs: GW, V_{FINAL})

Command speed to be computed	$V_{NOMINAL}$	K_{GW}	K_V
Flaps 2	200	0.00060	0
Flaps 5	185	0.00075	0
Flaps 15	174	0.00070	0
Gear	165	0.00070	0.333
Flaps 25	152	0.00065	0.2
EPR 1.1	143	0.00065	1.73
Flaps 30	134	0.00060	0.932
APP EPR	131	0.00055	1.068

The flaps versus speed schedules are selected to minimize the pitch attitude variations required to maintain 1-g flight during flap extension on final approach. This is desirable for glide slope tracking both by the pilot and autopilot. Fortunately, the minimum $\Delta\theta$ schedule also provides adequate speed margins from safety limits, is compatible with ATC speed limits, and is a good compromise with respect to fuel and noise benefits.

To maximize the fuel/noise benefits, it is desirable to delay gear extension as long as possible. The large gear drag increment dissipates energy rapidly, thus shortening the distance that can be flown at idle power. In the selected procedure, the gear is extended in sequence following flaps 15. This is consistent with current Boeing pilot training procedures for normal ILS approaches and, in combination with the thrust schedule, results in gear extension slightly above 305-m (1000-ft) altitude during a delayed flap approach.

For nonicing conditions, the deceleration phase of the approach is initiated by retarding throttles to idle. The deceleration is arrested by reapplying thrust in two steps, first to EPR 1.1 and then to normal approach power settings. The first step to EPR 1.1 initiates engine acceleration to a power setting near the surge bleed valve operating point from which further acceleration can be obtained more rapidly when required. The increased thrust at EPR 1.1 reduces the rate of airspeed decay which lessens the likelihood of undershooting the final approach speed and extends the overall deceleration distance. The distance effect is used to adjust the point at which the gear down speed is reached. In light wind conditions, EPR 1.1 is set just prior to selecting landing flaps. However, in strong headwinds, the deceleration becomes compressed with respect to ground distance, so thrust is advanced to EPR 1.1 sooner for headwinds.

6.2.2 COMPUTED FLIGHT PROFILES

Nominal flight profiles corresponding to the selected speed schedules are shown in figures 26 and 27 for a range of weight and wind conditions. The profiles were computed on the flight controls technology minicomputer (NOVA) using the path prediction model defined for the airborne computer. These particular profiles were initiated from a flaps 2 configuration. If initiated from a clean configuration, power would normally be cut at a higher speed, and flaps 2 would be commanded at about the same point as the power cut points (IDLE) indicated on curves (slight variations due to effects of flap extension rates and engine spool downtime).

The profiles in figure 26 illustrate that weight variations have little effect on the deceleration distance and general shape of the profiles in still air condition. The gear extension altitude increases slightly with weight. However, the airspeed also increases so the time available for accomplishing checklist items is essentially the same. As indicated in figure 27, the procedure becomes more compressed by headwinds. Contributing factors are the reduced groundspeed and the higher airspeeds scheduled for flaps 25 and flaps 30. (Current procedures specify increasing the final approach speed by one-half the reported wind speed plus all of the gust; not to exceed a 20-kn total increase.) The higher final airspeeds require less speed reduction (initial speeds not changed) and also place the airplane further on the front side of the drag curve, resulting in more rapid deceleration. These effects are compensated by advancing the EPR 1.1 command speed in strong headwinds.

6.2.3 PROFILE ANALYSES

Some of the factors considered in selecting the flight profiles are discussed in the following paragraphs.

6.2.3.1 Pitch Attitude

The variation of pitch attitude with speed is shown in figure 28 for trimmed 1-g flight on a 3° glide slope at a typical landing weight. The speed schedules for flap extension are selected to minimize the pitch attitude variations from the final approach attitude as indicated.

6.2.3.2 Speed Margins

The relationship of the flap versus speed schedule to various operating limits is indicated in figures 29 through 31. Reasonable margins are provided relative to flap placards and 1.3 V_S.

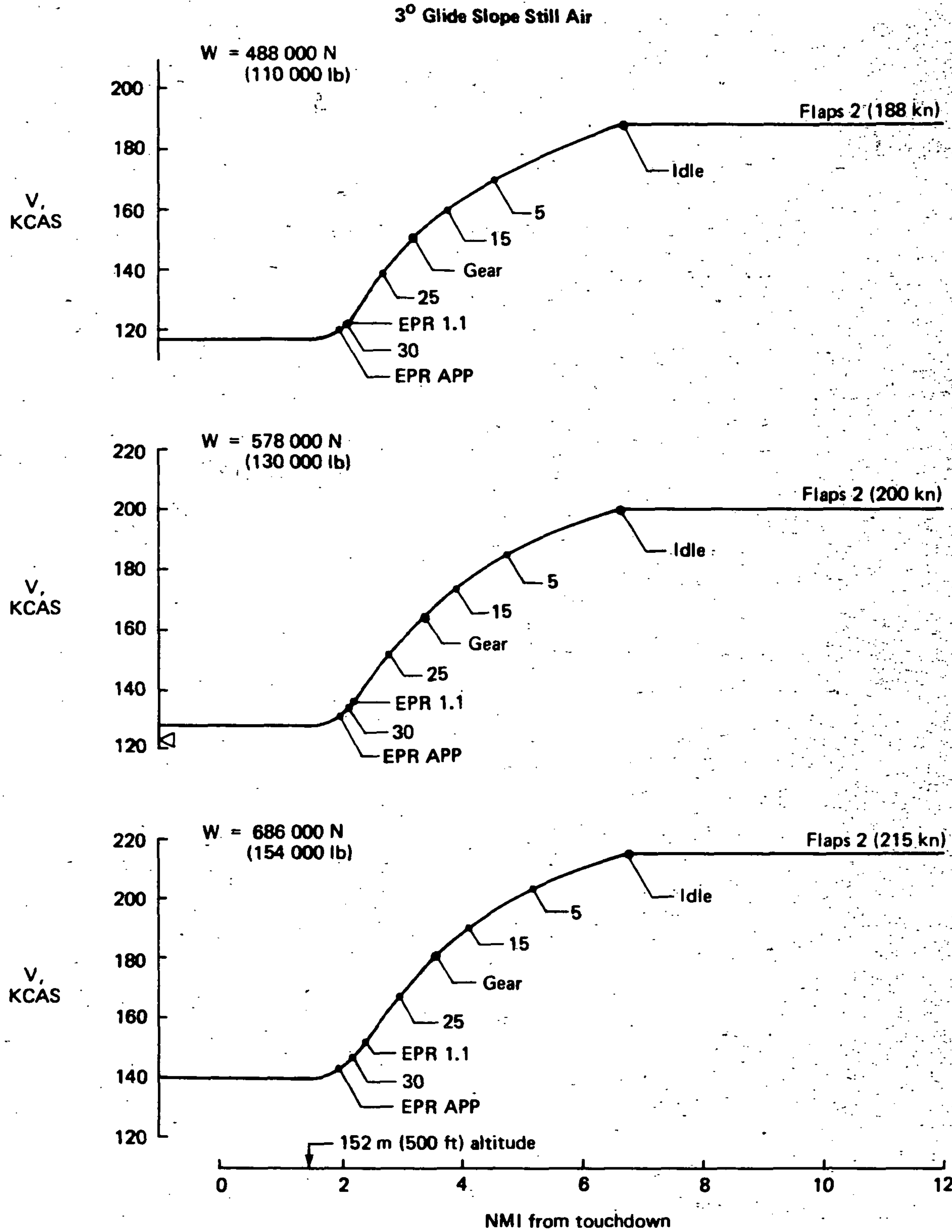


Figure 26.—Effect of Weight on Predicted Deceleration Profiles

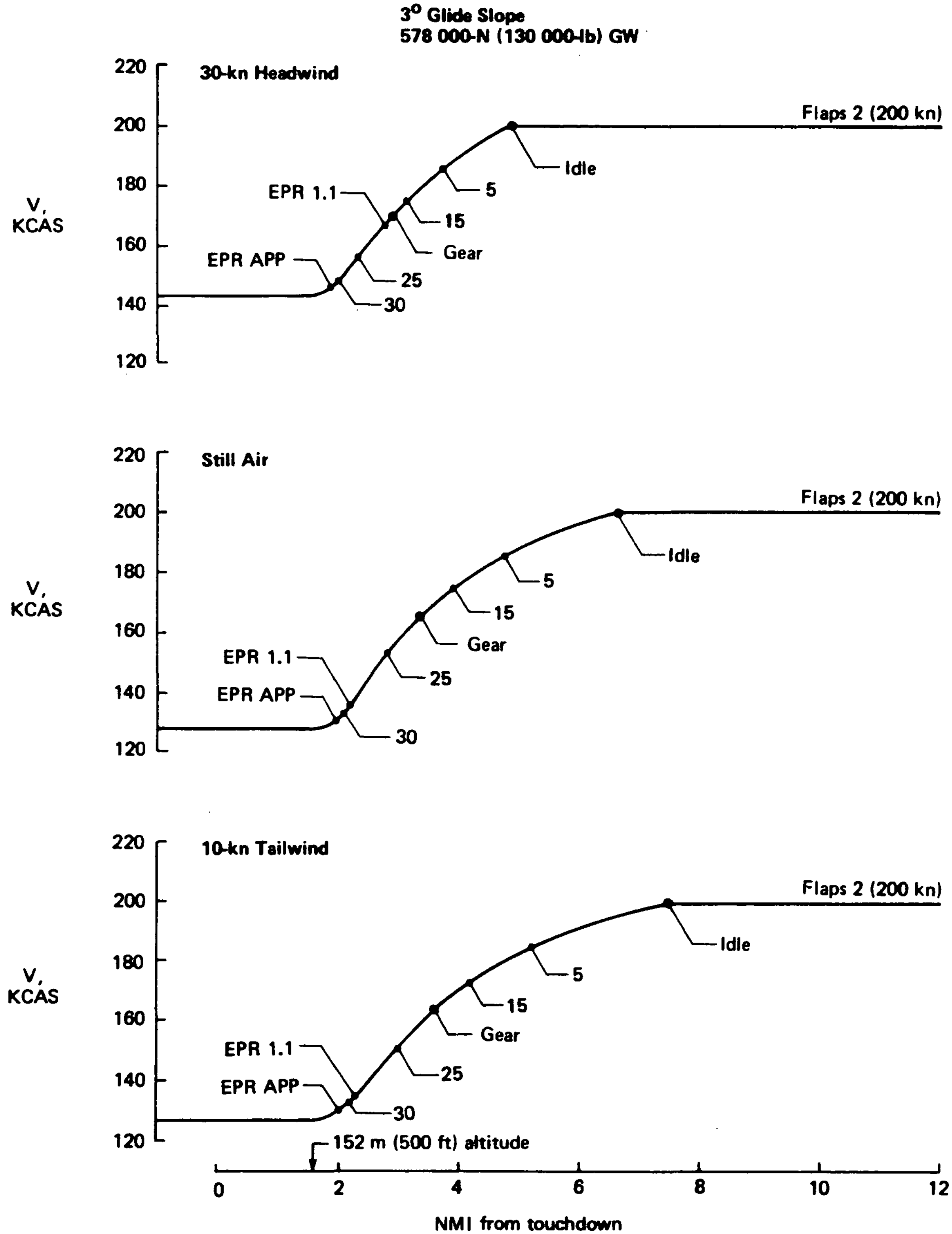


Figure 27.—Effect of Winds on Predicted Deceleration Profiles

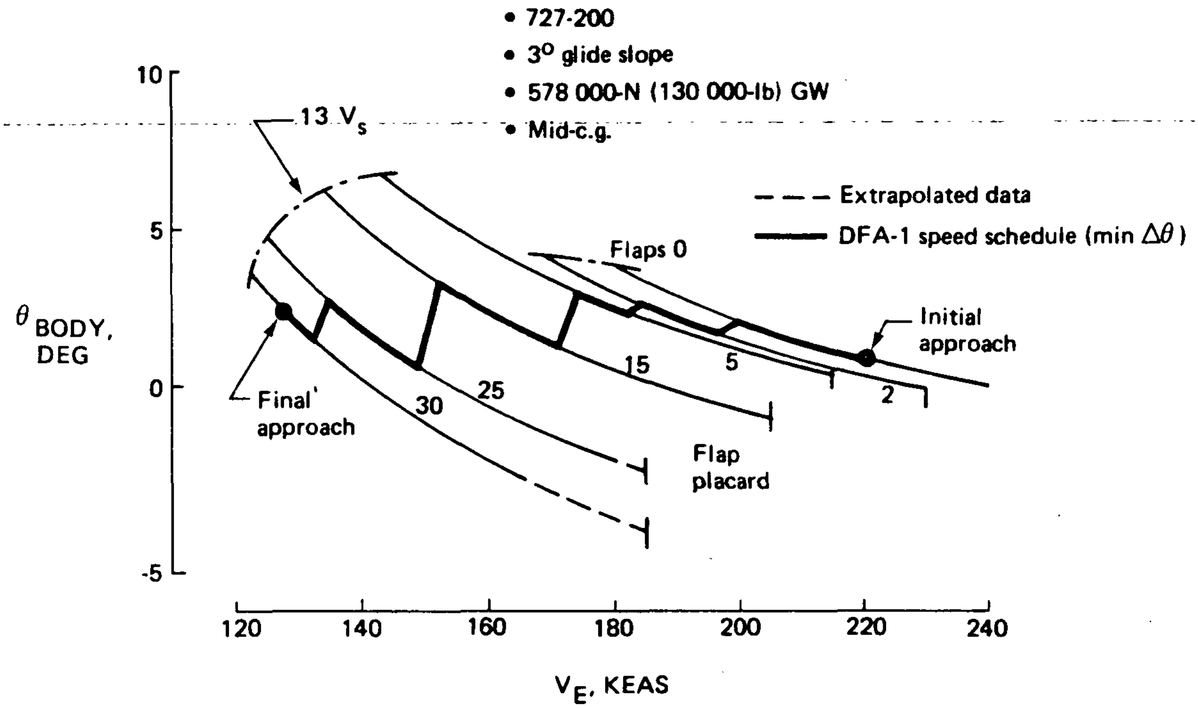


Figure 28.—Trimmed Pitch Attitude Variation with Speed

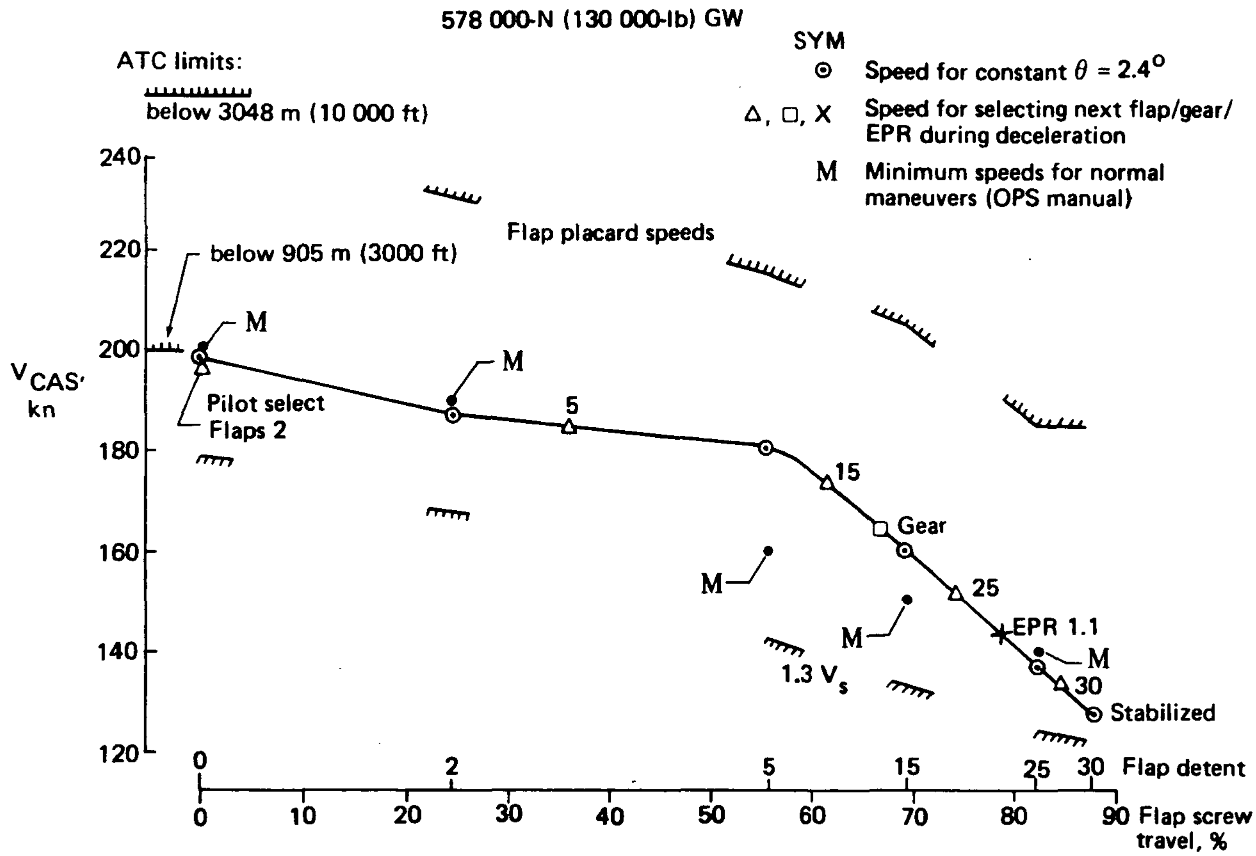


Figure 29.—DFA Speed Margins Relative to Flight Limits For Typical Landing Weight

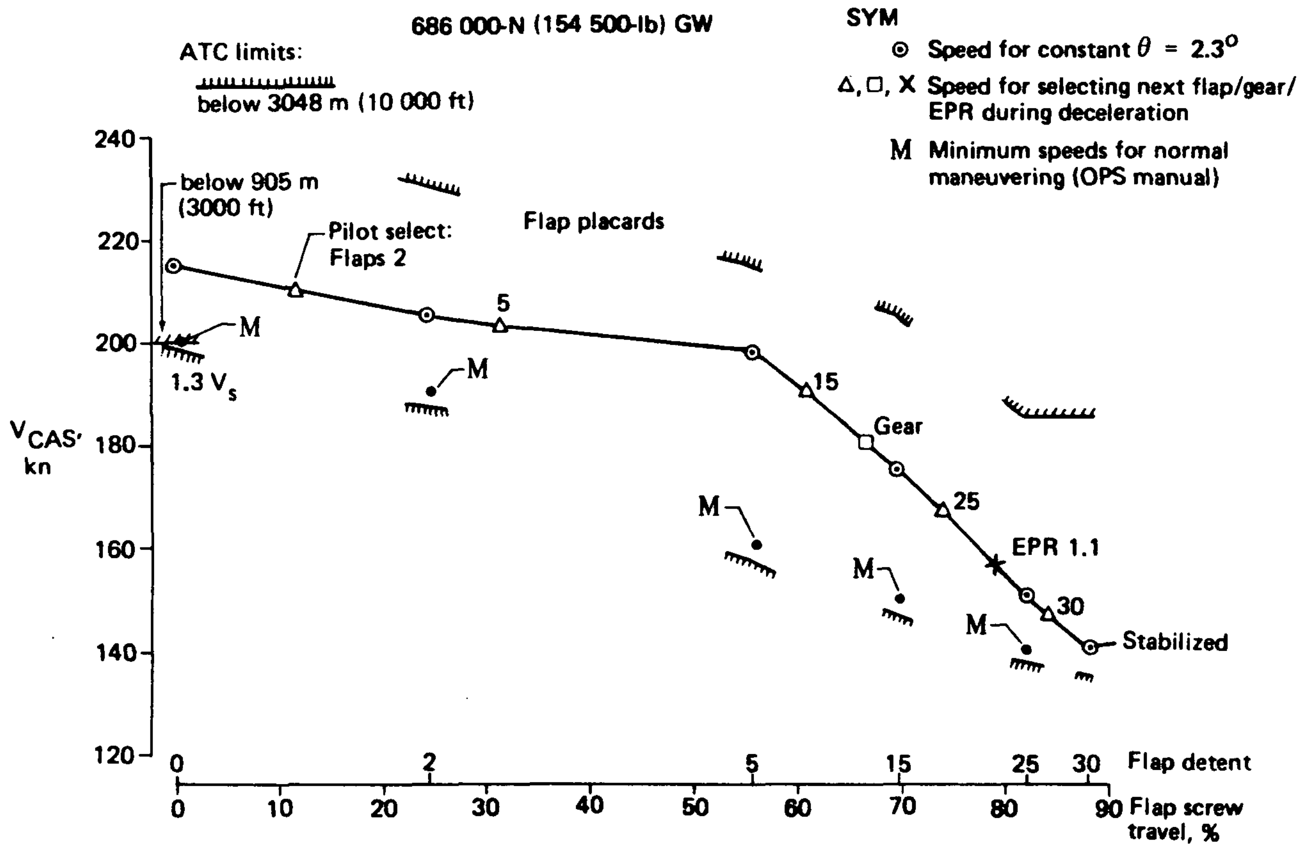


Figure 30.—DFA Speed Margins Relative to Flight Limits at Maximum Landing Weight

At high landing weights there is a slight conflict with the ATC guideline of 200-kn maximum when below an altitude of 915 m (3000 ft) in the terminal control zone. However, if this becomes a problem, flaps 2 could be used for the initial approach phase at high weight conditions.

At low weight conditions, the delayed flap approach speed schedule requires speeds slower than the approach maneuver speeds currently published in the 727 Operations Manual. This could present an operational and/or training problem, since aircrews memorize the speeds shown in the operations manual (based on maximum landing weight) and treat them as minimum speeds for all landing weights. Since this is an operational as well as an engineering concern, resolution of the question has been deferred until the next phase of the AEMS development program that would provide for airline pilot evaluations and further engineering development of the concept.

The preferred solution from an engineering and safety point of view is to implement an independent speed monitor based on angle-of-attack information obtained from the existing 727 stick shaker system. Other less expensive possibilities are to manually set plastic "bugs" on the airspeed indicator at 1.3 V_s for each flap position as part of the AEMS setup procedure, or to use the published (higher) speeds and accept the larger pitch excursions. Use of the manually set bugs was assumed in defining the avionic configuration and flight profiles for this feasibility study.

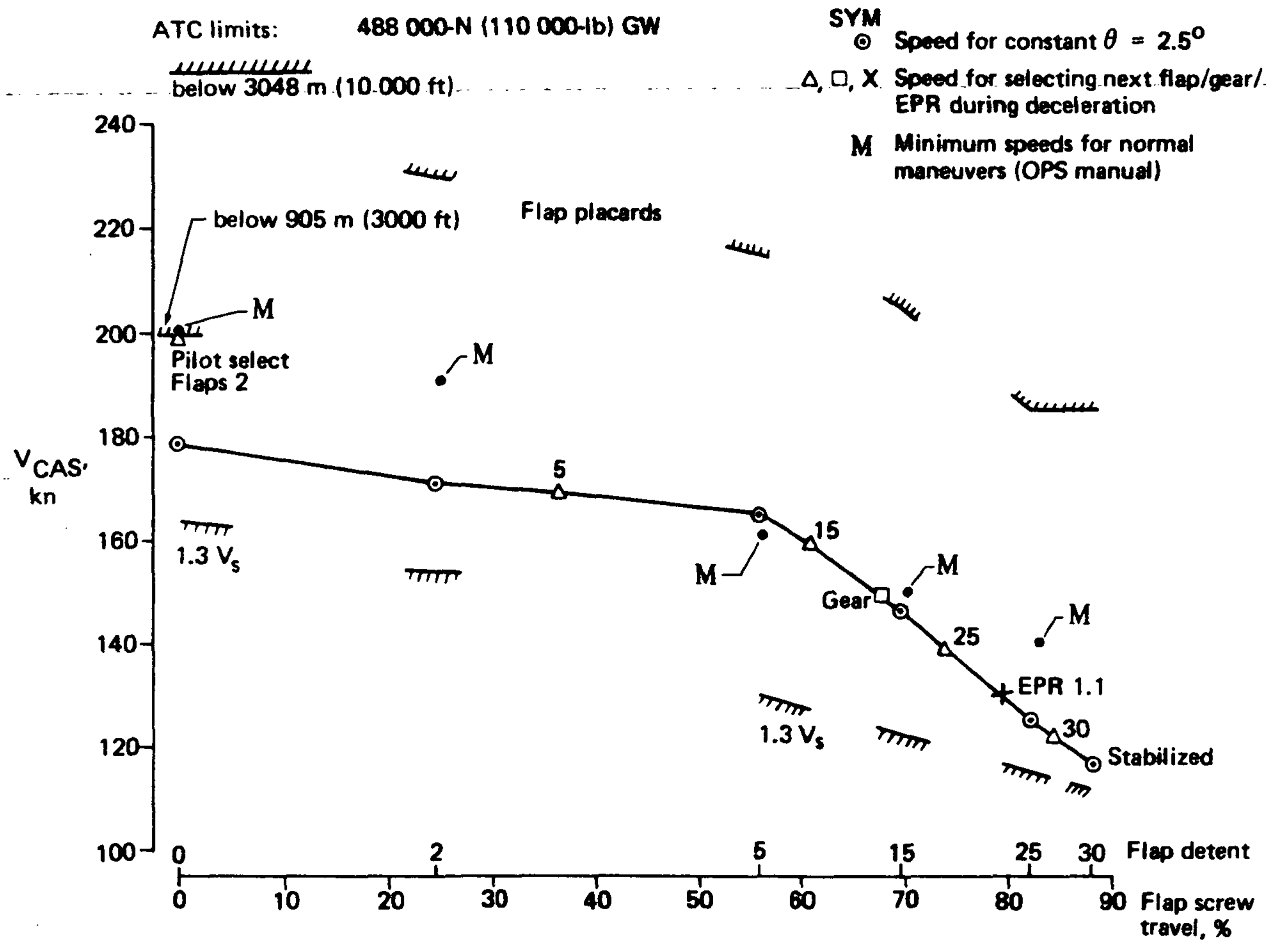


Figure 31.—DFA Speed Margins Relative to Flight Limits For Minimum Landing Weight

6.2.3.3 Fuel Trends

Fuel trends were studied using performance data and unpiloted digital computer routines to determine if a different speed schedule would increase the fuel benefits of the procedure. As shown in figure 32, the minimum $\Delta\theta$ schedule closely approximates the speeds for maximum nautical miles per pound of fuel, assuming thrust is trimmed for a 3° glide slope. With thrust fixed at an arbitrary value (e.g., idle), fuel consumption varies primarily with elapsed time, so high speeds are best. It was concluded that for practical DFA speed schedules no significant improvement could be obtained relative to the minimum $\Delta\theta$ schedule.

6.2.3.4 Deceleration Capability

The longitudinal deceleration capability of the 727 when trimmed on a 3° glide slope in still air is shown in figures 33 and 34 for two power settings:

- Idle (fig. 33)

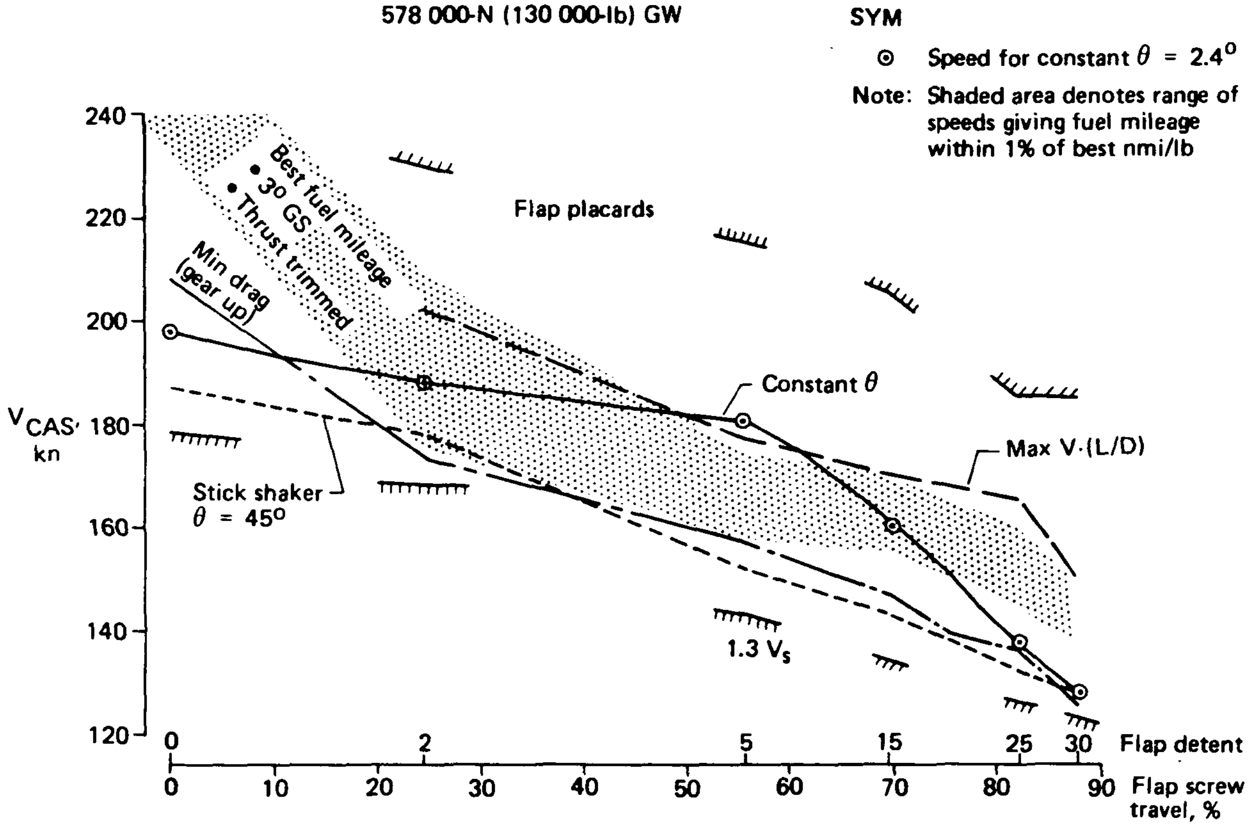


Figure 32.—Comparison of Constant θ Speed Schedule to Best Fuel Mileage, Minimum Drag, and Stick-Shaker Speeds

- EPR 1.2 (fig. 34); this is the minimum power setting that will ensure $N_1 \geqslant 55\%$, required for inlet anti-icing on cold day conditions

It is apparent that the ability to decelerate on glide slope in a clean configuration is marginal, even at idle power. When inlet anti-icing is required, a gear down, flaps ≥ 15 configuration must be used.

6.2.3.5 Noise Trends

Noise trend data showing the separate effects of varying thrust, speed, and configuration at constant altitude—304 m (1000 ft)—were developed for reference in defining the flight profiles. Unlike a stabilized approach, the delayed flap procedure allows power settings and speeds during the deceleration phase to be specified independently (within broad limits) of flap position. With a range of possible profiles, the noise trend data provided insight into the effects of individual parameter variations on the total computed noise. The noise trends concerning three aspects of the procedure were of particular interest:

- *Power Setting*—Thrust levels near idle are required to initiate the deceleration in a clean configuration on a 3° glide slope. However, higher power settings are preferable with respect to engine response time. Hence, the AEMS design criteria (table 7) require ad-

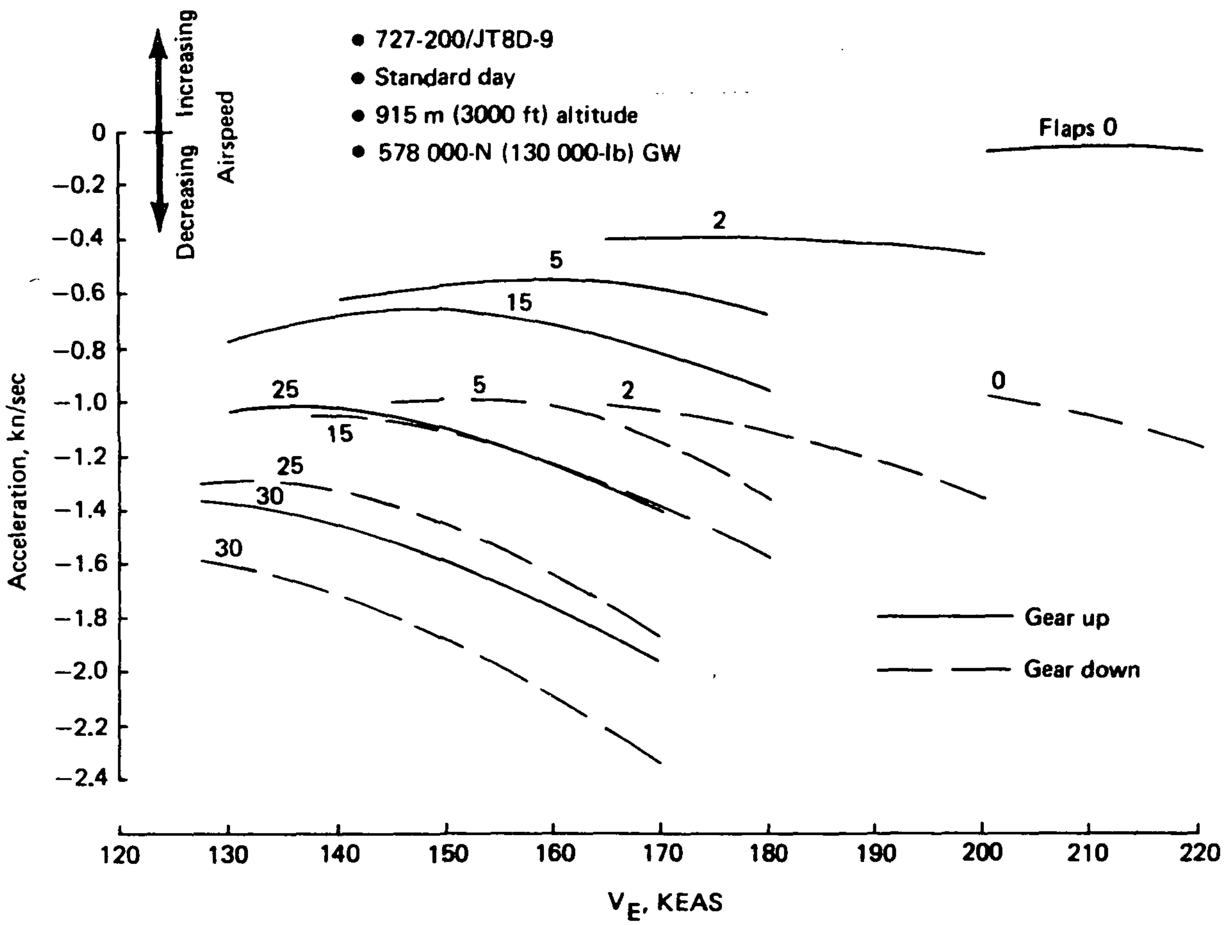


Figure 33. —Acceleration at Idle Thrust on 3°-Glide Slope

vancing power to EPR 1.1 prior to selecting the final flaps. Except for the adverse effect on noise, it would be desirable to select the higher power setting earlier in the approach (e.g., immediately after gear extension). The noise trends shown in figures 35 and 36 indicate that increasing thrust from IDLE to EPR 1.1 increases centerline noise about 3 EPNdB for untreated nacelles at the speeds and configurations of interest. This was considered to be a large enough noise increment to warrant retaining idle power as long as practical. Although thrust reductions are less effective at the higher speeds due to the airframe noise contribution, total noise decreases with thrust reductions all the way to idle power.

- *Speeds*—Total airplane noise is computed as the logarithmic sum of the airframe and engine contributions. For a given thrust level, airspeed influences total noise through the airframe noise contribution and through the time duration effect in the EPNL calculation. An increase in airspeed tends to increase the airframe noise contribution; but, through the time duration effect, also tends to reduce the EPNL. The overall effect of the speed increase on the EPNL depends on which is larger, the airframe noise effect or the time duration effect. This results in the crossover of the constant airspeed lines that is apparent in figures 35 and 36. At high power settings where

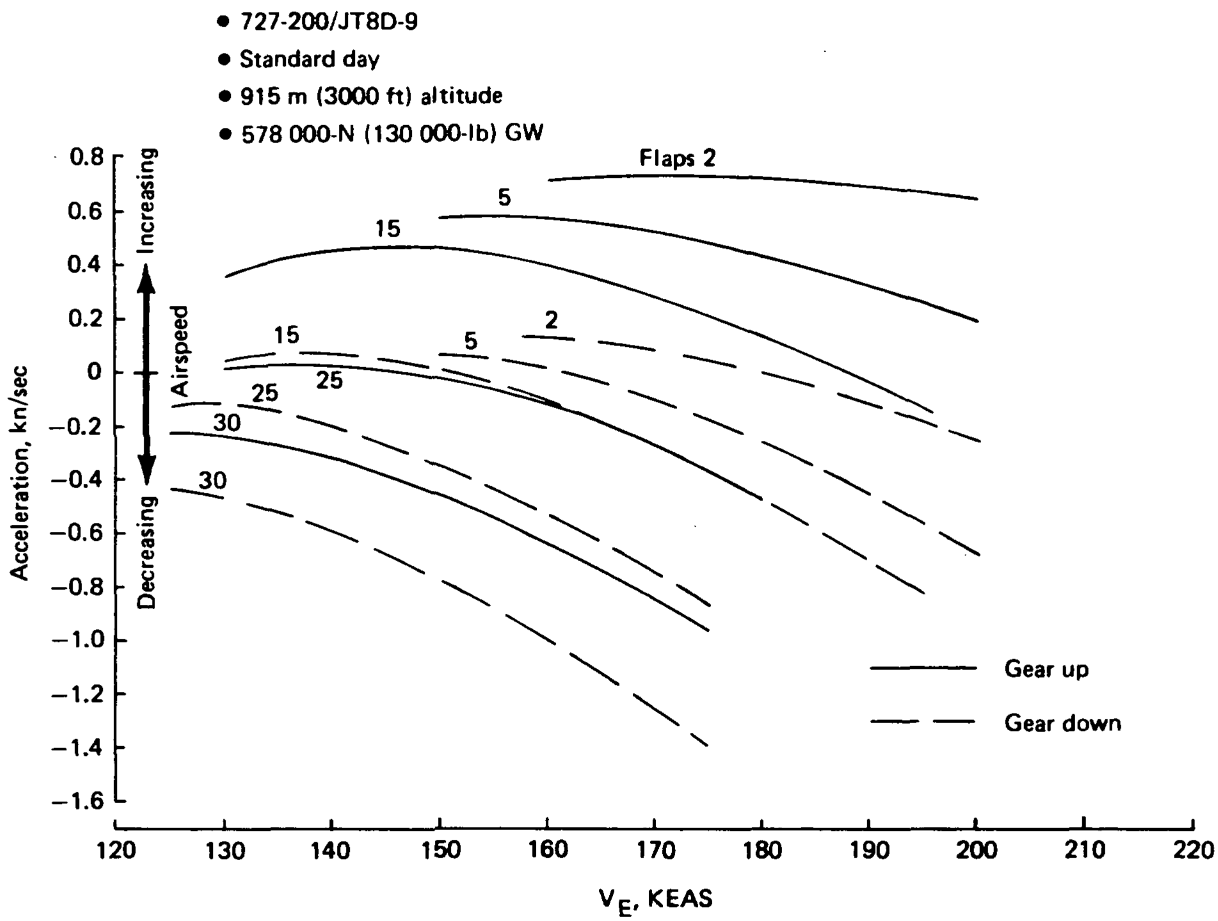


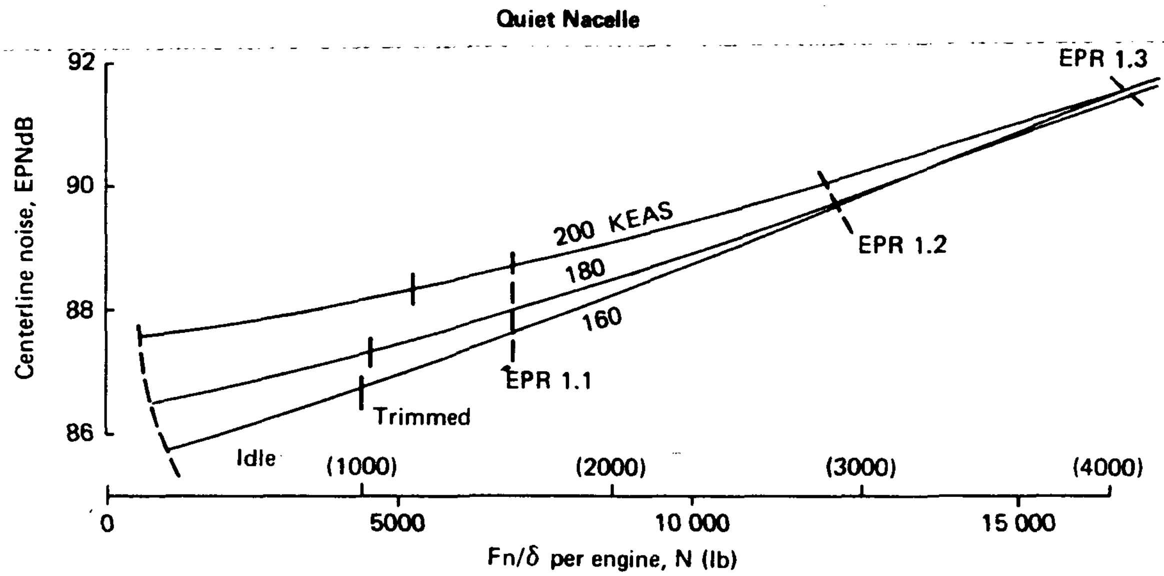
Figure 34.—Acceleration at 1.2 EPR On 3° Glide Slope

engine noise predominates, the total noise decreases as speed increases. The opposite trend is apparent at lower power settings where airframe noise predominates.

The variation of noise with speed at idle power is shown in figure 37 for various flap settings, gear up and gear down. Note that the curve is almost flat for the clean configuration, so the higher initial approach speeds do not penalize the noise benefits prior to flap sequencing.

The flap-extension speeds for the delayed flap approach speed schedule are a little higher than the minimum-noise speeds at idle power, particularly for flaps 2. However, the use of the higher speeds allows idle power to be maintained over a longer distance that extends the noise benefit over more of the community. In addition, the higher speeds reduce approach time, fuel, and pitch attitude variation.

- *Configuration Sequencing*— From figure 37 it is obvious that noise at idle thrust is minimized by maintaining a clean configuration as long as possible. There is a sizable increase in noise when either the gear or the flaps are extended. When gear and flaps



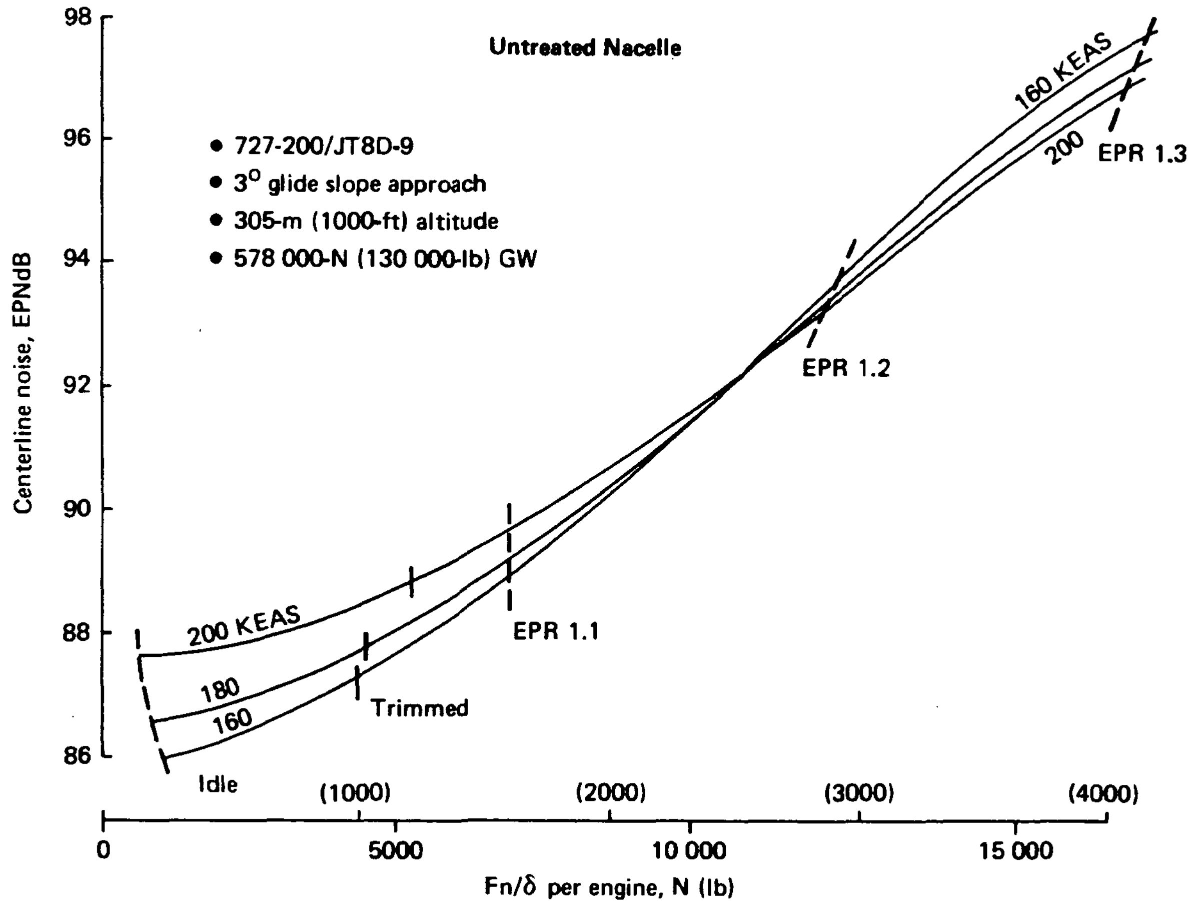
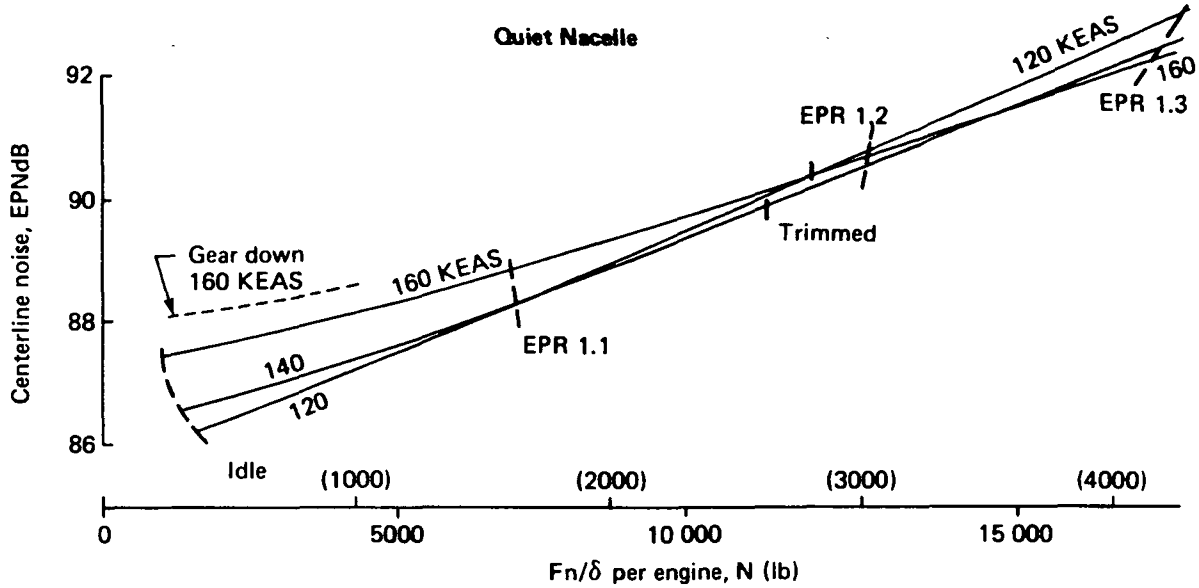


Figure 35.—Noise Variation with Thrust and Speed, Flaps 2°, Gear Up



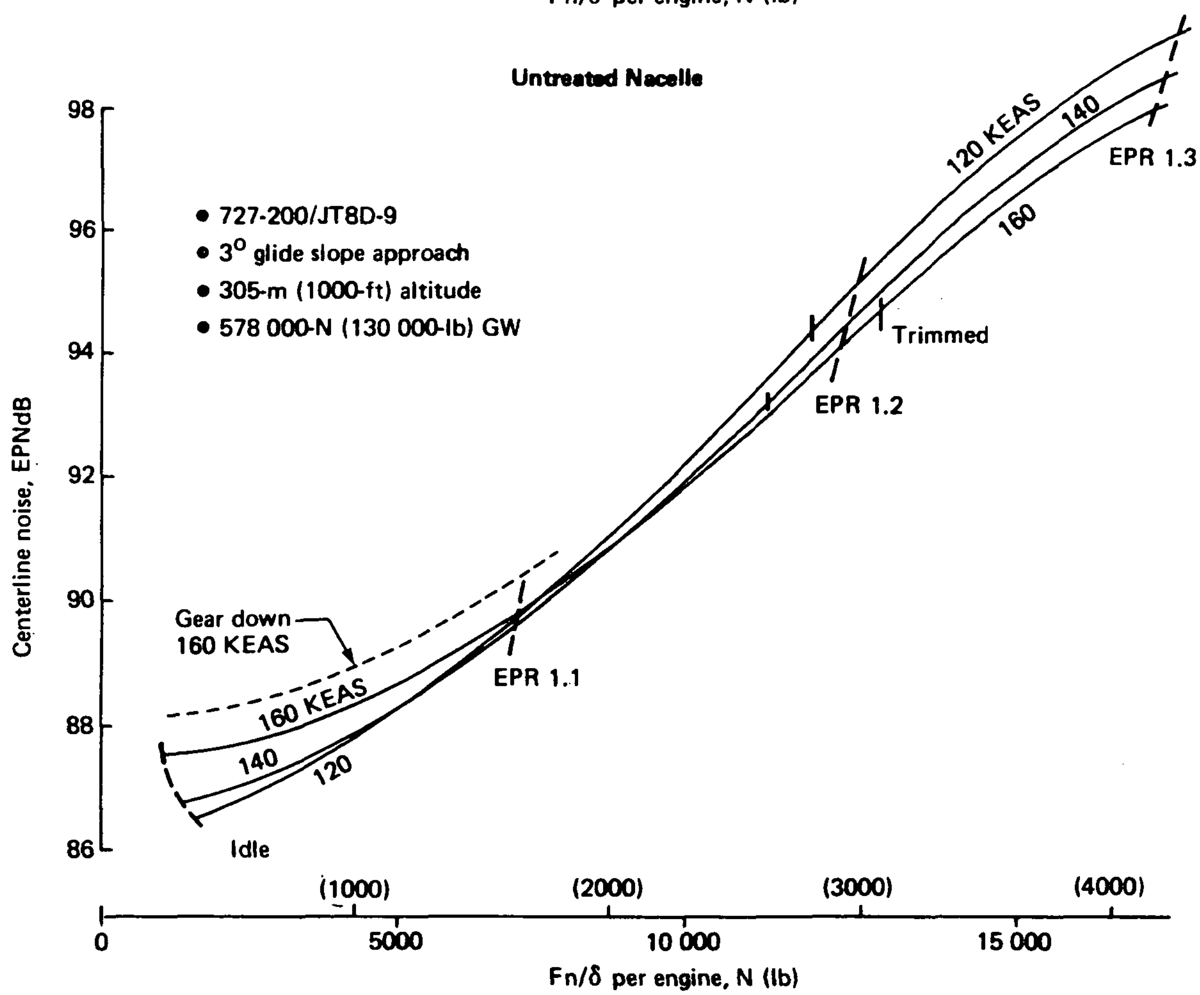


Figure 36.—Noise Variation with Thrust and Speed, Flaps 25°, Gear Up

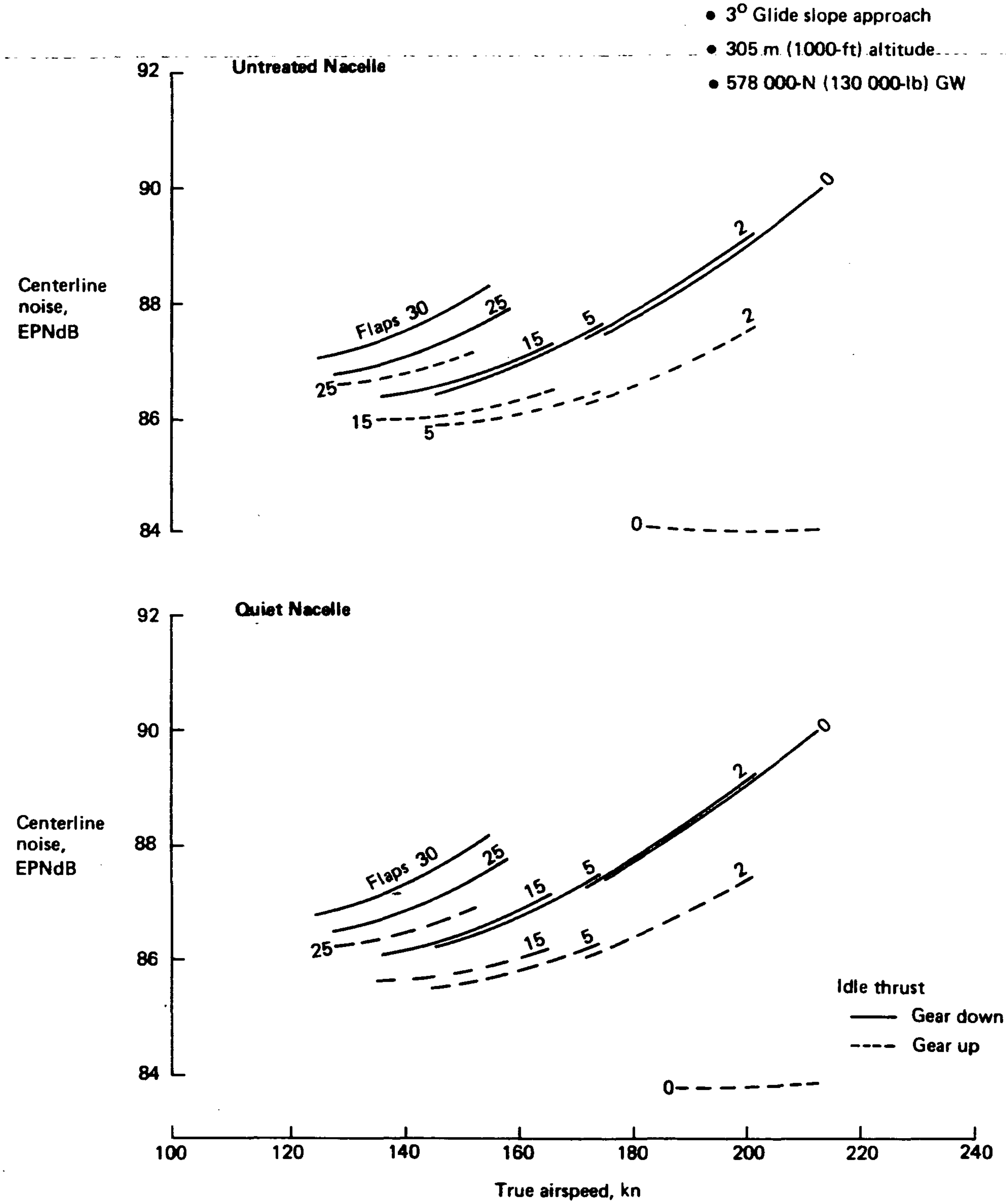


Figure 37.—727-200/JT8D-9 Noise Trends

are both extended, the additional noise increment due to the gear is larger at the higher speeds and reduced flap deflections. For the defined 727 speed schedules (table 8) the gear is extended in sequence following flaps 15, so the noise increment due to gear extension is less than 1 EPNdB.

From the noise trend data it was concluded that:

- Power settings should be the minimum consistent with safety and pilot acceptance
- The selected DFA speed schedules appear reasonable for noise abatement
- Flap and gear extension should be delayed as long as practical, and gear extension should not be scheduled prior to flaps 5

6.3 COMPUTER ALGORITHM

The algorithm concept and operation are previously discussed in section 4.0. Additional engineering details and results of the algorithm development phase of the study are presented below.

6.3.1 DEVELOPMENT SEQUENCE

After reviewing the CV-990 system, a basic algorithm was first developed for the configuration sequencing phase of the approach (see fig. 5b). The flight controls technology minicomputer (NOVA) was used to allow algorithm development to proceed in parallel with the 727 airplane simulation development. Further, the NOVA provided a convenient and economical way to obtain computed profiles for parametric studies and simulator checkout.

The algorithm was then added to the piloted simulation for further development and evaluation. Because of size and computation cycle time of the 727 airplane simulation, it was necessary to program the profile prediction portion of the algorithm on a separate minicomputer (VARIAN) interfaced with the main simulation computer (EAI-8400), where the remainder of the algorithm was programmed.

The basic algorithm contained all of the elements discussed in section 6.3.4. However, the initialization routine did not originally contain provisions for computing the IP, and the path geometry routine initially contained only the one-segment path plus energy compensation scheme (fig. 7). This setup generated all the commands and displays necessary to fly a complete delayed flap approach, if started from a suitable condition. Although the basic algorithm did not provide a fast/slow indication prior to the power cut, it was complete in all other respects and was used to evaluate flight profiles and to further develop the algorithm.

When the basic algorithm was functioning properly, the simulation was then modified to incorporate the IP concept for driving the fast/slow indicator during the initial approach phase (see fig. 5a). The complete algorithm was used in the final simulator evaluation, including the time/fuel/noise benefits comparisons, the NASA pilot evaluation, and subsequent Boeing demonstrations to ATA and ALPA pilots.

6.3.2 PROGRAM LANGUAGE

The algorithm was originally developed on the NOVA in the FORTRAN language. The algorithm for the piloted simulation was programmed in computer assembly languages on the VARIAN and EAI-8400 computers. Refinements developed on the simulator were then incorporated in the NOVA program.

The FORTRAN listing attached to the AEMS avionic specification (ref. 3) was obtained from the NOVA. While the FORTRAN listing is not precisely the same as the simulator programs, this approach provides a working program in a common language that defines the algorithm functions without introducing extraneous instructions peculiar to the simulation.

6.3.3 COMPARISON WITH CV-990 SYSTEM

The 727 algorithm concept is operationally similar to the CV-990 from the pilots' viewpoint. However, there are several differences in the detailed implementation. The differences resulted primarily because of the more numerous commands to be generated for the 727 and differences in gear/flap/power sequencing; i.e.,

CV-990 commands	727 commands
Idle	Idle
Gear down	Flaps 2
Flaps 10	Flaps 5
Flaps 36	Flaps 15
Approach power	Gear down Flaps 25 EPR 1.1 Flaps 30 Approach EPR

The CV-990 uses both forward and backward integration of $\frac{dV_G}{dt}$ to compute the profiles, whereas the 727 uses only forward integration of $\frac{dV_G}{dX}$. The CV-9900 algorithm precomputes and stores maximum and minimum V-X deceleration profiles based on flap extension at maximum and minimum speeds for three preselected wind conditions. The maximum and minimum profiles for the prevailing winds are obtained from the stored profiles by interpolation. The fast/slow indicator is scaled relative to these energy limits with the desired profile taken as midway between the two extremes. The 727 profile prediction takes the prevailing wind into account directly and bases the prediction on the desired profile rather than on the energy limit profiles. Although the fast/slow indicator does not provide an indication of energy limits, this feature could be added if required; e.g., by also integrating along maximum and minimum energy dissipation schedules. The 727 algorithm uses the same energy correction (phugoid approximation) as the CV-990 to compensate the profile predictions for deviations from the glide slope. However, prior to glide slope capture, the 727 concept employs an assumed path intercept geometry in lieu of the phugoid approximation.

6.3.4 COMPUTATIONAL FLOW SEQUENCE

A macroflow diagram of the algorithm is presented in figure 38. A more detailed diagram is contained in reference 3.

After the necessary inputs have been made on the pilots' control panel, the preliminary calculation routine computes and stores the minimum operational speed boundary (1.3 V_S) for each flap position. The routine also computes and stores the configuration selection speeds to be used in predicting the desired flight profile for the delayed flap approach. The minimum speeds vary with airplane weight only, while the desired profile speeds also depend on the final approach speed selected by the pilot and the status of the anti-icing switch. This section of the algorithm also sets up all constants and flags required to do the initialization for the V-X profile calculations.

In the *nav parameter update* section, the sensor information calibrated airspeed, altitude, distance, and groundspeed are updated, and true airspeed and glide path deviations are computed. Here, also, the warning flag (IWARN) is tested. If IWARN = 1, the computer is inoperable and resets all displays. The warning flag can be set by system failures or by an overspeed condition that would prevent stabilizing at the target altitude.

The *path geometry routine* uses airplane position, the glide slope angle set into the control panel, and the last computed IP distance to determine the path geometry. The geometry is updated prior to each profile prediction.

The *wind reference section* first computes the wind at flight altitude (V_W) from actual airspeed and DME groundspeed inputs. A reference wind at tower height ($V_{W_{ref}}$) is then computed for an assumed shear profile. This reference wind (filtered) and the same shear profile are later used in the V-X profile computation routine to define the assumed wind variation as computed altitude varies along the predicted profile.

The starting conditions for the profile computation are updated in the initialization section prior to each profile prediction. Normally, the starting conditions correspond to the actual airplane position, speed, configuration, and thrust. However, when computing the IP location, the prediction is initialized at the last computed IP position at the IP flight conditions. These are outlined in section 4.3.1. The initialization routine also contains logic that deter-

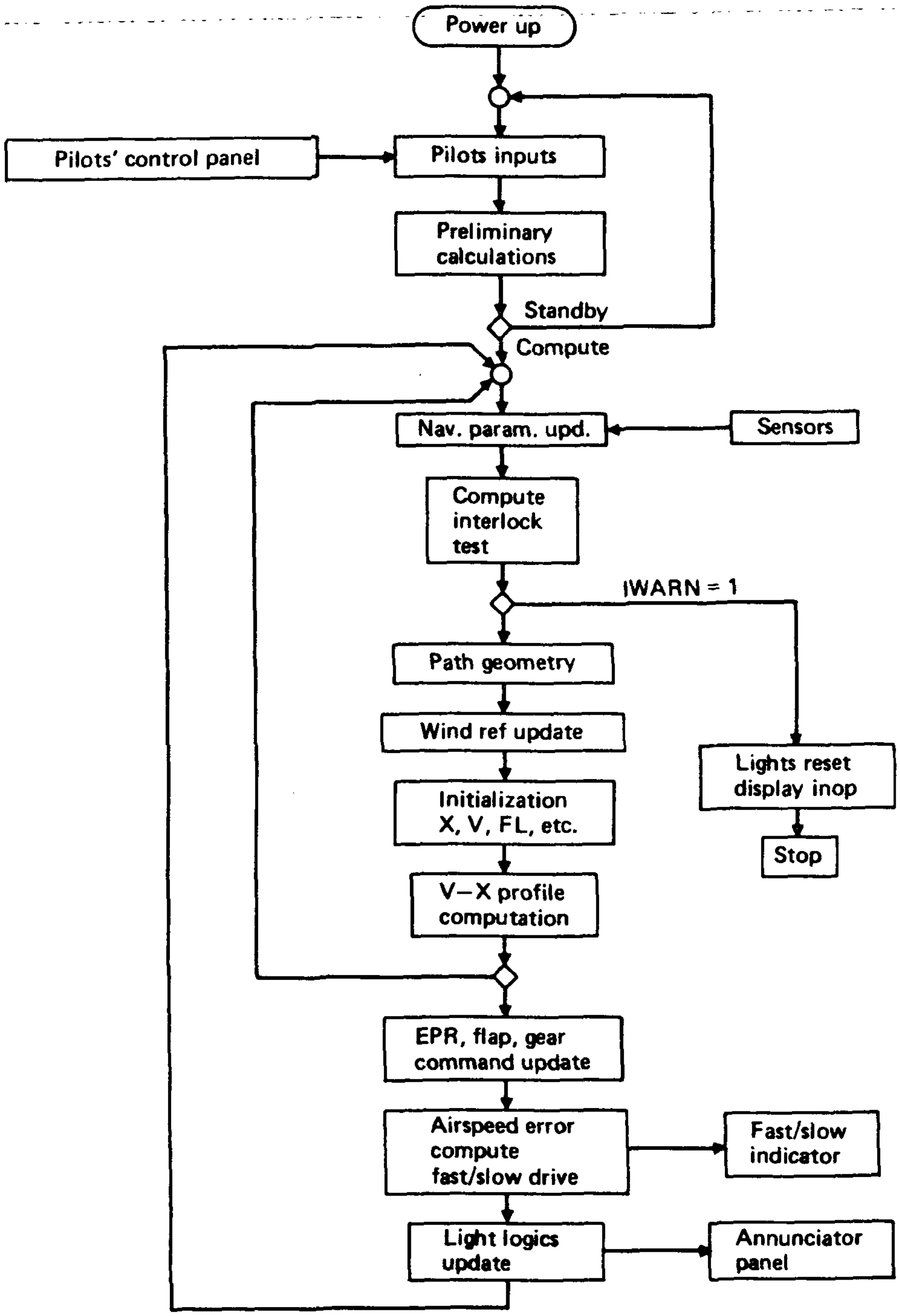


Figure 38.—727 AEMS Macroflow Chart

mines when an IP update is required and switches the starting conditions accordingly. The stopping point for the profile calculations is set at the same time. Normally, the profile calculation is stopped when the predicted speed reaches the final approach speed. However, it may also be stopped as a function of distance, e.g., to determine predicted speed error at the IP for display.

The profile computation loop predicts a flight profile between the beginning and end points set by the initialization routine. When the test speed or distance for terminating the profile computation is reached, the algorithm branches to the EPR, flap, and gear command update section.

A new command is generated whenever the speed at the end point is greater than desired or the distance is closer to the touchdown point than desired. However, if the airplane speed is higher than the placard speed, the command is not displayed. If an overshoot is predicted for the desired speed/configuration schedule, then a fast deceleration sequence is entered within the V-X profile computation loop to test if the overshoot could be prevented by extending flaps at the placard speeds. If so, the commands will continue to be given. If not, the warning flag will be set (IWARN = 1) and further computations halted.

After the commands are updated, the algorithm continues with airspeed error computation and fast/slow drive. Next the light logics for command display are updated, and the algorithm is then ready to cycle back to the NAV parameter update routine to begin X computation of a new V-X profile.

The algorithm continues to cycle through these routines until the last command has been generated, then continues to generate a fast/slow indication until the airplane reaches the runway threshold. At this point the computer commands and displays are cleared in the lights reset routine.

6.3.5 PROFILE PREDICTION

The profile prediction concept is depicted in figure 6. Thrust, lift, and drag are computed first and used together with glide slope angle and wind information to find the deceleration. The deceleration and the groundspeed are integrated numerically for step size Δt, using a simple rectangular integration routine to obtain the next point of the V-X profile. Groundspeed is converted to airspeed and the computation then cycles back to recompute thrust, lift, and drag for the next point, etc. At the same time at the scheduled airspeeds, the flaps and landing gear are lowered with the appropriate rates. Thrust changes are represented as first-order lags.

6.3.5.1 Deceleration Equation

The deceleration equation is programmed in the algorithm in the form:

$$\frac{dV_G}{dt} = g \cos^2 \gamma \left[\frac{F_n - D}{L} - \left(1 + \frac{V_W}{V_T} \cos \gamma \right) \tan \gamma \right] \qquad (1)$$

6.3.5.2 Configuration Sequencing

The thrust and drag terms of equation (1) are updated as the computation progresses to reflect the preprogrammed configuration/thrust command sequence. The starting configuration normally is the same as the actual airplane configuration. (The IP calculation is an exception.) The profile prediction then begins with the next command to be displayed to the pilot; e.g., if at flaps 2, the prediction would begin with the flaps just starting to move from 2 to 5.

The sequencing logic is implemented by a set of counters within the digital program, which are first set to the desired initial condition (e.g., synchronized to match actual airplane flap and gear position). The counters are then incremented to denote configuration changes as the profile computation progresses. The counters are reset prior to each profile prediction, so any configuration change made by the pilot would automatically be reflected in the initial conditions for the next prediction.

6.3.5.3 Thrust

The thrust calculation assumes three engines operating at equal power setting. Steady state curves converting power setting into corrected net thrust (F_n/δ) are used. The atmospheric pressure ratio (δ) and Mach number are computed for the instantaneous condition to obtain total net thrust (F_n).

It was found necessary to include the initial power setting and the effects of engine dynamics to obtain sufficiently accurate modeling of the airplane deceleration profiles. The thrust calculation for this feasibility study only provides for standard day conditions.

6.3.5.4 Lift Coefficient

The lift coefficient calculation was simplified considerably by using calibrated airspeed instead of equivalent airspeed. This was done because the complicated conversion formulas would slow down the profile computation, thereby losing accuracy in the timing of the commands, while gaining little in the computation of the correct speed.

6.3.5.5 Drag Coefficient

The drag coefficient (C_D) calculation includes polars for every flap detent that were curve-fit with the data points used in the airplane simulation in the region between V_{ref} and the flap placard.

The drag for two flap detents is used to interpolate to the actual flap position. Landing gear drag is calculated separately; gear transition effects are included, but speed brake drag is not.

6.3.5.6 Path Geometry

The path geometry (γ) routine determines the initial (γ_2) and final (γ_{GS}) path angles and the intersection point for switching the value of γ in the deceleration equation from γ_2 to γ_{GS}. The logic is depicted in figure 7.

6.3.5.7 Wind Profile

The profile prediction uses the ARB wind shear profile (ref. 5) to account for wind variations along the computed profile. The ARB profile is defined by the equation

$$\frac{V_W}{V_{W_{ref}}} = 0.43 \log_{10} h + 0.35 \qquad (2)$$

where V_W is the wind at the altitude (h), which varies along the computed profile. The logarithmic function was approximated by

$$\frac{V_W}{V_{W_{ref}}} = \frac{(2.226\ h + 2893)}{(h + 2152)} \qquad (3)$$

in the algorithm, to simplify the computation.

The referenced wind velocity $\left(V_{W_{ref}}\right)$ at 10 m tower height (33 ft) is held constant during each profile prediction. The reference wind is computed onboard (i.e., not set by the pilot) and is updated prior to each profile prediction.

6.3.6 PROFILE MATCHING

It was found necessary to model the thrust and drag quite accurately to obtain commands at their scheduled speeds, for the nominal no-wind case, particularly for the low drag configurations. The explanation is found in the low deceleration rates and the small deceleration changes between the initial configurations. A small error in the deceleration slope, therefore, projects into a large speed change to make up for the drag error between the modeled and the real airplane.

This error in the timing of the initial configuration change commands does not affect the accuracy of the end point of the deceleration, but it could affect the pilots' workload if the commands bunch together or if the speed deviations require large attitude changes to track the glide slope.

6.3.7 COMMAND GENERATION

The first configuration/thrust change assumed in the profile prediction (sec. 6.3.5.2) is also used to arm the corresponding command circuit to the pilots' annunciator panel. Normally, the command will be illuminated when the profile prediction indicates that the final speed will be reached at (or below) the target altitude. An exception is the initial power cut command that is based on predicted speed at the IP.

If exactly on the desired profile, the commands will be displayed at the desired speeds. The algorithm will shift the commands to higher speeds to decelerate faster in case of an overspeed condition and to lower speeds to decelerate slower in case of an underspeed condition. However, a command that would violate placard speed is inhibited until the placard speeds are cleared. Similarly, if during deceleration a speed equal to or less than 1.3 V_S is reached for any flap detent position, a command is generated to go to the next flap detent.

6.3.8 FAST/SLOW SCALING

Although the fast/slow should be interpreted as meaning high or low on energy, the algorithm output to the instrument is in speed units. The fast/slow displays two types of information depending on the approach phase (fig. 5) with scaling as follows.

Phase	Data displayed	Half-scale indication (to first index mark)
I	Speed error predicted at the IP	20 kn
II	Speed deviation from desired profile[a]	10 kn

[a]*Desired* profile is stored when each command is given. Below the stabilization point the *desired* speed is constant at the VFINAL selected by the pilot.

The 20-kn scaling for Phase I gives the pilot an indication of whether or not to use speed brakes prior to the IP. If the fast indication is below the first index mark (20 kn), the airplane will arrive at the IP at less than the flap placard speed. The Phase II scaling is expanded for better sensitivity on final approach.

6.4 SIMULATION

A low-speed six degree-of-freedom fixed-base simulation of the 727 was implemented on the Boeing engineering simulator at Renton, Washington. Programming and checkout of the basic airplane simulation were initiated immediately upon contract go-ahead and proceeded in parallel with development of the AEMS computer algorithm, which was later added to the simulation. The simulation included a jet transport cockpit and TV display.

6.4.1 BASIC AIRPLANE SIMULATION

Existing aerodynamic, powerplant, and flight control system data for the 727 were programmed into an existing, standard simulation model. Aerodynamic data were included for flap detents 0 through 30, with particular attention given to accurately representing drag, pitch attitude, and stabilizer trim characteristics. The flight control system models included the pitch and roll autopilots and flight directors in addition to the manual controls and yaw dampers.

The engine model was tailored to closely represent JT8D-9 steady state thrust and dynamic response at low power settings. Fuel flow and centerline noise calculation routines were included, which provided realtime outputs to the data recorders. The noise routine calculated the combined airframe and engine noise for both untreated and quiet nacelles. This was done by computing airframe noise and engine noise independently of each other, and summing the values logarithmically to obtain the total aircraft noise. The airframe noise was obtained as a function of gear and flap position from data tables for reference values of speed and altitude. The output of the tables was then adjusted by an equation that accounted for speed and altitude variations from the reference. The engine noise was obtained from tables that provided engine noise as a function of corrected net thrust (F_n/δ) for a family of constant altitude lines. These data were then adjusted for speed variations from the engine noise data reference speed. The engine noises for untreated and quiet nacelles were individually summed (logarithmically) with airframe noise to obtain the total noise for each configuration. The output of the simulator noise model agreed within ±1.5 EPNdB of 727 certified noise levels and other Boeing noise test data.

Before conducting piloted evaluations of the DFA procedures, the basic 727 simulation was validated against flight test data in those areas considered pertinent to this program. This included:

- Angle of attack, stabilizer, elevator positions, and airplane drag for trimmed flight at several speeds, flap and gear settings, and c.g. locations
- Airplane acceleration, deceleration, rate of climb, and rate of descent at several power settings
- Engine fuel flow, pressure ratio (EPR), low pressure compressor speed (N_1), and net thrust (F_n) for engine transient and steady state conditions
- Engine acceleration and deceleration response at normal and low power settings
- Total airplane noise (airframe and engine) for FAR 36 certification points and for other available flight test points
- Stabilizer trim motor rates and position limits for manual and autopilot trim
- Flap rates/operating times
- Gear extension times
- Autopilot/flight director performance for localizer and glide slope capture and tracking

- Primary flight control system characteristics in terms of column/wheel/rudder pedal forces, gearing, limits, hysteresis, and dead zones

Short period pitch response was compared to a computed response for a column step input and was evaluated on the simulator by the Boeing test pilot assigned to this project. Lateral/directional dynamic characteristics such as Dutch roll and turn coordination were not emphasized in the DFA simulation evaluation. However, detailed comparisons with flight data were made as part of a separate Boeing simulator improvement program, and qualitative lateral/directional checks were made by the DFA simulation validation pilot.

Some deficiencies were noted during the simulation checkout and validation process, and most were corrected as part of the separate Boeing simulator improvement program. The completed simulation was judged to be adequate for the DFA evaluation, and, in general, quite good. The most significant unresolved pilot complaints were that pitch control was not as precise as in the actual airplane and that excessive column input was required to control pitch when flaps were extended from 25 to 30 and power was advanced from idle to approach power. The Boeing evaluation pilot flew several DFA approaches (on a noninterference basis) during scheduled Boeing test flights, and concluded that pitch control in the areas noted above was easier in the airplane than on the simulator.

6.4.2 AEMS SIMULATION

The AEMS computer algorithm was simulated by programming the path prediction routine on a VARIAN computer that was interfaced with the EAI-8400 computer containing the basic airplane simulation and the command logic portion of the algorithm. Considerable difficulty was encountered in debugging the algorithm simulation; but once operating, it worked quite well. No significant changes were required to the fundamental algorithm concept definition, although several improvements were made based on simulation results.

The cockpit displays used for the AEMS simulation are shown in figure 39. The moving bug on the airspeed indicator was used for simulation convenience in lieu of multiple plastic bugs but is not included in the system specification. Annunciator lights rather than the numeric displays defined in the system specification were used to reduce simulation hardware costs and programming time.

Note: For engineering simulation use only.

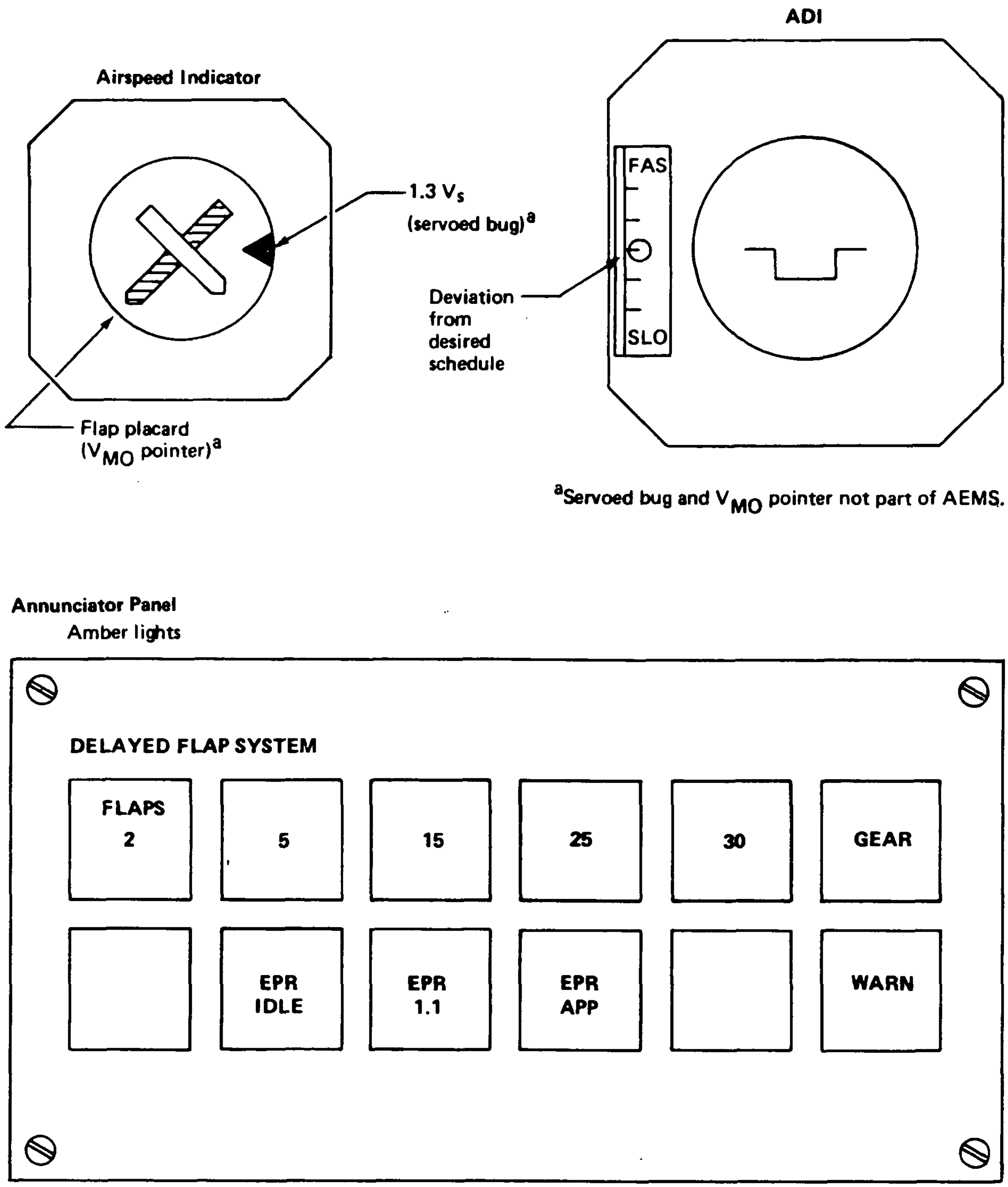


Figure 39.—Cockpit Displays For Delayed Flap Simulation Studies

7.0 EVALUATION

The development and evaluation phases overlapped somewhat, in that modifications were developed to correct significant deficiencies as they were noted. During this combined development/evaluation process, the simulator evaluations were conducted by the test engineers (autopilot) and by one Boeing test pilot assigned as the project pilot for this study. When the simulation appeared satisfactory for purposes of this study, the NASA project pilot evaluated the 727 delayed flap procedures for conformity with the NASA CV-990 concept. The simulation was then "frozen," and further evaluations were conducted by additional Boeing pilots to assess workload, checklist compatibility, and fuel/noise benefits.

Fuel and noise data were also computed independently by unpiloted computer routines (sec. 5.0). Correlation with simulator results was good.

Compatibility with existing systems was evaluated on the basis of simulator results and engineering experience. Availability of required equipment (e.g., fast/slow indicator) was briefly reviewed for the 727-200 fleet.

7.1 PILOT EVALUATION

7.1.1 FLIGHT PROFILES AND PROCEDURES

The Boeing project pilot assisted in development of the procedures and display concepts. During the course of this development process, the speed/configuration schedules were evaluated for a number of conditions as summarized in table 11. Both manual and autopilot control were tested. To reduce costs, the simulation vision system was used only when checking for attitude variations and for stabilization height. Otherwise, the approaches were flown entirely IFR and terminated at the runway threshold.

A majority of the runs were made with the pilot following the commands displayed on the annunciator panel and using normal glide slope tracking technique following capture at an altitude of 915 m (3000 ft). Except for the strong headwind case where the configuration scheduling needs improvement, the AEMS performed satisfactorily. To check operational flexibility of the system, other conditions were flown in which a different flightpath was followed or the pilot deviated from the computed configuration sequence. Three general types of conditions, which might be expected to occur routinely, were tested with results as shown in table 12.

The simulation was then flown by the NASA project pilot with the technical monitor observing. Both concluded that the 727 AEMS operation was quite similar to the CV-990 from the pilots' point of view.

Table 11.—Evaluation of Nominal Profiles

Test series	Conditions tested	Test pilot and engineer comments
1. Normal profile checks	1. Matrix of cases C.G. / WT / Wind	1. Able to track glide slope and remain in trim. Pitch changes and column forces not excessive. Busy at end of approach but OK for VFR.
a. Weight	Mid Avg Calm Mid Max Calm Mid Min Calm	a. Weight change not apparent except for different speeds. Below current maneuver speeds at lighter weights.
b. C.G.	Fwd Avg Calm Aft Avg Calm	b. C.G. variation shifts command speeds (5-kn max).
c. Wind (with ARB shear profile)	Mid Avg 10-kn tail Mid Avg 30-kn head Mid Avg 15-kn cross	c. Profile OK in 10-kn tailwind. Two problems in strong headwind. • Gear extension below 305 m (1000 ft) • Commands too close together at low altitude. Crosswind has no apparent effect.
2. Stabilization	2. 91, 152, 244, 305 m (300, 500, 800, 1000 ft)	2. Less work and better tracking precision if stabilized higher. Pitch autopilot tracking unsatisfactory for 91-m (300-ft) stabilization. Suggested minimums: 152-m (500-ft) VFR; 244- to 305-m (800- to 1000-ft) IFR.
3. High field elevation	3. 1524 m (5000 ft)	3. Deceleration starts sooner; OK.
4. Trimmability checks	4. Hands off at 91 m (300 ft) also, Autopilot disconnect at several points	4. Requires attention but can be in trim at 91 m (300 ft). Thrust trim more difficult than pitch. Acceptable autopilot disconnect transients for worst case. In trim at 91 m (300 ft).
5. Turbulence	5. Spot checked in light turbulence	5. No apparent problem, but needs more evaluation.

Table 12.—Evaluation of Other Profiles

Condition checked	Comments
1. Speed reduction requested by ATC which requires extending flaps prior to first flap command	1. OK, except the fast/slow indication is confusing. The fast/slow is centered following the initial power cut. When flaps are extended prematurely, the system resets and gives a slow indication meaning power cannot be left at idle. However, airplane is actually fast for the selected flap.
2. Glide slope capture at altitudes from 457 to 1219 m (1500 to 4000 ft)	2. OK.
3. High and fast	3. OK to a point, as system advances flap commands to compensate. However, system presently will not take gear out of normal sequence so overshoot warning will be given unnecessarily.
4. Low and slow	4. OK to a point, as system delays flap commands to compensate. At present, system commands next flap at 1.3 V_s. This concept and the need for additional speed monitoring require more evaluation.

7.1.2 FUEL/NOISE COMPARISONS

Two other Boeing pilots, one from Crew Training and one from Production Test, flew a series of approaches for the final fuel/noise comparisons, as described in section 5.5. The simulator data presented in this report were taken from runs by these pilots.

7.1.3 CHECKLIST COMPATIBILITY

Total crew workload and checklist compatibility were evaluated by a normal 727 three-man crew. The crew consisted of a pilot and flight engineer from Crew Training who had not previously flown the procedures, in addition to the Boeing project pilot who acted as First Officer. Computer setup was accomplished as part of the descent checklist. All checklist items and other callouts for an ILS approach to 61-m (200-ft) minimums were made as the delayed flap approach was flown manually under IFR conditions. It was concluded that the checklist could be completed above a 152-m (500-ft) stabilization height, but that to do so required more crew alertness than for normal ILS procedures. However, the crew workload and checklist completion was considered a little easier than for current IFR nonprecision approach procedures.

With current airline procedures, the landing checklist (table 13) is performed following gear extension. The delayed flap approach delays gear extension to about 305 m (1000 ft) of altitude which was considered marginally satisfactory in terms of crew workload. If the

Table 13.—727 Normal Checklist (with AEMS Added)

After Takeoff

Ignition	OFF/ON	F/E
No smoking and seat belt	OFF/ON	F/E
Anti-ice	CLOSE/OPEN	F/O
Gear	UP & OFF	F/O
Flaps	UP, NO LIGHTS	F/O
Hydraulics	PRESS & QTY NORMAL	F/E
Pressurization	CHECKED & SET	F/E
Autopack trip switch	CUTOUT	F/E
After takeoff checklist	COMPLETE	F/E

Descent Approach

Seat belt	ON	F/E
Anti-ice	CLOSE/OPEN	C,F/O
Landing lights	ON	F/O
Altimeters	SET & X-CHECKED	C,F/O
Radio altimeter	SET	C,F/O
Flight instruments, FDS and radios	SET & X-CHECKED	C,F/O
Go-around EPR and V_{ref}	BUGS SET	ALL
➧ AEMS	SETUP	
Fuel	SET FOR LANDING	F/E
Hydraulics	PRESS & QTYS NORMAL	F/E
Pressurization and cooling doors	SET	F/E
Circuit breakers	CHECKED	F/E
Descent approach checklist	COMPLETE	F/E

Landing

Antiskid	NO LIGHTS	F/E
Ignition	ON	F/E
Speedbrake lever	ARM, GREEN LIGHT	C
No smoking	ON	F/E
Gear	DOWN, IN, 3 GREEN	C
Flaps	GREEN LIGHT	C
Hydraulics	PRESS & QTYS NORMAL	F/E
Landing checklist	COMPLETE	F/E

Reference: B727 Operations Manual, 15 July 75 procedures were used operationally, the checklist sequence should be reviewed; e.g., it might be necessary to turn on the NO SMOKING sign before gear extension to give the flight attendants time to check seat belts, etc.

7.1.4 OVERALL

The consensus of the Boeing pilot opinion was that the procedures are reasonable on the simulator, provided a stabilization height of 800 to 1000 ft is used for IFR, but there are still a lot of rough edges to be worked out before the system could be used operationally.

7.1.5 DEMONSTRATIONS

After the Boeing evaluation was complete, the 727 simulation was demonstrated to the ATA and ALPA pilots, Captains Bob Byrd and Ray Lahr, respectively, who had also flown the CV-990 system, and who subsequently reported their observations at the NASA RTAC conference, May 11, 1976 at Edwards AFB.

7.2 DISPLAYS

Cockpit displays were partially evaluated using the simulation hardware (sec. 6.4.2). To avoid the expense of building and programming the various control panel and annunciator panel configurations, paper mockups were used in lieu of actual hardware. These were positioned in the cockpit and discussed with the pilot. While suitable for purposes of this study, further evaluations should be done with actual hardware.

7.2.1 ANNUNCIATOR PANEL

The configuration used in the simulator (figure 39) was too confusing and too far out of the pilots' normal scan range for an operational system. However, several useful conclusions were drawn:

- *Alert Light*—Because of the numerous commands, the 727 simulator display looked too much like a pinball machine when the CV-990 concept of a steady alert plus a flashing command were used. Pilots tended to make the configuration change as soon as the alert light came on instead of waiting for the command. In addition, the alert feature added considerable complexity to the 727 algorithm, and it was quite difficult to obtain the same alert time for all commands. Consequently, the alert light was eliminated. The current 727 concept is to wait until it is time to make the configuration change, and then turn on a steady light.

- *Flap Command Light*—Originally, the flap command lights were programmed to stay on until the flaps had reached the commanded position. This was annoying, so the logic was changed to turn the light off as soon as the flaps started to move toward the commanded position.

- *Thrust Command Light*—The first concept tried was to turn off the light when the commanded EPR had been reached. However, because of engine lags at low power settings, there was a tendency to push the throttles too far, resulting in an overshoot of the desired EPR. This tendency was considerably reduced by using throttle position rather than EPR to turn off the light. The pilot can now advance throttles until the light goes out and then make a small adjustment, if necessary, after the engines have spooled up.

- *Separation*—Because of the sometimes simultaneous EPR and flap commands, it is essential to configure the annunciator panel so as to easily distinguish which is which.

7.2.2 FAST/SLOW INDICATION

The fast/slow indication concept was modified several times during the study, and was finally "frozen" for purposes of completing the remainder of the study. The concept, as currently simulated and defined in the preliminary avionic specification, is still not entirely satisfactory. The basic problem is that the one instrument is being used to present several types of information. The result is that the pilot has to remember that the same indication can require a different action (or nonaction) depending on the approach phase; i.e.,

		Meaning of fast/slow indication and pilot action expected	
	Approach phase	Fast	Slow
I	Prior to first flap command	Excess energy. Cut power. If more than one-half scale, with flaps up, extend speed brakes.	Not enough energy to complete approach at idle power. Action depends on situation. Use thrust to control airspeed determined by pilot.
II	Configuration sequencing	Excess energy. Do nothing except recheck configuration and wait for next command.	Low energy. Recheck configuration. Add power if beyond one-half scale.
III	Final	Too fast. Reduce power if out of normal speed tolerance band.	Too slow. Add power.

Although complicated, this logic might be satisfactory with sufficient training and experience if the desired profile could be flown without interruption. However, the situation becomes more confusing if it becomes necessary to extend flaps after the power has been cut but before the first flap command has been given. The fast/slow, which was centered (or fast) at the time of the power cut, will suddenly indicate slow when the flaps are extended prematurely. This is confusing because the flaps were probably extended to reduce speed. If the pilot mentally "shifts gears" back to the start of Phase I, he will ignore the slow indication and fly basic airspeed to determine power setting. In this case he was at idle power, so he must advance power to hold the desired speed. When the doughnut centers again, he can cut power again.

Other examples could be cited, but the point is that the whole fast/slow and speed monitoring concept should be carefully reviewed. While providing some indication of both energy limitations and speed deviation, the 727 algorithm does not do a particularly good job with either function. The best solution may be to use the fast/slow for the more customary function of speed monitoring and to provide a separate energy indication.

7.3 SYSTEMS COMPATIBILITY

7.3.1 AUTOPILOT/FLIGHT DIRECTOR

The autopilot and flight director were checked for compatibility with the AEMS. Particular attention was given to the effects of glide slope and localizer captures at higher than usual speeds and at different flap settings. Also the effect of configuration changes on glide slope tracking was evaluated. Both autopilot and flight director were found to be compatible with the AEMS. As illustrated by figures 40 versus 41 (flt dir) and figures 42 versus 43 (AP), the delayed flap procedures had little effect on glide slope tracking for stabilizaton altitudes as low as 152 m (500 ft). However, glide slope tracking became unacceptable for stabilization altitudes below 152 m (500 ft). No autopilot/flight director modifications are expected to be required for compatibility with the recommended procedures.

7.3.2 ENGINE AND ANTI-ICING SYSTEM

The delayed flap approach is satisfactory for nominal JT8D-9 response characteristics. The power setting is increased from idle to EPR 1.1 well in advance of the stabilization point, and the engine is operating at normal power settings below 152 m (500 ft)–VFR and 305 m (1000 ft)–IFR. The EPR 1.1 setting is near the surge bleed valve operating point so reasonably fast acceleration can be achieved, if required.

When engine-to-engine variations (e.g., due to wear or manufacturing and maintenance tolerances) are considered (not part of this study), it may be necessary to use a specific EPR setting in lieu of throttles idle for the first power setting. An EPR slightly above the nominal idle position would have two advantages: (1) the thrust could be predicted more accurately, which would give better profile matching, and (2) engine acceleration following prolonged dwell at the specified EPR would be more consistent than if allowed to stabilize at throttles idle. This would not alter the concept, and the increase in noise and fuel consumption would probably be imperceptible.

In the case of icing conditions, the profiles must be modified to maintain $N_1 \geqslant 55\%$ for inlet anti-icing. An EPR of 1.2 is the minimum that would ensure this. When wing deicing is needed, the required power setting ($N_1 \geqslant 80\%$) is so high that a stabilized approach must be flown.

7.3.3 EQUIPMENT AVAILABILITY

The AEMS requires a fast/slow indicator on the ADI. Equipment lists for 825 airplanes operated by 14 domestic airlines were reviewed for fast/slow indicator availability. Results were:

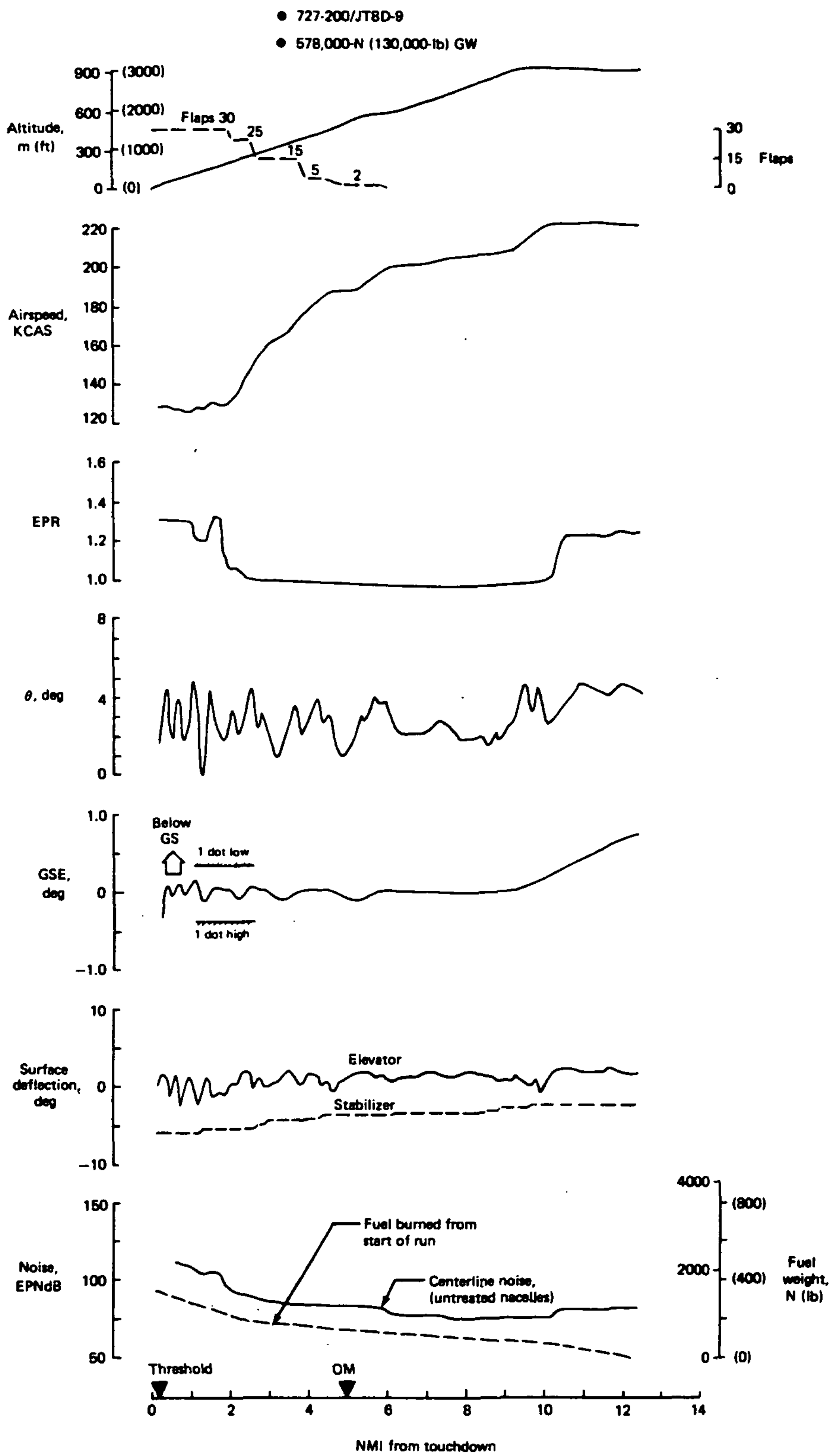


Figure 40.—Simulator Data for DFA-1, Manual Control, Still Air

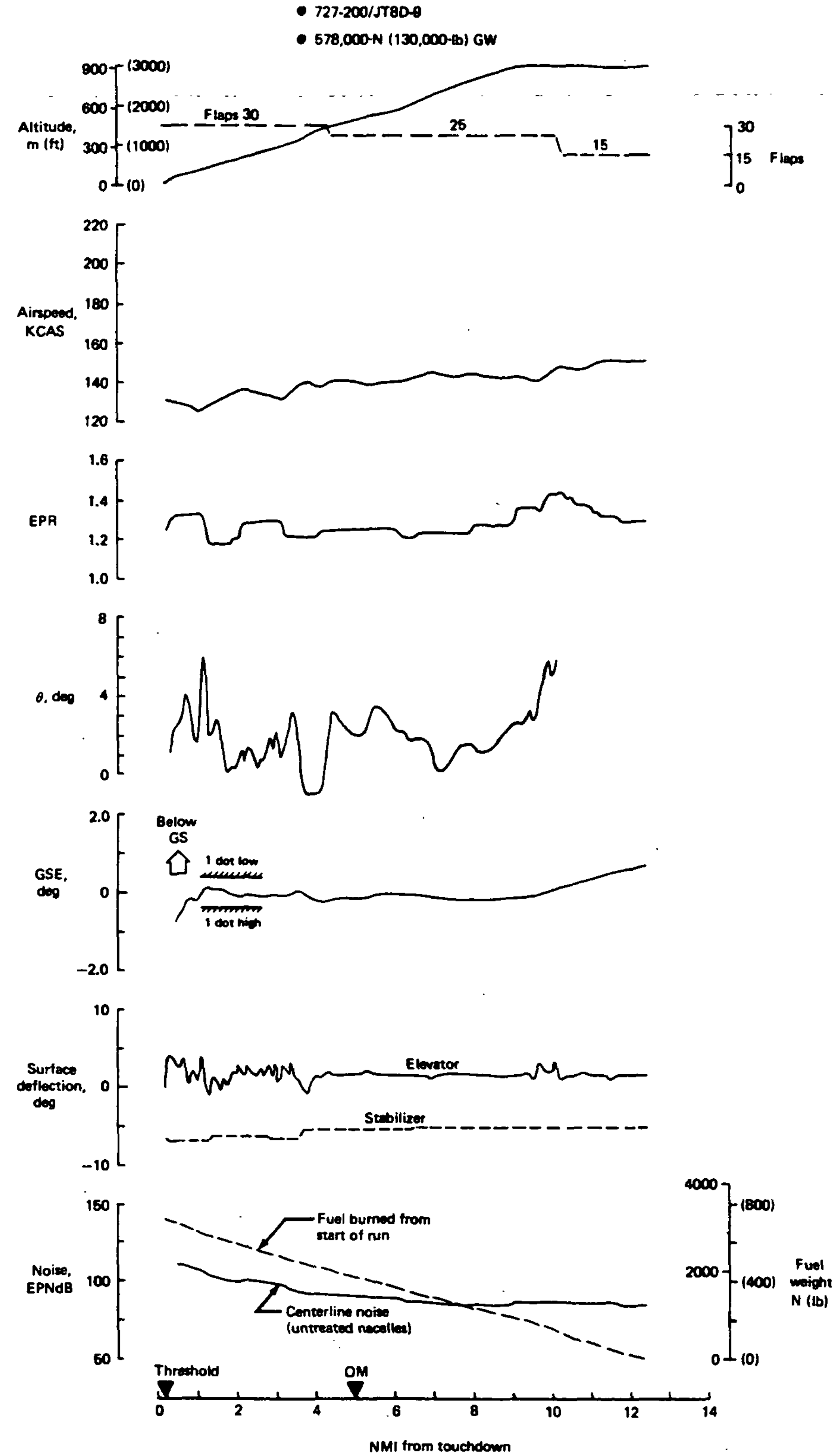


Figure 41.—Simulator Data for Current Airline Procedure (A-1), Manual Control, Still Air

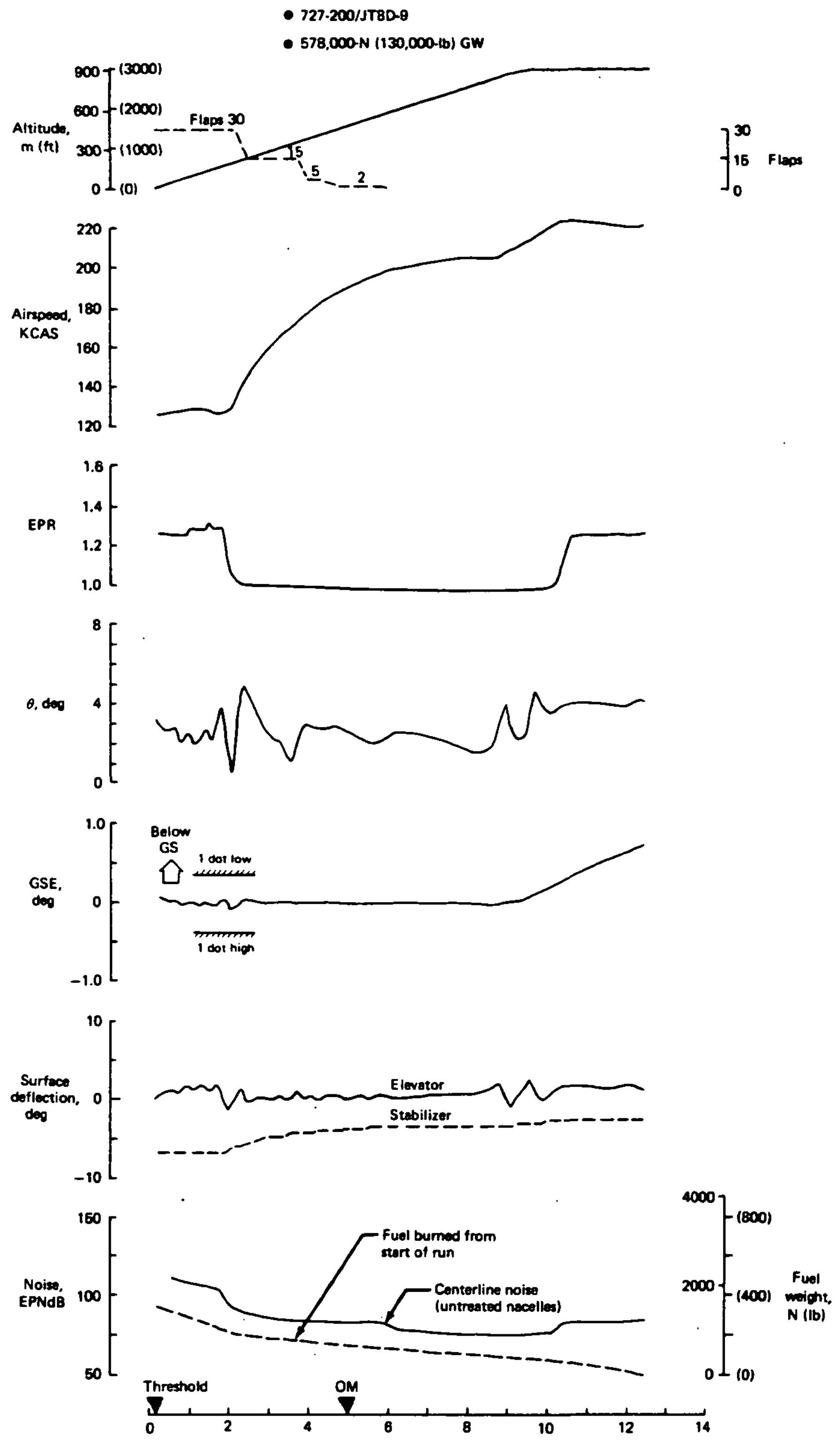


Figure 42.—Simulator Data for DFA-1, Autopilot On, Still Air

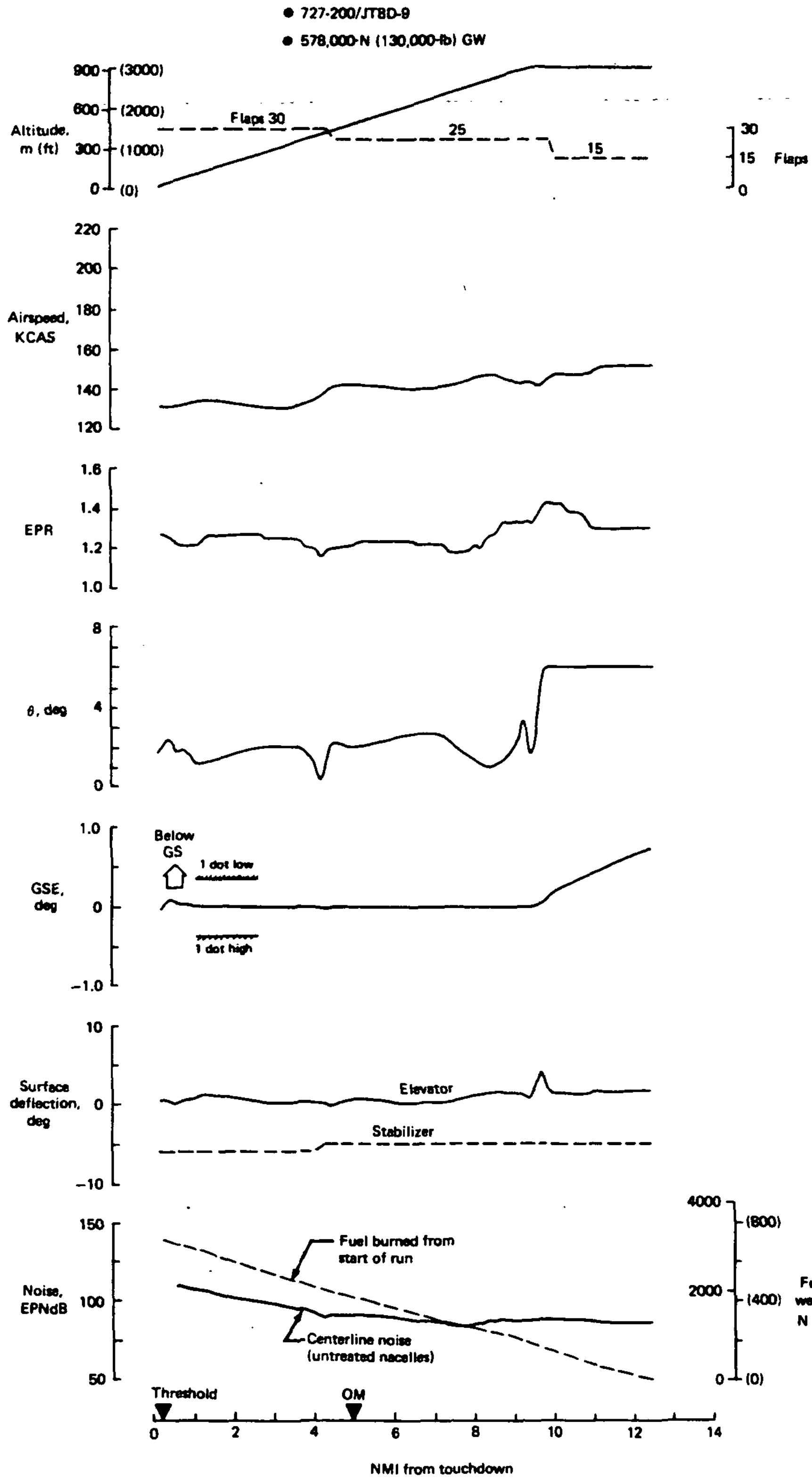


Figure 43.—Simulator Data for Current Airline Procedure (A-1), Autopilot On, Still Air

Fast/slow instrument	Percentage of fleet (so equipped)
None	38%
Unscaled	44%
Scaled	18%

The unscaled indicator has a fast/slow pointer but no index marks other than zero. Implementation of the CV-990 concept, which uses a scaled indicator, would require modification or replacement of most of the existing ADIs. An alternative is to implement a separate energy indicator.

The AEMS also requires inputs from existing airplane systems (fig. 2). The required inputs are available on all aircraft as noted:

Airspeed	Calibrated airspeed is obtained from the CADC.
Altitude	Barometrically corrected altitude is obtained from the altimeter output that also serves the altitude alert system.
DME	DME range is available on all aircraft. Later models with the newer digital systems covered by ARINC Spec. 568 have both digital range and range rate signals available.
Flap position	Flap position information is available from the outboard position transmitter.
Gear	Landing gear position information can be provided from a switch on the gear lever.
Anti-icing	Anti-icing switch status can be provided from additional contacts on the switch.
Field elevation	Field elevation is obtained from the electronic cabin pressure control system, available on some B727 models.

7.4 PERFORMANCE AND SAFETY

7.4.1 AEMS PERFORMANCE

The AEMS system was demonstrated to give consistent guidance in assisting the pilot to execute the delayed flap approach and to stabilize the airplane at the target altitude. This is evidenced by the simulation traces of figures 40 through 49.

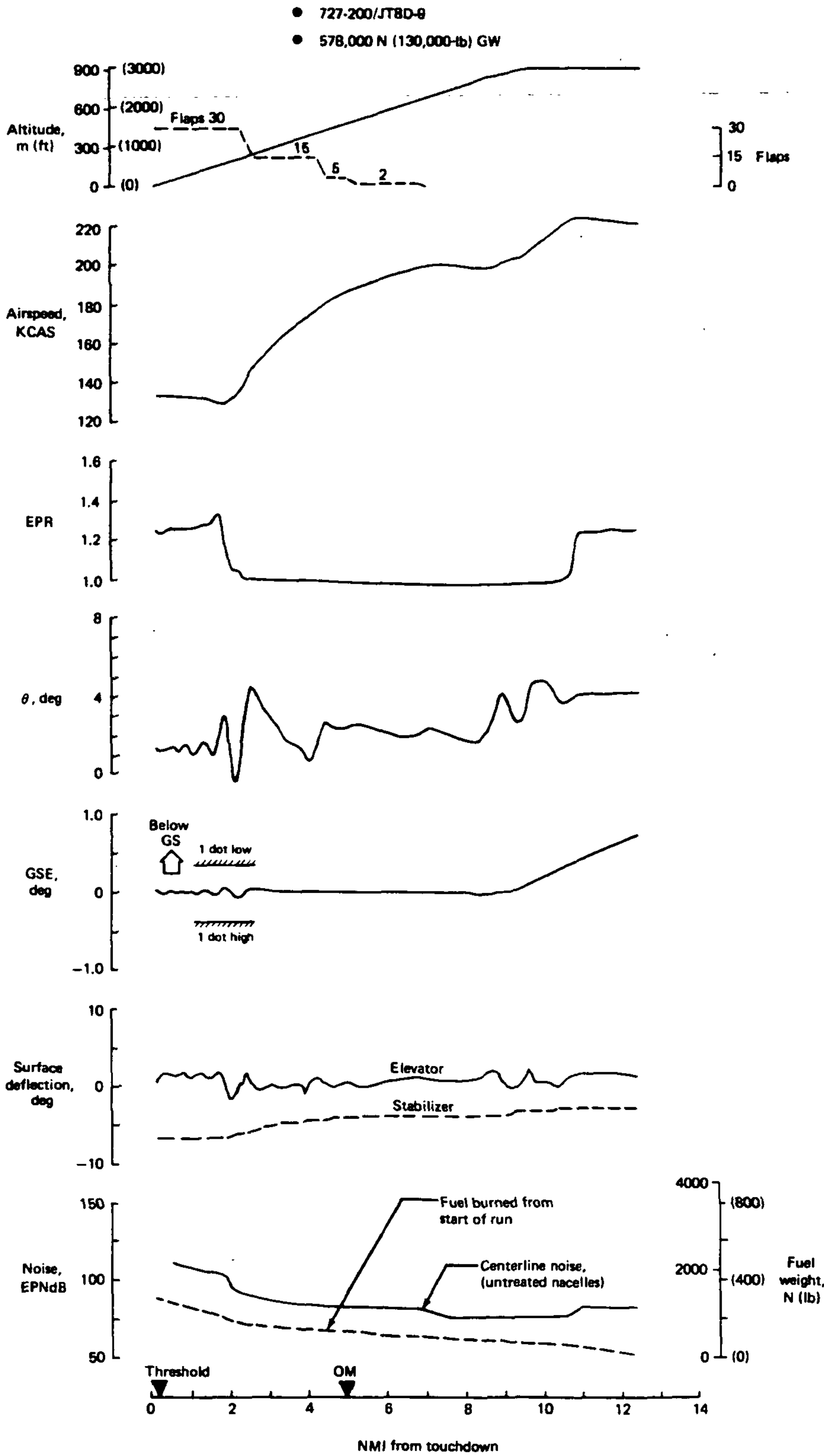


Figure 44.—Simulator Data for DFA-1, Autopilot On, 10-kn Tailwind

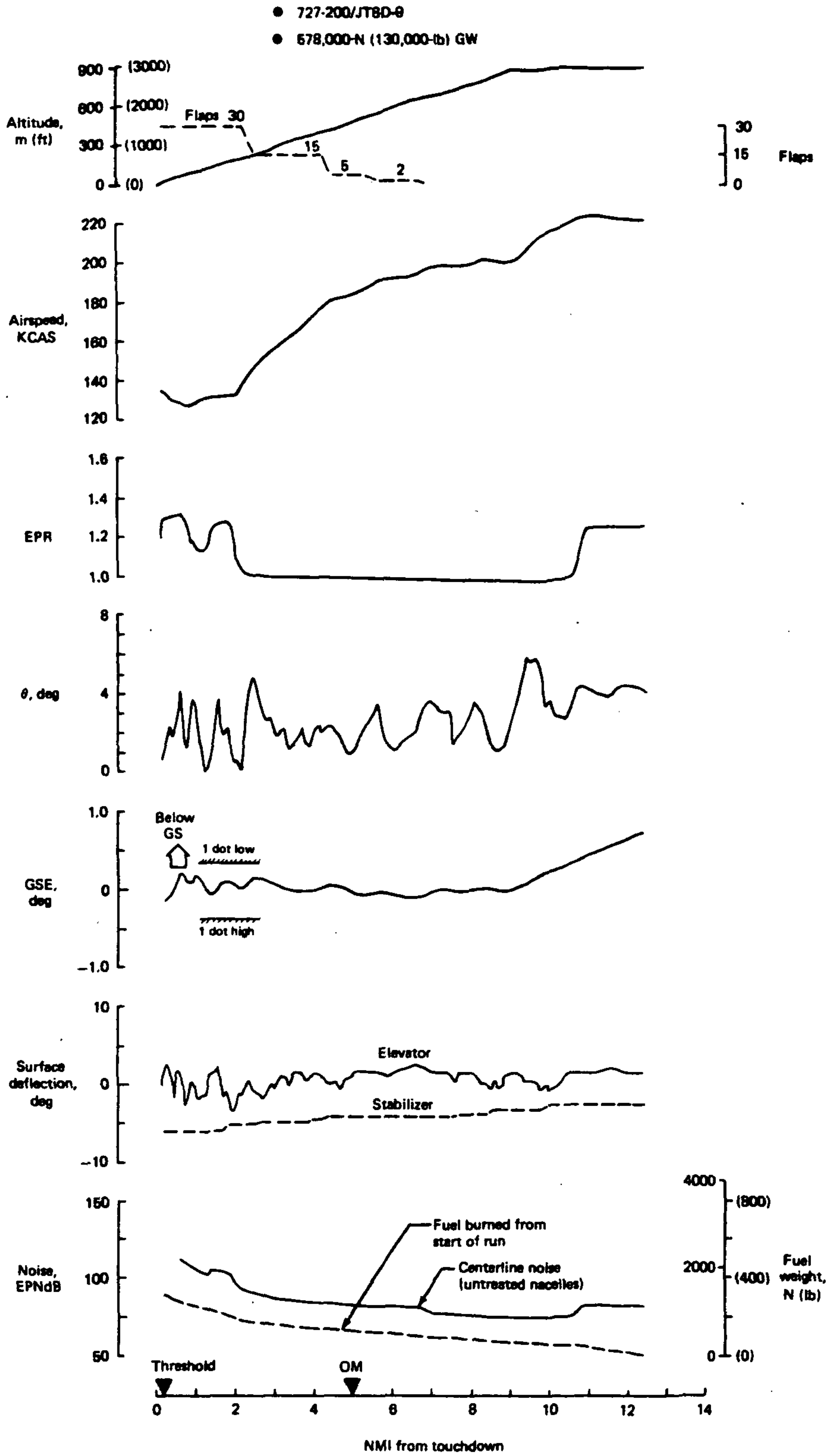


Figure 45.—Simulator Data for DFA-1, Manual Control, 10-kn Tailwind

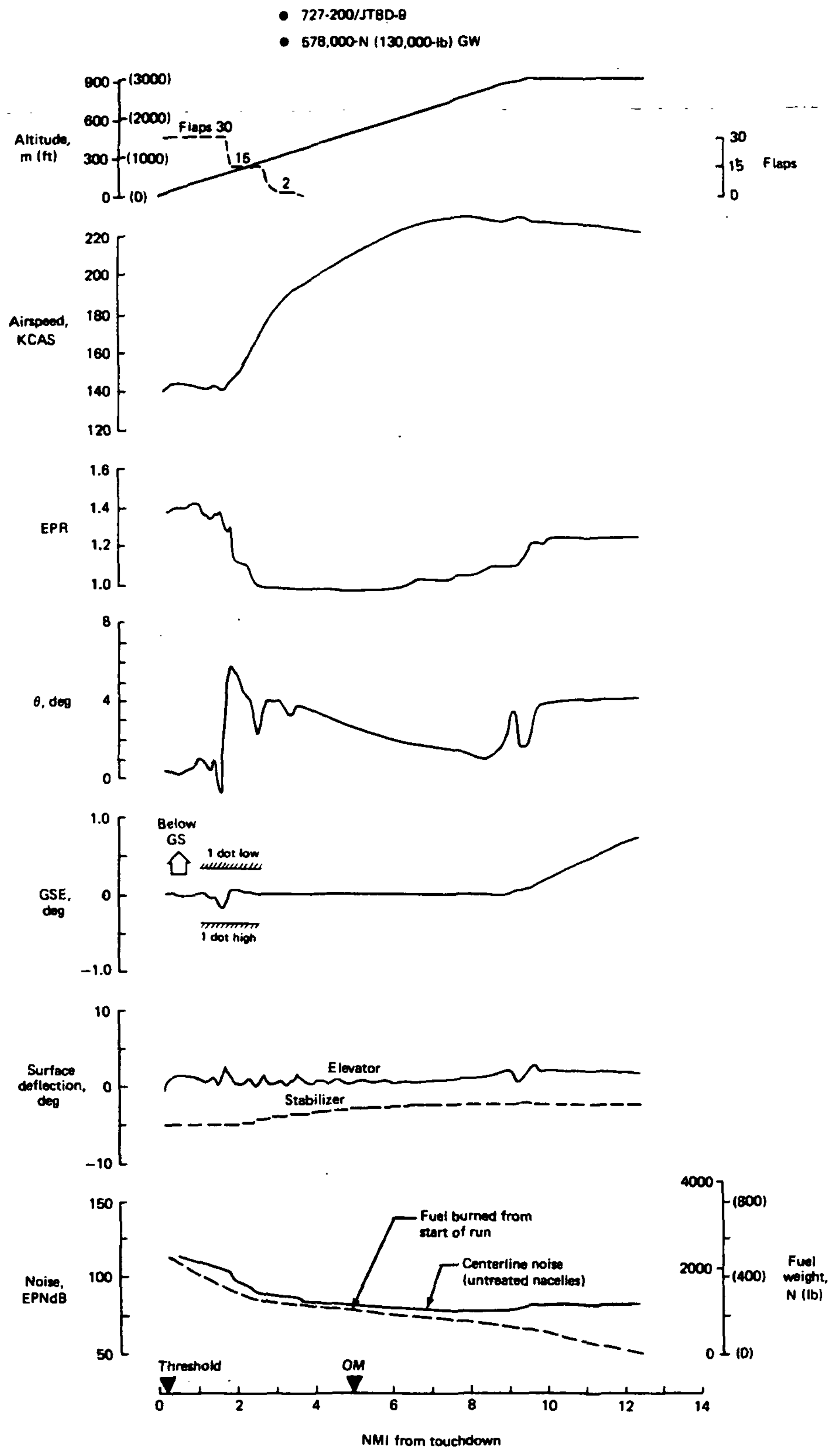


Figure 46.—Simulator Data for DFA-1, Autopilot On, 30-kn Headwind

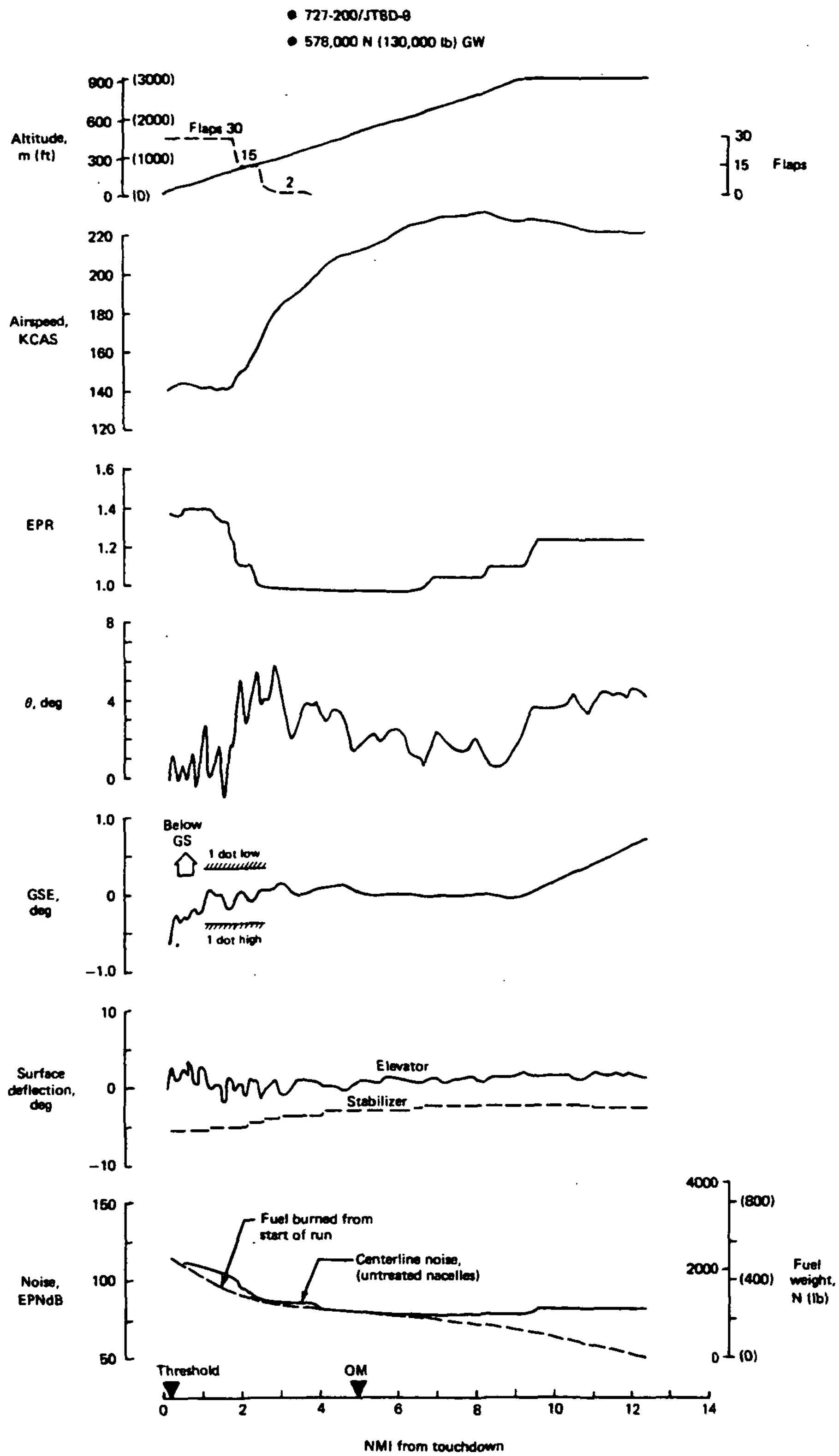


Figure 47.—Simulator Data for DFA-1, Manual Control, 30-kn Headwind

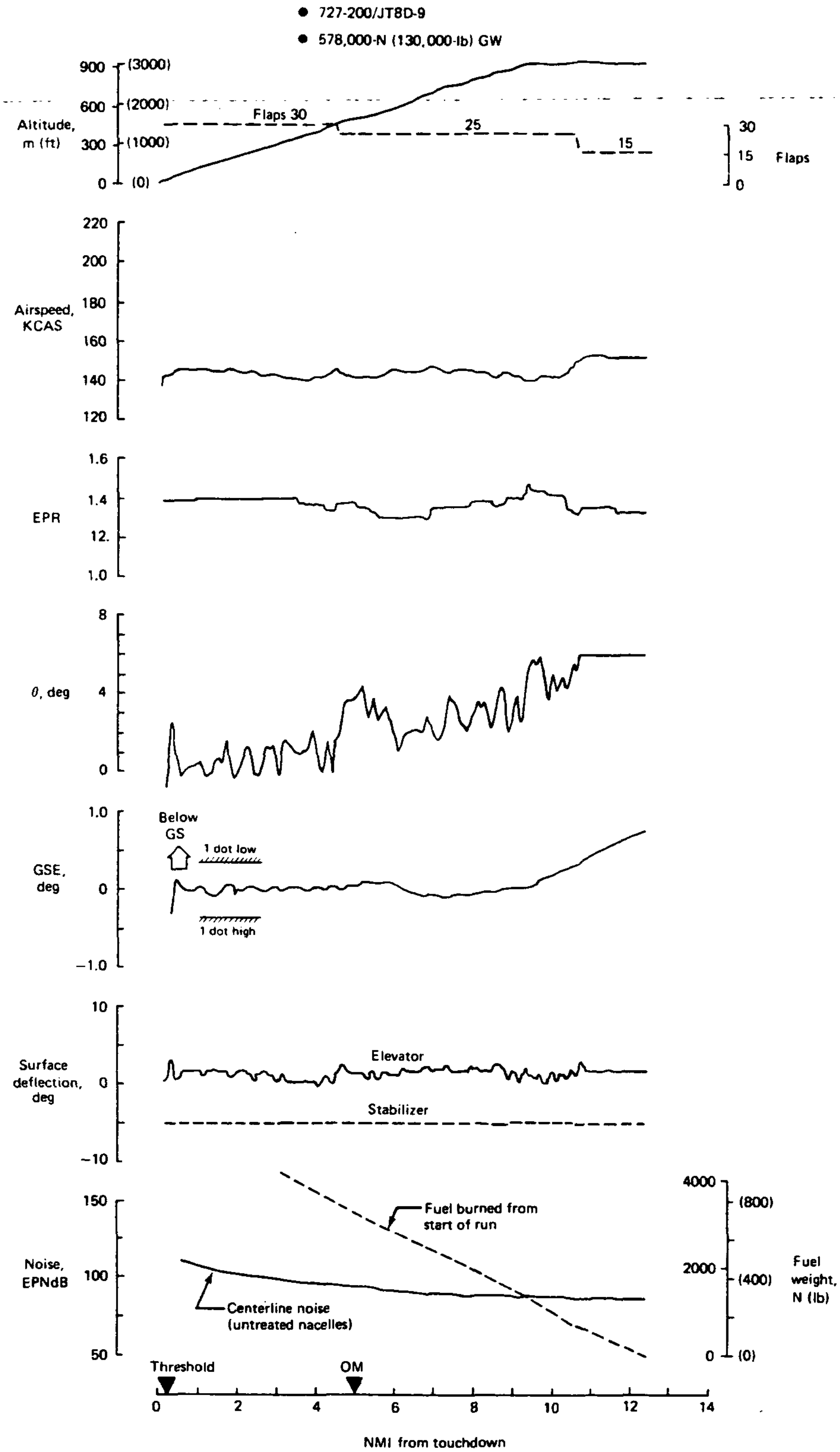


Figure 48.—Simulator Data for Current Airline Procedure (A-1), Manual Control, 30-kn Headwind

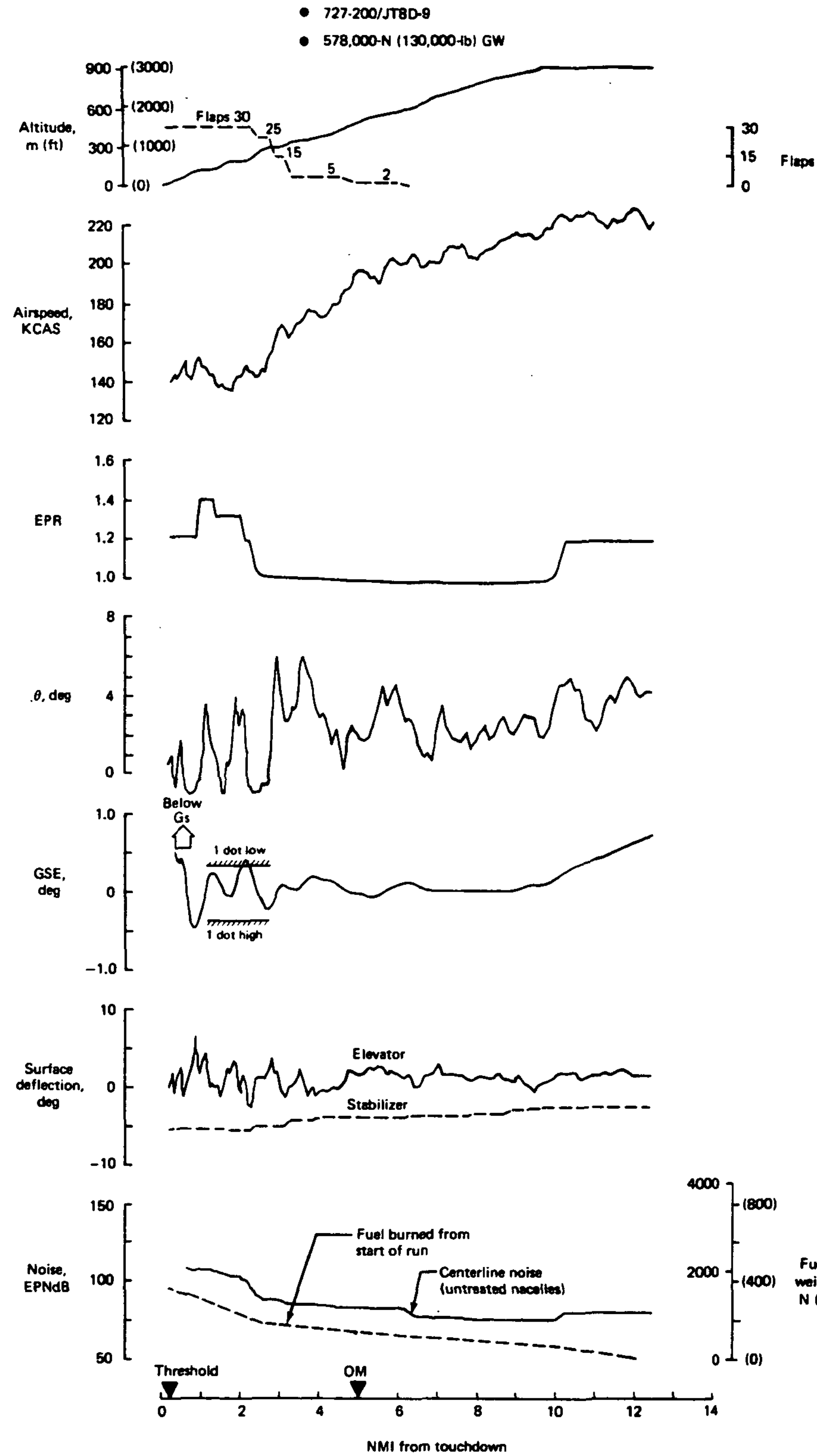


Figure 49.—Simulator Data for DFA-1, Manual Control, Moderate Turbulence

For nominal, no disturbance, on glide slope conditions, the actual flap and gear command speeds matched the flap and gear speed schedule to within 1 kn. The first flap command may deviate slightly from the scheduled speed for conditions where the actual glide slope intercept geometry differs considerably from the assumed geometry of the prediction of the deceleration profiles. However, the remaining commands would compensate.

The AEMS airspeed signal is taken from the CADC, which uses the same pitot-static system as the captain's airspeed indicator. Small differences between the CADC and the airspeed indicator may contribute to an apparent shift of the AEMS commands from their scheduled speeds, but this should not significantly affect performance.

7.4.2 EFFECT OF WINDS

The AEMS was demonstrated to handle strong headwinds (figs. 46 and 47) and tailwinds (figs. 44 and 45) with little effect on the stabilization point. However, the simulation shear profile was the same as that assumed in the algorithm. Effects of various shear profiles should be considered if the system is further developed. The fuel conservation benefit of the DFA procedure in a strong headwind is evident from comparison of figures 47 and 48. Effects of turbulence briefly spotchecked in this study (fig. 49) should be further evaluated.

7.4.3 FLIGHT DIRECTOR/AUTOPILOT

The AEMS is compatible with both manually flown flight director and autopilot approaches. The flight director performed satisfactorily in spite of higher approach speeds and changing flap configurations; no deficiencies were noted. The pitch autopilot glide slope capture and tracking performance were at least as good as for standard approaches, and possibly slightly better during the deceleration phase when thrust stays constant.

7.4.4 LATERAL AUTOPILOT

The lateral autopilot localizer captures were found to exhibit larger overshoots for delayed flap approaches when compared to standard captures at the same distance and localizer intercept angle. This is due to the increased turning radius for the higher speeds associated with delayed flap approaches and the limited autopilot bank angle. However, equivalent localizer capture performance is obtained when the capture distance is increased by the square of the velocity increase factor, approximately 4.83 km (3 miles).

7.4.5 MANUAL APPROACHES

Speed and path control during manual delayed flap approaches using the AEMS compared well with standard approaches. Simulator comparisons are presented in figures 40 and 41. Note the additional throttle activity for standard approaches, which results from using throttles for speed control. On the other hand, there is less trim activity and pitch attitude variation for the normal approach.

7.4.6 TRIM

As a result of speed, configuration and thrust sequencing, the trim continually changes during the delayed flap approach until the airplane is stabilized in the final approach configuration. The autopilot trim motor rate (0.1^{o}/s) was adequate to keep the airplane approximately trimmed at all times. The autopilot was disconnected at various points along the delayed flap approach profile, with no significant autopilot disengage transients. The trim motor actuated by the pilots' trim button has a higher rate (0.5^{o}/s) than the autopilot, so trim rates for manual flight are also no problem.

As a further check that the airplane would be in trim for final appraoch and landing, the pilot took hands off at 91 m (300 ft), and the speed and glide slope deviation were checked at 61 m (200 ft). It was found that the criteria (±1/2 dot, ±5 kn) could be met. However, it took some practice and considerable pilot attention to get the thrust exactly trimmed by 91 m (300 ft) when the stabilization altitude was 152 m (500 ft). Pitch trim was not much of a problem except when thrust mistrims resulted in speed changes.

For autopilot approaches, mistrim was checked likewise by disconnecting at 91 m (300 ft) and checking the deviation at 61 m (200 ft). Here also, the criteria could be met with much less pilot effort.

7.4.7 SAFETY

It is difficult to fully evaluate safety of procedures on a simulator, primarily because the pilot usually is concentrating exclusively on the task at hand. Real-life distractions and the inattention that sometimes results from long periods of uneventful flight are hard to simulate. Some of the more obvious safety-related items can be, and were checked; e.g.,

- *Speeds*—At no time did speed inadvertently go below 1.3 V_S or above placards. The final speed was controlled within +10 to -5 kn. Proximity to placards is illustrated in figure 8 for a nominal run.

- *Path Control*—Except on familiarization runs, the pilots always stayed within ±1 dot of the glide slope.

- *Go-arounds*—No difficulty was encountered in executing a go-around.

However, a great deal more evaluation is needed to determine if additional monitors or warnings are required; e.g., independent speed monitor and additional warning for failure to set final power.

7.4.7.1 Speed Monitoring

No provisions have presently been made for independent speed monitoring other than reference to the airspeed indicator. This may be adequate, but the relatively fast sequencing of flaps could leave the pilot uncertain of the minimum speed in case the AEMS malfunctions or the approach has to be aborted during the deceleration sequence. The existing stick shaker will give independent stall warning. However, it might be desirable to provide an earlier indication, possibly using the same angle-of-attack signal as the stall warning system. The speed monitor could make use of visual (fast/slow indicator or lights) and/or aural warnings.

7.4.7.2 Thrust Monitoring

The present system uses a steady annunciator light to indicate that throttles should be advanced. If not advanced in 3 sec, the steady light changes to a flashing light. Possibly, an additional warning that would operate even if the AEMS has failed should be provided.

7.4.7.3 Failure Monitors

The annunciator panel includes an INOP light that illuminates when the computer has detected a failure. However, it is impractical for a system of this type to monitor all potential failures. Consequently, pilot judgment or the independent speed/thrust monitors (if provided) would have to be relied on to determine when the AEMS should be ignored.

7.5 ABUSES AND FAILURES

7.5.1 ABUSES

The AEMS was tested to determine the effects of likely abuses. The abuses and their effects are presented in table 14.

The system has a wide enough authority range and sufficient algorithm logics to handle the abuses in table 14 smoothly and without reaching the airplane's operating limits (1.3 V_S or placards). The effect of failing to set the actual glide slope angle into the computer is illustrated in figure 50. These data show that differences of 0.25° in the glide slope setting shift the flap command speeds by as much as 8 kn, and the stabilization distance by about 0.2 nmi. It was concluded that the G/S input should be retained on the control panel, but that failure to make the input would not cause an unsafe situation.

There are numerous other abuses and departures from the normal flight profiles and procedures that were not evaluated. For example, the adequacy of the interlocks was not tested to determine the effects of premature engagement of the AEMS by the pilot before intercepting the final approach course. These questions should be studied in more detail in a future development program.

7.5.2 FAILURES

Although it is almost impossible to predict the results of computer hardware failures in detail before the hardware is actually built and the algorithm finalized, some general failure

Table 14.—Abuse Test Results

Condition	Effect	Remarks
1. Wrong weight setting. AEMS weight = 578 000 N (130 000 lb) Airplane weight = 686 000 N (154 000 lb)	Configuration commands at speeds slightly above speeds for set weight.	All commands above 1.3 V_s.
2. Wrong glide slope setting. Glide slope = 3° Setting = 2.75°	Configuration commands at speeds lower than scheduled VFINAL	All commands above 1.3 V_s. (see fig. 50)
3. Wrong field elevation setting. Field elevation = 2438 m (8000 ft) Setting = 0 m (0 ft)	Configuration commands at speeds higher than scheduled.	Deceleration 10 kn more than computation assumes.
4. Delayed execution of FL 15 command.	Next scheduled command comes at higher than scheduled speed or immediately after delayed command.	
5. Skip FL 15 detent. Go from 2°→15° at FL 5 command.	No FL-15 command. Landing command delayed 2 kn.	
6. Advance flaps 2 prematurely, then reset.	System works normally.	

categories and their effects can be summarized without knowing their source. As described in the following paragraphs, AEMS failures resulting in inadvertent deceleration below 1.3 V_S are possible. It is, therefore, recommended that an independent speed warning system based on angle of attack be considered.

7.5.2.1 No Scheduled Commands Generated

This may occur before the power cut command has been generated. If this occurs before the power cut command, the final approach zone might be entered at too high a speed necessitating go-around. After power cut, the airplane will continue to decelerate until 1.3 V_S where the minimum speed routine would generate an independent flap advance command.

7.5.2.2 Computer Dead

The specification requires that an unserviceable computer, which fails to cycle through the program, will have built-in hardware logics to display the INOP light.

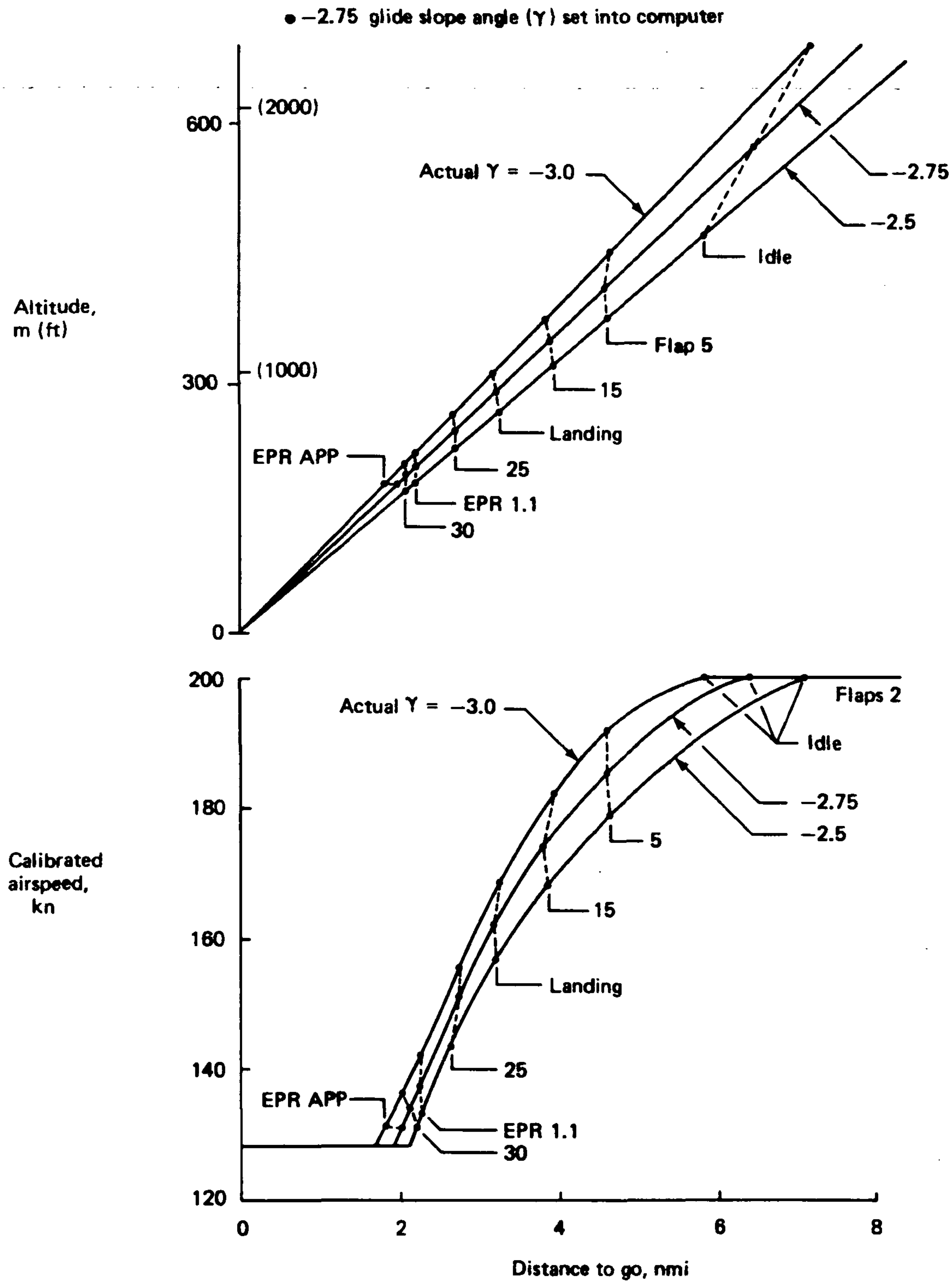


Figure 50.—Effect of Misset Glide Slope Angle

7.5.2.3 Multiple Commands

If the computer generates all commands in one string, the pilot would know that the system has failed and take appropriate action.

7.5.2.4 Annunciator Panel Light Failures

The annunciator panel has lights for EPR, flaps, and gear commands and also numerical EPR and flap command displays. Each of these may fail independently of the computer. Failure of either flaps or EPR light may result in the failure of the pilot to execute these commands. In the worst case, this could result in deceleration until the stick shaker comes on to warn against impending stall. Failure of the numerical display may cause some confusion, which may lead the pilot to turn the system off and revert back to a standard approach. Failure of the landing gear light may result in late gear extension and a possible go-around.

7.5.2.5 Sensor Failures

Sensor failures having a sensor flag (DME and CADC) will result in a computer shutdown and display of the INOP light. Incompatible sensor information (wrong sign, out of bounds) will also be detected by the AEMS computer interlocks and will result in system shutdown. Further spurious sensor failures may result in unacceptable system performance. In such cases, the pilot is advised to shut the system off and revert to a standard approach.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The acceptability of new equipment and procedures for airline use must be evaluated by the airlines and airline pilots. This report presents technical data, based on engineering analyses, fixed-base simulation, and Boeing pilot opinion for reference in making judgments concerning operational acceptability. Within that context, the following conclusions were drawn from this study:

- The NASA CV-990 AEMS concept can be adapted to the Boeing 727 and is helpful in flying optimized delayed-flap approach (DFA) procedures.

- The DFA procedures substantially reduce approach time, fuel and community noise in nonicing conditions. Alternate profiles, with reduced benefits, must be used to maintain $N_1 \geq 55\%$ when inlet anti-icing is required.

- The procedures are acceptable to Boeing pilots on the simulator. Minimum stabilization altitudes of 152 m (500 ft) for VFR and 305 m (1000 ft) for IFR are recommended pending further evaluation. Additional evaluation is required to assess safety aspects in an operational environment. The IFR stabilization altitude could probably be reduced with experience, particularly for autopilot-coupled approaches.

- With a 152-m (500-ft) stabilization altitude, the pilot workload is higher than for current ILS procedures, but reasonable, being comparable to current IFR nonprecision approaches.

- With a stabilization altitude of 152 m (500 ft) or higher, the DFA procedures are compatible with existing systems. No flight director, autopilot, or other flight control system modifications are required. Existing autopilot trim motor rates are adequate.

- In addition to reducing pilot workload, use of the autopilot may help to avoid undesirable thrust transients near the approach stabilization point.

- Autothrottles were not evaluated in this study. Results of the study indicate manual thrust control is satisfactory. However, safety implications should be further evaluated. An additional input to the autothrottle would be necessary, for airplanes so equipped, to use autothrottles during delayed flap approaches.

- Typical airline 727 instrument panel layouts can accommodate the required annunciator and control panels. Only 18% of the fleet has the desired type of fast/slow indicator. An additional 44% have an unmarked indicator which might be usable. (Not studied).

- The preliminary AEMS avionic specification is suitable for obtaining budgetary cost estimates. A complete detailed design and evaluation cycle, involving the airlines and avionic vendor, would be required before releasing a production specification.

Specific recommendations for further work include:

- ATC compatibility assessment
- Airline pilot evaluation of the 727 procedures and cockpit displays on the Boeing fixed-base and/or NASA moving-base (FSAA) simulator
- Further algorithm and flight profile development to include nonstandard days, incorporate improvements as indicated by evaluation results, and explore alternate algorithm and display concepts that could simplify the system and/or increase operational flexibility, safety, or pilot acceptance
- Further consideration of safety implications, including development and evaluation of independent monitoring and warning systems
- Application of the AEMS computer and displays to other flight phases such as takeoff and cruise

If further development of the AEMS concept appears warranted, a schedule of events involving all concerned airline, pilot, industry, and government groups should be established leading to a go-no go decision concerning flight hardware development and DME installation.

9.0 REFERENCES

1. *ATA Operations Policy Manual, Noise Abatement Approach and Landing Procedures.* OPS-8, June 15, 1974.

2. Bull, J. S., and Foster, J. D.: *Jet Transport Energy Management for Minimum Fuel Consumption and Noise Impact in the Terminal Area.* Paper presented at AIAA Mechanics of Control and Flight Conference, August 1974.

3. Jackson, D. O.: *Delayed Flap Avionics Specification.* Contract NAS2-8953, 1976.

4. Allison, R. L.: *Applicability of NASA (ARC) Two-Segment Approach Procedures to Boeing Aircraft.* NASA CR-114678, January 1974.

5. *British Civil Airworthiness Requirements.* "Airworthiness Requirements for Automatic Landing Including Automatic Landing in Restricted Visibility Down to Category 3," paper 367, issue 3, June 1970.

Boeing Commercial Airplane Company
P.O. Box 3707
Seattle, Washington 98124
February 1977