REPORT NO. DOT-TSC-OST-74-3. III

STRATEGIC CONTROL ALGORITHM DEVELOPMENT
Volume III: Strategic Algorithm Report

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AUGUST 1974

FINAL REPORT

Prepared for
U.S. DEPARTMENT OF TRANSPORTATION
OFFICE OF THE SECRETARY
Office of the Assistant Secretary
For Systems Development and Technology
Office of Systems Engineering
Washington DC 20590

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Technical Report Documentation Page

1. Report No.
DOT-TSC-OST-74-3. III

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

STRATEGIC CONTROL ALGORITHM DEVELOPMENT
Volume III: Strategic Algorithm Report

5. Report Date
August 1974

6. Performing Organization Code

7. Author(s) R.L. Erwin, M.J. Omoth, W.H. Galer, D. Hartnell, A.L. Yarrington et al.

8. Performing Organization Report No.
DOT-TSC-OST-74-3. III

9. Performing Organization Name and Address
Boeing Commerical Airplane Company*
P.O. Box 3707
Seattle WA 98124

10. Work Unit No. (TRAIS)
OS404/R4509

11. Contract or Grant No.
DOT-TSC-538-3

12. Sponsoring Agency Name and Address
Department of Transportation
Office of the Secretary
Office of Systems Engineering
Washington DC 20590

13. Type of Report and Period Covered
Final Report
Nov. 1972-Dec. 1973

14. Sponsoring Agency Code

15. Supplementary Notes
*Under contract to: Department of Transportation
Transportation Systems Center, Kendall Sq.
Cambridge MA 02142

16. Abstract

The strategic algorithm report presents a detailed description of the functional basic strategic control arrival algorithm. This description is independent of a particular computer or language. Contained in this discussion are the geometrical and environmental considerations and the required arrival traffic data requirements. The methods of providing sequencing and control point scheduling are discussed as is the means of developing a conflict-free, four-dimensional route-time profile that achieves the scheduling objectives.

17. Key Words
Air traffic control
Airplane operations analyses
Computer modeling
Benefits analysis
Control algorithms
Functional analysis
RDT&E plans
Data processing

18. Distribution Statement
DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22151.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
94

22. Price

Form DOT F 1700.7 (8–72)

PREFACE

The Strategic Control Algorithm Development program is a first study in the evolution of the strategic control concept. Previous work accomplished during the concept formulation stage of the Advanced Air Traffic Management System (AATMS) indicated that this technique held potential benefit for accommodating high traffic demands projected for the 1990's and beyond. The present effort explored the feasibility of basic strategic arrival control via analysis and fast-time simulation. This work included the design of a basic arrival control algorithm which accomplished sequencing, scheduling and generation of conflict-free four-dimensional flight paths for assignment to each arrival in the demand scenario.

In addition to the basic algorithm design and testing, tasks were accomplished to determine potential airports for application of strategic control; assess the resulting benefits; make a preliminary estimate of data processing requirements; and refine the concept. A Research, Development, Test and Evaluation (RDT&E) program was also developed.

In accomplishing this study it was necessary to provide an integration of technologies in the study team. As strategic control is primarily designed for automatic operation, it is necessary to understand airplane performance capability, wind and temperature effect, avionics capability, and computing technology, as well as comprehensive understanding of the Air Traffic Control environment. Successful integration of these technologies resulted in considerable insight into the requirements imposed on strategic flight path generation.

In the future, the evolution of the strategic control concept will require studies designed to establish the feasibility, requirements, and algorithms for strategic departure and en route airplanes. Further refinement of the basic arrival strategy and means of accommodating system perturbations will need to be accomplished. Real-time simulations, including those using strategically equipped airplane(s) will provide a logical test-bed for concept demonstration and testing.

The work of the following personnel is acknowledged: A.F. Norwood, Chief, ATC and Electronics, representing the executive level and ensuring full company support to the program and coordination with other Boeing ATC-related activities; E.A. Delanty, algorithm design; R.W. Schwab, evaluation model design; S.G. Datar, evaluation model design; R.O. Barnes, terminal and airspace requirements; E.A. Olmstead, data processing requirements; J.T. Burghart, benefits analysis; J.M. Bedregal, programming and analysis; W.L. Chu, programming and analysis; H.F. Lee, programming and analysis; E.D. Ramer, programming and analysis; J.M. Sherwin, programming and analysis supervision; R.L. Swanson, programming and analysis; J. Yonekawa, engineering support.

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1.0 INTRODUCTION

This strategic algorithm report, volume III, is designed to provide a detailed explanation of the techniques and logical detail that form the basis for the computer mechanization reported in volume IV. This volume is restricted to a discussion of those aspects of the resulting program that would be mechanized in a real-time ATC environment in the future. This volume is, by design, independent of a particular computer or language. Sections 2 through 7 consider detail of the algorithm in its current simulation environment while section 8 is a discussion of considerations that would be required to adapt to a real-time environment. This algorithm is constrained to the arrival problem except that departures are considered as they impact runway scheduling and arrival/departure separation.

The reader must adjust his thought process to the expanded terminal area which is inherent in this strategic control concept. Historically, the terminal area has been defined in terms of the approach and departure control volume as seen by the IFR room (e.g., TRACON). This leads to a very restricted terminal area of perhaps 30 miles in radius and 10,000 feet above ground level (AGL). The IFR room, upon receipt of airplanes at the initial fixes to this area, provides the path stretching and speed control necessary to sequence and space the stream to achieve separation and adequate runway utilization. The strategic control concept, on the other hand, considers the terminal area to encompass the airplanes from en route altitude to landing and from takeoff to en route cruise. The expanded terminal area encompasses two distinct parts: (1) the transition region and (2) the historic or near-terminal area. This particular mechanization of the concept uses the transition region for speed control to achieve the necessary time controllability to derandomize the arriving traffic mix into an ordered and separated stream at the runway. The near-terminal area has a fixed path and velocity profile that is used for all participating airplanes. As the en route letdown is part of this control technique, the expanded terminal area covers an area of approximately 150 to 175 nautical miles around the airport.

In addition to the above considerations, several other ideas should be kept in mind. The first of these is that this representation of the strategic control concept is designed to handle an equipped airplane fleet. The basic assumption is that the airplane's avionics complement is designed for a navigation and control capability suitable for achieving four-dimensional (i.e., X, Y, Z, T) control to a predetermined flight plan. In this regard, the ground-based system receives an entry request; considers other traffic in the system; considers environmental forecasts; generates a four-dimensional, conflict-free, route-time profile (RTP); and ultimately transmits this route-time profile to the airplane. The airplane capability is such as to adapt to perturbations in the actual environmental conditions found during flight to make good the RTP.

The requirement thus imposed on the algorithm is primarily one of establishing the sequence and schedule, and determining the RTP. This RTP is then passed to the airplane for flight execution. Figure 1-1 diagrams this process.

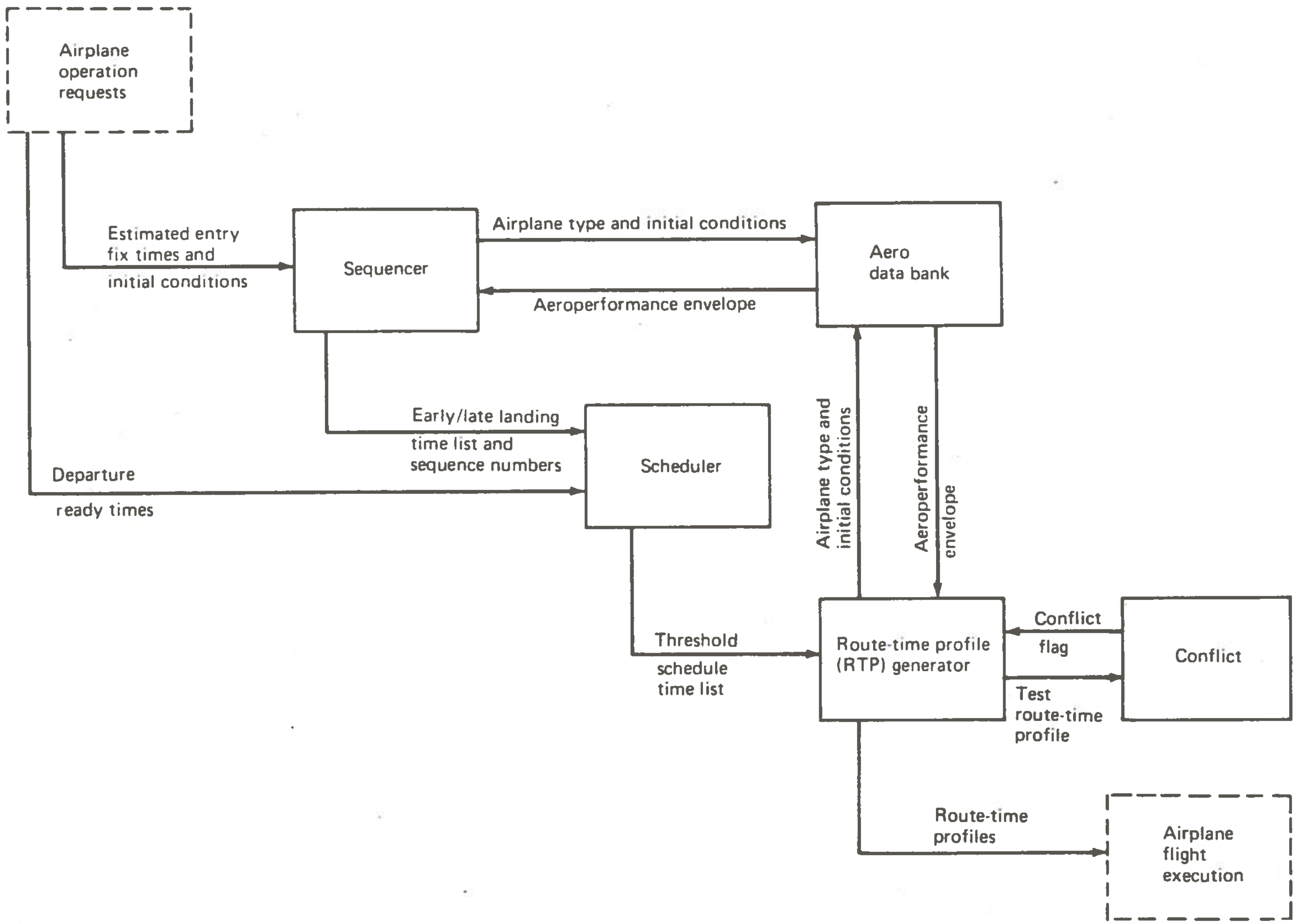


FIGURE 1-1.—STRATEGIC ARRIVAL CONTROL ALGORITHM STRUCTURE

2.0 GEOMETRY CONSIDERATIONS

The application of long-range planning of the flow of airplanes into and out of an airport requires an expansion of the traditional concept of the terminal area. From considerations of the airplane approach and landing operations, the terminal control region can be divided into three distinct operational areas:

- En route transition
- Near terminal
- Final approach

The en route transition occurs between 100 and 175 nautical miles from the airport. In this region the airplane must descend from en route altitude, convert from Mach to calibrated airspeed operation, and slow to 250 knots at or below 10,000 feet. In the near-terminal area the operational problem consists of regulating the flow of airplanes, merging traffic streams, and maintaining safe separation. As the airplanes approach the runway the traffic density increases and an ATC system must impose more stringent control. The final approach problem is one of allowing the airplanes to select an approach speed high enough to prevent stall, but low enough to land and stop safely.

2.1 GENERAL CONSIDERATIONS AND ASSUMPTIONS

Figure 2-1 shows a schematic of the strategic control geometry selected for developing the algorithm. Critical assumptions include:

- A fixed-track structure with respect to selected waypoint positions (as determined by airport environmental considerations)
- Entry into the strategic system at fixed points (12 entry fixes) located in four sectors (quadrants)
- A series of control points (fixes) through which an arrival flies in approach and landing

The entry fix to initial approach fix region is the en route transition. The near-terminal geometry contains initial approach (IAF), turn (TF), merge (MF), and final approach (FAF) fixes and the outer marker (OM). The outer marker to threshold (TH) control fixes are part of final approach.

Airplanes arrive in a terminal area under strategic control through the preassigned entry points. Associated with each entry point is a flight trajectory (primary path) passing through the series of specified control points. Control points located at the entry and the runway threshold constitute the initial and terminal points of the trajectory. In the en route region between the entry fix and initial approach fix, an airplane can be assigned one of a finite

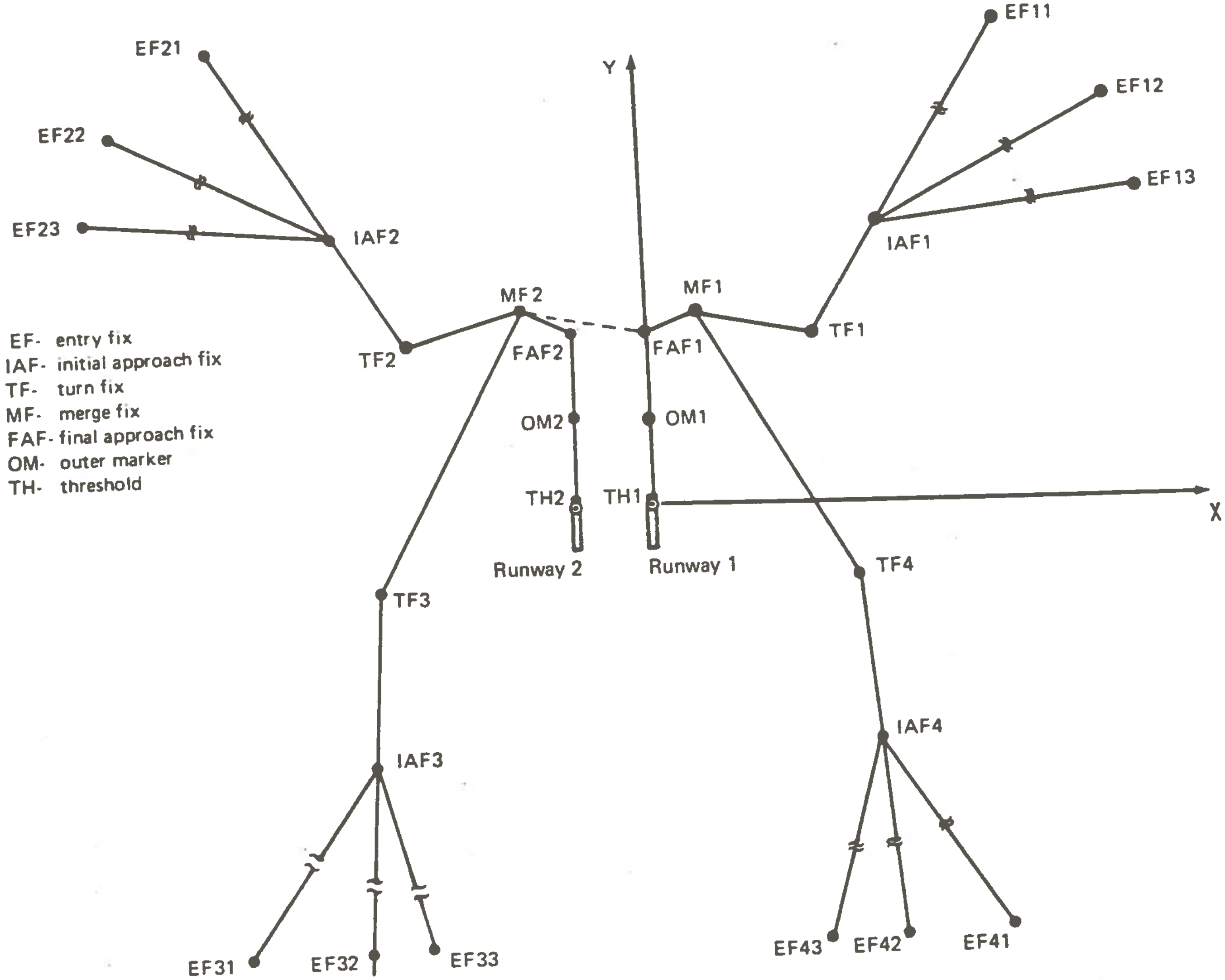


FIGURE 2-1.–STRATEGIC CONTROL GEOMETRY

number of paths (the primary path or a path parallel to the en route region primary path). A trajectory segment between two neighboring control points constitutes either a straight line segment or a straight line section and a circular arc segment (turn circle arc). Any required heading changes are made by circular turns. Turns are initiated at a point on the straight section of a flight segment such that the turn exit (completion) point coincides with the control point.

Linear descent profiles are assumed. Current descent procedures do not result in a linear track descent; however, linear altitude-distance tracks are desirable from scheduling and guaranteed conflict-free airspace consideration. A discussion of the constant gradient descent is reported in volume II, section 3, System Requirements. A descent track meeting aeroperformance requirements is shown in figure 2-2.

The remaining sections consist of a trajectory analysis undertaken to provide path distances and headings for various geometry assumptions, a discussion of turn radii considerations, and a presentation of the strategic control geometry assumptions applied to the Los Angeles International Airport terminal area.

2.2 TRAJECTORY ANALYSIS

A trajectory analysis follows in this section. Based on geometry inputs, flightpath segment lengths and headings are determined. Geometry inputs consist of:

- X, Y coordinates of the control points
- Total number of control points along a track
- Radius of the turn circle associated with each control point
- Distance of parallel offset paths from the primary path
- Number of parallel offsets

Figure 2-3 illustrates schematically a flight trajectory (in the XY-plane) passing through the seven control points. The control points are numbered from 1 through 7 and represent in sequential order the entry fix (1), initial approach fix (2), turn fix (3), merge fix (4), final approach fix (5), outer marker (6), and threshold (7). Layout of the parallel offset paths between the entry fix and the initial approach fix is shown in the figure. An airport-centered Cartesian coordinate system as shown in the figure is employed in the trajectory analysis. The system is oriented so that the positive Y-axis points away from the runway toward the final approach. The origin of this coordinate system is assumed to be located at the threshold of the runway.

Starting from the terminal point (threshold) and proceeding backward, each successive trajectory segment is determined. Turn initiation points and heading changes are determined from the relative positions of any three consecutive points. The segment between the outer marker and the threshold is assumed to be a straight line.

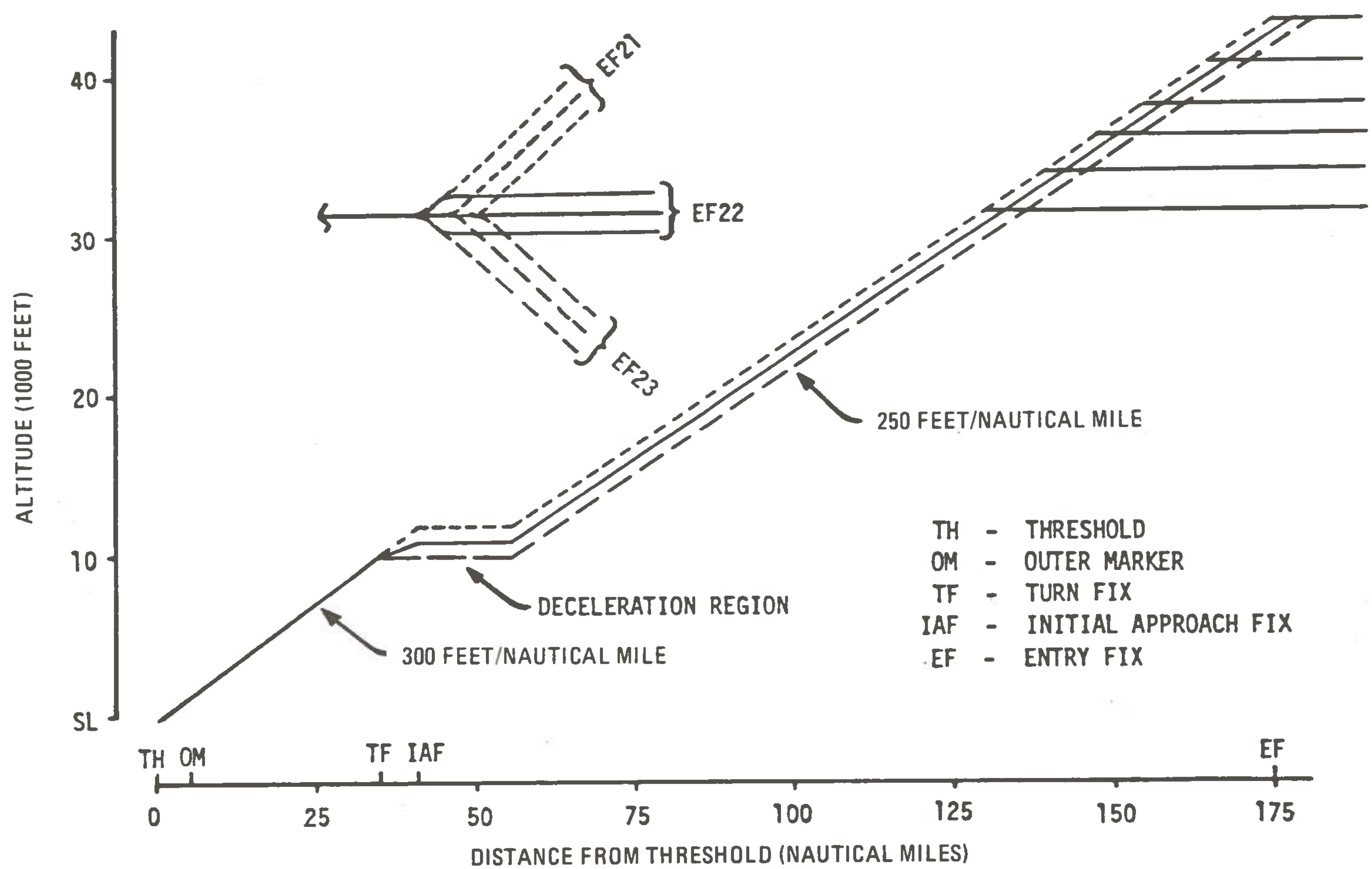


FIGURE 2-2.—DESCENT TRACK

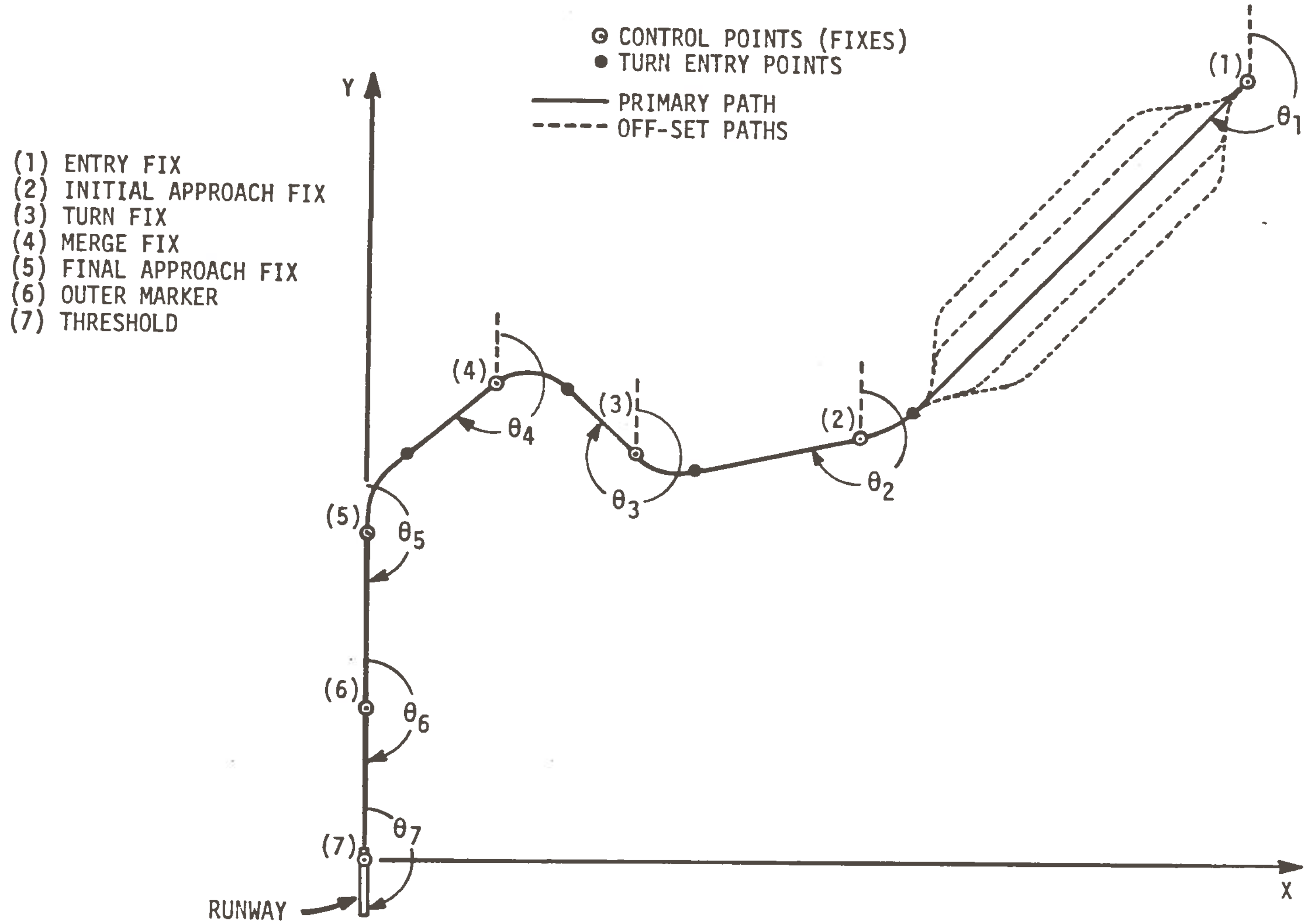


FIGURE 2-3.—TYPICAL FLIGHT TRAJECTORY

Figure 2-4 shows the flight trajectory passing through three points in the XY-plane. The sense of flight direction is from C to A via B. C and B are control points. Point A is either a turn entry point or a control point depending on whether a turn is required to fly from B to the next immediate control point. The control point B, by assumption, is a turn exit point. B_I is the turn entry point corresponding to the exit point B. R is the center of the circle associated with the turn at B.

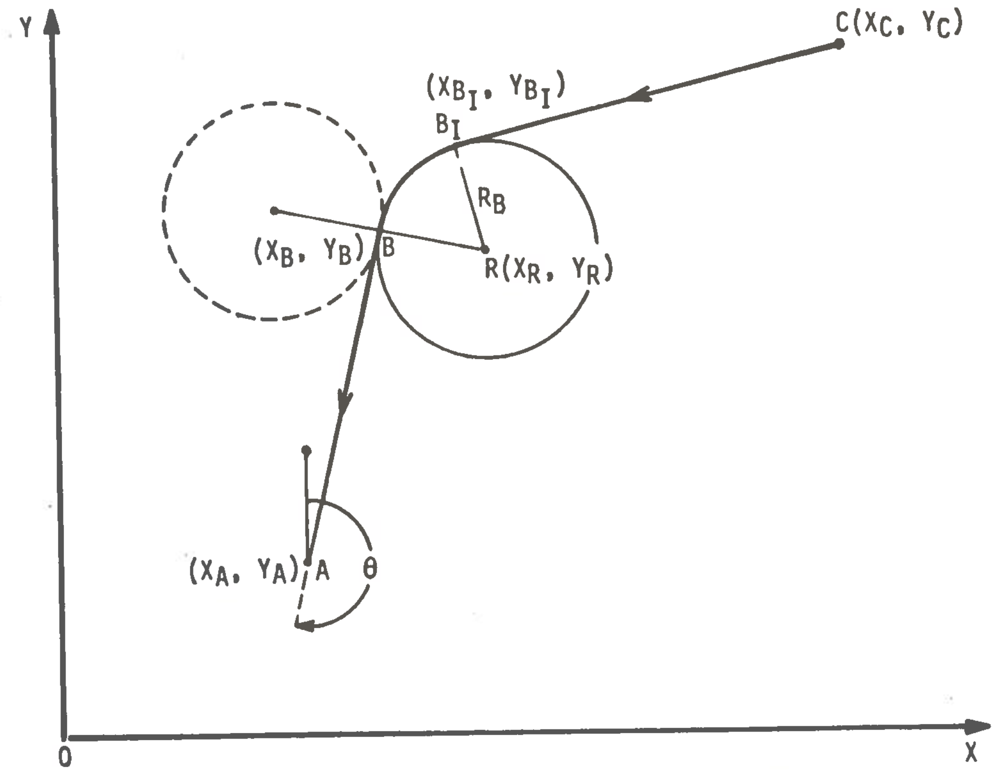


FIGURE 2-4.–FLIGHT SEGMENT GEOMETRY

Let the coordinates of A, B, B_I, C, and R be (X_A, Y_A), (X_B, Y_B), (X_{BI}, Y_{BI}), (X_C, Y_C), and (X_R, Y_R), respectively.

2.2.1 Path Angle

The path angle is the angle subtended by the straight section of a segment with the positive Y-axis. This angle, for the straight section BA, is given by

$$\theta = \cos^{-1} (YBA/DBA)$$

where:

$$Y_{BA} = Y_A - Y_B$$

$$D_{BA} = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2}$$

For the cases when $\theta > \pi$ (i.e., when $X_A > X_B$) this angle is set equal to

$$\theta = 2\pi - \cos^{-1} (YBA/DBA)$$

2.2.2 Path Length

For the case when A is a control point, the segment length between B and A equals D_{BA}; thus

$$D_{seg} = D_{BA}$$

For the first three consecutive points (where A is the runway threshold) the above is obviously true because, by assumption, BA is a straight segment. For the case when A is a turn entry point, the arc length (D_{arc}) of the turn at A (calculated from the previous set of consecutive points) is added to the straight section to obtain the path length. The method of determining the arc length is described in section 2.2.6.

2.2.3 Turn Criteria

Flying from C to A via B, a turn (initiated at B_I and completed at B) is required if the points C, B, and A are not collinear. This condition is established by comparing the slopes of the straight lines CA and CB, respectively. Equivalently, this condition can be expressed by the equality,

$$\frac{Y_{BA}}{D_{BA}} = \frac{Y_{CA}}{D_{CA}} \tag{1}$$

where:

$$Y_{BA} = Y_A - Y_B$$

$$Y_{CA} = Y_A - Y_C$$

$$D_{BA} = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2}$$

$$D_{CA} = \sqrt{(X_A - X_C)^2 + (Y_A - Y_C)^2}$$

If the above equality is true, the flight from C to A via B is a straight path; otherwise the flight segment between C and A contains a straight section CB_I and a circular arc section B_IB.

2.2.4 Coordinates of Turn Circle

The coordinates X_R, Y_R of the turn circle center R are determined from the equation circle with center at (X_R, Y_R) and the equation of the tangent to the circle from point A.

The equation of the circle is

$$(X - X_R)^2 + (Y - Y_R)^2 - R_B{}^2 = F(X,Y) = 0 \qquad (2)$$

A vector, normal to the circle at X,Y, is

$$\nabla F(X,Y) = i\,(X - X_R) + j\,(Y - Y_R) = 0 \qquad (3)$$

The equation of the tangent AB to the circle is obtained from the scalar product of the vector $\overline{BA}$ and normal to the circle:

$$(X_B - X_R)(X_A - X_B) + (Y_B - Y_R)(Y_A - Y_B) = 0 \qquad (4)$$

Substituting X_B and Y_B for X and Y respectively in (2) yields

$$(X_B - X_R)^2 + (Y_B - Y_R)^2 - R^2{}_B = 0 \qquad (5)$$

Denoting

$$\xi_r = X_B - X_R, \quad \eta_r = Y_B - Y_R, \quad X_{BA} = X_A - X_B \qquad (6)$$

equations (4) and (5) can be written as

$$X_{BA}\,\xi_r + Y_{BA}\,\eta_r = 0 \qquad (7)$$

$$\xi_r{}^2 + \eta_r{}^2 = R_B{}^2 \qquad (8)$$

Solving (7) for η_r

$$\eta_r = -\frac{X_{BA}\xi_r}{Y_{BA}} \qquad (9)$$

Substituting (9) in (8), ξ_r can be obtained as

$$\xi_r = \pm\sqrt{\frac{R_B{}^2 Y_{BA}{}^2}{D_{BA}}} = \pm\frac{R_B Y_{BA}}{D_{BA}} \qquad (10)$$

where:

$$D_{BA} = \sqrt{X_{BA}^2 + Y_{BA}^2}$$

Substituting for ξ_r in (8), η_r can be written as

$$\eta_r = \pm \frac{R_B X_{BA}}{D_{BA}} \tag{11}$$

The coordinates of X_R, Y_R can be obtained from (10), (11), and (6) as

$$X_R = X_B \pm \frac{R_B Y_{BA}}{D_{BA}}$$

$$Y_R = Y_B \pm \frac{R_B X_{BA}}{D_{BA}} \tag{12}$$

X_R, Y_R admit two solutions corresponding to the two centers located on either side of the line AB. Denoting the two solutions by (X_{R1}, Y_{R1}) and (X_{R2}, Y_{R2}), the distances of the two centers from point C can be obtained as

$$D_{R1} = \sqrt{(X_{R1} - X_C)^2 + (Y_{R1} - Y_C)^2}$$

$$D_{R2} = \sqrt{(X_{R2} - X_C)^2 + (Y_{R2} - Y_C)^2} \tag{13}$$

The applicable solution (X_R, Y_R) is selected by comparing D_{R1} and D_{R2} and choosing the point corresponding to the smaller of the two.

2.2.5 Turn Entry Point

The turn entry point B_I is determined from the equation of tangent to the turn circle and the equation of the circle. The equation of the tangent from C with point of tangency at B_I can be represented by an expression similar to equation (4); thus

$$(X_{BI} - X_C)(X_{BI} - X_R) + (Y_{BI} - Y_C)(Y_{BI} - Y_R) = 0 \tag{14}$$

For the point B_I, the equation of the circle takes the form

$$(X_{BI} - X_R)^2 + (Y_{BI} - Y_R)^2 \quad R_B^2 = 0 \tag{15}$$

Denoting

$$\alpha_X = X_{BI} - X_R, \quad \alpha_Y = Y_{BI} - Y_R \tag{16}$$

and

$$X_{CR} = X_R - X_C, \qquad Y_{CR} = Y_R - Y_C$$

Equations (14) and (15) can be written as

$$(\alpha_X + X_{CR})(\alpha_X) + (\alpha_Y + Y_{CR})(\alpha_Y) = 0 \tag{17}$$

$$\alpha_X^2 + \alpha_Y^2 = R_B^2 \tag{18}$$

Substituting (18) into (17) yields

$$\alpha_X X_{CR} + \alpha_Y Y_{CR} = -R_B^2 \tag{19}$$

Solving for α_Y from (19),

$$\alpha_Y = \frac{-(R_B^2 + \alpha_X X_{CR})}{Y_{CR}} \quad \text{for } Y_{CR} \neq 0 \tag{20}$$

Equation (18), when substituted for α_Y, yields

$$\alpha_X^2 + \frac{(R_B^2 + \alpha_X X_{CR})^2}{Y_{CR}^2} = R_B^2 \tag{21}$$

After rearrangement, (21) can be written as

$$\alpha_X^2 (X_{CR}^2 + Y_{CR}^2) + \alpha_X (2 X_{CR} R_B^2) + R_B^4 - R_B^2 Y_{CR}^2 = 0 \tag{22}$$

Letting:

$$\begin{aligned} A &= X_{CR}^2 + Y_{CR}^2 \\ B &= 2 X_{CR} R_B^2 \\ C &= R_B^4 - R_B^2 Y_{CR} \end{aligned} \tag{23}$$

Equation (22) takes the form

$$A \alpha_X^2 + B \alpha_X + C = 0$$

Solving (23) for α_X yields

$$\alpha_X = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{24}$$

Corresponding α_Y can be obtained by substituting for α_X in (20), namely

$$\alpha_Y = \frac{-(R_B{}^2 + \alpha_X X_{CR})}{Y_{CR}} \tag{25}$$

α_X and α_Y, in general, admit two solutions each corresponding to the two tangents to the circle from point C. The two solutions can be expressed as

$$\alpha_{X1} = \frac{-B + \sqrt{B^2 - 4AC}}{2A}, \quad \alpha_{Y1} = \frac{-(R_B{}^2 + \alpha_{X1} X_{CR})}{Y_{CR}}$$

and (26)

$$\alpha_{X2} = \frac{-B - \sqrt{B^2 - 4AC}}{2A}, \quad \alpha_{Y2} = \frac{-(R_B{}^2 + \alpha_{X2} X_{CR})}{Y_{CR}}$$

The corresponding two solutions for the coordinates of the tangent point (X_{BI}, Y_{BI}) can be obtained from (26) and (16) as

$$X_{BI1} = \alpha_{X1} + X_R, \quad Y_{BI1} = \alpha_{Y1} + Y_R$$
$$X_{BI2} = \alpha_{X2} + X_R, \quad Y_{BI2} = \alpha_{Y2} + Y_R \tag{27}$$

For the case when $Y_{CR} = 0$, equation (19) yields for α_X,

$$\alpha_X = -\frac{R_B{}^2}{X_{CR}}$$

The corresponding α_Y is obtained from (18), as

$$\alpha_Y = \pm \frac{R_B}{X_{CR}} \sqrt{X_{CR}{}^2 - R_B{}^2}$$

It is evident α_X and, hence, X_{BI} in this case will have only one solution while Y_{BI} (or α_Y) will have two solutions corresponding to points on either side of the straight line CR and equidistant from it. Thus

$$Y_{BI1} = \frac{R_B}{X_{CR}} \sqrt{X_{CR}^2 - R_B^2}$$

$$Y_{BI2} = -Y_{BI1}$$

$$X_{BI1} = X_{BI2}$$

Similarly, when $Y_{CR} = 0$, it can be shown

$$X_{BI1} = \frac{R_B}{Y_{CR}} \sqrt{Y_{CR}^2 - R_B^2}$$

$$X_{BI2} = -X_{BI1}$$

$$Y_{BI1} = Y_{BI2}$$

X_{BI} and Y_{BI} admit two solutions corresponding to the two tangents to the turn circle from the point C as shown in figure 2-5.

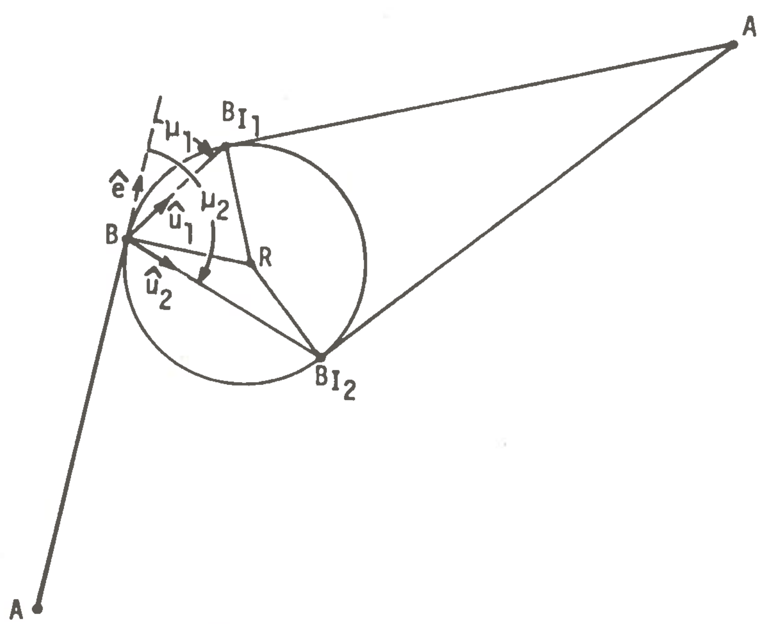


FIGURE 2-5.—TURN ENTRY POINTS

The applicable solution is chosen based on the following. Let $\hat{u}_1$, $\hat{u}_2$, and $\hat{e}$ represent unit vectors parallel to the vectors $\overline{BBI1}$, $\overline{BBI2}$, and $\overline{AB}$ (see fig. 2-5), respectively. $\hat{u}_1$, $\hat{u}_2$, and $\hat{e}$ can be expressed as

$$\hat{u}_1 = \frac{1}{D_{BBI1}}[i(X_{BI1} - X_B) + j(Y_{BI1} - Y_B)]$$

$$\hat{u}_2 = \frac{1}{D_{BBI2}}[i(X_{BI2} - X_B) + j(Y_{BI2} - Y_B)]$$

$$\hat{e} = \frac{1}{D_{AB}}[i(X_B - X_A) + j(Y_B - Y_A)]$$

where

$$D_{BBI1} = \sqrt{(X_{BI1} - X_B)^2 + (Y_{BI1} - Y_B)^2}$$

$$D_{BBI2} = \sqrt{(X_{BI2} - X_B)^2 + (Y_{BI2} - Y_B)^2}$$

and

$$D_{AB} = \sqrt{(X_B - X_A)^2 + (Y_B - Y_A)^2}$$

The angles μ_1 and μ_2 between the vector pairs $\hat{e}$, $\hat{u}_1$ and $\hat{e}$, $\hat{u}_2$, respectively, can be obtained from the scalar products $\hat{e} \cdot \hat{u}_1$ and $\hat{e} \cdot \hat{u}_2$ as

$$\mu_1 = \cos^{-1}\left[\frac{(X_B - X_A)(X_{BI1} - X_B) + (Y_B - Y_A)(Y_{BI1} - Y_B)}{D_{AB} \cdot D_{BBI1}}\right]$$

$$\mu_2 = \cos^{-1}\left[\frac{(X_B - X_A)(X_{BI2} - X_B) + (Y_B - Y_A)(Y_{BI2} - Y_B)}{D_{AB} \cdot D_{BB12}}\right]$$

The applicable solution for (X_{BI}, Y_{BI}) is determined by comparing μ_1 and μ_2 and selecting the solution corresponding to the smaller of the two.

2.2.6 Turning Arc Length

The circular arc length BB_I (see fig. 2-5) is given by

$$D_{arc} = R_B \cdot \Omega$$

where Ω is the included angle between the radii RB and RB_I and is given by

$$\Omega = \cos^{-1}\left[\frac{(X_B - X_R)(X_{BI} - X_R) + (Y_B - Y_R)(Y_{BI} - Y_R)}{R_B^2}\right]$$

In the event the points A, B, and C are collinear, D_{arc} is set equal to zero.

2.2.7 Parallel Offset Path Distance

Figure 2-6 shows schematically the parallel offset path geometry. BA is the straight section of primary path segment between entry fix and initial approach fix. From the figure it is seen that the lengths d_A, d_B representing the distance between M_1,P_1 and M_1,P_2 are given by

$$d_A = 2\,R_A - d_p$$

$$d_B = 2\,R_B - d_p$$

where R_A and R_B are the radii of the turn circles associated with IAF and EF and it is assumed that the parallel offset distance d_p is smaller than $2\,R_A$ and $2\,R_B$.

The angles γ_A and γ_B are given by

$$\gamma_A = \cos^{-1}\frac{2\,R_A - d_p}{d_A}$$

$$\gamma_B = \cos^{-1}\frac{2\,R_B - d_p}{d_B}$$

The lengths of the S turns at A and B are computed as

$$d_{AS} = 2\,R_A\gamma_A$$

and

$$d_{BT} = 2\,R_B\gamma_B$$

The distance d_{ST} of the straight section ST of a parallel offset path is

$$d_{ST} = D_{AB} - (\ell_A + \ell_B)$$

where:

$$D_{AB} = \sqrt{(X_B - X_A)^2 + (Y_B - Y_A)^2}$$

$$\ell_A = \sqrt{4R_A^{\,2} - d_A}$$

$$\ell_B = \sqrt{4R_B^{\,2} - d_B}$$

The parallel offset path distance thus is

$$d_{OFS} = d_{AS} + d_{ST} + d_{BT} + d_{arc}$$

where d_{arc} is the circular arc length of the primary segment between EF and IAF.

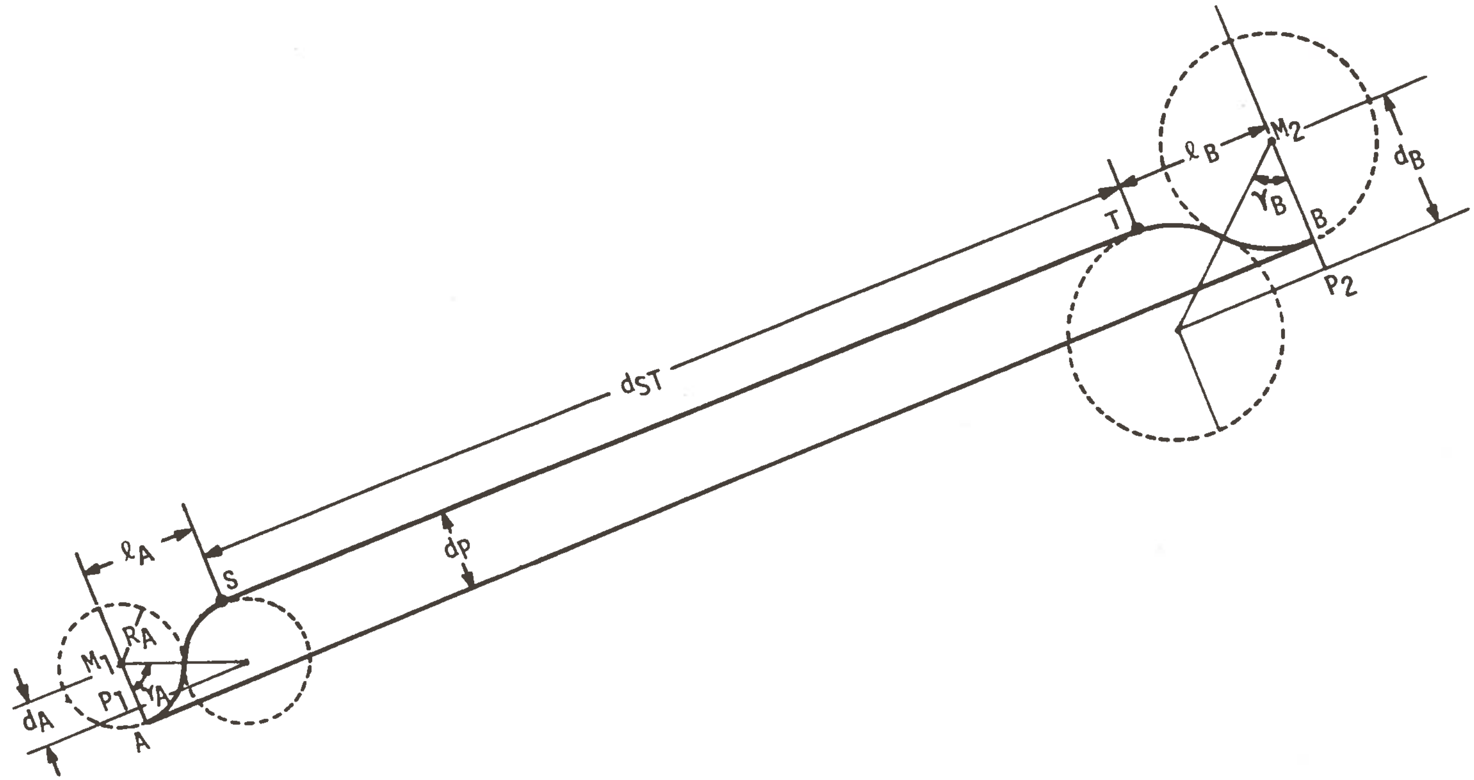


FIGURE 2-6.--PARALLEL OFF-SET PATH GEOMETRY

2.3 TURN RADII CONSIDERATIONS

The choice of a turn radius will constrain the range of airplane velocities and desirable bank angles at that point in the flight regime. Figure 2-7 indicates the interrelationship between velocity, turn circle radius, and bank angle. For the strategic control geometry a fixed-radius turn is assumed associated with each control fix. As fixed-radius turns are at constant bank angle only in nonaccelerating, level, no-wind conditions, the airplane guidance system will necessarily contain a variable bank angle turn capability. The corresponding velocity constraints are "feasible" for all commercial jet airplanes.

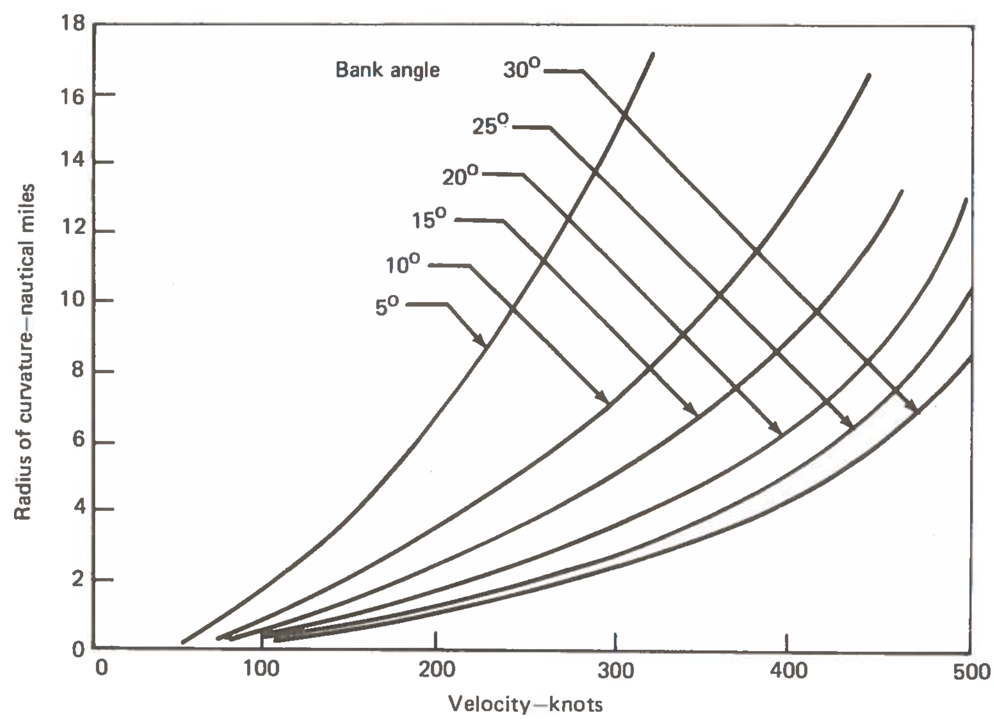


FIGURE 2-7.—VELOCITY VERSUS TURN RADIUS AND BANK ANGLES

A discussion of the turn radii selected (for modeling purposes) at the various control points follows:

- The final approach turn radius was set equal to 2.25 nautical miles. This value resulted from assuming a nominal velocity of 200 knots true airspeed (KTAS) at a 15° bank angle.

- From the IAF to the merge fix, the airplanes are bounded by the 250 knots calibrated airspeed (KCAS) limit. The highest true airspeed corresponding to this value is 290 KTAS at 10,000 feet. For a nominal bank angle of 15° the resulting turn radius is 5 nautical miles.

- During the transition from the entry fix to the IAF, the true airspeeds will vary over a range of perhaps 250 KTAS to over 500 KTAS. Using a 15° bank angle for the fast airplane (500 KTAS) results in a turn radius of 18.6 nautical miles.

2.4 LOS ANGELES GEOMETRY

The adaption of the conceptual geometry to a specific terminal area is shown in figure 2-8. The Los Angeles arrival geometry for a strategic control system is shown. Nine entry fixes (using three of the quadrants) are used. A detailed discussion of the selection of fix locations, paths, turns, etc., is found in volume II, section 6.3.1. The impact of the physical environment, surrounding airfields, and aviation requirements is discussed.

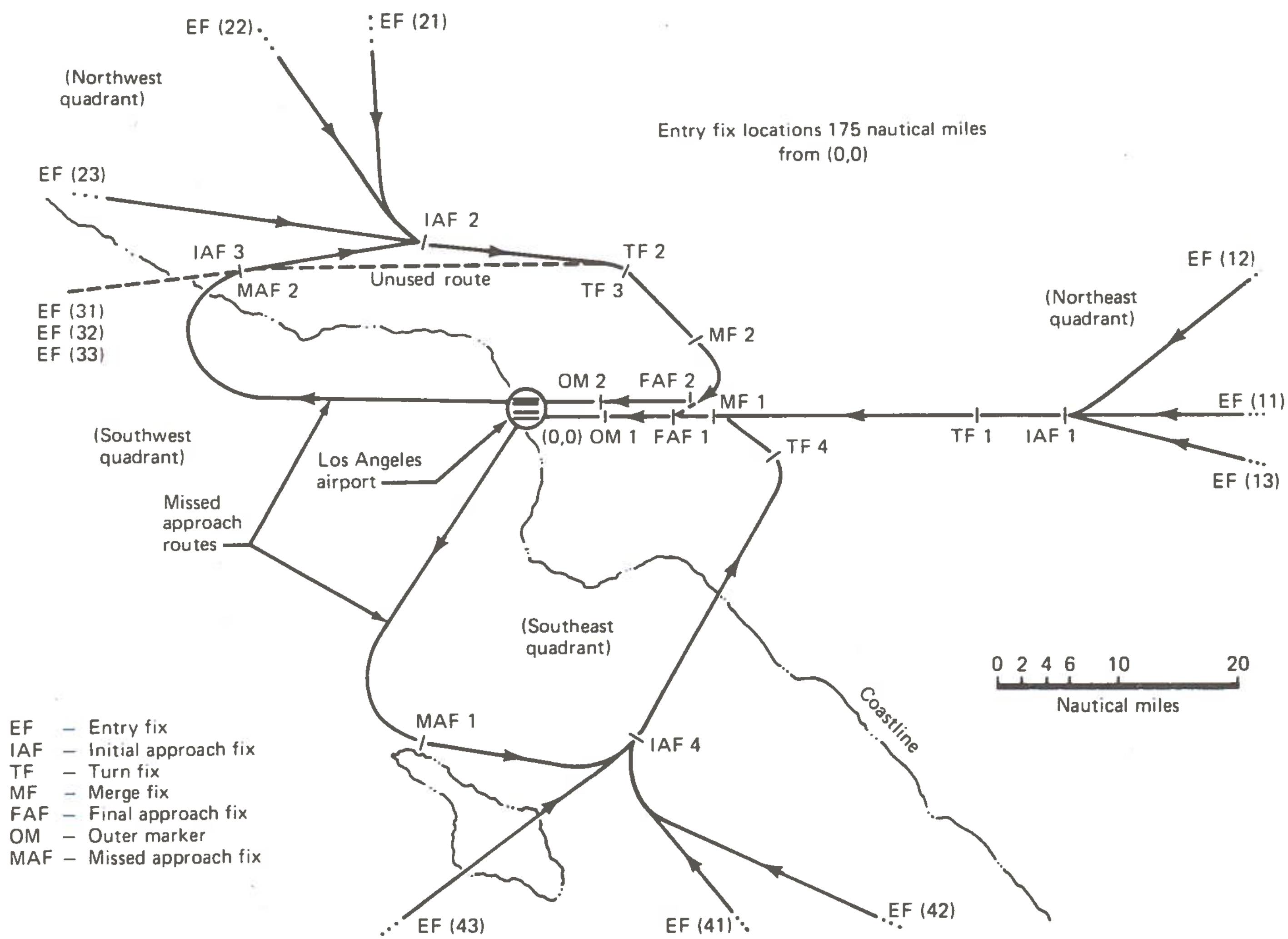


FIGURE 2-8.—LOS ANGELES STRATEGIC ARRIVAL GEOMETRY

3.0 ENVIRONMENTAL AND AIRSPEED CONSIDERATIONS

The purpose of this section is to discuss the environmental conditions and their impact on airspeed/groundspeed conversions. The environmental conditions describe the airmass in which the airplane operates. As the strategic control algorithm creates a desired route-time profile (RTP) with respect to geographical points, it is necessary to predict the airplane's performance with respect to the ground. Winds and temperatures must be forecast accurately to ensure the airplane an RTP that is within its aeroperformance capability to achieve.

3.1 WIND DATA

The speed at which an airplane is moving with respect to the airmass is called true airspeed (TAS). This speed is along the longitudinal axis of the airplane and hence at the heading angle of the airplane. The vector sum of TAS and the wind vector results in the ground velocity vector. It is necessary, then, to know the wind velocity vector in order to convert from true airspeed to groundspeed and vice versa. Knowledge of the wind vector is required at the point the airplane is operating. In a general sense, a knowledge of the wind vector is required over the entire path within which a strategic airplane must operate. As a practical matter, it is more reasonable to assume that point information will be available and an interpolation program will exist to create environmental forecasts at all other points in the terminal airspace. This contract did not address the method of obtaining the necessary weather data base but rather addressed the method of use. It is interesting to note that airplanes equipped for strategic control have airspeed, groundspeed, and position knowledge and therefore could be a source of continuous wind and temperature information to the system. These data would represent excellent near-term forecasts on the specific tracks of the strategic system. A means of continuous automatic reporting would, of course, be necessary and perhaps be similar to transponder mode-C altitude reporting.

Figure 3-1 shows the block diagram of the wind model used in the computer program. Volume IV contains detailed information of the mechanization. From the algorithm point of view, it is necessary only to obtain a wind forecast at any altitude on demand.

3.2 TEMPERATURE DATA

The pressure and density at any altitude are related by a knowledge of the air temperature at that altitude. The governing relationship is commonly expressed as

$$\delta = \sigma\theta$$

where:

$$\delta = \text{pressure ratio} = \frac{\text{pressure at altitude considered}}{\text{standard day sea level pressure}}$$

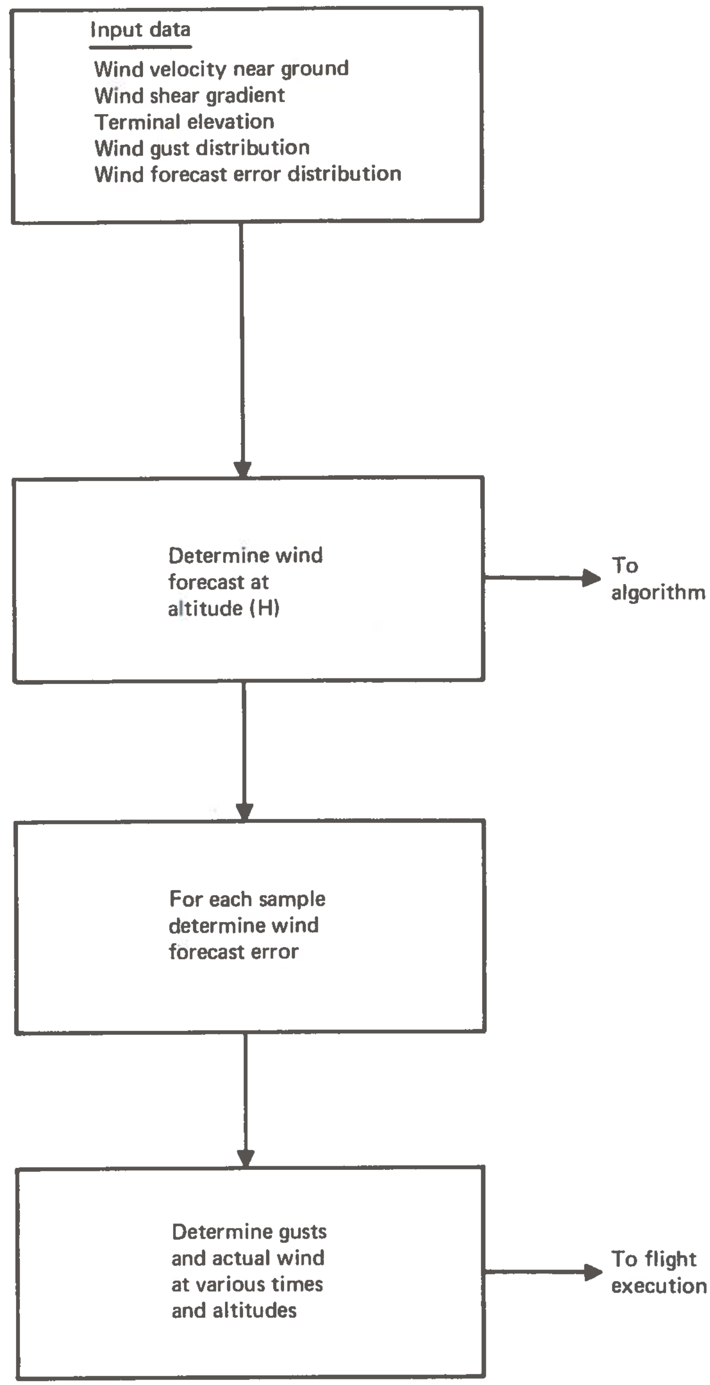


FIGURE 3-1.—WIND MODEL

$$\sigma = \text{density ratio} = \frac{\text{density at altitude considered}}{\text{standard day sea level density}}$$

$$\theta = \text{temperature ratio} = \frac{\text{temperature at altitude considered}}{\text{standard day sea level temperature}}$$

The pressure is essentially a known quantity as it is a primary measurement of the airplane air data system and is used to define pressure altitude (i.e., the altitude measured with an altimeter set at 29.92 inches mercury). The temperature is also an easily measured quantity, and from these two the density ratio is computed.

Standard day conditions represent an atmospheric model accepted throughout the world, and are used as a common baseline for computing aerodynamic parameters and performance curves. The current definition is called the ICAO (International Civil Aviation Organization) Standard Atmosphere and was adopted in 1952 by the National Advisory Committee for Aeronautics. The standard day tables are computed from pressure altitude, a standard day temperature model, and a standard day sea level density. All other values are computed from the above expression, relating pressure, temperature, and density.

The standard day temperature model involves a linear decrease in temperature of 1.98°C per thousand feet of altitude until an altitude of 36,089 feet is reached. Above this altitude, temperature has a constant value of 216.66°K. The sea level temperature is 15°C or 288.16°K. These relationships are expressed mathematically as follows for T in degrees Kelvin:

$$TSD(H) = 288.16 - 0.00198 \times H \qquad H \leq 36{,}089 \text{ feet}$$

$$TSD(H) = 216.66 \qquad H > 36{,}089 \text{ feet}$$

The standard day sea level pressure is given as 2116 lb/ft^2 and the corresponding value of density is 0.002377 $slugs/ft^3$.

The pressure ratio, δ, may be computed as follows for any temperature, T, and altitude, H:

$$\theta = T/T_o$$

$$\delta = \theta^{5.256} \qquad H \leq 36{,}089$$

$$\delta = 0.2234e^{-[(H-36{,}089)/20{,}806]} \qquad H > 36{,}089$$

Pressure altitude results from a special case of the above calculations. If the altitude, H, is used in the standard day temperature model to develop T, the resulting pressure ratio defines the pressure that will cause an altimeter (set at 29.92 inches mercury) to read altitude H. Thus, nonstandard day temperatures cause a deviation between pressure altitude and height above sea level. It should also be noted that if an altimeter is set to the local barometric (QNH) value, nonstandard temperature lapse rate will cause the altitude to be in error in an absolute sense also.

The above considerations have a special significance to the strategic control algorithm as aeroperformance curves are typically available in terms of pressure altitude, Mach number, and either equivalent or calibrated airspeed. These values are referenced to true airspeed by assuming standard day conditions. As a standard day rarely, if ever, exists, it is necessary to have a temperature forecast data bank if predicted performance over the ground is to be accurate. The following relationship illustrates the nature of the problem.

The Mach number, M, may be converted to true airspeed by the following equation:

$$V_{TAS} = Ma$$

where a is the speed of sound. The speed of sound in turn is related to absolute temperature (degrees Kelvin) by:

$$a = 38.975\sqrt{T}$$

The true airspeed (and hence the groundspeed) is therefore a simple function of temperature for a given Mach number.

Figure 3-2 illustrates the logical structure used to provide atmospheric conversion factors for changing calibrated and equivalent airspeed to true airspeed. This logic is appended to the weather generation subroutine in the computer model so that wind, temperature, and atmospheric parameters are generated for any desired altitude (H).

3.3 AIRSPEED/GROUNDSPEED CONVERSIONS

In the algorithm logic it is often necessary to convert from airspeed to groundspeed and vice versa. This section provides the governing relationships and relies on the parameters developed in the preceding sections.

The following definitions relate the various types of airspeeds that are commonly used. Indicated airspeed, IAS, is the airspeed that results from the pitot-static system on the airplane. If IAS is corrected for "position" error (as is commonly the case in modern commercial airplanes) the airspeed indicator reads calibrated airspeed, CAS. The IAS and CAS values are within a few knots of each other. If CAS is corrected for compressibility, the result is equivalent airspeed, EAS. EAS and CAS may differ on the order of 25 knots depending on altitude and Mach number. If the density ratio factor is applied to EAS, the resulting value is called true airspeed, TAS. KIAS, KCAS, KEAS, and KTAS indicate the value is in knots. As TAS combined with the wind vector yields groundspeed, the usual conversion is to obtain TAS from either Mach number, CAS, or EAS. This relationship may be expressed as follows:

$$TAS = Ma = 38.975M\sqrt{T}$$

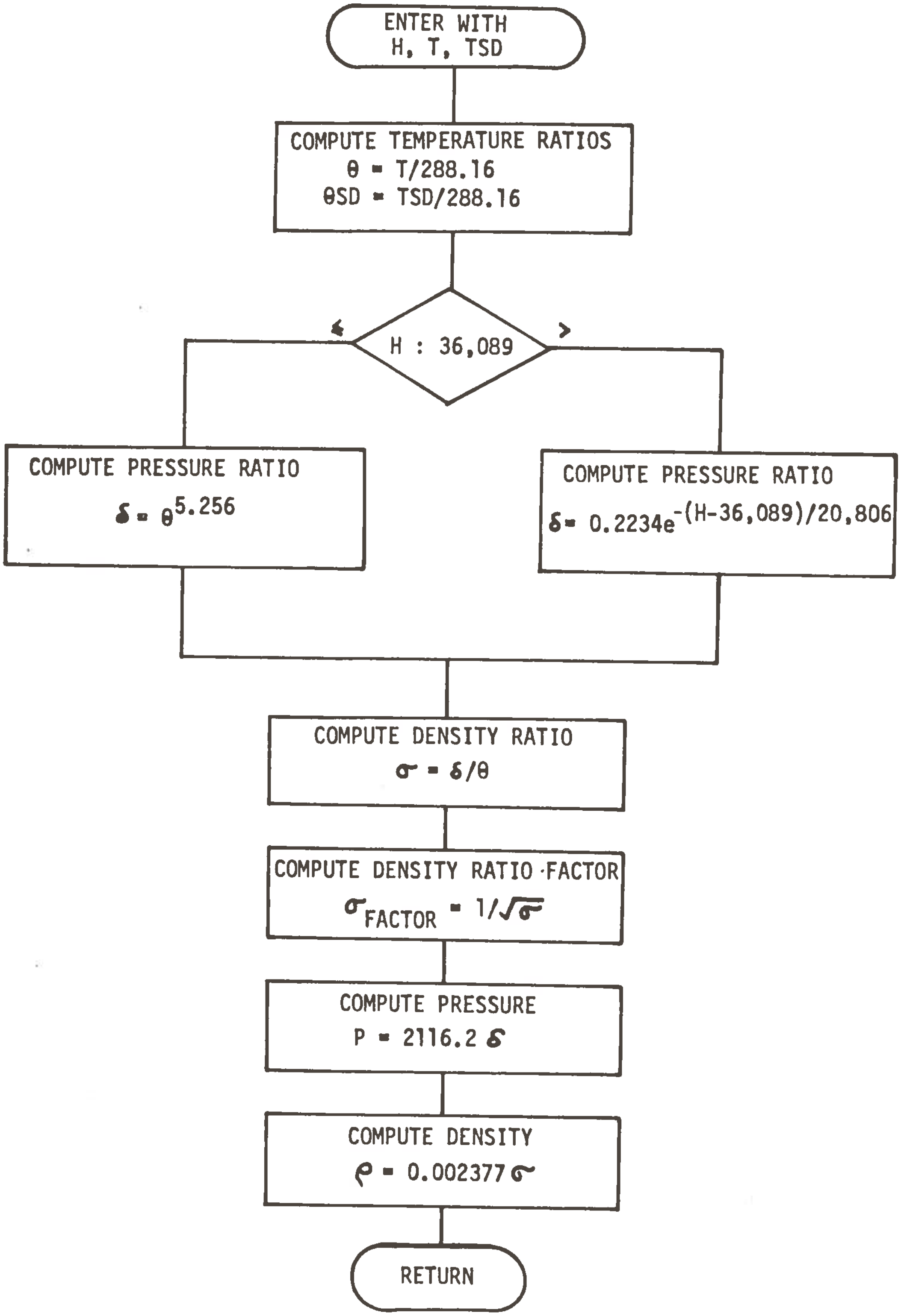


FIGURE 3-2.—ATMOSPHERIC CALCULATIONS

$$TAS = EAS/\sqrt{\sigma}$$

$$TAS = \frac{1479}{\sqrt{\sigma}} \sqrt{\delta \left\{ \left(\frac{[1 + 0.2(CAS/661.5)^2]^{3.5} - 1}{\delta} + 1 \right)^{1/3.5} - 1 \right\}}$$

In the mechanized algorithm, subroutines TASCAS, CASTAS, and TRWIND handle airspeed/groundspeed computations and subroutine WETHER provides wind and temperature forecasts.

4.0 TRAFFIC DATA REQUIREMENTS

This section describes the form and quantity of information required for each airplane handled by the terminal area strategic control system. The traffic data requirements provide the essential boundary conditions from which the algorithm develops a suitable RTP and its associated sequencing, scheduling, and path assignments. In addition, the traffic data provide the required identity information to allow retrieval of airplane or type unique data from the ATC system data banks.

4.1 ARRIVAL TRAFFIC

Table 4-1 represents a sample Los Angeles arrival traffic list. The essential elements that must be provided to the strategic control system prior to each airplane arrival at the entry fix are shown. In addition, an airplane identification number is required to correlate the information to the specific arrival. The entry fix time is the estimated time that the airplane will arrive at the entry fix. This time is shown in seconds from an arbitrary reference in table 4-1. In an operational system this time would likely be a standard ATC time reference such as Greenwich Mean Time (GMT). The resolution and accuracy of this system time element should be small with respect to the time separation between airplanes at any common point in the system. Numerically, time-keeping accuracies of approximately 1 second should be sufficient to minimize errors from this source.

Type information is required for each arrival. This information could be obtained from an ATC data bank by association with the airplane identification number or conversely it could originate from the airplane at the time a terminal area RTP request is made. The airplane-type information must include any specification of any deviations from the basic type that are peculiar to the requesting airplane. Specifically, model modifications such as different powerplants that impact the aeroperformance curves create essentially a different airplane type from an algorithm point of view and hence must be identified.

In order to convert the generalized aeroperformance information to a specific airplane performance window, it is necessary to know the estimated entry fix gross weight for the airplane. This information is likely to be known only to the airplane and so will form a portion of his terminal area RTP request.

The estimated entry fix altitude data can either be determined by the ATC system (i.e., clear the airplane to the entry fix at stated altitude) or could be supplied by the airplane at time of the request for an RTP. The former seems more probable but, on any account, it is a necessary piece of information for the terminal area algorithm.

The estimated speed or Mach number at the entry fix is a necessary boundary condition. This value could either be supplied by the entering airplanes or it could be assigned by the ATC system and executed by the arrival. The basic algorithm developed under this contract made the assumption that the entry fix velocity was estimated by the arriving airplane and treated that value as the initial RTP velocity.

TABLE 4-1.—SAMPLE LOS ANGELES INTERNATIONAL TRAFFIC INPUT

ARRIVALS

ID	ENTRY FIX TIME (SECONDS)	TYPE	ALTITUDE (FEET X 1000)	MACH NUMBER	ENTRY FIX NUMBER	GROSS WEIGHT (LB X 1000)	VREF (KNOTS)
1	0	747	37	.84	(2,3)	480	136.0
2	400	707	37	.82	(1,1)	200	125.2
3	460	727	29	.82	(1,3)	130	122.0
4	740	720	33	.80	(4,2)	160	127.0
5	860	727	26	.82	(2,2)	130	122.0
6	1060	737	32	.75	(2,1)	95	127.0
7	1460	727	26	.82	(2,2)	130	122.0
8	1500	DC9	31	.75	(1,1)	95	127.0
9	1560	747	37	.84	(2,3)	480	136.0
10	1700	727	28	.81	(2,2)	130	122.0
11	1860	747	37	.84	(1,2)	480	136.0
12	1860	727	34	.80	(1,2)	130	122.0
13	2260	727	35	.80	(1,1)	130	122.0
14	2360	727	24	.82	(2,2)	130	122.0
15	2440	720	33	.80	(1,3)	160	127.0
16	2460	DC8	37	.82	(1,2)	200	125.2
17	2740	727	35	.80	(1,1)	130	122.0
18	3060	747	37	.84	(1,2)	480	136.0
19	3100	DC8	37	.82	(1,3)	200	125.6
20	3360	747	37	.84	(1,2)	480	136.0
21	3400	DC9	30	.75	(4,2)	95	127.0
22	3560	727	26	.82	(2,2)	130	122.0
23	3560	727	28	.82	(2,2)	130	122.0
24	3660	747	37	.84	(2,3)	480	136.0
25	4120	727	32	.80	(1,2)	130	122.0
26	4160	DC8	36	.82	(2,1)	200	125.2
27	4440	DC9	32	.75	(1,1)	95	127.0
28	4440	737	22	.72	(1,2)	95	127.0

4.2 DEPARTING TRAFFIC

While departures were considered only from a runway time-slot scheduling point of view in the basic arrival algorithm, a general understanding of the traffic data required is possible. As in the case of arrivals, an initial set of boundary conditions and airplane identity information will be required. The source of the required data is dependent upon the strategy used to assign departure slots. If an opportunity departure strategy is used, the actual start of roll time, runway number, airplane identification, type of airplane, and gross weight would be the pertinent information. Flight objective (e.g., destination, route, initial cruise altitude, etc.) could be obtained from flight plan information. If a more regimented preassigned departure slot system were implemented, the information requirement would be similar except the start of roll time becomes preknown to the system and allows an earlier determination of the departure RTP.

4.3 UNEQUIPPED TRAFFIC

Unequipped traffic consists of two distinct situations. The first is the normal participant (i.e., high-performance airplane) in the strategic system who is operating with something less than a full complement of avionics, perhaps due to malfunction. The ATC system requires the same type of information for these airplanes as discussed in sections 4.1 and 4.2 above. They will be handled as normal strategic airplanes except that separation standards must be increased to allow for the degraded ability to accurately follow the RTP. The second type of unequipped airplane that may operate occasionally to a strategically controlled runway is the low-performance general aviation airplane. This type of airplane is not envisioned to be equipped for strategic operation and will represent only a small fraction of the operation on a strategically controlled runway. The strategic algorithm must have a capability for providing a sufficiently large time slot so that this type of operation can be manually inserted into the strategic stream at a common point close to the runway. This common point is likely to be at or inside the outer marker. The airplane identification, estimated insertion time, airplane type, and planned landing speed should be sufficient information to provide a safe slot.

4.4 AEROPERFORMANCE DATA

For each participating airplane type in the strategic control system it is necessary to have an aeroperformance data bank. This data bank is prestored as an integral part of the ATC system. The basic arrival algorithm operates on the premise that all airplanes can operate on a common track and airspeed profile from the initial approach fix (IAF) to the outer marker. The time controllability necessary to derandomize the arrival stream is achieved by speed control from the entry fix to the IAF. With this type of mechanization, the velocity versus altitude profiles that define the permissible high- and low-speed boundaries of the aeroperformance envelope must be encoded and prestored. Figure 4-1 shows the form of these raw data. The velocities shown are true airspeeds of the airplane. The use of this information for a specific arrival requires the corrections for the particular gross weight and environmental conditions to obtain an aeroperformance envelope that defines the groundspeed versus altitude envelope for the particular arrival. This process is discussed in detail in sections 5.0 and 7.0.

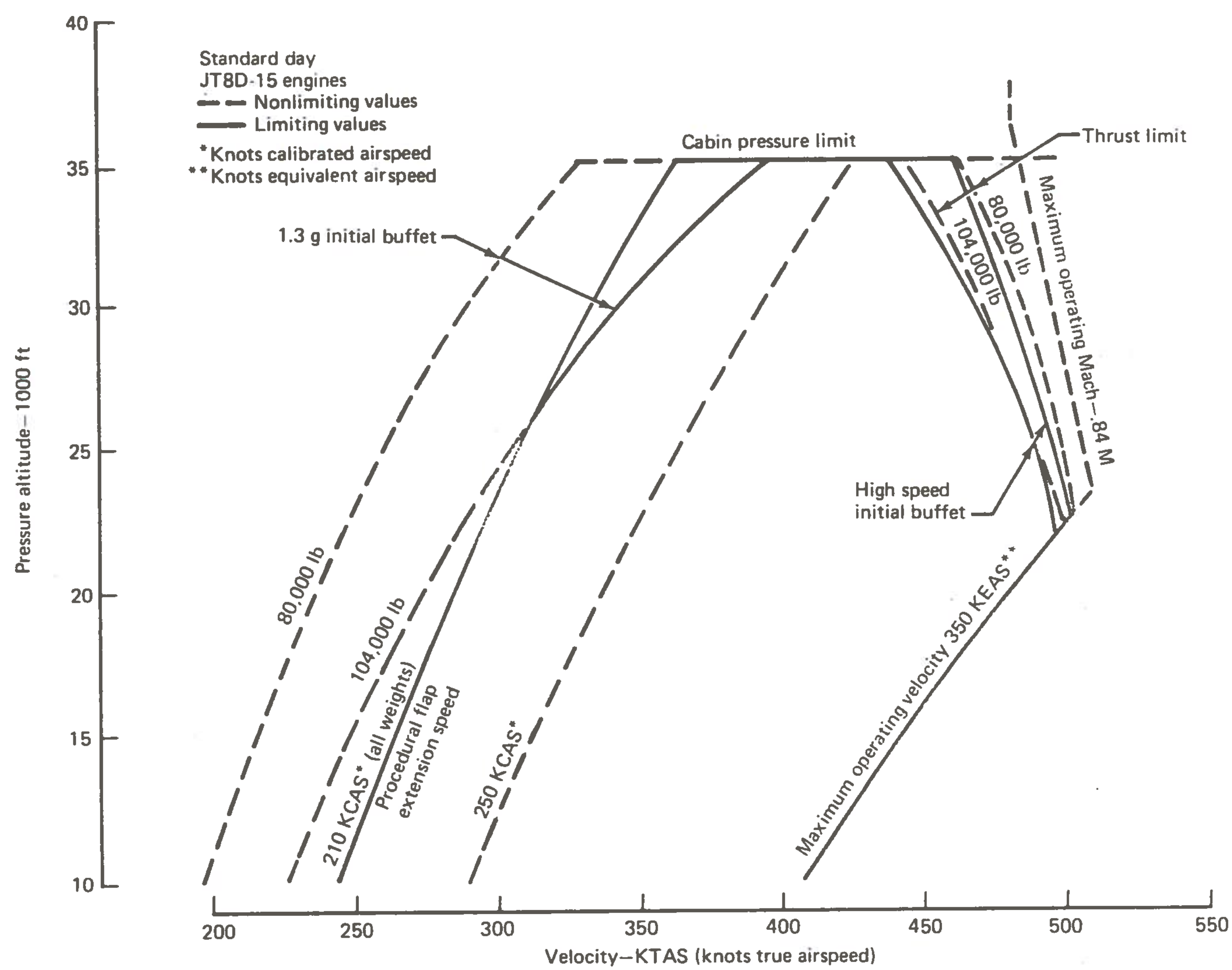


FIGURE 4-1.—AEROPERFORMANCE ENVELOPE (737-200)

5.0 SEQUENCING STRATEGY

The basic sequencing problem involves the determination of arrival order at the threshold. Simply viewed, this is a "who follows who?" question and time assignments are made after sequencing by the scheduling strategy. The basic algorithm uses a "first runway capability, first sequenced" strategy. The strategy employs the technique of computing the earliest estimated landing time (EELT) for each entry request by integrating the fastest groundspeed profile that the airplane's performance envelope allows to obtain this estimate. The ordered list of these EELTs forms the basis for determining scheduling priority. Because of the similarity of the data bank and computational process, the estimated latest landing time (ELLT) is also computed during the sequencing process. These early and late time estimates then form the airplane's time window from which the scheduler logic must assign a scheduled time. The sequencing logic also accommodates airplane cabin repressurization time if it is a limiting value. Figure 5-1 shows the arrival sequencing logic.

5.1 EARLY/LATE TIME DETERMINATION

The process of determining the earliest and latest arrival times for an upcoming arrival may be conceptually viewed as a three-step process. The first of these steps is to compute the outer marker to threshold time requirement. The second step involves computing the IAF to outer marker time requirement. The third step is computation of the shortest and longest time possible in transitioning the distance from the entry fix to the IAF. The sum of these three steps, when adjusted to reflect the expected entry fix time, provides the earliest and latest times that the airplane can make the threshold. A scheduled landing time that is earlier than the EELT cannot be achieved from an aeroperformance point of view. A scheduled landing time later than the ELLT will require holding prior to the entry fix insertion. The amount of holding prior to system entry is a function of the demand and the time controllability possible for the individual airplanes. This latter consideration is in turn a function of the path lengths and airplane performance windows.

5.1.1 Outer Marker to Threshold Time Determination

The process of determining the outer marker to threshold time is required for each airplane as each will have a reference velocity (VREF) that is a function of the gross weight and the airplane type. VREF is the still air, standard day airspeed at which the airplane will cross the threshold on final approach. The actual airspeed flown will be this value as modified for environmental deviations from these standard conditions. This corrected value is referred to as the "bug." (Note: Another common usage of the term "bug" is to represent the uncorrected VREF, but this definition is not satisfactory for the purposes of this documentation.) Basically the bug has a value equal to the VREF + 1/2 of the reported threshold headwind component + the reported gusts. Figure 5-2 indicates the logical process for computing the groundspeed value corresponding to the airspeed value of the bug. Assuming a linear transition between the outer marker and the threshold, and with the distance provided by the geometry considerations, the time required to go from the outer marker to the threshold may then be computed.

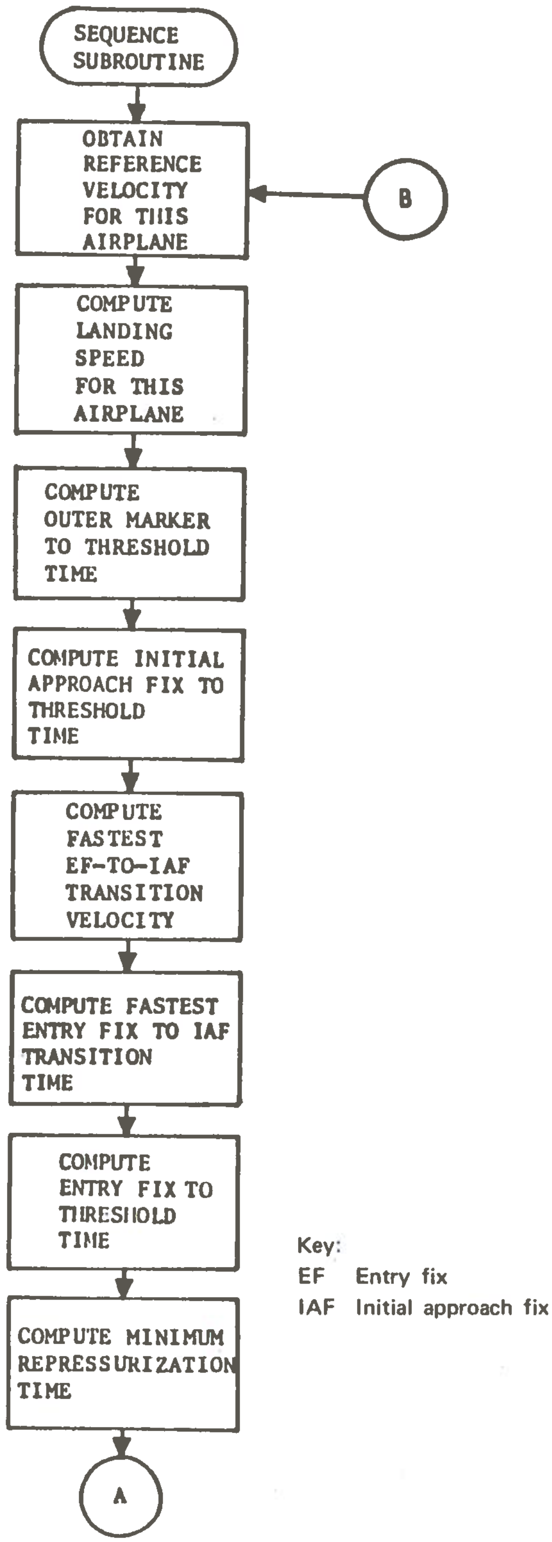


FIGURE 5-1.—SEQUENCING LOGIC

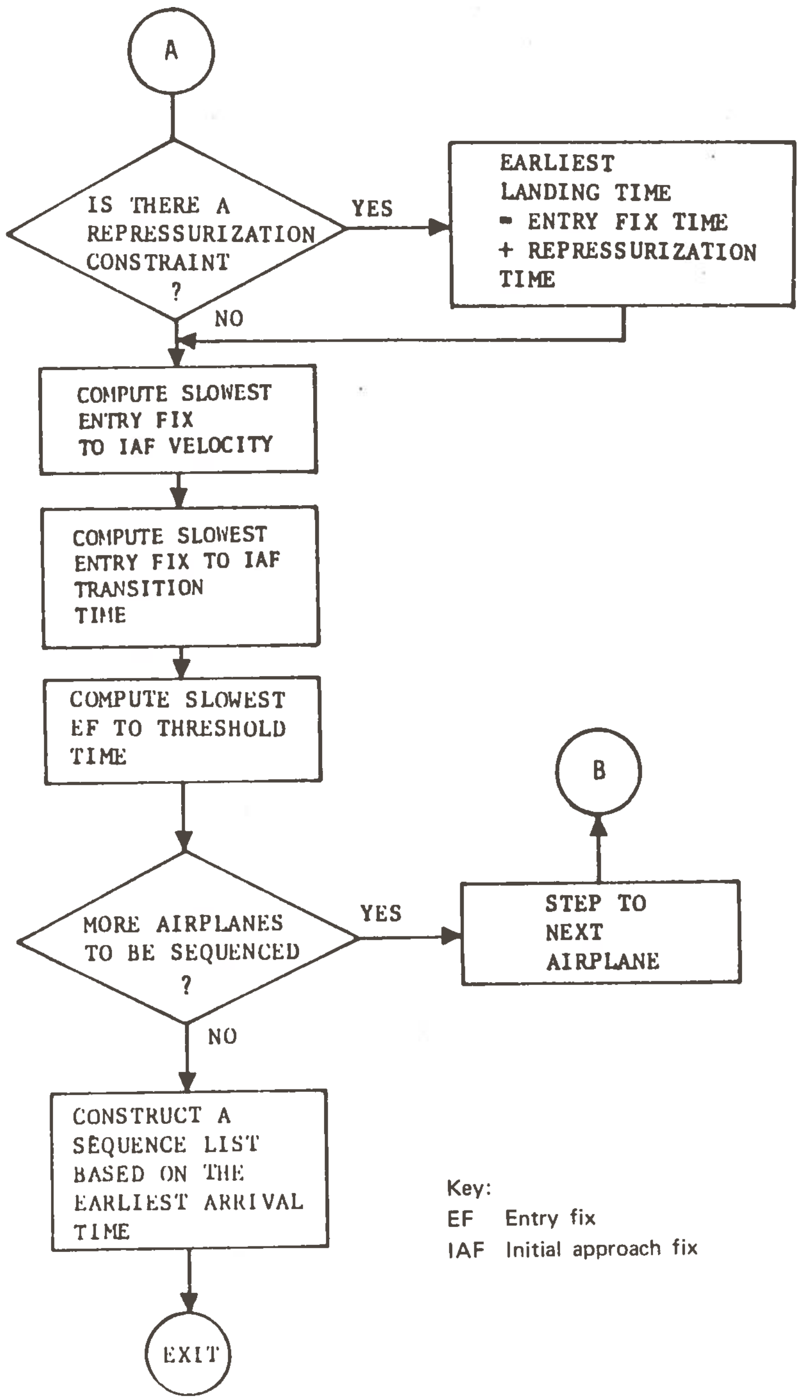


FIGURE 5-1.—CONCLUDED

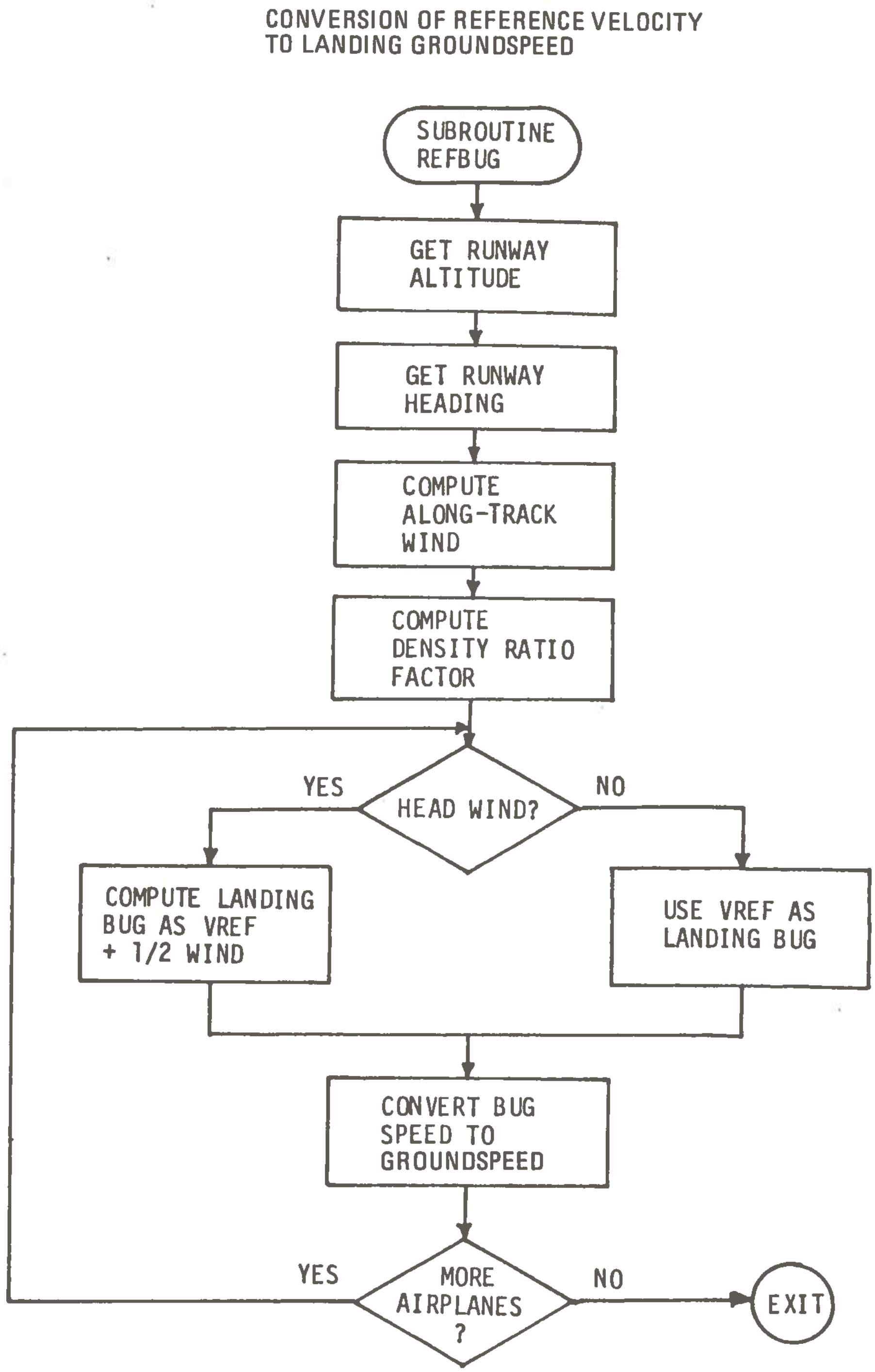


FIGURE 5-2.—THRESHOLD VELOCITY COMPUTATION

5.1.2 IAF to Outer Marker Time Determination

The time required to go from an IAF to the outer marker needs to be accomplished only once per weather forecast update. This results from the common velocity profile for all airplanes within this region. The times, of course, must be computed for each IAF in the system. Figure 5-3 shows the logic structure of this computational process, which is a subroutine called AERO1. Input information for AERO1 is shown in figure 5-4 and basically consists of the target airspeeds to be achieved at each control point in this region. From these values AERO1 computes the groundspeeds and times required between each control point by assuming a linear velocity transition between points. The groundspeeds account for wind and temperature impact.

5.1.3 Entry Fix to IAF Time Determinations

The determination of the time required to transition the entry fix to IAF portion of the arrival makes use of the high- and low-speed aeroperformance boundary for the airplane. The fastest and slowest transition that the airplane can achieve is by flying at the boundary for the entire transition. As a practical matter, present day airplanes do not have sufficient drag to maintain the fixed rate of descent and also decrease airspeed significantly. This lack of gradient capability (see Discussion in vol. II, sec. 3.1) makes it impossible to follow most of the low-speed boundaries. However, a close approximation to the slow-speed boundary may be achieved by slowing in level flight to the low-speed aero limit and then making a constant airspeed letdown at that limit. This technique allows slow-speed operation while maintaining gradient capability consistent with actual airplane performance. On the high-speed side of the performance envelope, a similar limitation exists with respect to transitioning via the maximum thrust constraint–in this case, speeding up to the high-speed aero limit and then making a constant Mach descent to a critical altitude defined herein as the altitude at which the airplane's M_{MO} (i.e., Mach maximum operational) curve intersects the V_{MO} (i.e., velocity maximum operational) curve. From the critical altitude the descent continues via a constant calibrated airspeed letdown to the IAF altitude. The effect of this process is to approximate the high-speed envelope quite closely and yet stay within the descent capability of the airplane.

Conceptually the standard day aeroperformance envelope as represented in figure 4-1 of the previous section is modified by along-track temperature and wind to obtain an envelope that represents groundspeed boundaries as a function of altitude. This process is diagrammed in figures 5-5 and 5-6. Figure 5-7 shows a typical performance envelope during each step of the modification process. The RTP, which ultimately will be computed to achieve a scheduled landing time, must be based on groundspeeds within this resultant envelope.

The logic structure of the aeroperformance conversion process is diagrammed in figure 5-8, which is a subroutine called AERO. AERO functionally adjusts the raw, standard day aeroperformance envelope to achieve a groundspeed envelope representative of the airplane's gross weight and the forecast environmental conditions. The raw aero information represented by figure 5-9 is encoded by representative points for four descriptive boundaries. These are the high- and low-speed boundaries for the lightest gross weight and

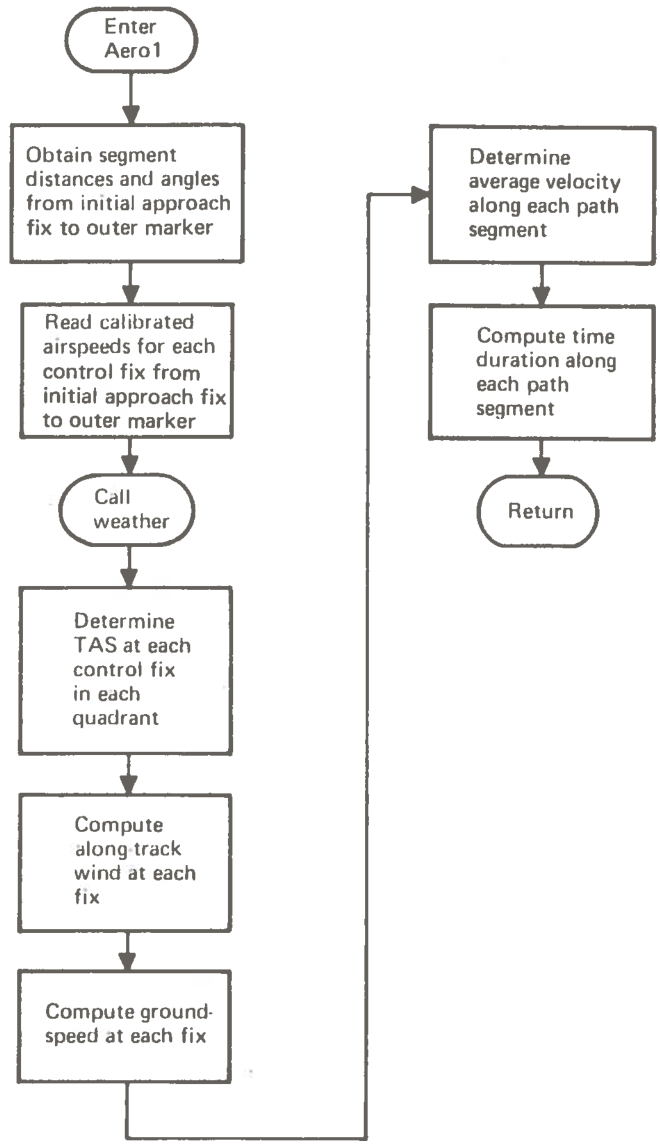
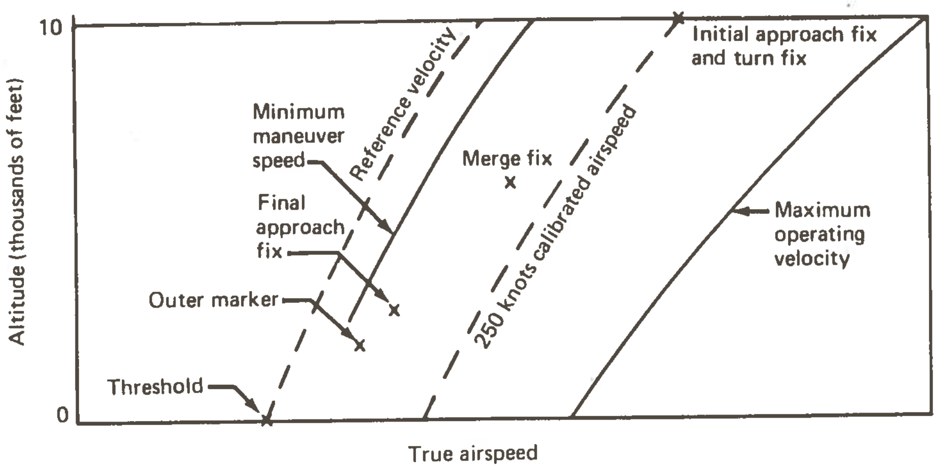


FIGURE 5-3.—COMMON PROFILE TIME COMPUTATION



Algorithm initial approach fix to outer marker velocity/time format

Index	Waypoint	Velocity (knots calibrated airspeed)	Groundspeeds (for each quadrant)	Times (for each quadrant)
1	OM	175	– – – Computed by subroutine	AERO1 – – –
2	FAF	180		
3	MF	200		
4	TF	250		
5	IAF	250		

FIGURE 5-4.—COMMON PROFILE DATA STRUCTURE

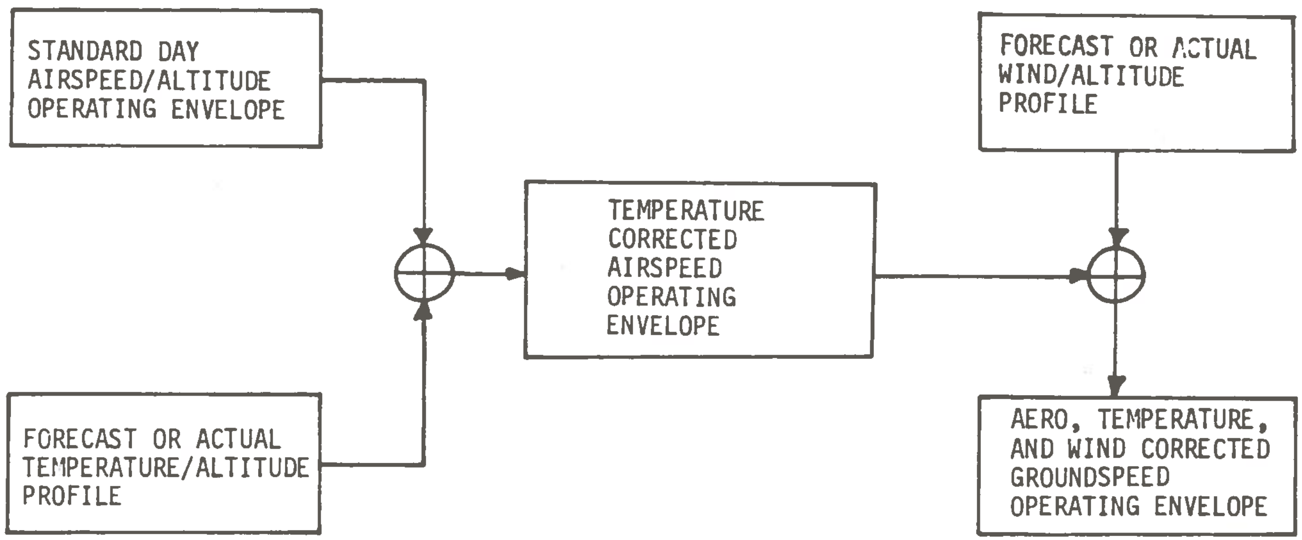


FIGURE 5-5.—AIRPLANE OPERATING ENVELOPE CORRECTIONS

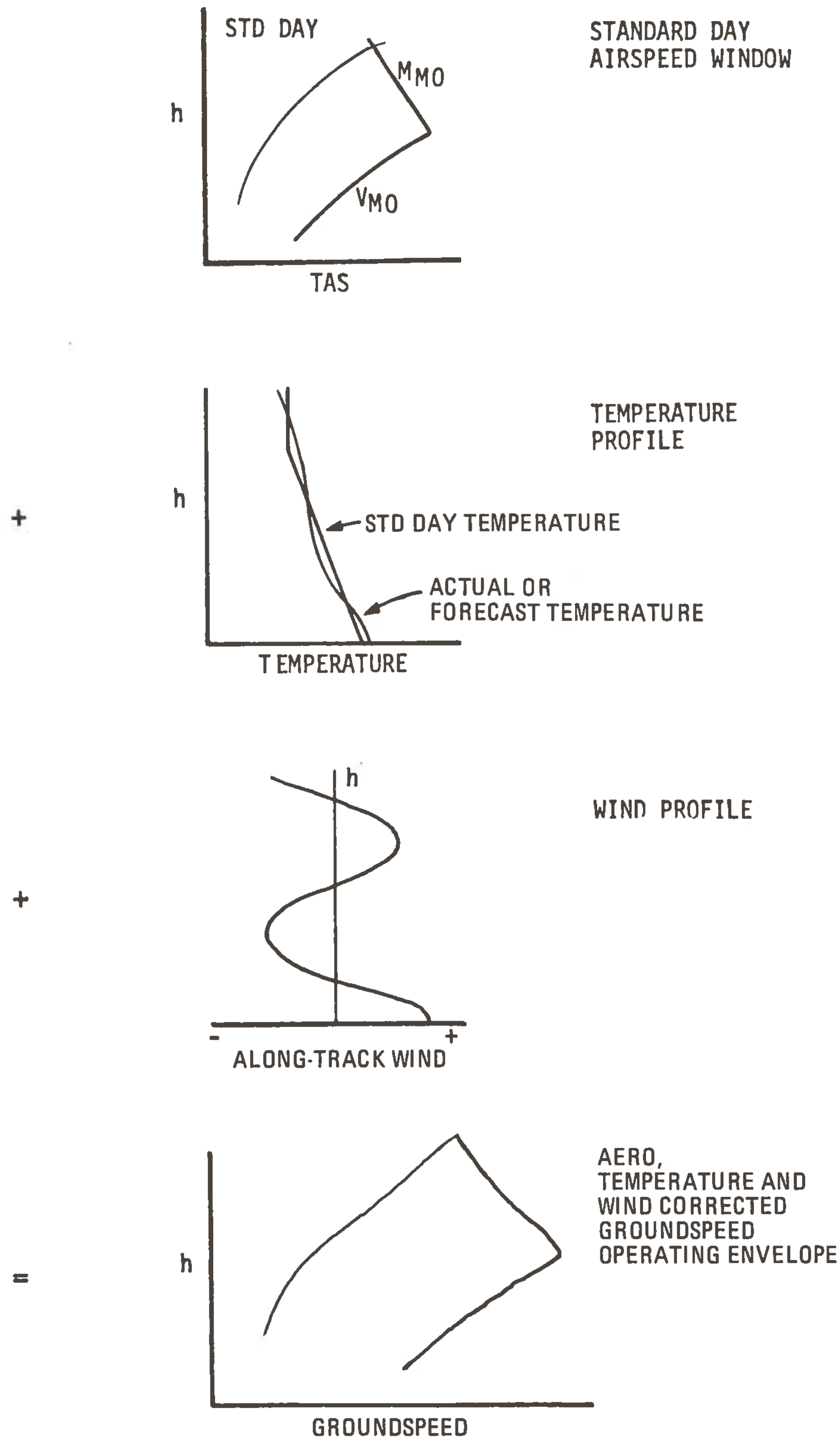


FIGURE 5-6.—AIRSPEED/TEMPERATURE/WIND TO GROUNDSPEED TRANSFORMATION

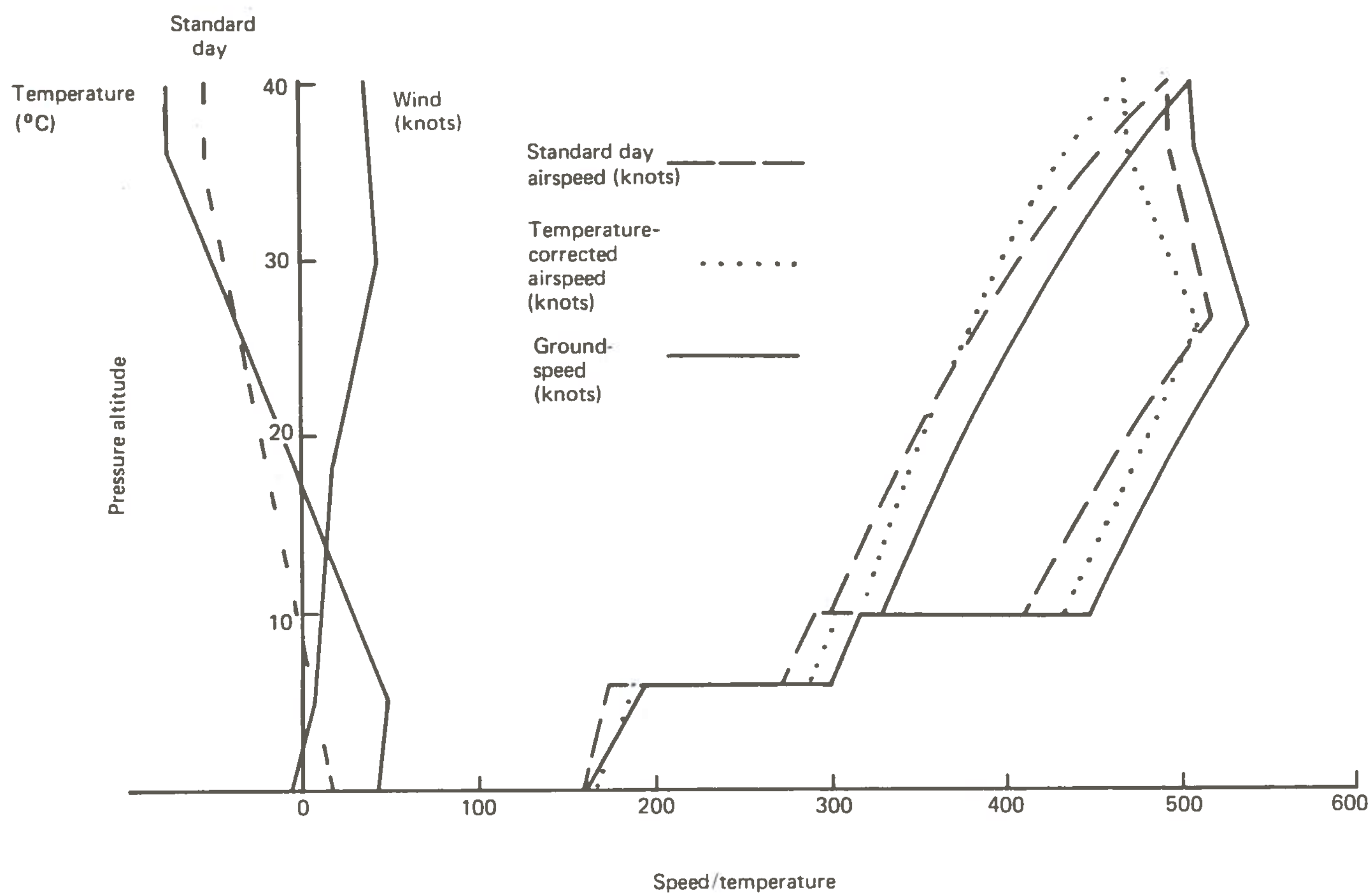


FIGURE 5-7.—TYPICAL GROUNDSPEED OPERATING ENVELOPE

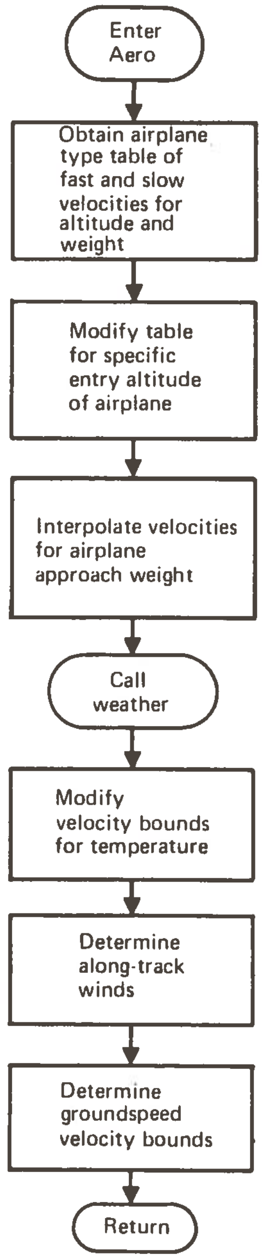
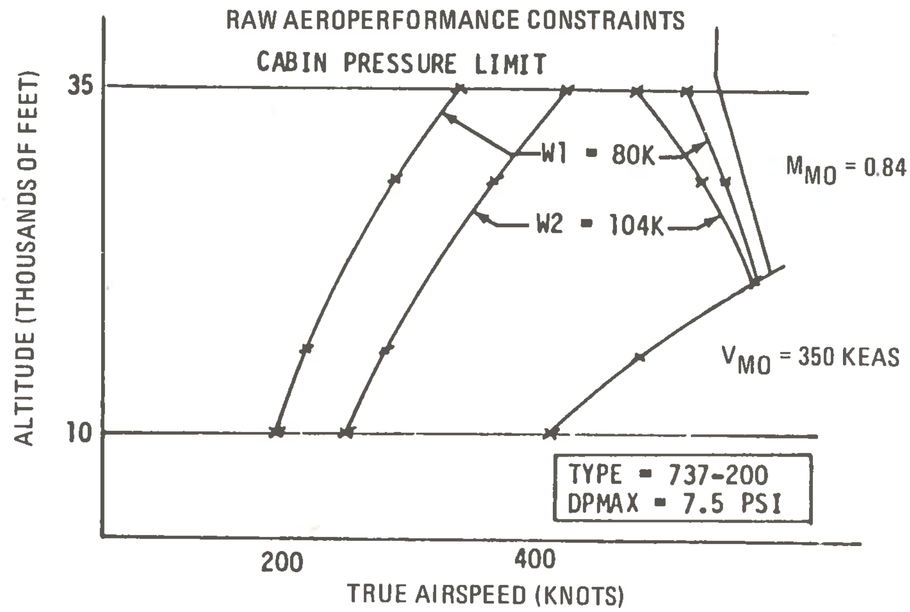


FIGURE 5-8.—AEROPERFORMANCE CONVERSION LOGIC



ALGORITHM RAW AERO FORMAT

I	ALTITUDE	VSLOW1	VSLOW2	VFAST1	VFAST2
1	10,000	197	225	407	407
2	17,500	225	260	460	460
3	22,000	246	287	495	495
4	29,000	282	333	490	473
5	35,000	330	397	466	443

TYPE	W1	W2	IMAX	DPMAX
737-200	80,000	104,000	5	7.5

I	ALTITUDE	VSLOW	VFAST
1	10,000	-- COMPUTED BY SUBROUTINE AERO. THESE ARE GROUNDSPEEDS. ---	
2	17,500		
3	22,000		
4	EF ALT		

VFAST AND VSLOW REPRESENT THE ALGORITHM GROUNDSPEED BOUNDARY FOR A PARTICULAR ALTITUDE AND ARRIVAL WEIGHT

FIGURE 5-9.—TRANSITION REGION AERO DATA STRUCTURE the maximum landing weight for a particular airplane type or derivative. An entry to this subroutine with gross weight, entry fix, altitude, and airplane type will provide the high- and low-speed limits. Linear interpolation is used for intermediate weights and altitudes.

During the early/late time determination process the sequencing routine uses the RTP generation logic to generate the actual velocity schedule and to accomplish the integrations based on the envelope extremes. These RTP subroutines return a single time for each call, based on the conditions set up by the sequencing logic.

5.1.4 Cabin Repressurization Considerations

The cabin of a commercial airplane is pressurized to reduce the total pressure differential between the cabin interior and exterior. The exterior pressure decreases with altitude and the cabin pressure is constrained by passenger comfort and the maximum pressure differential for which the airframe structure is designed. The passenger comfort constraint restricts the cabin to a pressure corresponding to an altitude of 8000 feet. The maximum cabin pressure differential is a function of the specific airplane design type.

During descent it is necessary to equalize the cabin and exterior (i.e., barometric) pressure before landing in such a way that the maximum cabin pressure differential is not exceeded and, in addition, the rate of change of cabin pressure does not exceed 300 feet/minute sea-level equivalent. This latter restriction is a passenger comfort consideration. Unrestricted airplane descent rates may exceed the possible cabin repressurization rate, thereby placing the airplane at the runway with the cabin at a pressure that has not had time to equalize. To prevent this occurrence, it is necessary to restrict the letdown rate to allow proper repressurization of the cabin. This situation is more time critical at the higher cabin altitudes associated with a high-altitude en route cruise. The required repressurization time may be expressed as

$$\text{Repressurization time} = \frac{\text{initial cabin altitude pressure}}{\text{sea-level equivalent repressurization rate}}$$

The repressurization time can be minimized for a given repressurization rate by maintaining the cabin altitude as low as possible. This is equivalent to maintaining the maximum cabin pressure differential. For algorithm design purposes the assumption was made that all airplanes arrive with the cabin pressure differential adjusted to the maximum allowable value for the particular type. The aero data bank contains this value (CABPRS) for each type. With a knowledge arrival and threshold pressure, the repressurization time may then be computed from the following equation.

Let: TREPRS = repressurization time (seconds)
THPRES = threshold barometric pressure (lb/ft^3)
PRESUR = arrival pressure altitude (lb/ft^3)
CABPRS = maximum cabin pressure differential (psi)

Then: TREPRS = (THPRES-PRESUR + CABPRS x 144.)/22.9

Requiring all airplanes to arrive at the maximum cabin pressure differential would not be necessary if an arriving airplane were to transmit the actual cabin pressure as part of the request for an RTP. This alternate method requires a slight increase in communication bandwidth but would allow the airplane more freedom in controlling the cabin pressure. If the alternate is adopted, however, the cabin repressurization time constraint will be the limiting factor more often, with a resultant decrease in speed controllability.

5.2 SEQUENCE NUMBER ASSIGNMENT

Once the early/late times have been established, the estimated earliest landing times are sorted. The airplane with the earliest threshold capability will be the first airplane scheduled. A pointer list is established that directs the computing system to the appropriate traffic information as each landing is scheduled and an appropriate RTP is computed. Each airplane receives a landing order assignment by the above process even if during scheduling it is necessary to create holds outside the entry fix. The ultimate RTP generated will then be for the scheduled threshold time and will preserve the ordered relationship to the other arrivals. This technique will spread any system holding delays in an equitable manner among all arrivals.

5.3 UNEQUIPPED AIRPLANE INSERTION

In the case of close-in, common path insertion of unequipped (nonstrategic) airplanes, it is anticipated that slots will be created based on estimated insertion time. A sequence number will be assigned based on this estimate and the next available slot. During scheduling, the appropriate separation criteria for unequipped airplanes will be reflected in the scheduled landing time of this airplane and those that follow. This insertion process is conceived to be handled in a manual fashion by a controller but could also be done with an automated tactical command loop interfaced to the strategic control system.

6.0 SCHEDULING

The scheduling function accomplishes the threshold time assignment for each airplane, subject to the constraints imposed by (1) the scheduling windows derived by the sequencing function, (2) the ATC rules and procedures, and (3) the interaction between arrivals and departures. In accomplishing the scheduling function, an airplane will always be assigned the earliest time, within the scheduling window, that is consistent with the scheduling strategy and constraints. This results in a runway schedule that makes the best use of the runway resource subject to the sequencing strategy, the demand, and the ATC rules.

Figure 6-1 shows the logical structure of the scheduling function. This logical structure resolves the scheduling problem into one of four possible conditions:

- Arrival following departure (D/A)
- Departure following arrival (A/D)
- Departure following departure (D/D)
- Arrival following arrival (A/A)

Three subconditions of the arrival following arrival case are considered to determine if the threshold is the critical scheduling point for the arrival stream. These subconditions result from considerations of the relative final approach speeds of two successive arrivals. If the two airplanes fly the same velocity profile from the outer marker to the threshold, then separation will not change during this leg, and if adequate separation is provided at the threshold the same separation will exist at the outer marker. If the following airplane is faster on approach, the separation will be closing during the approach and the threshold becomes the critical scheduling point. The outer marker separation will always exceed the threshold separation in this case. The third subcondition exists when the following airplane is slower than the preceding airplane. In this case, the separation is increasing as the threshold is approached. If the schedule time was based on threshold separation, the separation existing at the outer marker would be less than adequate. Thus, the outer marker becomes the critical point for scheduling purposes and the threshold schedule must be relaxed to ensure adequate critical point separation. These considerations are shown graphically in figure 6-2. In this figure the I+1 airplane follows airplane I at the threshold and VBUG represents the threshold speeds.

In understanding the scheduling strategy logic (fig. 6-1), it is necessary to recognize that the "next available arrival schedule slot" (NASLOT) is a dynamically assigned variable at any point in the logic. NASLOT takes on a value that may be modified several times before all conditions are satisfied in order to make it a firm scheduled landing time (SLT). Figure 6-3 shows some typical samples of the progression of the NASLOT variable for different conditions. On the left of the figure the Ith airplane has an earliest runway capability of EELT and that runway slot was available, so the NASLOT value was set to $NASLOT_1$ and the airplane was scheduled at landing time SLT(I). The anticipated runway

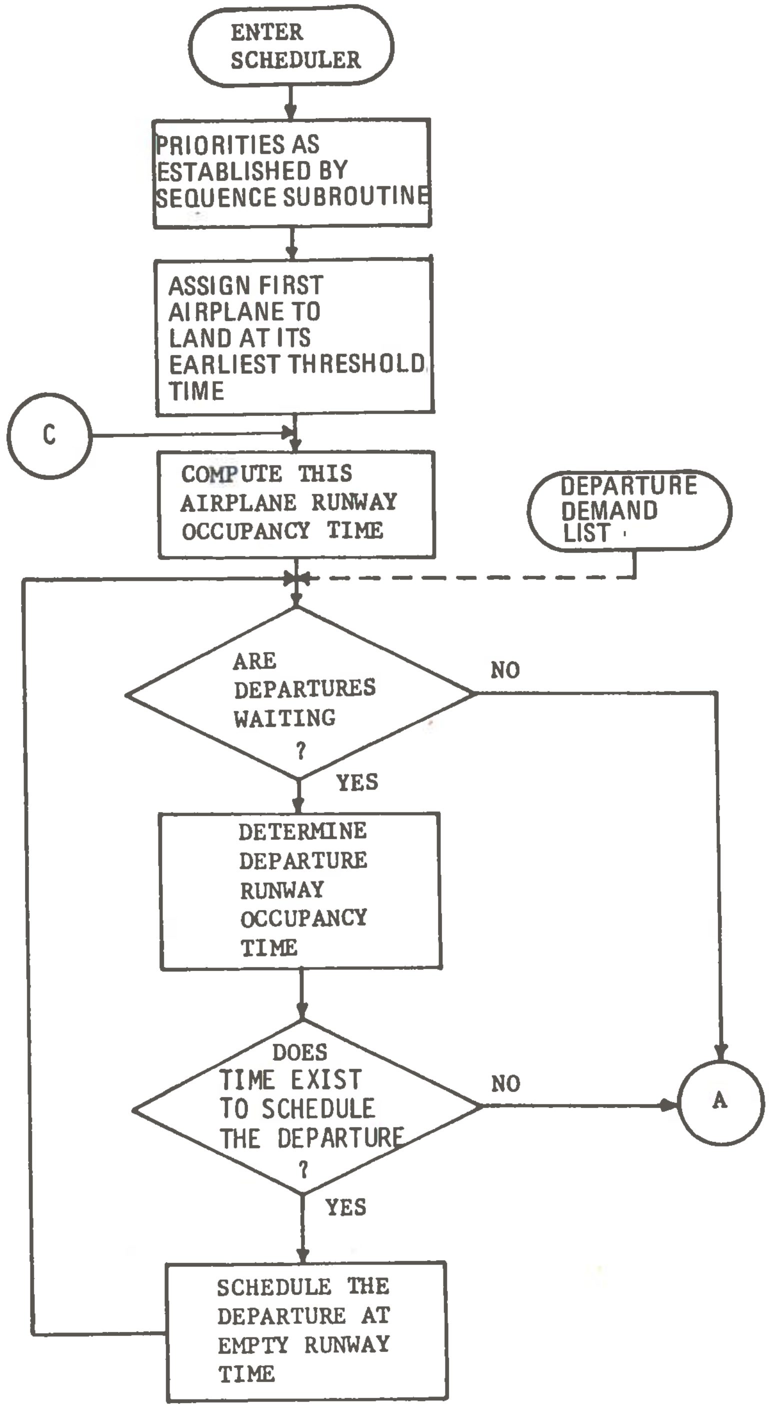


FIGURE 6-1.—SCHEDULING LOGIC

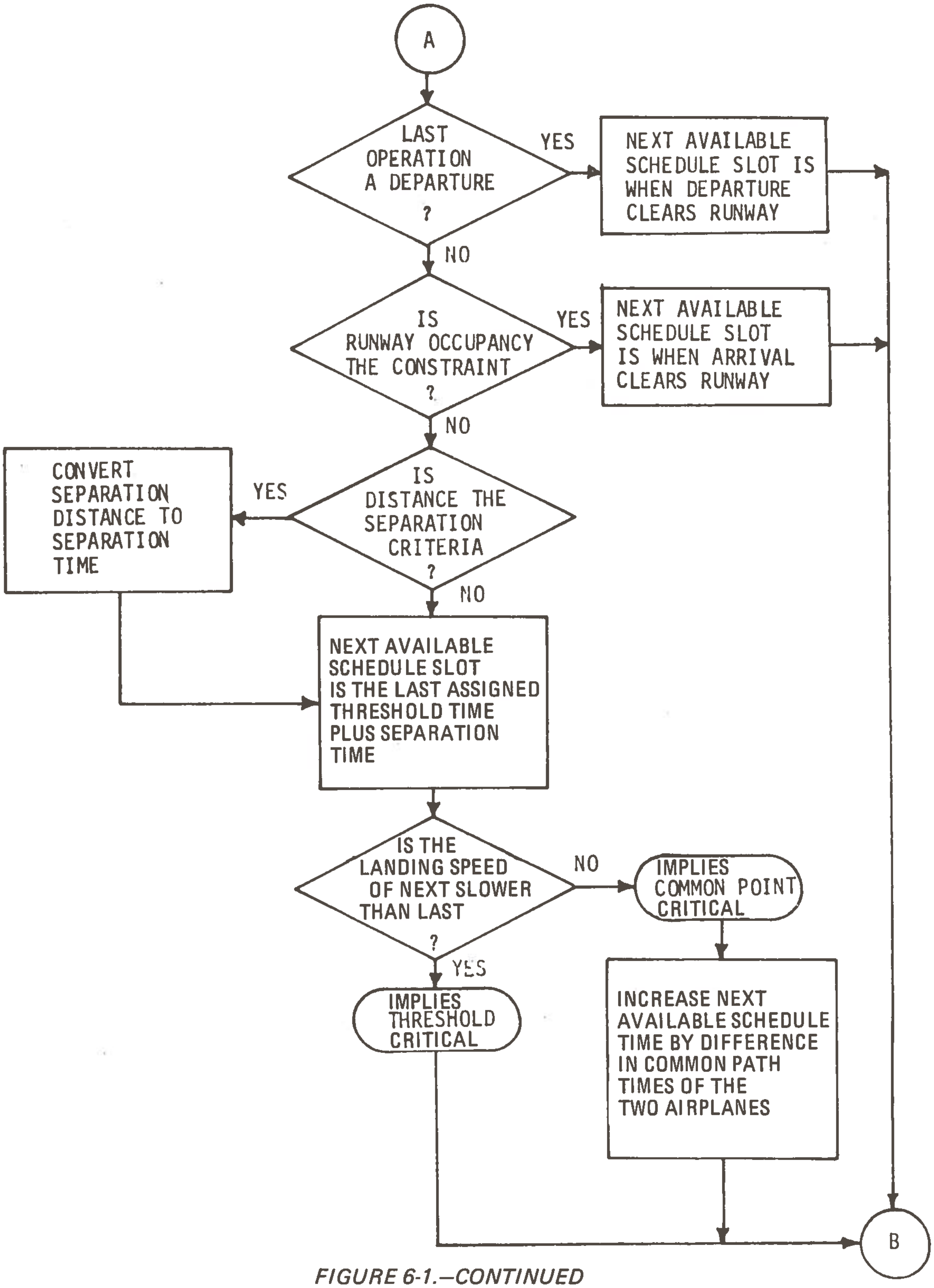


FIGURE 6-1.—CONTINUED

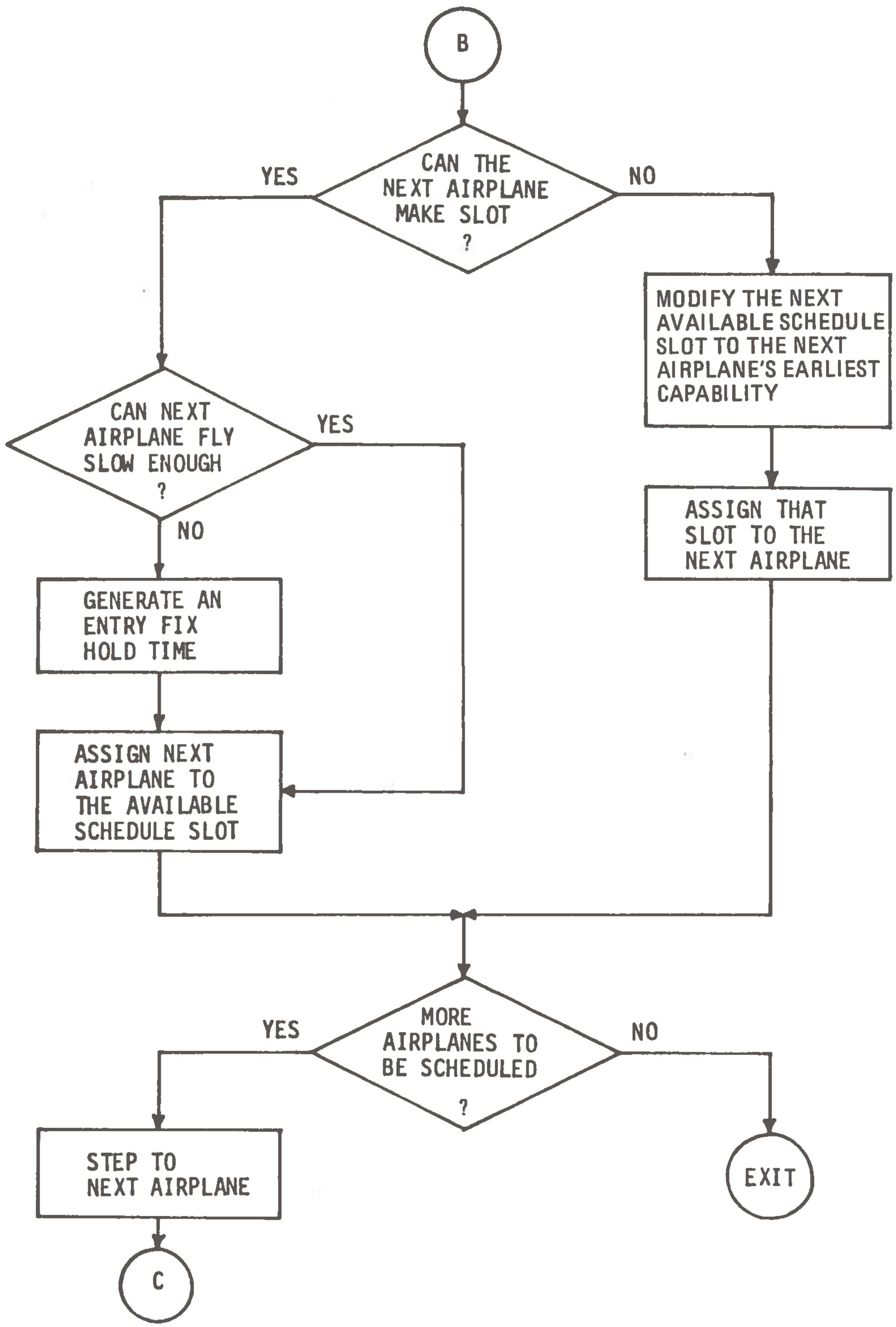
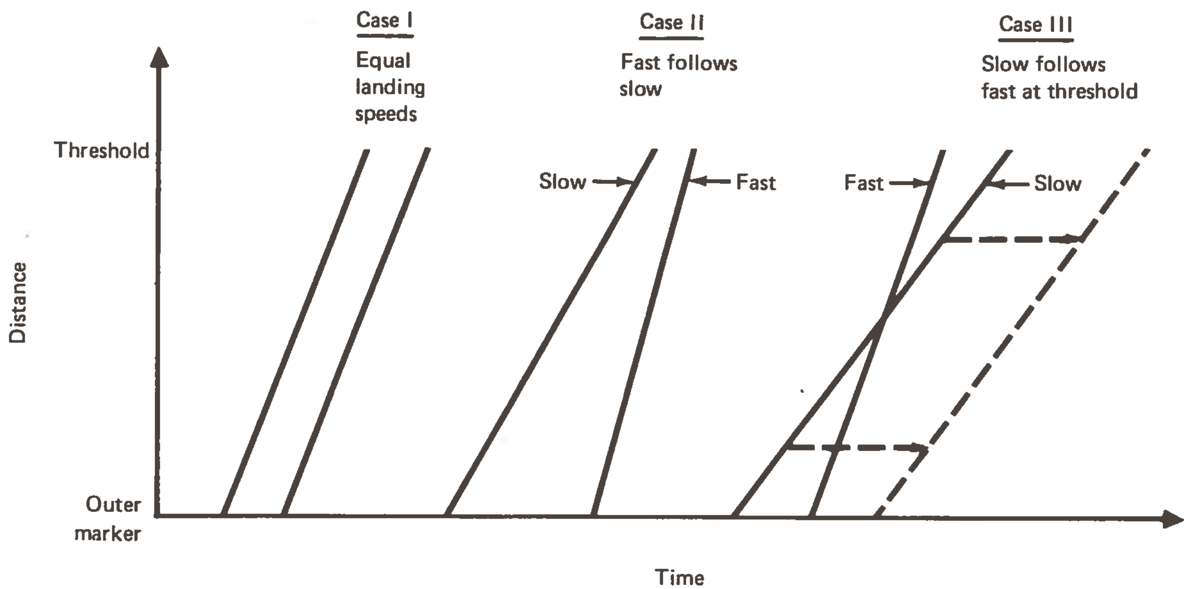
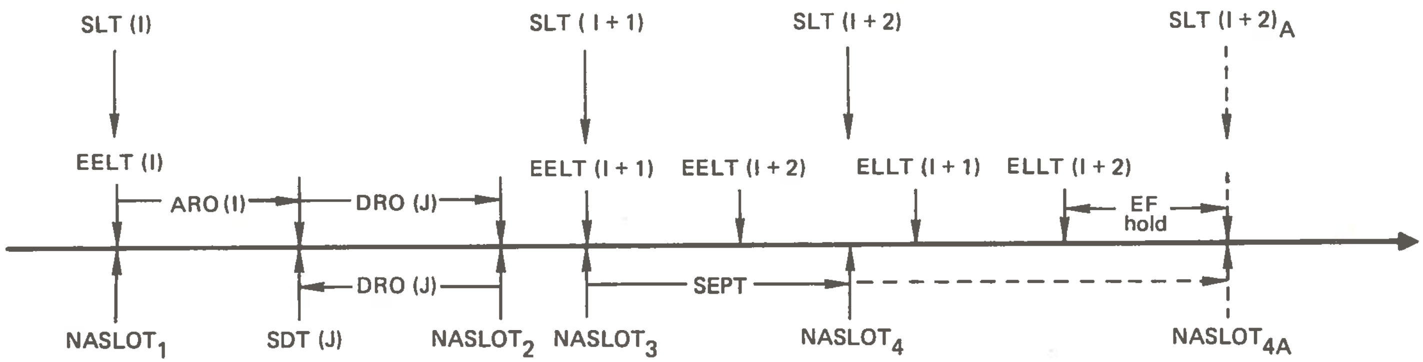


FIGURE 6-1.—CONCLUDED



Case	Action	Condition
I	None(threshold separation provides OM separation)	VBUG(I) = VBUG (I + 1)
II	None (OM separation exceeds threshold separation)	VBUG(I) $<$ VBUG (I + 1)
III	Threshold separation must be increased to provide OM separation	VBUG(I) $>$ VBUG (I + 1)

FIGURE 6-2.—CRITICAL POINT SCHEDULING



Key:

ARO (I) – Arrival runway occupancy time for i^{th} arrival
EELT (I) – Earliest available landing time for i^{th} arrival
ELLT (I) – Latest available landing time for i^{th} arrival
DRO (J) – Departure runway occupancy time for j^{th} departure
SDT (J) – Departure time assigned to j^{th} airplane
SEPT – Arrival-arrival separation time constraint
SLT(I) – Arrival time assigned to the i^{th} airplane

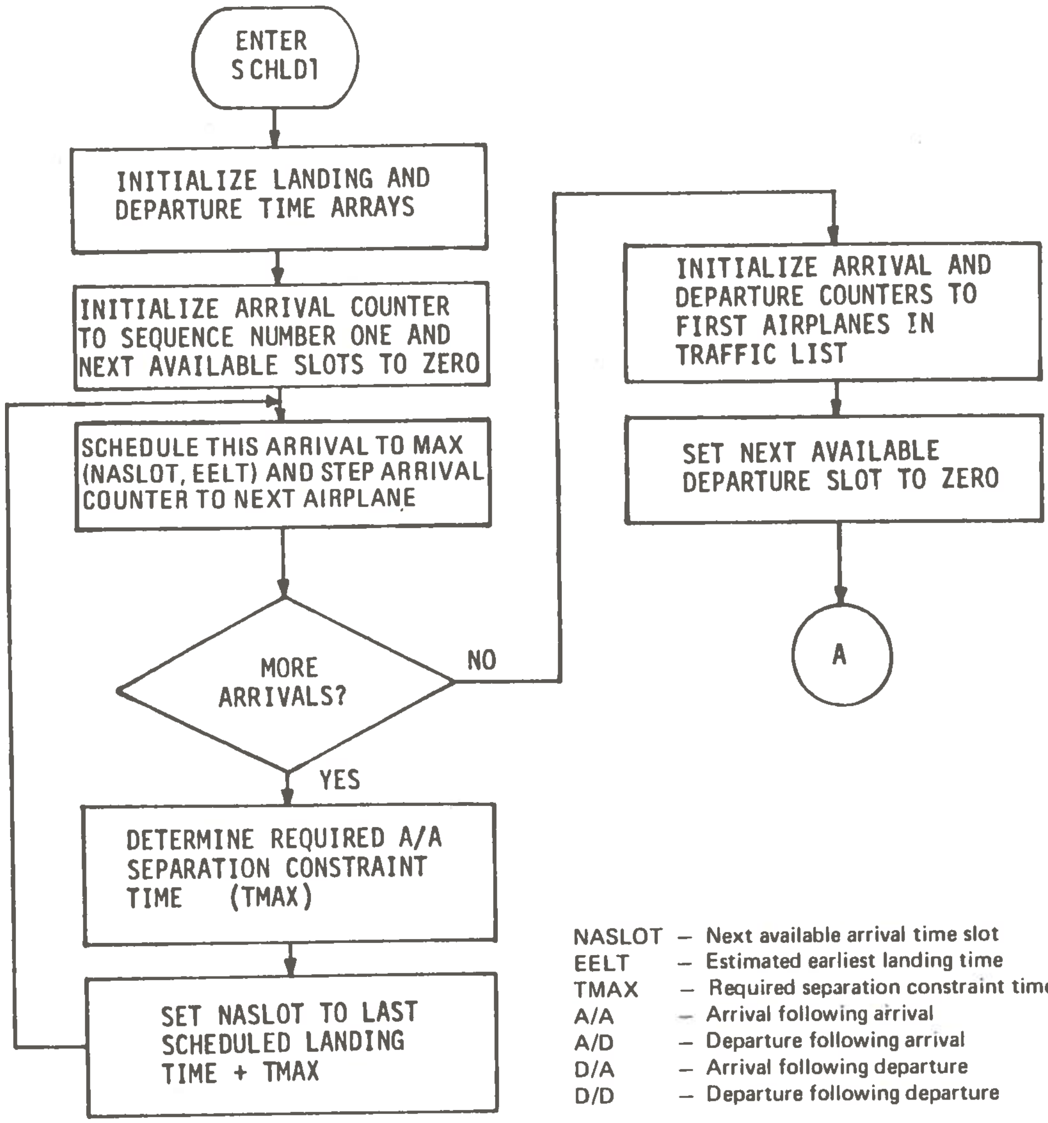
FIGURE 6-3.—SCHEDULING EXAMPLE SITUATIONS occupancy time for that arrival, ARO(I), was then added to $NASLOT_1$ to form a new NASLOT that reflects the time another arrival could be scheduled if available. As the earliest next arrival could not reach the runway before EELT(I+1) and a departure (J) was waiting, NASLOT was increased by this departure runway occupancy time to form $NASLOT_2$. In this case, there was time available to land I and depart J before EELT(I+1). The departure was assigned a time, SDT(J), which was determined by subtracting the departures runway occupancy time from the current value of NASLOT (i.e., SDT(J) = $NASLOT_2$ - DRO(J)). The departure was released as the first arrival cleared the runway and any further arrivals are prohibited from landing until the departure clears the runway (by the current $NASLOT_2$ value).

At this point, no further departures were waiting and no arrivals had the capability to make good the value of $NASLOT_2$. Some runway time had to be wasted. Further investigation shows that the next arrival could be at the runway at EELT(I+1), and as that time was available, the NASLOT variable was increased to $NASLOT_3$ with value of EELT(I+1) and the I+1 airplane was scheduled at time SLT(I+1). The next candidate for scheduling is the I+2 arrival, who could be there by time EELT(I+2). $NASLOT_3$ was increased by the required separation time between I+1 and I+2, SEPT, to form $NASLOT_4$. (In this case, in-air separation was more constraining than runway occupancy.) $NASLOT_4$ now represents the earliest time that the I+2 airplane could be assigned subject to the separation constraint. Investigation of the I+2 airplane's latest possible landing time estimate (without holding), ELLT(I+2), then produces two options. Either $NASLOT_4$ lies between EELT(I+2) and ELLT(I+2) and therefore is within the scheduling window or, conversely, ELLT(I+2) occurs earlier in time than $NASLOT_4$ and an entry fix hold of the difference must be demanded. This case is represented by the positioning of $NASLOT_{4A}$ with the hold time assigned as $NASLOT_{4A}$ - ELLT(I+2) and the resulting runway time assignment, $SLT(I+2)_A$ being equal to $NASLOT_{4A}$.

These procedures are carried out for each new operation request to the scheduling function. The principal items of note are that the scheduler (1) packs the threshold times as tight as the demand and constraints will allow, and (2) assigns scheduled operations times (SLT and SDT) consistent with the airplane's ability to make them good from an aeroperformance, geometry, and weather point of view.

The algorithm resulting from the above considerations is in the form of three separate scheduler versions. Any one of the versions may be selected by controlling input parameters to the main program. This technique allowed the evaluation of differing techniques for handling approach-departure priorities.

Scheduler 1 is functionally described in figure 6-4. This version gives absolute priority to arriving airplanes without regard to the departure requirements. Opportunity departures are then interspersed as demand-related openings occur in the arrival steam and departures become available. The output of this function is the threshold time assignment list. The RTP generation function then assigns the route-time profile required for the arrivals to achieve the particular time assignment within the arrival window.



NASLOT – Next available arrival time slot
EELT – Estimated earliest landing time
TMAX – Required separation constraint time
A/A – Arrival following arrival
A/D – Departure following arrival
D/A – Arrival following departure
D/D – Departure following departure

FIGURE 6-4.–SCHEDULER (VERSION 1) FUNCTIONAL LOGIC

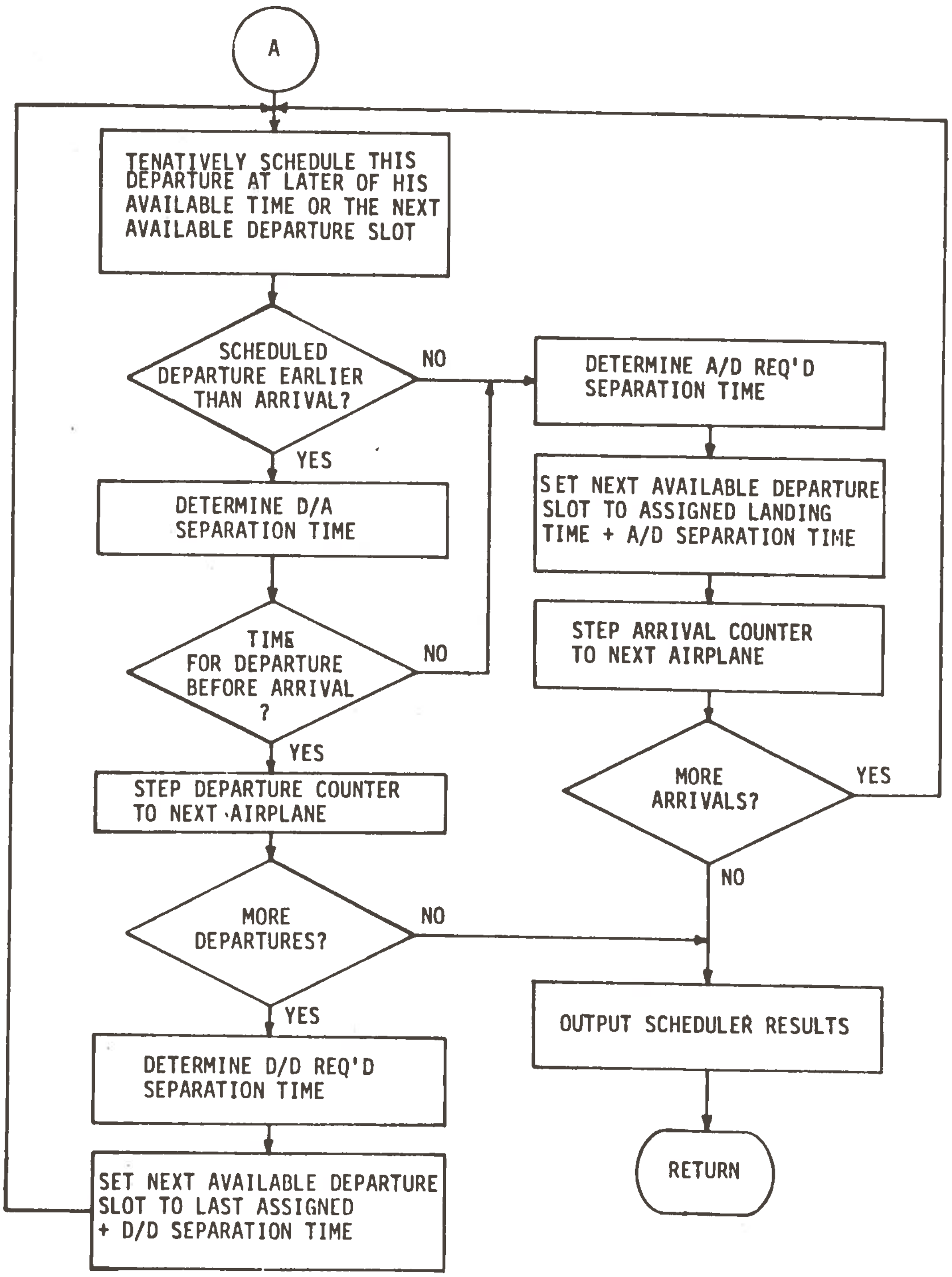


FIGURE 6-4.—CONCLUDED

Scheduler 2 is identical to scheduler 1 except that during the arrival scheduling, each potential departure is investigated to determine the required separation constraint times required to insert any departure between the two arrivals. Thus, during the actual flight operation any available (i.e., opportunity) departure can be released between an arrival pair. The functional logic for scheduler 2 is illustrated in figure 6-5.

Scheduler 3 is designed to operate with a specific tentative departure time list. This version balances the priority between arrivals and departures. The separation times between operations are based on specific airplanes using the assigned operation time. The functional logic for scheduler 3 is illustrated in figure 6-6.

Four logic elements were defined to provide the separation time constraint to whichever scheduler has been selected. One constraint time logical element was designed for each of the four operational situations (i.e., arrival-arrival, arrival-departure, departure-arrival, and departure-departure). Each of these logical elements utilizes the input ATC rules and separation requirements to determine the most constraining requirement that must be met during scheduling.

Figure 6-7 illustrates the arrival-arrival separation time constraint determination logic. This element determines the limiting time requirement between final approach, threshold, and arrival-arrival runway occupancy. Figures 6-8, 6-9, and 6-10 illustrate, respectively, the constraint time selection process for the arrival-departure, departure-arrival, and the departure-departure cases.

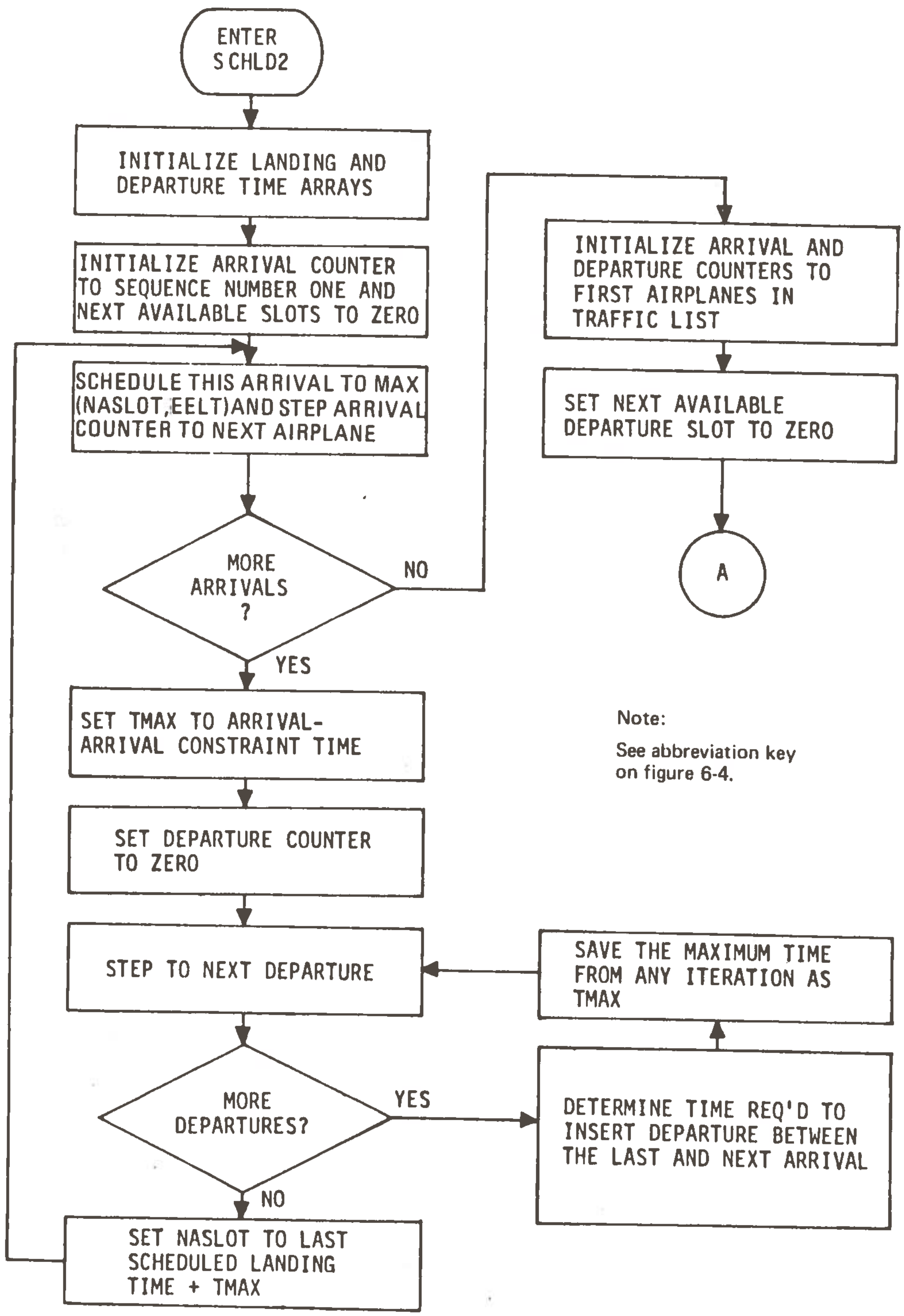


FIGURE 6-5.—SCHEDULER (VERSION 2) FUNCTIONAL LOGIC

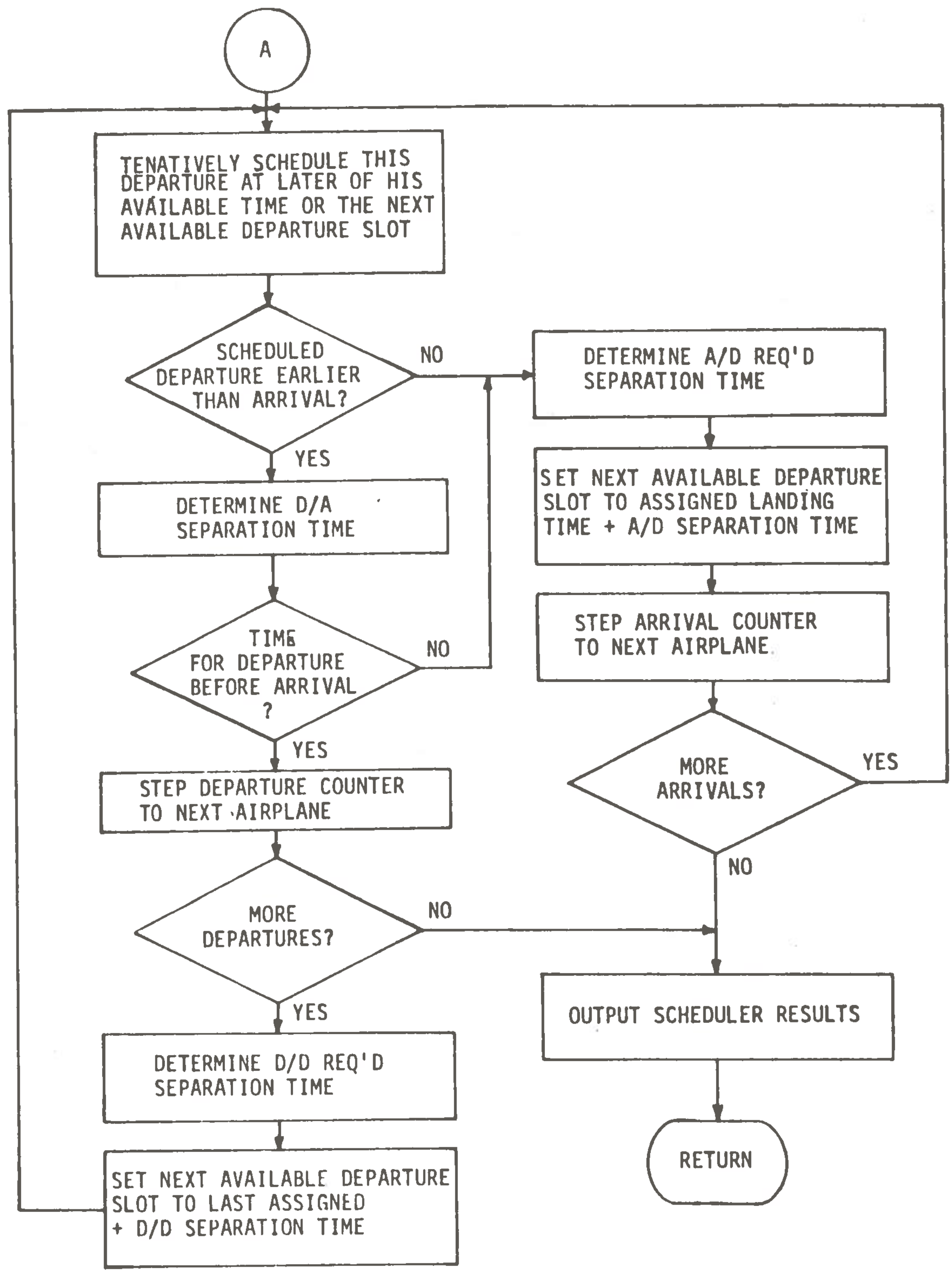


FIGURE 6-5.—CONCLUDED

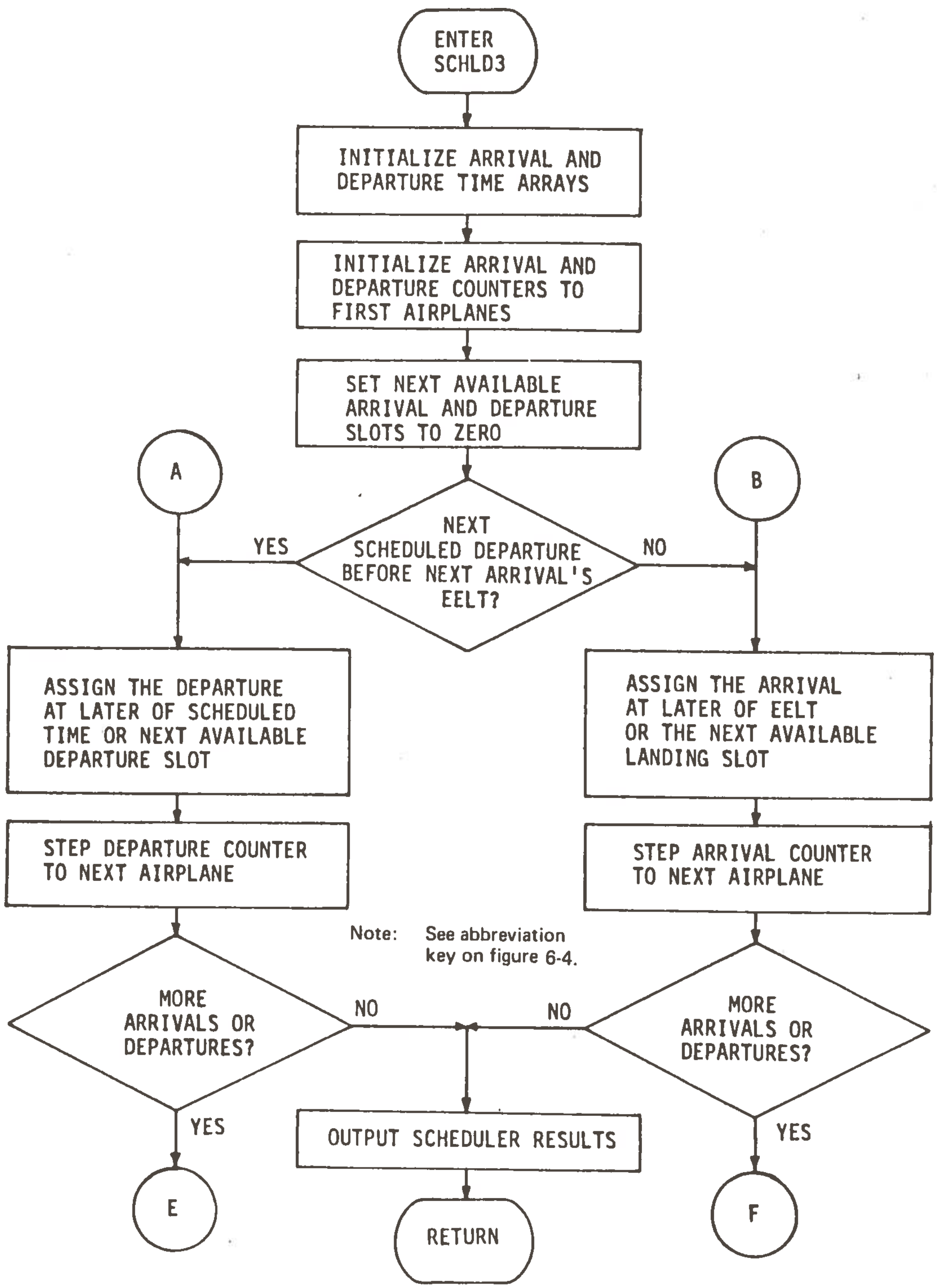


FIGURE 6-6.—SCHEDULER (VERSION 3) FUNCTIONAL LOGIC

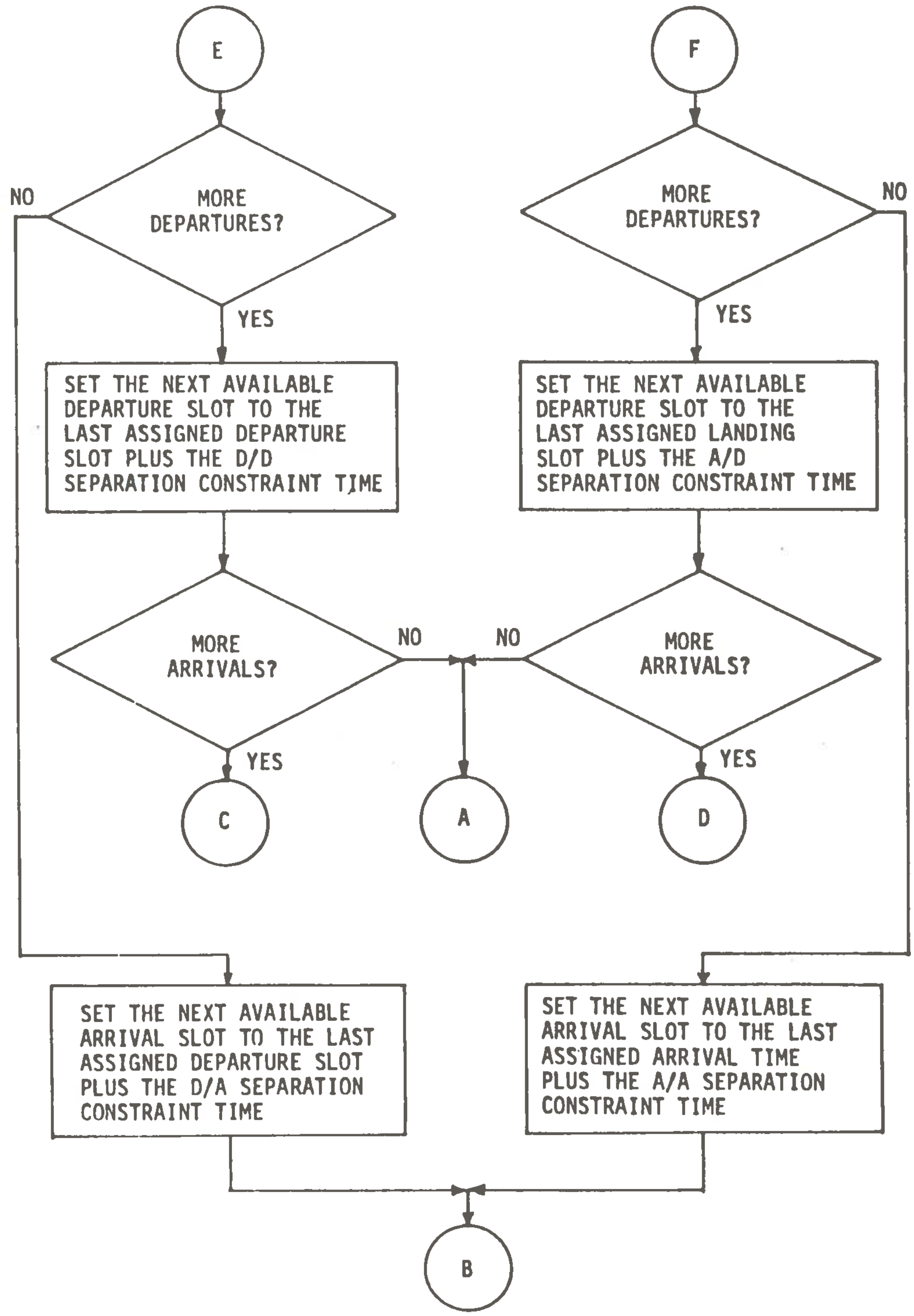


FIGURE 6-6.—CONTINUED

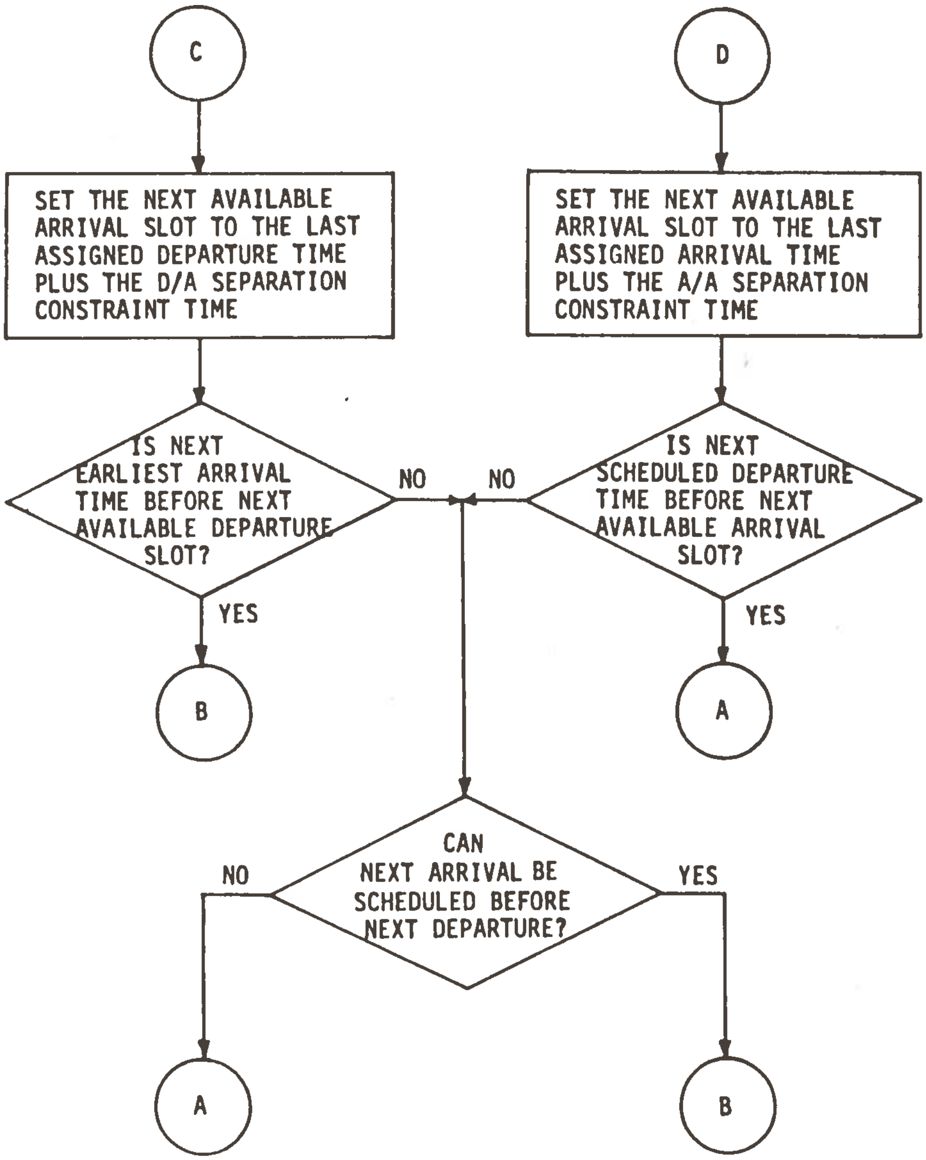


FIGURE 6-6.—CONCLUDED

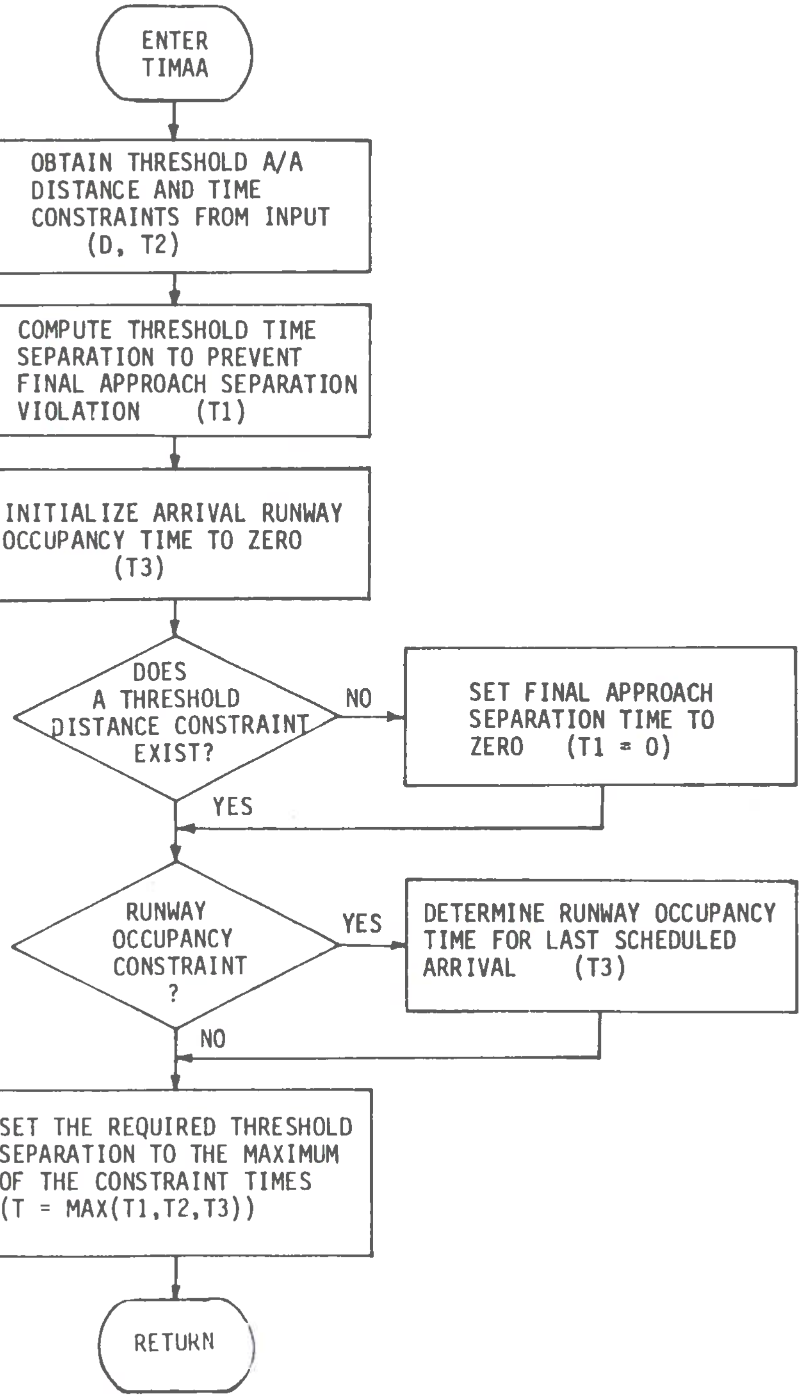


FIGURE 6-7.—ARRIVAL-ARRIVAL SEPARATION TIME CONSTRAINT DETERMINATION

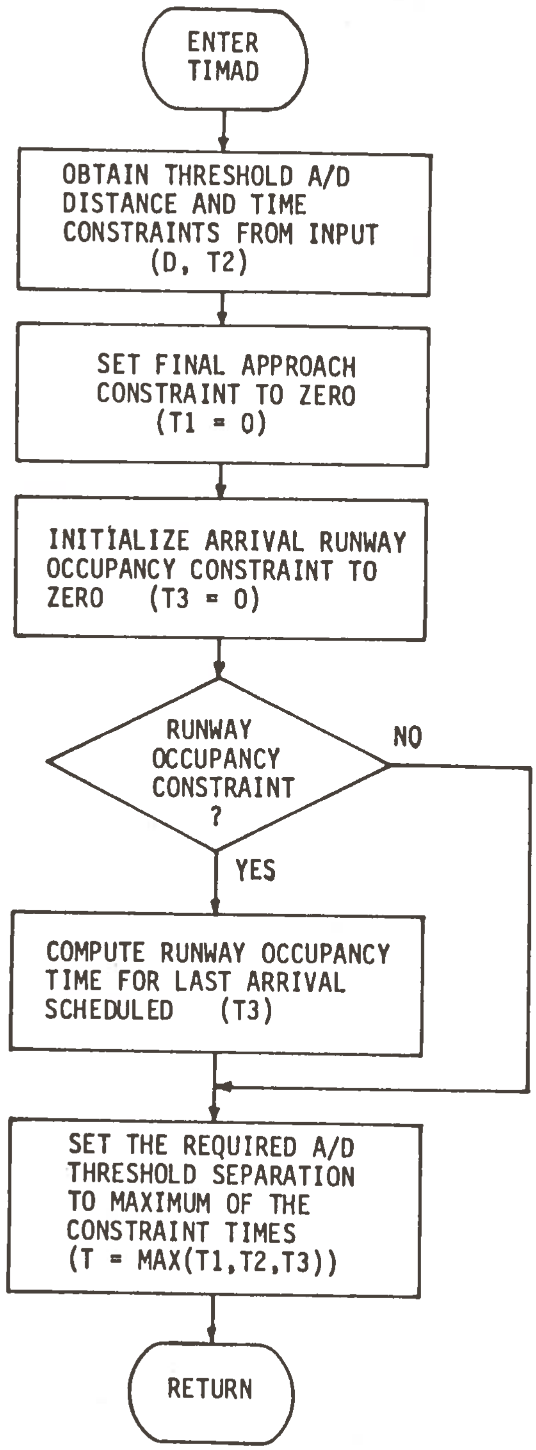


FIGURE 6-8.—ARRIVAL-DEPARTURE SEPARATION TIME CONSTRAINT DETERMINATION

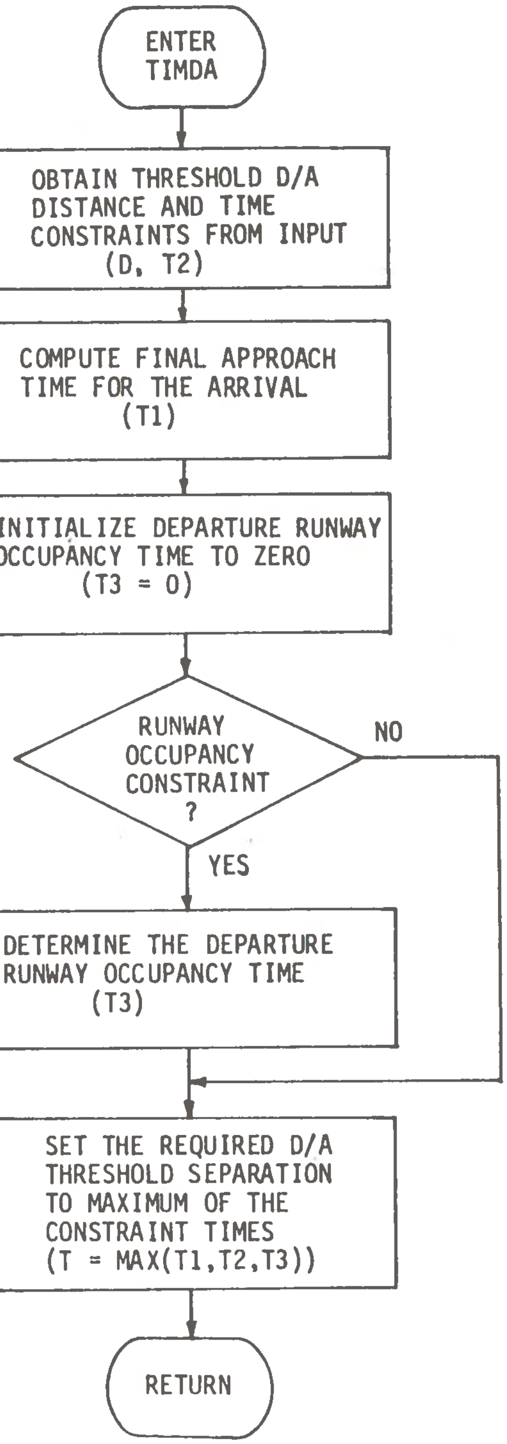


FIGURE 6-9.—DEPARTURE-ARRIVAL SEPARATION TIME CONSTRAINT DETERMINATION

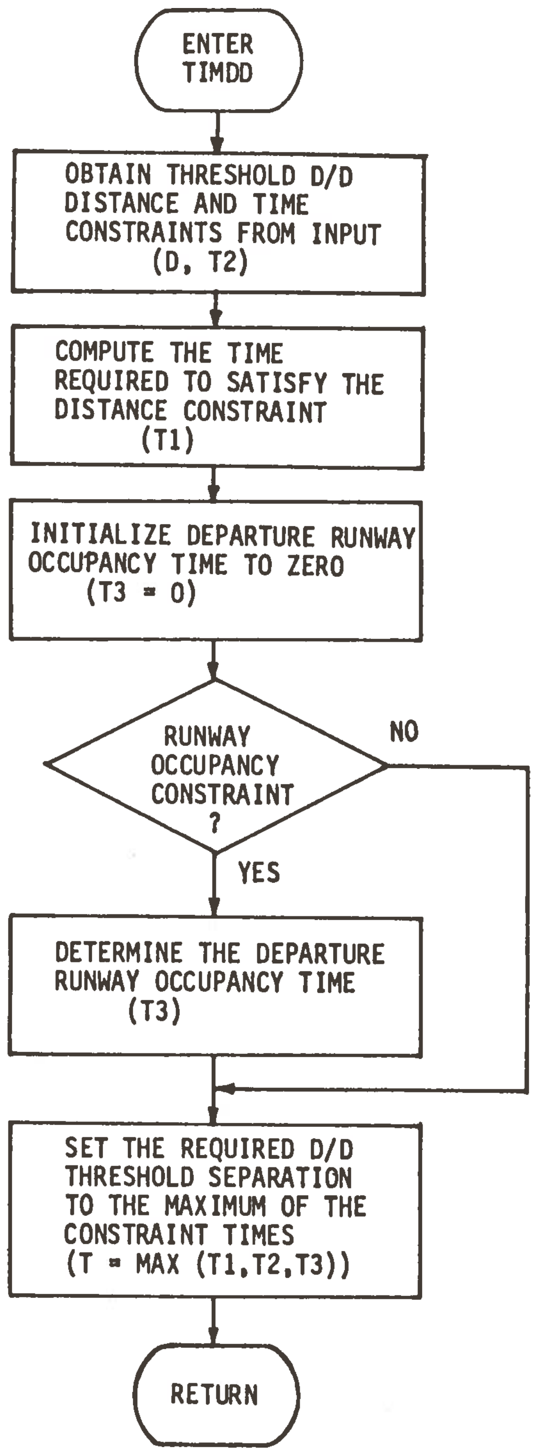


FIGURE 6-10.—DEPARTURE-DEPARTURE SEPARATION TIME CONSTRAINT DETERMINATION

7.0 ROUTE-TIME PROFILE (RTP) GENERATION STRATEGY

The purpose of the route-time profile generation function is to determine the waypoints and times that the airplane must fly to ensure a conflict-free transition from the entry fix to the threshold. The macro logic for accomplishing this function is shown in figure 7-1. Functionally this process is as follows for each airplane:

1) Determine the IAF time (TIAF) implied by the scheduled landing time (SLT).

2) Select a trial parallel path geometry.

3) Select a trial groundspeed profile that is consistent with the aeroperformance window.

4) Integrate the speed profile over the trial geometry to determine a total entry fix to threshold time.

5) Compare this trial profile to the desired scheduled landing time. If the transition is too fast or slow, modify the trial groundspeed profile and repeat steps 4 and 5 until the profile satisfies the scheduled landing time.

6) When a satisfactory RTP results from step 5, test for conflicts with airplane ahead on the trial path. If a conflict exists, assign a new trial parallel path and repeat steps 3 through 6 until a conflict-free path is obtained.

7) Assign the resulting conflict-free RTP to the airplane.

The process above is highly simplified to show the intention of the RTP generation process. The mechanization shown in the logic flow charts of this section actually performs the functions in a slightly different fashion. The difference results from a recognition that the near-terminal area (i.e., IAF to outer marker) is a common path/profile region. The profile for this area is accomplished only one time for each path for a given environmental forecast. The resulting incremental time for transitioning from a given IAF to the outer marker is the same for all airplanes. The details of this process have been discussed in section 5.1.2.

The RTP generator uses the common profile times in the following fashion:

1) Compute the time to transition from the outer marker to the threshold.

2) Add the common profile time to the time generated in item 1 above.

3) Determine the IAF time of arrival required by subtracting the result of item 2 from the scheduled landing time.

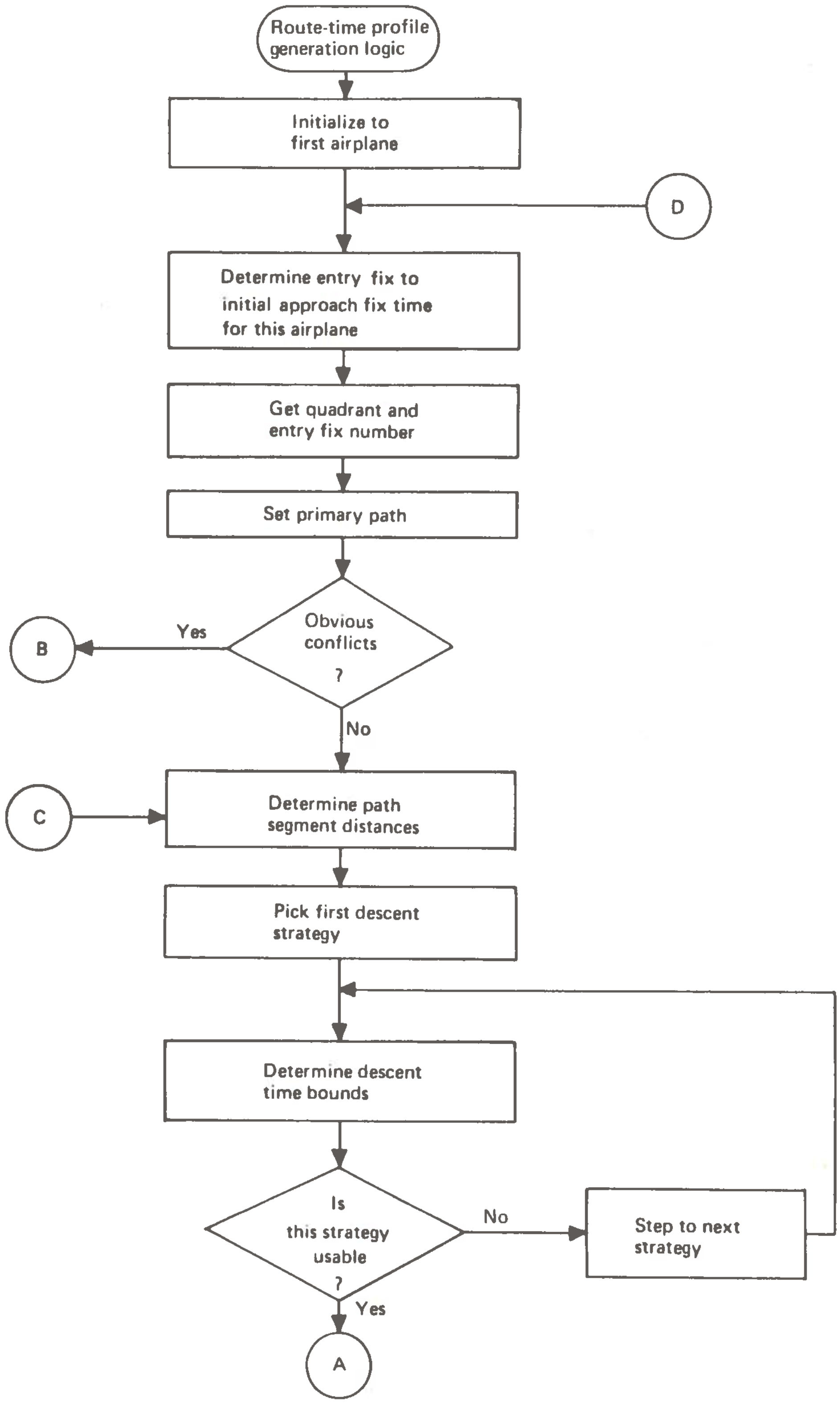


FIGURE 7-1.—RTP GENERATION MACRO-FLOWCHART

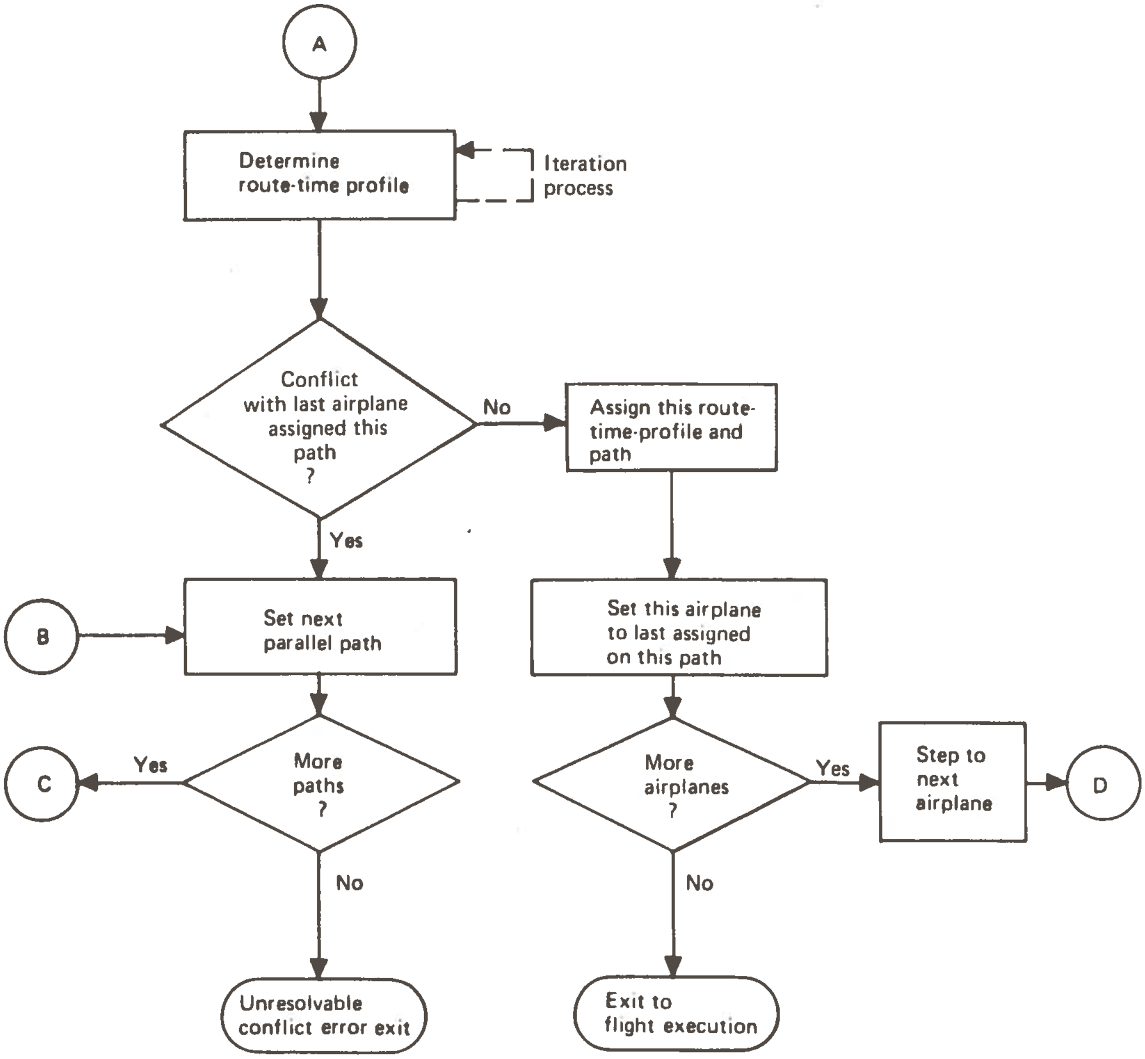


FIGURE 7-1.–CONCLUDED

The RTP generator now has an estimated entry fix time (from traffic considerations—sec. 4.0) and a required time for the airplane to be at the IAF from the above considerations. The difference between these times is the transition time for the outer terminal area. As the required time controllability for the system must be achieved in this outer area, the principal function of the RTP generator is to find a profile that will integrate to the required transition time, is conflict free, and is consistent with aeroperformance capability as modified by environmental considerations. Execution of such a profile ensures a properly metered and spaced arrival stream at the IAFs that will satisfy the required runway schedules. It is important to recognize that, if the airplanes fly common profiles from the IAF to the outer marker, the spacing considerations will be achieved throughout this region. As the IAF times are based on suitable separation at the outer marker (from scheduling considerations—sec. 6.0), this also ensures the proper merging inside the IAF.

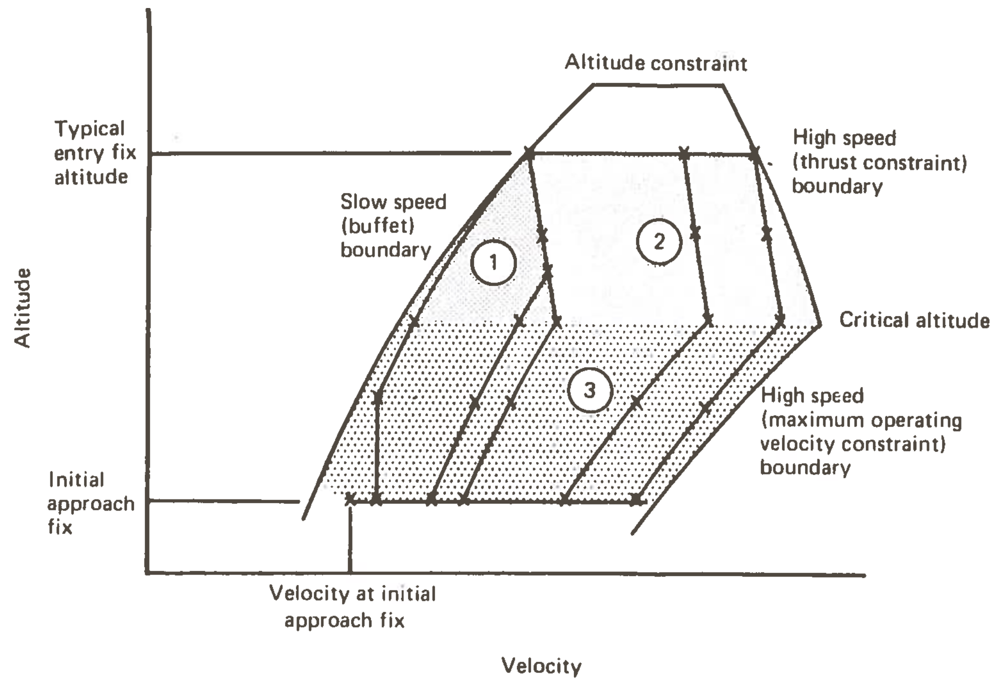
7.1 RTP GENERATION PROCESS

As discussed above, the principal function of the RTP generator is to provide velocity/position/time points that satisfy the boundary conditions at the entry fix and the IAF.

The velocity boundary condition at the IAF is a groundspeed that is equivalent to 250 KCAS at 10,000 feet. This represents today's regulatory value as opposed to values resulting from aeroperformance considerations. At the entry fix the velocity boundary condition is the estimated entry fix Mach number or airspeed at which the airplane will be inserted from the en route system. This value must be converted to a groundspeed compatible with the environmental conditions and entry fix altitude.

In general, the airplane will be accelerated or decelerated in level flight to the point where the descent path is intercepted, and then fly a velocity profile during descent that approximates a Mach/CAS profile. Upon reaching the IAF altitude, another deceleration takes place in level flight to the IAF groundspeed.

In accomplishing this process, a number of intermediate waypoints are created between the entry fix and the IAF. The first intermediate waypoint inside the entry fix is the point at which descent begins. The velocity assignment at this point is the primary variable in searching for a velocity profile that satisfies the boundary conditions. The choice of velocity at this initial descent point implies a particular Mach number and CAS for the letdown. Different values of the constant Mach value represent a change in area under the groundspeed curve and, with fixed-path distances, this results in a change of transition time. The RTP generation process makes a trial letdown at a particular choice of velocity at this start of descent point and then makes successively better choices until a solution is found that satisfies the boundary conditions. Figure 7-2 illustrates the altitude versus velocity profile window with some representative Mach/CAS lines inserted. This figure illustrates the regions that form the basis for different letdown strategies. Figure 7-3 shows the altitude versus along-track distance over which the velocity points chosen must be integrated to determine the transition time.



(1) Mach/calibrated airspeed* letdown via low speed aero boundary and computed altitude breakpoint

(2) Mach/calibrated airspeed* letdown via critical transition altitude

(3) Calibrated airspeed* letdown for airplanes arriving below critical altitude

*The route-time profile is generated in terms of ground-speeds which are piecewise linear approximations to constant Mach and/or calibrated airspeeds and reflect appropriate wind and temperature corrections.

FIGURE 7-2.—ROUTE-TIME PROFILE GENERATION STRATEGIES

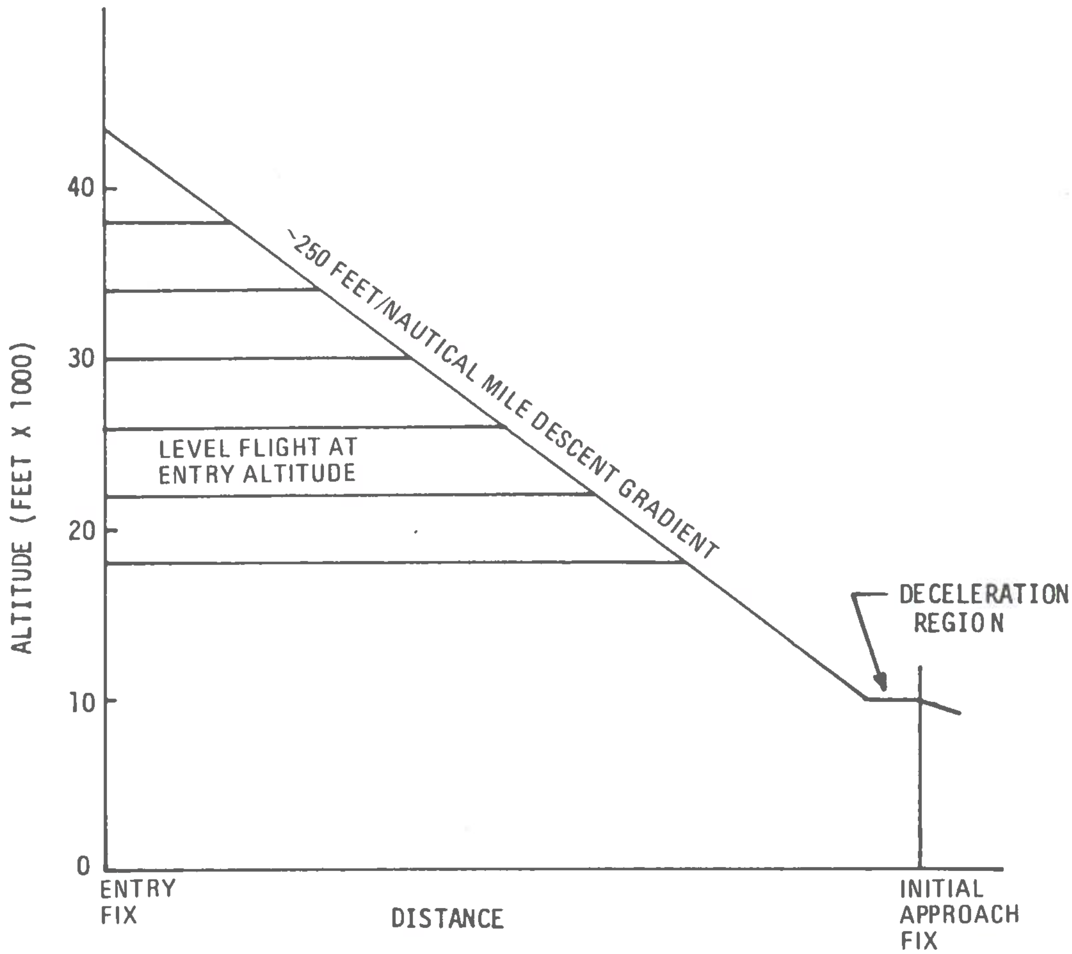


FIGURE 7-3.—TRANSITION REGION DESCENT PROFILE

The Mach/CAS strategy was picked for several important reasons. The first of these reasons was to ensure that the resulting rate of change of velocity with respect to altitude (dv/dH) did not exceed the gradient capability of the airplane. Both constant Mach number and constant CAS are feasible for an airplane to fly while making the descent gradient. The second reason involves the nature of the aeroperformance envelope. The bounds of the envelope are closely related to Mach number and equivalent airspeeds (EAS). As EAS and CAS differ only by the compressibility factor (see sec. 3.3 for further discussion), this means that almost the entire aeroperformance envelope is available to maximize the resulting time controllability. The Mach/CAS letdown strategy also ensures a consistent process for determining an RTP for any time within the aeroperformance envelope. One potential disadvantage of this process is that airplanes receive velocity schedules that are not optimized for reserve gradient capability and this implies less airplane control in adapting to perturbations. To maximize reserve gradient, but with a reduction in total controllability time, a system using constant true airspeed values can be formulated. This approach would require a step or level flight region at approximately 25,000 feet. This strategy has considerable merit and should be studied further.

As the airplane performance is with reference to the air mass in which it flies and the times are related to geographically fixed positions, it is necessary to convert the pertinent parameters to a common system. This is achieved by a conversion of all airspeed and Mach numbers to groundspeeds. These groundspeeds, along with the rule for transitioning between them, form the basis for integrating over the distances to obtain the times required. To achieve a balance between the number of intermediate waypoints required and the desire to achieve the curve form of constant Mach numbers and calibrated airspeeds, a process was selected to yield a selection of five or six (depending on letdown strategy) intermediate altitude points at which velocities and times are specified. These points tend to be on the order of 5000 feet apart in altitude. This technique preserved the form of the airspeeds and allowed point application of the wind and temperature considerations in generating the groundspeeds and times. The points marked on figure 7-2 indicate these relationships if the velocity scale is interpreted as groundspeed, and the curves represent airmass parameters translated to the groundspeed domain. In addition to this figure, a rule for transitioning between points is implied. The algorithm is based on a linear groundspeed transition with respect to time. This allows a simple trapezoidal integration process using the average velocity and distance between waypoints to obtain segment times. Future consideration of the four-dimensional airplane profile-keeping capability and environmental forecast accuracy could make it desirable to perform this integration on smaller altitude steps. The algorithm structure can easily accommodate this change to improve time predictability but it appears that the number of intermediate waypoints (ultimately transmitted to the airplane) is sufficient. It is also possible that the rule for transitioning from one velocity to another might be different but here again the algorithm structure can readily accommodate this change.

Table 7-1 shows the resulting RTP output format as it is generated by the algorithm in the CDC 6600 mechanization. In this mechanization the distance along path from the entry fix locates the waypoints. An operational algorithm would likely convert these values to corresponding latitude and longitude points.

Figure 7-4 represents the detailed logic (in word form) of the RTP generation function. This figure illustrates in detail the iteration processes required and the interrelationships with the aero and conflict checking routines. Some branches of this logic lead to error messages that should not occur if the sequencing, scheduling, and RTP generation functions are properly functioning. If these error traps do occur, the best RTP found is assigned. The logic which indicates a particular strategy is related to figure 7-2.

7.2 CONFLICT DETECTION

The conflict detection function determines whether a trial RTP will cause a separation closure with an airplane that is ahead on the same path. If a conflict would result, a flag is set and the RTP generation logic will attempt a different path for further trial. The conflict detection function operates only on two airplanes at any one time: (1) the airplane ahead

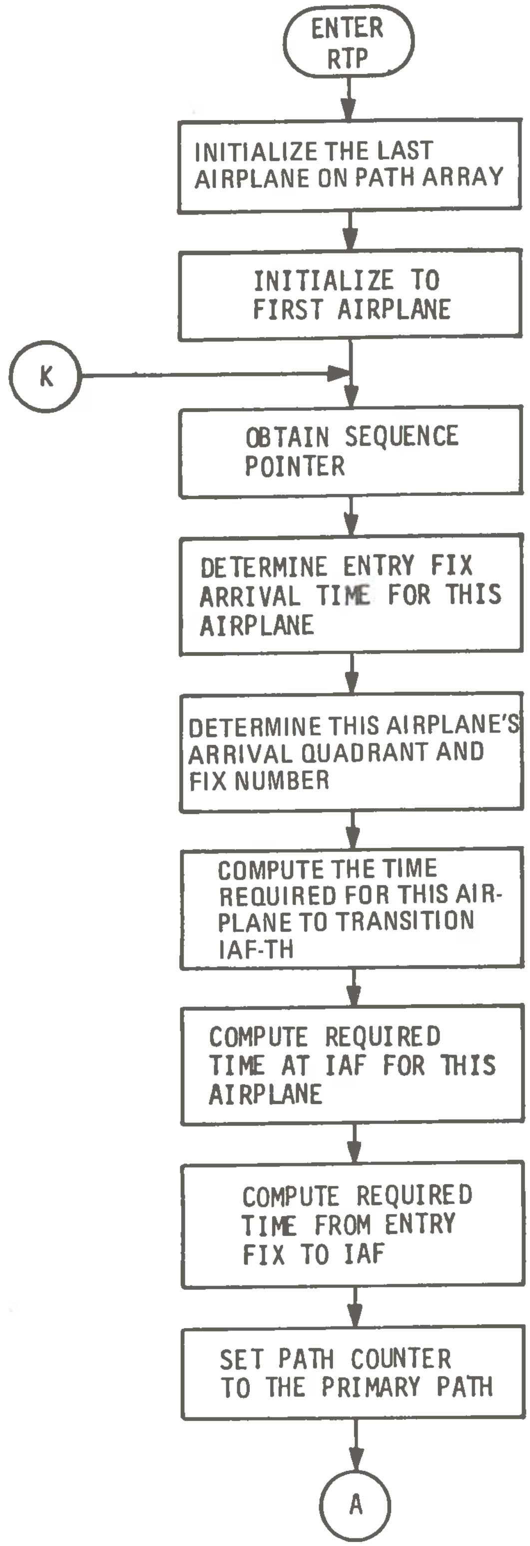


FIGURE 7-4.—RTP GENERATION MICRO-FLOWCHART

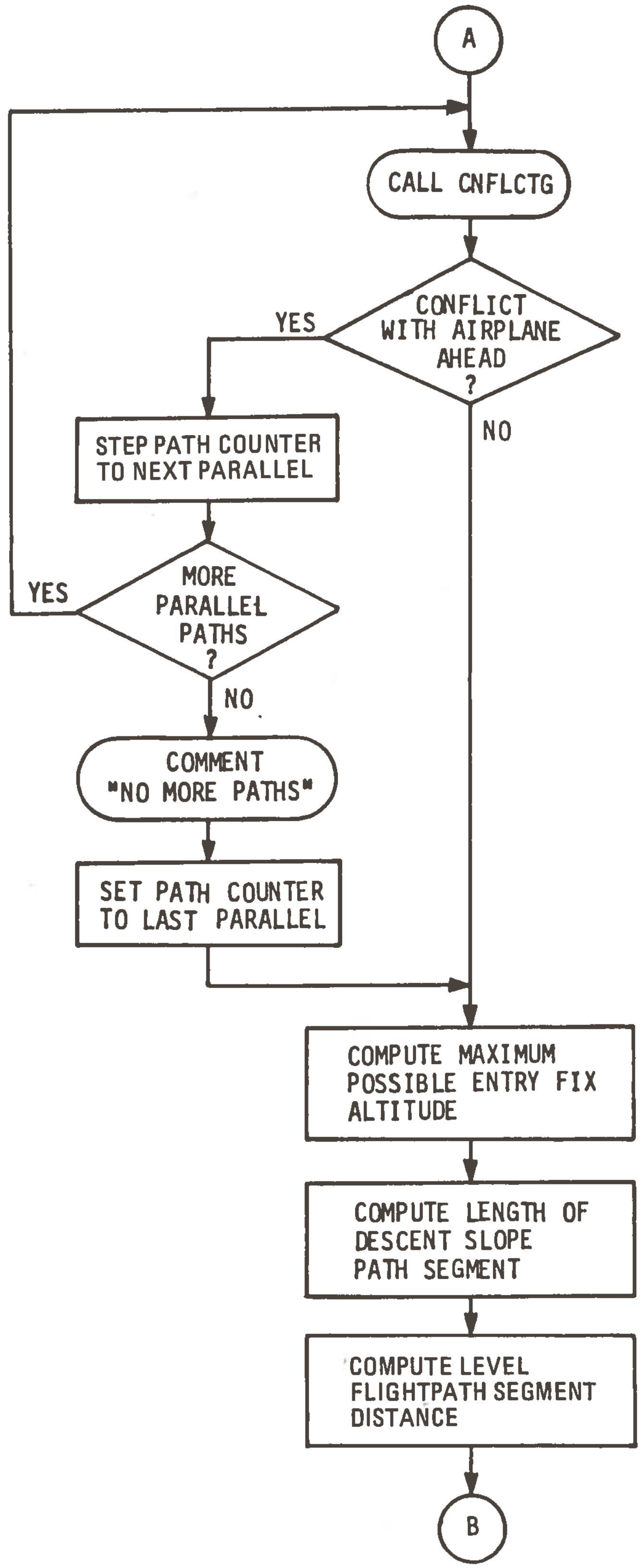


FIGURE 7-4.—CONTINUED

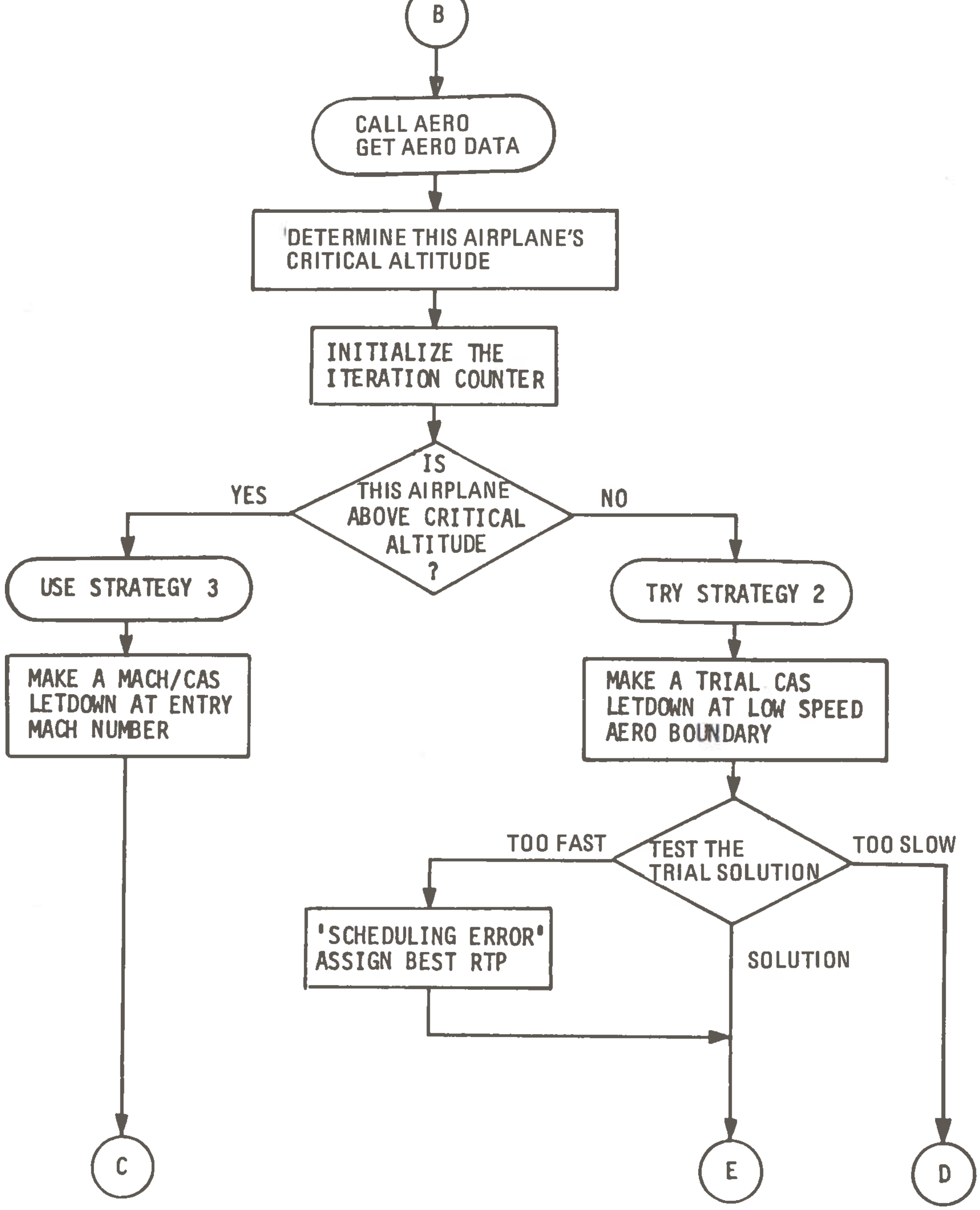


FIGURE 7-4.—CONTINUED

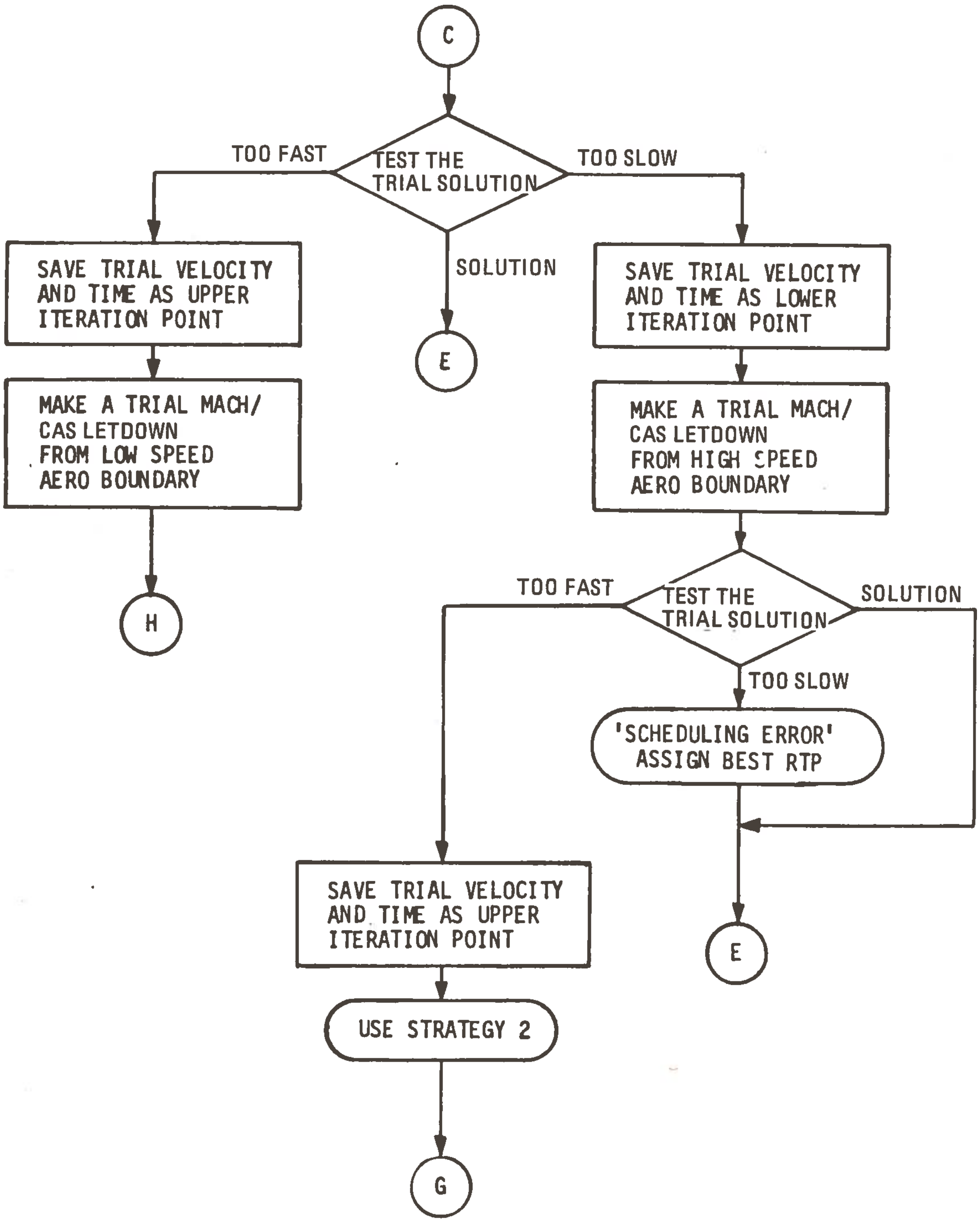


FIGURE 7-4.—CONTINUED

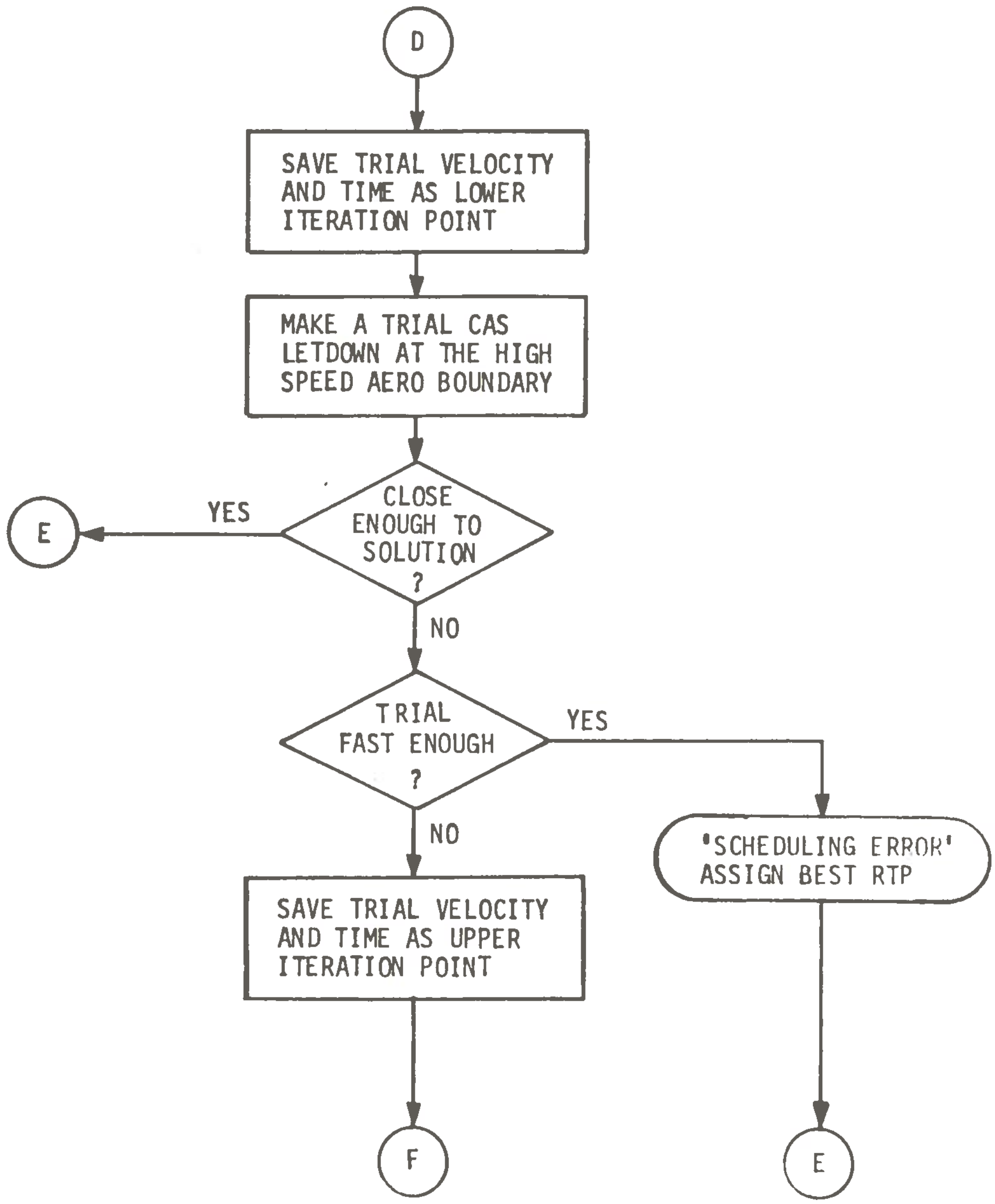


FIGURE 7-4.—CONTINUED

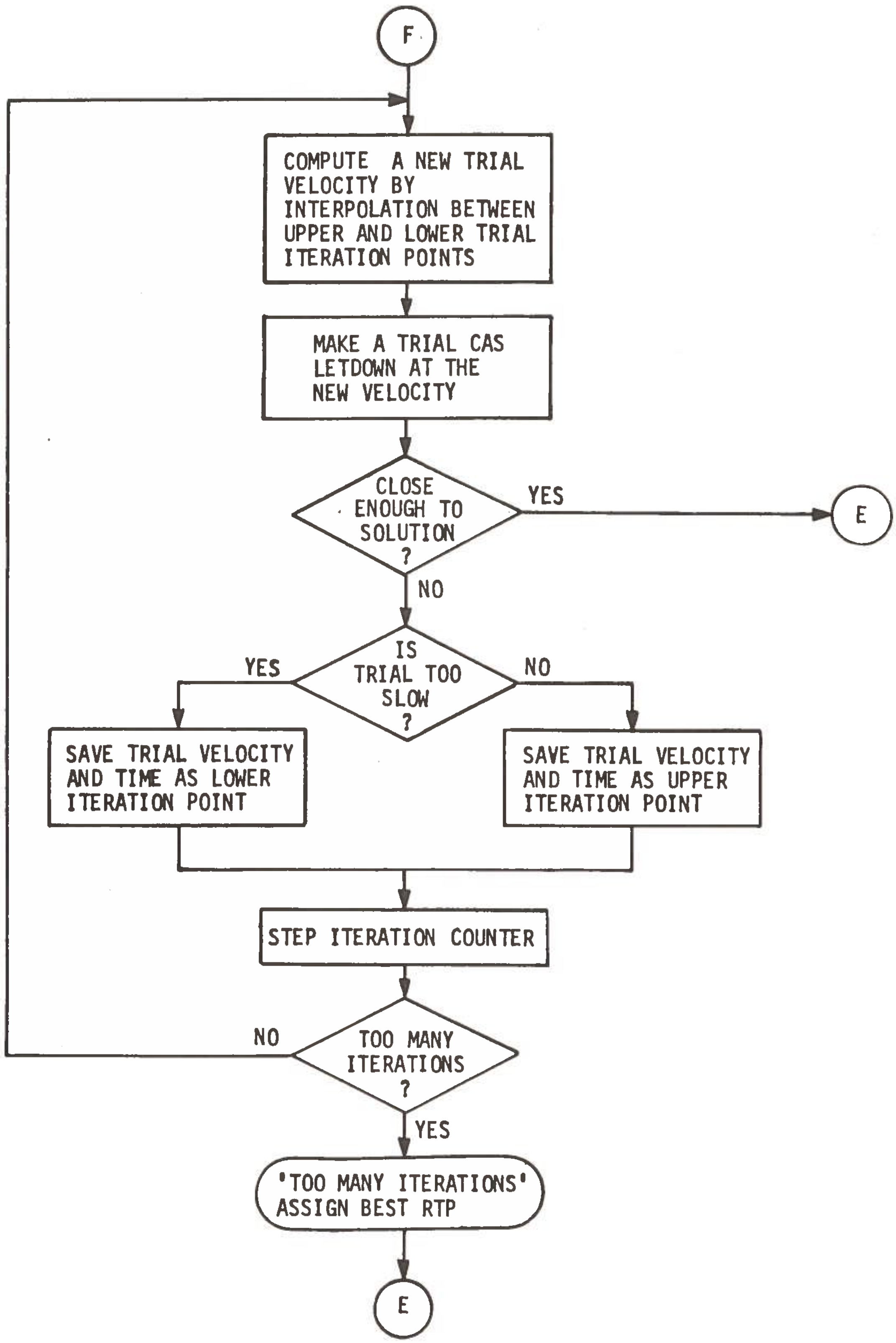


FIGURE 7-4.–CONTINUED

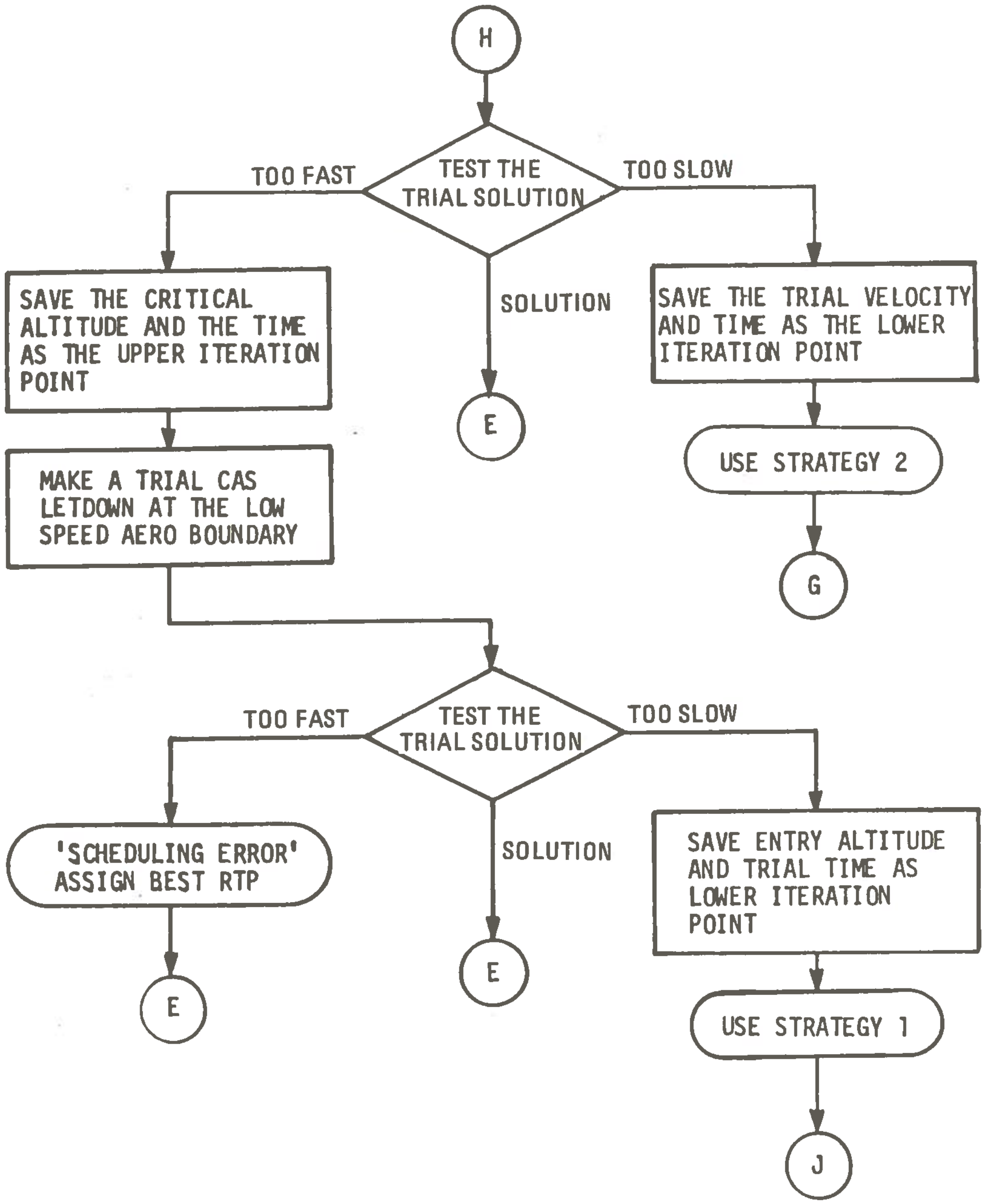


FIGURE 7-4.—CONTINUED

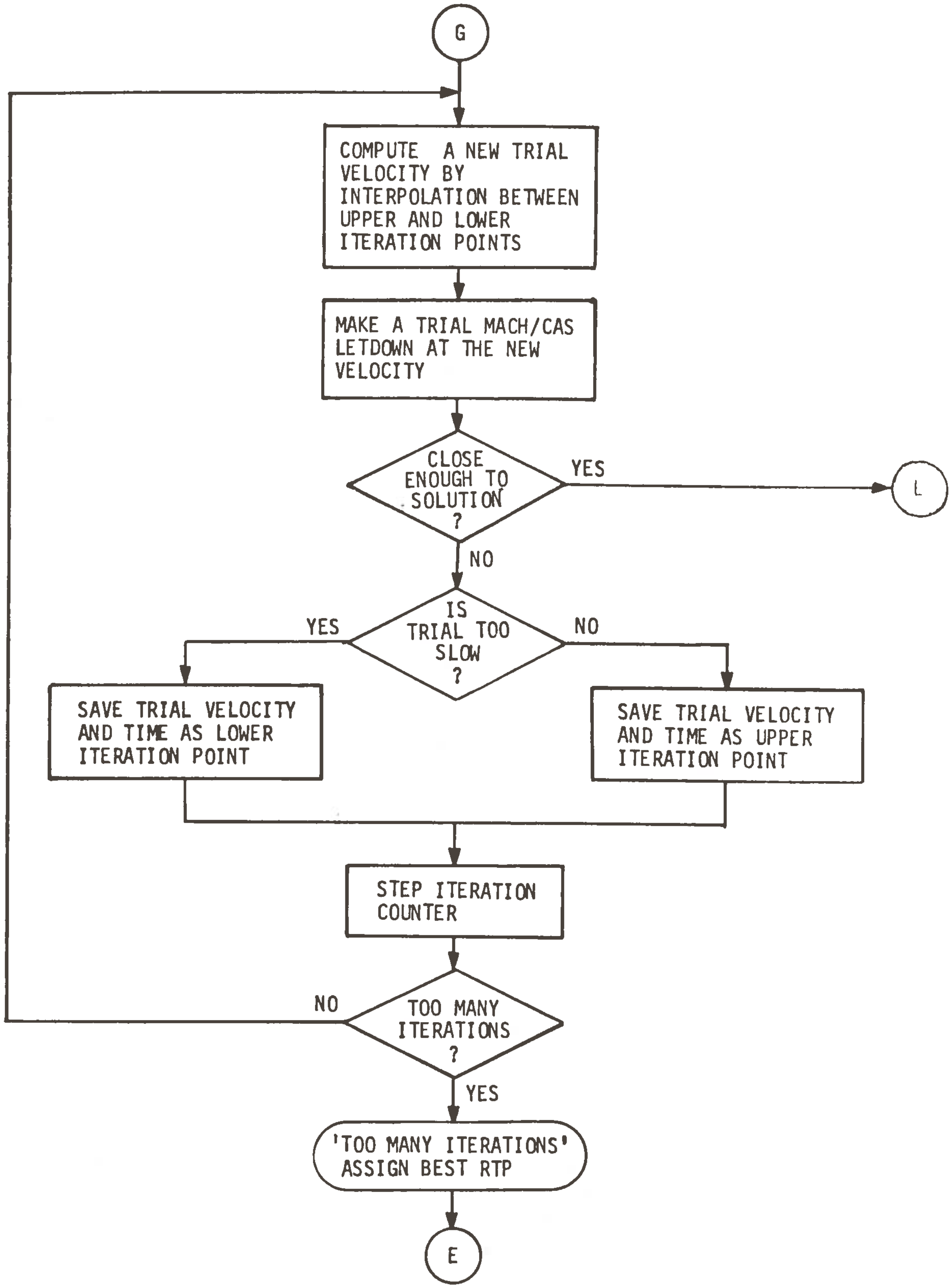


FIGURE 7-4.—CONTINUED

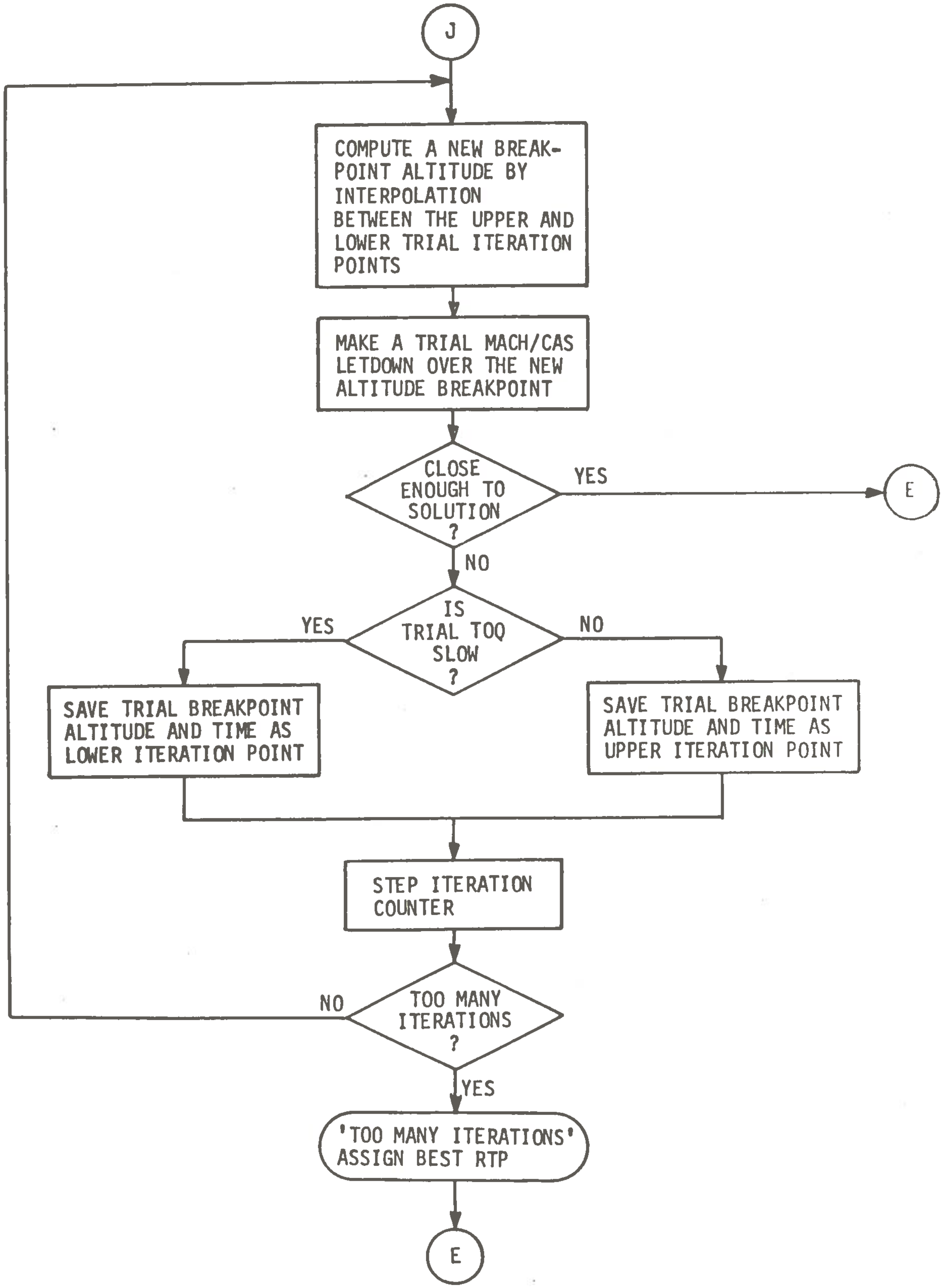


FIGURE 7-4.—CONTINUED

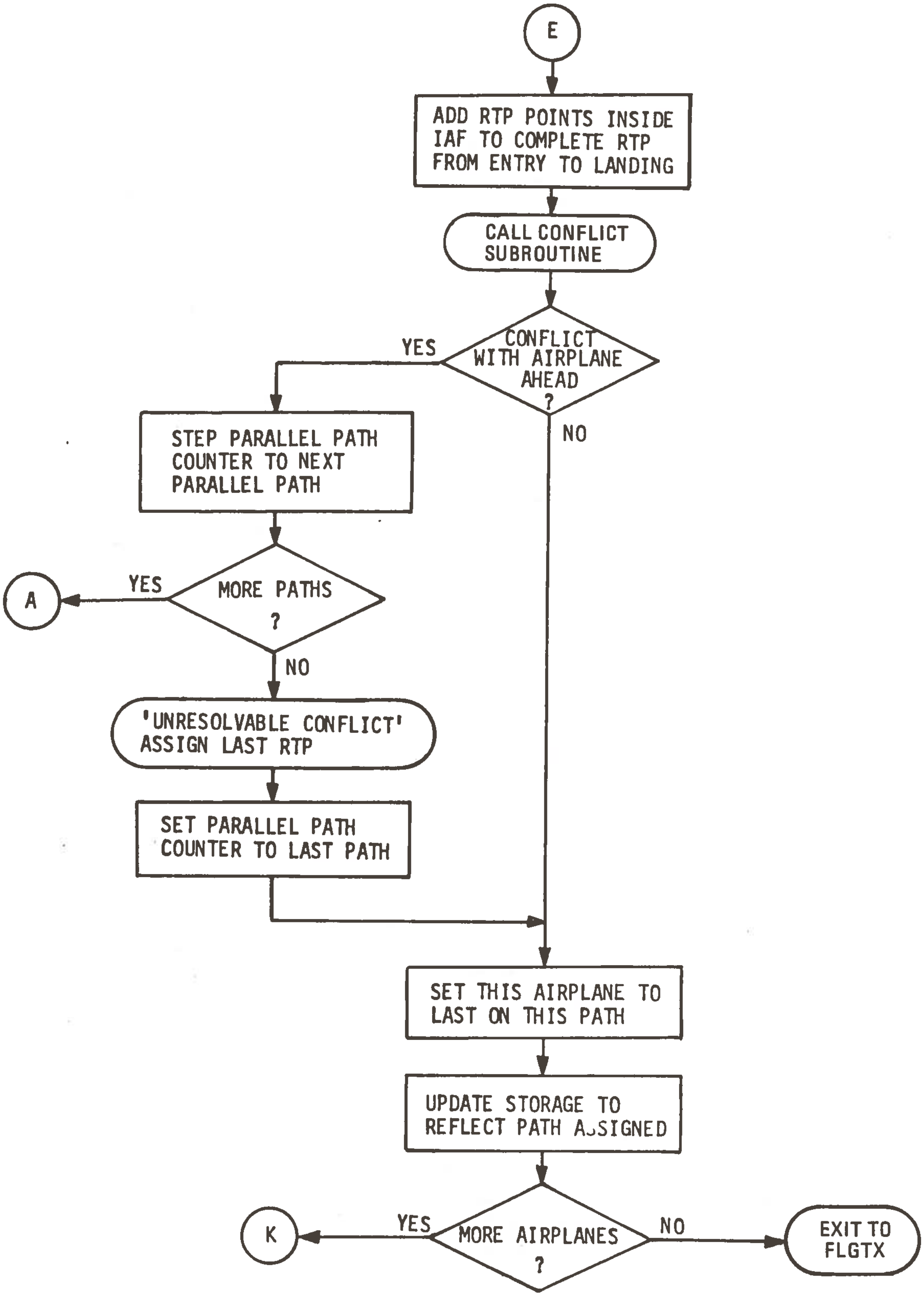


FIGURE 7-4.—CONCLUDED

TABLE 7-1.—RTP OUTPUT FORMAT

Index number	Altitude (feet)	Distance from entry fix (nautical miles)	Ground-speed (knots)	Clock time (seconds)	Control point indicator
1	32,681	0	455	18	1 (entry fix)
2	32,681	39	423	340	0
3	27,340	61	427	521	0
4	22,000	82	432	700	0
5	16,000	106	392	910	0
6	10,000	130	356	1141	0
7	10,000	140	287	1253	2 (initial approach fix)
8	10,000	145	273	1325	3 (turn fix)
9	4,800	161	238	1541	4 (merge fix)
10	2,400	169	185	1685	5 (final approach fix)
11	1,500	172	179	1757	6 (outer marker)
12	0	177	131	1877	7 (threshold)

on the path and (2) the airplane for which an RTP assignment is being considered. This function is concerned only with strategically controlled airplanes and is not related to intruders into the strategic airspace (see Basic Assumptions, para. 4.1.1(5), vol. II).

Conflict detection is accomplished in two different ways. The first way is accomplished prior to generating an RTP. This is a simple test to ensure that entry fix conditions are not violated at time of airplane entry and to determine whether a "passing" situation exists. Simply stated, if two airplanes must pass between the entry fix and the IAF, they cannot be assigned to the same path, regardless of the assigned RTP. The logic for this determination is shown in figure 7-5. This preliminary check reduces the number of trial RTP computations that must be made.

Figure 7-6 illustrates the logic for the second means of conflict detection, which makes a point-by-point comparison between the airplane ahead on the proposed path and the airplane being considered for assignment to the path. The times at every waypoint in the two RTPs are merged for the time region in which any possible conflict can occur. The distance from the entry fix, the groundspeed, and the altitudes are then computed for each airplane at each point. A point-by-point determination is then made to determine if the separation constraints have been violated at any point. Figure 7-7 graphically shows this conflict detection process. A flag is set to relay conflict or no-conflict information to the RTP generation function.

7.3 CONFLICT RESOLUTION

The conflict resolution function determines the action to be taken as a result of a detected conflict during the RTP generation process. This conflict resolution function is accomplished by the RTP logic previously shown in section 7.1. If a conflict has been detected, the RTP generation function will assign a new trial parallel path and generate a

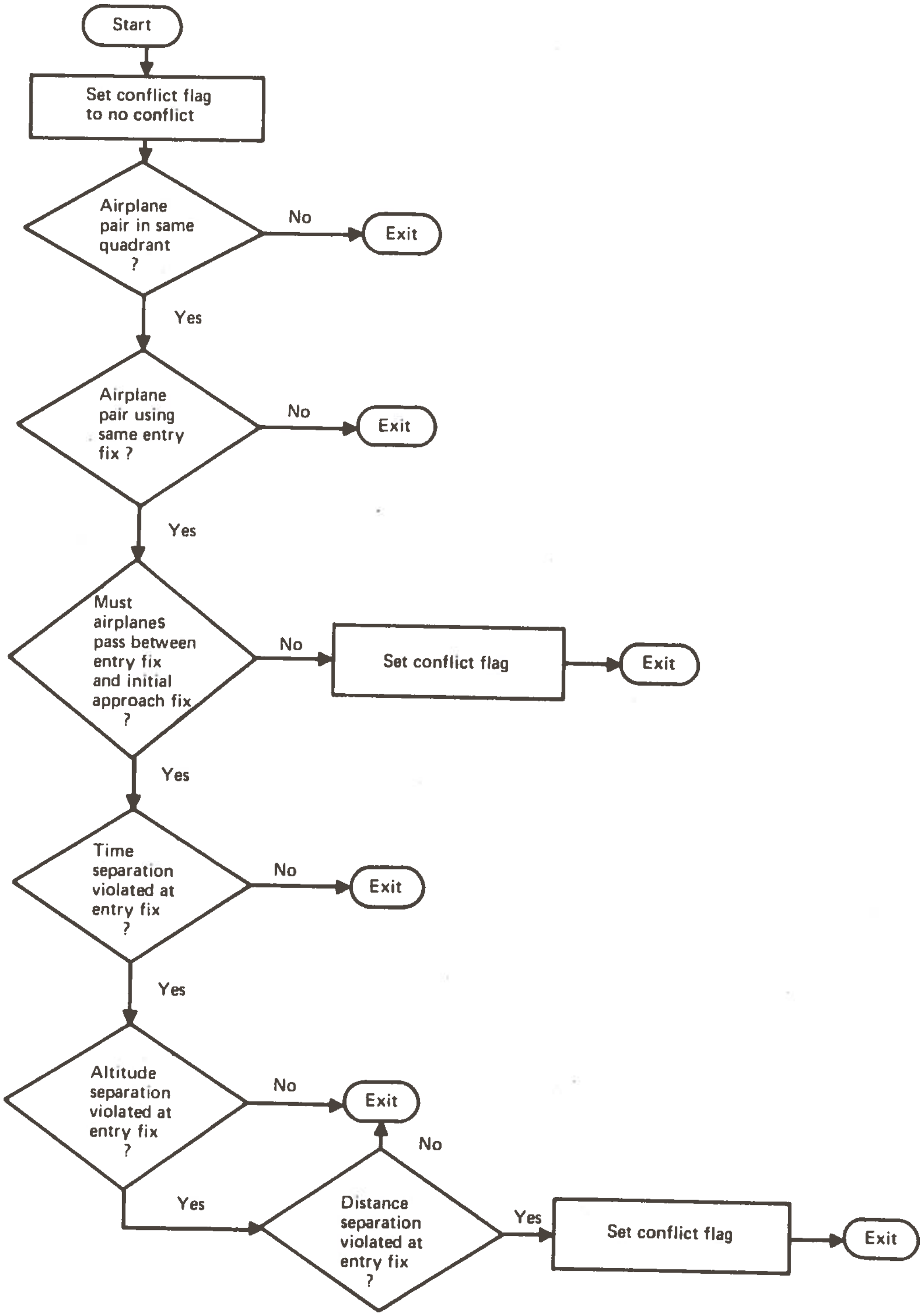


FIGURE 7-5.—SIMPLE CONFLICT DETECTION LOGIC

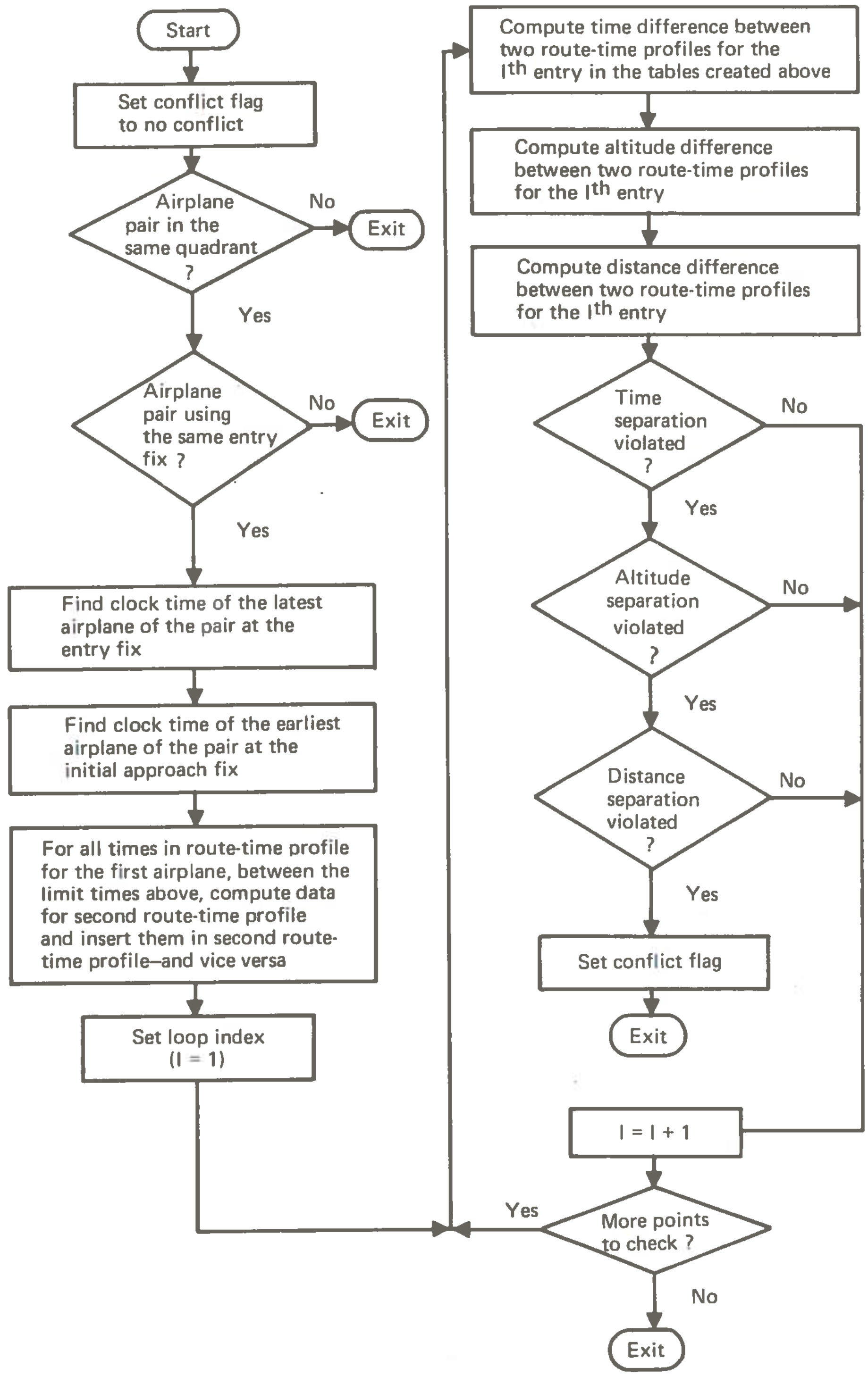
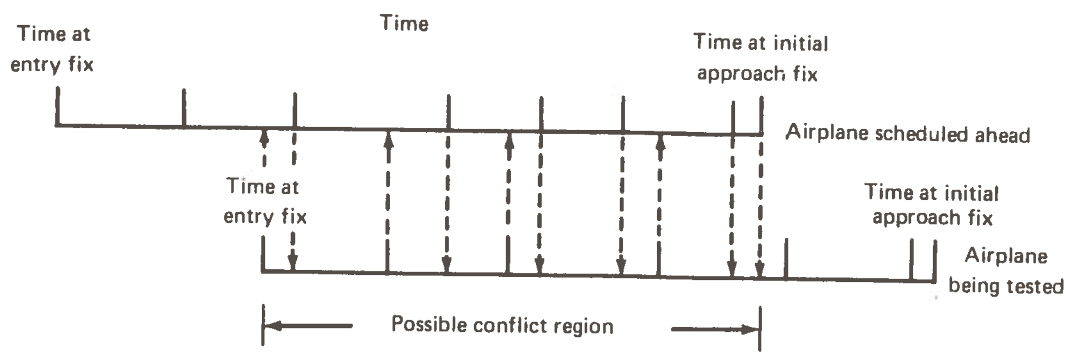


FIGURE 7-6.—COMPLEX CONFLICT DETECTION LOGIC

(1) Merge airplane waypoint times in both lists.



(2) Compute distance, velocity and altitude for added points in each list.

(3) Determine if distance, time or altitude constraints violated at any point in the list pertaining to the airplane being added.

(4) If constraints are violated, a conflict exists and a new trial path must be selected for the airplane being tested.

(5) If contraints are not violated, the tested route-time profile is assigned to the airplane.

FIGURE 7-7.—CONFLICT DETECTION PROCESS

new trial RTP. This new RTP is then checked for conflict and the process is repeated. The algorithm, as mechanized, has up to five parallel paths per entry fix that may be assigned to accomplish this conflict resolution function. Preliminary operation of the model indicates it is unusual to use even four of these with heavy traffic demands. Further model operation will yield more information as to the sufficiency of the number of parallel paths mechanized.

8.0 REAL-TIME IMPLEMENTATION CONSIDERATION

The algorithm, as mechanized on the CDC 6600 for evaluation purposes, is a Fortran IV program that depends on the driving model for traffic, wind, temperature, and interfacing for data retrieval. In general, the subroutines that are part of the algorithm can be isolated for mechanization on a real-time system. Without very specific information about the form of the real-time computer mechanization and its operating system, it is extremely difficult to predict the difficulty of adapting the algorithm to it.

If a real-time system were modified to present the same data base structure used in the CDC 6600 program, the inclusion of the algorithm would be appreciably easier. In this case, the principal work would be to modify the indexing structure in the sequencing, scheduling, and RTP generation functions to work on a continuous, rather than fixed-length, traffic stream. This will require a "look-ahead" structure (perhaps 5 to 10 minutes of real time) to interleave the arrival schedules. This is necessary to prevent late airplane entries from causing a need to resequence and reschedule. The present mechanization has total traffic list visibility and hence sequencing, scheduling, and RTP generation are accomplished serially with all airplanes at each step being accommodated. The real-time implementation needs to accomplish these functions for a partial list involving the new entry and those airplanes for the "look-ahead" time, which will follow it.

An additional modification necessary is to ensure that a proper reexecution of one-time-only subroutines is accomplished with changing weather forecast. The principal function affected by this item is the common path time computations (i.e., IAF to outer marker).