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SUMMARY

A guidance scheme has been developed for use during the atmospheric reentry phase of a fixed-trim, roll-modulated, $(L/D)_{max} = 0.5$ vehicle. The scheme is basically a reference trajectory type of guidance. Below circular velocity a fixed reference trajectory is used, but during the most critical portion of the reentry at supercircular speeds the guidance continuously recomputes a reference trajectory dependent on the state of the vehicle.

The scheme is capable of handling velocities ranging from satellite reentry to those expected at return from the manned Mars mission which utilizes the Venus swing-by mode (50,000 feet per second).

It is shown that for parabolic and higher velocities, the guidance scheme is capable of controlling the vehicle to ranges of 1,500 to 11,000 nautical miles. Reentry at angles corresponding to the extremes of the corridor defined by the vehicle capability can be handled in the presence of large variations of atmosphere density and realistic control dynamics.

INTRODUCTION

The guidance of aerospace vehicles requires information regarding the future consequences on the vehicle trajectory of a given control action, information which is available through solution of the equations of motion. Schemes which have been proposed for aerospace vehicle guidance in the Earth's atmosphere can be loosely classified according to the manner in which these solutions are obtained. Most schemes fall into one of three broad categories, namely:

(1) Numerical solutions of the nonlinear equations of motion,
(2) Closed-form analytical solutions of simplified equations of motion,
(3) Approximate numerical solutions in the neighborhood of an exact precomputed numerical solution (nominal trajectory) of the equations of motion.

Examples of guidance schemes representative of these categories are given in references 1 through 3, respectively.

The guidance scheme of category 1 is based upon rapid and repeated solutions of the equations of motion on board the vehicle. There are many advantages of this type of guidance accruing from the large amount of trajectory information which is generated in addition to that specifically related to reaching the destination. It has been demonstrated in reference 1 that with this type of guidance a reentry vehicle can be maneuvered to ranges as great as one-half the Earth's circumference in the presence of realistic constraints, such as atmospheric density variability and vehicle control dynamics. The primary disadvantage lies in the need for rather extensive and elaborate computing equipment.

An example of guidance of type 2 is given in reference 2. Closed-loop guidance schemes of this type have not been investigated as thoroughly as those based on the other two categories, and not much can be said regarding their capability.

Guidance based upon a nominal trajectory (category 3) generates much less information than is available from the repetitive solution type of guidance, and in this respect is less desirable. However, its relative simplicity makes it much better suited to the constraints imposed by the on-board computer. An application of this scheme which has demonstrated a potential capability for guidance to one-half the Earth's circumference is given in reference 3. However, further investigation of this scheme has revealed substantial deterioration of its capability when additional constraints not considered in reference 3 were imposed, such as error in one of the state variables used for guidance information, realistic control dynamics, and greater variations of atmospheric density.

The present guidance scheme was developed as a result of these findings. Basically the scheme remains one of nominal trajectory guidance, and thus preserves the relative computational simplicity associated with this type. Below circular velocity a fixed reference trajectory is used, as in reference 3. The guidance during the most critical portion of the trajectory at supercircular speeds was made variable in that a new reference trajectory was continuously recomputed dependent on the state of the vehicle. By this means the shortcomings of the previous system were overcome.

NOTATION

A	aerodynamic acceleration, g units
A'	$\frac{\partial A}{\partial V}$, $\frac{g}{ft/sec}$
C_D	drag coefficient
F_A	guidance gain (eq. (1)), g^{-1}
$F_{A'}$	guidance gain (eq. (1)), $\left(\frac{g}{ft/sec}\right)^{-1}$

F_x	guidance gain (eq. (1)), $(\text{n.m.})^{-1}$
g	acceleration due to gravity at Earth's surface
h	altitude, ft
L/D	lift-drag ratio, dimensionless
S	vehicle reference area, ft^2
t	time, sec
V	velocity relative to rotating atmosphere, ft/sec
V_I	inertial velocity, ft/sec
W	vehicle weight at Earth's surface, lb
x_f	range to destination at time of initial reentry, nautical miles (n.m.)
x_T	traversed range, nautical miles (n.m.)
x_{TG}	range to go, $x_f - x_T$, nautical miles (n.m.)
x_S	skip range, nautical miles (n.m.)
γ	flight-path angle relative to the rotating Earth, positive for increasing altitude, deg
ϕ	vehicle roll angle, deg

Subscripts

c	command value
e	exit from atmosphere
i	initial value
r	reference value
$(\dot{\ })$	time derivative, $\frac{d(\ )}{dt}$

REQUIREMENTS AND CONSTRAINTS

The guidance scheme was developed and evaluated in accordance with the following requirements and constraints regarding the vehicle, type of simulation, and guidance capability.

The vehicle was assumed to be a lifting capsule with a fixed angle of attack; its range control was effected by controlling the vertical component of lift by varying the vehicle roll angle. The characteristics of the vehicle, assumed constant, were $(W/C_D S) = 50\ \text{lb/ft}^2$, and a maximum $L/D = 0.5$. Roll of the vehicle was assumed to be controlled by means of an on-off type of control system similar to that of reference 4. The characteristics of the roll dynamics were as follows:

Maximum roll acceleration	$\pm 10^\circ/\text{sec}^2$
Maximum roll rate	$\pm 20^\circ/\text{sec}$
Roll rate deadband	$\pm 2^\circ/\text{sec}$
Roll angle deadband	$\pm 4^\circ$

Time responses of the vehicle roll angle to step inputs of 90° and 180° are shown in figure 1.

The simulation incorporated a spherical rotating Earth; however, for this investigation the vehicle trajectory was restricted to the equatorial plane, with the vehicle flying in the direction of Earth rotation. The 1959 ARDC atmosphere model (ref. 5) was used as the standard, and the extremes of the density variability from this standard which were assumed are shown in figure 2. These density extremes were taken from reference 6.

The capability of the guidance scheme should be determined primarily by the capability of the vehicle; it is preferable, of course, that the guidance not unduly restrict the vehicle from operating under those conditions which are reasonable or desirable from the standpoint of mission success. The range of entry angles for the assumed atmospheres is presented in figure 3 for velocities of 30,000 to 60,000 feet per second. The shallow angle limit shown (capture boundary) is that for which it is possible for the vehicle to attain sufficient aerodynamic force to be able to remain thereafter in the atmosphere. The steep angle limit shown is defined as the steepest angle for which the vehicle is capable of not exceeding a specified aerodynamic acceleration, taken here to be 10 g. These limits are shown in figure 3 for the standard atmosphere and for the assumed density extremes. It was further assumed that no information regarding atmospheric density will be available prior to reentry, and it is therefore necessary, in order to assure capture and to assure compliance with the maximum acceleration constraint, to use the most restrictive limits shown. The permissible range of entry angles resulting from this assumption is then given by the crosshatched portion of the figure.

The range capability requirement for the guidance was set essentially equal to the capability achieved by the guidance scheme of reference 3;

1,500 to 11,000 nautical miles, with an accuracy at the destination of ±10 nautical miles. These limits are more than adequate to satisfy the constraint of a single recovery site.

The final constraint imposed on the guidance was that it must operate in the presence of an uncertainty of alinement of the inertial measurement unit on board the vehicle, that is, an uncertainty of the knowledge of the local vertical. One consequence of this uncertainty is inaccurate knowledge of the altitude rate $\dot{h}$ of the vehicle, one of the state variables which was used for guidance information in the scheme of reference 3. Reference 7 indicates that even with advanced optical means, an uncertainty of the order of 0.2° is possible. At parabolic speed this produces an uncertainty in altitude rate of the order of 100 feet per second, a magnitude of error which the guidance of reference 3 was unable to handle. As noted previously, the present investigation was undertaken as a result of the deterioration of the capability of that scheme when operating under the constraints detailed in this section. The guidance scheme developed to overcome these shortcomings is described in the next section.

Description of Guidance Scheme

The uncertainty associated with altitude rate is obviously the result of insufficient accuracy in the resolution of a small component of the large velocity vector. Reference 7 indicates that there are probably physical limits which make significant improvement in the resolution accuracy somewhat doubtful, and the greater reentry velocities which will be associated with the more distant planetary missions severely compounds the problem. One of the more obvious solutions to the problem is to use for guidance information those state variables which do not require accurate angular resolution for their determination. The primary measurements made on board the vehicle are three orthogonal components of acceleration and the appropriate angles of the inertial measurement unit. The magnitude of the angular uncertainty does not prevent acceptably accurate calculation of velocity V and range x and, of course, has no effect on the calculation of acceleration magnitude A. One further quantity which can be calculated simply and accurately from these quantities by the on-board computer is the rate of change of acceleration with velocity, A'. These are the state variables chosen for use in the present guidance scheme. With velocity the independent variable, the control equation associated with these variables has the general form

$$(L/D)_c = (L/D)_r + F_A(A - A_r) + F_{A'}(A' - A_r') + F_x(x_{TG} - x_{TG_r}) \tag{1}$$

where

$$|(L/D)_c| \leq 0.5$$

It is understood that in general each term is a function of V, and it is further understood that equation (1) refers to the vertical component of the lift-drag ratio, the only component of significance in the present investigation. The command roll angle of the vehicle is thus determined from equation (1) by

$$\phi_c = \cos^{-1}[2(L/D)_c] \qquad (2)$$

Figure 4 presents a portion of an acceleration-velocity trace of a representative trajectory divided into various numbered phases. The guidance scheme will be described in terms of the quantities of equation (1) used in each phase. A list of these guidance quantities, as well as the switching condition which initiates each phase, is given in table I. A block diagram of the complete guidance is presented in figure 5.

The control logic for the first three phases in figure 4 is concerned only with insuring the aerodynamic capture of the spacecraft and compliance with the maximum acceleration constraint (10 g), and is therefore extremely simple. The control logic for phase 1 is simply full up or down lift depending on whether the initial flight-path angle γ_i is steeper or shallower than some designated switching value γ_s. That is,

$$(L/D)_c = (L/D)_r \qquad (3)$$

where for

$$\gamma_i < \gamma_s \qquad (L/D)_r = +0.5$$

$$\gamma_i > \gamma_s \qquad (L/D)_r = -0.5$$

It will be noted that this is the only phase for which the control action depends on flight-path angle. As will be discussed subsequently, for most of the velocities investigated, there is a range of γ_i values for which it is immaterial whether the lift vector initially is full up or full down; the uncertainty in γ which will result from inertial measurement unit alinement uncertainties prior to reentry thus essentially has no effect on guidance capability.

The rays shown in figure 4 delineate the switching conditions for initiating the logic of the subsequent phases. Once a given phase has been initiated, there is no return to the logic of a previous phase. The switching conditions which initiate phases 2, 3, and 4 are given by

$$A = -0.0000577\ (V - 24{,}000) \qquad (4)$$

$$A = -0.000333\ (V - 25{,}000) \qquad (5)$$

and

$$A = -0.00125\ (V - 25{,}000) \qquad (6)$$

respectively.

The purpose of each ray is to initiate the logic of the succeeding guidance phase so as to provide the greatest possible guidance capability over the greatest possible range of reentry velocities. The position of each ray was a compromise between the requirements thus generated and the desire to maintain the simplicity of a single slope for each ray.

During phase 2 the control equation is given by

$$(L/D)_c = F_{A'}(A' - A'_r) \tag{7}$$

where

$$F_{A'} = 1000$$

and

$$A'_r = 0.0027$$

This value of A'_r is intermediate to the two extremes experienced by the vehicle on the capture and 10 g boundaries, and so controls the vehicle to ensure capture, and to enable phase 3 logic to prevent the vehicle from exceeding the acceleration constraint. In phases 2, 3, and 4, the gain level shown was experimentally determined on the basis of vehicle response and stability.

The control equation for phase 3 is

$$(L/D)_c = (L/D)_r + F_{A'}A' \tag{8}$$

where

$$F_{A'} = 1000$$

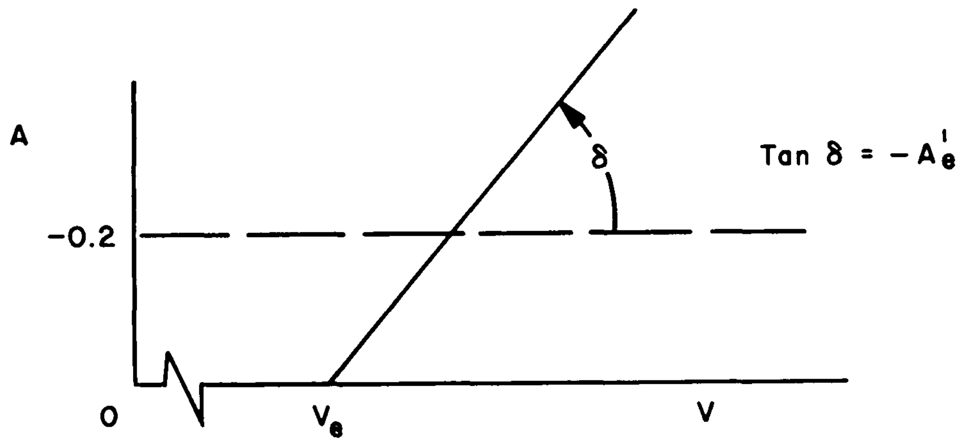
$$(L/D)_r = -0.2$$

This phase simply maintains the vehicle at a constant acceleration level until sufficient velocity has been lost to initiate the logic of phase 4.

The guidance logic utilized in these first three phases is extremely simple, since its function, as mentioned, is solely that of insuring capture and compliance with the maximum acceleration constraint. The logic of phase 4 is somewhat more complex as the accuracy of long-range guidance is directly dependent on the control action taken during this phase.

In order to achieve guidance to long ranges, it is generally necessary, in the case of the low L/D type of spacecraft being considered, for the vehicle to exit from the sensible atmosphere. The range which will be traversed during such a "skip" is a function of two variables at the time the vehicle leaves the atmosphere, the velocity and flight-path angle or any equivalent pair of variables. For a given atmosphere and given vehicle, these variables can be related to two of the variables used in the present guidance scheme, namely, velocity and rate of change of acceleration with velocity.

Since $A' = A = 0$ when the vehicle is outside the sensible atmosphere, skip range must be related to A' while the vehicle is still in the atmosphere; that is, while measurable increments of acceleration and velocity are still occurring. The present guidance scheme utilizes skip range determined for various values of A_e' (A' at $A = -0.2$ g) and various values of velocity, V_e. These data are presented in figure 6. Skip range was defined as the distance traversed by the vehicle with $L/D = 0$ from the condition $A = -0.2$ g during atmosphere exit to $h = 100{,}000$ feet at the second reentry. The reason for this choice of A will be discussed subsequently. The exit velocity V_e is defined as shown in the sketch, which represents the low acceleration portion of phase 4 (see fig. 4).



During the critical skip-out portion (phase 4) of the reentry, the data of figure 6 are used as the basis for a guidance which continually computes a nominal trajectory which is dependent upon the instantaneous state of the vehicle, and which causes the vehicle to exit at the conditions necessary to achieve the desired skip range. Since the range traversed during the skip is a function only of the exit conditions V_e and A_e', the specific path in the A,V plane traced by the vehicle in achieving the proper exit conditions is immaterial; a linear variation of acceleration with velocity is the simplest and will be used in the results to be presented. More complex curves may be useful in some instances in order that the trajectory satisfy some desired auxiliary conditions. The vehicle is commanded to follow the nominal trajectory by means of the control equation

$$(L/D)_c = (L/D)_r + F_{A'}(A' - A_r') \tag{9}$$

where

$$F_{A'} = 1000$$

$$(L/D)_r = -0.1$$

The slope A_r' of the nominal trajectory is given by (for the "linear" nominal trajectory being used)

$$A_r' = \frac{A}{V - V_e} \tag{10}$$

Throughout phase 4, in order to compute the correct value of V_e for use in equation (10), it is necessary to know the distance the vehicle will be required to skip when it exits from the atmosphere. If x_f is the total range, x_T is the range the vehicle will have traversed at the time it leaves the atmosphere, and x_m is the range to the destination desired to remain at the end of the skip for the purpose of terminal maneuvering (chosen as 100 nautical miles), then the required or command skip distance is equal to

$$x_{s_c} = x_f - x_T - x_m \tag{11}$$

With the command skip range and actual value of A' known, it is possible to determine an approximate value of V_e from the data of figure 6 by assuming that $A' = A_e'$, that is, that the present value of A' will be maintained to the exit condition. Equation (10) then determines the nominal trajectory slope A_r' for use in the control equation (9). As the vehicle maneuvers in response to the commands of equation (9), a new value of V_e is continuously computed corresponding to the instantaneous value of A'. This process continues until the value of A' converges to the slope of the "linear" nominal trajectory connecting the instantaneous values of A and V to the computed value of V_e which is specified at zero acceleration. This is the nominal trajectory which, if followed, will cause the vehicle to exit at the conditions necessary to achieve the command skip range. In the absence of disturbances, and if the calculation of x_T is accurate, no further corrections to V_e will be made, and the nominal trajectory will remain unchanged during the rest of phase 4.

The data of figure 6 were put in a form suitable for use in this guidance scheme by fitting it with the equation

$$x_{s_p} = a + bA_e' + d(A_e')^2 \tag{12}$$

and the coefficients a, b, and d stored as a function of V_e (table II). The variation of these coefficients with V_e is shown in figure 7. The subscript p (for predicted skip range) in equation (12) is used to denote the fact that the values thus computed are accurate only for the "standard" atmosphere (and given vehicle) and for values of A_e' more negative than approximately -0.0006. Equations (11) and (12) are used in the continuous computation of V_e according to

$$V_e = K\int\left(x_{s_c} - x_{s_p}\right)dt \tag{13}$$

The gain K of the loop formed by this computation scheme is not critical; it was chosen to insure a sufficiently rapid rate of convergence and still maintain loop stability. Because of the high rate of convergence, the initial value of V_e is also immaterial.

The use of the definition given x_T in equation (11) would require that some means be available for predicting the range to be traversed to the exit condition during the entire phase 4. Actually, this is an unnecessary complication and was not used. Instead, x_T was defined as the instantaneous range traversed; the skip range x_{s_c} thus commanded varied throughout phase 4 as the range to the destination continuously decreased. As a result, the nominal trajectory also varied continuously, converging, of course, to the exit conditions actually necessary as the vehicle left the atmosphere.

Two difficulties regarding the logic of phase 4 are as follows: First, it can be seen from equation (10) that as the vehicle is controlled to the nominal trajectory and the atmosphere exit condition is approached, then $A \rightarrow 0$, $V \rightarrow V_e$, and A_r' becomes indeterminate. Second, when the velocity of the vehicle equals V_5 ($=V_e$), the control logic of phase 5 is initiated. It will be recalled that equation (12) accurately represents skip range only for values of A' more negative than about -0.0006. However, as noted previously, $A' \rightarrow 0$ as $A \rightarrow 0$, and therefore incorrect values of V_e will always be computed by equation (13) as the vehicle leaves the atmosphere. To avoid the erroneous maneuvering and logic switching which results from these difficulties, the values of A_r' and V_e were held constant at their last computed value as the aerodynamic acceleration became more positive than -0.2 g.

Phase 5 is that part of the trajectory from $V = V_5$ to $h = 100{,}000$ feet altitude. Only the initial part of this phase is indicated in figure 4. The control equation used during this phase of the trajectory is the full equation (1). A fixed nominal trajectory is used for control information. The trajectory is essentially that used in reference 3, which is a relatively high skip type of trajectory, characteristic of most of the trajectories produced by the present guidance scheme. The feedback gains were computed on the basis of linear perturbation theory as described also in reference 3. The gains and nominal state variables are presented in table III as functions of velocity, the independent variable of equation (1).

Because the guidance as described causes the vehicle to skip out of the atmosphere, one would expect that some modification must be made in order to achieve short ranges. The most difficult reentry condition from which to achieve short-range guidance occurs at the capture boundary for the reduced density condition. Figure 8 presents, for conditions on this boundary, a comparison of the minimum range capability of the vehicle with that obtainable with the skip guidance just described. The vehicle capability was determined by maintaining a 10 g acceleration level from the earliest point in the trajectory permitted by vehicle roll dynamics. The minimum range thus attainable depends decisively, of course, on how close the true capture boundary is approached. To the accuracy with which the boundary was determined for this investigation (the closest 0.1°) these results apply. The comparison shows that considerable improvement is possible in short-range guidance capability.

The modification made to achieve short-range capability was a simple change to the logic of phase 4; whereas ranges greater than 2,500 nautical miles were achieved by varying V_5 ($=V_e$) and maintaining a zero value of acceleration, A_5, at that velocity, ranges less than 2,500 nautical miles were achieved by maintaining a constant value of V_5 (=23,586 ft/sec) and varying acceleration ($=A_5$) at that velocity according to the desired range. The two modes of operation are

$$\left.\begin{array}{lll} x_f \geq 2{,}500 \text{ nautical miles:} & A_5 = 0 & V_5 = V_e \\ x_f < 2{,}500 \text{ nautical miles:} & A_5 = -11.125 + 0.00375\, x_f & V_5 = 23{,}586 \end{array}\right\} \quad (14)$$

As indicated in figure 8, a constant switching condition of 2,500 nautical miles can be maintained at the lower velocities only through reentry at angles steeper than the capture boundary; at 30,000 feet per second the corridor loss amounts to 0.1°. This loss is probably inconsequential because of the large corridor at the lower velocities.

Guidance System Performance

Examples of trajectories resulting from reentries into an atmosphere of standard density at angles corresponding to the reduced density atmosphere capture boundary for velocities of 30,000 to 50,000 feet per second are presented in figure 9. Figure 9(a) shows the rays denoting the simple switching criteria described in the previous section, and the resulting acceleration-velocity histories. These trajectories correspond to the minimum and maximum ranges obtainable with this guidance scheme; 1,500 and 11,000 nautical miles for the higher velocities, 1,500 and 8,000 nautical miles for the 30,000 feet per second reentry. These short-range trajectories are shown in the small inset to figure 9(b). Figure 9(a) shows the variations in the acceleration-velocity histories caused by the phase 4 logic for these range extremes. For clarity, the acceleration histories are shown only for velocities above V_5.

The 8,000 nautical-mile trajectory is the only true maximum for the guidance scheme as formulated; increased range capability for the entries at higher velocity can be accomplished simply by extending the stored coefficients of table II (fig. 7) to the value of V_e necessary to generate the increased skip range desired. No change in the logic would be necessary. Increasing the range capability for a reentry velocity of 30,000 feet per second would require a change in logic; the switching criteria shown results in values of aerodynamic acceleration which remove sufficient kinetic energy from the vehicle to prevent it from attaining its full range potential at this entry angle.

The effect of atmosphere deviations on long-range trajectory shape is illustrated in figure 10 for reentry at parabolic velocity. The initial angle again corresponds to the capture boundary for reduced density. The primary effect of density deviations is on the maximum skip altitude as shown in figure 10(b), and this only for reduced density. The effects of increased density were relatively minor.

A comparison of 11,000 nautical-mile trajectory shapes for reentries into a standard atmosphere at angles corresponding to the reduced density capture boundary and the increased density 10 g boundary is made in figure 11 for parabolic initial velocity. Large differences in minimum skip altitude and acceleration level are evident. As shown in figure 11(a), these entries from the extremes of the corridor require initial control action of full negative lift at the capture boundary and full positive lift at the 10 g boundary. For a range of angles intermediate to these two extremes the initial control action should be arbitrary. This region of arbitrary initial control action is shown in figure 12. Also shown is the reentry corridor from figure 3. The upper boundary of the shaded region was defined as the angle for which the vehicle could reenter a reduced density atmosphere with full positive lift and be successfully guided to ranges of 1,500 to 11,000 nautical miles for the higher velocities, and from 1,500 to 8,000 nautical miles at 30,000 feet per second. For parabolic and greater velocities, the lower boundary of the shaded region was defined as the angle at which the vehicle could reenter an atmosphere of increased density with full negative lift and not exceed an acceleration level of 10 g. Full range capability of 1,500 to 11,000 nautical miles was automatically satisfied. At velocities less than parabolic, however, the maximum range requirement became the controlling factor, as indicated by the sharp break in the boundary. In regard to the previous discussion of the logic of phase 1, it can be seen that the switching value γ_s of the initial flight-path angle can be designated to lie anywhere within the shaded region of figure 12. At a velocity of 50,000 feet per second the boundaries have crossed; that is, at this velocity there is no region of arbitrary control action, and, in fact, there exists the possibility of reaching an acceleration level somewhat in excess of 10 g (if the atmosphere happens to have increased density) because full negative lift is necessary (in case the atmosphere happens to have reduced density) to insure full range capability. Either designing the switching logic for a reentry velocity associated with a specific mission, or slightly increasing the complexity of the logic could remove this possibility. In any event, the excess acceleration (if it occurs) is a momentary condition and is probably of little importance.

Guidance and vehicle capability for velocities of 30,000 to 50,000 feet per second are compared in figure 13. It can be seen that at 30,000 feet per second the guidance is able to utilize virtually full vehicle capability for ranges less than 8,000 nautical miles. At the higher velocities the vehicle range capability is greater than half the Earth's circumference for all angles within the reentry corridor and thus are not shown: guidance to ranges of half the circumference of the Earth was the desired goal, and this was achieved. The range capability of the guidance can be increased simply be extending the storage of the skip range coefficients, as has been discussed.

It was shown in reference 3 that almost full vehicle capability at satellite velocity was possible with the phase 5 logic of the present guidance scheme. Figure 13 shows that the spectrum of reentry velocities which the guidance scheme is able to handle extends to velocities the vehicle will reach on return from the manned Mars mission which utilizes the Venus swing-by mode (ref. 8).

CONCLUDING REMARKS

A guidance scheme has been developed which is applicable to a low L/D type of capsule reentering the Earth's atmosphere.

The scheme is capable of handling velocities ranging from satellite reentry to those expected at return from the manned Mars mission which utilizes the Venus swing-by mode.

For parabolic and higher velocities, the guidance scheme is capable of controlling the vehicle to ranges of 1,500 to 11,000 nautical miles. Maximum range capability of the system can be extended easily.

Reentry at angles corresponding to the extremes of the corridor defined by the vehicle capability can be handled in the presence of large variations of atmosphere density and realistic control dynamics.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., March 4, 1965

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TABLE I.- GUIDANCE QUANTITIES FOR BLOCK DIAGRAM OF FIGURE 5

Guidance phase (See fig. 4)	Switching condition	Guidance quantities
1		$(L/D)_r = +0.5$ } See figure 12 $(L/D)_r = -0.5$ } $F_A = F_{A'} = F_x = 0$
	$A = -0.0000577(V - 24{,}000)$	
2		$(L/D)_r = 0$ $F_A = F_x = 0$ $F_{A'} = 1{,}000$ $A'_r = 0.0027$
	$A = -0.000333(V - 25{,}000)$	
3		$(L/D)_r = -0.2$ $F_A = F_x = 0$ $F_{A'} = 1{,}000$ $A'_r = 0$
	$A = -0.00125(V - 25{,}000)$	
4		$(L/D)_r = -0.1$ $F_A = F_x = 0$ $F_{A'} = 1{,}000$ $A'_r =$ Eq. (10)
	$V = V_5$ (See eqs. (14))	
5		$(L/D)_r = 0.1$ F_A, $F_{A'}$, F_x table III A_r, A'_r, x_{T_r} table III

TABLE II.- QUADRATIC COEFFICIENTS FOR SKIP RANGE COMPUTATION

V_e	a	$b \times 10^{-6}$	$d \times 10^{-8}$
14,500	458	-0.03688	1.055
18,200	458	-.03688	1.055
20,200	577	-.14188	1.101
22,200	696	-.50563	1.148
23,000	744	-1.05264	.815
23,400	670	-1.96194	-.786
23,600	633	-2.85194	-2.836
23,800	596	-4.20889	-6.572
23,950	1,286	-5.18833	-10.033
24,000	1,962	-5.21569	-10.649
24,050	3,132	-4.81292	-10.304
24,100	5,034	-3.72805	-8.364
24,150	7,886	-1.71708	-4.196
24,200	10,765	.27875	-.125
24,250	13,873	2.50687	4.523

TABLE III.- PHASE 5 NOMINAL TRAJECTORY CONTROL VARIABLES

V	A_r	F_A	A_r'	F_A'	x_{TG_r}	F_x
>23,586	0	0	0	125	431	0
23,586	0	0	.00145	125	431	0
22,000	-1.80	-.009	.00080	129	363	0
19,000	-3.45	-.027	.00037	136	234	.001
15,000	-4.40	-.050	.00015	145	139	.002
10,400	-4.70	-.070	0	170	66	.007
6,000	-4.15	-.230	-.00027	260	22	.038
4,000	-3.40	-1.120	-.00045	810	7	.197
0	-1.50	-1.120	-.00100	810	0	.197

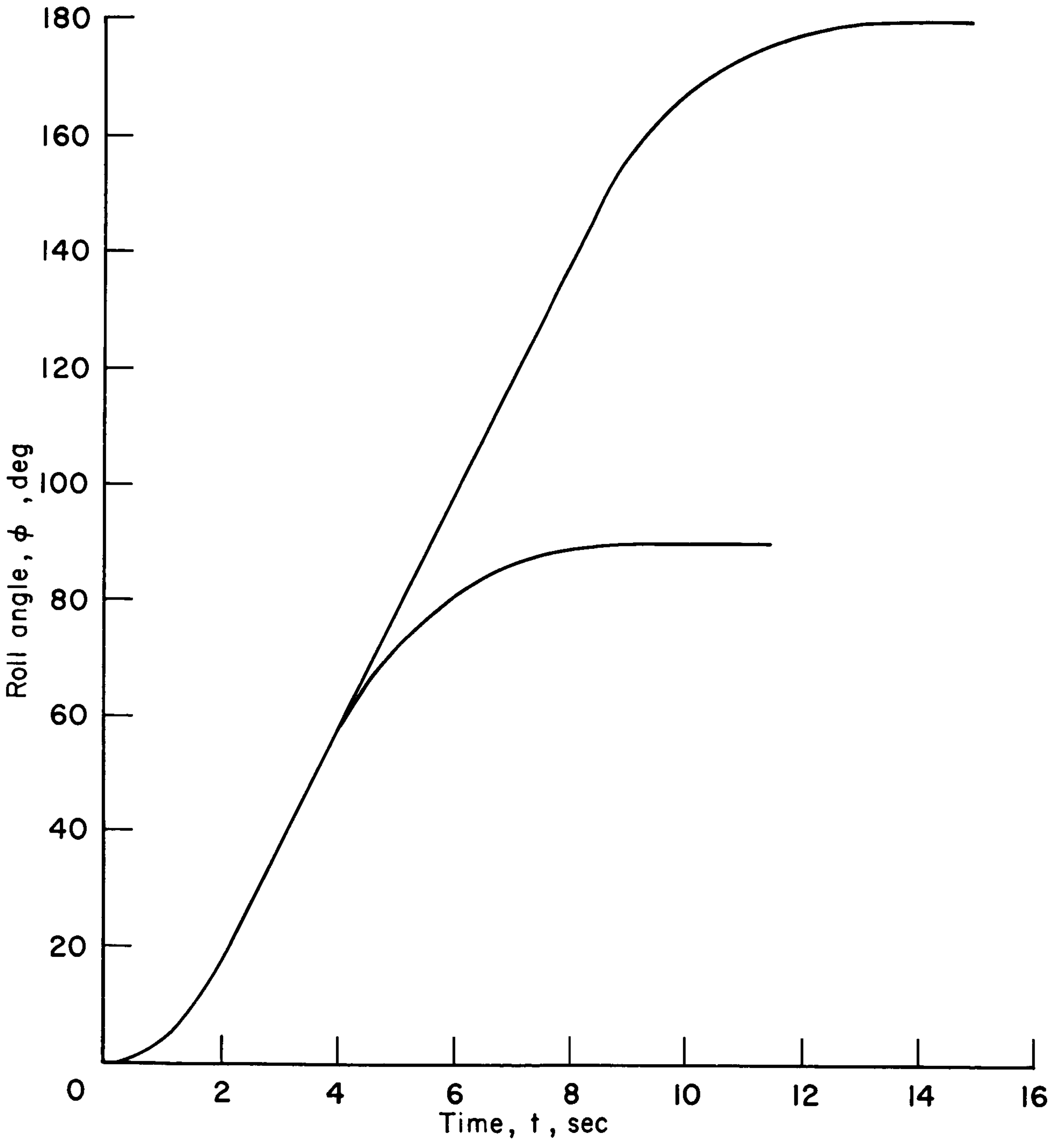


Figure 1.- Roll angle response to step commands of 90° and 180°.

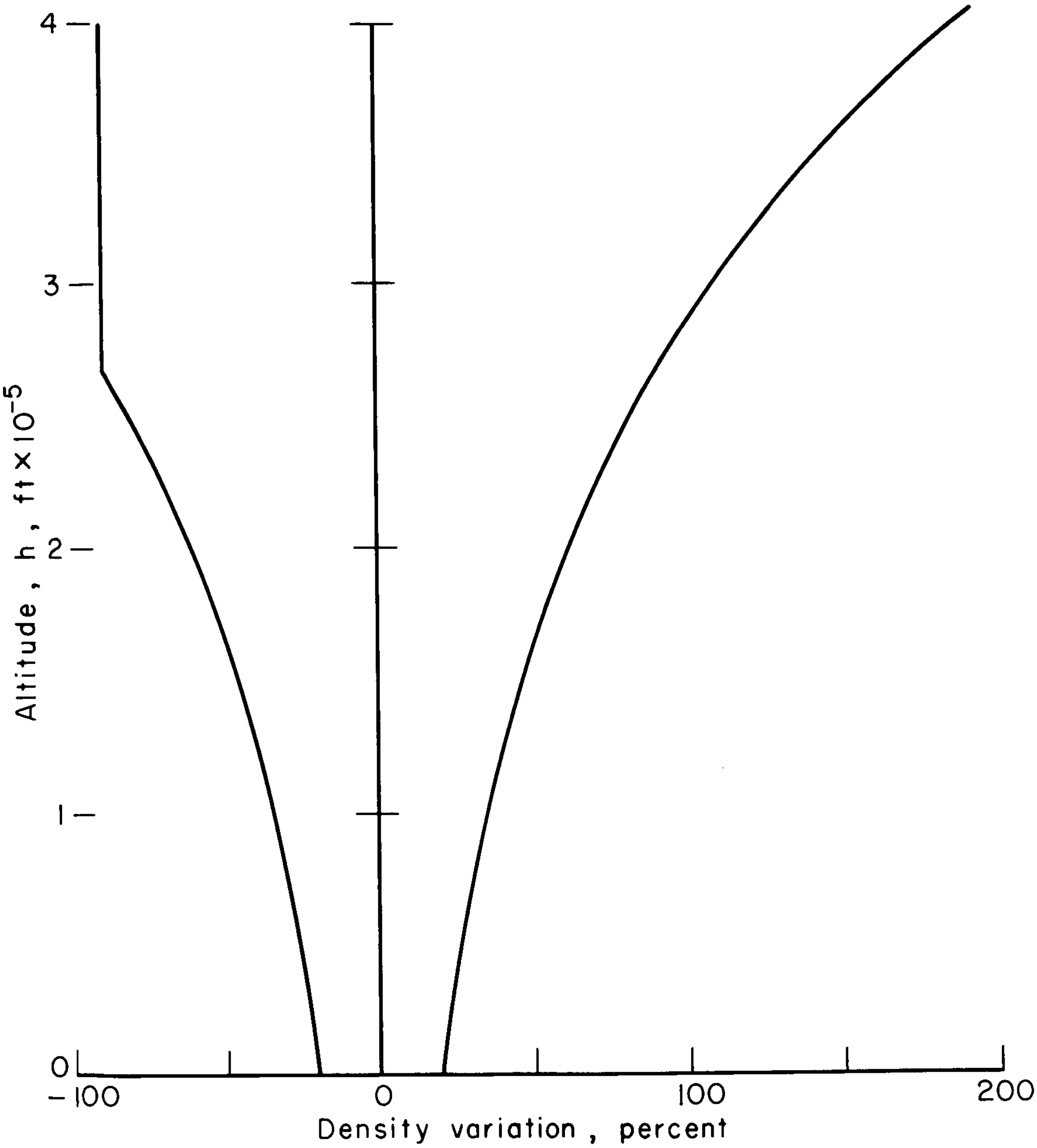


Figure 2.- Range of density variations from the 1959 ARDC model atmosphere.

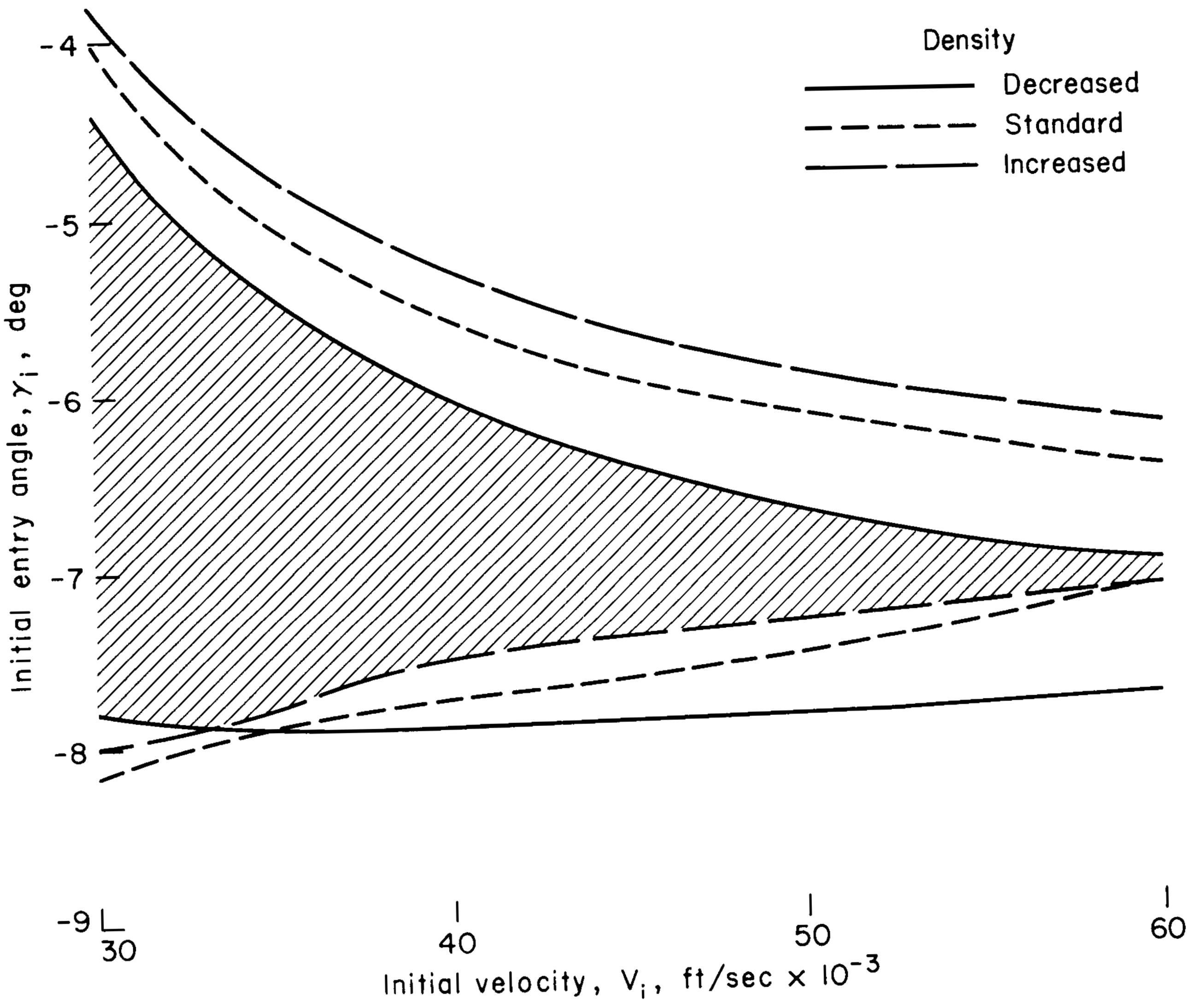


Figure 3.- Reentry angle limits for the assumed vehicle; $(L/D)_{max} = \pm 0.5$, $W/C_DS = 50$ lb/ft^2.

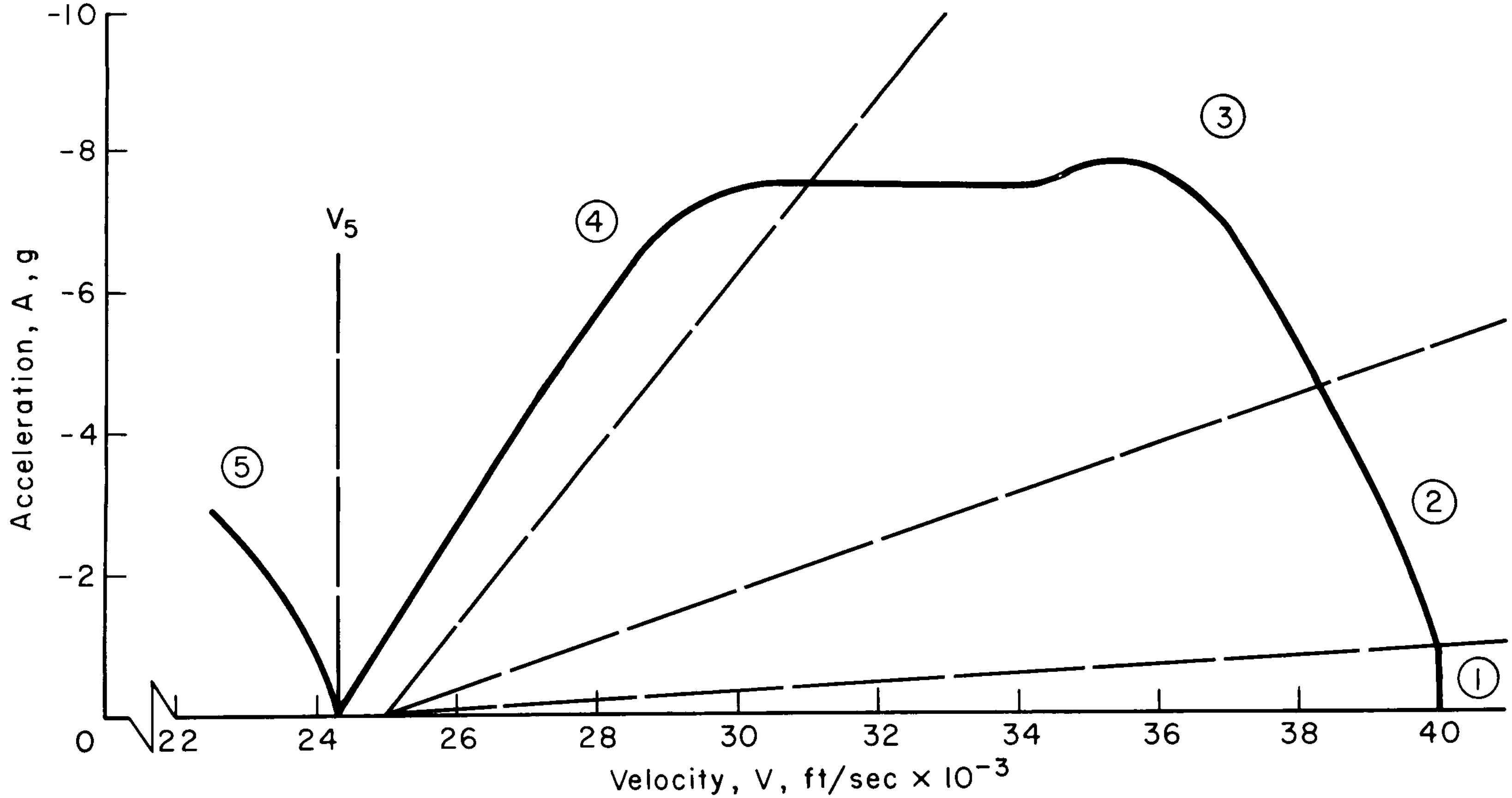


Figure 4.- Representative acceleration-velocity history illustrating the various guidance phases and switching conditions.

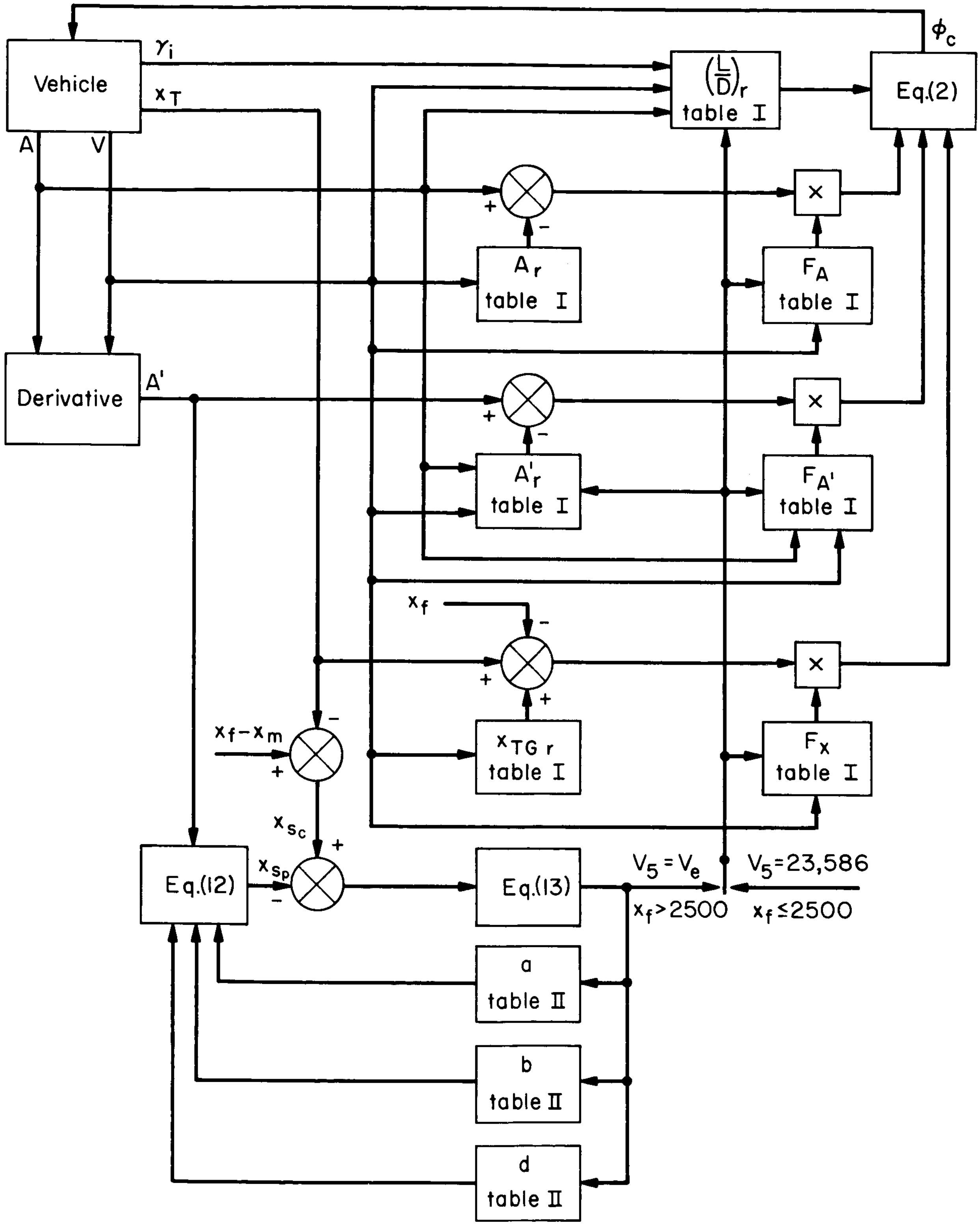


Figure 5.- Block diagram of the guidance scheme.

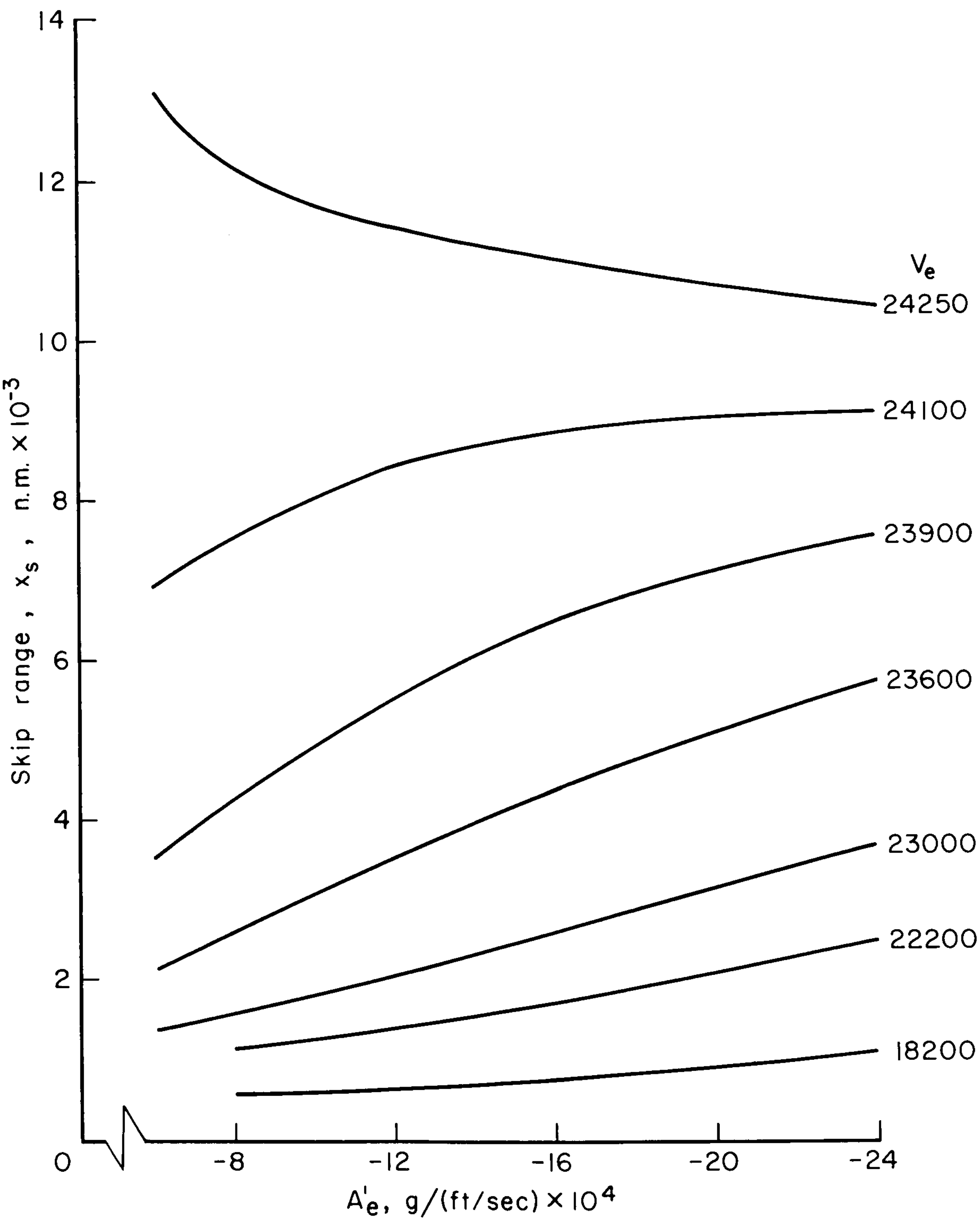


Figure 6.- Skip range as a function of A'_e and V_e.

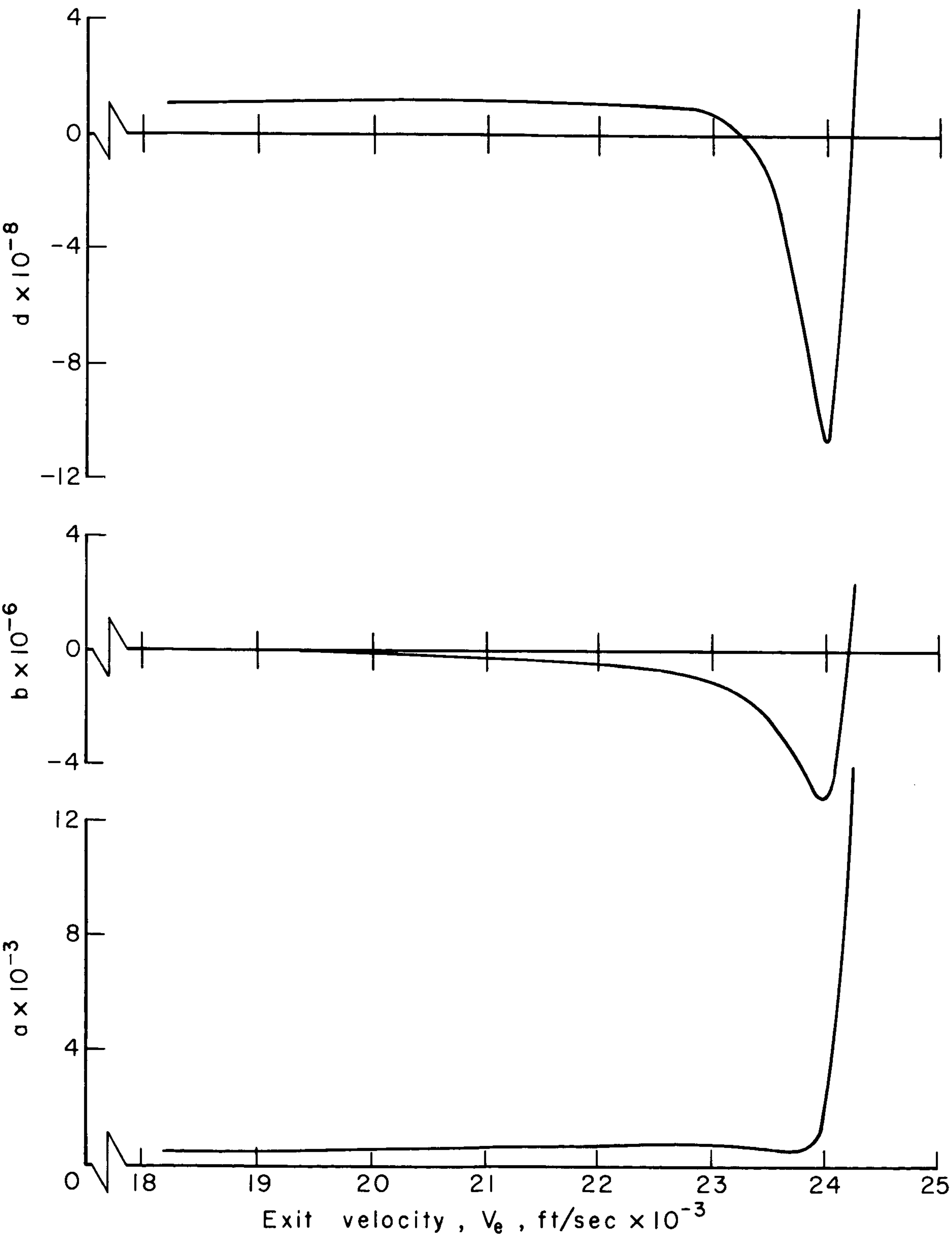


Figure 7.- Quadratic coefficients for prediction of skip range.

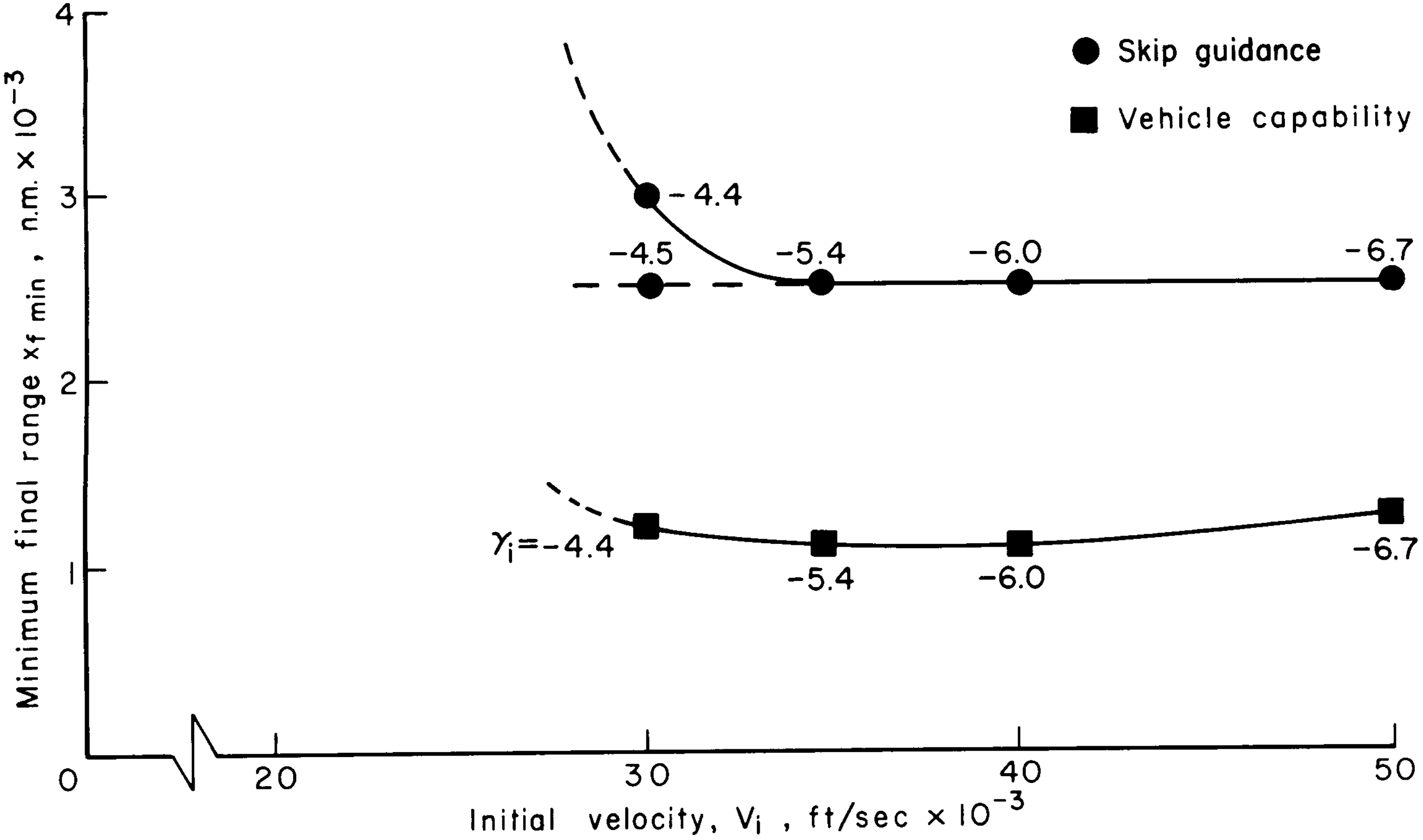
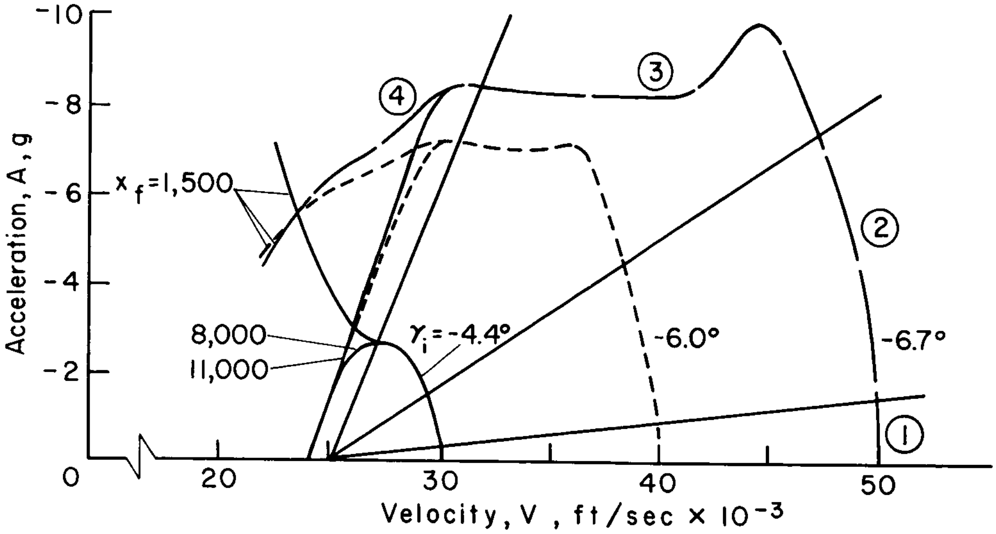
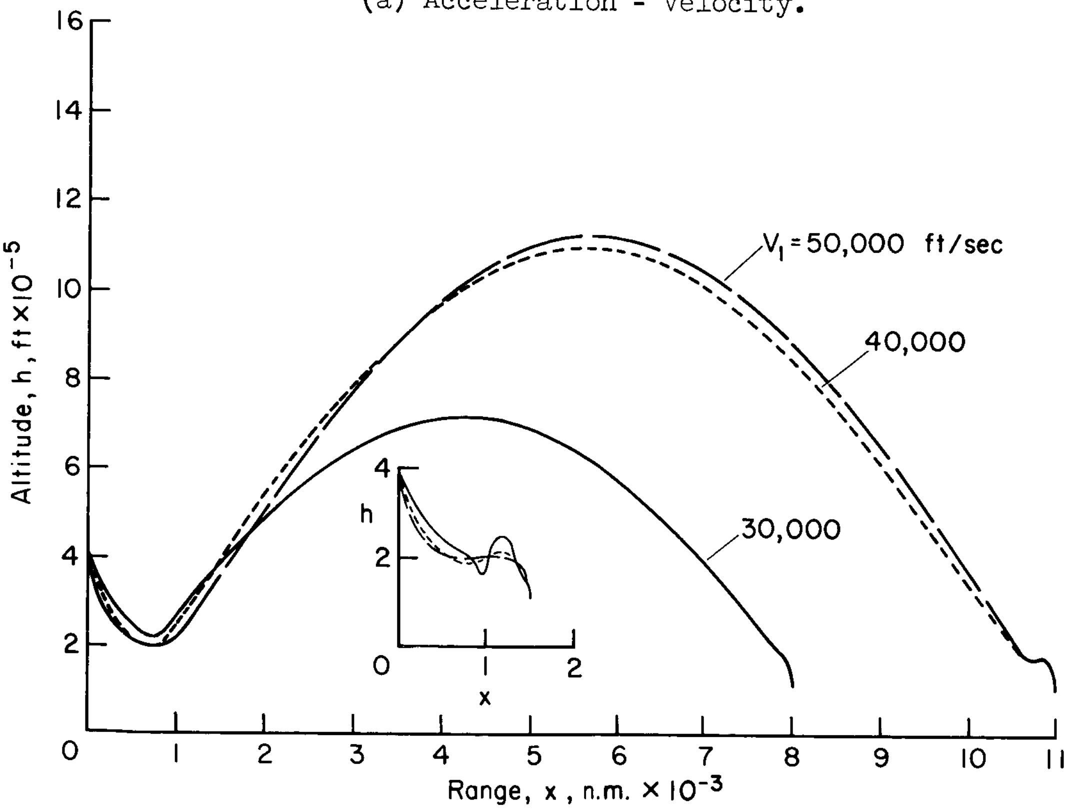


Figure 8.- Comparison of vehicle minimum range capability with that attainable with skip type guidance.

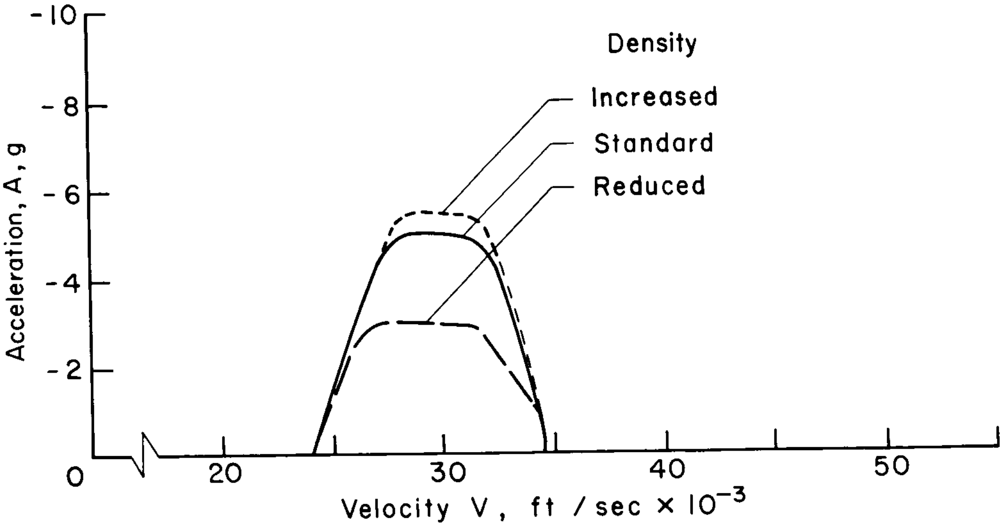


(a) Acceleration - velocity.

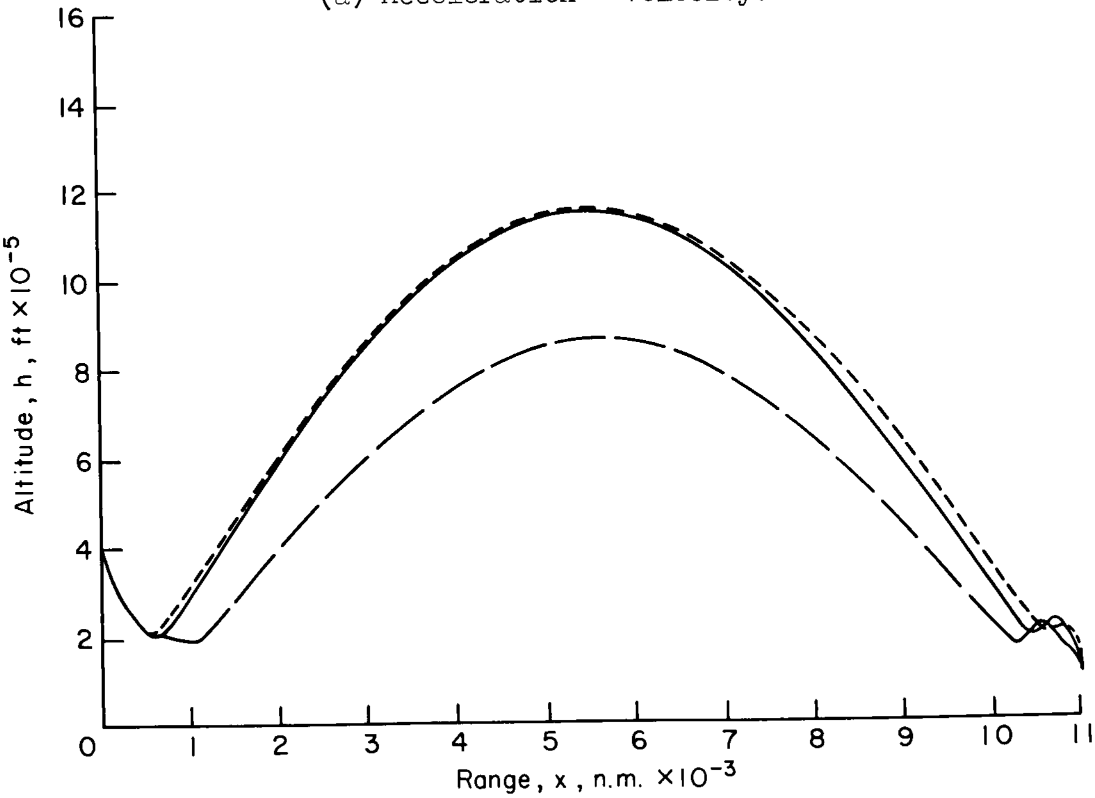


(b) Altitude - range.

Figure 9.- Minimum and maximum range trajectories for various reentry velocities, standard atmosphere.

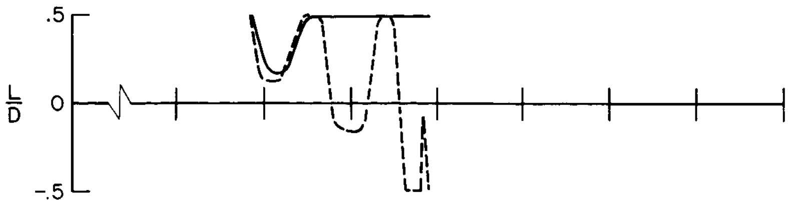


(a) Acceleration - velocity.

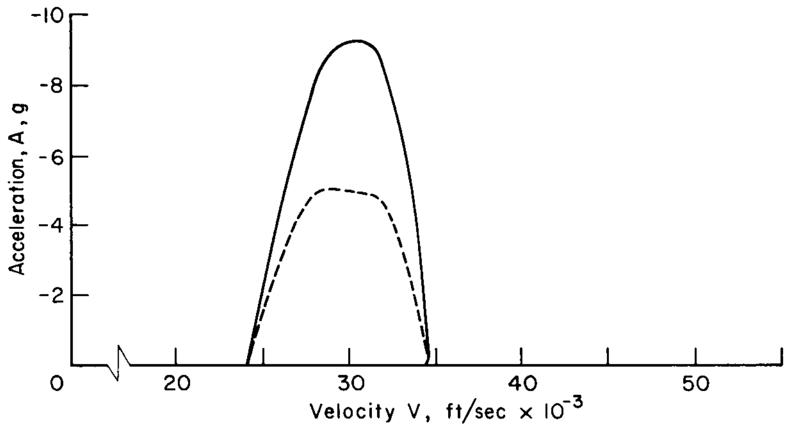


(b) Altitude - range.

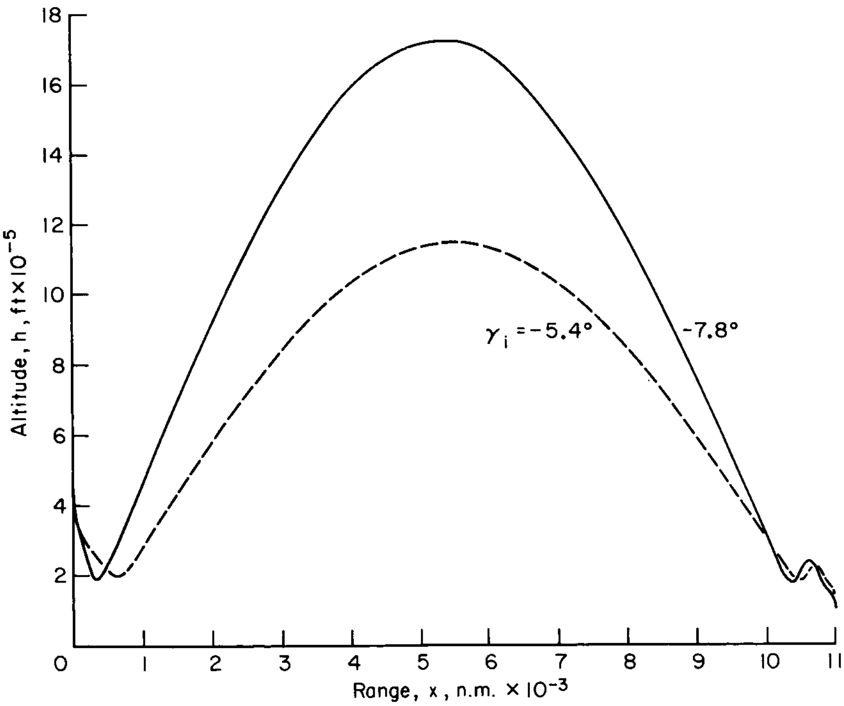
Figure 10.- Effect of atmosphere variations on trajectory shape for parabolic reentry speed; $\gamma_i = -5.4^\circ$.



(a) L/D - velocity.



(b) Acceleration - velocity.



(c) Altitude - range.

Figure 11.- Effect of reentry angle on trajectory shape for parabolic reentry speed, standard atmosphere.

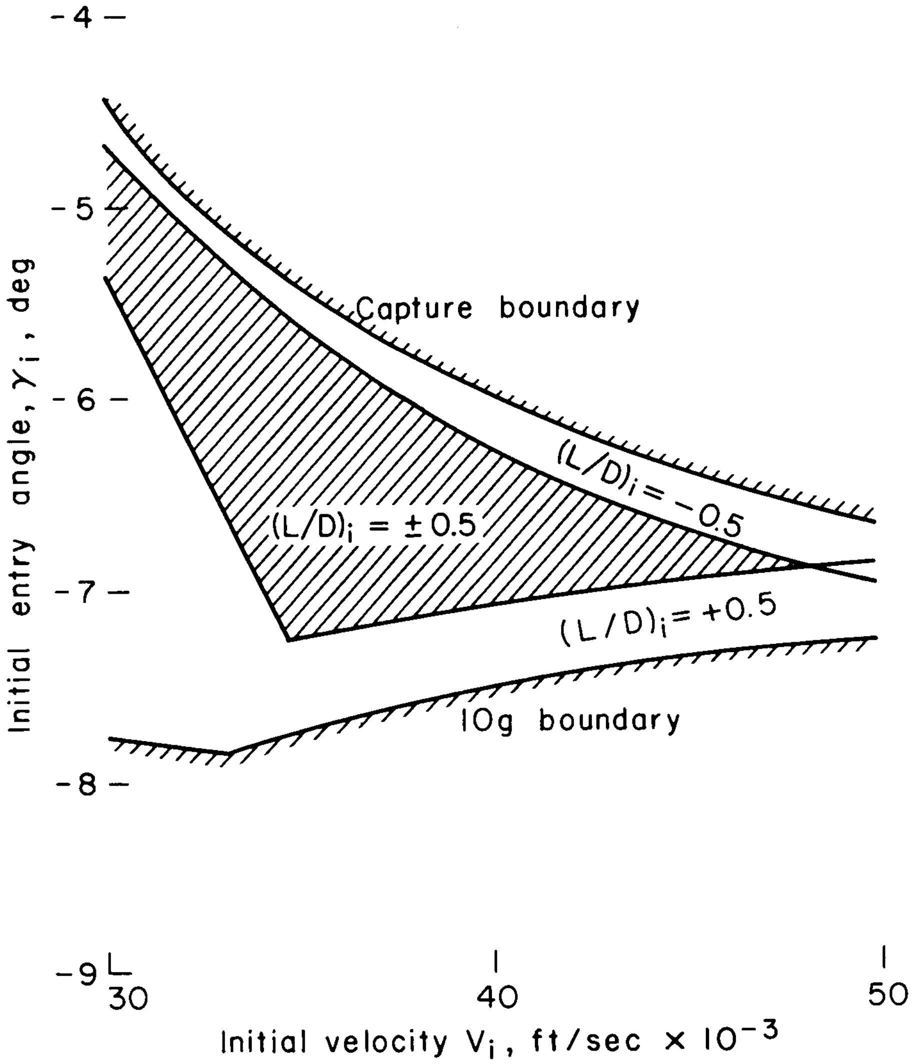
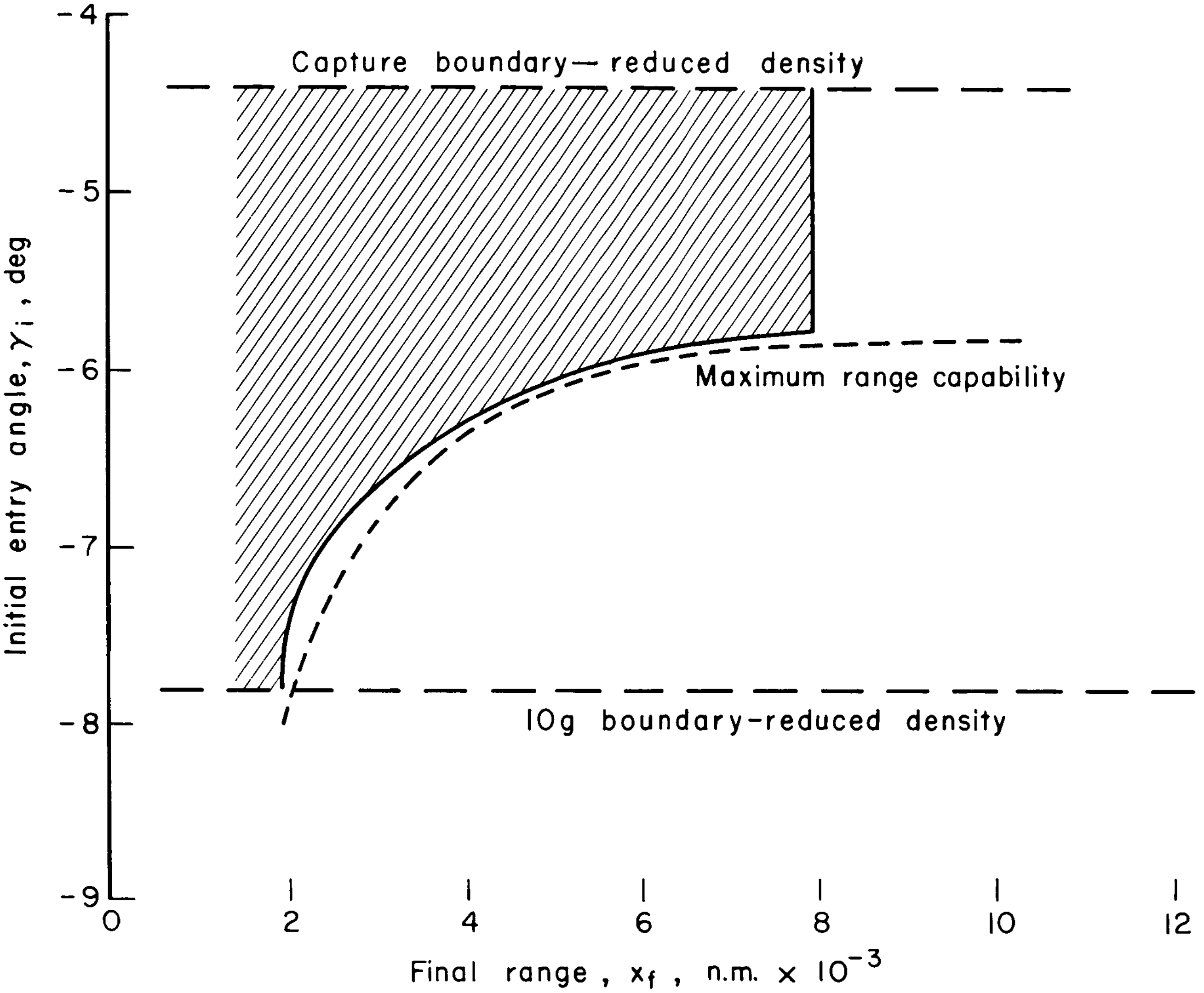
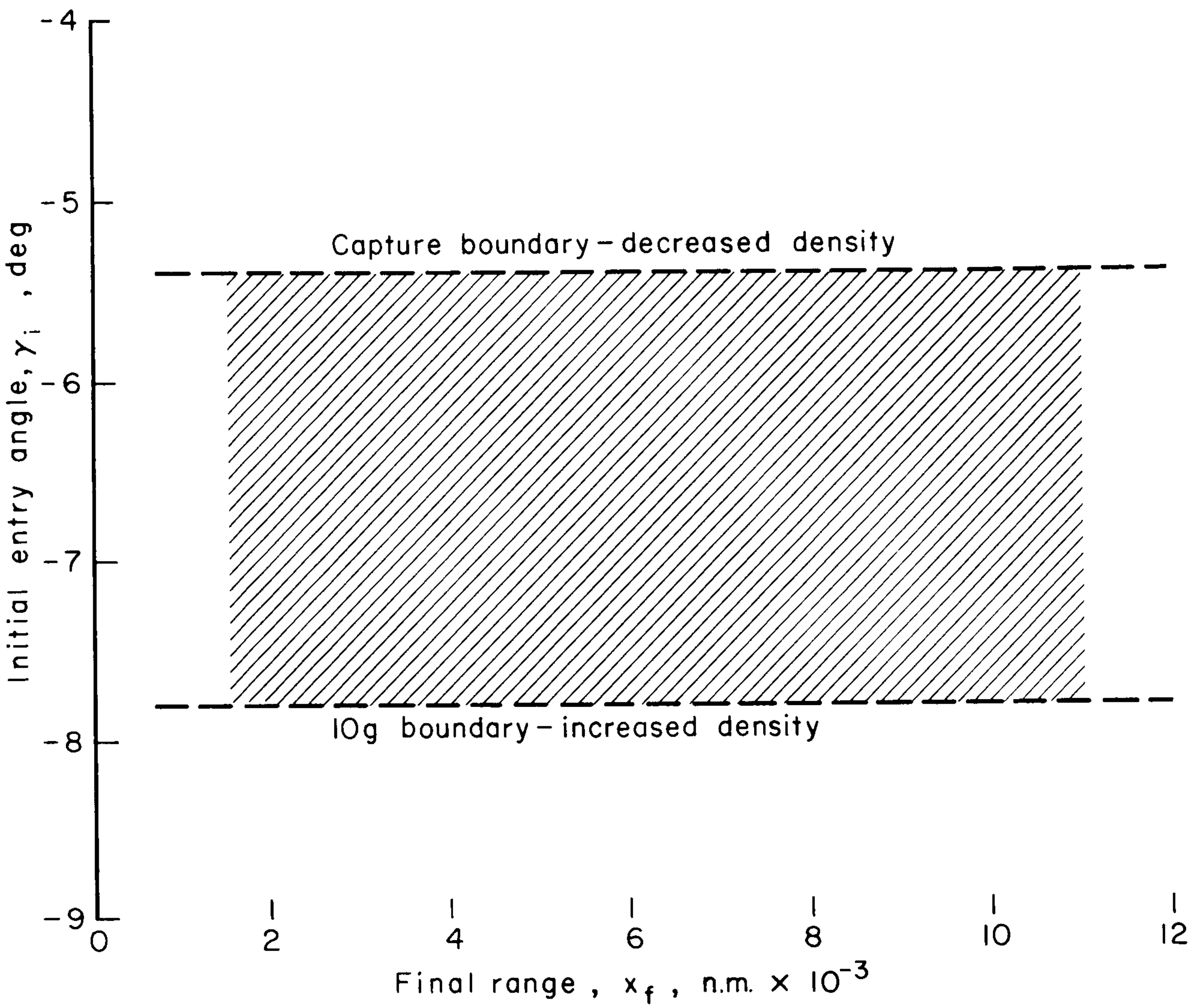


Figure 12.- Variation with velocity of reentry angles for which initial control action is arbitrary.



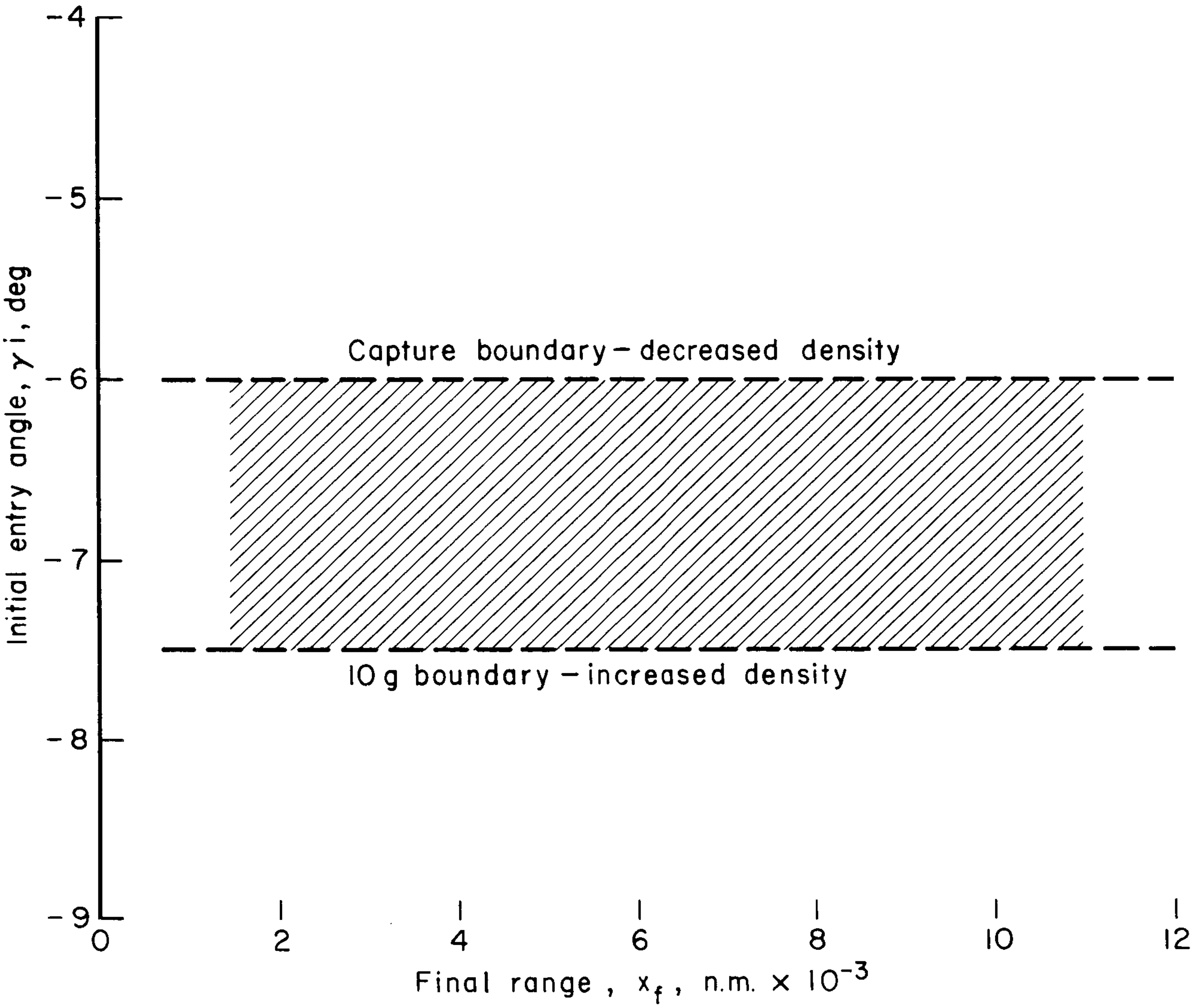
(a) V_i = 30,000 ft/sec.

Figure 13.- Comparison of vehicle and guidance capability.



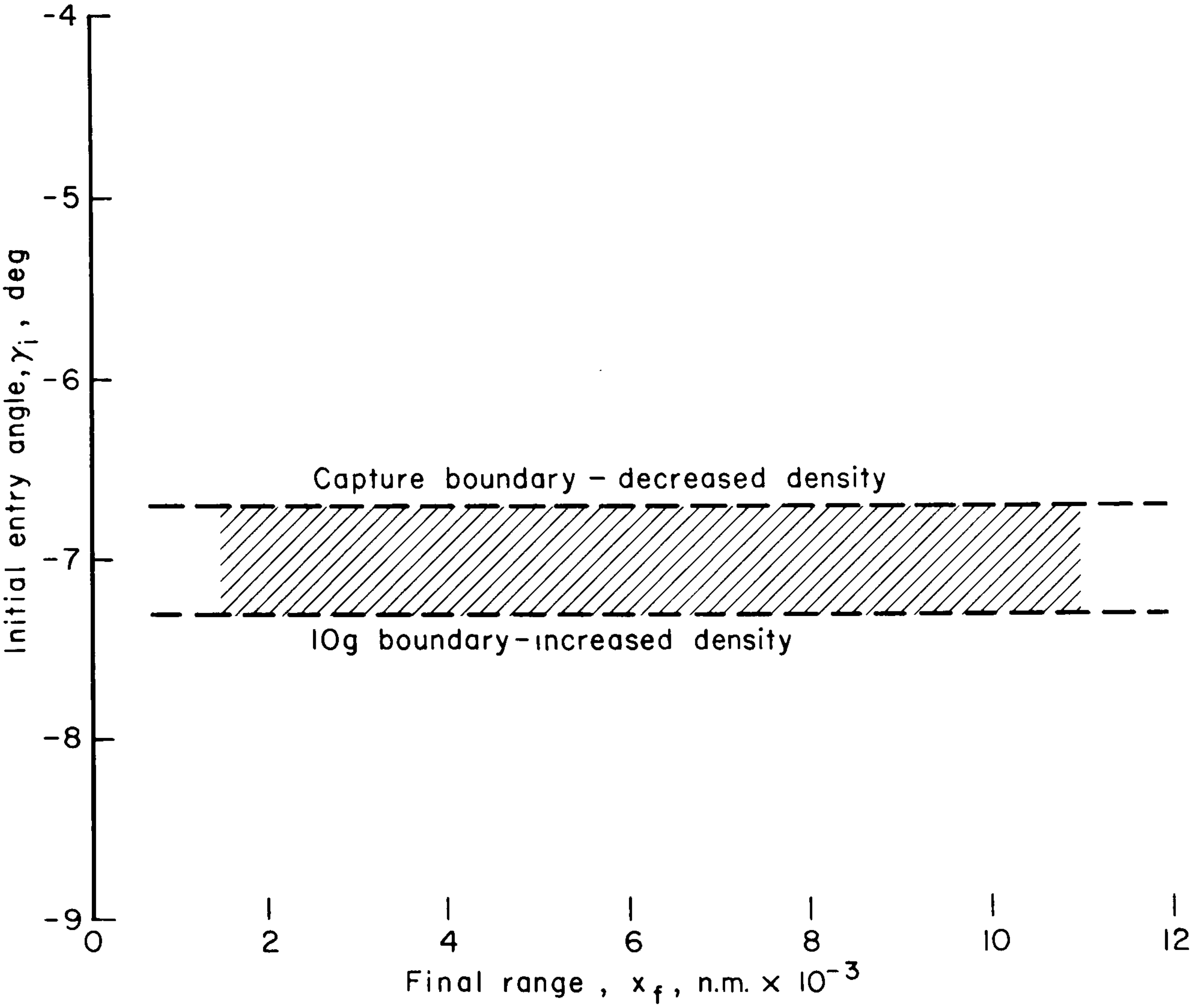
(b) V_i = 34,450 ft/sec.

Figure 13.- Continued.



(c) V_i = 40,000 ft/sec.

Figure 13.- Continued.



(d) V_i = 50,000 ft/sec.

Figure 13.- Concluded.

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