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LUNAR ORBIT RENDEZVOUS REFERENCE TRAJECTORY DATA PACKAGE (U)

PREPARED UNDER CONTRACT NO. 10001
TO BELLCOMM, INC.

PRELIMINARY APOLLO ABORT STUDY
TRAJECTORY ANALYSIS

8408-6032-RC-000 NOVEMBER 12, 1963

(NASA-CR-117263) LUNAR ORBIT RENDEZVOUS REFERENCE TRAJECTORY DATA PACKAGE (Space Technology Labs., Inc.) 186 p

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for R. M. Page, Manager
Systems Analysis Department

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TRW SPACE TECHNOLOGY LABORATORIES
One Space Park
Redondo Beach, California

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NOMENCLATURE

Parameters

A	=	azimuth
a	=	semi-major axis
DCA	=	distance of closest approach
e	=	eccentricity
h	=	altitude
i	=	inclination
P	=	period
r	=	radial distance
t	=	time; a double subscript indicates a time increment
v	=	velocity
Δv	=	abort velocity impulse
x, y, z	=	cartesian coordinates; usually earth equatorial inertial
α	=	right ascension
β	=	velocity flight path angle measured from the vertical
δ	=	declination
η	=	true anomaly
θ	=	the angle between the pre-abort and post-abort velocity vector at the abort point
λ	=	longitude
μ	=	latitude
Ω	=	position of the ascending node
ω	=	argument of perigee

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Subscripts

Note: The following subscripts have been adopted for the above set of parameters and are used where ambiguity may be possible.

a	=	apogee
b	=	abort trajectory and abort point
d	=	lunar orbit deboost
i	=	translunar injection
n	=	nominal (or reference) trajectory
p	=	perigee point
r	=	re-entry point

Trajectory Designation

A, B, ---, E	=	the pre-abort trajectories resulting from translunar injection.
M, N, ---, S	=	the pre-abort trajectories resulting from lunar orbit deboost.
1, 2, 3, ---, 8	=	abort points on the pre-abort trajectory increasing with time.

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I. INTRODUCTION AND SUMMARY

In accordance with the Bellcomm, Inc., Contract No. 10001, Space Technology Laboratories, Inc., is pleased to submit the first deliverable item associated with a preliminary Apollo abort analysis. This volume contains the complete trajectory study performed to determine the abort paths emanating from a nominal Apollo LOR trajectory during the translunar injection, translunar coast, and deboost into lunar parking orbit. The study has been limited where applicable to analyses based on analytic free flight simulation and impulsive velocity changes.

The nominal Apollo trajectory, which forms the study basis, is that generated for LOR RTDP Issue 2 (Reference 1). This trajectory is considered suitable in the present study for the following reasons:

1) It represents a practical and typical free circumlunar trajectory in the time period of interest in the Apollo program.

2) It is a numerically integrated simulation and considers all significant forces in powered and free flight. Also, powered flight optimizations have been included at both translunar injection and at deboost into the lunar parking orbit.

3) The inputs used to generate the reference trajectory are considered to be the most recent data available for the Apollo mission.

It is realized that an abort analysis on a single trajectory does not constitute a complete abort study, however, it is hoped that this study, by indicating some gross properties of abort trajectories, will aid in laying the groundwork of future analyses.

In this preliminary abort analysis, the following conditions for abort were postulated:

1) Cessation of S-IVB thrust at various times during the lunar injection maneuver. Reasons for thrust termination unknown and unimportant.

2) Unknown cause requiring an abort at points along the translunar phase of the nominal free-flight circumlunar trajectory.

3) Cessation of the Service Module thrust at various times during deboost into circular lunar orbit. Reasons for thrust termination unknown and unimportant.

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Since situations 1 and 3 represent premature cutoff of powered flight, it is clear that each cutoff time will result in a free flight trajectory with significantly different characteristics. It is then necessary to abort out of these "pre-abort" trajectories to return to the earth safely. For the parametric study, about 6 pre-abort trajectories were propagated from each of the above powered flight situations. On each pre-abort trajectory, about 6 "abort-points" were selected at which up to 15,000 feet per second impulsive velocity may be applied to return safely to earth. In the case of situation 2, several abort points on the nominal trajectory, both in the earth phase and the moon phase, were chosen for study.

The method used in this analysis has been to generate several abort trajectories from each abort point. Considering that there are approximately 80 abort points and that an average of 10 abort trajectories were found per abort point, it was necessary to generate these trajectories in an efficient manner. This was accomplished by means of two analytic programs. A discussion and accuracy of these programs are presented in Sections III.A and C.

All post-abort trajectories determined during this study have been constrained to re-enter the earth's atmosphere with a single common characteristic namely, an inertial flight path angle of 96.4 degrees at 400,000 feet altitude. A brief analysis was made using the methods of Reference (2) to determine the acceptability of this choice over the range of re-entry velocities to be expected. The result indicated that adoption of this angle does not obviously violate spacecraft physical limitations. The choice of a single angle does, however, eliminate the minor flexibility of post-abort trajectory configuration which accrues to its being a selectable quantity.

The results of this study have been presented in the form of abort trajectory characteristics at initiation and at re-entry as a function of the incremental impulsive velocity applied at the abort point. The velocity required to effect satisfactory abort trajectories has been compared with the capability of several assumed spacecraft configurations (i.e. condition and sequence of operation of stages) in order to evaluate limitations and emphasize minimum requirements.

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Aside from the detailed quantitative description of abort trajectories, an important result of this analysis has been the discovery that there are significant minimum requirements for spacecraft condition particularly with respect to returning from trajectories arising from a failure late in the hyperbolic deboost maneuver. Further description of this problem is given in Sections III.b and IV.

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II. ANALYSIS

A. Statement of the Problem

The purpose of this study has been to calculate and report the characteristics of abort paths emanating from a portion of a selected Apollo mission reference trajectory. Three phases of the mission have been considered for analysis: the S-IVB translunar injection maneuver, the nominal translunar free-flight trajectory, and the Service Module hyperbolic deboost maneuver into circular lunar orbit. Abort trajectory analysis has been made with analytic (conic and patched conic) and integrating computer programs but has been limited to study of those effects produced by impulsive velocity addition.

The role of the selected reference trajectory, which is a numerically integrated launch-to-mission completion simulation has been to provide initial conditions along a self-consistent and realistic Apollo mission designed for the lunar orbit rendezvous mode. The reference trajectory is fully documented in Reference (1) and has the following general characteristics pertinent to this study.

1) Launch from Cape Canaveral at $3^h 13^m 53.^s 12$ GMT, January 28, 1963 on an azimuth of 90 degrees.

2) Earth parking orbit at 100 n. mi. altitude of approximately two revolutions duration.

3) Outbound leg of trajectory is so designed that it circumnavigates the moon (79. 5 n. mi. pericynthion altitude) without midcourse correction and returns to earth with acceptable re-entry conditions.

4) An optimized lunar deboost maneuver from the hyperbolic approach trajectory (i = 172 deg) causes the spacecraft to enter an 80 n. mi. circular orbit which passes over an assigned landing site (3°S, 28°W).

5) Time of flight from launch to nominal pericynthion passage is $2^d 20^h 37.^m 2$.

As used in this study, an abort trajectory associated with a powered flight maneuver is understood to be composed of two parts: "pre-abort"

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and "post-abort" (or simply abort). The pre-abort trajectory is the free-flight path following premature powered flight cessation. As this pre-abort trajectory is propagated forward in time, various points are chosen at which to initiate return to earth. The paths returning safely to earth from these points are called post-abort trajectories. In the case of abort from the nominal translunar free-flight trajectory, all paths are of the post-abort variety.

Aside from a number of constraints and groundrules attending the basic reference trajectory, there are some specific groundrules in effect for this study.

1) All post-abort trajectories are determined by the application of an instantaneous velocity vector change.

2) All post-abort trajectories are constrained to have an inclination to the earth's equator equal to or less than 40 degrees.

3) All post-abort trajectories requiring more than 15,000 ft/sec initial velocity addition (or about 6000 ft/sec for paths initiated after hyperbolic deboost failures) or resulting in a re-entry velocity greater than 40,000 ft/sec have been neglected.

4) All post-abort trajectories must result in safe re-entry.

With regard to the last item, all abort trajectories determined during this analysis have been constrained to re-enter the earth's atmosphere with a single common characteristic namely, an inertial flight path angle of 96.4 deg at 400,000 ft altitude. Since this condition is forced to exist independent of other dynamical characteristics such as entry velocity, latitude, longitude, and azimuth, the applicability of such a choice was examined. From studies made, in support of Reference (1), with an integrating computer program using a complete force model, it was found that this angle produces acceptable atmospheric deceleration levels over a wide range of re-entry maneuver angles for a near parabolic re-entry velocity and suitable ranges of the other parameters. To substantiate the usefulness of this single angle for lesser values of entry velocity, data were generated for skip and initial deceleration pulse boundaries (by the methods of Reference 2)

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in effect with the presently stated CM configuration (i. e., $W/C_D A = 57$ lbs/ ft^2, $L/D = 0.4$ max). These data are plotted in Figure 1 and show, in general, that the higher the entry velocity the narrower the re-entry corridor but that $\beta = 96.4$ deg is everywhere acceptable. The effects on this corridor of other variable re-entry quantities were not investigated but previous work in this connection for near parabolic entries suggests that no compromise is necessary.

The influence of omitting re-entry flight path angle as other dimension for the study results was examined cursorily. However, it was found that a ± 1 deg variance about the nominal has very minor effects on both re-entry position and abort trajectory configuration especially for aborts initiated at distances greater than a few earth radii. It's omission from the study at this time was essentially a study ground rule similar in intent to the neglect of non-impulsive effects.

Finally, in order to evaluate the abort velocity requirements in terms of spacecraft performance and configuration, a number of configurations were assumed and their impulsive velocity capabilities have been listed in sub-sections II. C and II. D. Prior to hyperbolic deboost, and assuming all spacecraft stages to be operable, nearly 15,000 ft/sec is available for an abort velocity impulse. However, with Service Module failure during hyperbolic deboost, its remaining capability is lost and the abort velocity impulse available from the LEM alone drops to less than 6000 feet per second. The propellant specific impulse levels and weight data were taken from Reference (1).

B. Abort Geometry

A large part of the abort study is concerned with aborts in the vicinity of the earth. The class of trajectories which are considered to lie in this category is that in which neither the pre-abort nor about trajectory has penetrated the moon's sphere of action (MSA).* With this constraint it is possible to approximate the gravitational model by the earth's inverse

*In the present study this is taken to be a hypothetical sphere centered at the moon having a radius of about 10 earth radii.

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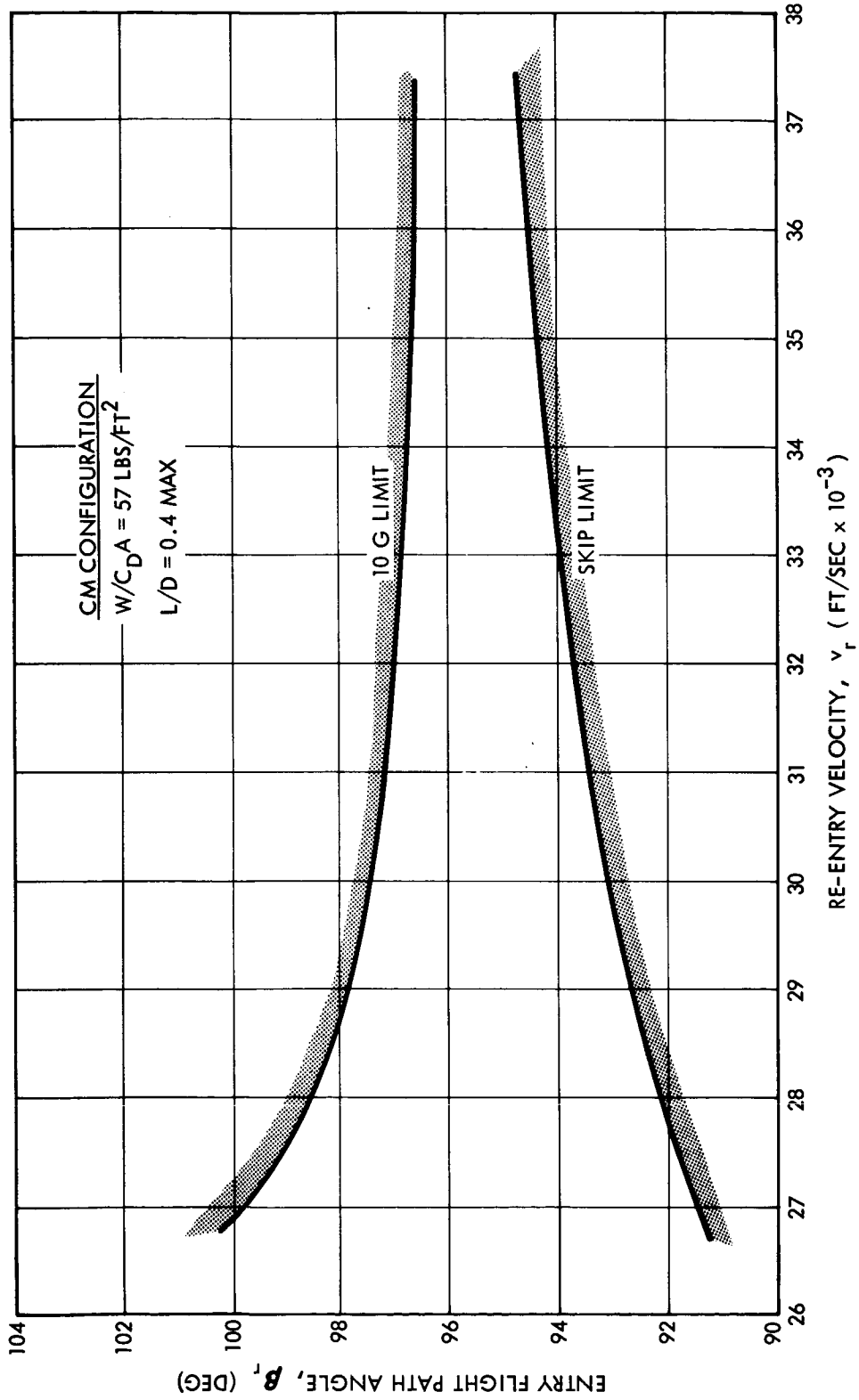

Figure 1. Re-entry Corridor

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square force field alone.[+] Thus all free flight portions of the pre-abort and abort trajectories will be conic sections.

Working within the framework of this model, it is next necessary to consider the abort trajectories which are possible for each abort point. The only condition which has been directly imposed on the abort conic is the prescribed re-entry altitude and flight path angle. Referring to Figure 2 it is seen that, at each abort point, there are four possible abort trajectories which have a single final velocity, v, and which lie in the same plane. Of the four conics, two will be directed towards the earth and the other two away from the earth. Also two of the trajectories will have the same inclination to the earth's equator and two will have the supplement of this inclination (i.e., two will be direct at identical inclinations and two will be retrograde at identical inclinations).

In addition to these possibilities there are the out-of-plane considerations. This is shown more clearly in Figure 3. If the dotted curve represents the trace of the pre-abort trajectory on an earth centered inertial unit sphere, then the above four abort possibilities will lie in that plane. If, however, the retrograde possibilities are neglected, it is still possible to abort into four out-of-plane trajectories having a single inclination i, as shown by traces (1) and (2). Viewed in this manner there are two possible trajectory planes, having inclination i, in each of which the two direct abort trajectories may lie with the abort velocity either pointing away from the earth, or towards the earth. The two inclination possibilities are distinguished by the fact that at the abort point the azimuth A will be either less than 90 degrees (directed away from the equatorial plane) or greater than 90 degrees (directed towards the equatorial plane). These azimuths are indicated in Figure 3 by A_1 and A_2 respectively.

With the above introduction it is now possible to discuss the general characteristics of all possible abort trajectories from a given point. Referring to Figure 1, it is clear that all possible abort trajectories for a given

[+] A comparison of the errors involved in this assumption is made in Section III.

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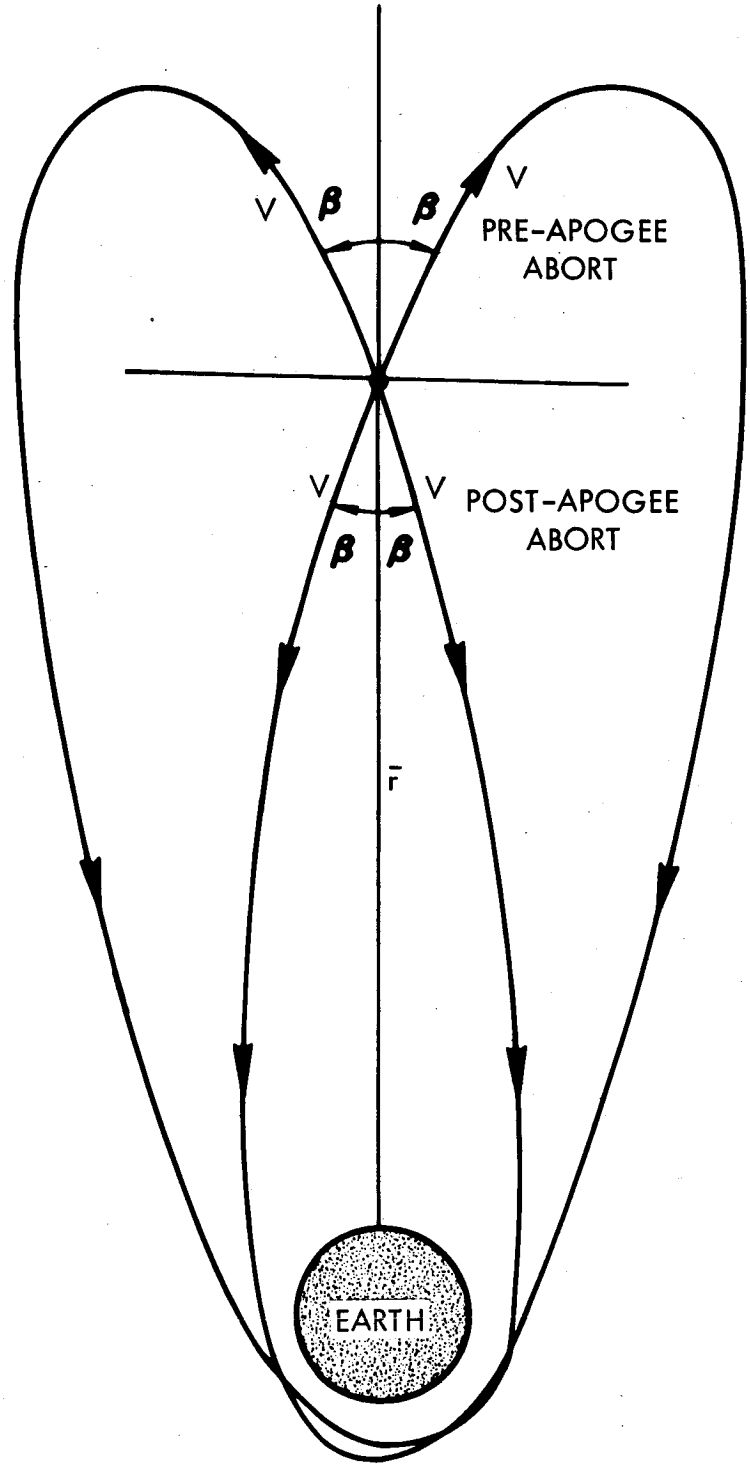

Figure 2. Abort Point Geometry for Planar Aborts

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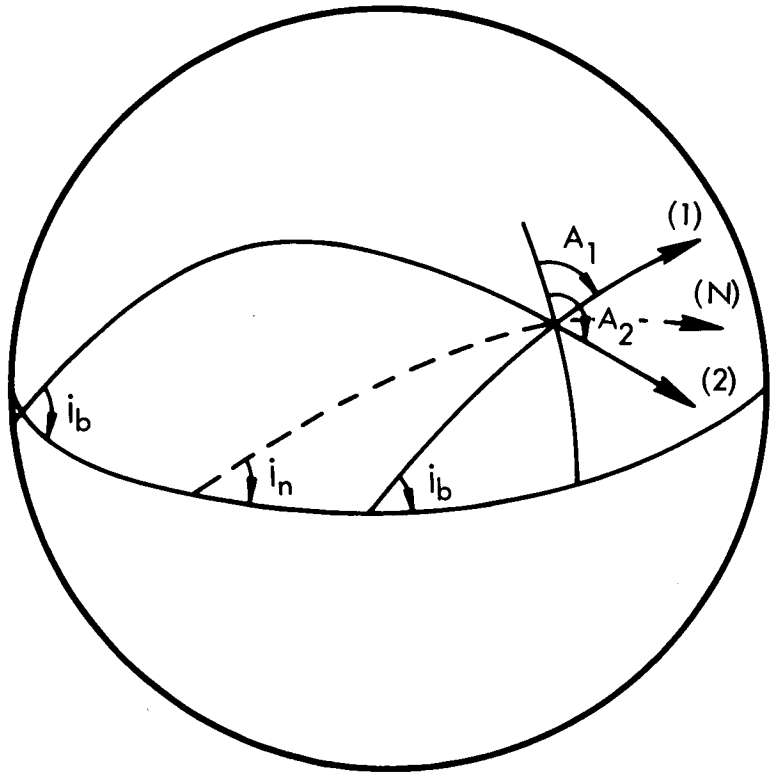

Figure 3. Out-of-Plane Aborts

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abort velocity v may be generated by rotating the conic shown about the radius vector $\bar{r}$. At the abort point the velocity $\bar{v}$ will generate a cone whose central angle is 2β where β is the abort flight path angle. Such a cone will be generated for each value of v chosen. A polar plot of v versus β is shown in Figure 4 for a typical abort point, remembering that the desired re-entry altitude and flight path angle are satisfied. Figure 4 is informative for several reasons. First, note that the velocity magnitude is a minimum when β is near 90 degrees. The reason that this is so becomes clear when one realizes that the perigee distance of all the conics satisfying the desired re-entry conditions do not differ appreciably from each other. Thus, an angle β of 90 degrees implies that the abort point is at the apogee of the abort conic. This results in a minimum major axis, and hence a minimum energy and velocity. As β moves away from 90 degrees, the velocity will increase until the conic becomes hyperbolic, i.e., eccentricity greater than one. At this point, the trajectories heading away from the earth will not return whereas those heading towards the earth with eccentricities greater than one are acceptable. The shaded region indicates that no possible velocity will result in a satisfactory conic for these values of β.

Figure 4 includes the effects of restrictions on flight path angle due to the invariant re-entry conditions, however, physical constraints further limit the range of β. These constraints are shown in Figure 5 for three abort points on the nominal translunar trajectory. The lower limit on β is due, as shown in Figure 4, to the fact that eccentricity becomes equal to unity. Since the nominal trajectory is also nearly parabolic, the direction of v is very close to the pre-abort direction of motion. The upper limit on β for all three distances is due to the limited propulsion capability to abort i.e., $\Delta v < 15,000$ feet per second. It is interesting to note from this figure that the range of β increases as the abort distance becomes greater. This behavior is due to two factors. The lower limit on β (velocity directed away from the earth) decreases because the abort conic eccentricities must be greater for greater abort point distances and hence β will be smaller. These eccentricities are greater since the abort perigee

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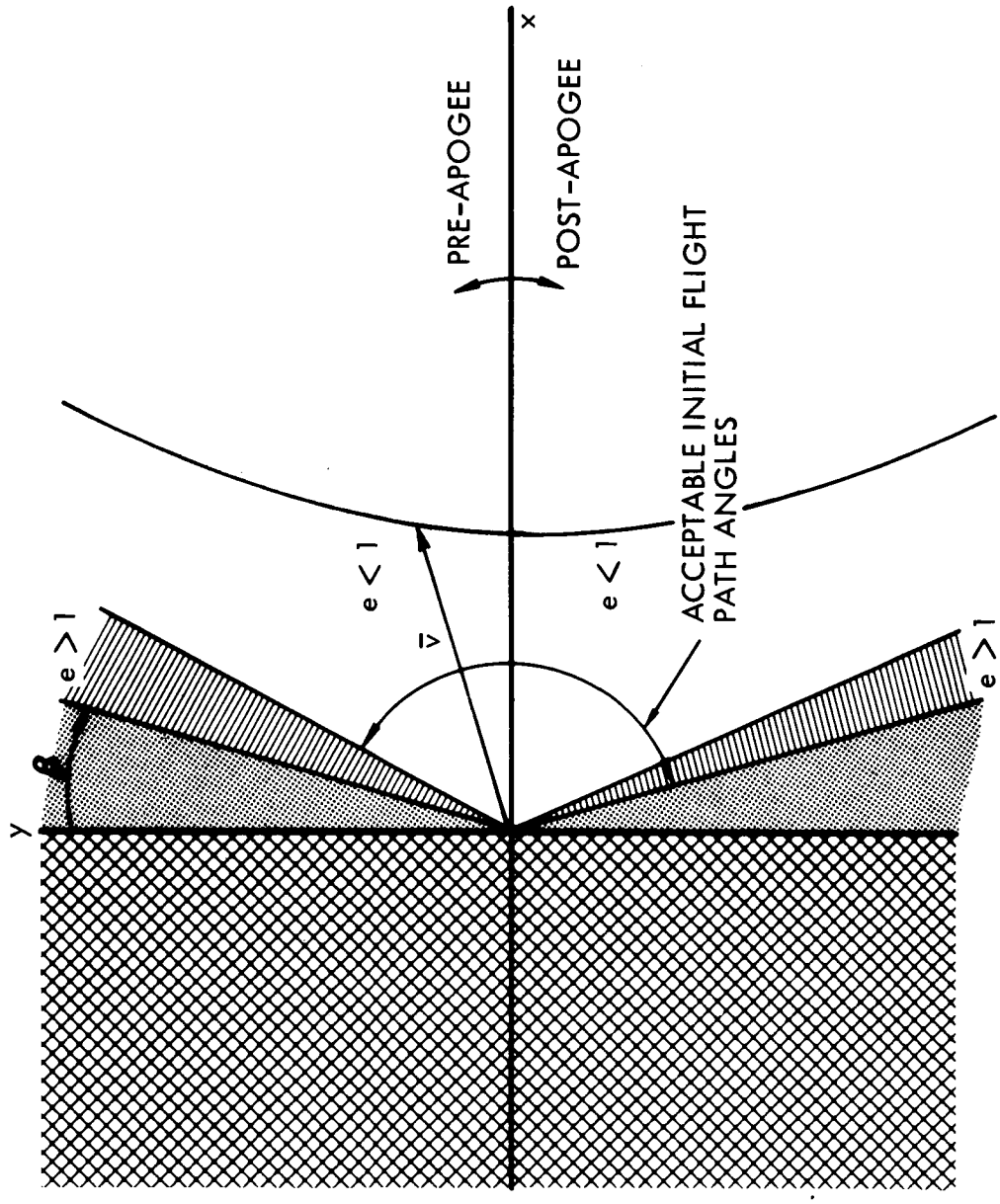

Figure 4. Abort Conic Flight Path Angle and Velocity Possibilities Schematic

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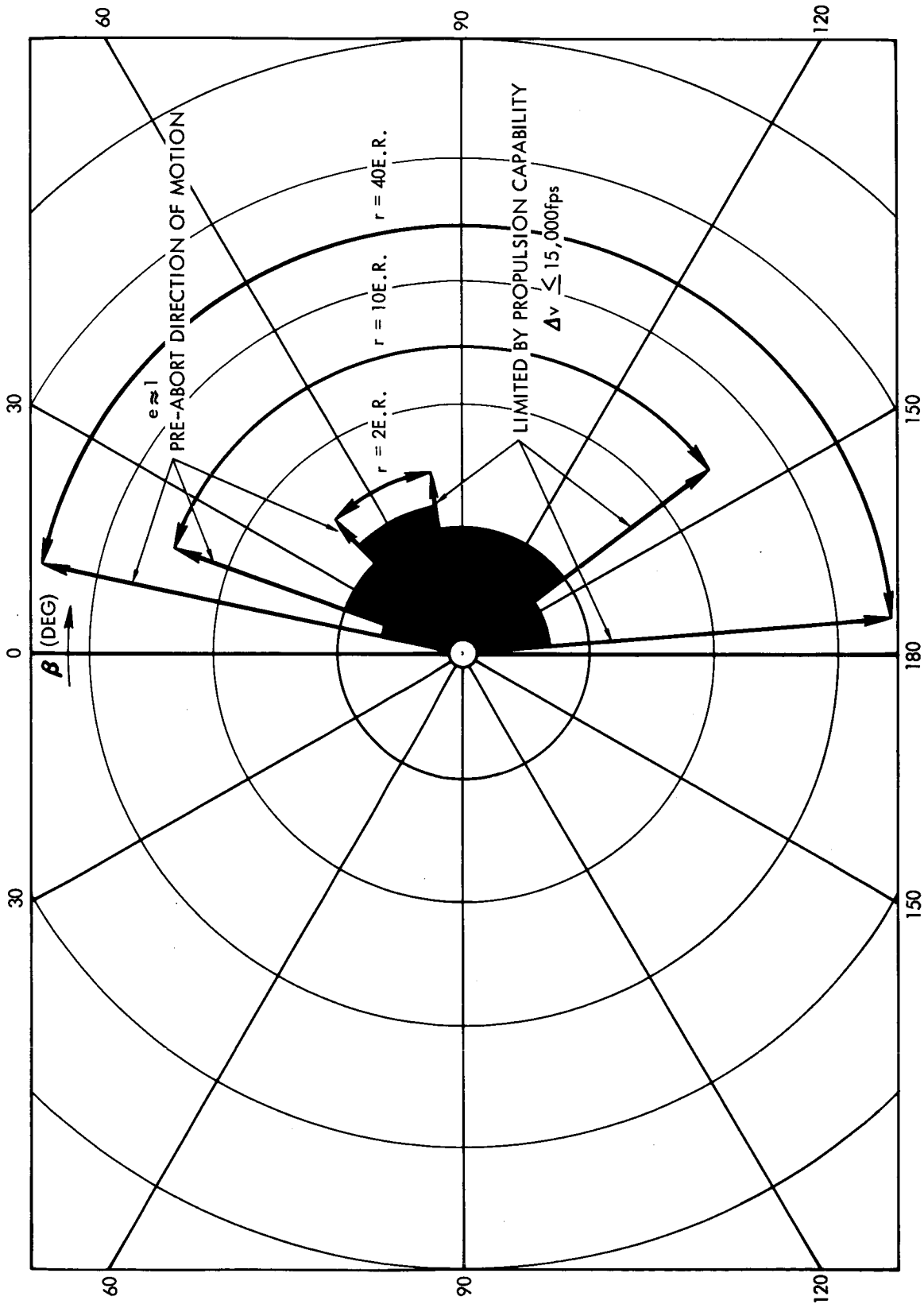

Figure 5. Range of Abort Flight Path Angles versus Abort Point Distance - Nominal Translunar Trajectory

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distance is nearly constant whereas the apogee of the abort conic must be greater than the distance to the abort point. The upper limit on β (velocity directed towards the earth) involves the limitation on Δv. Since the velocity along the nominal trajectory is much smaller for greater abort distances, the ability of the fixed maximum Δv to change the direction of v becomes more pronounced. Hence, the permissible values of β will increase for greater abort distance.

The requirements on Δv which will result in specific values of β are shown in Figure 6 for various abort points along the nominal translunar trajectory. Also shown are the directions of the nominal trajectory velocities existing at each abort distance. As indicated above, the velocity (now in terms of Δv applied) becomes greater as β is allowed to increase. This graph includes the return times of flight (in hours) for each abort choice.

An observation may now be made concerning the nature of the problem when the magnitude of the abort velocity impulse Δv remains fixed as opposed to the previous discussion of fixed resultant abort velocity. In this case it is necessary to add this impulse to the spacecraft pre-abort velocity vector and to aim it in a specific direction which will permit the spacecraft to return safely to earth. For the in-plane situation, the addition of velocities is shown in Figure 7. The velocity impulse may be aimed at any point on the circle shown and the resultant velocity vector will be from N to that point (e.g. point P). Referring back to Figure 4, it is clear that solutions which will cause the spacecraft to return safely to earth will lie on a dotted curve somewhat like that shown in Figure 7. The intersections of this curve with the circle represents points for which the Δv has both the desired magnitude and direction and the spacecraft returns safely. Note that at most two solutions are possible and that at both solutions $\bar{v}$ may be directed towards the earth, or directed away from the earth (the case shown in Figure 7), or one toward and one away from the earth. The existence of these different possibilities is evident in the results given in Section III. Also, if the Δv circle is such

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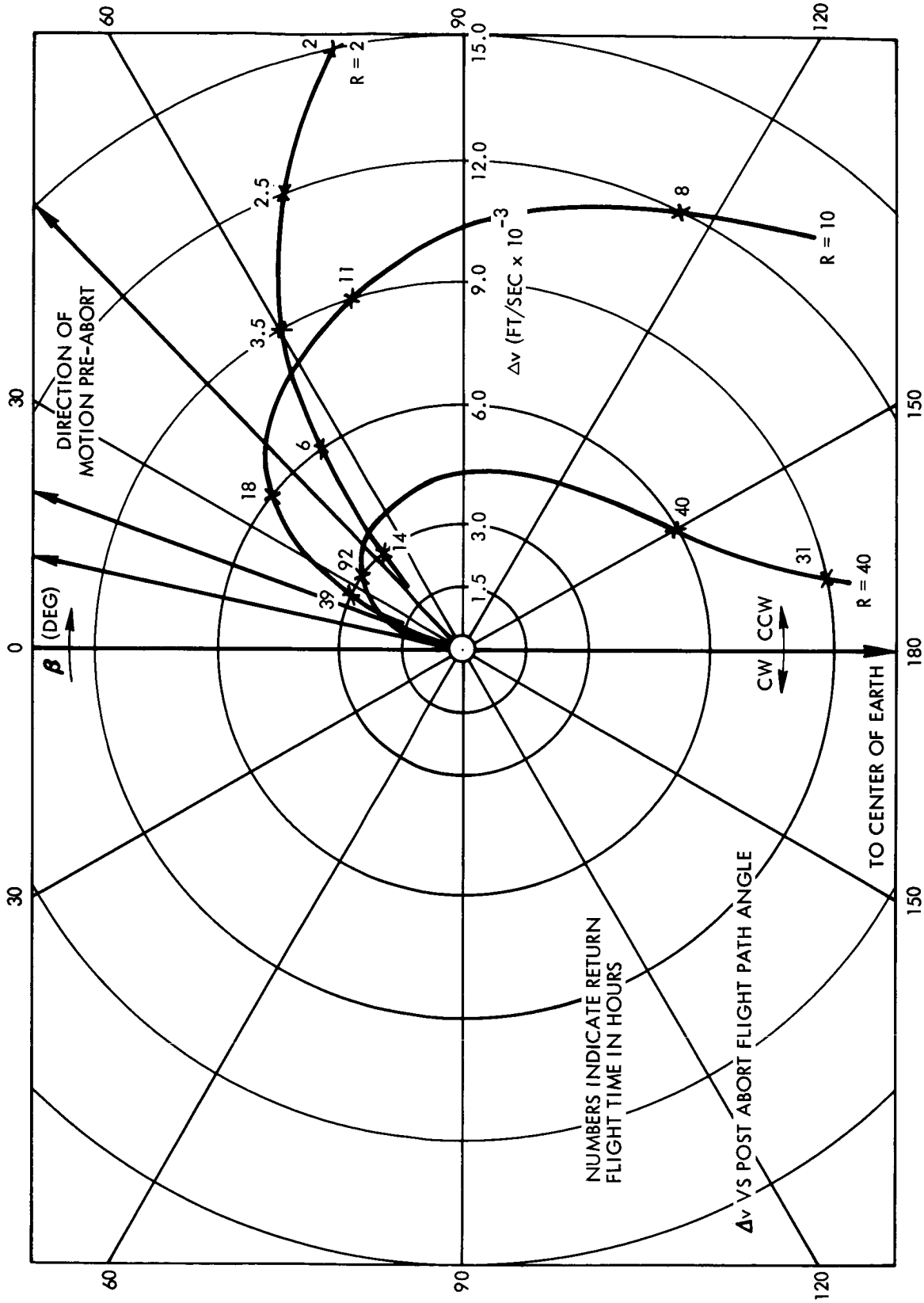

Figure 6. Abort Flight Path Angle versus Abort Velocity Impulse (Δv) for Three Abort Point Distances - Nominal Translunar Trajectory

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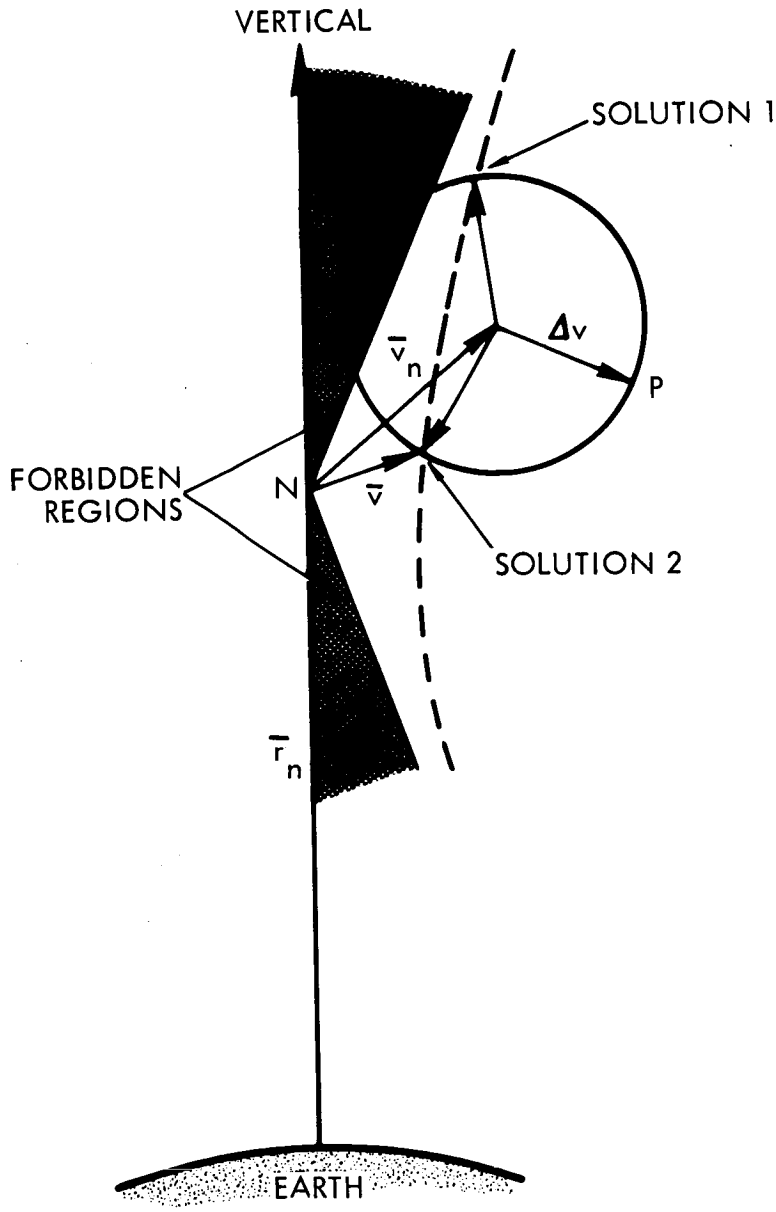

Figure 7. Permissible Vector Addition of the Pre-abort Velocity and the Abort Velocity Impulse

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that it does not intersect the dotted curve, there will be no solution. It is also possible that an intersection may be in a forbidden region in which case the physical constraint is violated resulting in no solution.

The out-of-plane case is no more difficult to analyze. This situation implies that the pre-abort velocity vector $\bar{v}_n$ lies in a different trajectory plane than the abort velocity vector $\bar{v}$. For impulsive thrust, both will contain the radius $\bar{v}_n$. The out-of-plane case can then be thought of as a rotation abort $\bar{r}_n$ from one plane to the other. Since the abort velocity impulse can now be fired out-of-plane, it can reach out to any point on a sphere of radius Δv whose center is at the tip of the $\bar{v}_n$ vector. If this sphere intersects the abort plane, the intersection will be a circle. The important thing to note here is that only directions of Δv which lie on this intersection will result in a vector $\bar{v}$ which lies in the desired abort plane. Therefore the problem reduces to the in-plane case where now the radius of the Δv circle is that of the intersection circle. Physically Δv can be thought of having an out-of-plane component emanating from the tip of the $\bar{v}_n$ vector to the center of the intersection circle. For a solution, Δv must be at least as large as the out-of-plane component required to change planes.

The analysis of abort from a point within the moon's sphere of action (MSA) is quite different than that for near earth aborts. The first observation which may be made is that since the moon is now the central gravitational body, the pre-abort path will lie in the trajectory plane containing the center of the moon but not necessarily the center of the earth. Thus, whereas in-plane aborts always exist for near earth aborts, they will not always exist for MSA aborts. This implies that an out-of-plane impulse will usually be necessary to return to earth. Further, the amount of plane change required will most likely vary as the time of the abort maneuver is changed. The complexity of this situation makes it difficult at the outset to analyze MSA aborts as thoroughly as near earth aborts. Although such an analysis will not be attempted here, several general observations will be made in subsection III.B of the results.

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C. Translunar Injection Pre-abort Trajectories

In order to perform the abort study, it is first necessary to examine the characteristics of the free flight trajectories resulting from premature cutoff of the S-IVB during translunar injection. These characteristics are presented in Figure 8 as a function of burn time and in the form of conic elements in Table I. As expected, the principal changes are in the eccentricity and the semi-major axis. The eccentricity increases at nearly a constant rate to the reference value of 0.979. The semi-major axis also increases but it is interesting to note that essentially all of the change occurs in the last minute of burn. Variations in inclination and the position of the ascending node are about 0.02 degrees whereas the argument of perigee varies by approximately 10 degrees.

Figure 9 shows an expanded scale for the growth of the semi-major axis and the eccentricity for the final three seconds of burn. The principal observation is that the semi-major axis nearly doubles during this time. This change is equivalent to an increase in apogee from approximately half of the lunar distance to the complete distance to the moon. Correspondingly, Figure 10 indicates the resultant history of closest approach distance of the spacecraft to the moon. These values were generated by numerical integration of eight trajectories evolving from premature cutoffs during the last three seconds of burn. Coordinate position plots of these trajectories are shown in Figures 11 and 12. The coordinate system used is the inertial earth equatorial true of date system. The dotted lines show the position of the moon and the spacecraft at the time of closest approach. The earlier trajectory does not quite reach the moon whereas the next four approach the moon from the trailing edge and in a counterclockwise manner. The last second of burn causes the trajectories to sweep across the moon's face, with impacts, until finally the reference trajectory, and clockwise motion, is generated. Note that it is not until the final 0.025 seconds of burn that the free flight trajectories take on the general characteristics of a free return trajectory.

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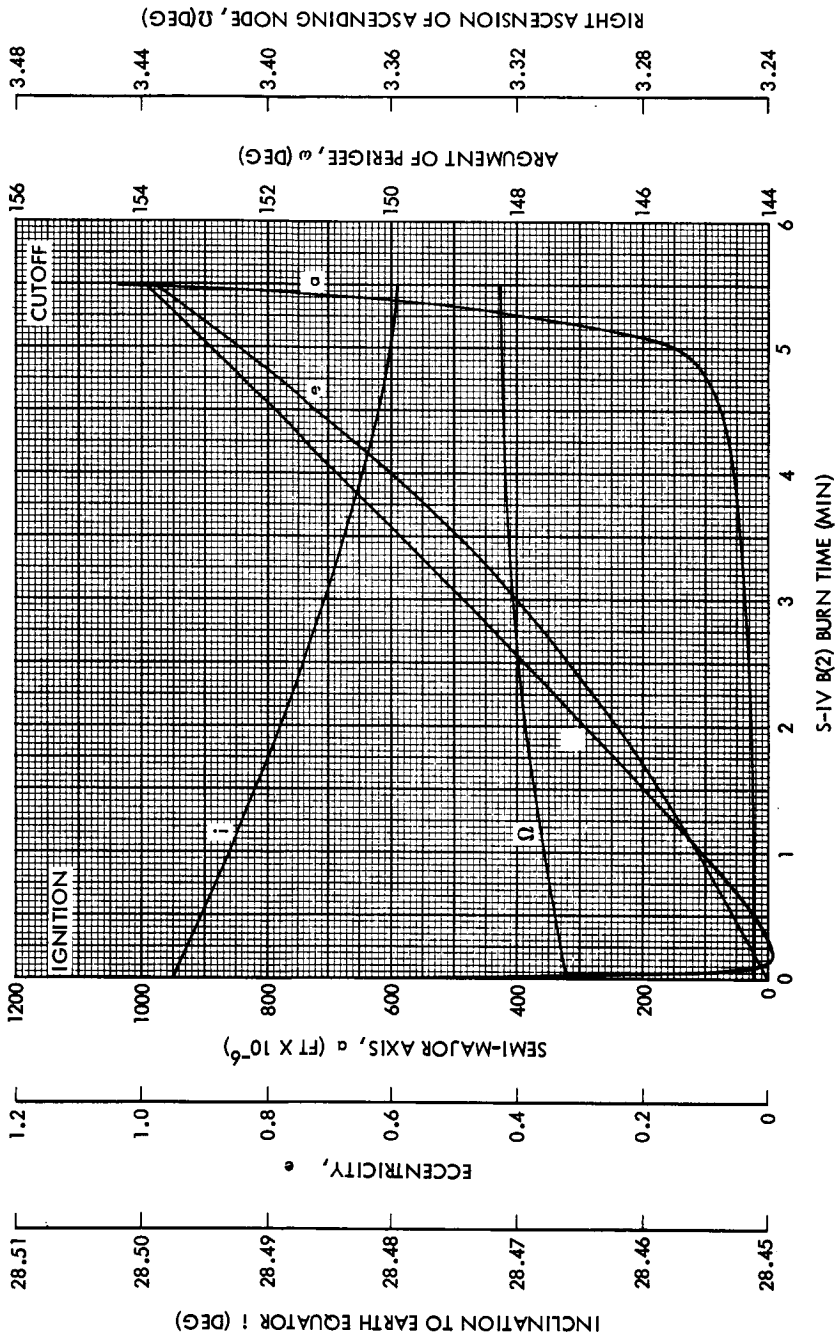

Figure 8. Osculating Orbit Elements as a Function of S-IVB Translunar Injection Burn Time

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TABLE I PRE-ABORT TRAJECTORIES AND CHOSEN ABORT POINTS

Pre-abort Trajectory A

Time to go in S-IVB second burn = 270 sec.

Orbital Elements

a	$= 24.17 \times 10^6$ ft	ω	$= 145.1^\circ$
e	$= .109$	h_p	$= 100.4$ n mi
i	$= 28.49^\circ$	h_a	$= 971.2$ n mi
Ω	$= 3.31^\circ$	P	$= 104.9$ min

Chosen Abort Points

	A1	A2	A3	A4
t_{ib} (hrs)	0.50	0.75	1.24	1.59
η (deg)	115	159	255	321
r (ft x 10^{-6})	25.0	26.6	25.0	22.0
α (deg)	262.2	311.2	301.8	111.6
δ (deg)	-28.0	-23.2	13.8	27.3
v (ft/sec)	23,277	21,815	23,277	26,404
β (deg)	84.1	87.5	95.9	93.6
A (deg)	95.3	73.0	64.8	98.6
Long.(deg)	30.9	76.2	147.7	223.9
Lat.(deg)	-28.0	-23.2	13.8	27.3

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TABLE I (Continued)

Pre-abort Trajectory B

Time to go S-IVB second burn = 210 sec.

Orbital Elements

a	$= 28.44 \times 10^6$ ft	ω	$= 146.9^\circ$
e	$= .243$	h_p	$= 100.7$ n mi
i	$= 28.49^\circ$	h_a	$= 2378.8$ n mi
Ω	$= 3.32^\circ$	P	$= 133.9$ min

Chosen Abort Points

	B1	B2	B3	B4	B5	B6
t_{ib} (hrs)	0.50	0.76	1.01	1.51	1.71	2.12
η (deg)	110	137	170	223	250	333
r (ft x 10^{-6})	29.2	32.5	35.2	32.5	29.2	22.0
α (deg)	258.6	288.6	324.1	12.5	36.7	126.3
δ (deg)	-27.7	-27.6	-18.9	4.9	16.6	24.5
v (ft/sec)	21,662	19,270	17,461	19,270	21,662	28,014
β (deg)	76.0	78.5	86.9	101.5	104.0	95.2
A (deg)	97.0	82.8	68.3	61.9	66.5	105.0
Long. (deg)	27.1	54.0	85.0	125.7	147.0	230.4
Lat. (deg)	-27.7	-27.6	-18.9	4.9	16.6	24.5

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TABLE I (Continued)

Pre-abort Trajectory C

Time to go in S-IVB second burn = 150 sec.

Orbital Elements

a	$= 36.10 \times 10^6$ ft	ω	$= 148.8^\circ$
e	$= .404$	h_p	$= 102.0$ n mi
i	$= 28.49^\circ$	h_a	$= 4898.8$ n mi
Ω	$= 3.32^\circ$	P	$= 191.5$ min

Chosen Abort Points

	C1	C2	C3	C4	C5	C6
t_{ib} (hrs)	0.50	0.80	1.47	2.35	2.65	3.09
ψ (deg)	106	134	174	226	254	338
r (ft x 10^{-6})	34.0	42.0	50.5	42.0	34.0	22.0
α(deg)	256.2	287.9	329.8	16.4	42.5	133.5
δ (deg)	-27.4	-27.7	-16.7	7.0	18.9	22.5
v (ft/sec)	20,932	16,745	12,945	16,745	20,932	29,829
β (deg)	66.4	68.0	86.1	112.0	113.6	96.3
A (deg)	98.1	83.1	66.6	62.3	68.3	107.9
Long. (deg)	24.4	51.6	83.5	116.8	138.4	222.7
Lat. (deg)	-27.4	-27.7	-16.7	7.0	18.9	22.5

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TABLE I (Continued)

Pre-abort Trajectory D

Time to go in S-IVB second burn = 90 sec.

Orbital Elements

a	=	58.84×10^6 ft	ω	=	150.8°
e	=	.600	h_p	=	104.7 n mi
i	=	28.48°	h_a	=	10733.7 n mi
Ω	=	3.32°	P	=	348.7 min

Chosen Abort Points

	D1	D2	D3	D4	D5	D6
t_{ib} (hrs)	0.50	1.43	2.63	4.32	5.25	5.72
η (deg)	102	148	175	212	258	341
r (ft x 10^{-6})	39.5	70.0	85.7	70.0	39.5	22.0
α (deg)	254.2	305.2	332.8	6.0	48.2	138.8
δ (deg)	-27.1	-24.7	-15.4	1.4	21.0	20.8
v (ft/sec)	21,243	11,863	8,188	11,863	21,243	31,910
β (deg)	56.1	57.0	83.1	123.0	123.9	97.1
A (deg)	99.0	75.4	65.7	61.6	70.3	109.9
Long. (deg)	22.2	59.2	68.6	76.4	104.7	188.2
Lat. (deg)	-27.1	-24.7	-15.4	1.4	21.0	20.8

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TABLE I (Continued)

Pre-abort Trajectory E

Time to go in S-IVB second burn = 30 sec.

Orbital Elements

a	=	140.73×10^6 ft	ω	=	152.9°
e	=	.847	h_p	=	109.7 n mi
i	=	28.48°	h_a	=	39331.4 n mi
Ω	=	3.33°	P	=	1473.6 min

Chosen Abort Points

	E1	E2	E3	E4	E5	E6
t_{ib} (hrs)	0.50	5.27	11.84	19.22	24.00	24.48
η (deg)	98	161	179	199	261	343
r (ft x 10^{-6})	45.4	200.0	259.7	200.0	45.4	22.0
α (deg)	252.2	321.0	338.3	356.2	54.4	143.3
δ (deg)	-26.8	-20.1	-12.9	-3.9	22.9	19.2
v (ft/sec)	22,806	6,383	2,895	6,383	22,806	34,346
β (deg)	46.3	35.9	84.8	144.1	133.7	97.6
A (deg)	100.0	69.4	64.4	61.8	72.6	111.4
Long. (deg)	200.2	17.0	295.5	202.3	188.7	270.4
Lat. (deg)	-26.8	-20.1	-12.9	-3.9	22.9	19.2

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TABLE I (Continued)

Nominal Translunar Free Return Trajectory

Time to go in S-IVB second burn = 0 sec.

Orbital Elements

a	= 1033.8×10^6 ft	ω	= 153.901°
e	= .97911	h_p	= 113.0 n mi
i	= 28.480°	h_a	= 333295 n mi
Ω	= 3.325°	P	= 29339.4 min

Chosen Abort Points

	r = 2 (E.R.)	5	10	15	20	30	40
t_{ib} (hrs)	0.39	1.48	3.92	7.07	10.87	20.35	32.38
η (deg)	88.7	127.2	144.4	152.0	156.6	162.3	166.1
α (deg)	242.8	285.9	304.9	312.8	317.5	323.2	326.7
δ (deg)	-25.0	-27.9	-24.8	-22.7	-21.2	-19.2	-17.9
v (ft/sec)	25,678	15,974	10,976	8,695	7,292	5,548	4,436
β (deg)	46.3	27.7	19.8	16.5	14.7	12.8	11.9
A (deg)	104.0	84.0	75.5	72.3	70.6	68.6	67.5
Long. (deg)	12.1	38.8	21.1	341.6	289.2	152.3	334.8
Lat. (deg)	-25.0	-27.9	-24.8	-22.7	-21.2	-19.2	-17.9

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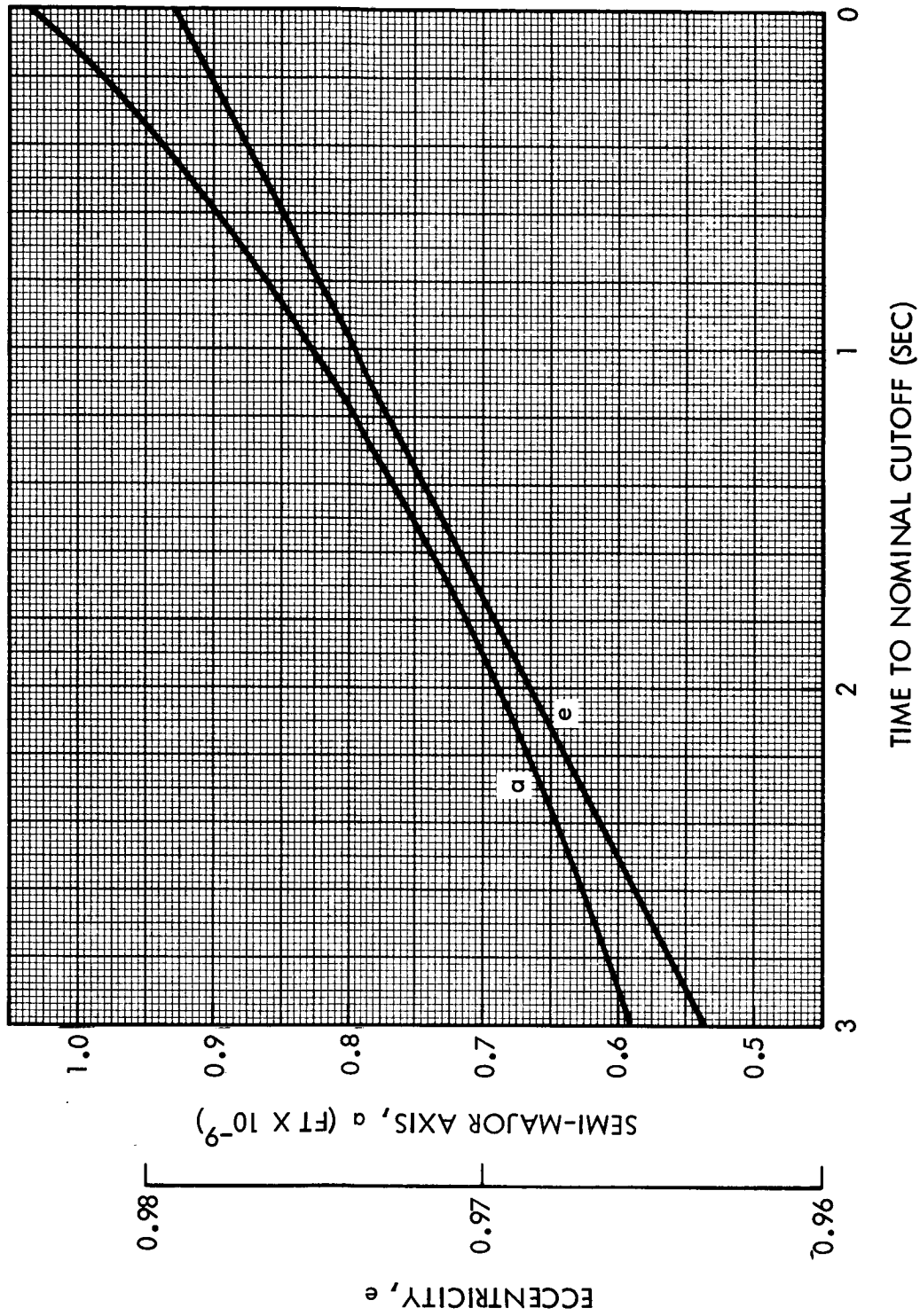

Figure 9. Semi-major Axis and Eccentricity versus Time to Go in S-IVB Injection Maneuver

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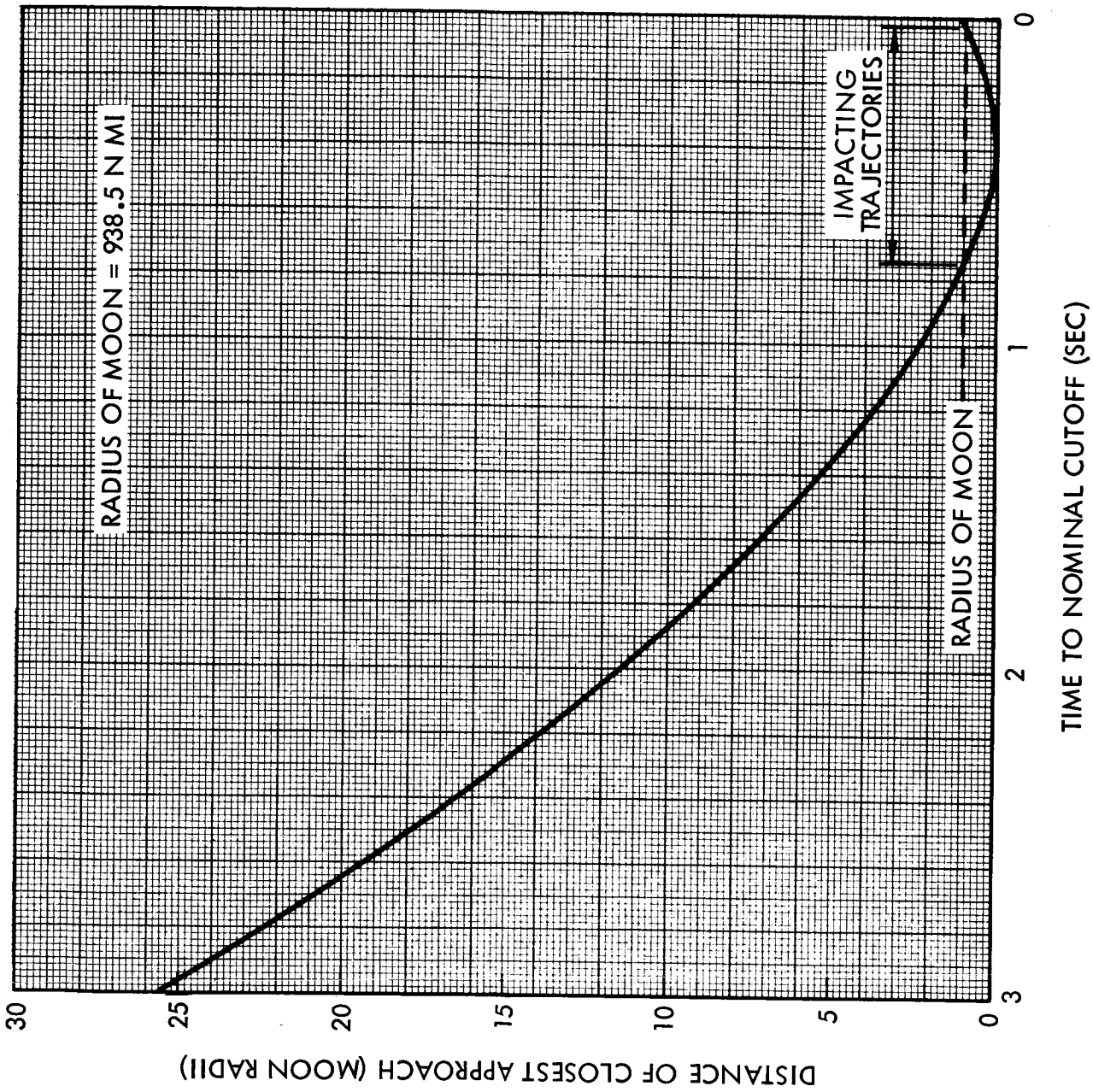

Figure 10. Distance of Closest Approach to Moon versus Time to Go in S-IVB Injection Maneuver

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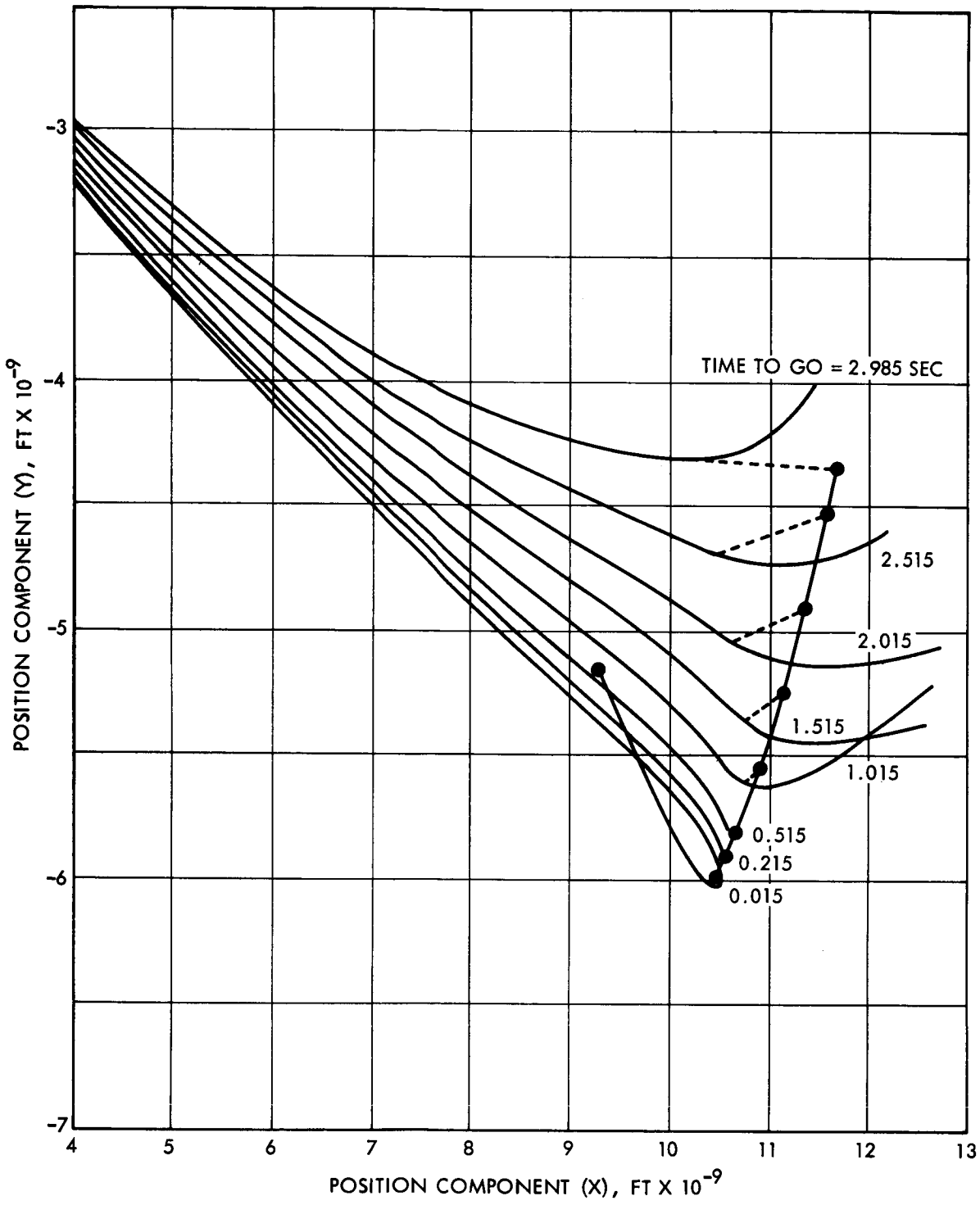

Figure 11. Pre-abort Trajectory Behavior in the Moon's Vicinity as a Function of S-IVB Burn Time Remaining

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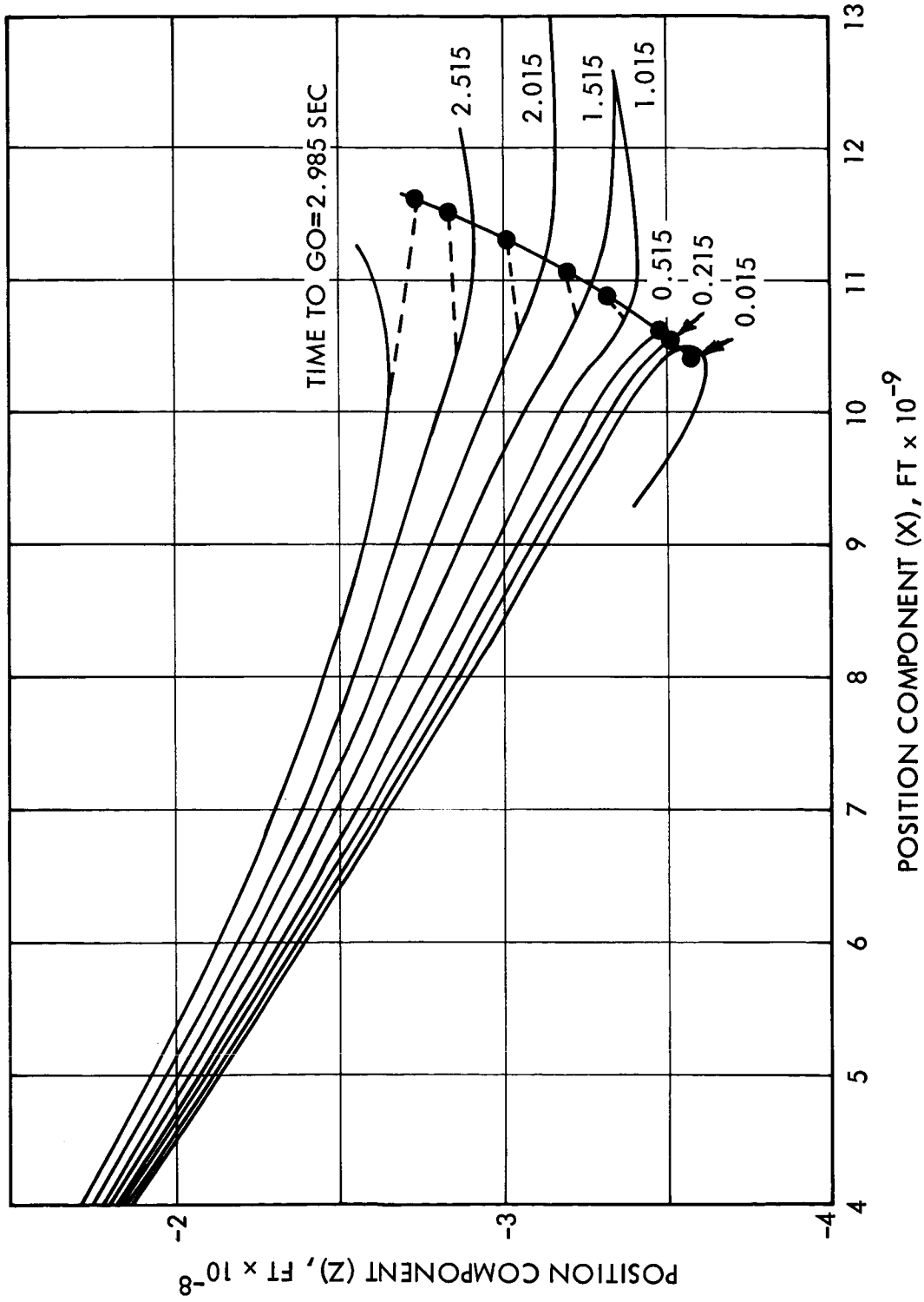

Figure 12. Pre-abort Trajectory Behavior in the Moon's Vicinity as a Function of S-IVB Burn Time Remaining

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With the general behavior of pre-abort trajectories evolving from premature cutoff of the S-IVB described, several specific cases were chosen for the parametric analysis. At five times during the S-IVB injection maneuver, corresponding to each minute of burn, points were chosen for the propagation of pre-abort trajectories. These trajectories are designated A, B, C, D, and E followed by the nominal translunar free return trajectory, and are so noted in the results. On each of these trajectories, six points were taken in systematic progression around the orbit. These abort points carry the double notation of A3, A4, ..., for example, to identify the trajectory as well as the abort point in question. Points on the nominal translunar trajectory are identified by their radial distance from earth. The general arrangement of pre-abort trajectory and abort point selection is shown in Figure 13 drawn to scale. Further quantitative detail is given in Table 1. All results contained in Section III are keyed to the letter/number identification system.

Since all results have abort velocity impulse as the argument, several different spacecraft configurations were postulated and their Δv capabilities calculated for comparison with velocity demand. Table II lists the applicable spacecraft weight and propulsion system data as taken from Reference (1). Table III enumerates the various assumed configurations and gives the impulsive velocity increments available from each stage.

D. Hyperbolic Deboost Pre-abort Trajectories

The orbital characteristics (semi-major axis and eccentricity) of the free flight trajectories resulting from cessation of the SM engine thrust during the hyperbolic deboost phase are presented in Figure 14. It is of interest to note that for the first 109 seconds of deboost the resulting trajectories retain lunar escape characteristics (for $e < 1$ still escape). A numerically integrated set of free flight trajectories were simulated for this time period. Figure 15, which shows the distance of closest approach to the earth as a function of hyperbolic deboost burning time, was generated from these trajectories. It can be seen that, if no

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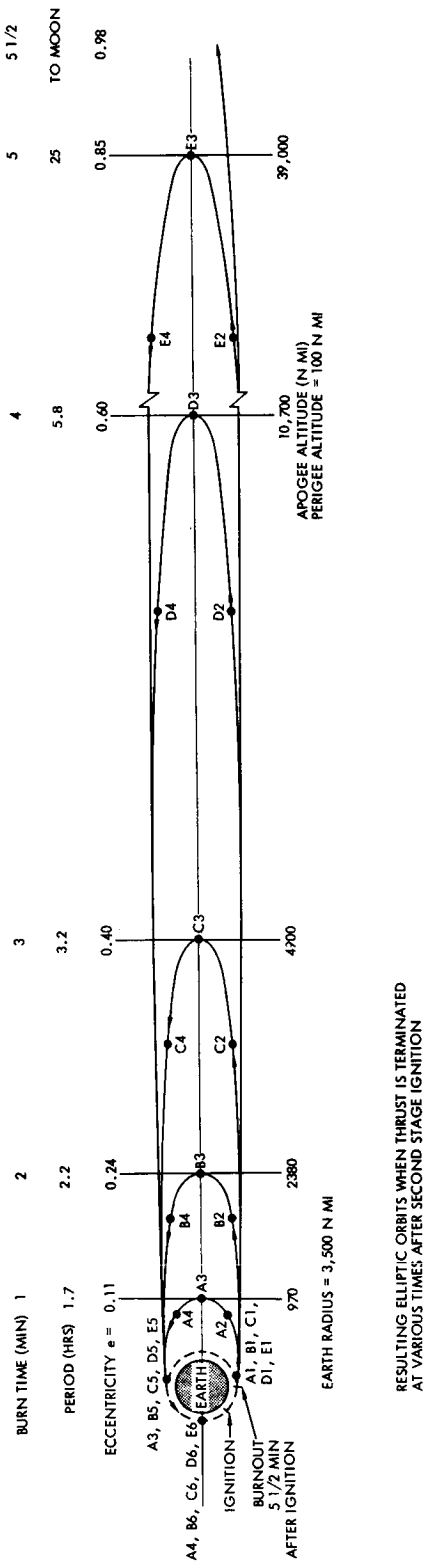

Figure 13. Pre-abort Trajectories and Chosen Abort Points

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TABLE II SPACECRAFT WEIGHT AND PROPULSION DATA

Weight Data

Module	Item	Weight (lbm)
CM	Structure	8840
	Three men at 176 and equip at 44	+ 660
	Liftoff and re-entry configuration	9500
SM	Structure	8000
	Residual propellant μ	+ 2500
	Burnout configuration	10500
	Useful propellant	39500
	Liftoff configuration	50000
LEM	Ascent stage structure	3800
	Ascent useful propellant	+ 4250
	Total ascent stage	8050
	Descent stage structure	+ 3700
	Minimum lunar landing weight	11750
	Descent stage propellant	+14750
	Total module weight	26500

Propulsion Data

Module	Thrust (lbf)	Specific Impulse (lbf-sec/lbm)	Flow Rate (lbm/sec)
SM	21500	323.0	66.563467
LEM			
Descent stage	10500 max 1050 min	309.0	33.980583 max
Ascent stage	3500	307.0	11.400651

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TABLE III SPACECRAFT CONFIGURATIONS AVAILABLE FOR ABORT PRIOR TO HYPERBOLIC DEBOOST*

Configuration	Δv_1(ft/sec)	Δv_2(ft/sec)	Δv_3(ft/sec)	Total Δv(ft/sec)
a) CM/SM without LEM (neither propulsion nor wt.)	11150			11150
b) CM/SM followed by LEM (both stages)	6340	3760	1600	11700
c) LEM both stages followed by CM/SM	1860	650	11150	13660
d) CM/SM followed by LEM first stage	6340	3760		10100
e) CM/SM followed by second stage	9020	1600		10620
f) LEM first stage followed by CM/SM	1860	11150		13010
g) LEM second stage followed by CM/SM	650	11150		11800
h) LEM first stage only (with CM/SM fueled wt.)	1860			1860
i) LEM second stage only (with CM/SM fueled wt.)	650			650

NOTE: * The Δv's contained in this table have been calculated with respect to the following assumptions:

1) When only the LEM ascent stage (LEM second stage) is used, the LEM descent stage has been jettisoned.

2) When only the LEM descent stage (LEM first stage) is used, the LEM ascent stage cannot be jettisoned.

3) In all cases, the CM/SM remains as part of the final burnout weight and that, as a minimum, its weight includes the CM, SM structure, and SM trapped propellant.

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TABLE III (Continued)

Configuration	Δv_1(ft/sec)	Δv_2(ft/sec)	Δv_3(ft/sec)	Total Δv(ft/sec)
j) LEM both stages (without CM/SM propulsion, with wt.)	1860	650		2510
k) LEM first stage only (with CM/SM unfueled wt.)	3760			3760
l) LEM second stage only (with CM/SM unfueled wt.)	1600			1600
m) LEM both stages (without CM/SM propulsion with unfueled wt.)	3760	1600		5360

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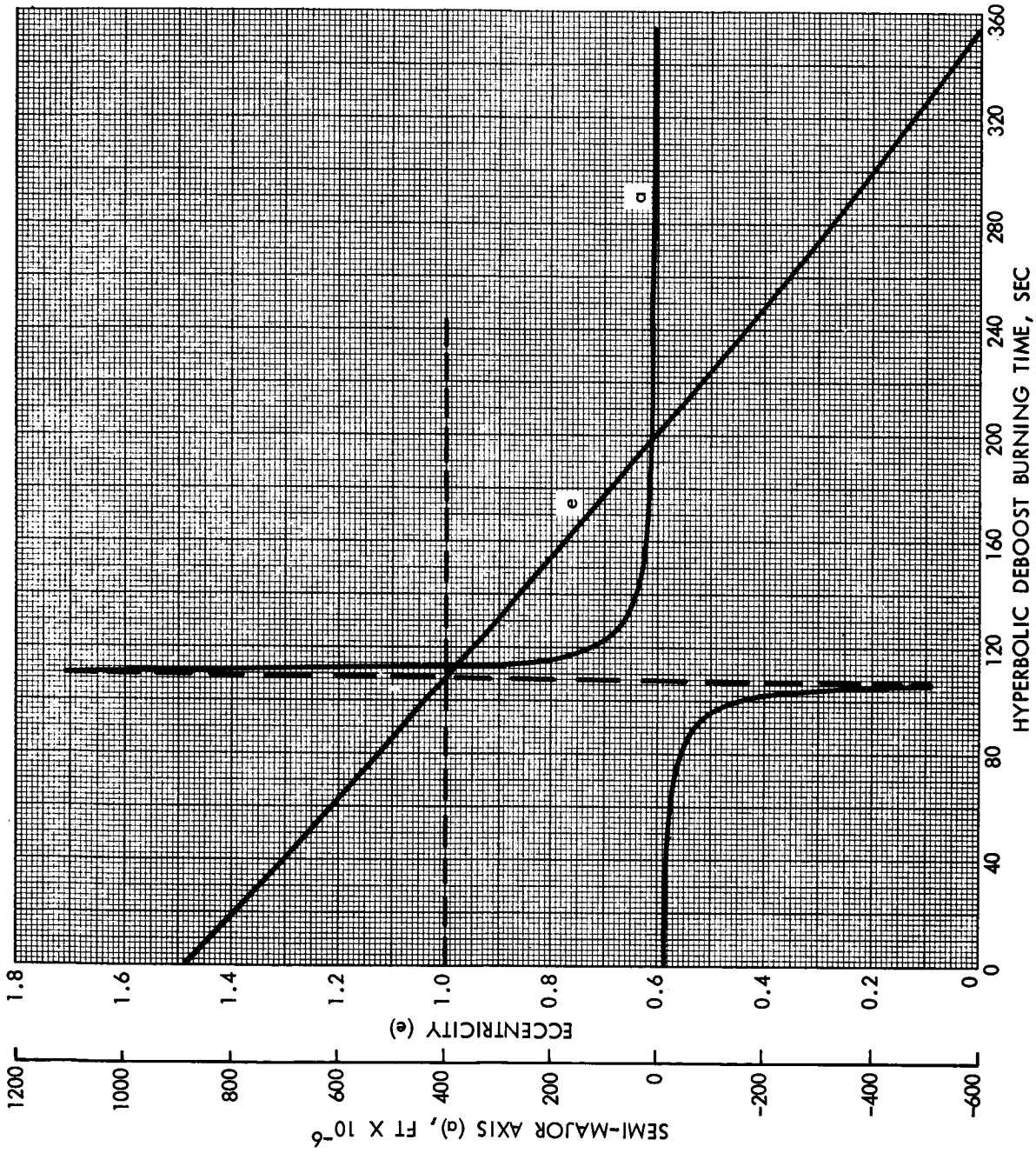

Figure 14. Orbit Elements Resulting from Premature Cutoff of Six Thrust During the Hyperbolic Deboost Maneuver

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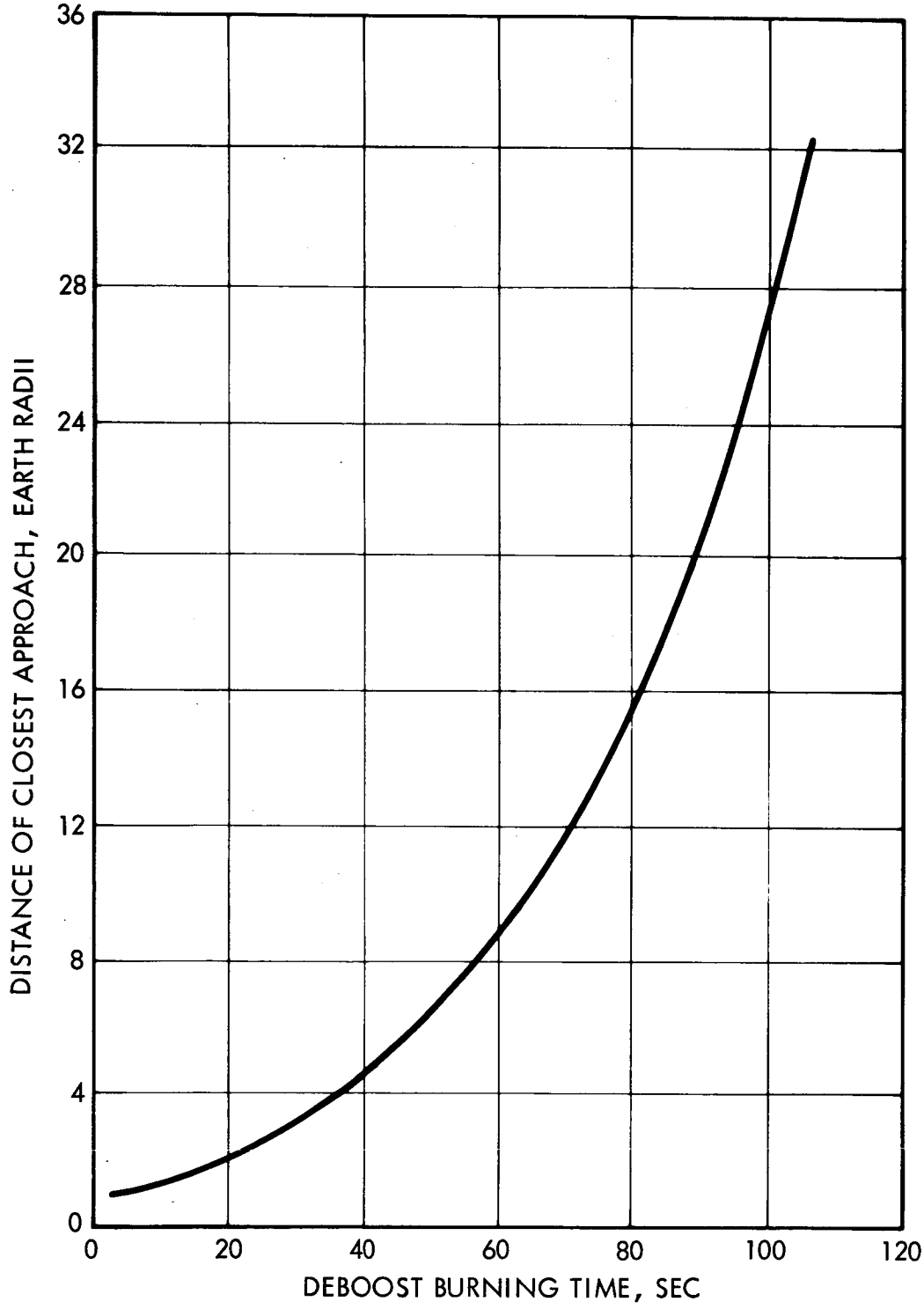

Figure 15. DCA to Earth as a Function of SM Burning Time

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thrust is applied, the DCA is approximately one earth radius since the nominal translunar trajectory circumnavigates the moon and returns to earth with safe re-entry conditions. Figures 16 and 17 show the position component relationship in the earth equatorial, true of date coordinate system of various free flight pre-abort trajectories emanating from the moon and returning to the vicinity of earth. It is interesting to observe how rapidly the distance of closest approach increases after approximately 20 to 30 seconds of hyperbolic deboost burning time.

A set of pre-abort trajectories (designated M through S) resulting from powered flight cessation at seven separate points during the entire hyperbolic deboost phase were chosen. The basic geometrical characteristics of these trajectories are shown in Figure 18 which is a projection into the lunar equatorial plane of the trajectory shape. Also noted, by the intersection of the dashed lines with the pre-abort conics, are the numbered abort points which were selected. The orbital characteristics of these trajectories are further detailed in Table IV, together with conditions existing at the abort points chosen for study.

As in the case of the translunar injection analysis, several spacecraft configurations were assumed and their Δv calculated for comparison with velocity demand. However, since three of these configurations assume that the SM propellant cannot be jettisoned after failure, the LEM capability is dependent on the amount of SM propellant remaining at failure. All selected configurations have their Δv capability given in Table V and again in Figure 19 to show the time dependence. These data include the effect of having allocated a nominal 300 ft/sec for translunar midcourse correction to be provided by the Service Module.

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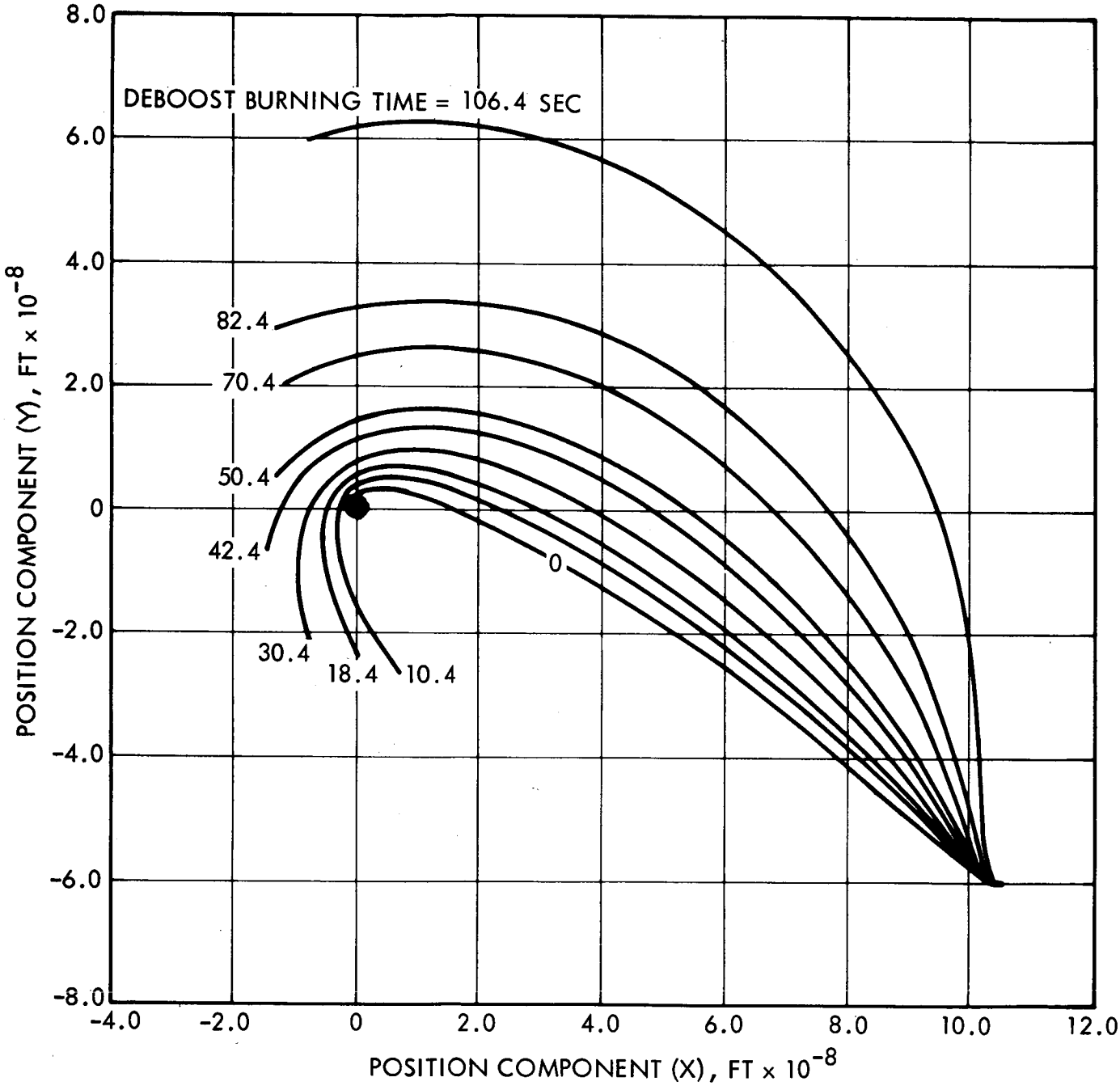

Figure 16. Position History of Pre-abort Trajectories Resulting from SM Thrust Cutoff in the Early Part of the Hyperbolic Deboost Maneuver

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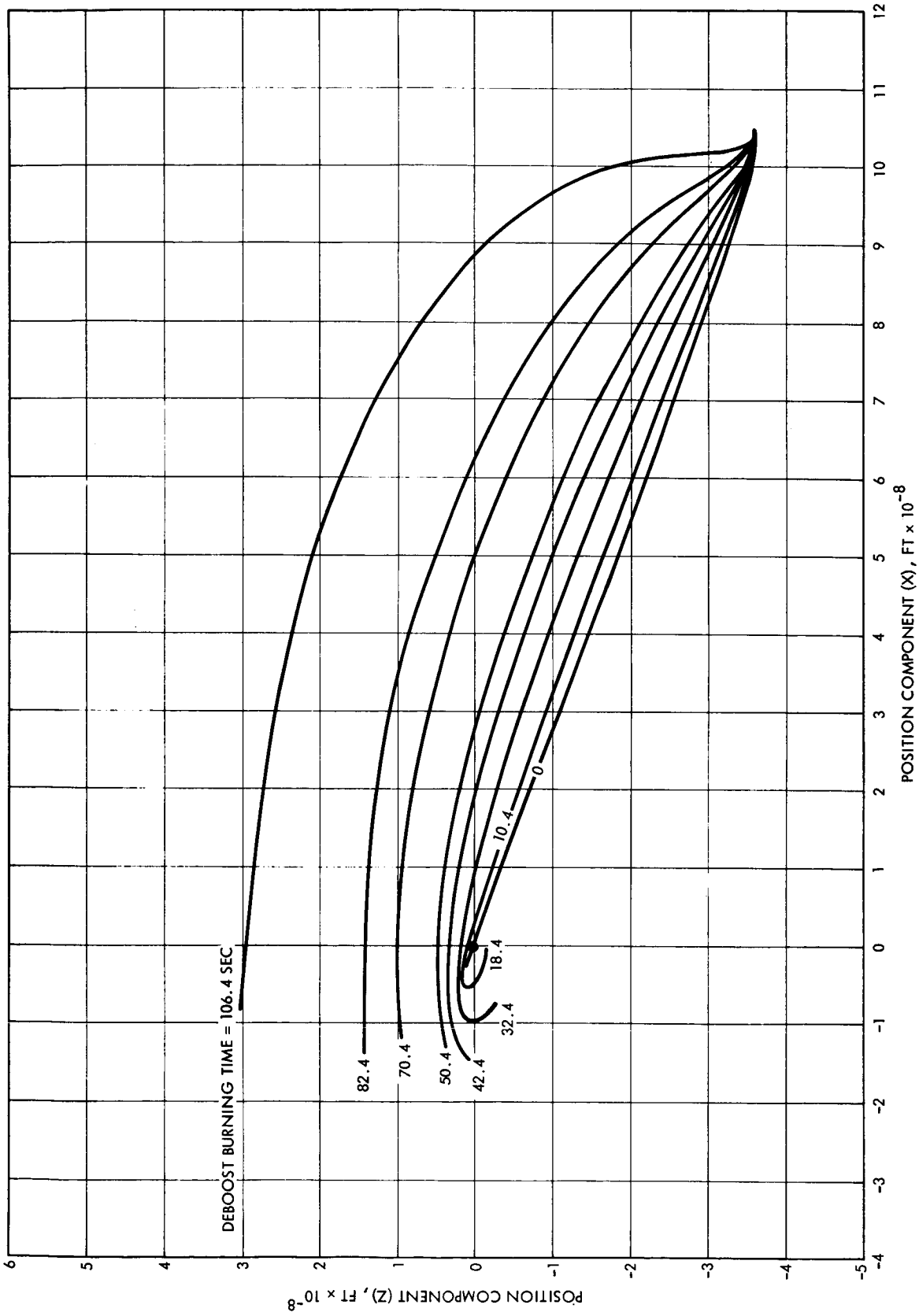

Figure 17. Position History of Pre-abort Trajectories Resulting from SM Thrust Cutoff in the Early Part of the Hyperbolic Deboost Maneuver

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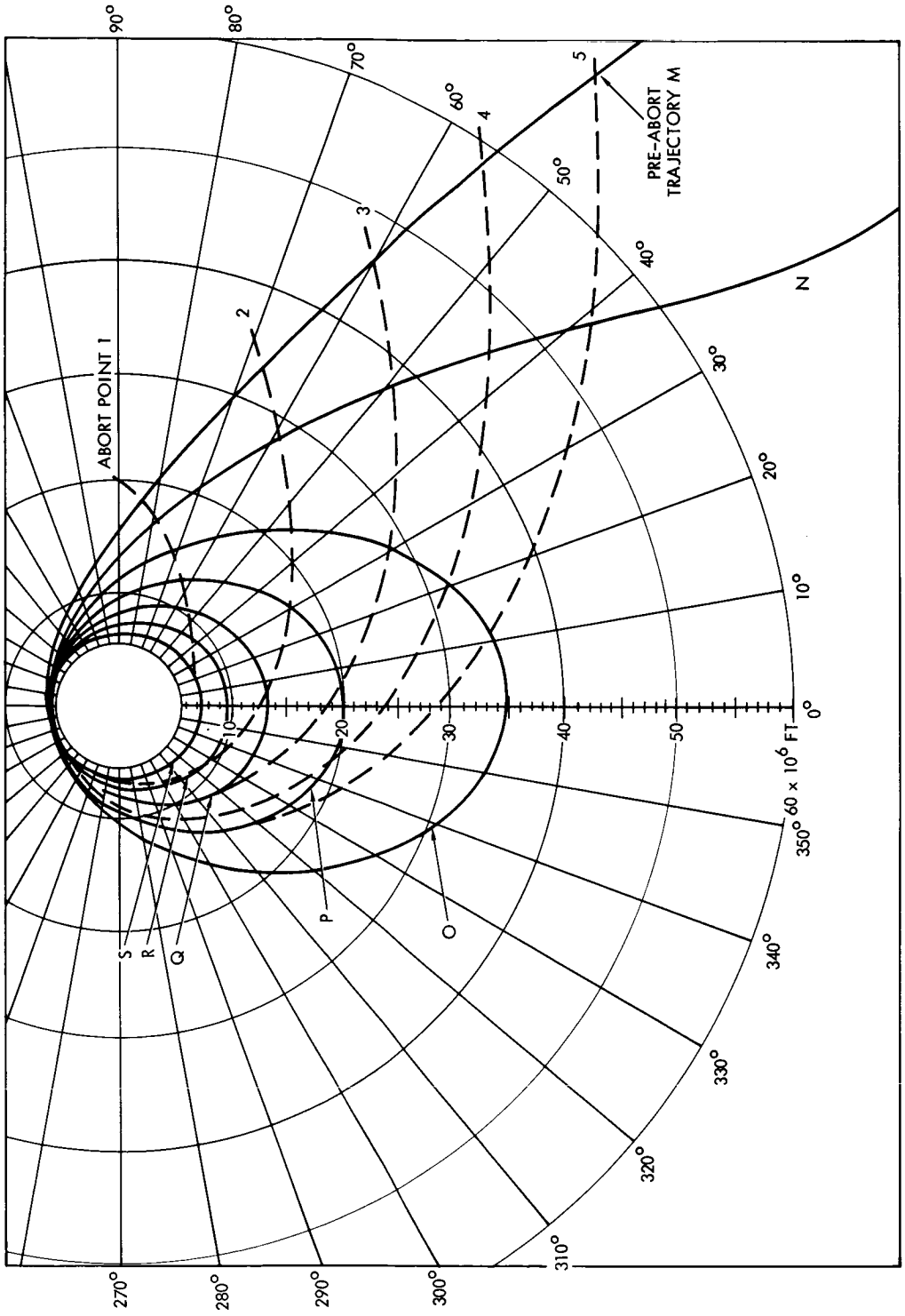

Figure 18. Selected Pre-abort Trajectories and Abort Points-Hyperbolic Deboost Maneuver

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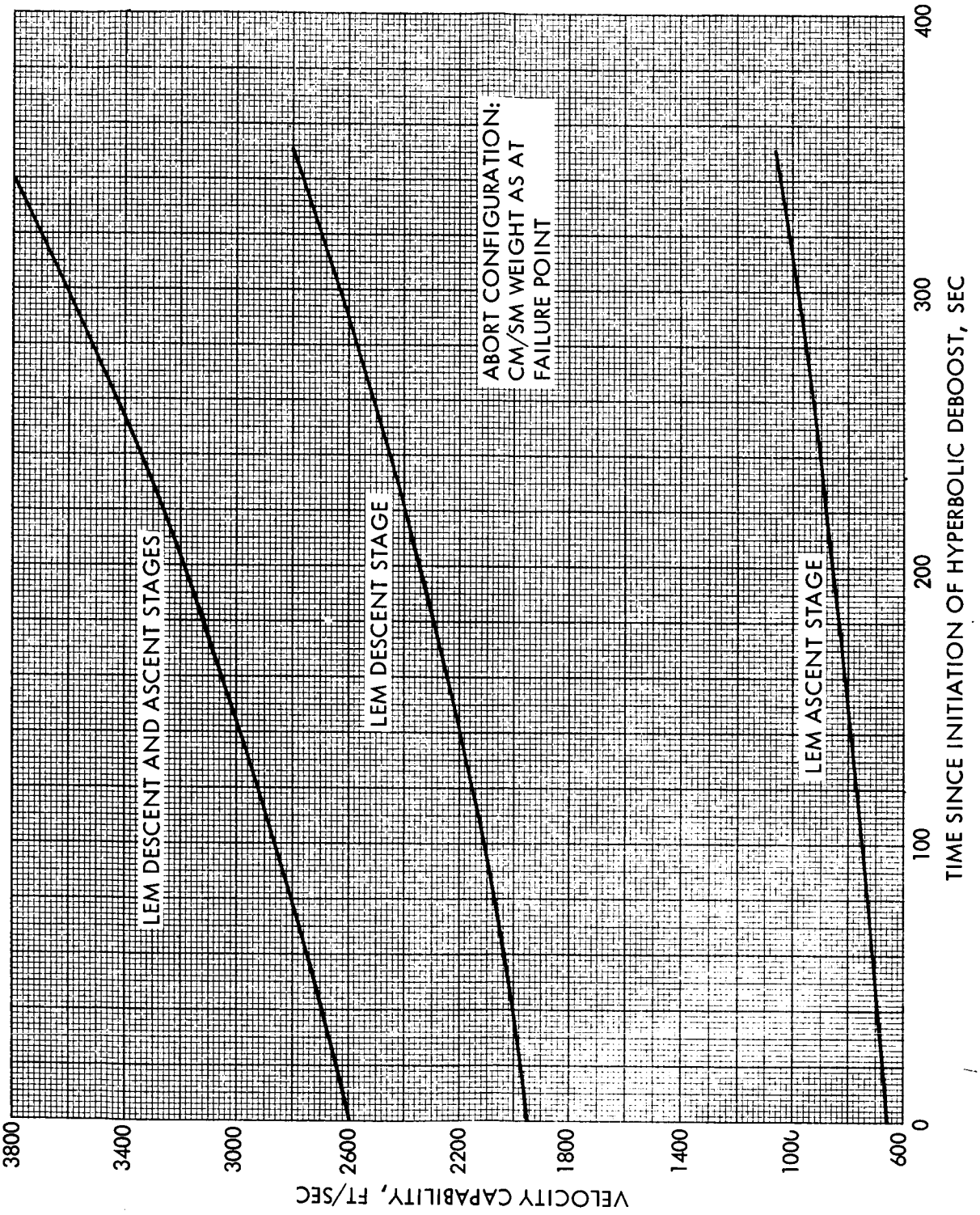

Figure 19. LEM Abort Velocity Impulse Dependence on SM Failure Time During Hyperbolic Deboost - SM Propellant Remaining not Jettisonable

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TABLE IV PRE-ABORT TRAJECTORIES AND CHOSEN ABORT POINTS

Nominal Translunar Free Return Trajectory

Time to go in S-IVB second burn = 0 sec.

Orbital Elements

a	$= 1033.8 \times 10^6$ ft	h_p	= 1130.0 n mi
e	= 0.97911	h_a	= 333295 n mi
i	= 28.480°	P	= 29339.4 min
Ω	= 3.325°	$DCA_{(moon)}$	= 6185760 ft
ω	= 153.901°	η	= 13.352°

Chosen Abort Points at and within the Moon's Sphere of Action

	r = 55.5 (E.R.)	56.9	57.7	58.25	60.0
t_{ib} (hrs)	56.5	59.0	61.0	63.0	64.37
Geocentric					
η (deg)	172.014	173.427	175.510	179.042	162.398
α (deg)	-29.765	-29.571	-29.456	-29.410	-29.485
δ (deg)	-16.468	-16.386	-16.338	-16.320	-16.357
v (ft/sec)	3332.91	3295.09	3304.47	3423.54	3798.82
β (deg)	8.732	7.169	4.773	0.930	13.639
A (deg)	66.331	66.324	66.581	237.789	243.552
Long. (deg)	-24.452	-61.861	-91.828	-121.864	-141.995
Lat. (deg)	-16.573	-16.491	-16.442	-16.424	-16.461
Selenographic					
r (ft x 10^{-6})	140.948	104.537	74.673	43.426	20.950
v (ft/sec)	4021.86	4123.06	4279.19	4652.23	5405.41
β (deg)	174.516	172.994	170.647	165.182	153.358
A (deg)	274.69	274.648	274.381	273.559	271.387
Long. (deg)	-40.673	-43.913	-47.776	-55.461	-71.772
Lat. (deg)	6.819	6.972	7.189	7.644	8.315

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TABLE IV (Continued)

Pre-abort Trajectory M

Time to go in CM/SM Hyperbolic Deboost = 295.6 sec.

Orbital Elements (Selenographic)

a	$= -2742 \times 10^4$ ft	h_p	= 79.83 n mi
e	= 1.22564	h_a	= undefined
i	= 172.839°	P	= undefined
Ω	= 5.811°	$DCA_{(earth)}$	= 29,194.3 n mi
ω	= 178.963°	η	= 347.44°

Chosen Abort Points

	M1	M2	M3	M4	M5	M6
t_{db} (hrs)	0.0	1.0	2.0	3.0	4.0	5.0
r (ft x 10^{-6})	6.270	18.711	33.168	46.406	58.893	70.878
α (deg)	341.016	221.181	205.163	198.967	195.533	193.300
δ (deg)	-5.132	-22.641	-17.031	-14.389	-12.823	-11.769
v (ft/sec)	7.845	4.981	4.092	3.710	3.491	3.347
β (deg)	96.918	31.594	21.094	16.499	13.788	11.963
Lat. (deg)*	1.678	-7.018	-6.348	-5.929	-5.658	-5.466
Long. (deg)*	-160.701	83.748	67.036	59.940	55.696	52.720
A (deg)	242.067	287.554	293.030	294.715	295.539	296.038

* Selenographic

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TABLE IV (Continued)

Pre-abort Trajectory N

Time to go in CM/SM Hyperbolic Deboost = 235.6 sec.

Orbital Elements (Selenographic)

a	=	15166×10^4 ft	h_p	=	79.98 n mi
e	=	0.95920	h_a	=	47962.31 n mi
i	=	174.378°	P	=	14863.67 min
Ω	=	2.607°	η	=	351.064°
ω	=	176.342°			

Chosen Abort Points

	N1	N2	N3	N4	N5	N6
t_{db} (hrs)	0.0	1.0	2.0	3.0	4.0	5.0
r (ft x 10^{-6})	6.225	16.674	28.118	37.920	46.643	54.597
α (deg)	337.277	216.917	197.639	189.488	184.639	181.288
δ (deg)	-7.024	-19.847	-12.612	-8.932	-6.613	-4.968
v (ft/sec)	7.381	4.429	3.342	2.826	2.507	2.283
β (deg)	94.375	38.343	29.196	25.344	23.133	21.675
Lat. (deg.)*	1.224	-5.479	-4.725	-4.202	-3.835	-3.559
Long. (deg)*	-164.858	79.103	58.636	49.263	43.380	39.117
A (deg)	244.042	288.428	293.877	295.411	296.080	296.438

* Selenographic

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TABLE IV (Continued)

Pre-abort Trajectory O

Time to go in CM/SM Hyperbolic Deboost = 175.6 sec.

Orbital Elements (Selenographic)

a	=	2054×10^4 ft	h_p	=	79.99 n mi
e	=	0.69877	h_a	=	4805.31 n mi
i	=	176.225°	P	=	741.08 min
Ω	=	357.327°	η	=	354.408°
ω	=	171.688°			

Chosen Abort Points

	O1	O2	O3	O4	O5	O6
t_{db} (hrs)	0.0	1.0	2.0	3.0	4.0	5.0
r (ft x 10^{-6})	6.201	14.384	22.359	27.934	31.698	33.964
α (deg)	333.665	210.798	185.610	172.963	164.016	156.575
δ (deg)	-8.679	-16.056	-5.934	-0.100	4.059	7.417
v (ft/sec)	6.886	3.954	2.656	1.992	1.581	1.332
β (deg)	92.300	48.593	45.941	50.112	58.451	70.791
Lat. (deg)*	0.906	-3.656	-2.845	-2.164	-1.600	-1.098
Long. (deg)*	-168.798	72.370	45.112	30.660	20.261	11.597
A (deg)	246.432	289.461	294.362	295.037	294.736	294.003

* Selenographic

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TABLE IV (Continued)

Pre-abort Trajectory P

Time to go in CM/SM Hyperbolic Deboost = 135.6 sec.

Orbital Elements (Selenographic)

a	= 1316×10^4 ft	h_p	= 79.97 n mi
e	= 0.52985	h_a	= 2375.51 n mi
i	= 177.660°	P	= 380.04 min
Ω	= 349.301°	η	= 356.461°
ω	= 164.108°		

Chosen Abort Points

	P1	P2	P3	P4	P5	P6
t_{db} (hrs)	0.0	1.0	2.0	3.0	4.0	5.0
r (ft x 10^{-6})	6.192	12.697	18.036	20.076	19.137	15.069
α (deg)	331.345	204.954	172.286	151.492	130.957	101.814
δ (deg)	-9.635	-12.641	0.817	9.580	16.693	22.662
v (ft/sec)	6.540	3.756	2.458	2.023	2.222	3.133
β (deg)	91.226	58.085	65.994	85.774	107.738	120.970
Lat. (deg)*	0.778	-2.281	-1.566	-0.781	0.072	1.168
Long. (deg)*	-171.283	65.889	30.232	7.225	-14.512	-43.076
A (deg)	248.296	290.157	293.641	291.735	287.016	277.000

* Selenographic

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TABLE IV (Continued)

Pre-abort Trajectory Q

Time to go in CM/SM Hyperbolic Deboost = 95.6 sec.

Orbital Elements (Selenographic)

a	=	9757×10^3 ft	h_p	=	79.94 n mi
e	=	0.36575	h_a	=	1254.55 n mi
i	=	179.118°	P	=	242.54 min
Ω	=	311.487°	η	=	358.361°
ω	=	126.765°			

Chosen Abort Points

	Q1	Q2	Q3	Q4	Q5	Q6
t_{db}(hrs)	0.0	1.0	2.0	3.0	4.0	5.0
r (ft x 10^{-6})	6.189	10.870	13.314	11.130	6.213	10.675
α (deg)	329.107	196.618	148.690	97.624	336.941	199.133
δ (deg)	-10.466	-8.082	10.613	21.711	-7.615	-9.014
v (ft/sec)	6.181	3.755	2.874	3.655	6.163	3.832
β (deg)	90.439	69.560	89.275	109.898	92.668	69.236
Lat. (deg)*	0.721	-0.849	-0.716	-0.064	0.762	-0.841
Long. (deg)*	-173.643	56.609	4.822	-45.783	-167.595	57.069
A (deg)	250.416	290.647	289.509	274.293	249.179	290.276

* Selenographic

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TABLE IV (Continued)

Pre-abort Trajectory R

Time to go in CM/SM Hyperbolic Deboost = 55.6 sec.

Orbital Elements (Selenographic)

a	=	7809×10^3 ft	h_p	=	79.93 n mi
e	=	0.20757	h_a	=	613.454 n mi
i	=	178.336°	P	=	173.67 min
Ω	=	210.483°	η	=	0.102°
ω	=	26.263°			

Chosen Abort Points

	R1	R2	R3	R4	R5	R6
t_{db} (hrs)	0.0	1.0	2.0	3.0	4.0	5.0
r (ft x 10^{-6})	6.188	8.912	8.644	6.257	9.125	8.333
α (deg)	326.962	183.714	96.726	306.404	174.495	84.906
δ (deg)	-11.168	-1.724	20.211	-16.453	1.693	20.331
v (ft/sec)	5.813	4.084	4.228	5.759	3.971	4.402
β (deg)	89.982	81.219	100.264	86.500	83.016	101.324
Lat. (deg)*	0.739	0.356	-1.609	1.217	0.071	-1.657
Long. (deg)*	-175.872	42.316	-45.992	161.847	30.843	-58.729
A (deg)	252.846	290.308	272.661	257.806	290.311	268.556

* Selenographic

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TABLE IV (Continued)

Pre-abort Trajectory S

Time to go in CM/SM Hyperbolic Deboost = 23.6 sec.

Orbital Elements (Selenographic)

a	=	6771×10^3 ft	h_p	=	79.95 n mi
e	=	0.08608	h_a	=	271.804 n mi
i	=	176.548°	P	=	140.221 min
Ω	=	195.985°	η	=	1.376°
ω	=	12.185°			

Chosen Abort Points

	S1	S2	S3	S4	S5	S6
t_{db} (hrs)	0.0	1.0	2.0	3.0	4.0	5.0
r (ft x 10^{-6})	6.188	7.303	6.433	6.949	6.939	6.442
α (deg)	325.317	166.947	22.780	210.933	75.912	264.622
δ (deg)	-11.633	5.194	6.788	-9.272	18.133	-18.693
v (ft/sec)	5.512	4.673	5.316	4.925	4.932	5.308
β (deg)	89.891	88.088	94.013	85.326	94.701	85.933
Lat. (deg)*	0.809	0.524	-2.499	2.819	-3.403	3.287
Long. (deg)*	-177.552	24.190	-118.677	69.221	-66.789	120.957
A (deg)	255.058	288.149	252.369	286.489	264.748	272.494

* Selenographic

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TABLE V SPACECRAFT CONFIGURATIONS AVAILABLE FOR ABORT AFTER HYPERBOLIC DEBOOST*

Time during hyperbolic deboost t (sec)	Configuration: a) LEM both stages (CM/SM wt. as at abort) Δv(ft/sec)	b) LEM first stage only (CM/SM wt. as at abort) Δv(ft/sec)	c) LEM second stage only (CM/SM wt. as at abort) Δv(ft/sec)
58.4	2746	2036	711
118.4	2918	2156	762
178.4	3113	2291	822
218.4	3258	2391	867
258.4	3417	2500	917
298.4	3594	2619	975
330.4	3749	2723	1025

d) LEM both stages (dry SM attached) Δv = 5416 ft/sec

e) LEM first stage only (dry SM attached) Δv = 3793 ft/sec

f) LEM second stage only (dry SM attached) Δv = 1623 ft/sec

NOTE: * See note on Table

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III. RESULTS

A. Translunar Injection and Translunar Free Flight

This section contains all of the quantitative information generated concerning the post-abort trajectories. These results were obtained with the use of two analytic programs which assume simple gravitational models. One program utilizes conics about the earth neglecting all forces except the inverse square force field of the earth and the second is a patched conic program which formerly had been used to generate moon-to-earth trajectories.

The first (or abort) program will accept the position, velocity and time of the initiation of free flight, which in this case will be the S-IVB engine cutoff point. The Julian date and Greenwich time are inputs in order to determine parameters with respect to a rotating earth. This program then determines the pre-abort trajectory and the conditions at the abort point. The post-abort trajectory is then searched for to satisfy a given abort velocity impulse and the desired re-entry conditions. Further calculations are then made to determine other desirable quantities.

The second (or Analytic Lunar Return Program) has been used for aborts from within the moon's sphere of action. This program will accept the selenographic latitude and longitude at the abort point and calculate a return trajectory to satisfy time of flight, return inclination and the proper re-entry conditions.

For the nominal trajectory both programs were used to generate abort trajectories, however, all aborts due to failure or cutoff of the S-IVB engine were restricted to lie completely outside of the moon's sphere of action. This is justified on the basis of the pre-abort trajectory characteristics. It is only in the last few seconds of burn that results in a trajectory whose apogee reaches out to the MSA. Further, the characteristics of abort trajectories from those pre-abort trajectories which do penetrate the MSA will be similar to aborts from the nominal trajectory. A further restriction has been made where it is assumed that those aborts which originate outside of the MSA remain outside of the MSA. Thus, near earth aborts which penetrate the MSA before returning to the earth were not considered.

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The abort data presented here has been grouped according to the parameter considered. For example, the abort flight-path angles of all the abort trajectories are included in Figures 20 to 25. Each graph represents a single pre-abort trajectory using the notation designated in Section II. Included in this group is the reference trajectory which in actuality represents the final cutoff (although successful) of the S-IVB engine.

Included in the following graphs are the abort conic elements as well as time of flight, re-entry velocity and latitude and longitude at re-entry. All variables are plotted as functions of Δv. As can be seen, all functions are double valued as indicated in Section II. B. Thus, for a single value of Δv, two acceptable return trajectories are generated. Since the perigee of the pre-abort conic is very close to that of the desired abort conic, it can be expected that minimum velocity impulse will occur near the pre-abort trajectory conditions. Thus, in the β graphs, minimum Δv occurs near the pre-abort value of β. From this point the two solutions will diverge, one resulting in a value of β greater than the pre-abort value and the other less. Parentheses indicate the leg of the curves whose β value is less than the pre-abort value.

As Δv is increased, a point is reached, in some cases, where the trajectory becomes hyperbolic and escapes. This is within the forbidden region discussed in Section II. These escape points are indicated on the graphs. Data, of course, could not be plotted beyond these points. The escape points may also be found by observing where the eccentricity becomes unity on the leg designated with parentheses.

Behavior of abort flight-path angles generated from the nominal trajectory (Figure 25) behave differently, however. Here, the reference trajectory is nearly parabolic so that slight increases in velocity will cause the spacecraft to escape. Thus, the $\Delta\bar{v}$ vectors must be directed essentially towards the earth, resulting in a single abort solution. As the magnitude of Δv increases, the flight-path angle increases and is eventually directed towards the earth. For comparison, out-of-plane aborts were computed. In most cases the resulting parameters were much the same as for the in-plane case.

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Beginning with Figure 26 it should be noted that a symmetry relationship in the conic elements exists between several abort points. For example, curves for abort points 1 and 3 on pre-abort trajectory A are sometimes identical. This is due to the fact that these abort points were chosen on opposite sides of the pre-abort trajectory but with the same radial distance resulting in abort points symmetric with the semi-major axis. A similar symmetry relationship exists for the abort pairs (1, 5) and (2, 4) on pre-abort trajectories B, C, D and E. For each abort pair of points, if one point has the abort directed away from the earth and the other has its abort directed towards the earth, then the conic elements a and e and the re-entry velocity will be the same for both. The argument of perigee, flight times and the re-entry point will differ however. Figures 26 to 31 present the values of the semi-major axis for all pre-abort trajectories plus the nominal. Figures 32 to 37 similarly present the eccentricities for these trajectories. All of these graphs display the property described above.

Figures 38 to 43 present the argument of perigee for all of the abort trajectories. Note that the range of ω narrows as the pre-abort trajectory extends farther out. Aborts from the final or reference trajectory have the argument of perigee limited to values between 100° and 160°. Also, for a given magnitude of the abort velocity impulse, the arguments of perigee are almost identical. Also plotted on this graph are out-of-plane aborts. Here, the values of ω have similar trends but are displaced from the in-plane cases.

Figures 44 to 49 present the times of flight from the abort point to re-entry. The most obvious characteristic of these curves is the fact that the flight time decreases as the velocity impulse increases if the abort trajectory is directed towards the earth (or has β greater than the pre-abort value). Figure 49, for example, which applies to aborts from the reference trajectory, has flight times less than 20 hours for values of Δv as high as 15,000 ft/sec. This applies to aborts from all the radial distances shown. On the other hand, these figures indicate that the time of flight increases prohibitively for aborts directed away from the earth (or have β less than the pre-abort value).

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Figures 50 to 55 present the re-entry velocities for all of the abort trajectories calculated. These graphs indicate which abort trajectories result in a re-entry velocity greater than the upper bound, 40,000 ft/sec. These figures also indicate that this value is most frequently exceeded for aborts from the points 5 and 6 which are on the return leg of the pre-abort trajectory. Point 6 is especially critical since this point is very close to the pre-abort perigee requiring large velocities to return to earth with the desired re-entry conditions. Note that in Figure 55, aborts from the reference trajectory (if Δv is limited to 15,000 ft/sec) never result in re-entry velocities exceeding 40,000 ft/sec.

Figures 56 to 61 present, in a limited manner, the longitudes of the re-entry point. Since, the earth rotates 15 degrees per hour and the abort flight times vary over many hours, the re-entry longitude will be very sensitive to the abort velocity impulse. This is not especially true for those aborts which are directed towards the earth. In these cases, the return flight will be more well behaved. However, for aborts directed away from the earth, the re-entry longitude becomes very sensitive. Rather than determine the fine detail of the behavior of this parameter which would require many additional points, the existing points have been connected by dotted lines.

The re-entry latitudes which are presented in Figures 62 to 67, on the other hand, are independent of time of flight and the rotation of the earth and hence are not as sensitive. In fact, since the abort inclination is essentially fixed at 28.5 degrees (only in-plane aborts are considered), the re-entry latitude will be limited between -28.5 and 28.5 degrees. It is interesting to note that minimum Δv results in re-entry latitudes which vary from 28 degrees to about 18 degrees as the pre-abort trajectory ranges from A through to the nominal. Also, the re-entry latitudes of those aborts directed towards the earth have a tendency to increase from its value at minimum Δv whereas aborts directed away from the earth tend to decrease from this value. Aborts from the reference trajectory all have re-entry latitudes above the equatorial plane. These values increase from about 16 degrees for minimum Δv to about 28 degrees for Δv near 15,000 ft/sec.

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Figure 68 presents a summary of the minimum abort velocity impulse required for each pre-abort trajectory. Values are plotted versus the true anomaly of the abort point. For all trajectories, the minimum velocity impulse required to successfully return to the earth occurs at the apogee ($\eta = 180^{\circ}$) of the pre-abort conic. It is clear that a maximum impulse is required near perigee ($\eta = 0^{\circ}$) since the pre-abort velocity is maximum and the perigee distance is near the desired re-entry altitude. Thus, the maximum velocity impulse is essentially that required to alter the pre-abort flight-path angle from 90° to the re-entry value of 96.4°.

Once the reference trajectory penetrates the moon's sphere of action, the spacecraft is no longer under the earth's influence exclusively. Earth centered conic elements, for example, will change with time (these are called osculating elements). Figure 69 relates the geocentric radial distance along the trajectory to time measured from penetration of the MSA. This auxiliary graph is presented for use with the following figures on aborts within the MSA. Figures 70 to 75 are plotted versus time from entry into the moon's sphere of action and for constant return times of flight from abort to re-entry. The return inclinations chosen were the minimum and $\pm 40^{\circ}$ where -40° implies that the abort trajectory exists the sphere of action heading below the earth's equatorial plane. The explanation for two solutions for a given inclination has been presented in Section II. Figure 70 indicates the velocities required to return safely to earth. Only those abort trajectories which are directed towards the earth at abort injection are considered. Note that the abort velocity requirement becomes very large as the deboost point is approached. Actual deboost does not occur until approximately 9 hours after entry to the MSA. Since the velocity increases as the deboost point is reached, the impulse required to cause a direct return trajectory also increases. If, however, it is possible to maintain the reference trajectory and circumnavigate the moon, it requires no abort impulse to return since the reference trajectory is an acceptable return trajectory. In Figure 71, the abort velocity displacement angle is the angle between the pre-abort velocity vector and thus includes the effect of any plane change. The larger

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this angle becomes the greater the abort velocity impulse needed. Also, larger angles are required as the time from penetration of the MSA increases. Note that the velocity requirements do not vary appreciably with the return inclination. This, of course, is due to the fact that at these great distances from the earth only slight velocity changes are required to effect a change in the return inclination.

Figure 72 presents the moon centered flight-path angle of the abort trajectory. Note that for each return time of flight these values remain fairly constant, increasing with increasing time of flight. The earth centered conic elements are presented in Figures 73 and 74. The first figure indicates that the semi-major axis remains nearly constant for all return flight times except the 50 hour flight time. The rapid increase for the flight time is due to the fact an eccentricity of one is being approached in which case the semi-major axis goes to infinity. Finally, Figure 75 presents the re-entry velocity for the MSA abort trajectories. For the flight times considered the values are well within the upper limit of 40,000 ft/sec. It is evident from these figures that if abort occurs well before the deboost point is reached, shorter flight times - perhaps as low as a single day - may be considered. However, conditions become very unfavorable for direct returns as the deboost point is approached.

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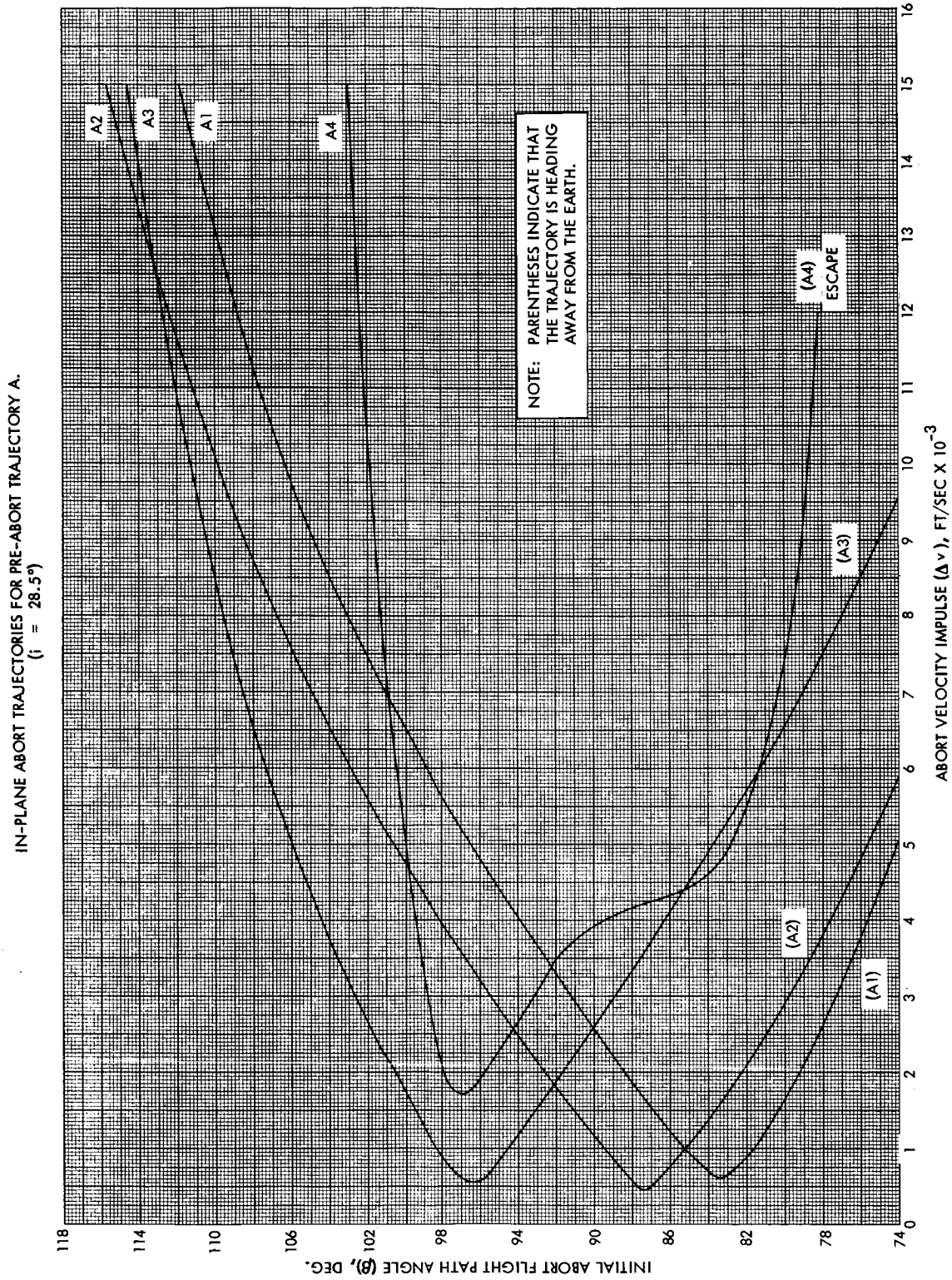

Figure 20. Abort Flight Path Angle (Pre-abort Trajectory A)

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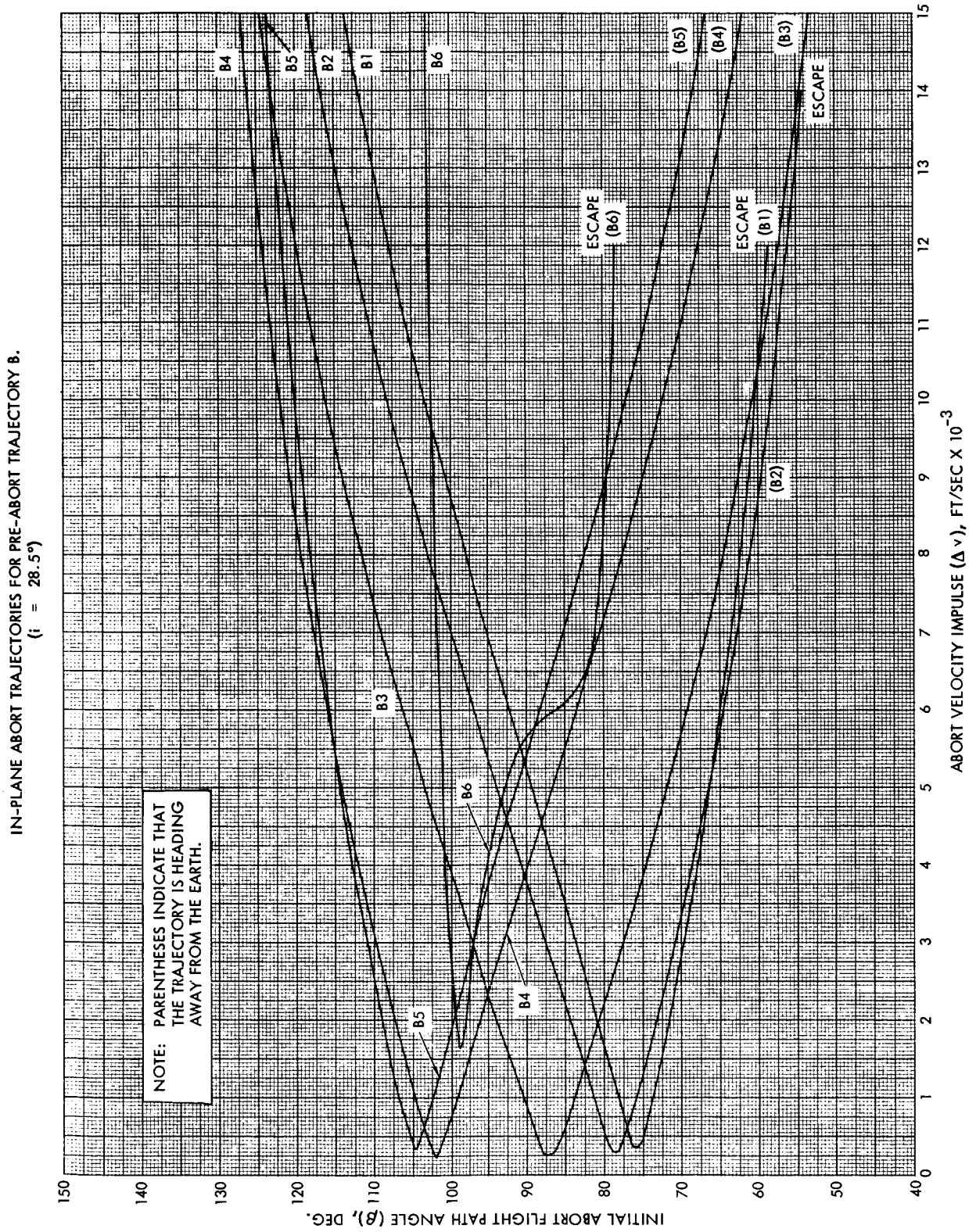

Figure 21. Abort Flight Path Angle (Pre-abort Trajectory B)

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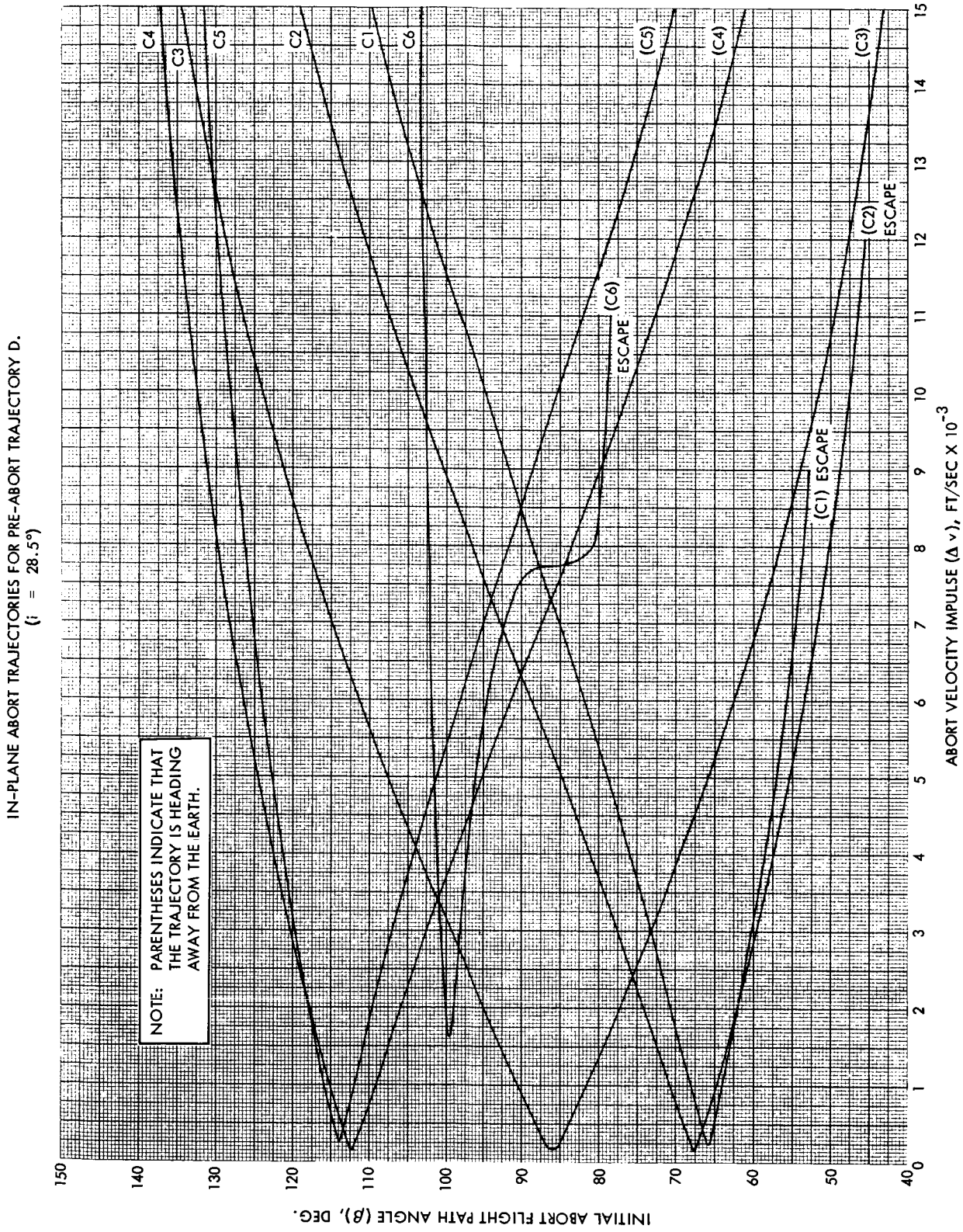

Figure 22. Abort Flight Path Angle (Pre-abort Trajectory C)

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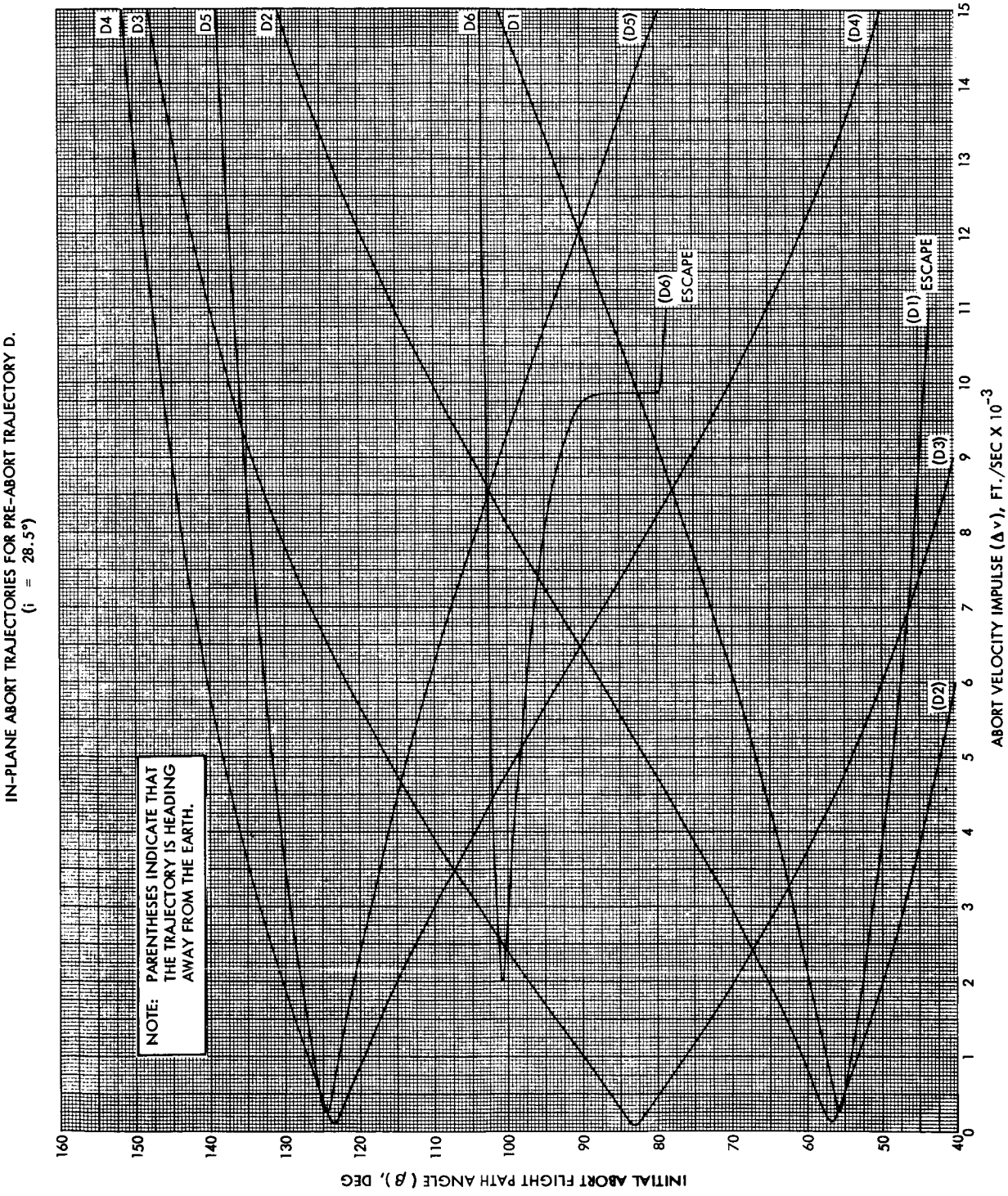

Figure 23. Abort Flight Path Angle (Pre-abort Trajectory D)

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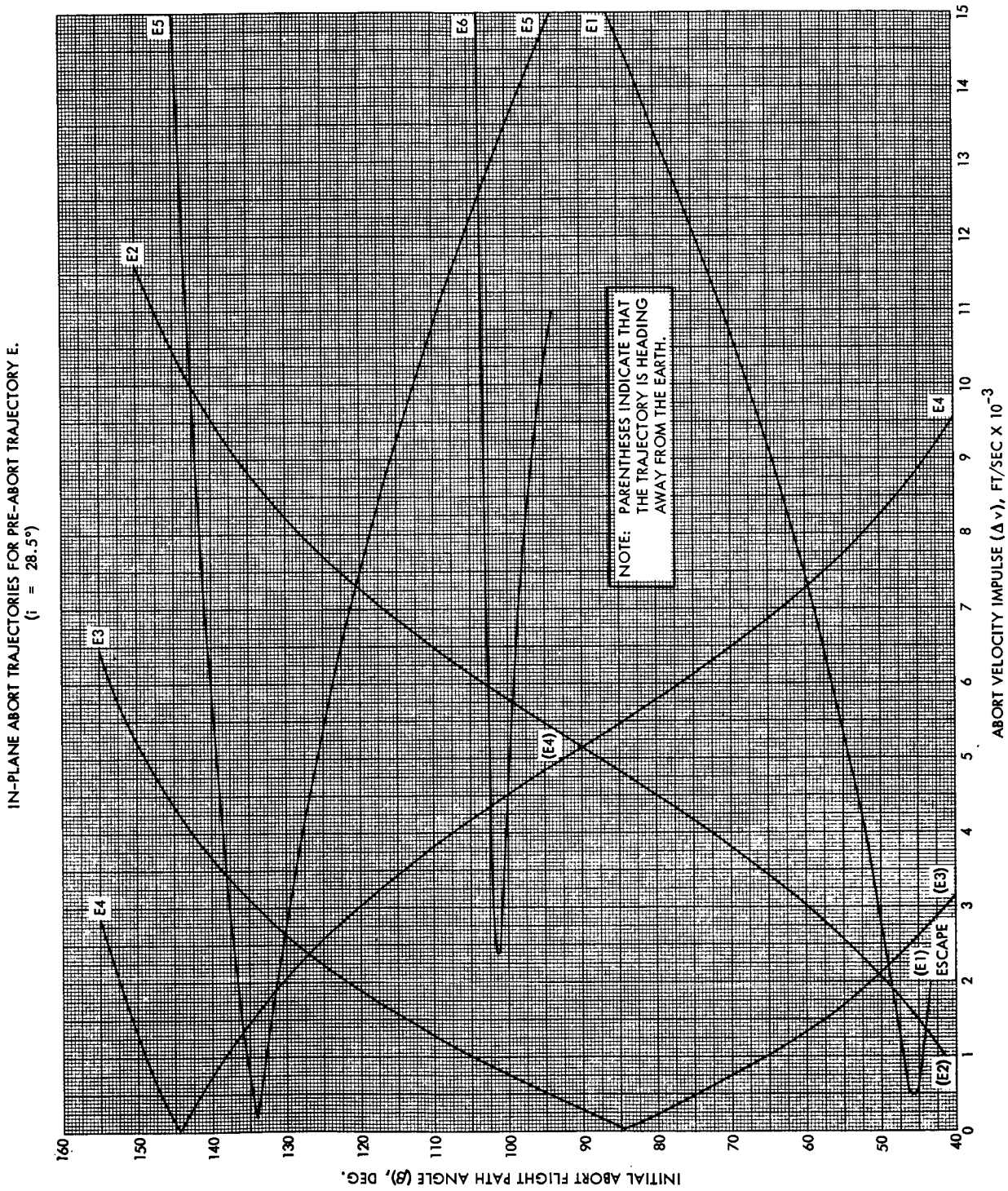

Figure 24. Abort Flight Path Angle (Pre-abort Trajectory E)

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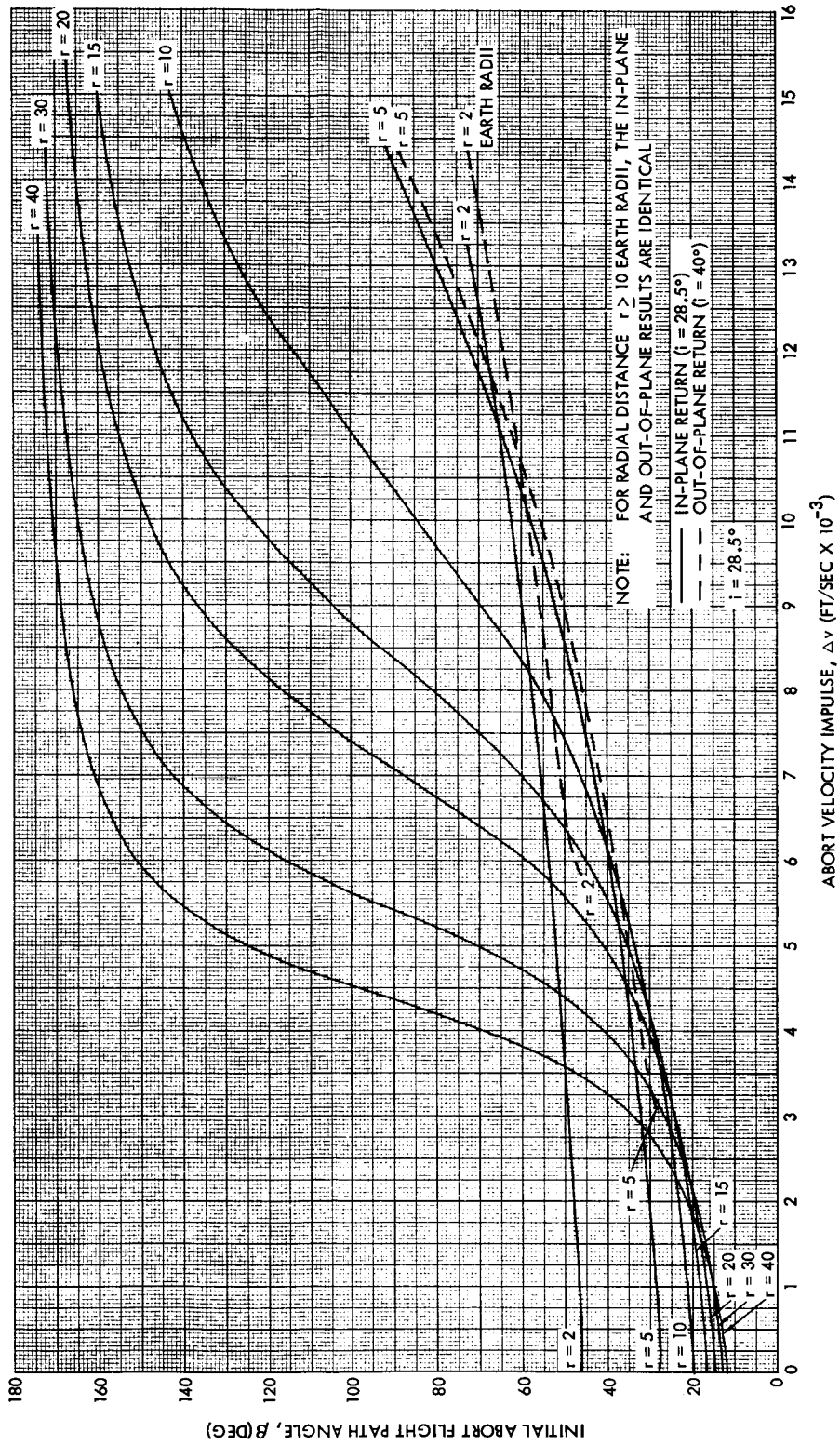

Figure 25. Abort Flight Path Angle (Nominal Translunar Trajectory)

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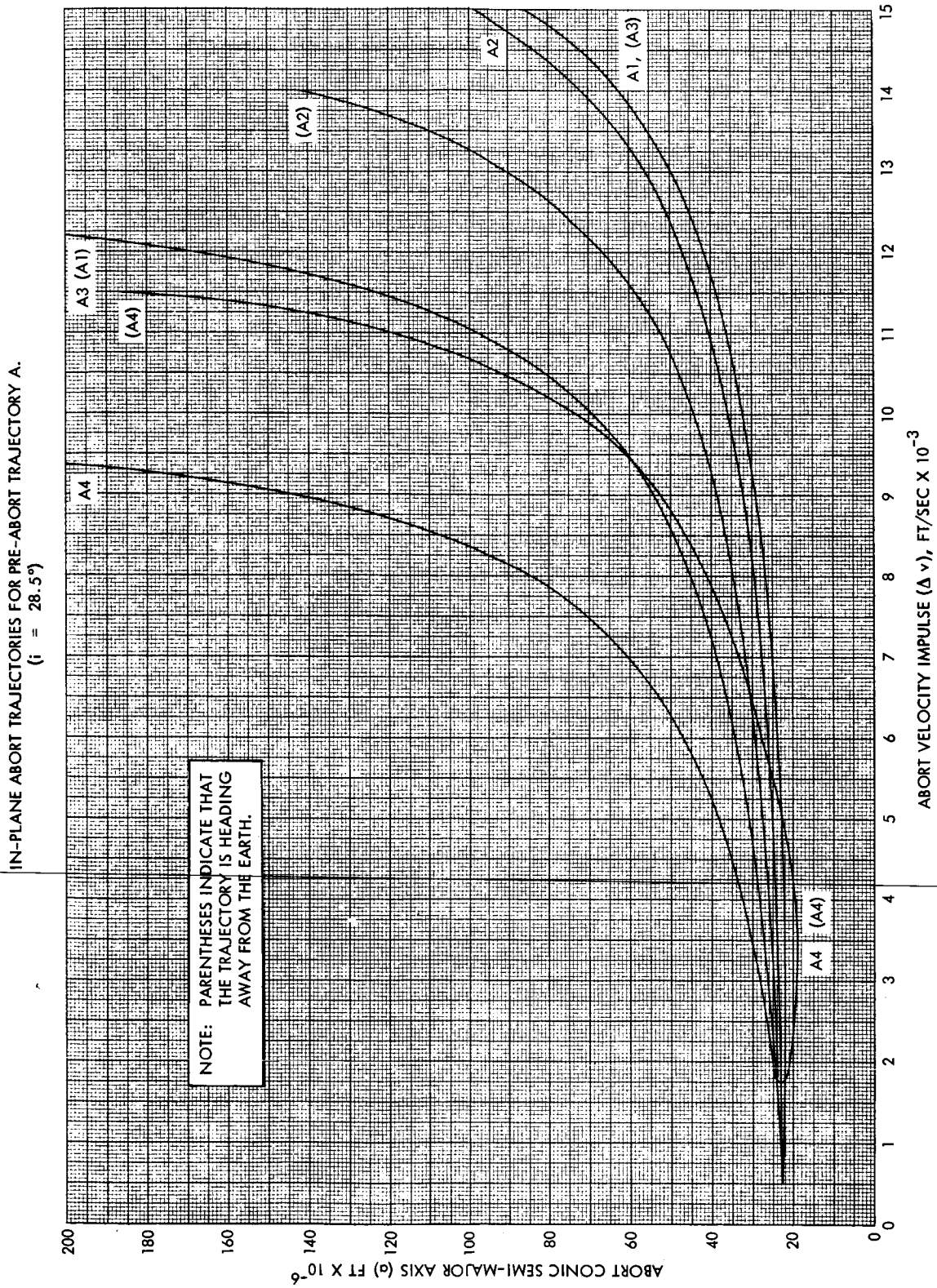

Figure 26. Abort Semi-major Axis (Pre-abort Trajectory A)

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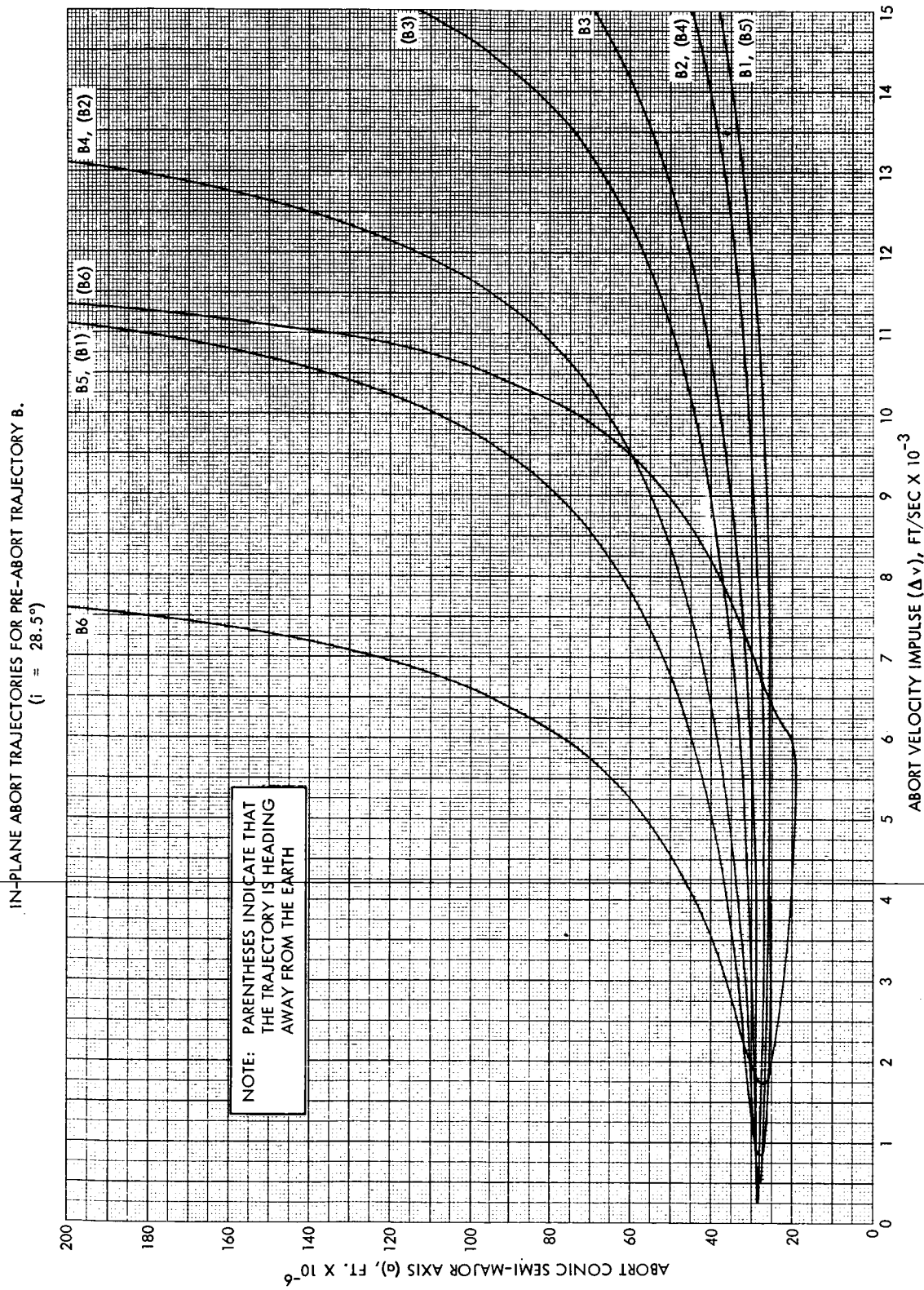

Figure 27. Abort Semi-major Axis (Pre-abort Trajectory B)

This document contains information affecting the national defense of the [redacted] States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which [redacted] on unauthorized person is prohibited by law.

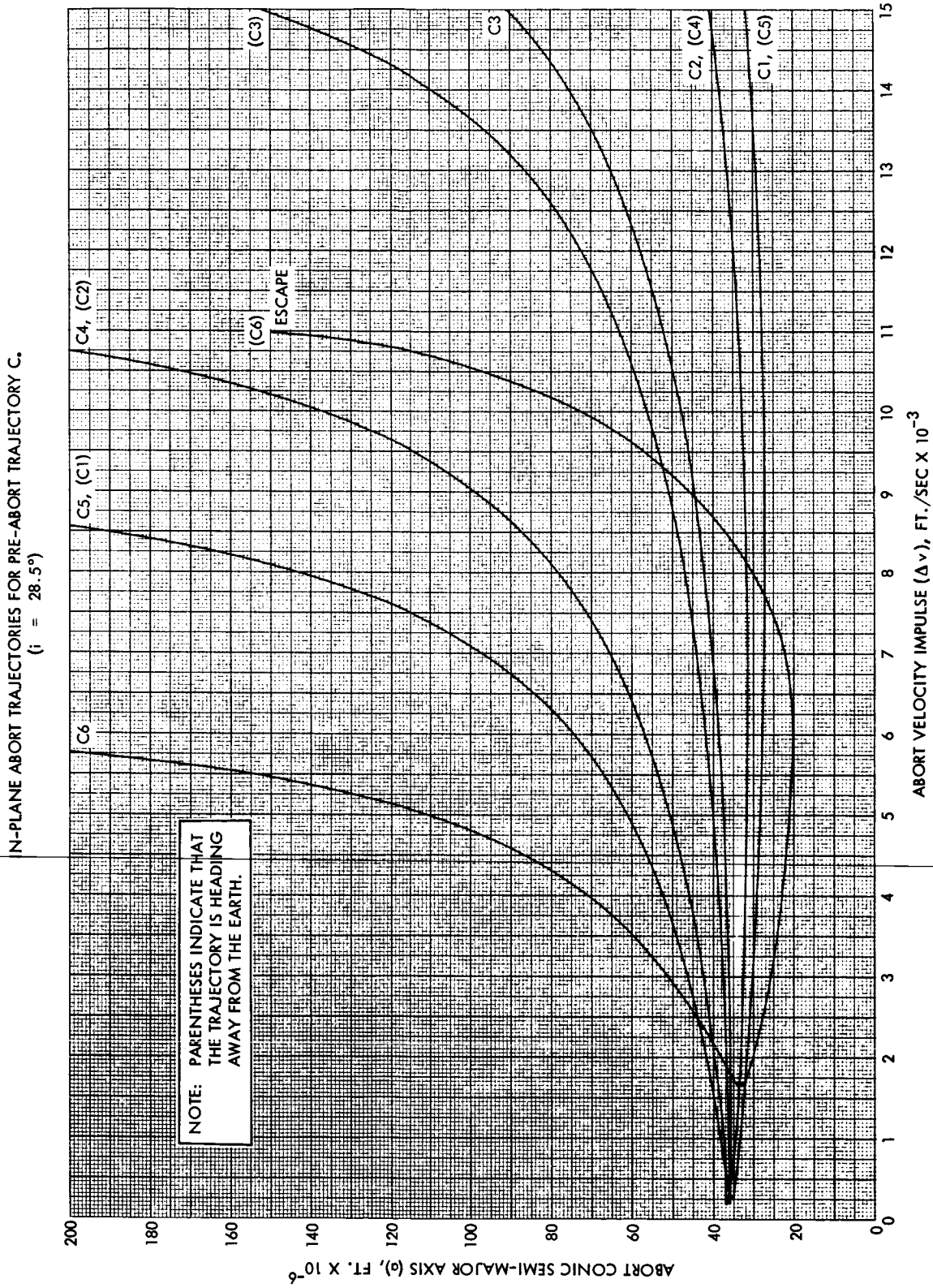

Figure 28. Abort Semi-major Axis (Pre-abort Trajectory C)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

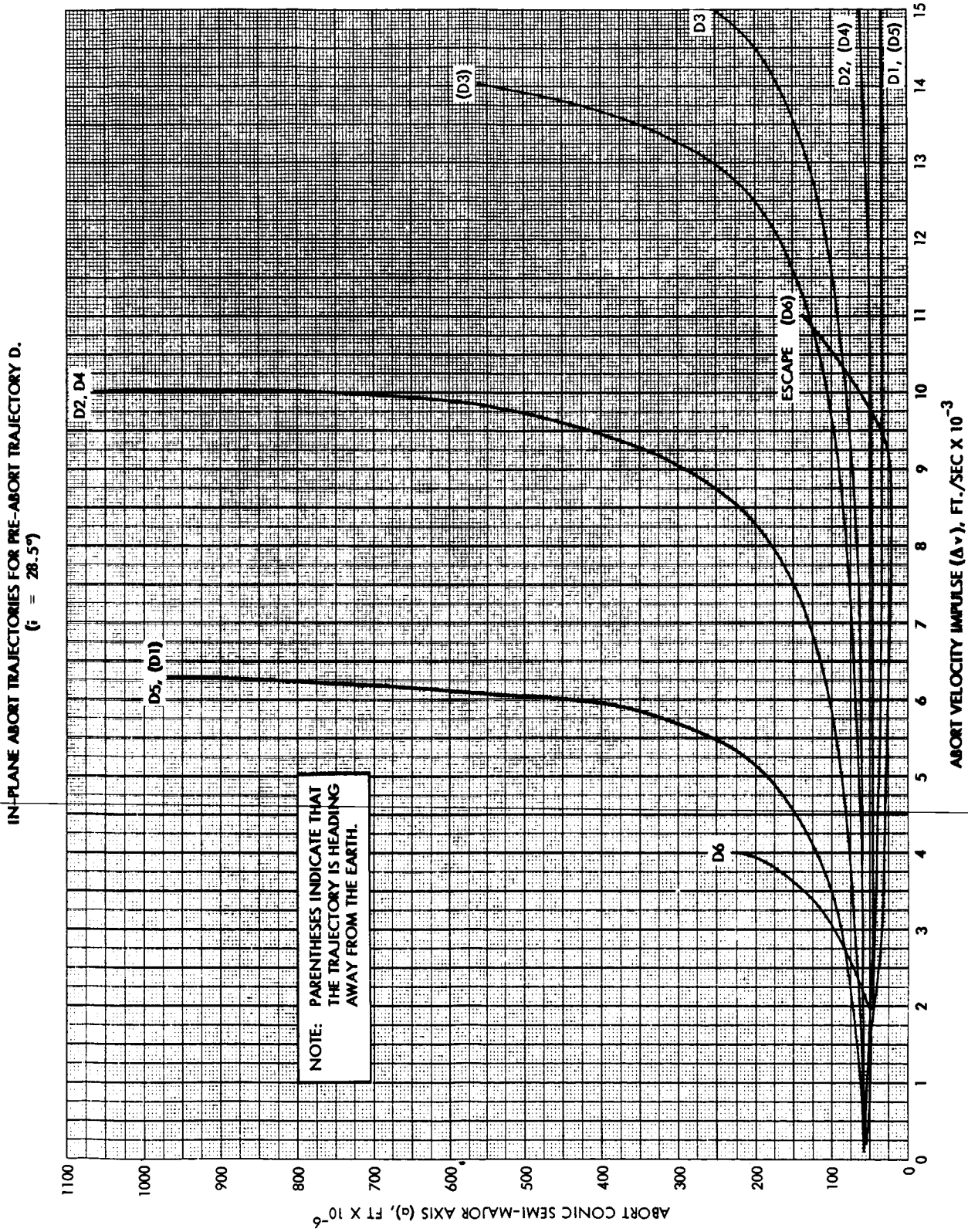

Figure 29. Abort Semi-major Axis (Pre-abort Trajectory D)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

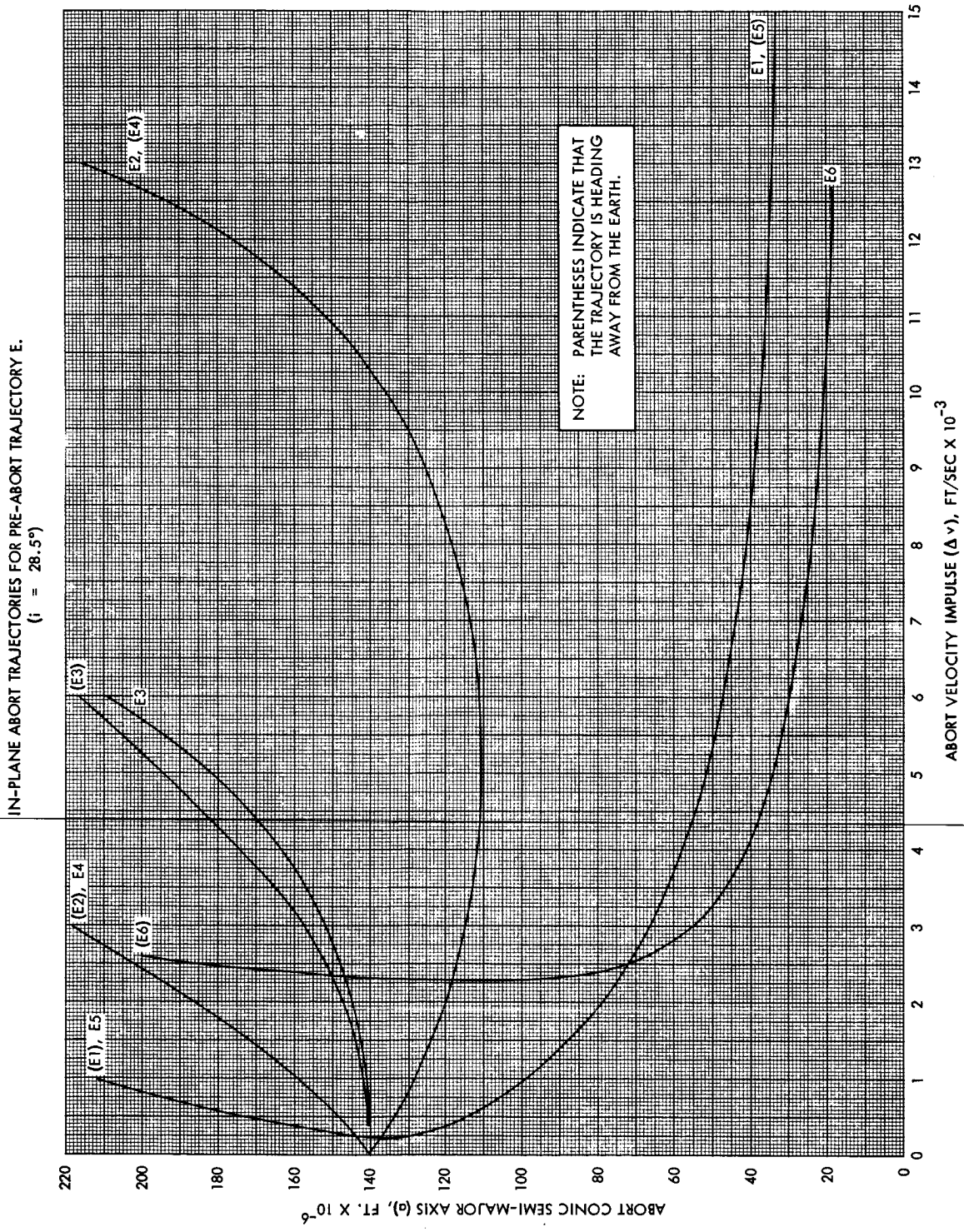

Figure 30. Abort Semi-major Axis (Pre-abort Trajectory E)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

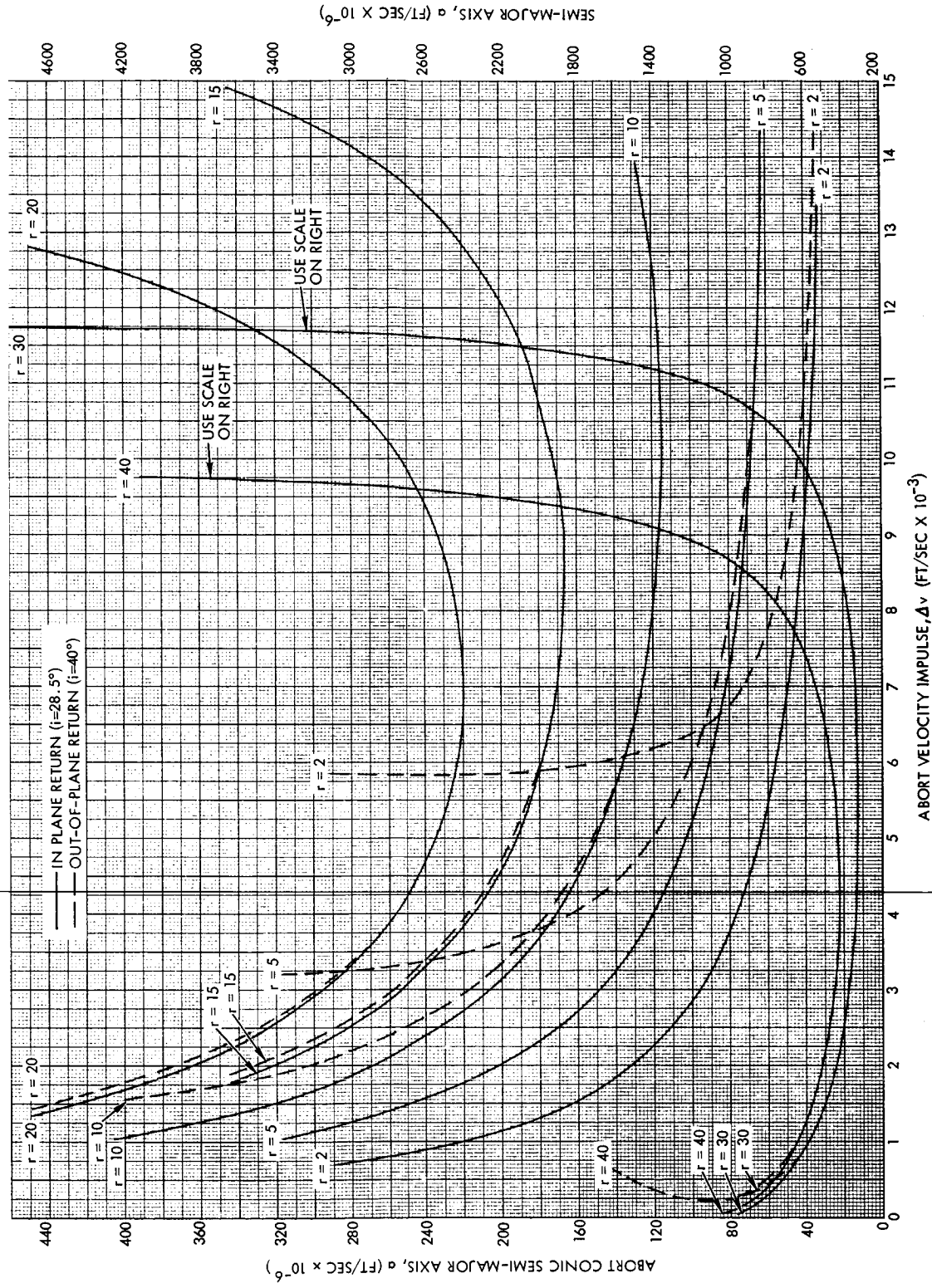

Figure 31. Abort Semi-major Axis (Nominal Translunar Trajectory)

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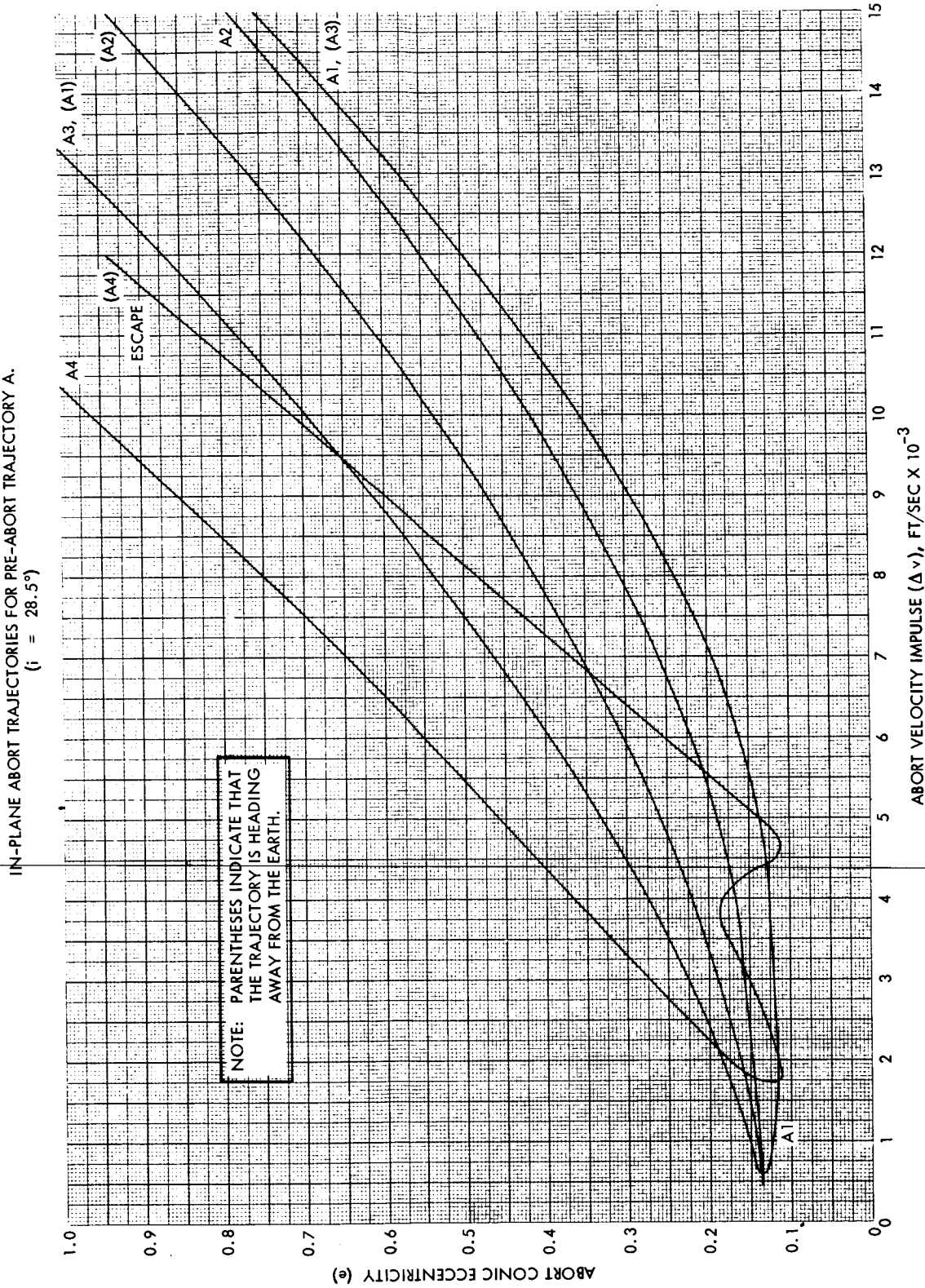

Figure 32. Abort Eccentricity (Pre-abort Trajectory A)

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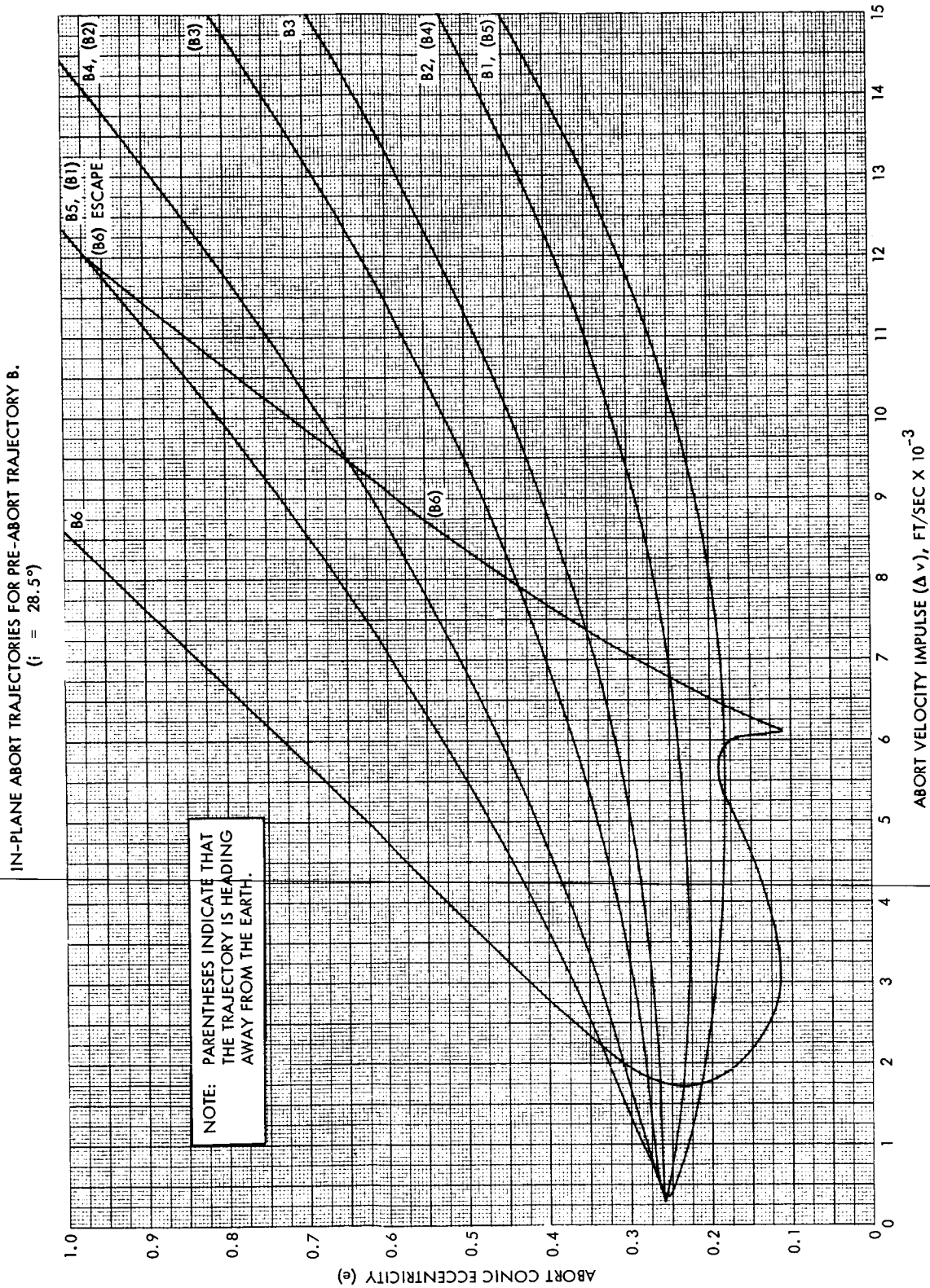

Figure 33. Abort Eccentricity (Pre-abort Trajectory B)

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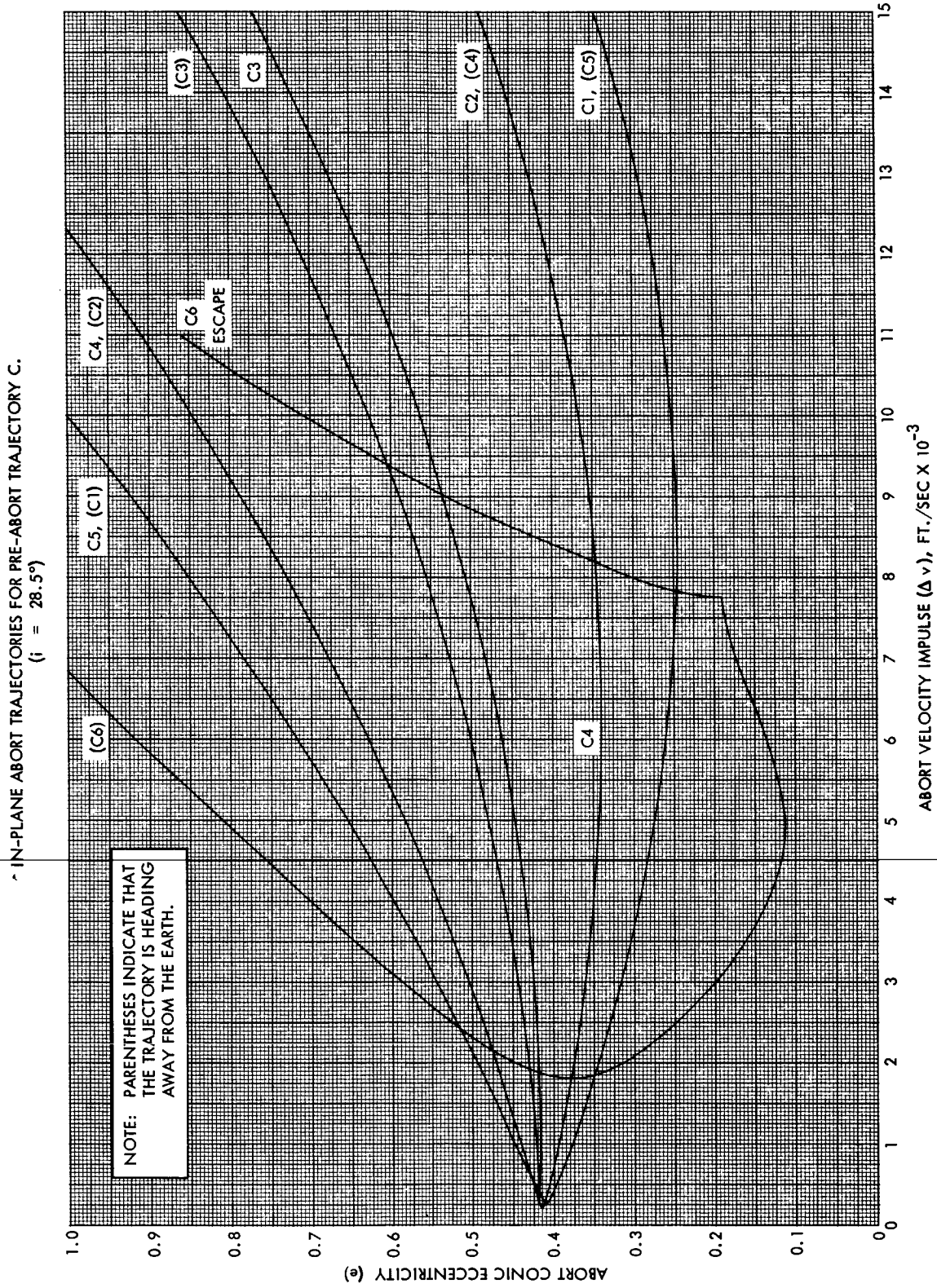

Figure 34. Abort Eccentricity (Pre-abort Trajectory C)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

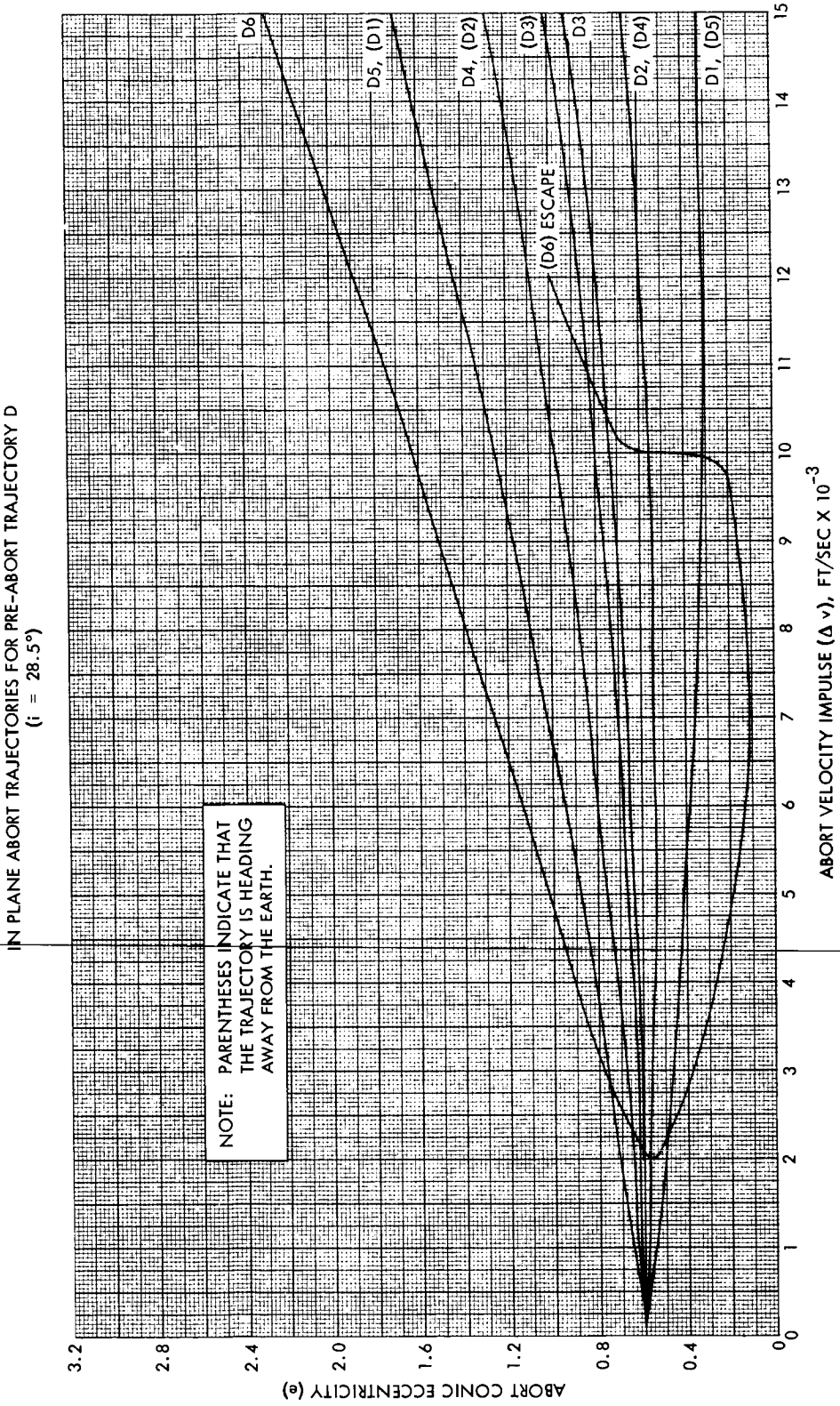

Figure 35. Abort Eccentricity (Pre-abort Trajectory D)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

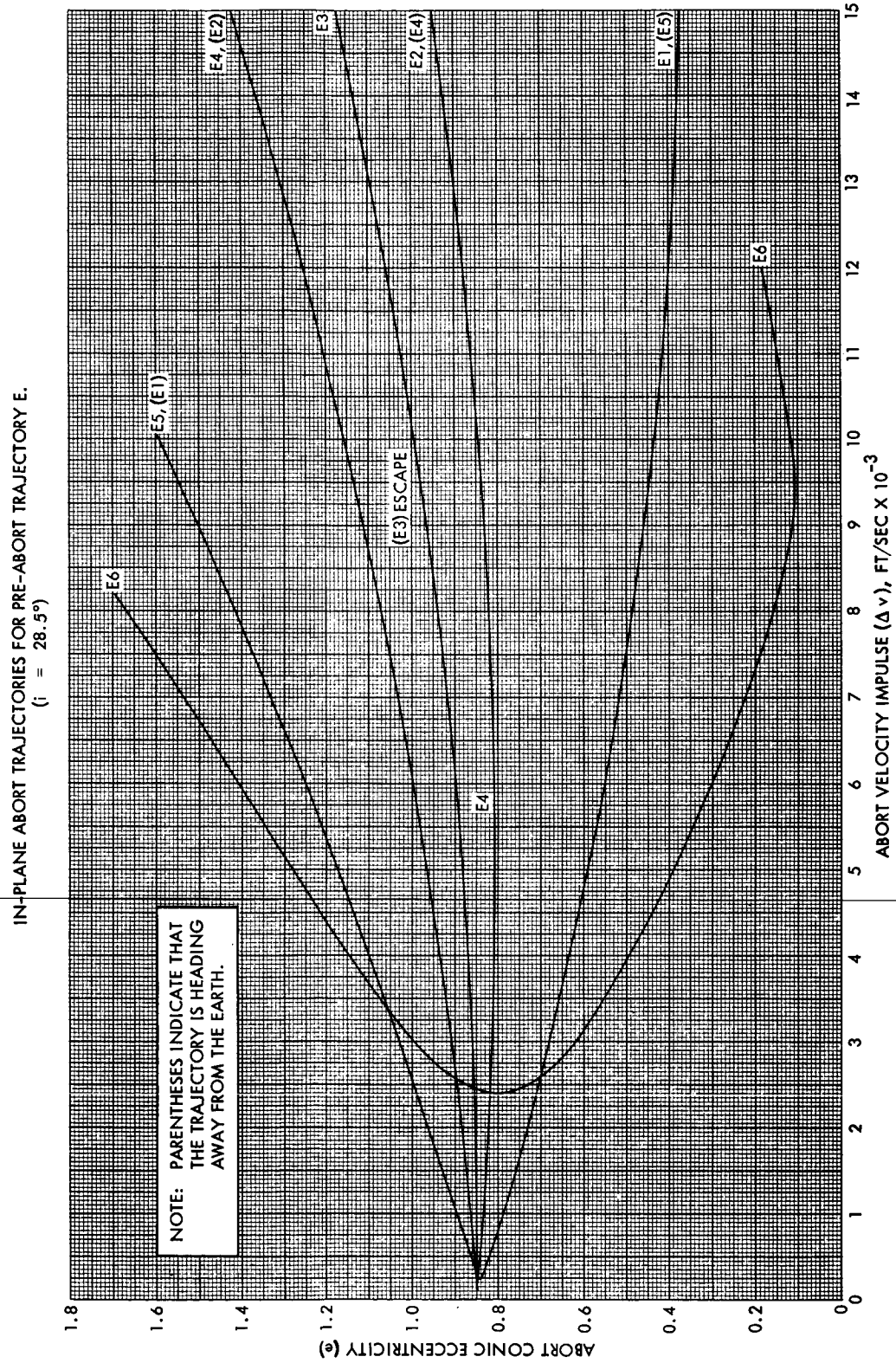

Figure 36. Abort Eccentricity (Pre-abort Trajectory E)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

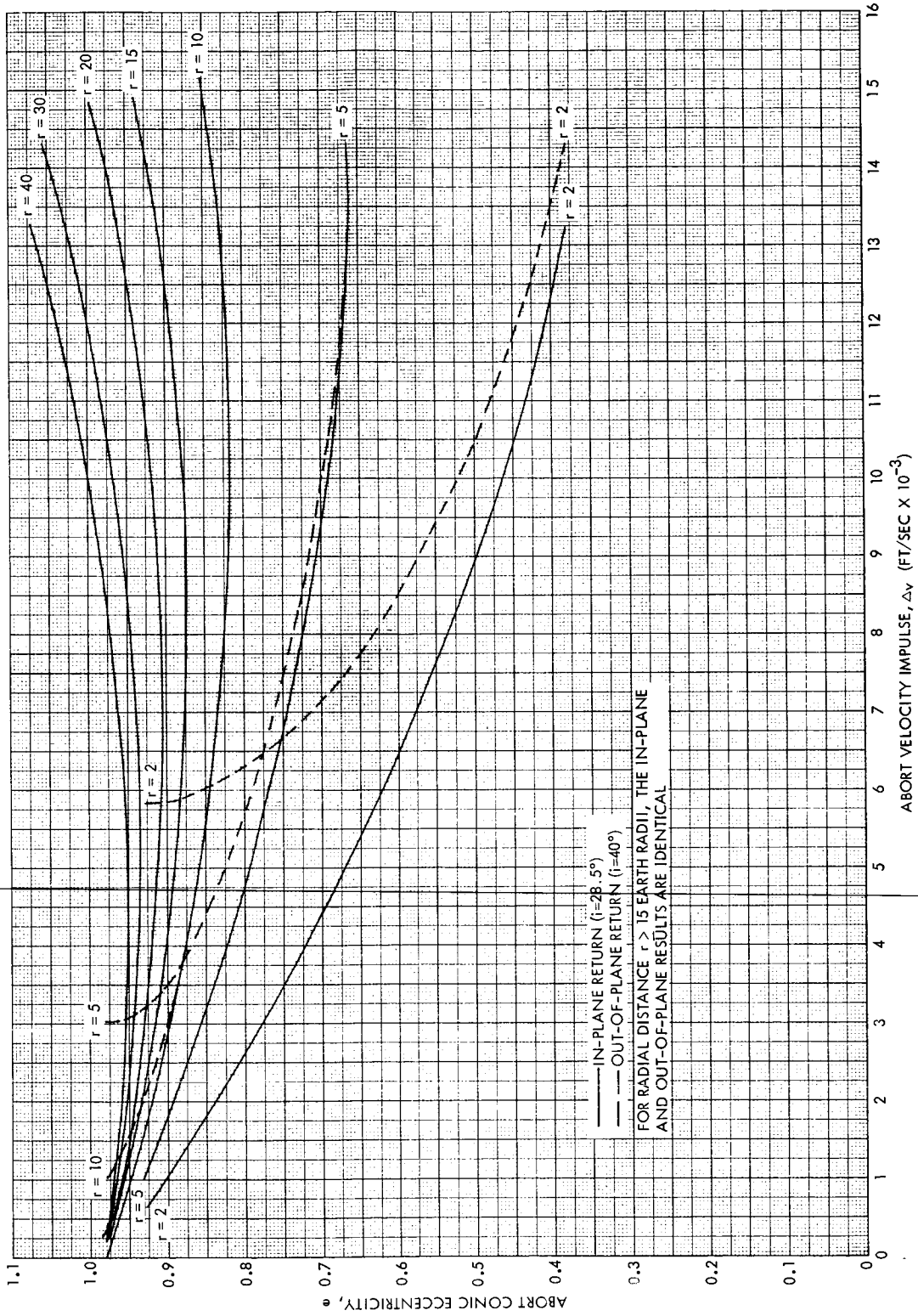

Figure 37. Abort Eccentricity (Nominal Translunar Trajectory)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

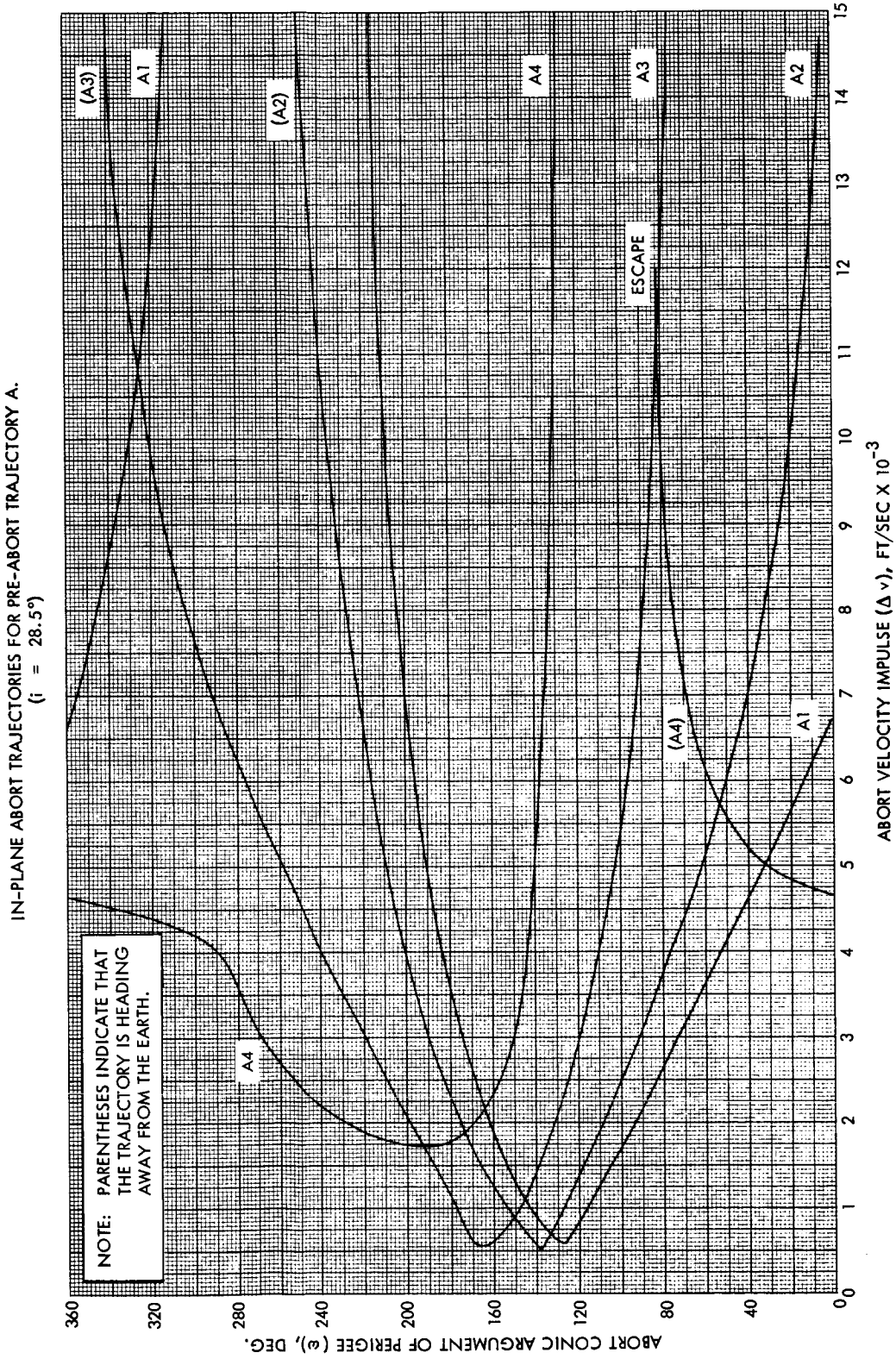

Figure 38. Abort Argument of Perigee (Pre-abort Trajectory A)

This document contains information affecting the national defense [redacted] United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of wh[redacted] manner to an unauthorized person is prohibited by law.

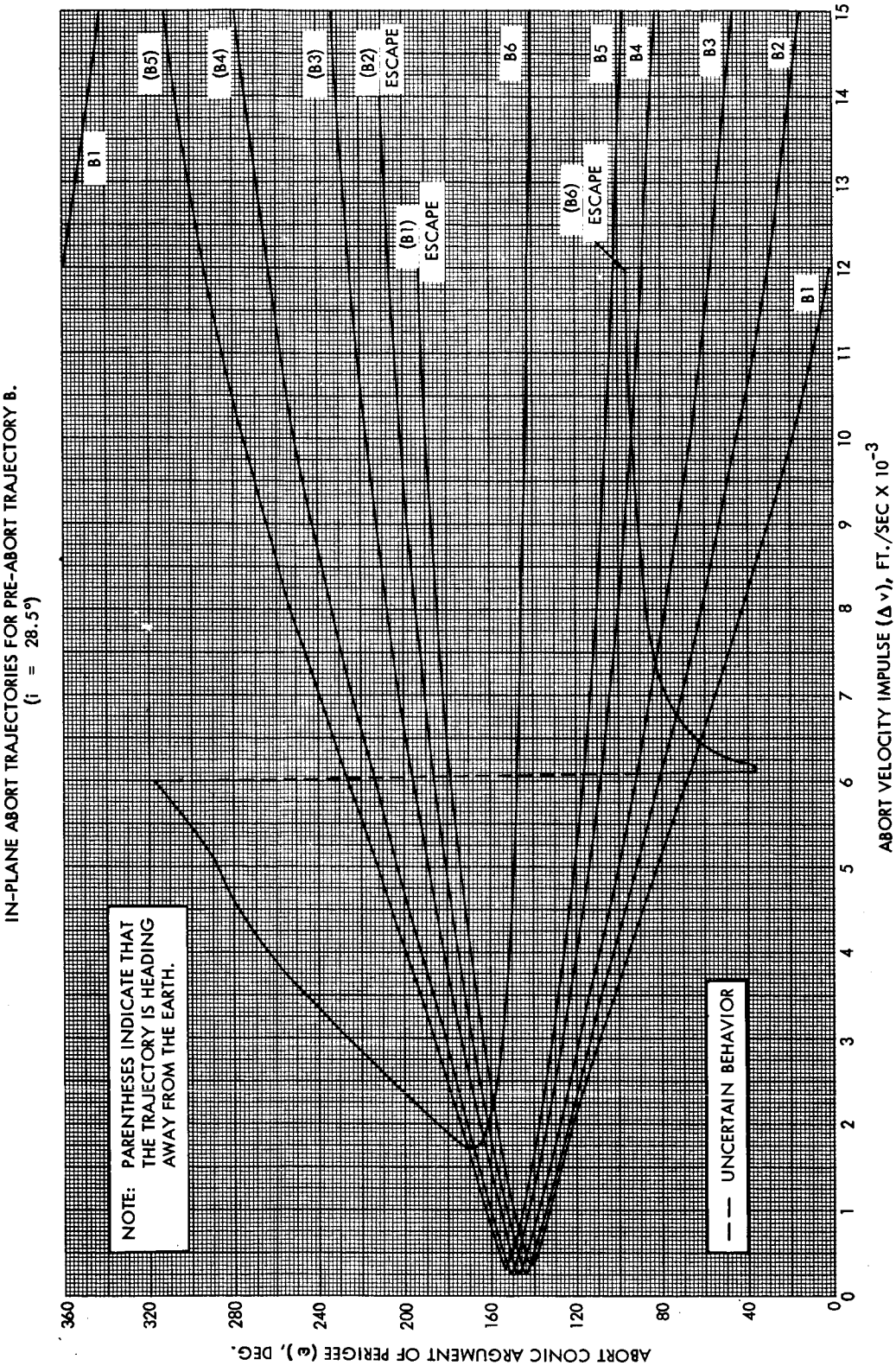

Figure 39. Abort Argument of Perigee (Pre-abort Trajectory B)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

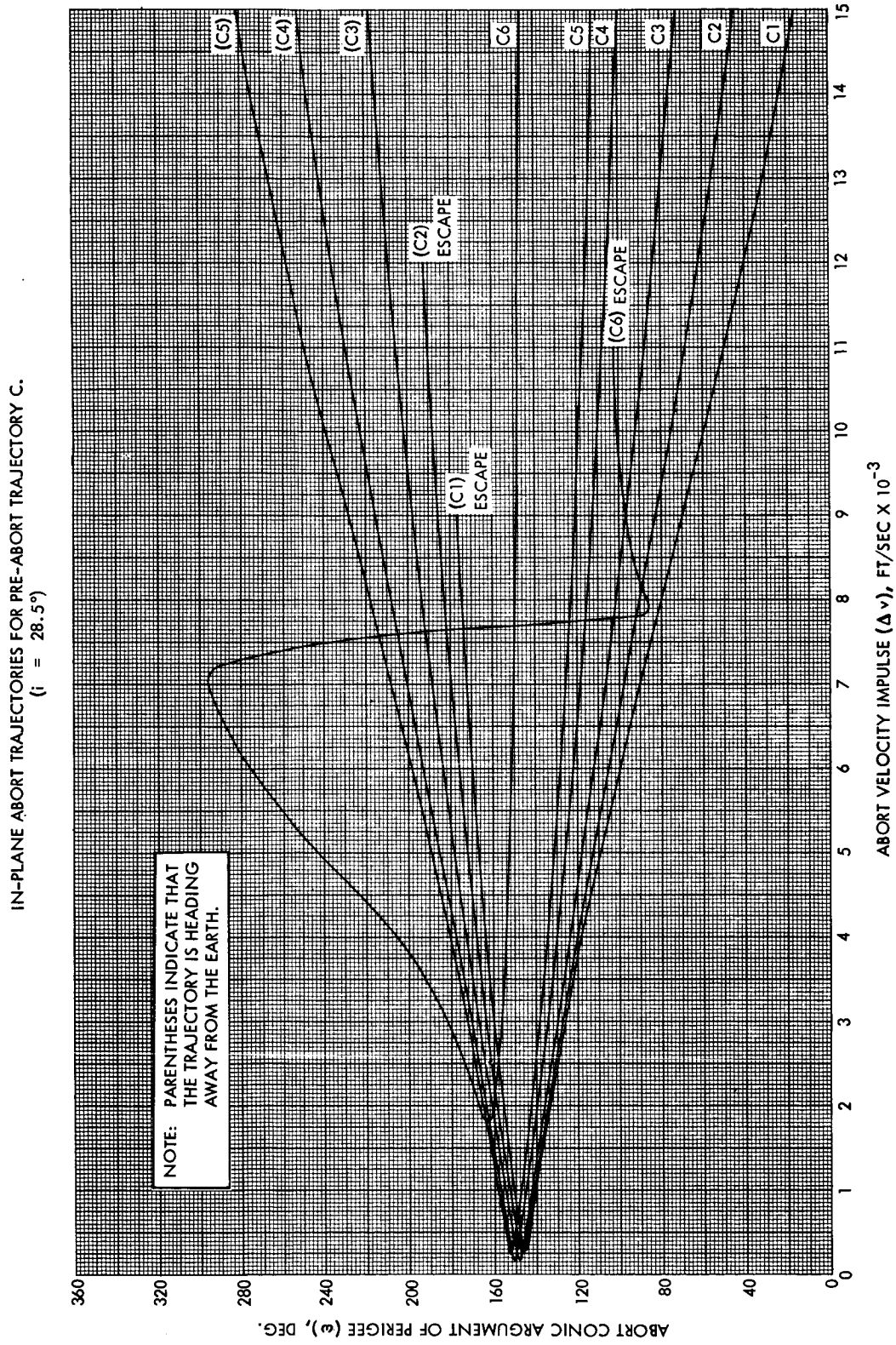

Figure 40. Abort Argument of Perigee (Pre-abort Trajectory C)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

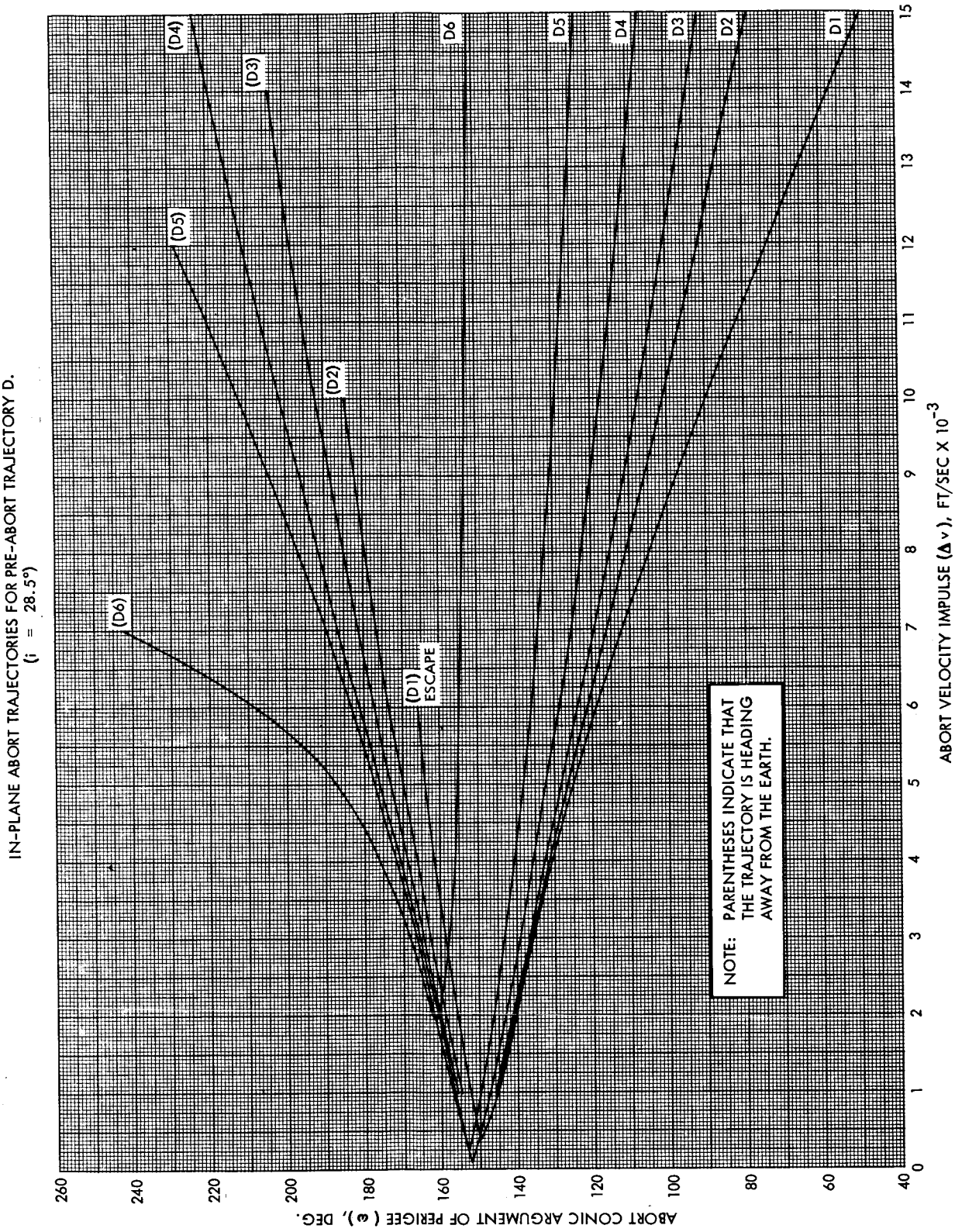

Figure 41. Abort Argument of Perigee (Pre-abort Trajectory D)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

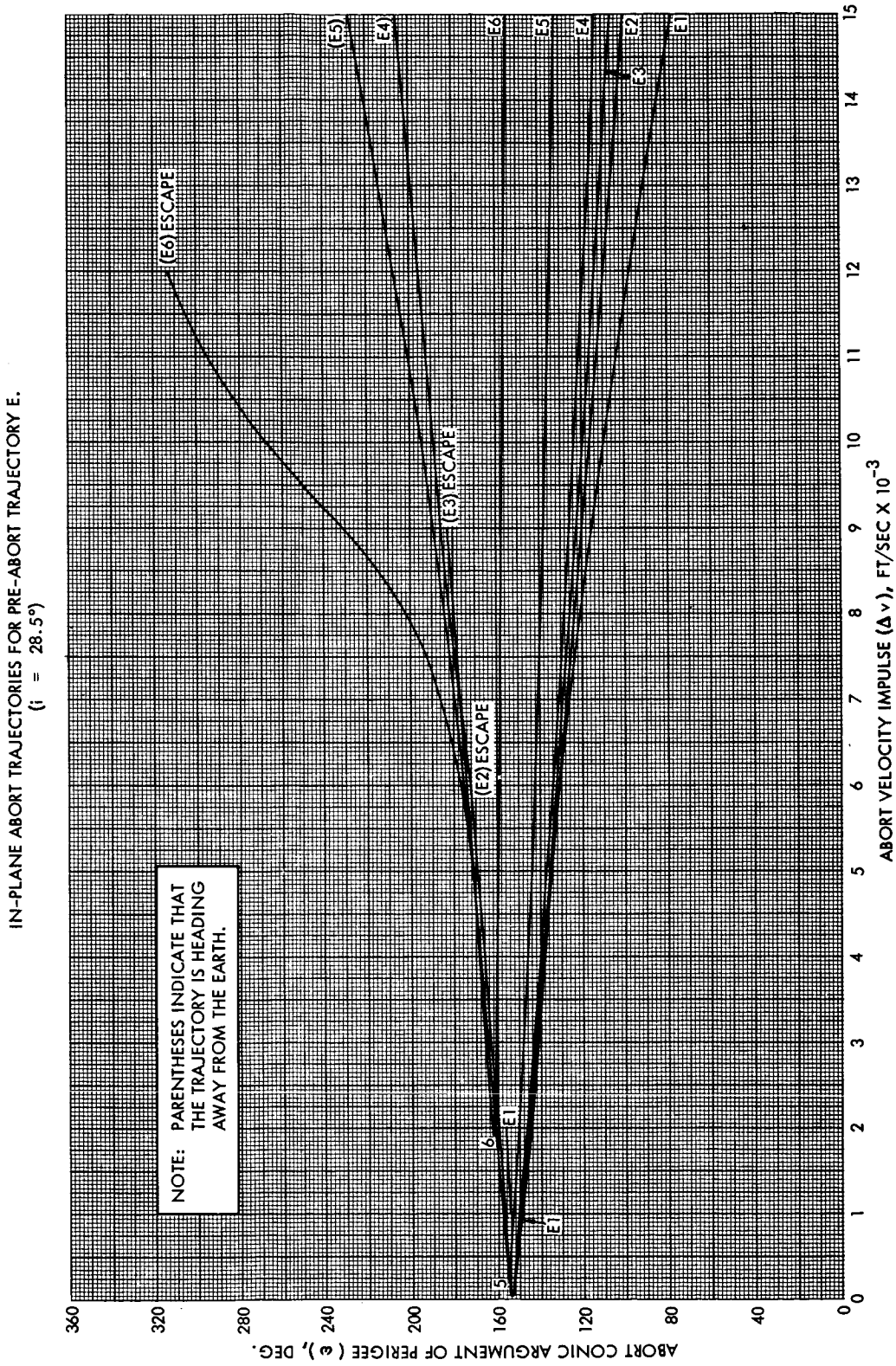

Figure 42. Abort Argument of Perigee (Pre-abort Trajectory E)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

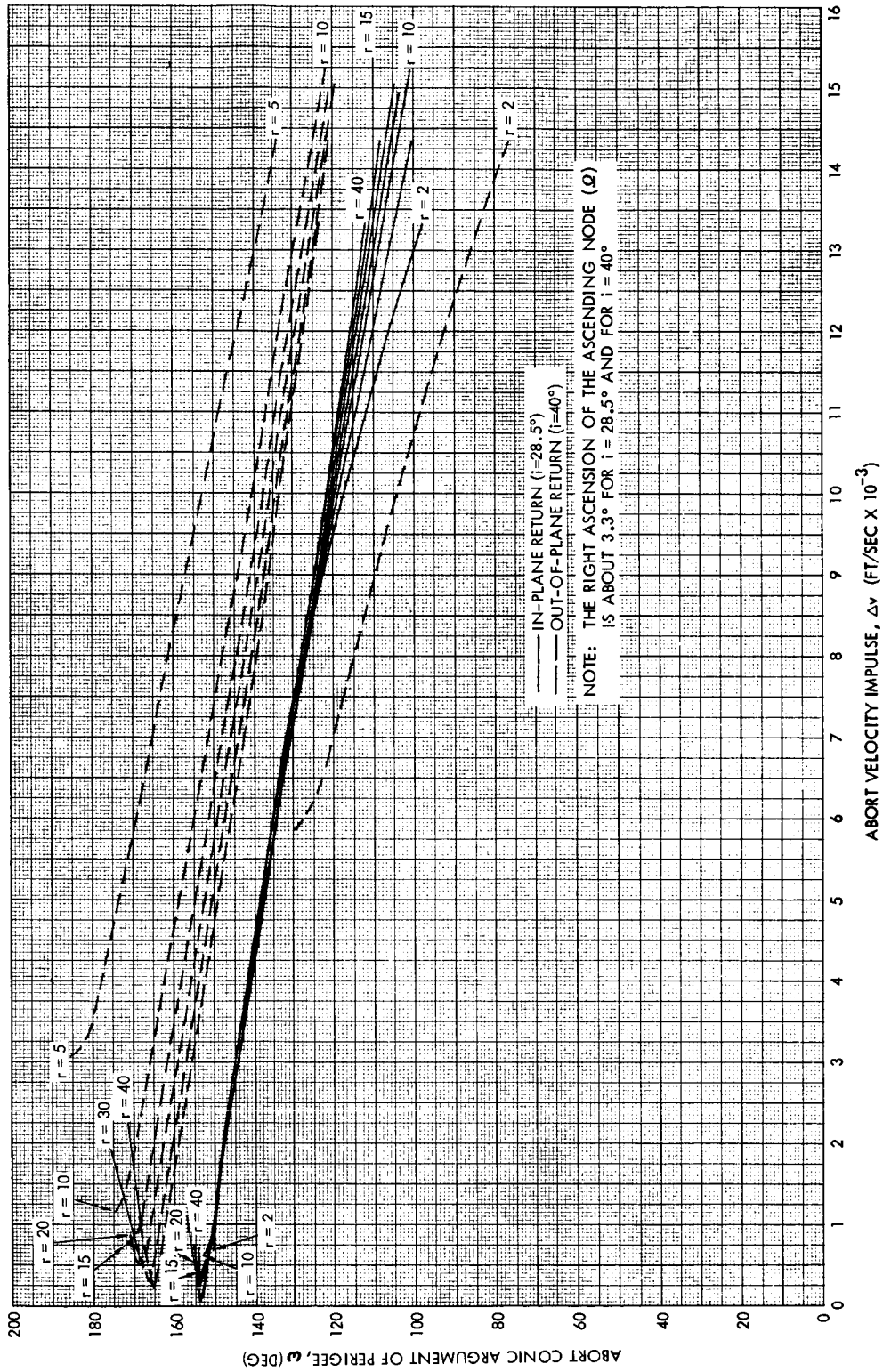

Figure 43. Abort Argument of Perigee (Nominal Translunar Trajectory)

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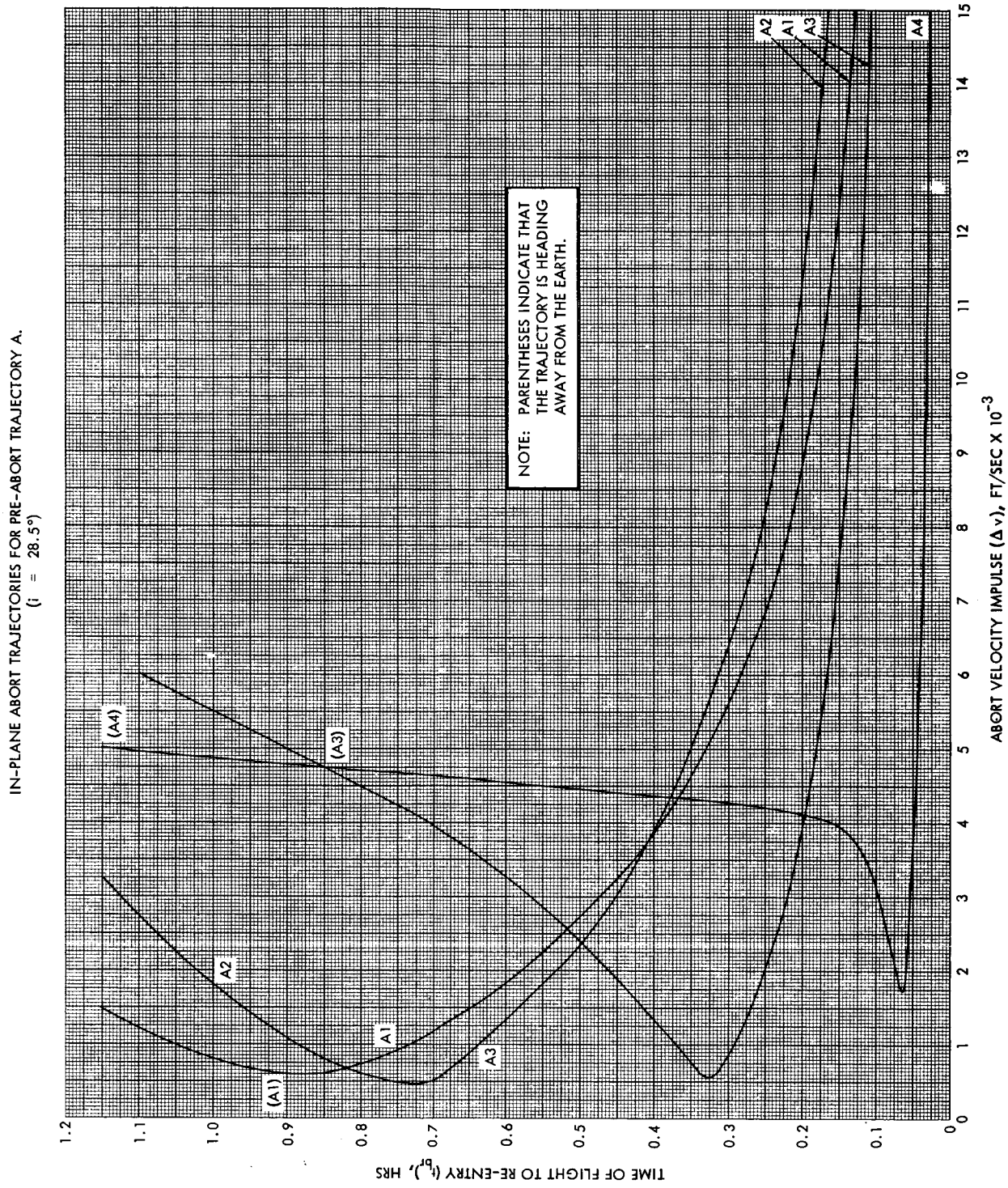

Figure 44. Abort Flight Time to Re-entry (Pre-abort Trajectory A)

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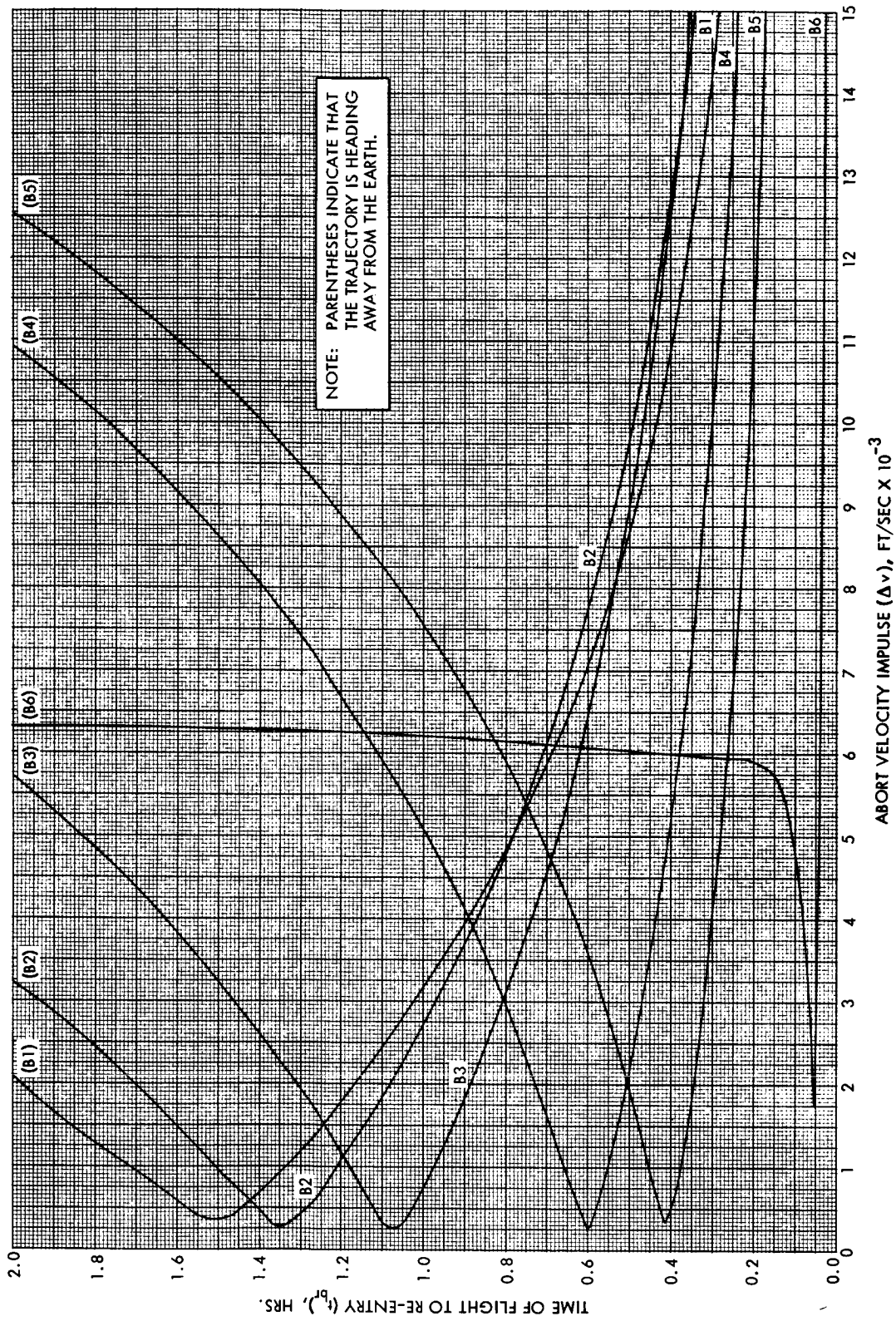
IN-PLANE ABORT TRAJECTORIES FOR PRE-ABORT TRAJECTORY B.
(i = 28.5°)



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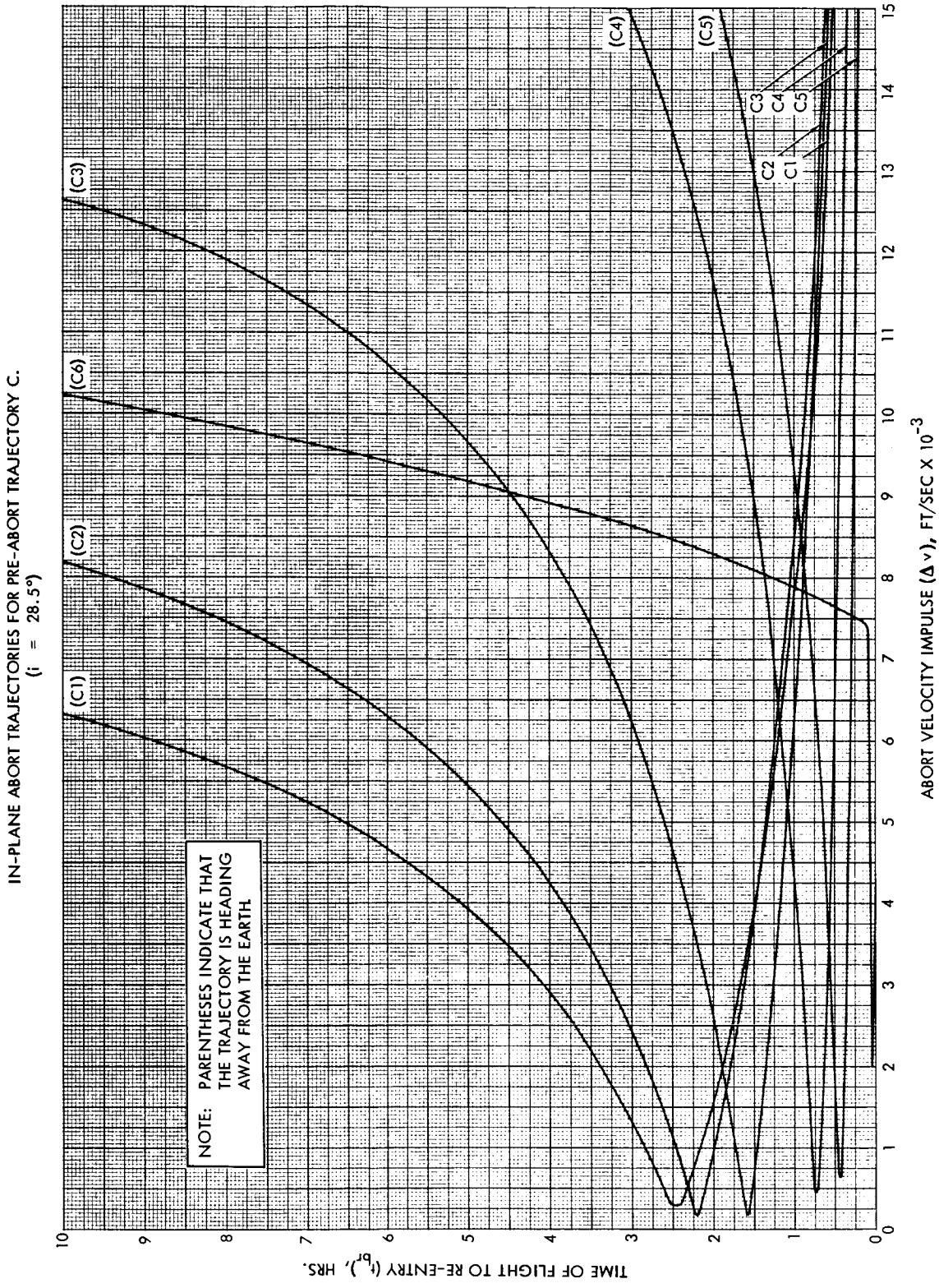

Figure 46. Abort Flight Time to Re-entry (Pre-abort Trajectory C)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

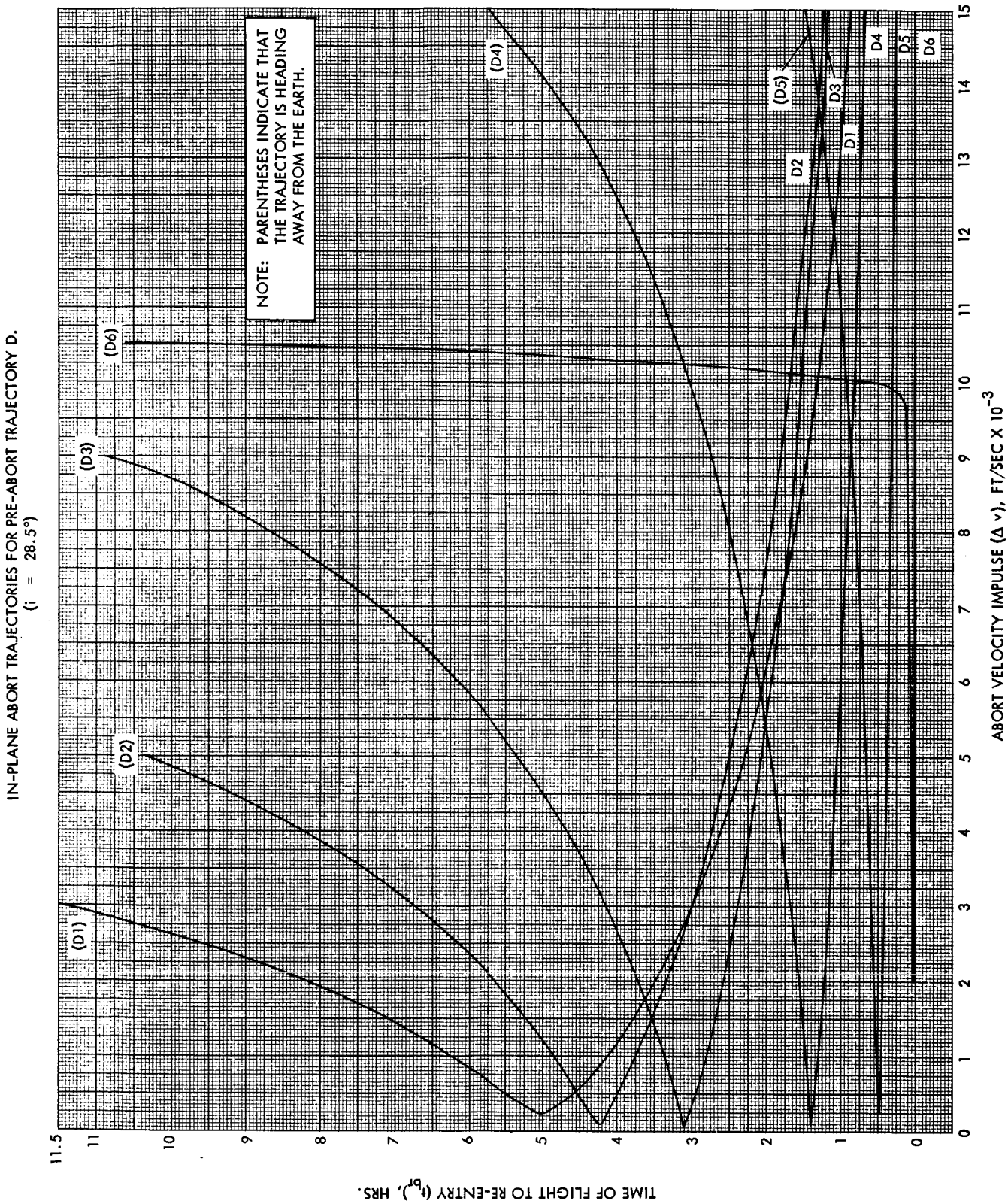

Figure 47. Abort Flight Time to Re-entry (Pre-abort Trajectory D)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

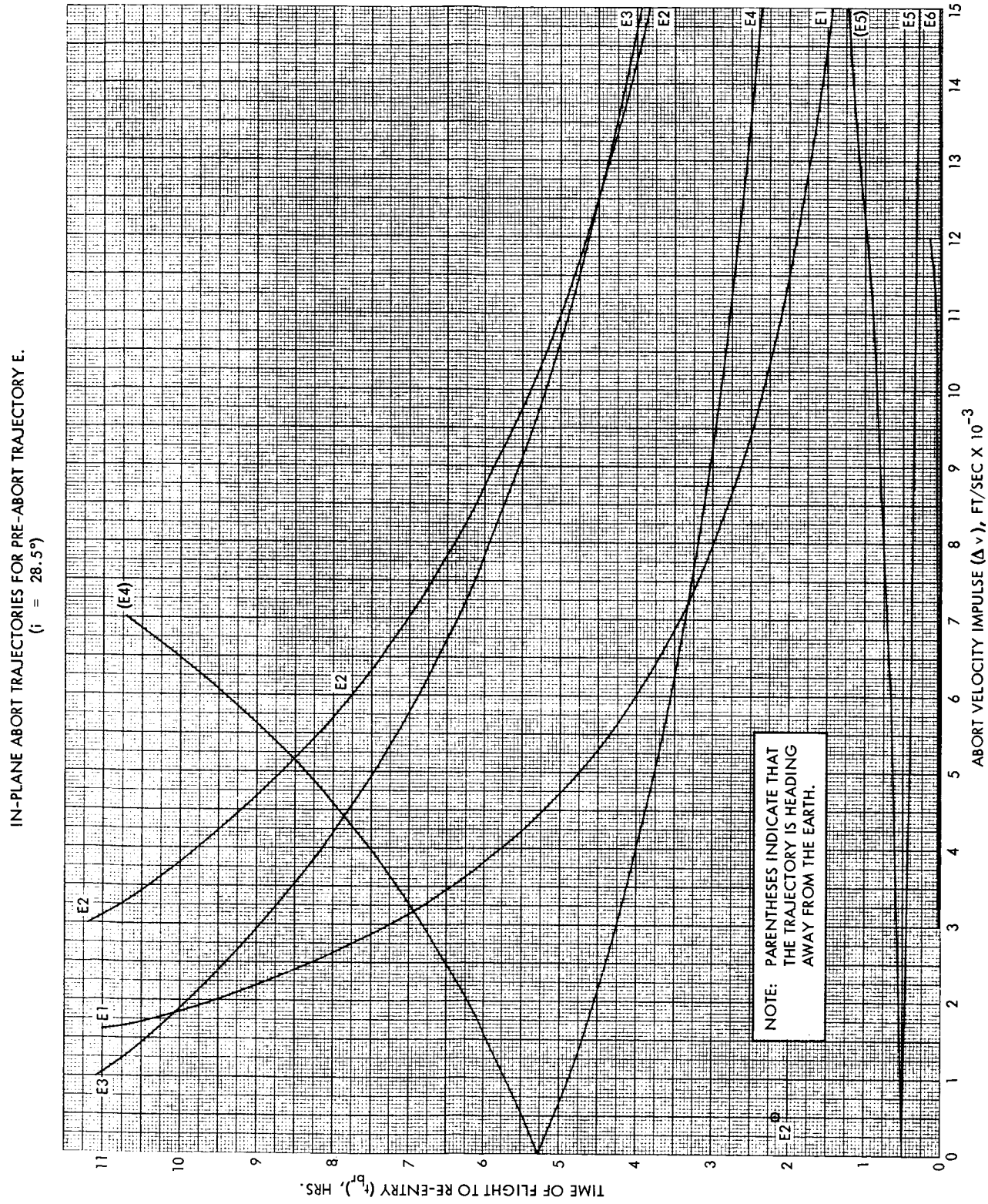

Figure 48. Abort Flight Time to Re-entry (Pre-abort Trajectory E)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

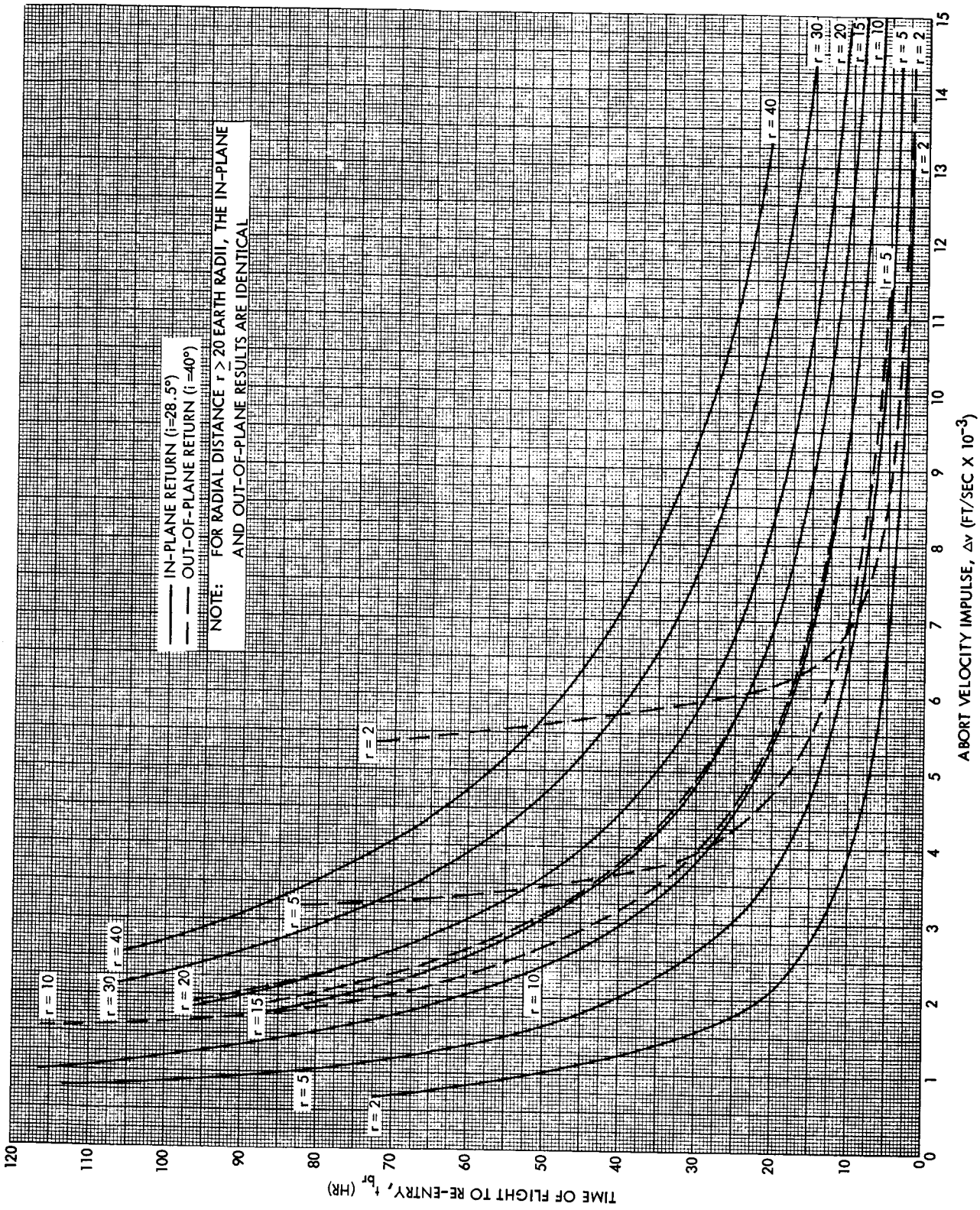

Figure 49. Abort Flight Time to Re-entry (Nominal Translunar Trajectory)

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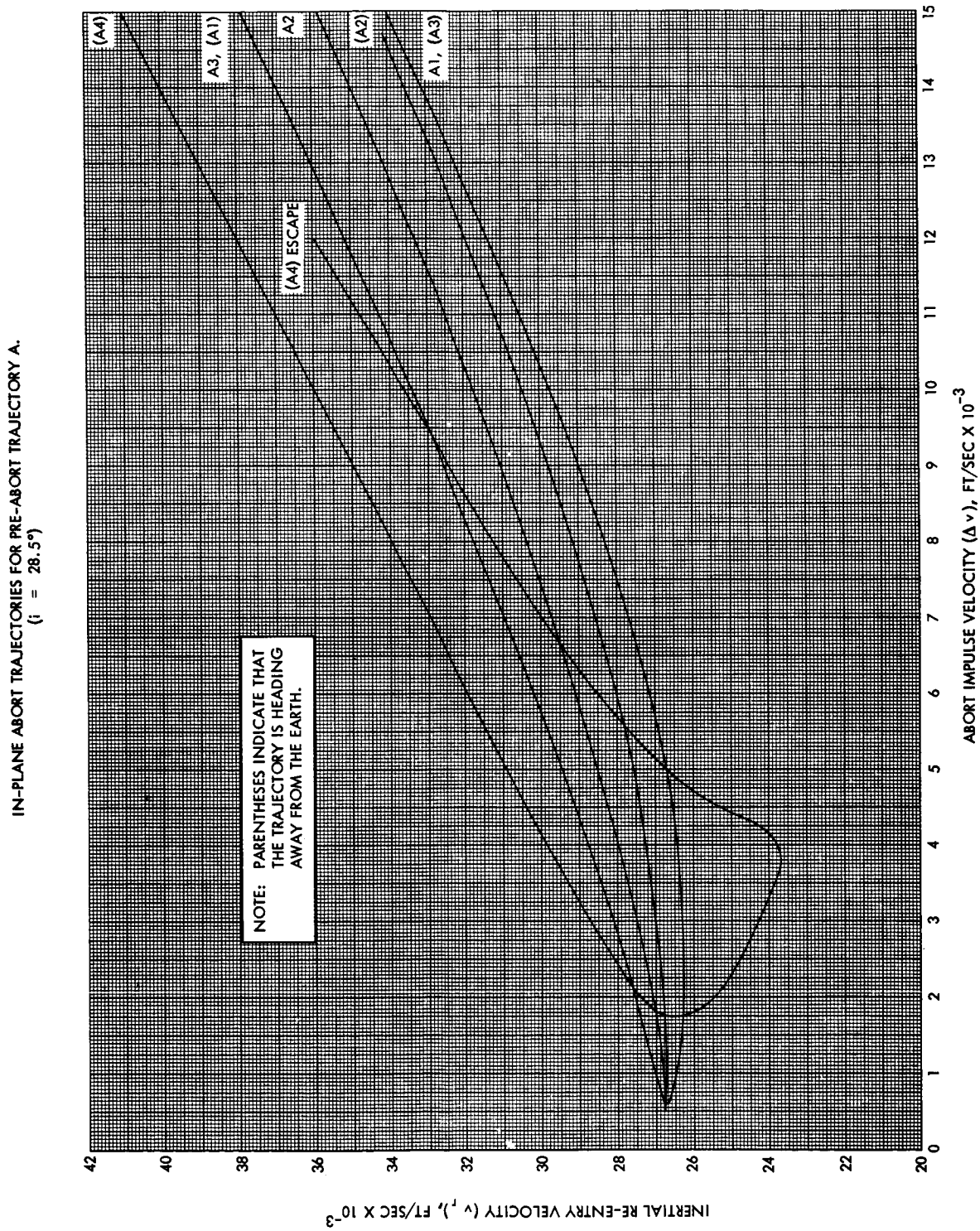

Figure 50. Abort Re-entry Velocity (Pre-abort Trajectory A)

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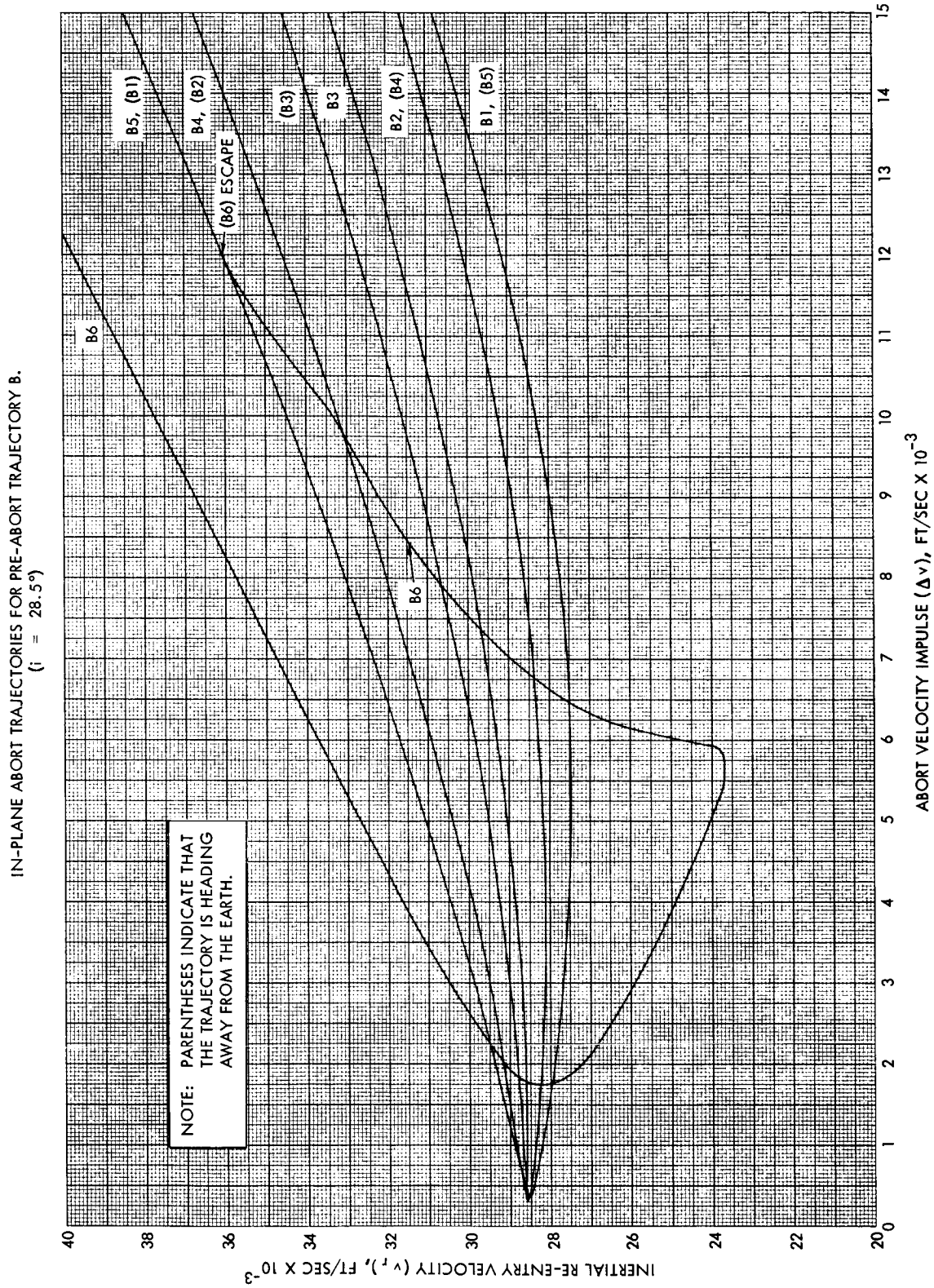

Figure 51. Abort Re-entry Velocity (Pre-abort Trajectory B)

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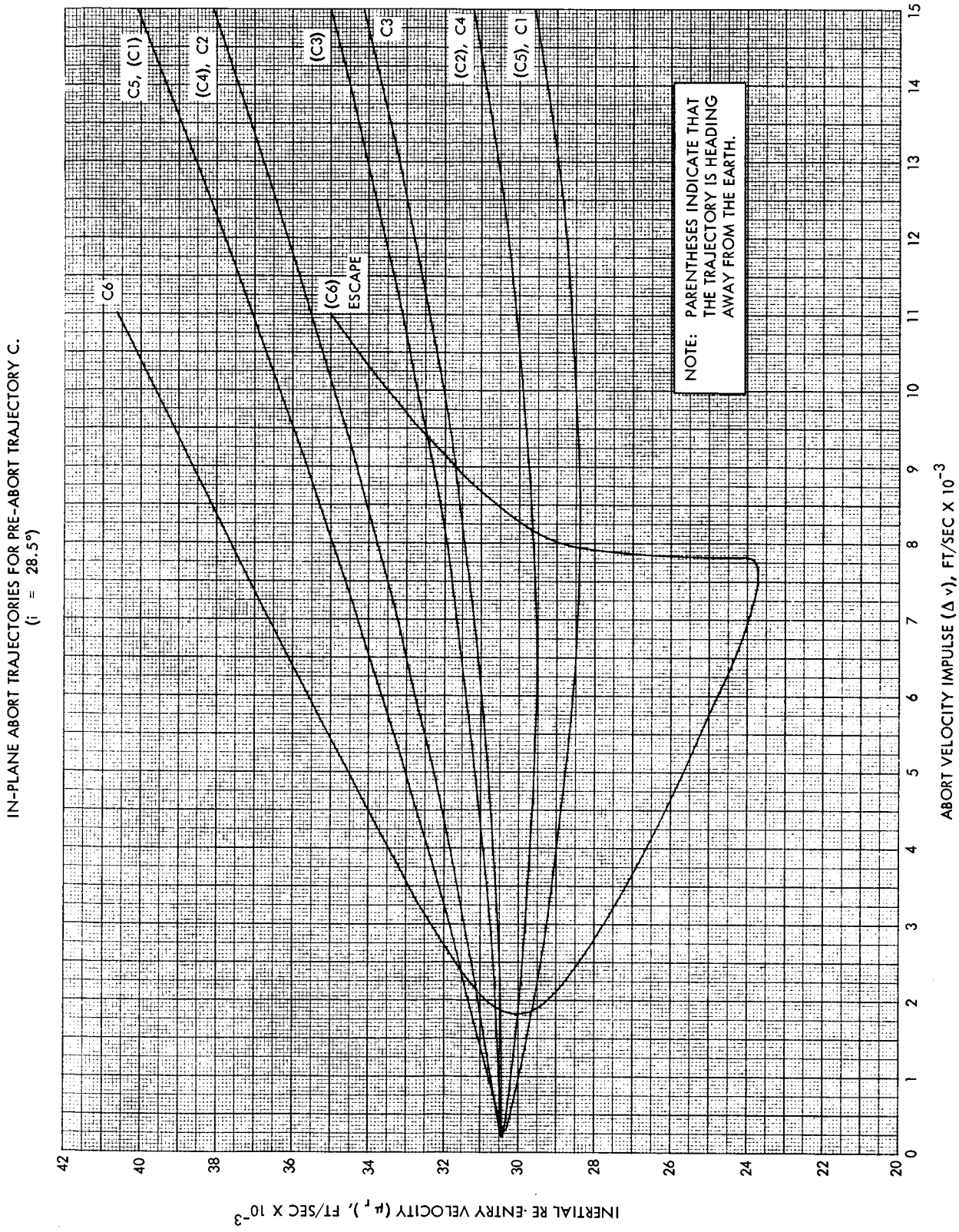

Figure 52. Abort Re-entry Velocity (Pre-abort Trajectory C)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

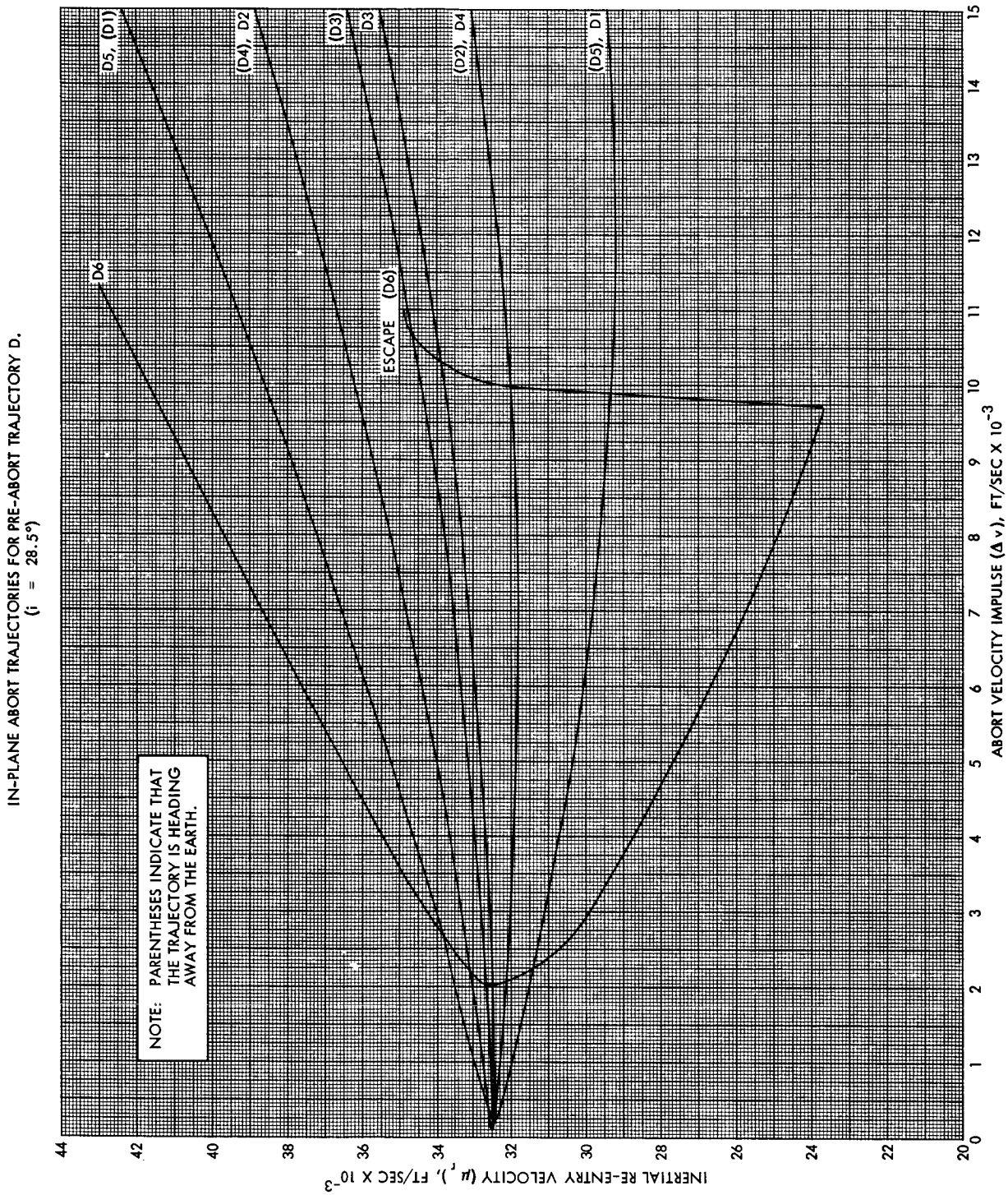

Figure 53. Abort Re-entry Velocity (Pre-abort Trajectory D)

This document contains information affecting the national de[redacted]nited States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation [redacted] in any manner to an unauthorized person is prohibited by law.

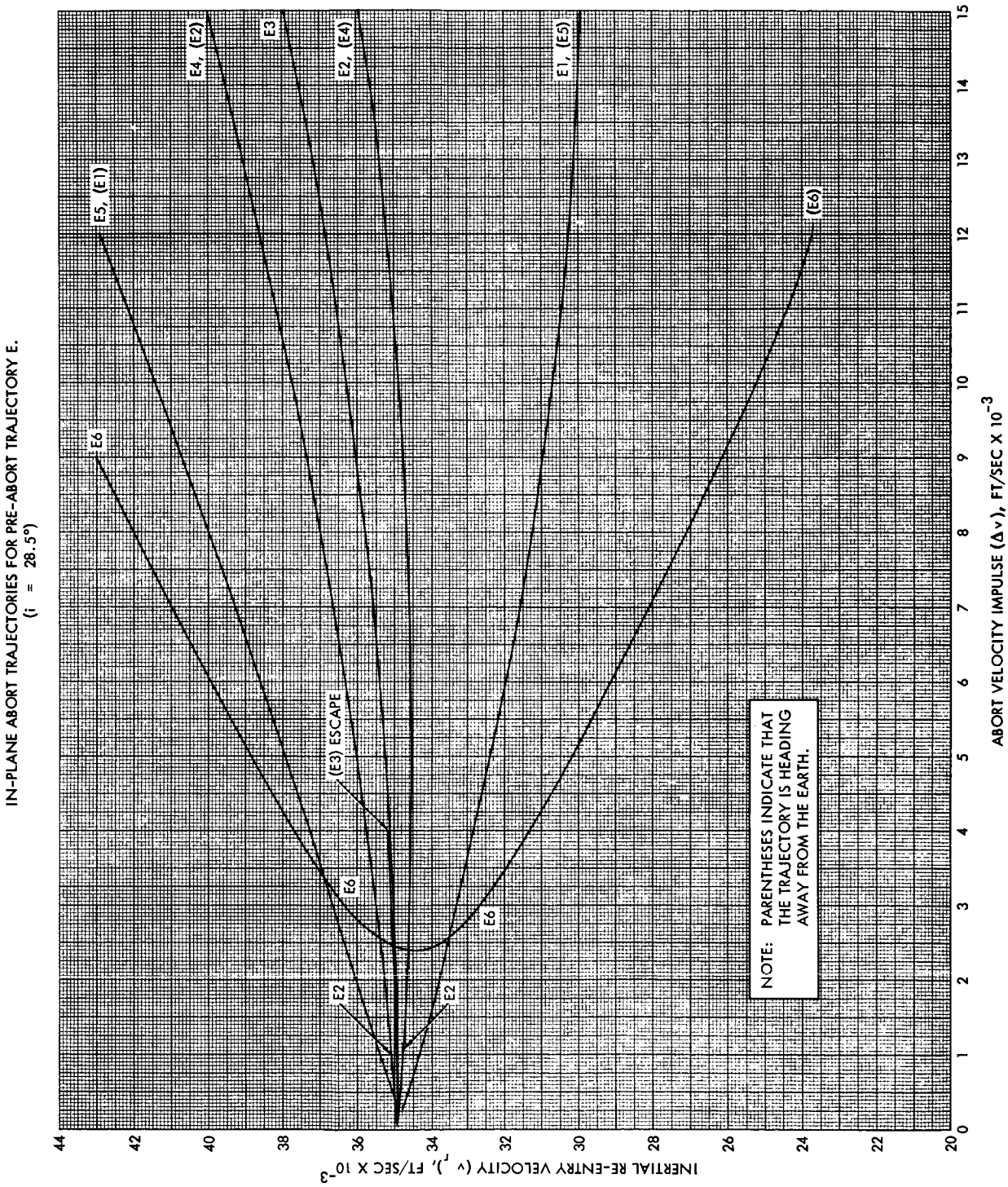

Figure 54. Abort Re-entry Velocity (Pre-abort Trajectory E)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

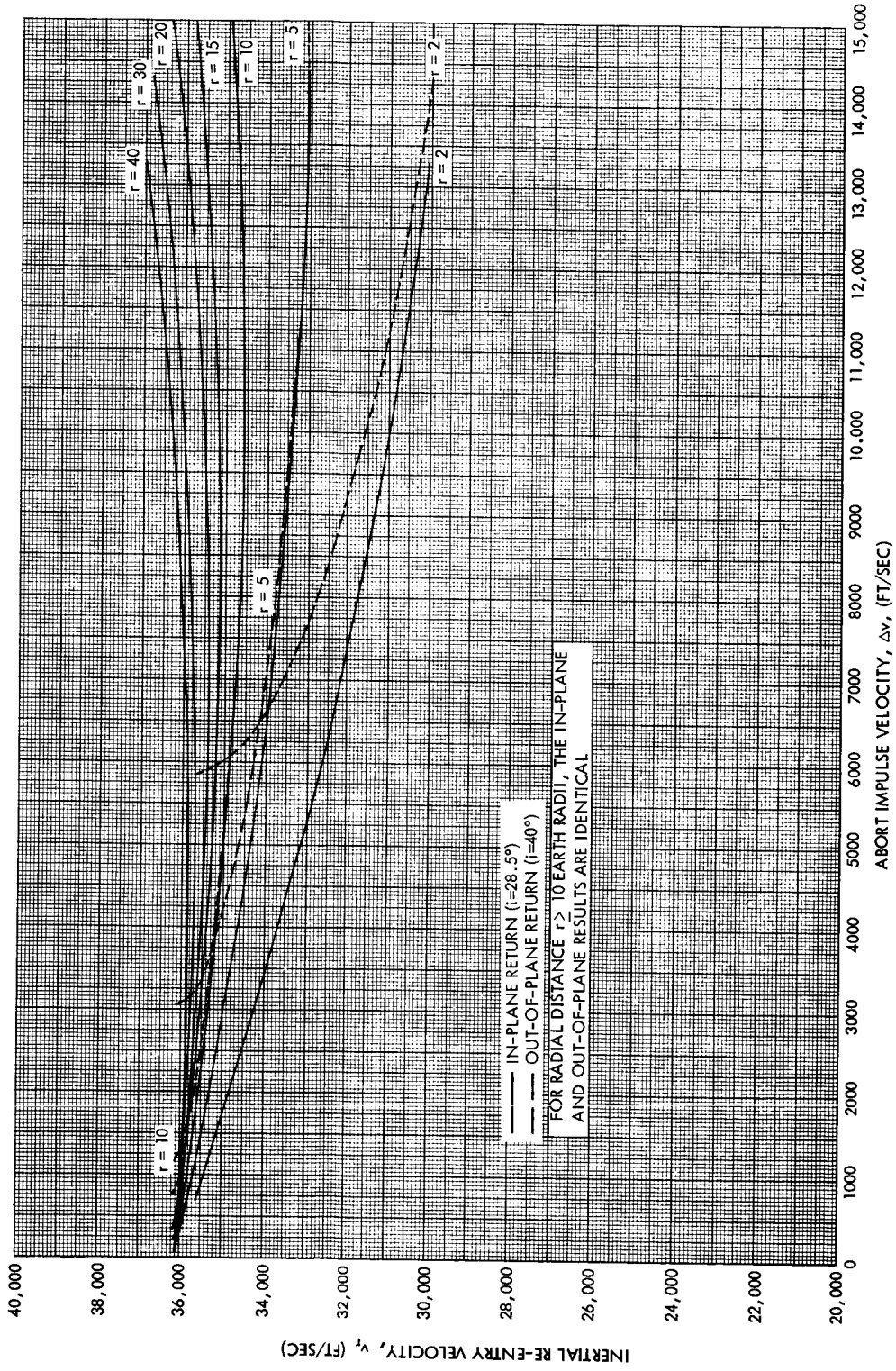

Figure 55. Abort Re-entry Velocity (Nominal Translunar Trajectory)

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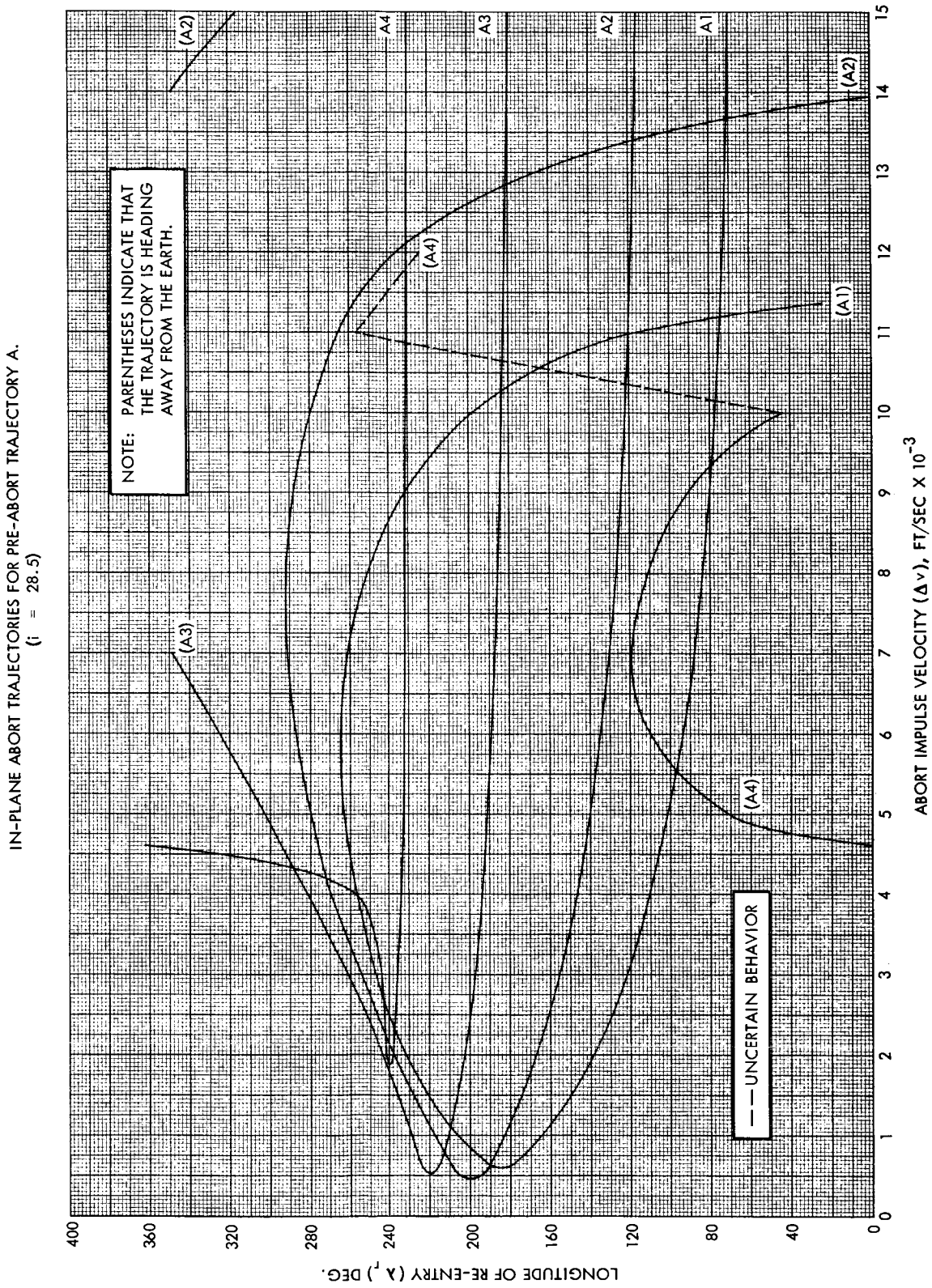

Figure 56. Abort Re-entry Longitude (Pre-abort Trajectory A)

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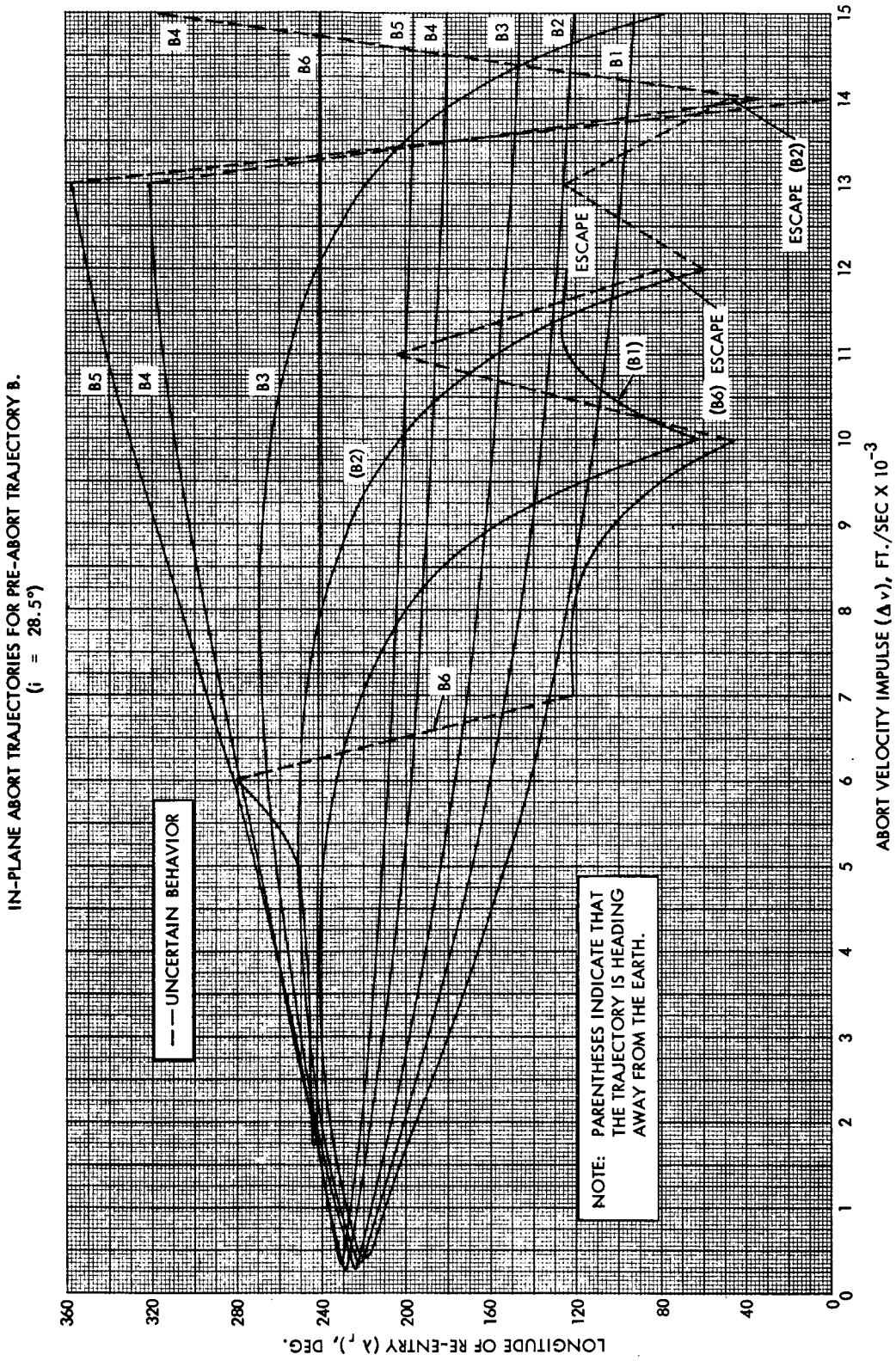

Figure 57. Abort Re-entry Longitude (Pre-abort Trajectory B)

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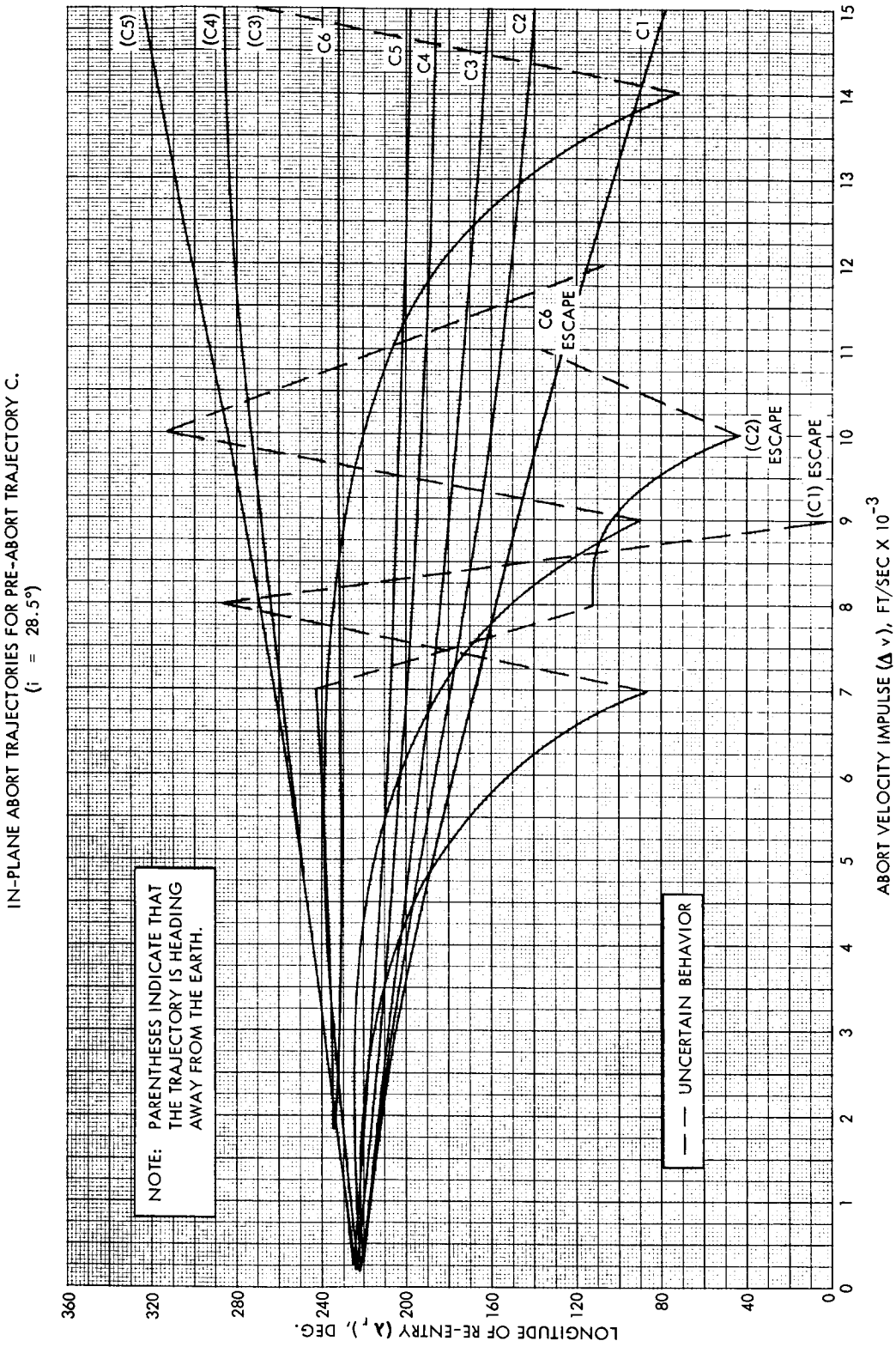

Figure 58. Abort Re-entry Longitude (Pre-abort Trajectory C)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

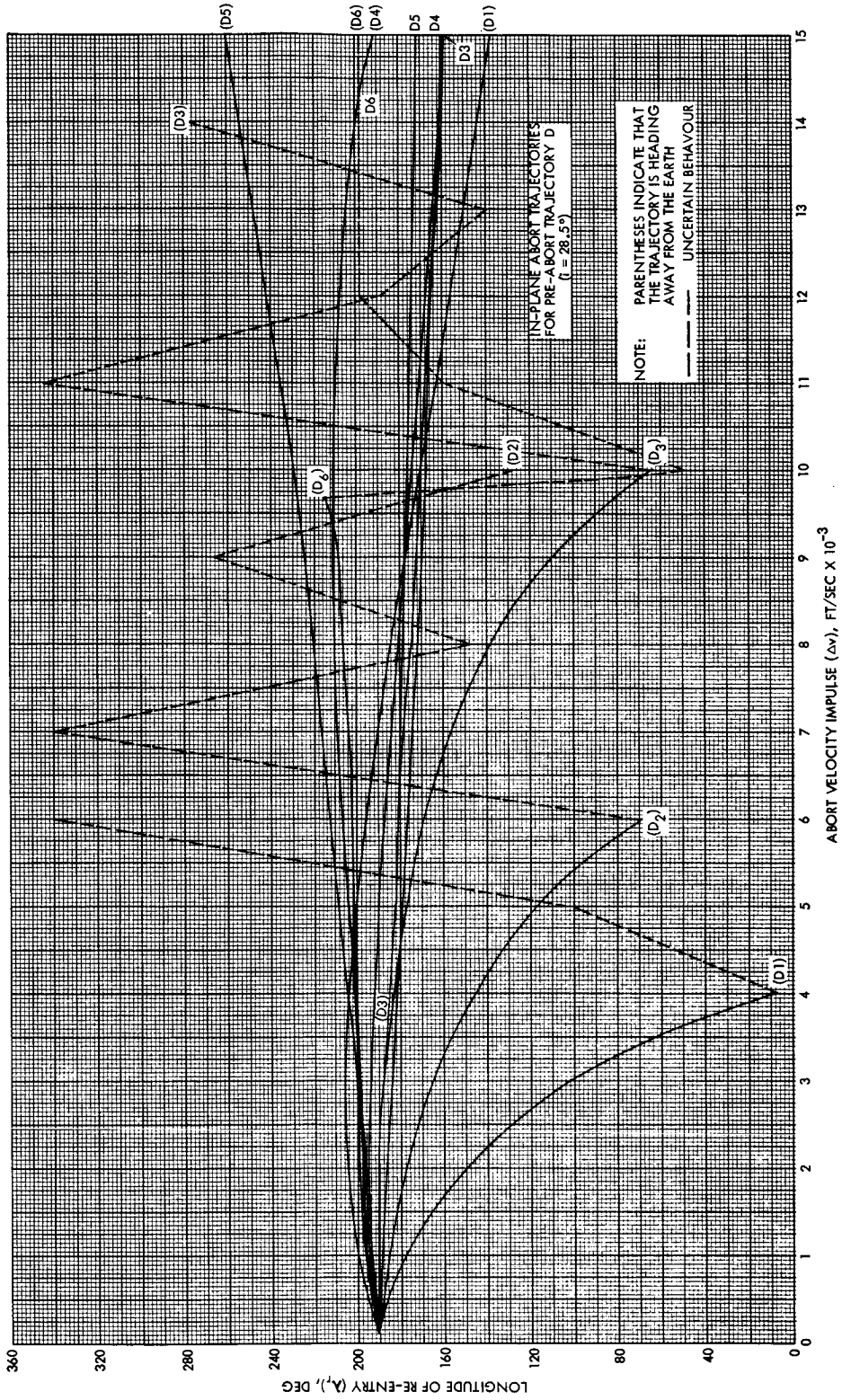

Figure 59. Abort Re-entry Longitude (Pre-abort Trajectory D)

This document contains information affecting [redacted] defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission [redacted]lation of which in any manner to an unauthorized person is prohibited by law.

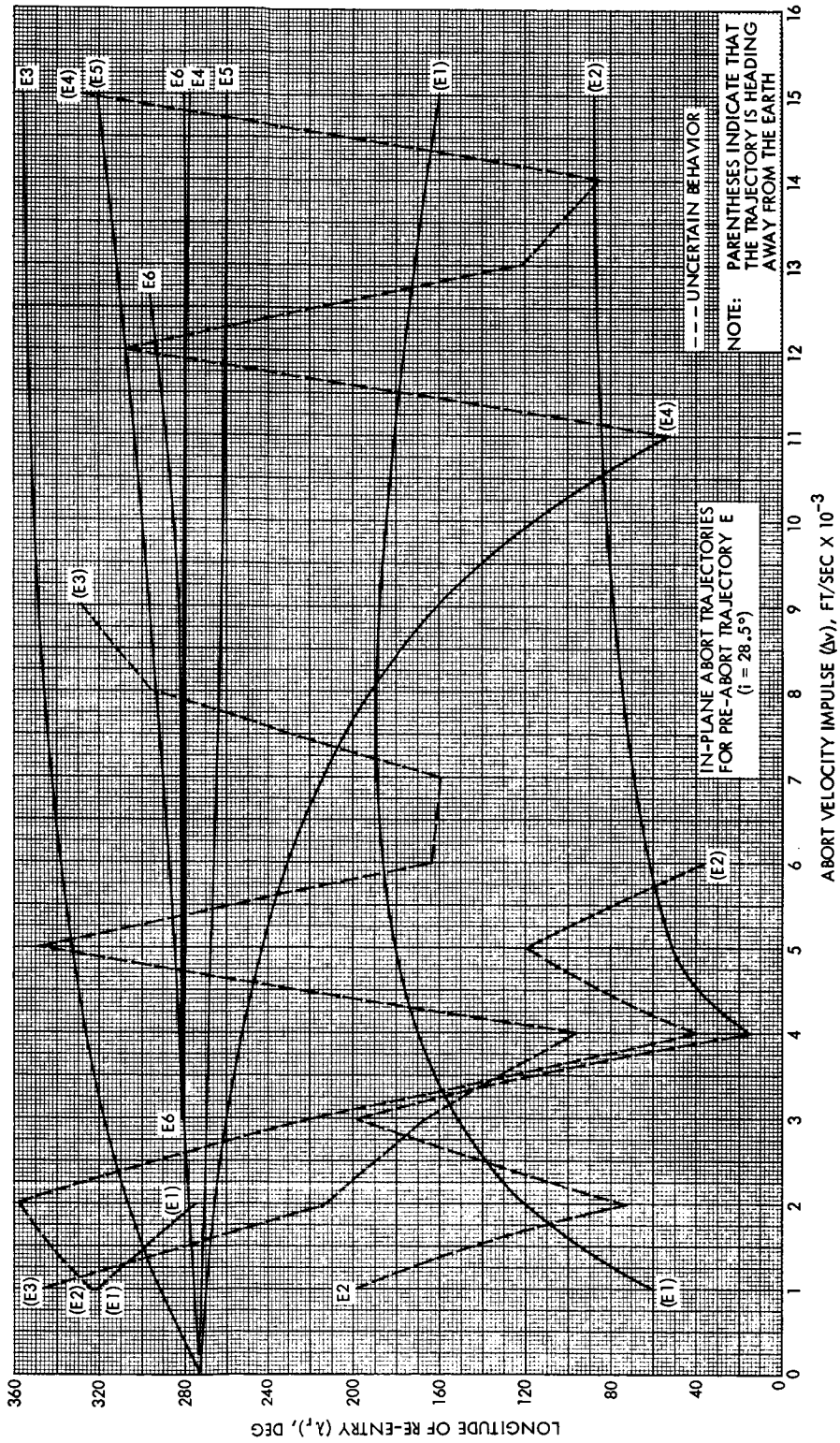

Figure 60. Abort Re-entry Longitude (Pre-abort Trajectory E)

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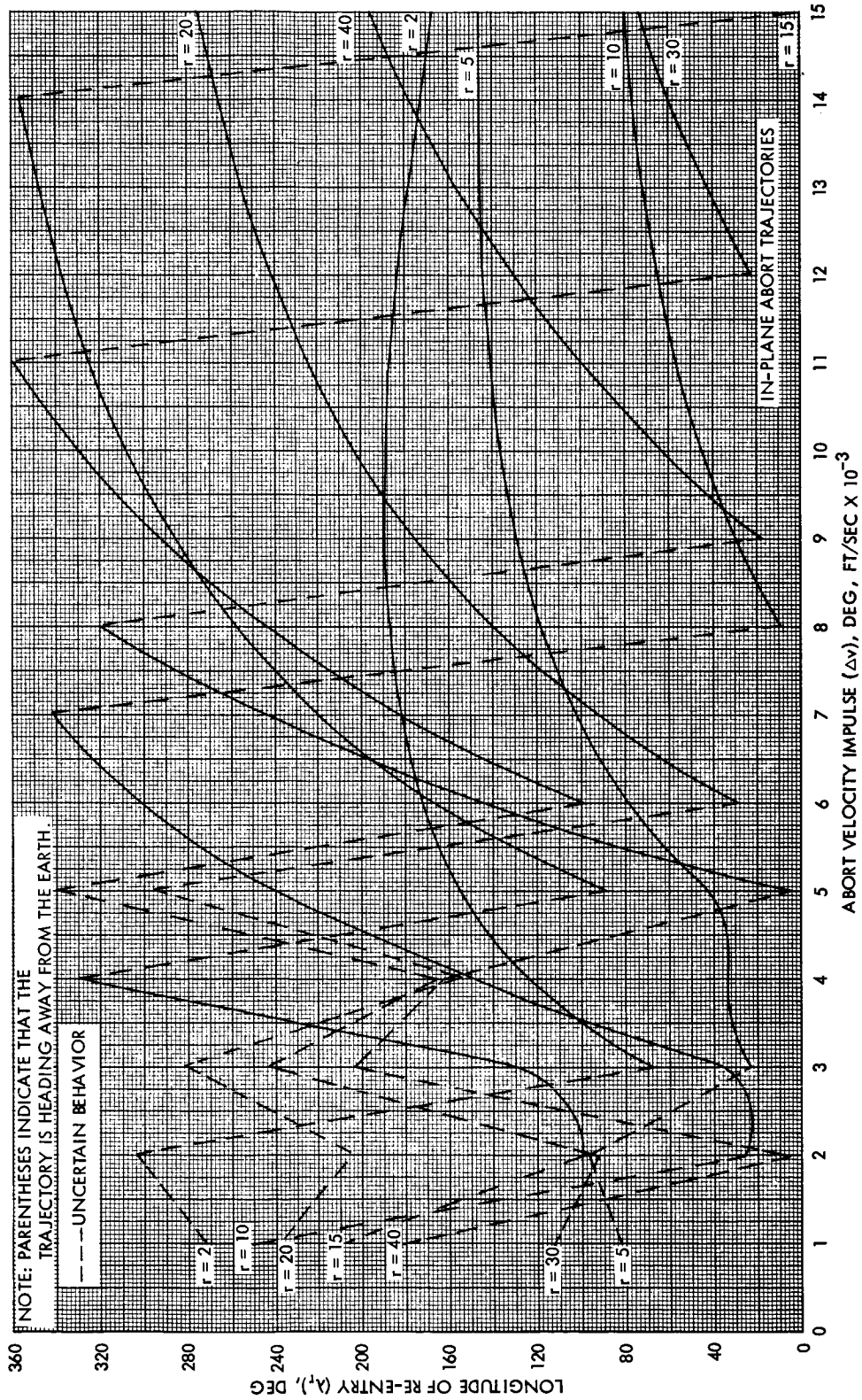

Figure 61. Abort Re-entry Longitude (Nominal Translunar Trajectory)

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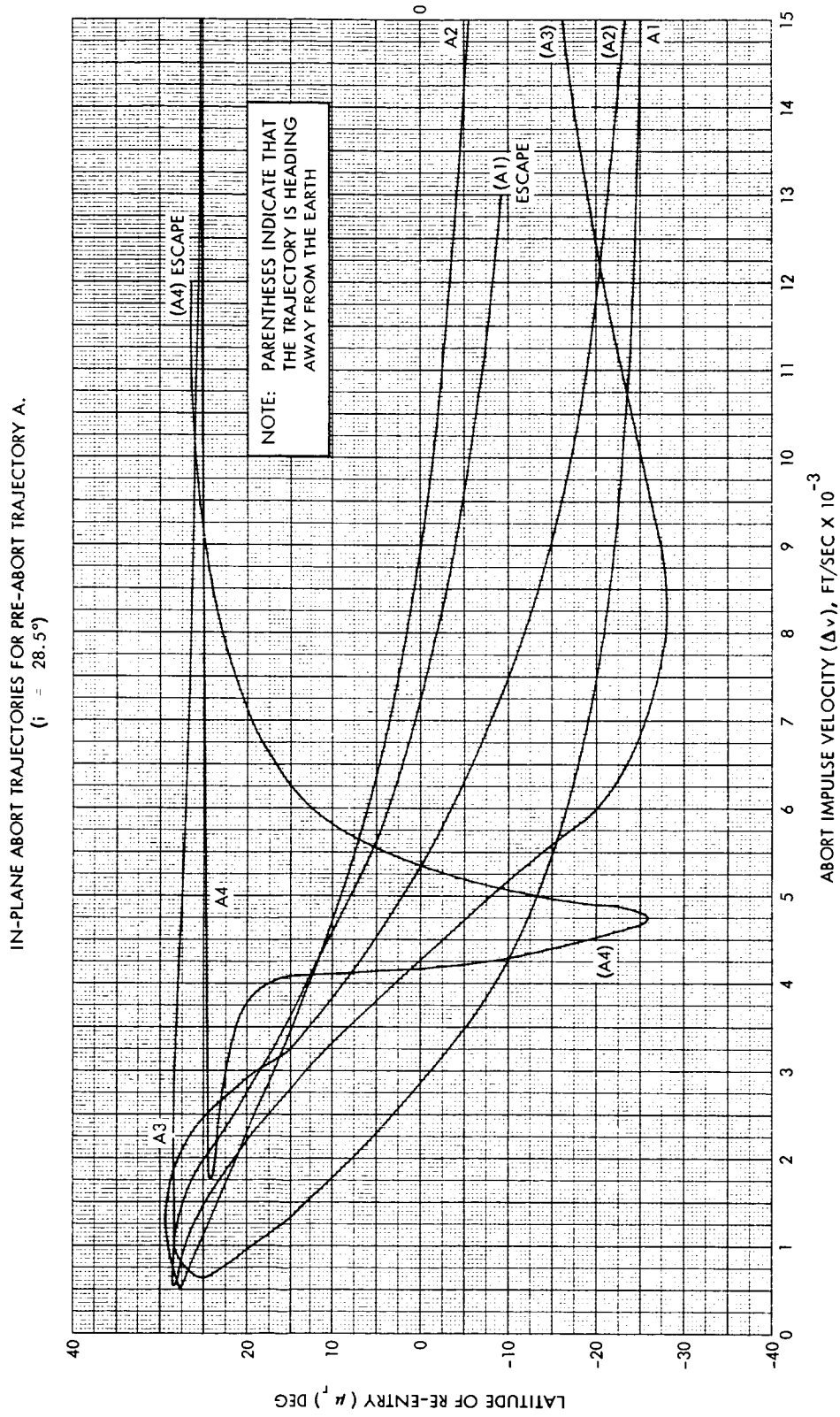

Figure 62. Abort Re-entry Latitude (Pre-abort Trajectory A)

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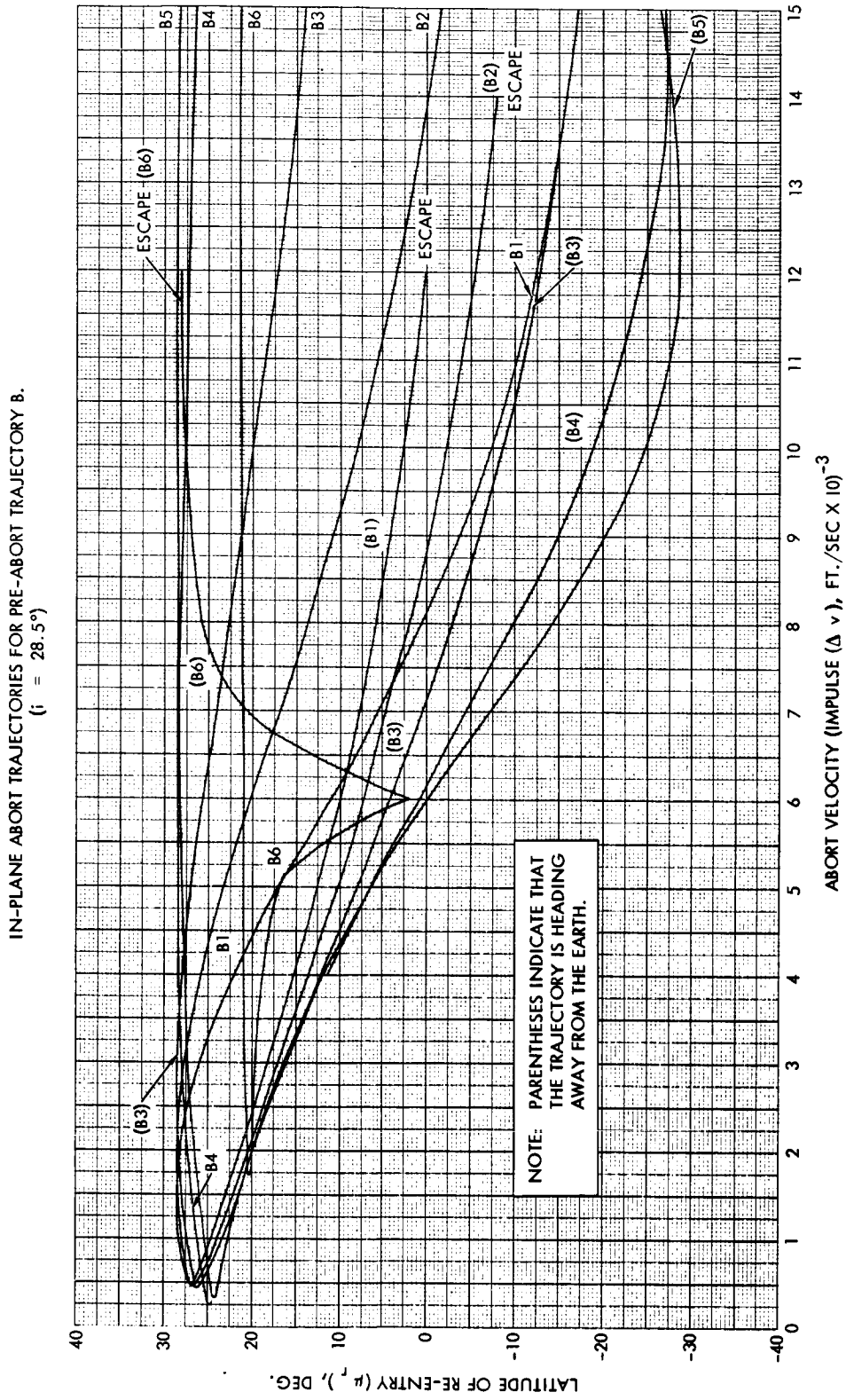

Figure 63. Abort Re-entry Latitude (Pre-abort Trajectory B)

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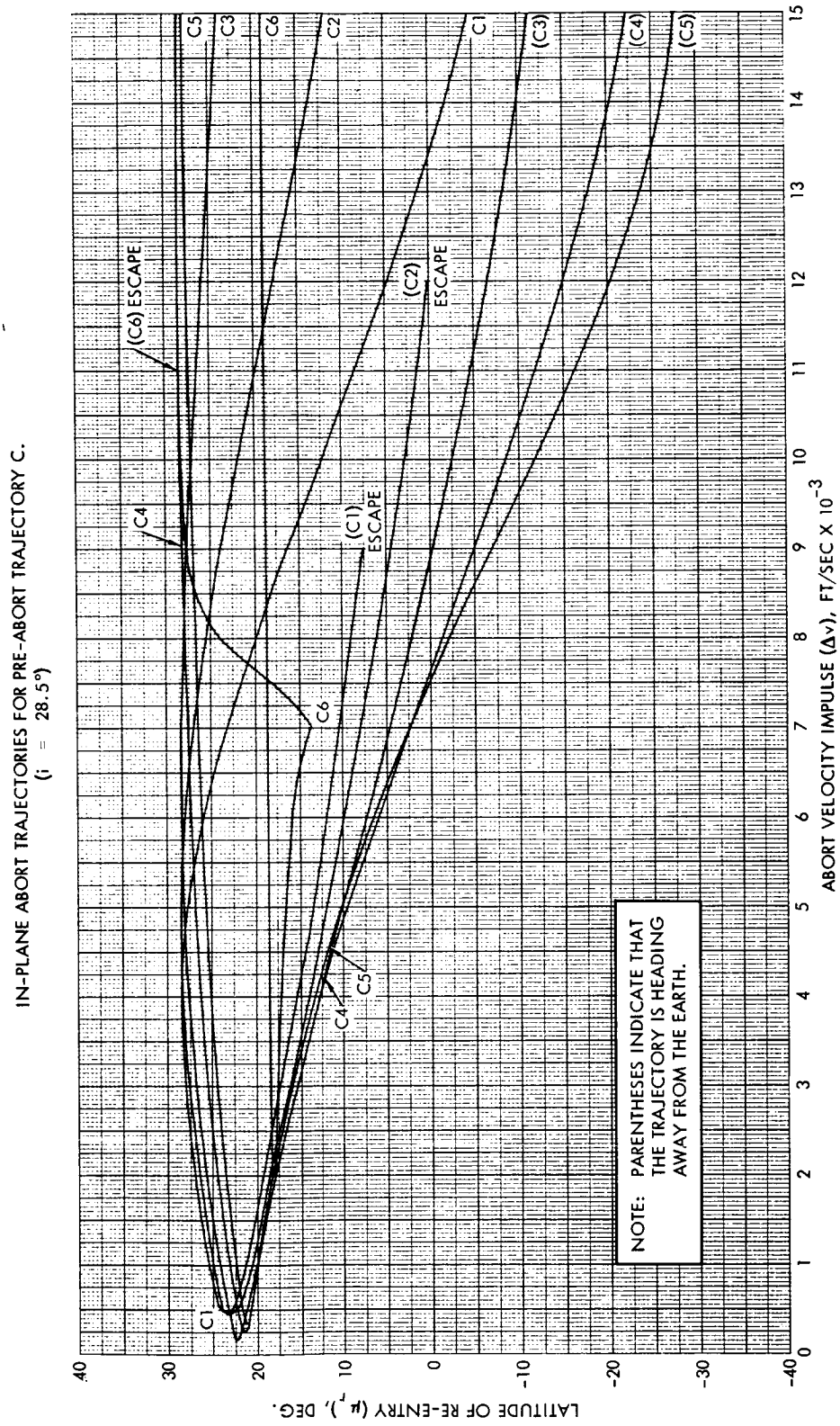

Figure 64. Abort Re-entry Latitude (Pre-abort Trajectory C)

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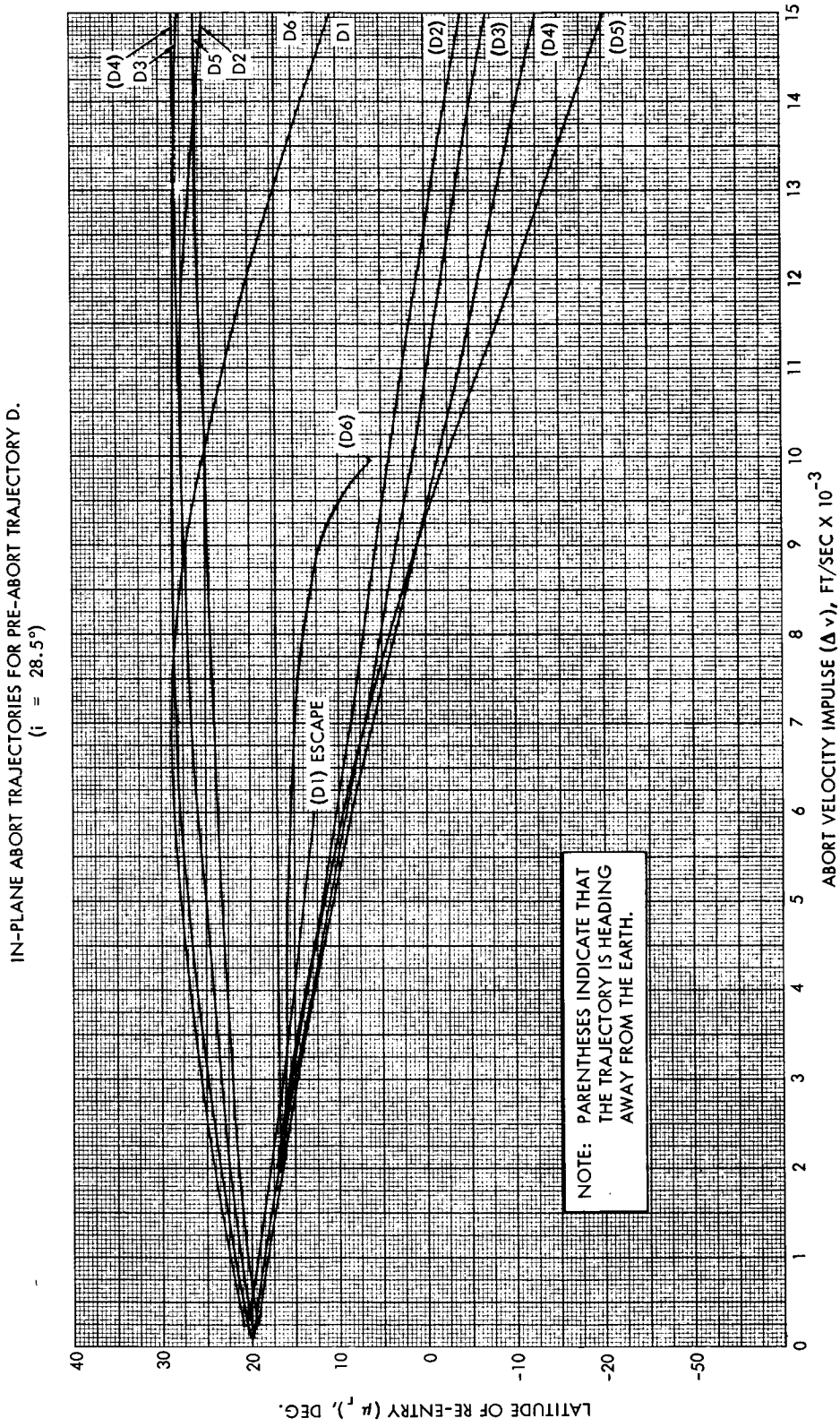

Figure 65. Abort Re-entry Latitude (Pre-abort Trajectory D)

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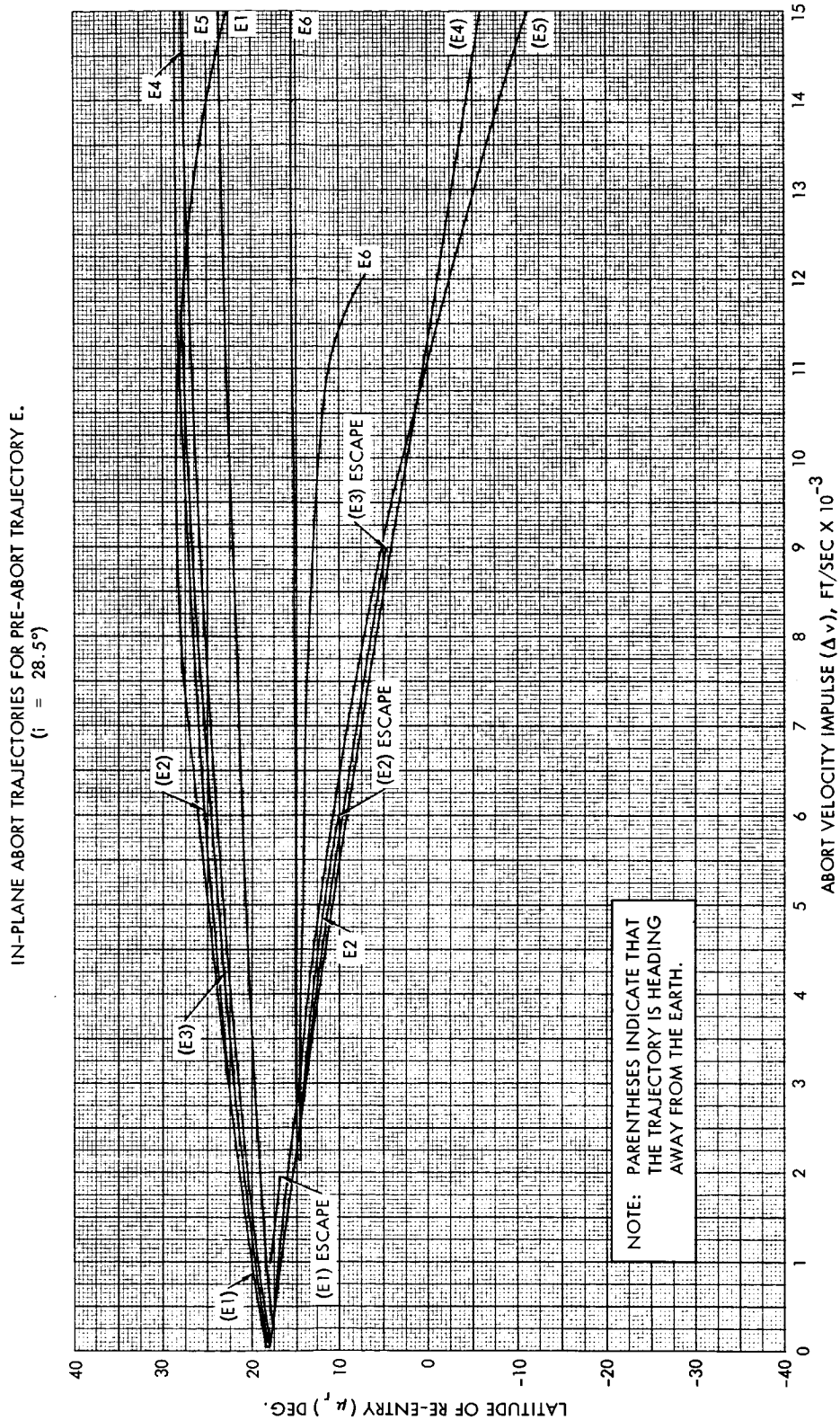

Figure 66. Abort Re-entry Latitude (Pre-abort Trajectory E)

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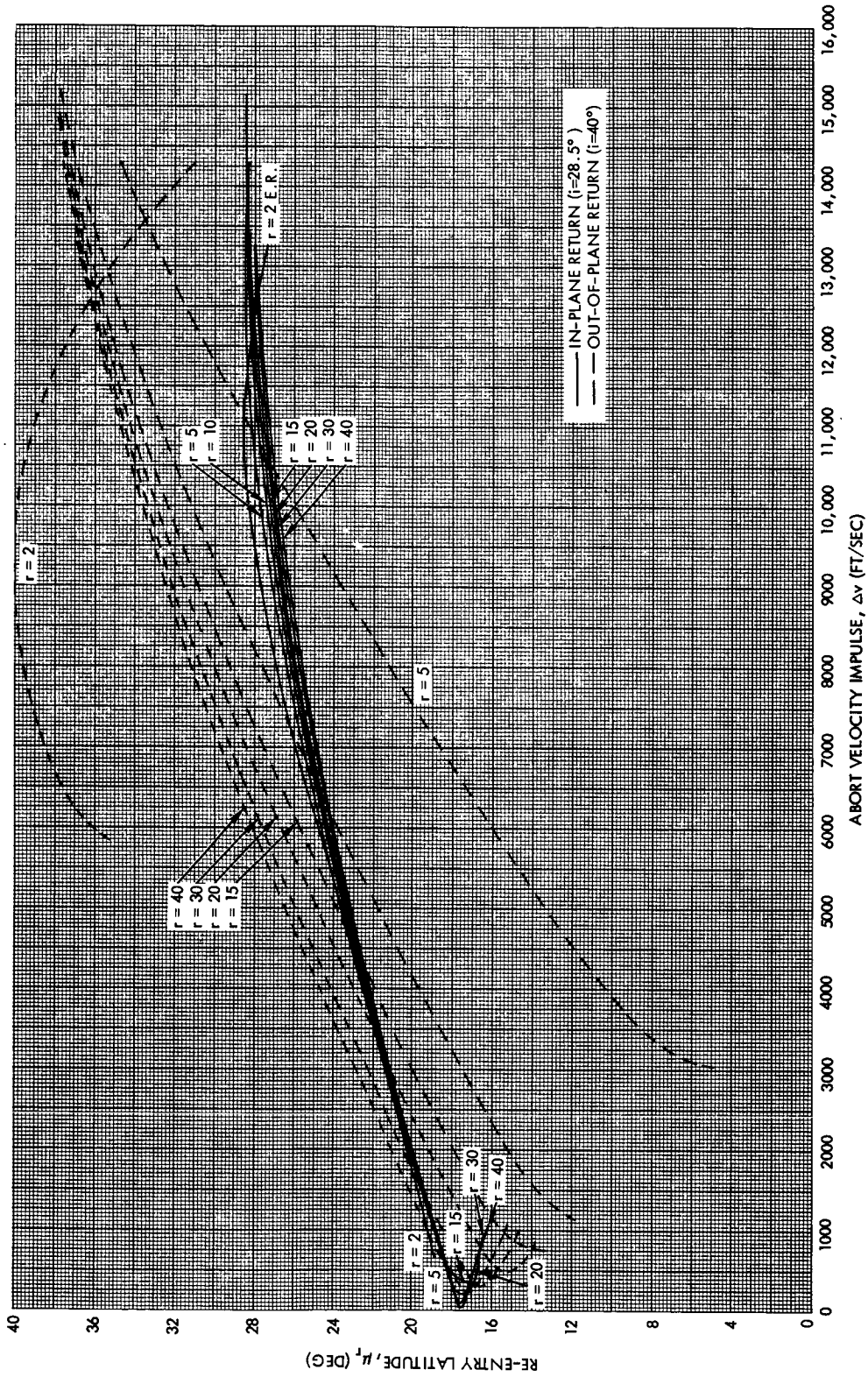

Figure 67. Abort Re-entry Latitude (Nominal Translunar Trajectory)

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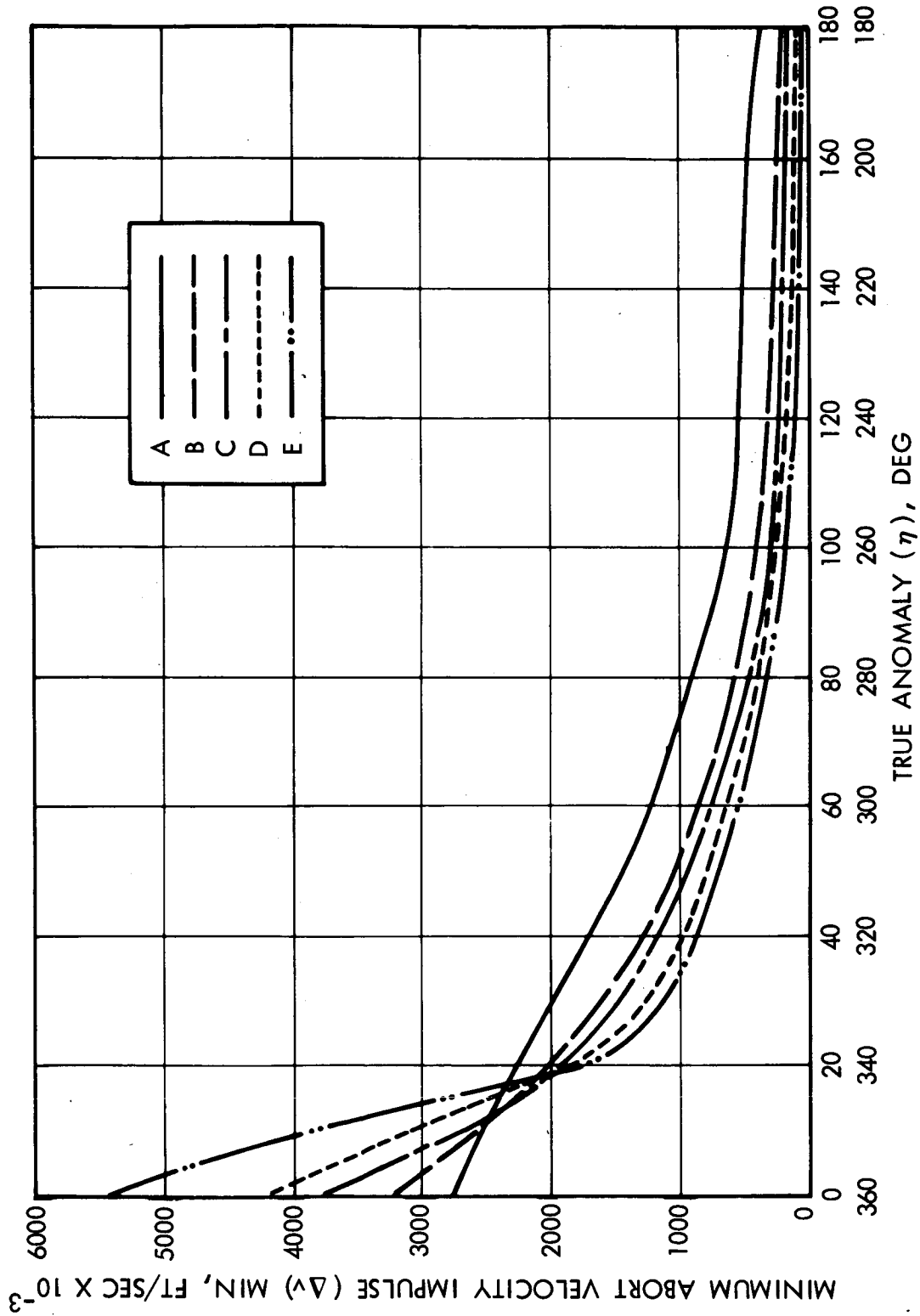

Figure 68. Minimum Abort Velocity Impulse versus True Anomaly of Abort Point for the Class of Pre-abort Trajectories

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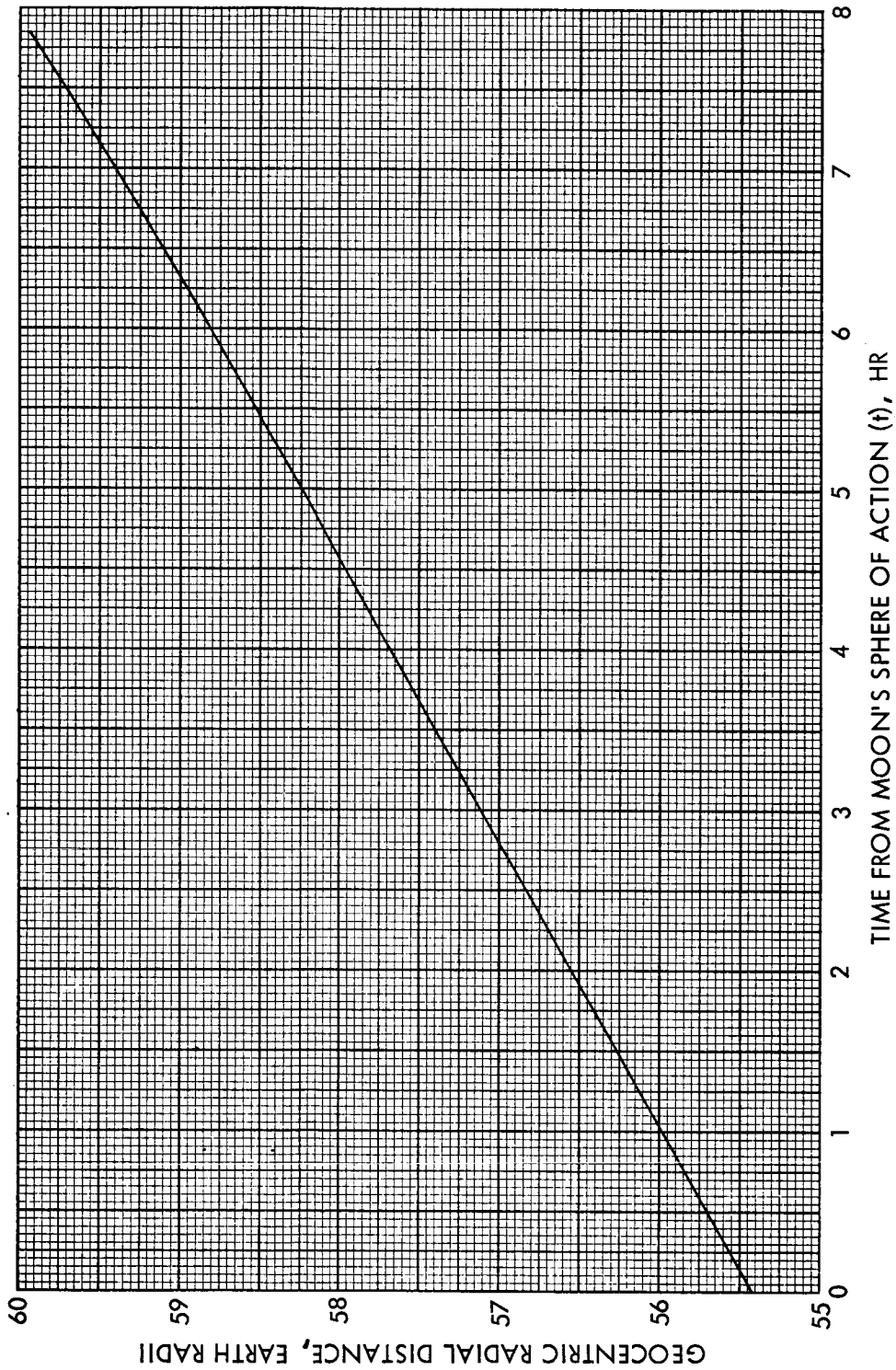

Figure 69. Geocentric Radial Distance versus Time from Penetration of the MSA (Nominal Translunar Trajectory)

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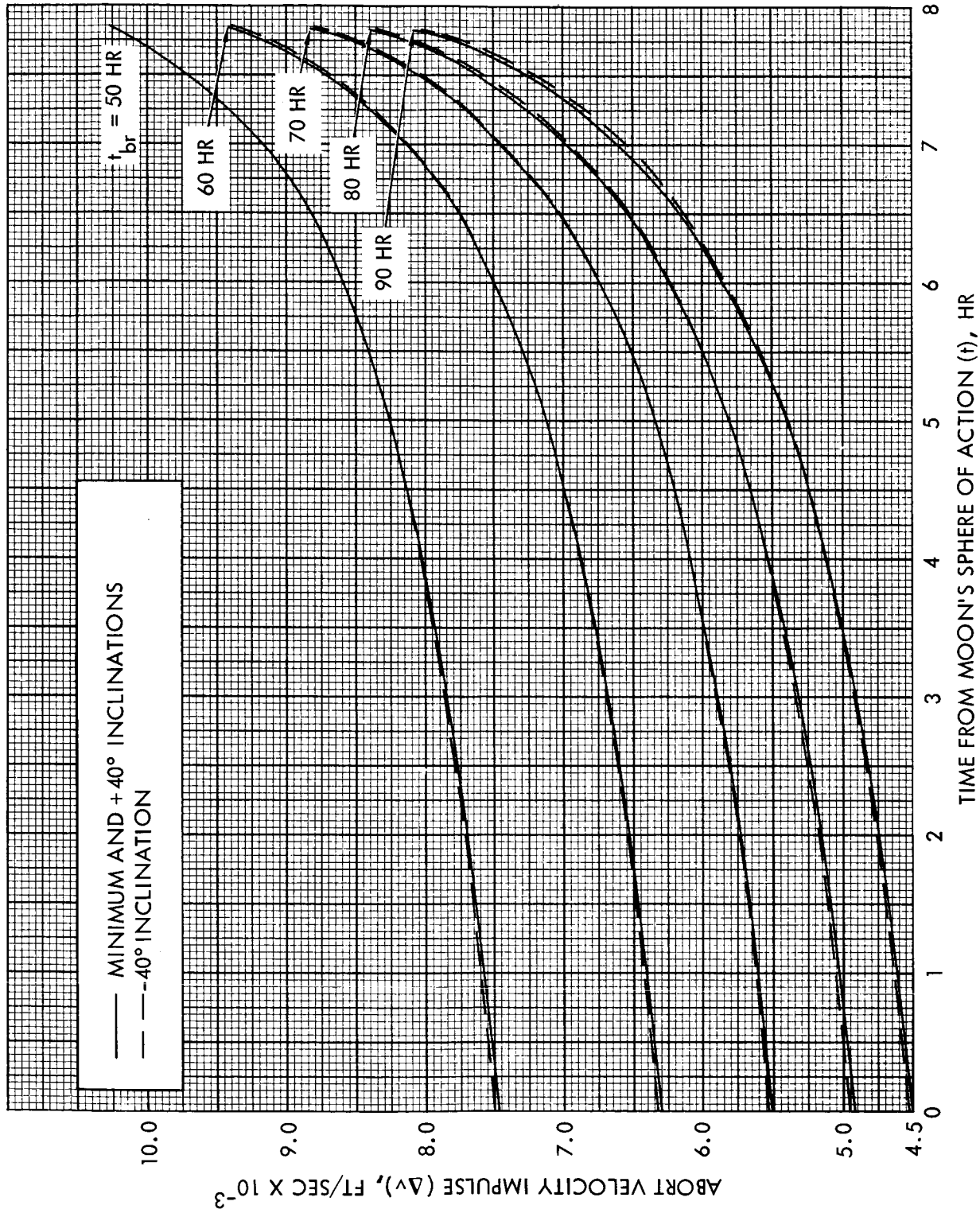

Figure 70. Abort Velocity Impulse Required versus Flight Time to Re-entry for Abort Points within the MSA (Nominal Translunar Trajectory)

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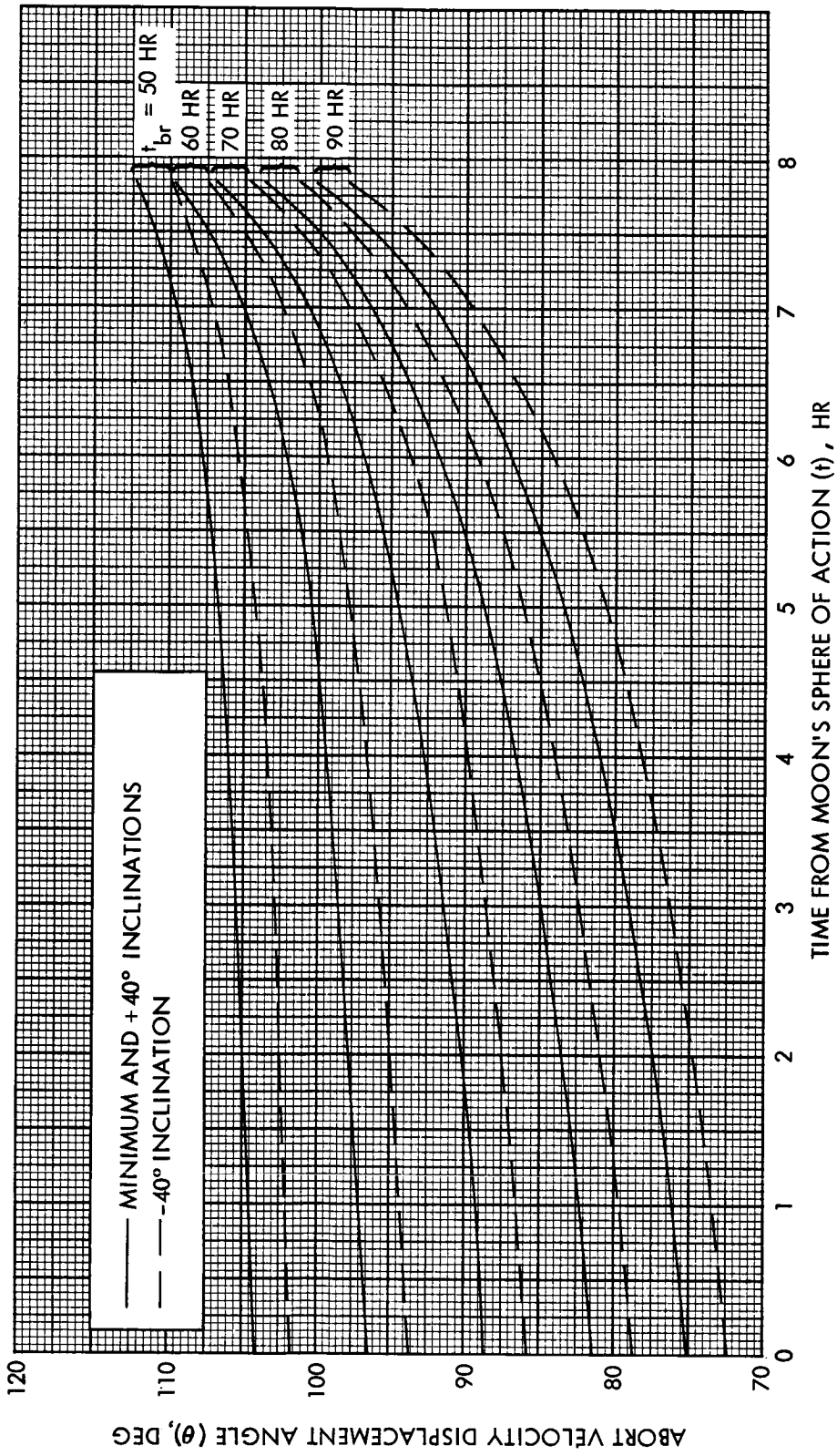

Figure 71. Abort Velocity Displacement Angle versus Flight Time to Re-entry for Abort Points within the MSA (Nominal Translunar Trajectory)

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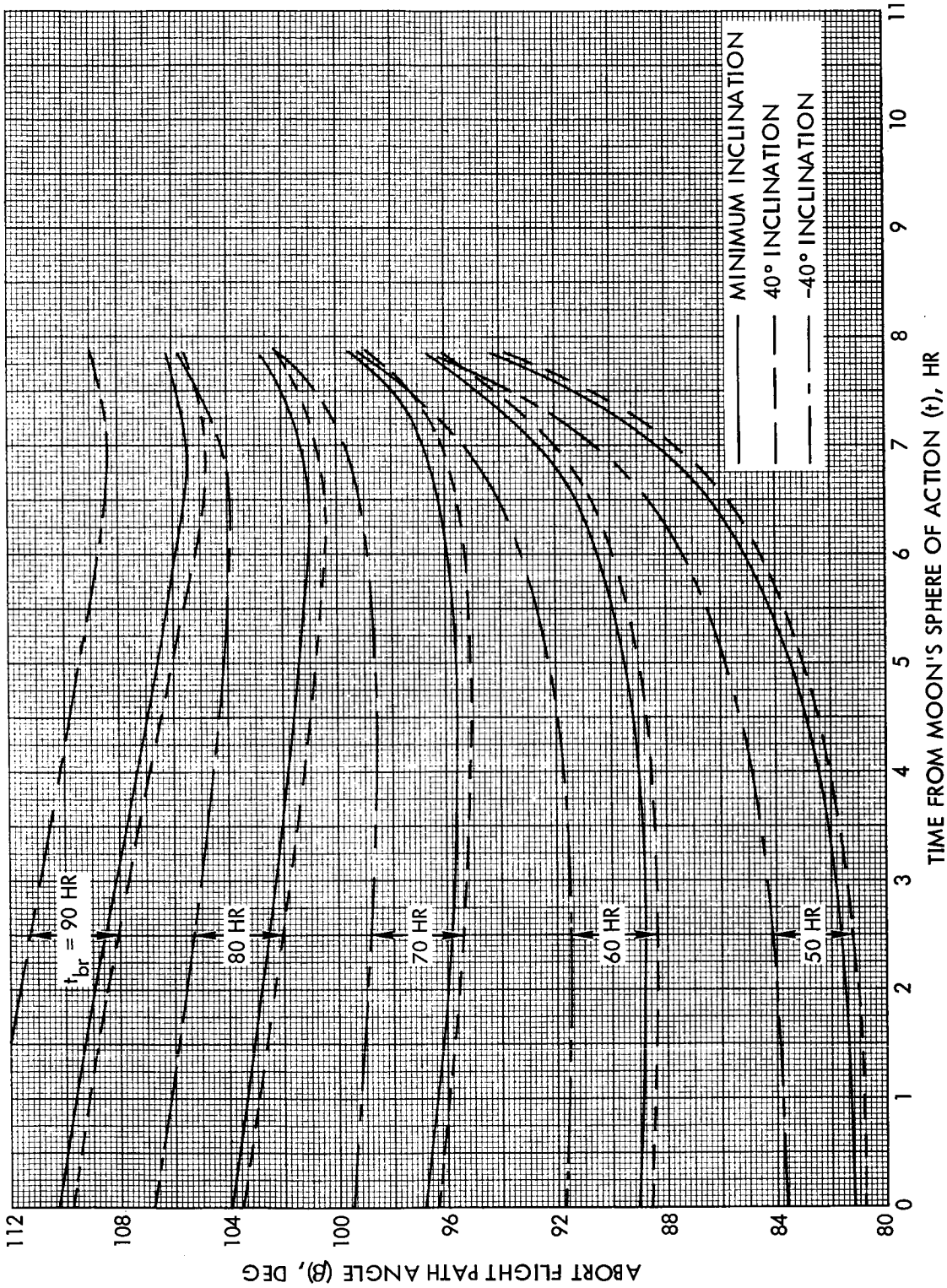

Figure 72. Abort Flight Path Angle versus Flight Time to Re-entry for Abort Points within the MSA (Nominal Translunar Trajectory)

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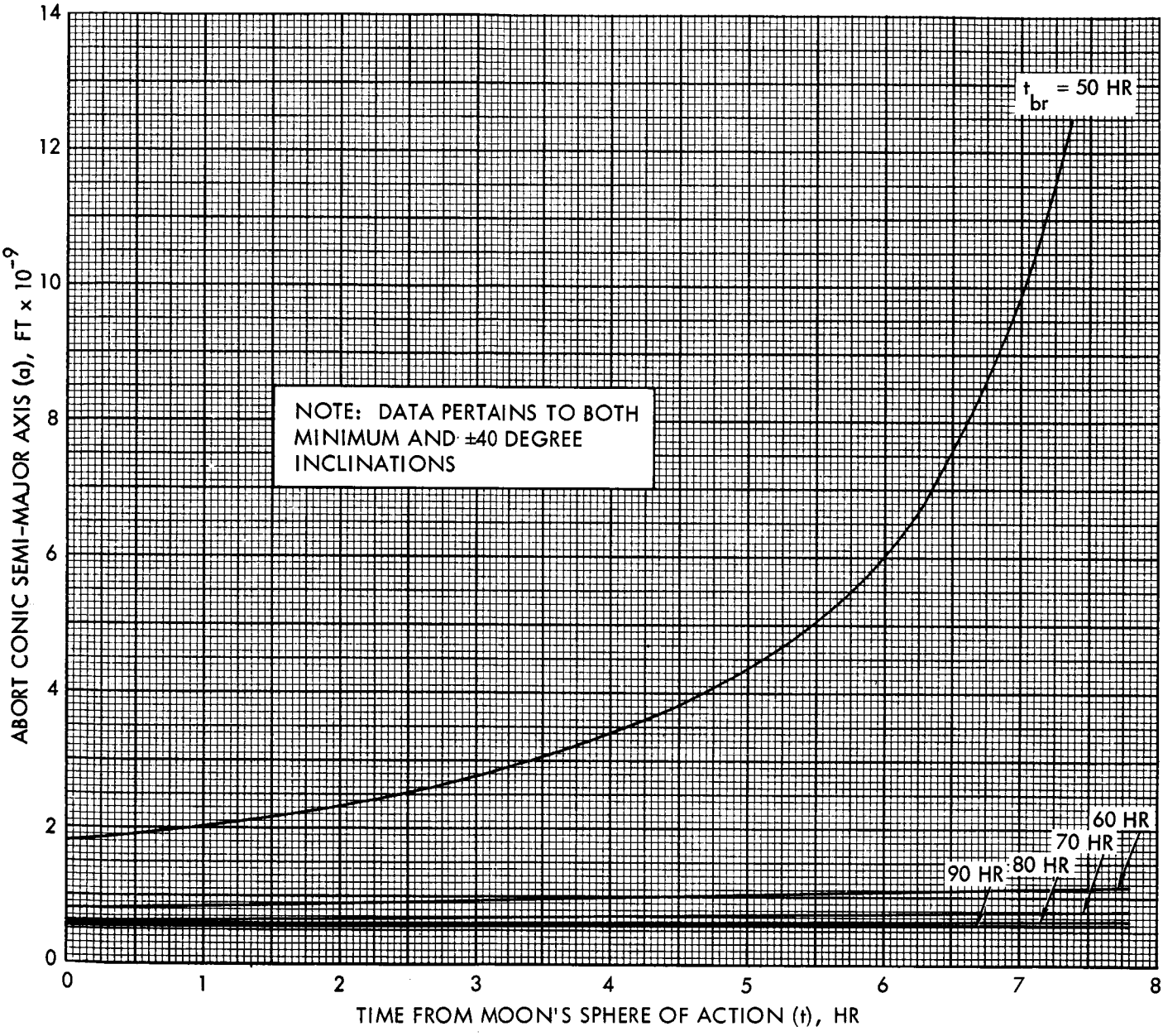

Figure 73. Abort Semi-major Axis versus Flight Time to Re-entry for Abort Points within the MSA (Nominal Translunar Trajectory)

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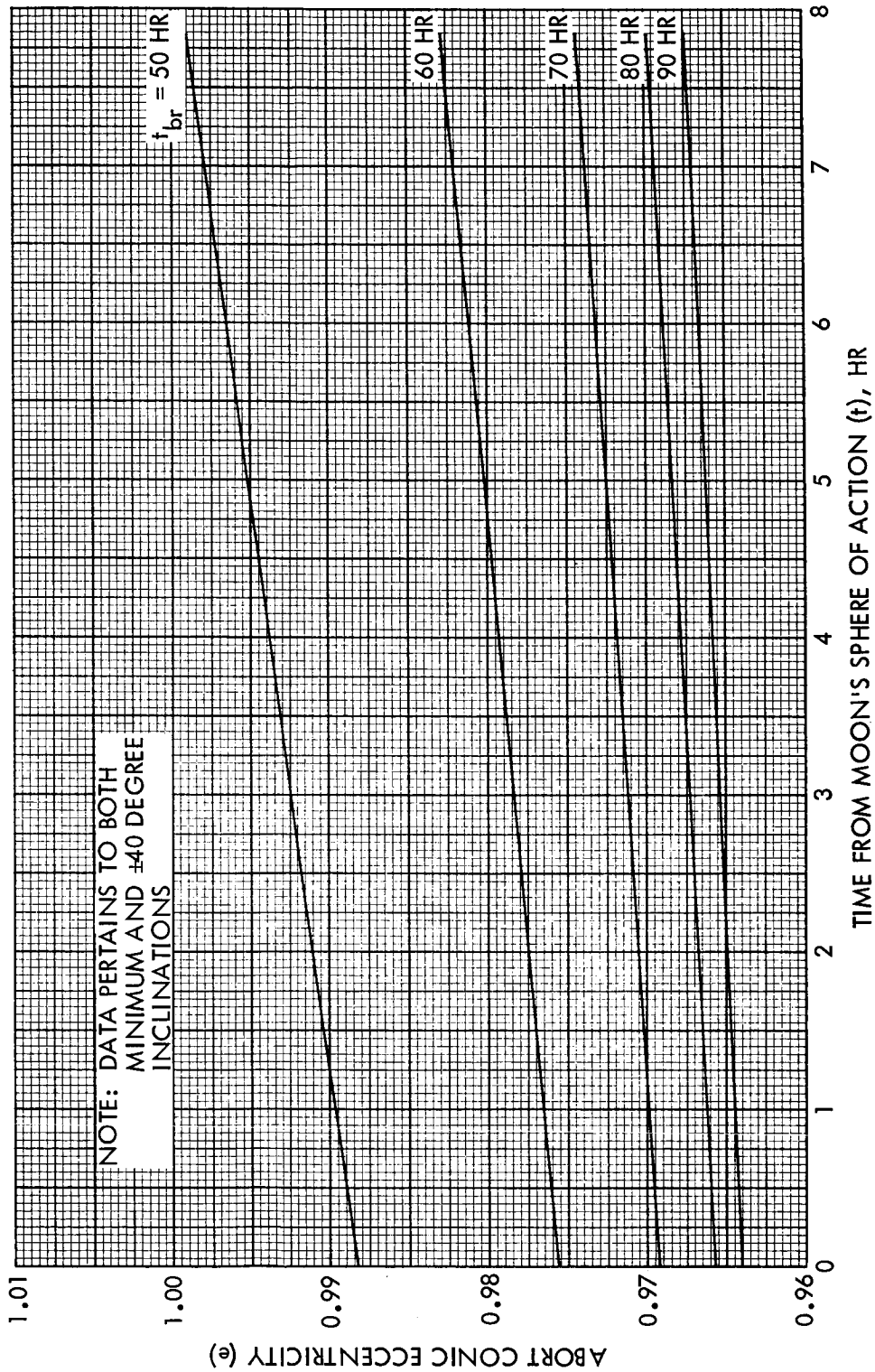

Figure 74. Abort Eccentricity versus Flight Time to Re-entry for Abort Points within the MSA (Nominal Translunar Trajectory)

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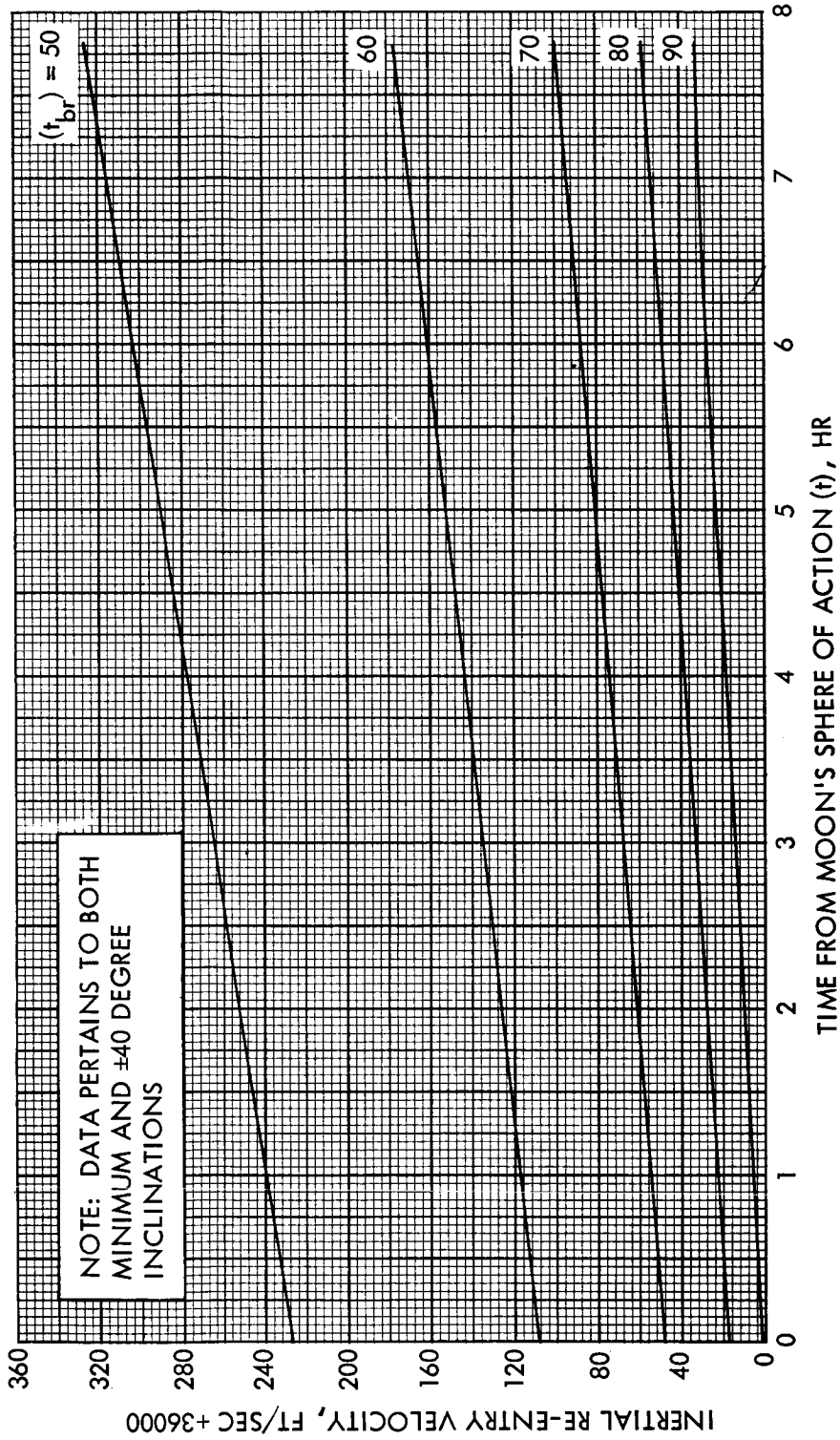

Figure 75. Abort Re-entry Velocity versus Flight Time to Re-entry for Abort Points within the MSA (Nominal Translunar Trajectory)

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B. Hyperbolic Deboost

As mentioned in Subsection III. A, the nature of the patched conic Analytic Lunar Return Program is such that the time of flight to return and the return inclination to the equatorial plane are input parameters. For this reason it is convenient to plot the abort trajectories, originating within the MSA and generated by this program, for constant flight times or return inclinations. As with near-earth aborts, all parameters are plotted as a function of the abort velocity impulse Δv. This velocity is determined within the computer program by differencing the pre-abort and the abort velocity vectors.

Once deboost into lunar orbit has been initiated the nominal free circumlunar trajectory has been destroyed. The resulting set of trajectories generated by the premature cutoff of the CM/SM engine will represent a new set of pre-abort trajectories along which abort paths will be studied. The nature of these pre-abort trajectories has been presented in Section II. Also, as discussed in that section, identifying nomenclature has been assigned to these trajectories and numbers assigned to the abort points. Specifically, pre-abort trajectories have been generated for abort every minute of CM/SM burn. Abort points along each of these trajectories have been taken for every hour of flight, after engine cutoff, up to five hours. Aborts at zero hours have been included.

As with Subsection III. A, the graphical results have been grouped according to the abort parameter studied. The first parameter considered is the time of flight. Figures 76 to 82 present this time of flight as a function of the abort velocity impulse for fixed return inclination. In choosing the return conditions, it was assumed that return flight times between 50 and 90 hours and inclinations between -40 degrees and 40 degrees would encompass most of the desirable abort trajectories. This is shown to be the case in Figure 76. The minimum value of abort velocity impulse Δv occurs near the 70-hour returns for all of the abort points. The effect of the return inclination on these minimum value is of the second order and will be discussed later. The exception to this trend is point M1, where Δv is more sensitive to varying return inclinations. Also note that for the velocity capability available, shorter (and perhaps longer) flight times could have been considered. This is at least true for the pre-abort trajectories M and N and for the initial abort points on the following pre-abort trajectories.

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Notable features of the M series of graphs are that the minimum Δv's are essentially constant. Since M is almost a free return trajectory; i. e., hyperbolic with respect to the moon, the pre-abort direction of motion remains "pointed" at the earth and changes little as a function of true anomaly. As we go to the N, O, P, Q, R and S orbits which progressively become more circular with respect to the moon, we can see that larger Δv's are required to turn the pre-abort velocity around to the direction of the earth. Another observation is given in Figures 76 to 82 which indicate that the longer the deboost thrust continues, the earlier the abort must be initiated. Thus, Figure 78 indicates that after three minutes of deboost thrusting, abort must occur within three hours of engine cutoff. To increase the time between engine cutoff and abort, it is necessary to remain in elliptical orbit about the moon until the second revolution when other abort opportunities arise.

Beginning with Figure 80, the results are not presented in the order of increasing time of abort, but in the order of increasing true anomaly from deboost. The reason for this is the fact that the pre-abort trajectories have periods shorter than the abort times considered. Thus, some hourly abort points are not in an opportune position to initiate abort. The characteristics of these abort points may be found in the tables of Section II.

Figures 83 to 89 present the abort velocity displacement angle as a function of abort velocity impulse. As defined earlier, this is the angle between the pre-abort and post-abort velocity vectors. Note that for pre-abort trajectories M and N, this angle remains less than 50 degrees. This is because the pre-abort trajectory is hyperbolic and close to the nominal free flight trajectory. As deboost continues, the pre-abort trajectory becomes elliptical so that aborts near the apocynthion point require large values of θ.

Figures 90 to 96 give the moon centered flight path angle of the abort trajectory at the abort point. As expected, this angle is near 90 degrees for abort points near the moon and decreases as the abort point draws away from the moon. This is the case for all pre-abort trajectories, elliptic cases included.

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The earth centered semi-major axis and eccentricity are presented in Figures 97 to 110. These values, of course, are a strong function of the return flight time and they exhibit the characteristics of 50 to 90 hour moon-to-earth trajectories; eccentricity for example, ranges between .96 and unity. Figures 111 to 117 present the inertial re-entry velocity. All values are within the 40,000 ft/sec limit as can be expected since the eccentricities presented above do not exceed parabolic or hyperbolic values.

The re-entry longitudes and latitudes are presented in Figures 118 to 131. To simplify the graphical results, these parameters were not plotted as a function of Δv, but rather as a function of the time from deboost cutoff to the abort point. Also, these values were graphed for constant times of return flight and return inclination. These values may be related to abort velocity impulse by means of Figures 76 to 82. Note that in all cases, the longitudes vary linearly with the time of abort. As expected, due to the earth's rotation, the longitude decreases about 15 degrees of every hour delay time in aborting. Only slight variations are noticable with changes in the return inclination. The latitudes, on the other hand, are essentially independent of the time of abort. Also, not too great a change is noticable with variations in the time of flight. For all pre-abort trajectories, the latitudes for minimum, 40 degree and -40 degree inclinations center about 16 degrees, 30 degrees and four degrees, respectively.

In all of the above analyses, only those abort trajectories were considered where the return inclinations are minimum, -40 degrees or 40 degrees. The results seem to indicate that these inclinations produce near minimum abort velocity impulses implying that other values of return inclination need not be studied. For completeness, a representative abort point was chosen from which abort trajectories for a number of return inclinations were calculated. The abort point chosen was O2 and the results are presented in Figure 132. This figure shows the abort velocity impulse as a function of inclination for constant times of flight. The negative inclinations indicate that the minimum Δv occurs near the 25-degree return inclination. The absolute minimum, which occurs at 25 degrees, is not significantly different from the minimum or the +40-degree value implying that all of the above results present near minimum abort velocity impulses.

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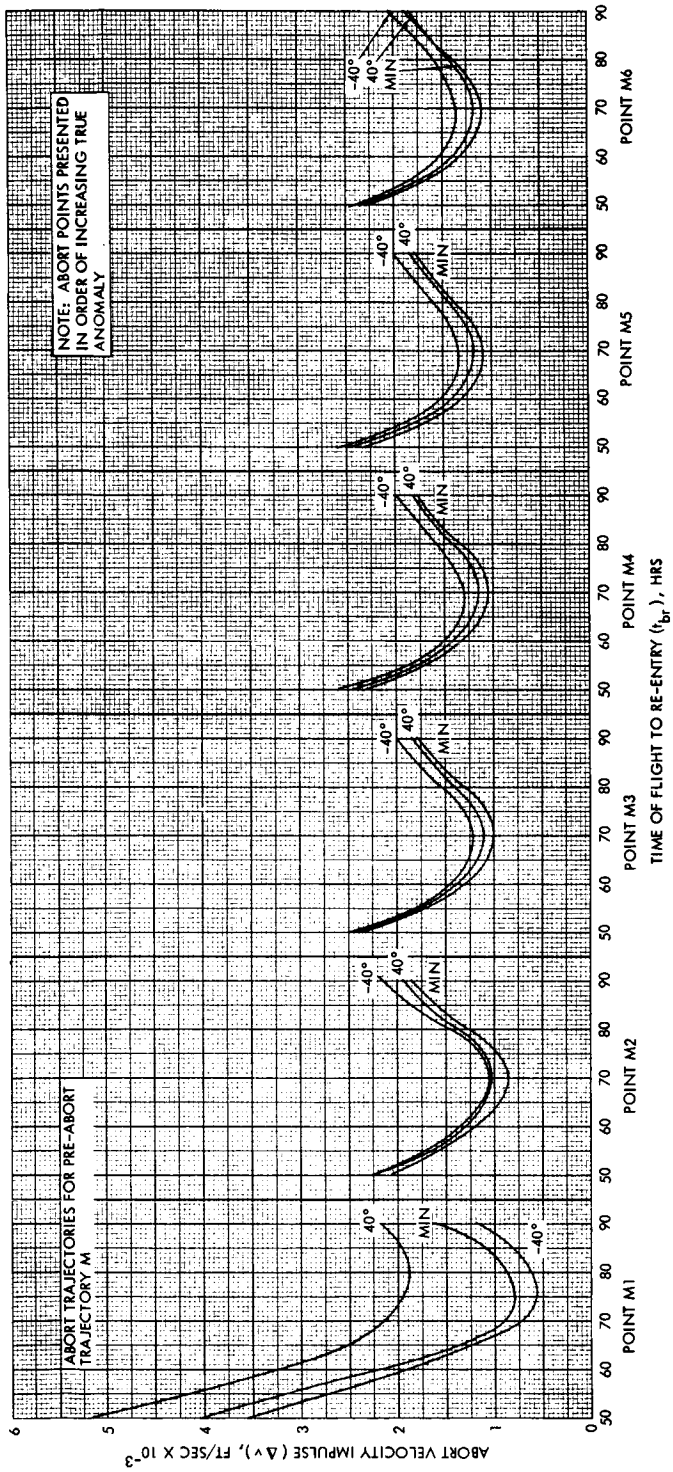

Figure 76. Abort Flight Time to Re-entry (Pre-abort Trajectory M)

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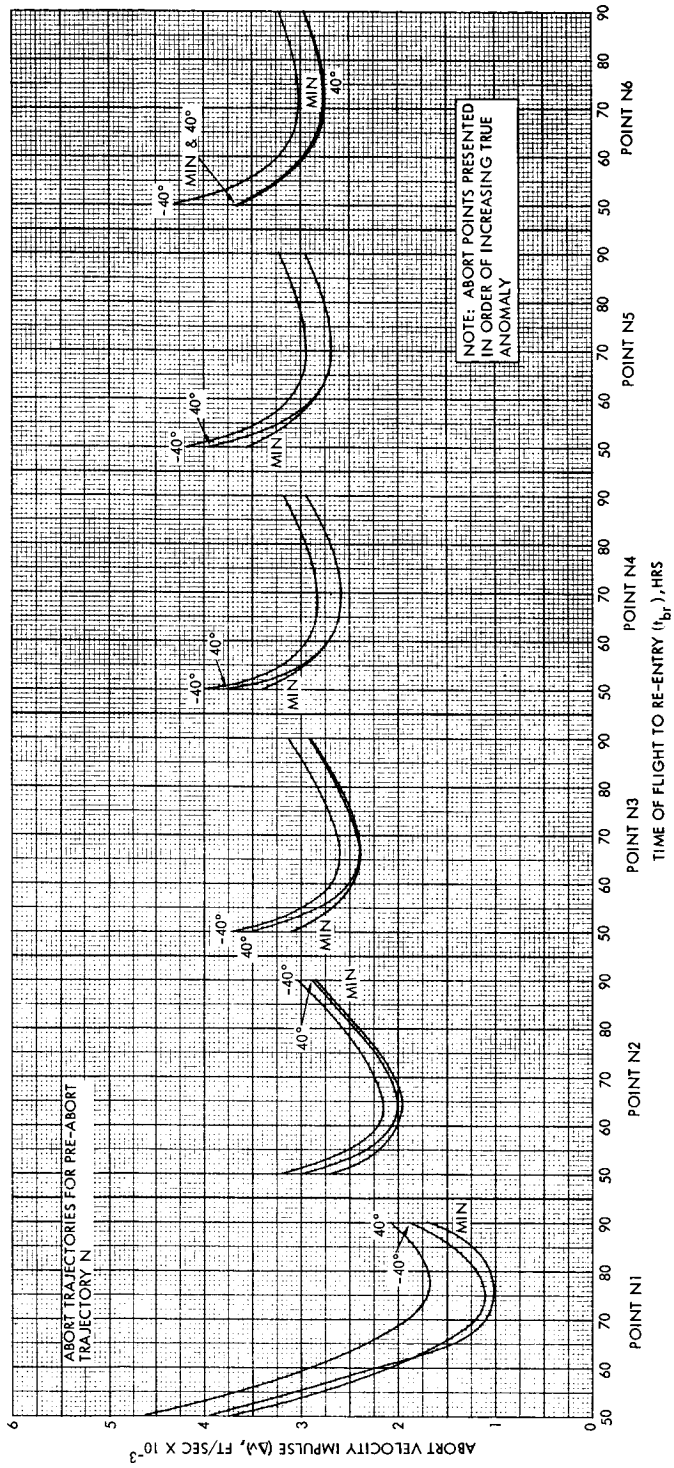

Figure 77. Abort Flight Time to Re-entry (Pre-abort Trajectory N)

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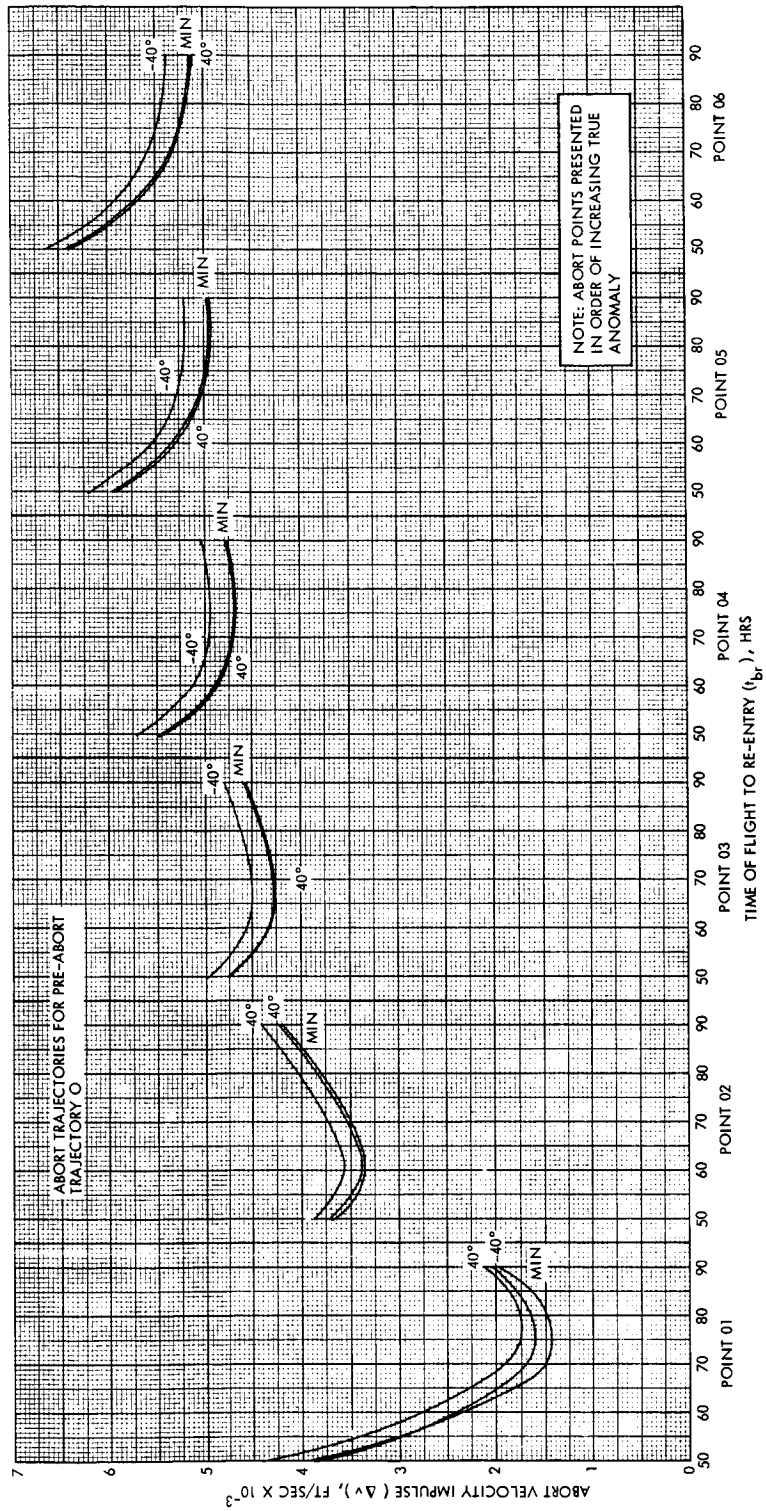

Figure 78. Abort Flight Time to Re-entry (Pre-abort Trajectory O)

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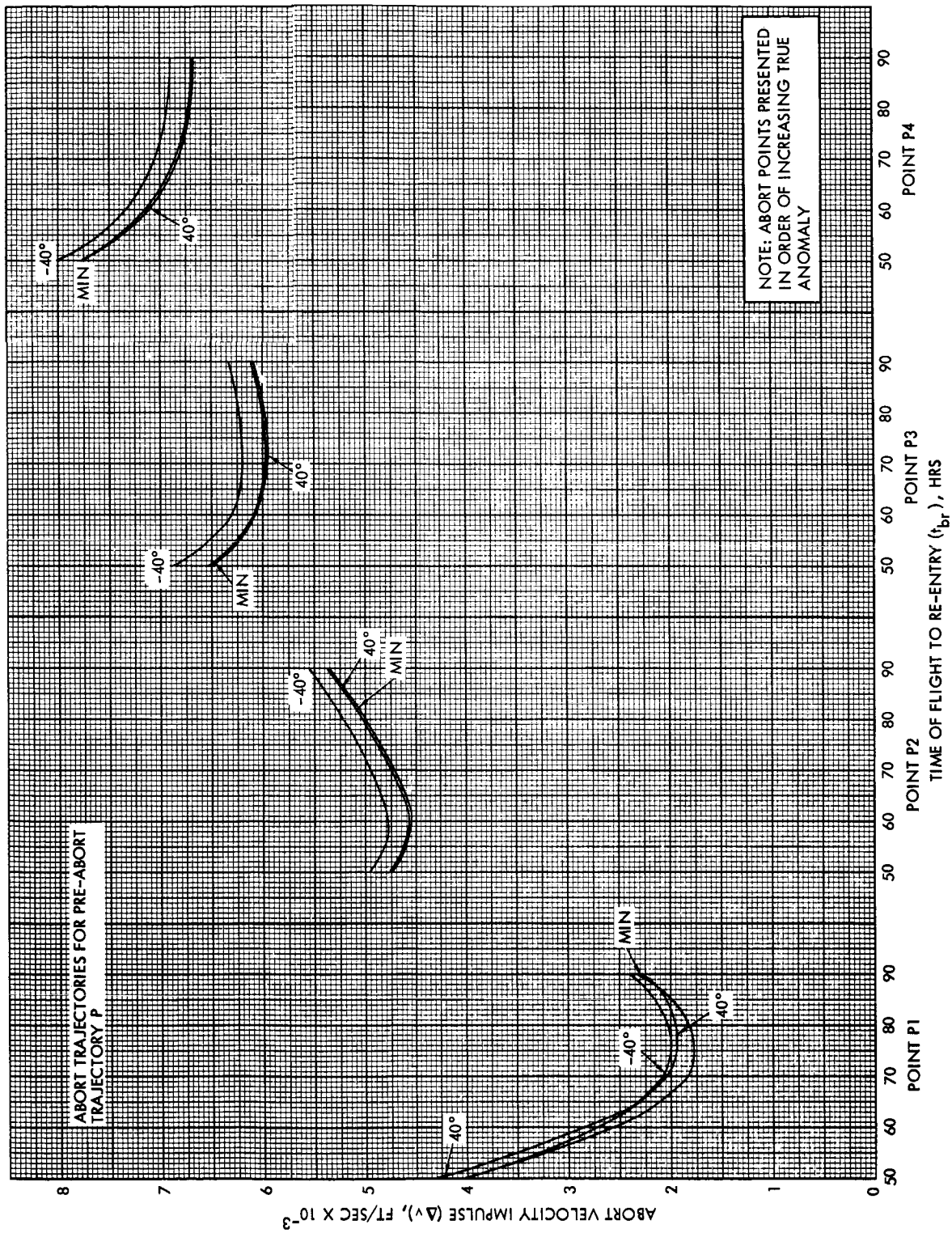

Figure 79. Abort Flight Time to Re-entry (Pre-abort Trajectory P)

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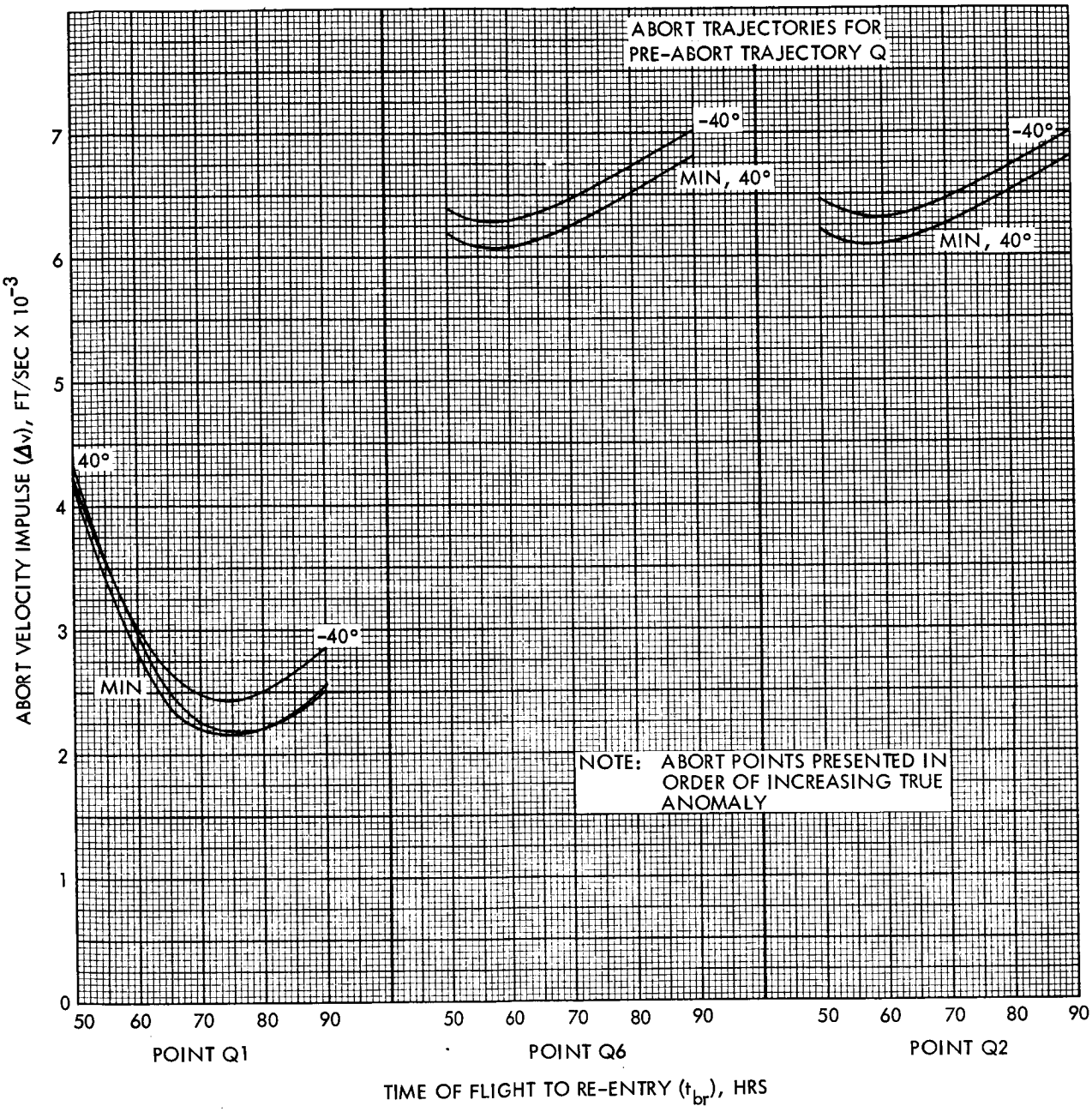

Figure 80. Abort Flight Time to Re-entry (Pre-abort Trajectory Q)

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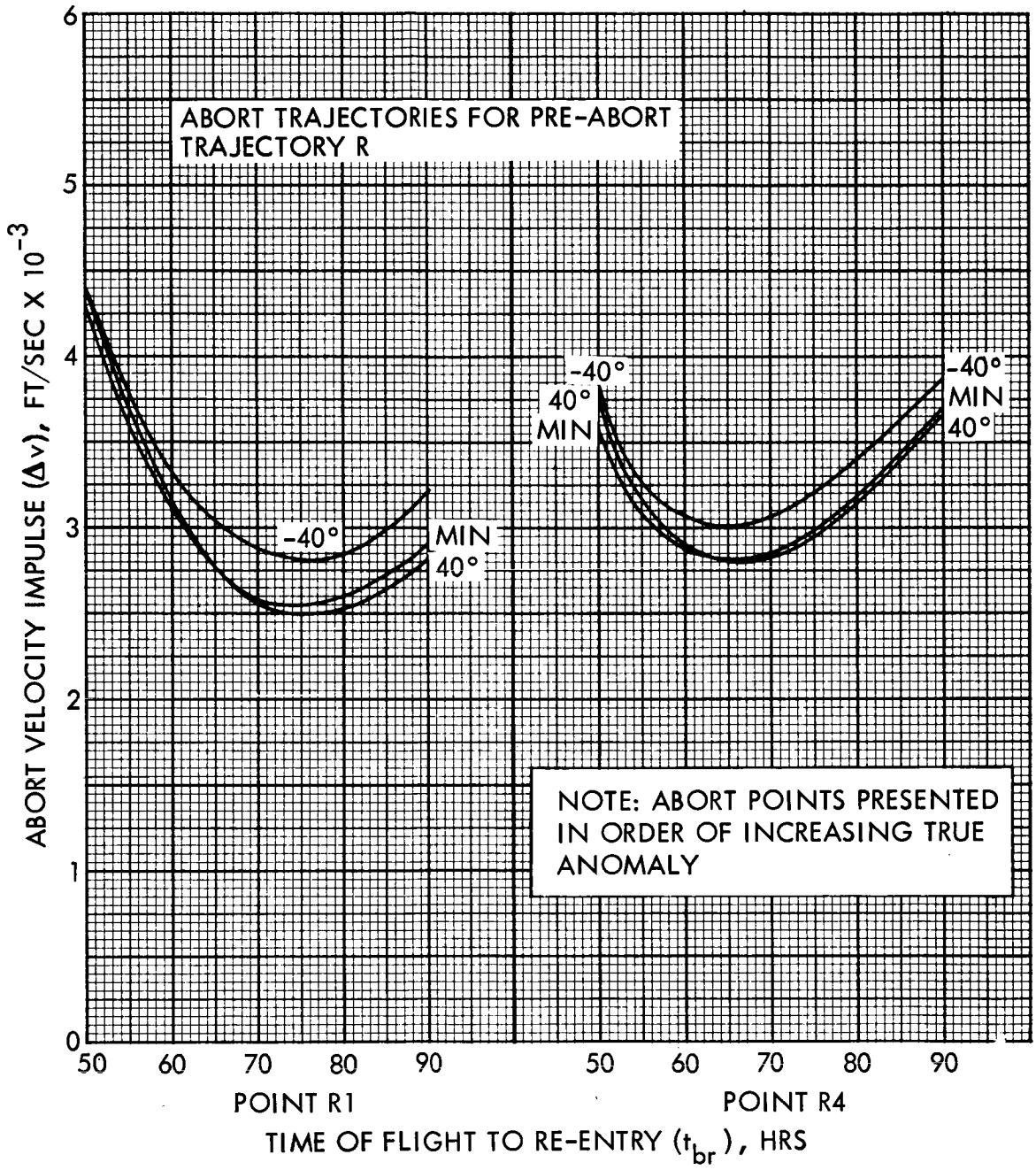

Figure 81. Abort Flight Time to Re-entry (Pre-abort Trajectory R)

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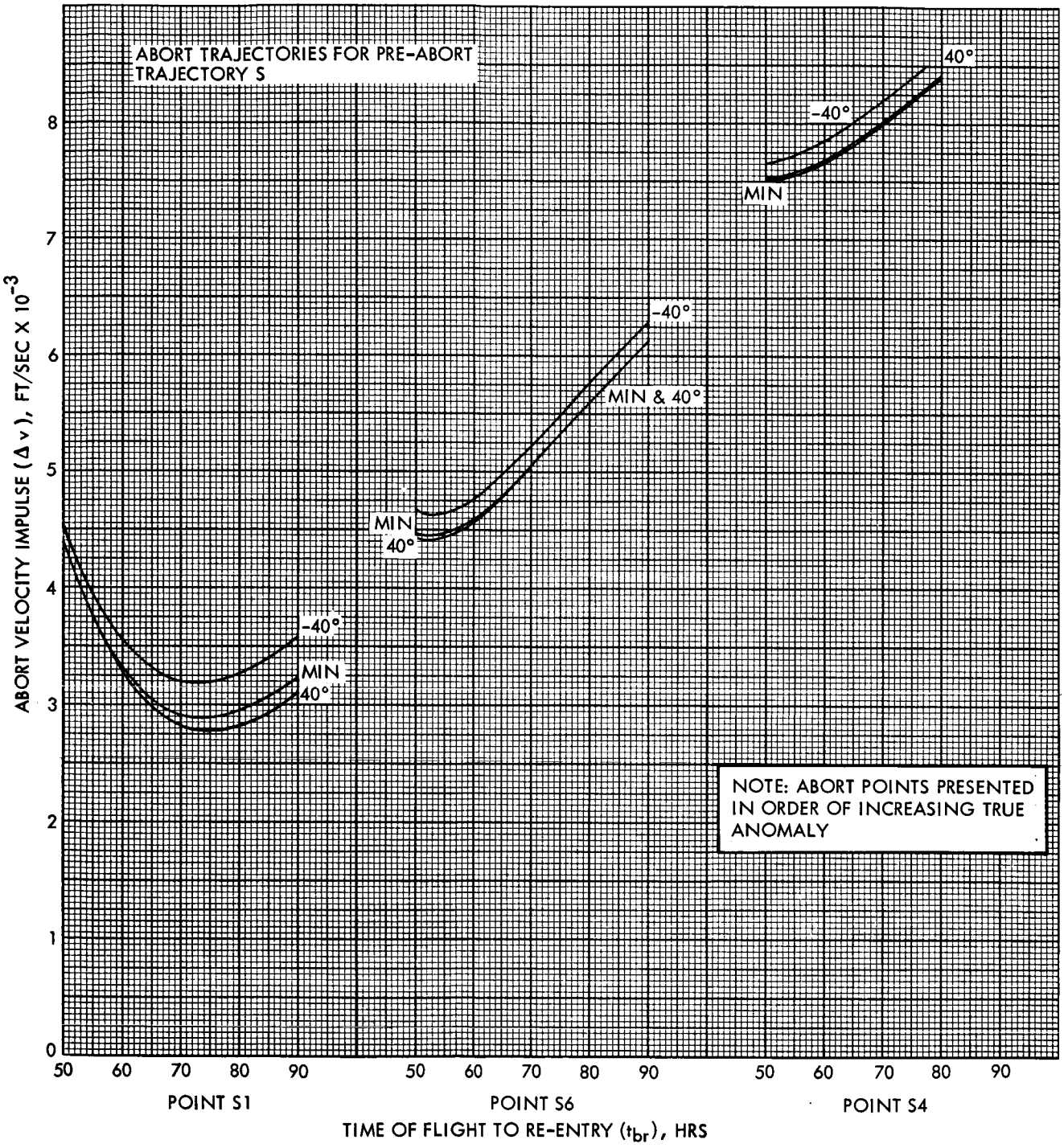

Figure 82. Abort Flight Time to Re-entry (Pre-abort Trajectory S)

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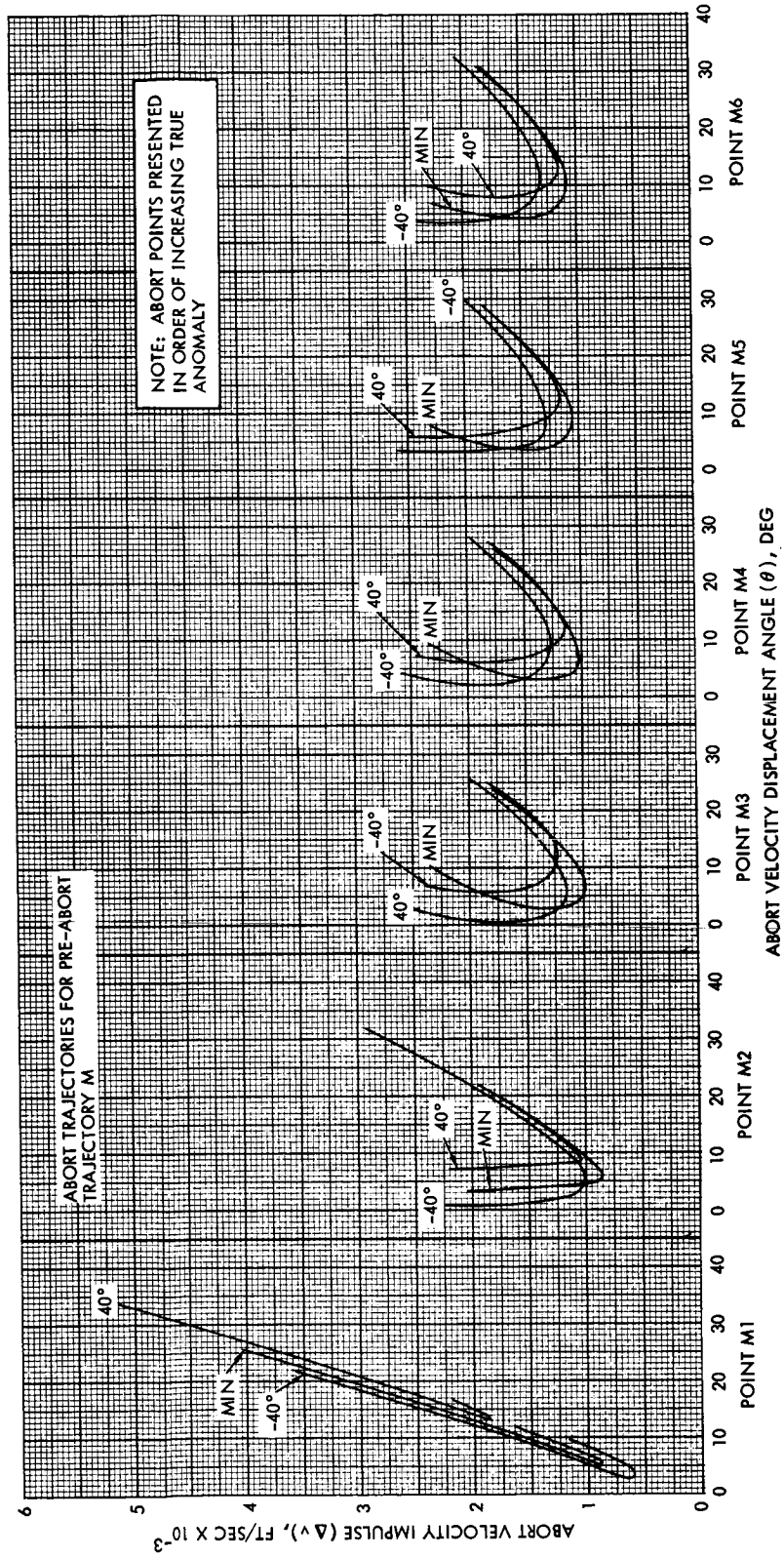

Figure 83. Abort Velocity Displacement Angle (Pre-abort Trajectory M)

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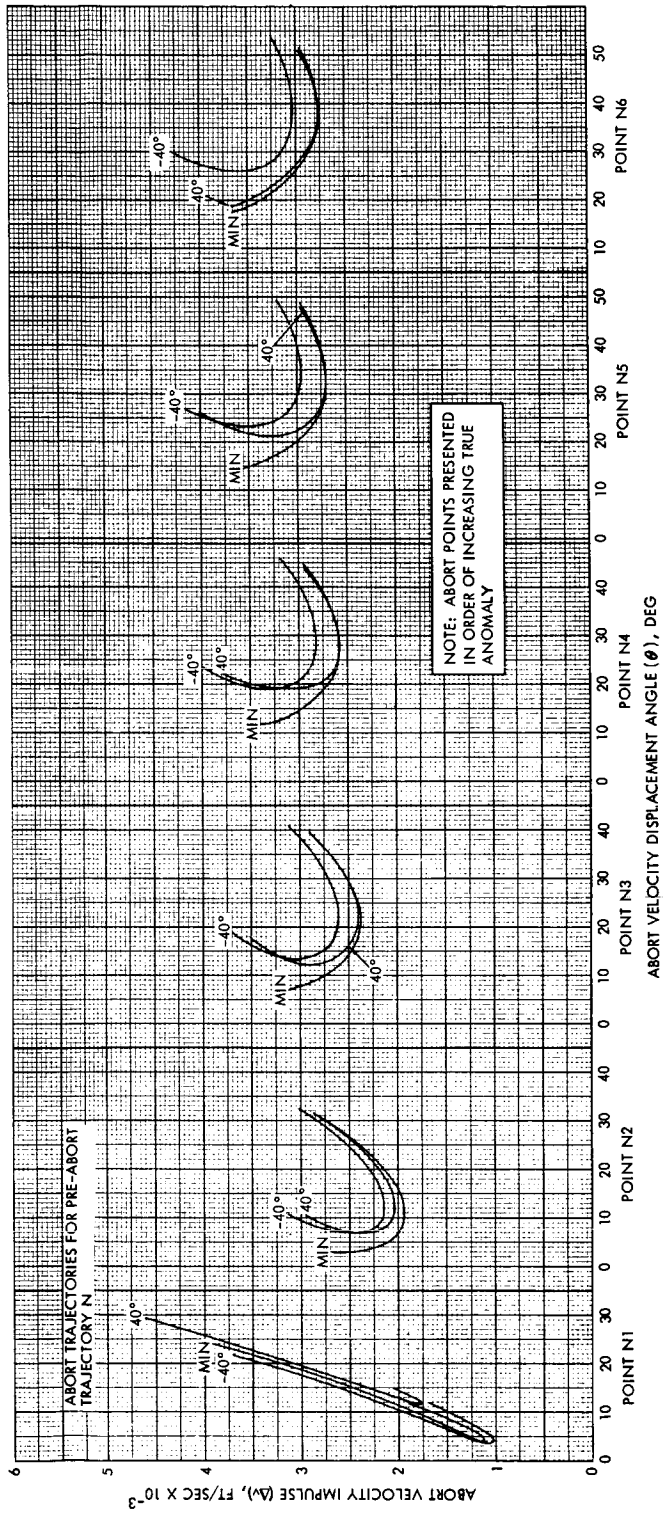

Figure 84. Abort Velocity Displacement Angle (Pre-abort Trajectory N)

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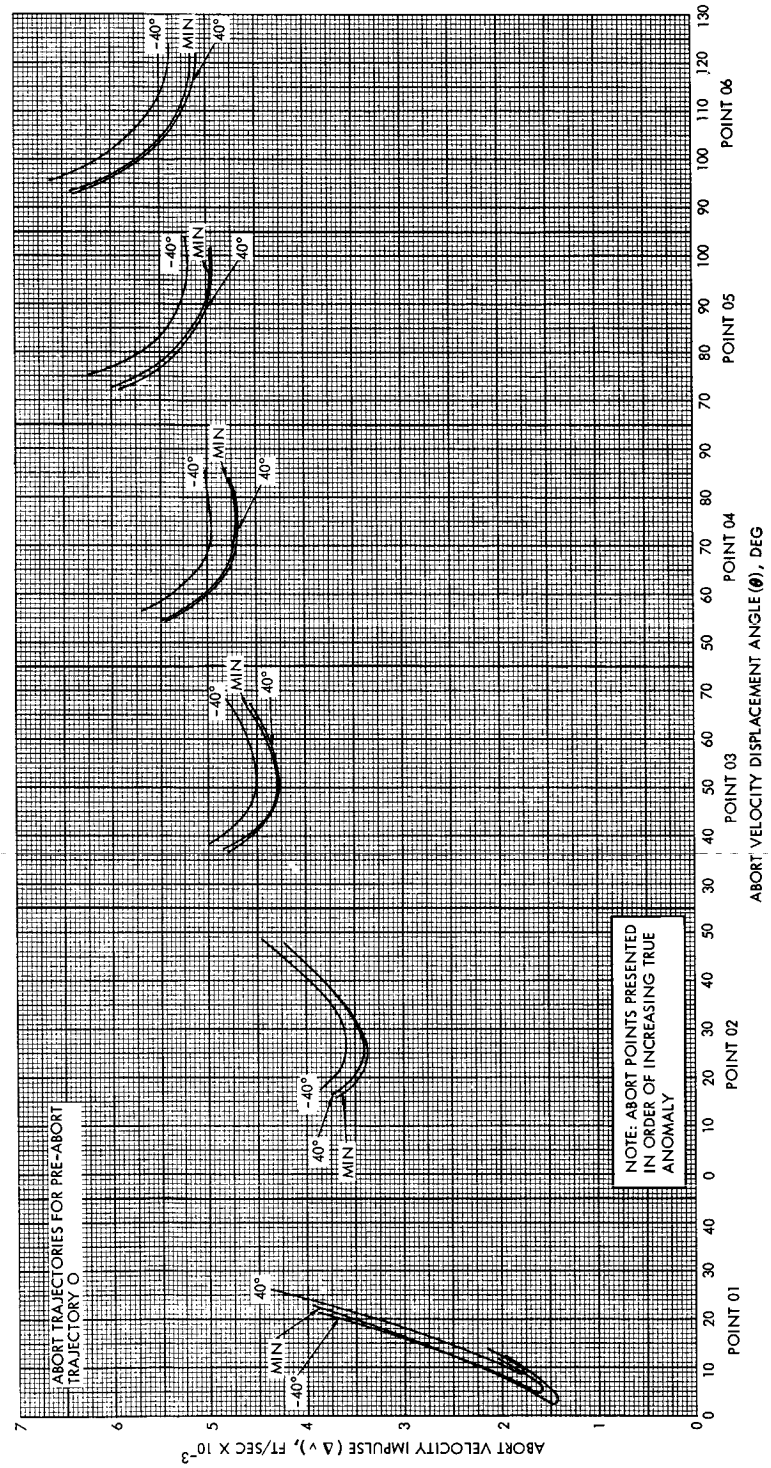

Figure 85. Abort Velocity Displacement Angle (Pre-abort Trajectory O)

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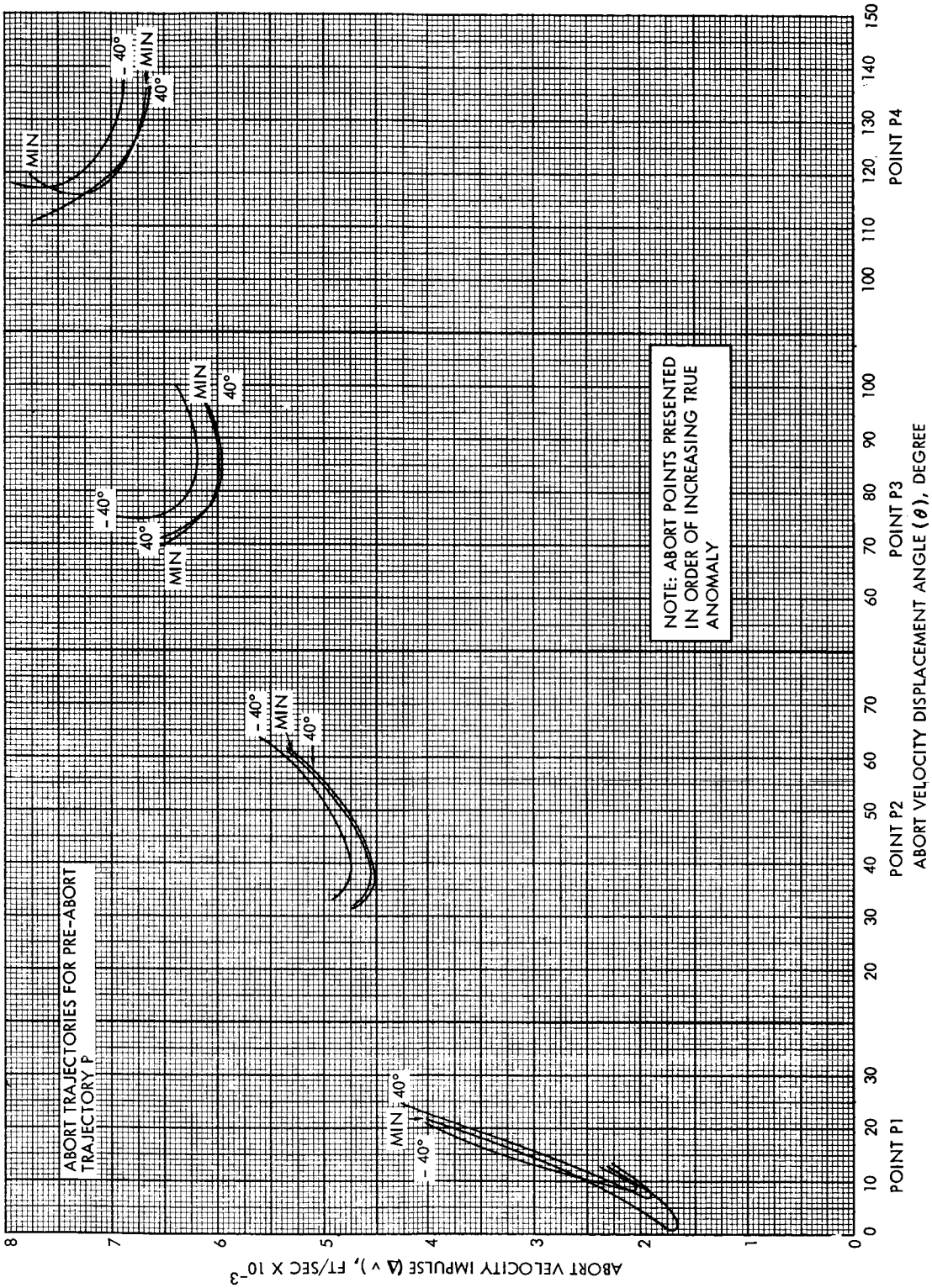

Figure 86. Abort Velocity Displacement Angle (Pre-abort Trajectory P)

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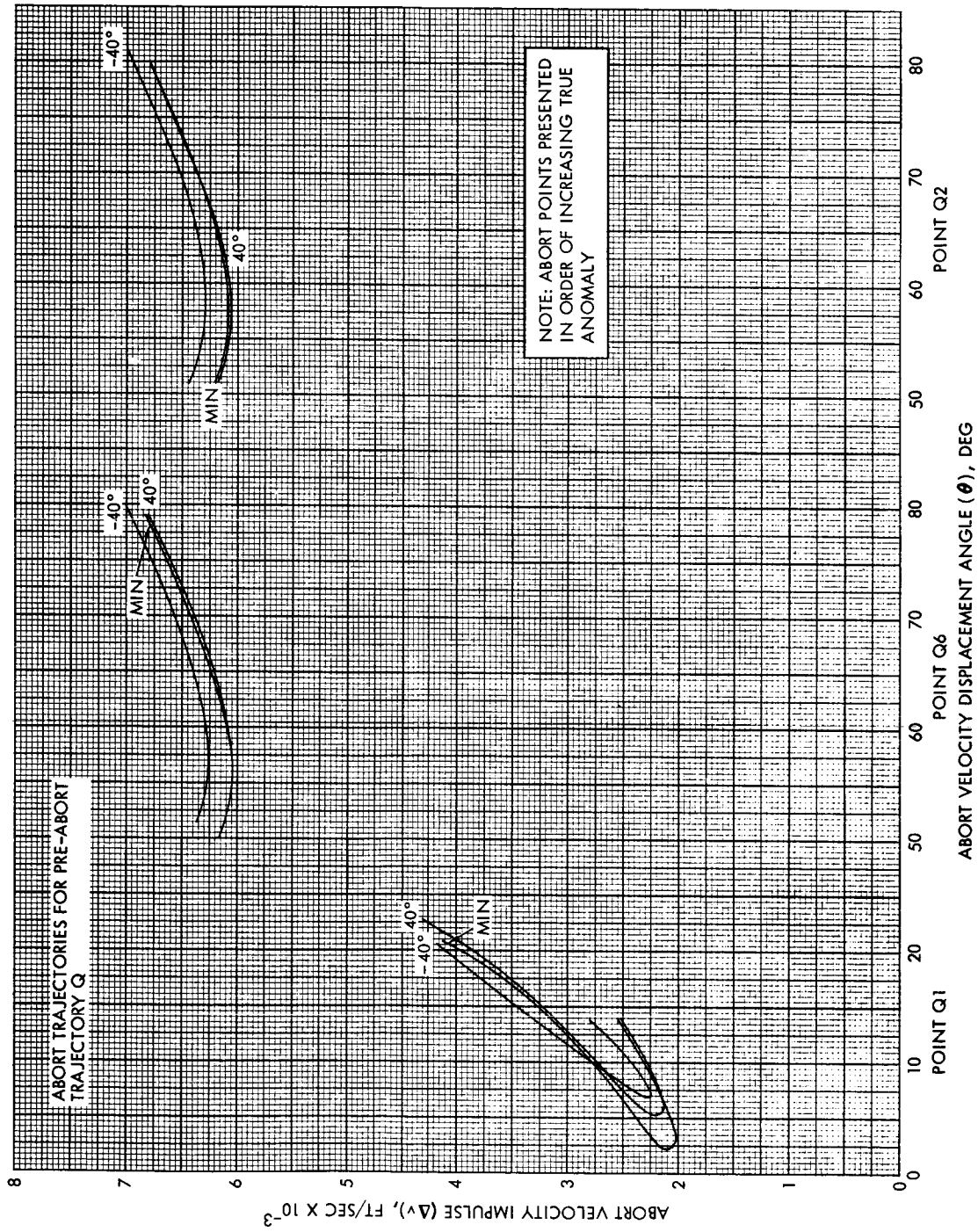

Figure 87. Abort Velocity Displacement Angle (Pre-abort Trajectory Q)

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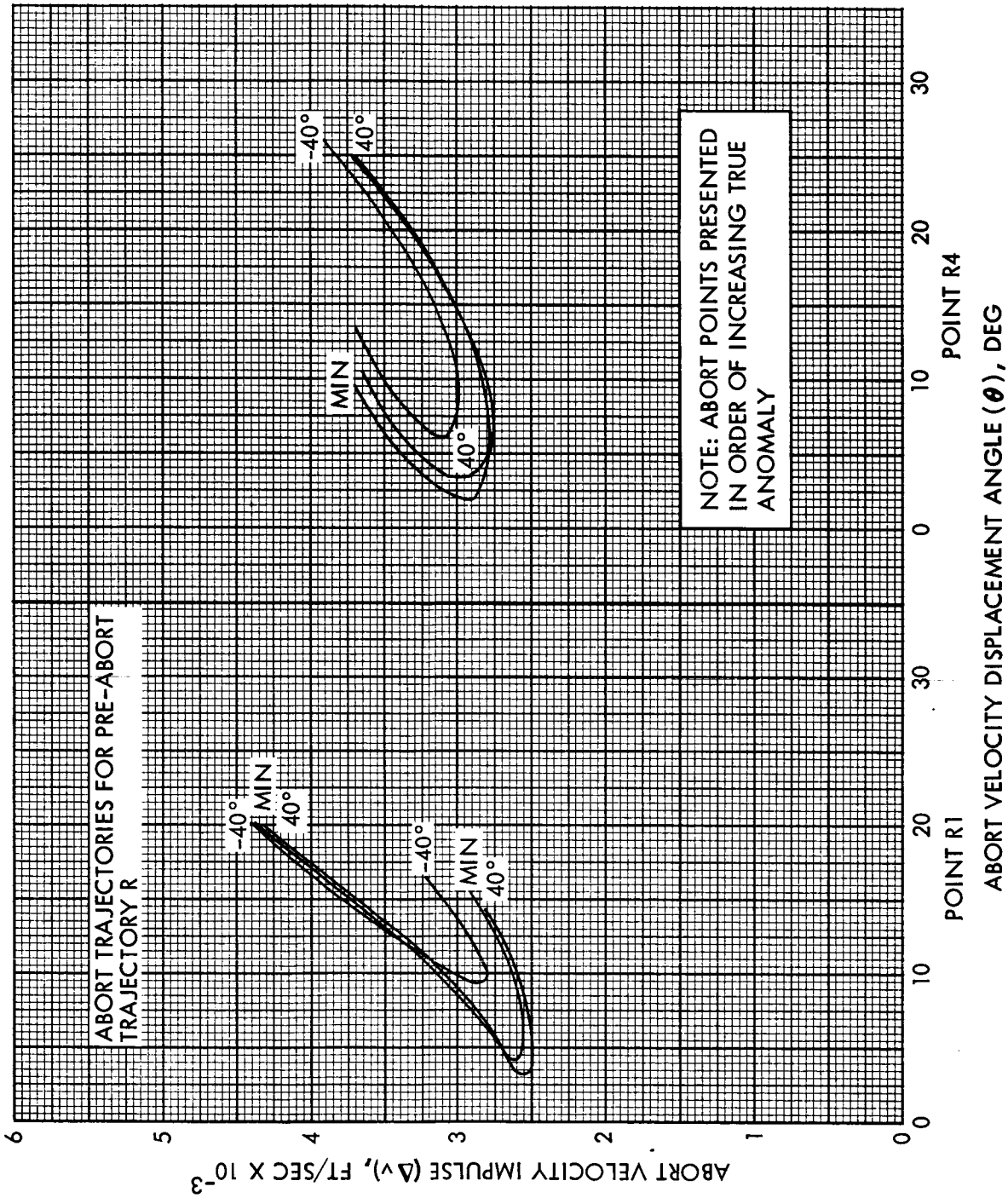

Figure 88. Abort Velocity Displacement Angle (Pre-abort Trajectory R)

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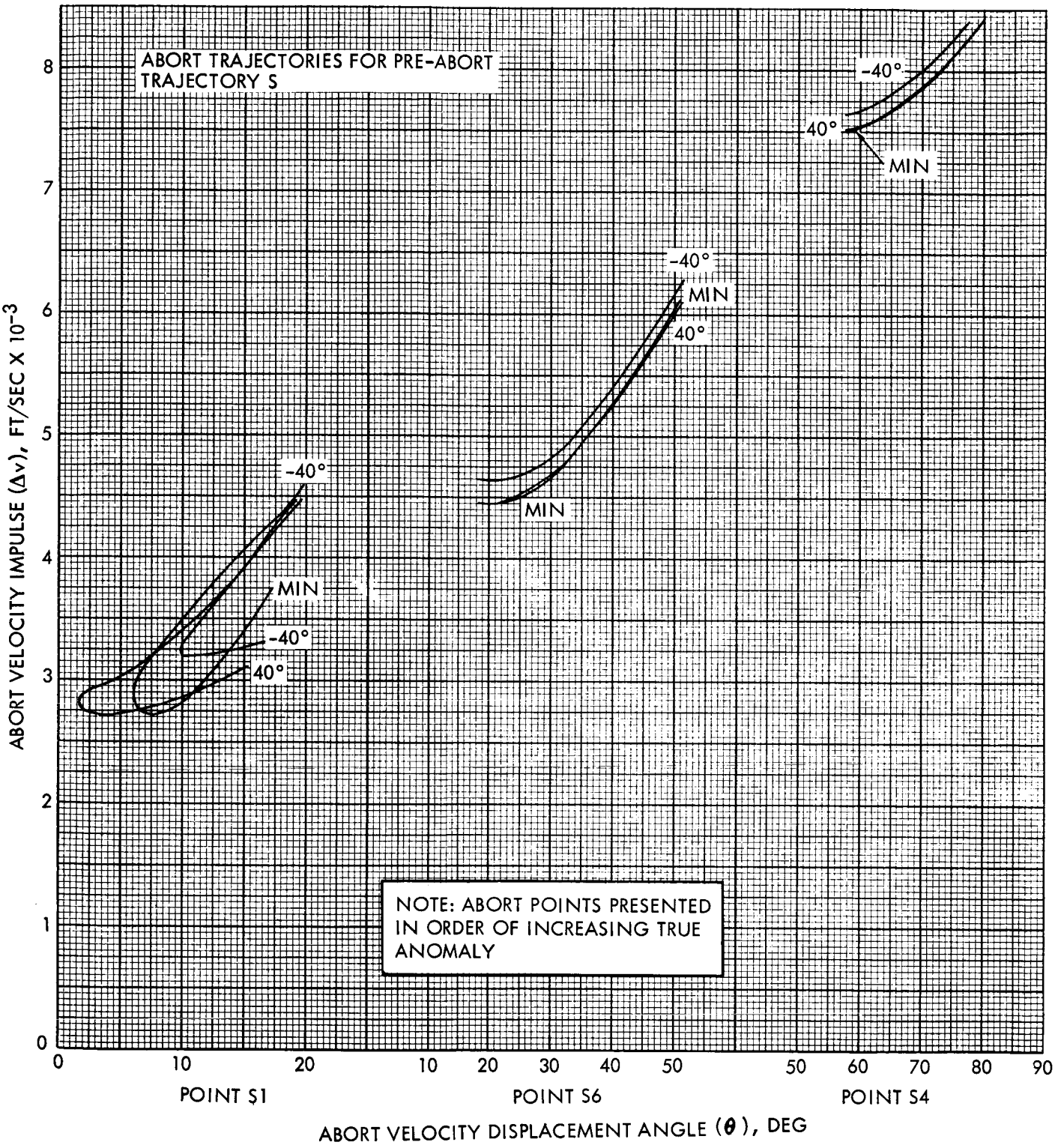

Figure 89. Abort Velocity Displacement Angle (Pre-abort Trajectory S)

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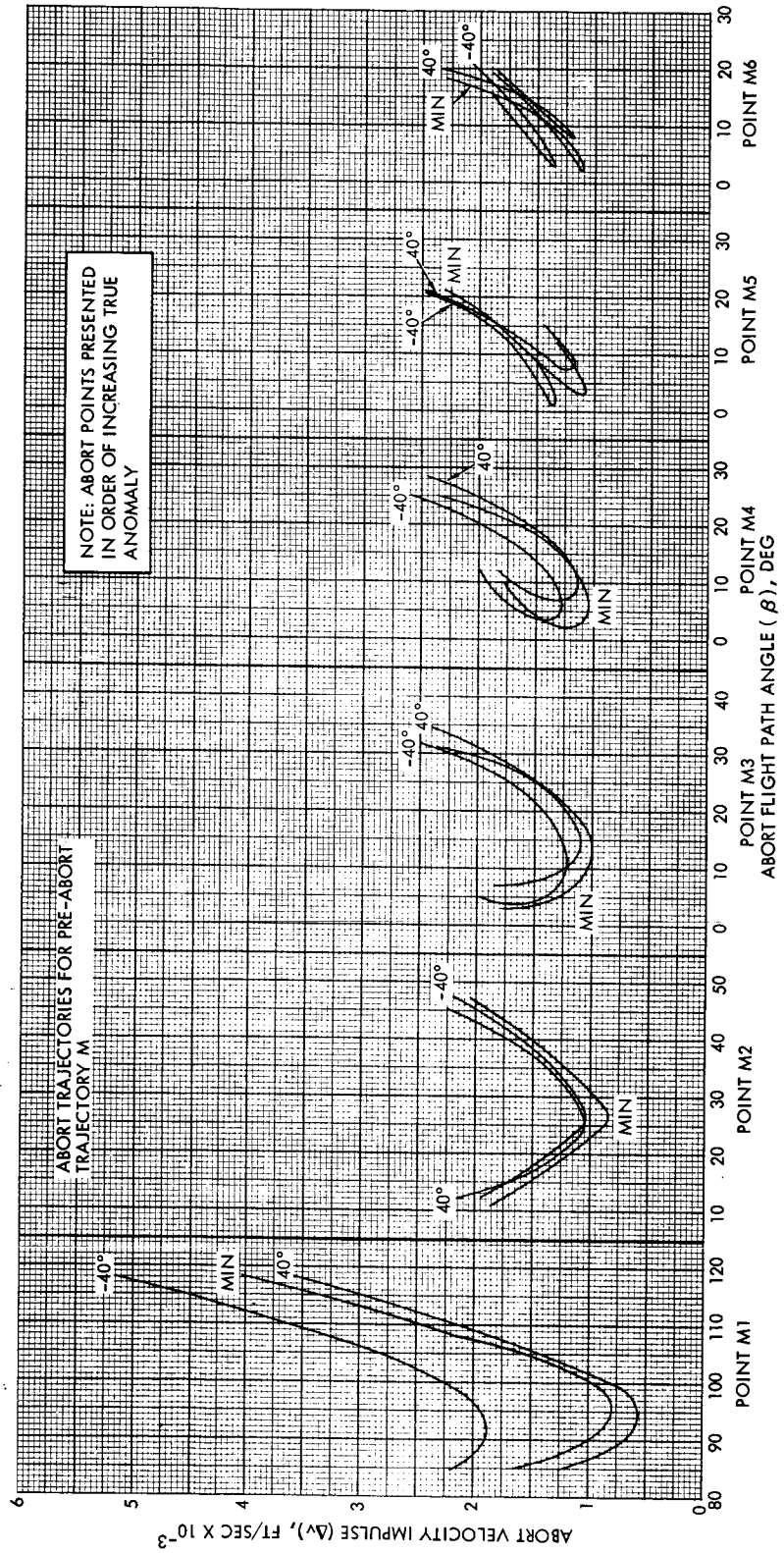

Figure 90. Abort Flight Path Angle (Pre-abort Trajectory M)

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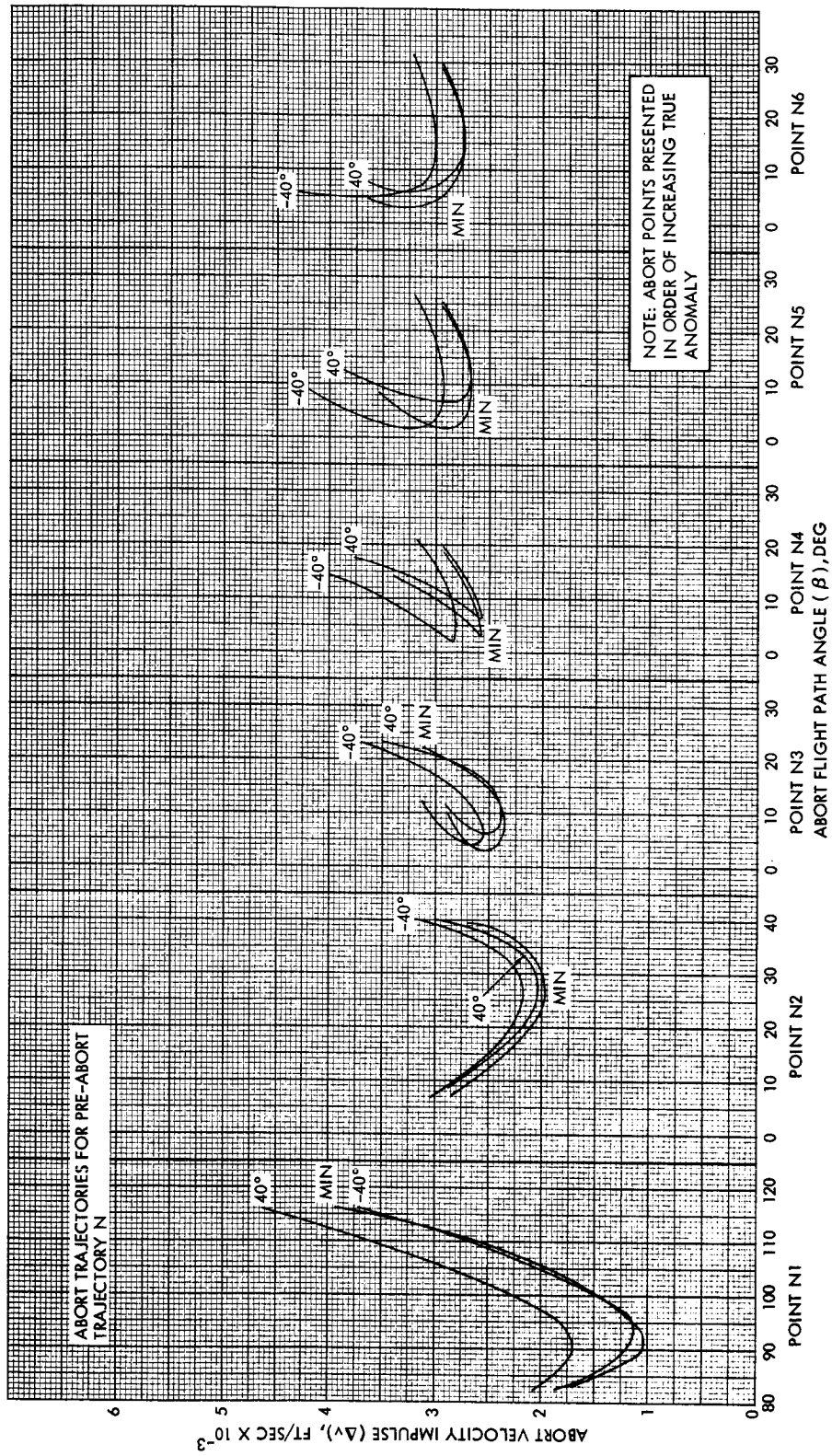

Figure 91. Abort Flight Path Angle (Pre-abort Trajectory N)

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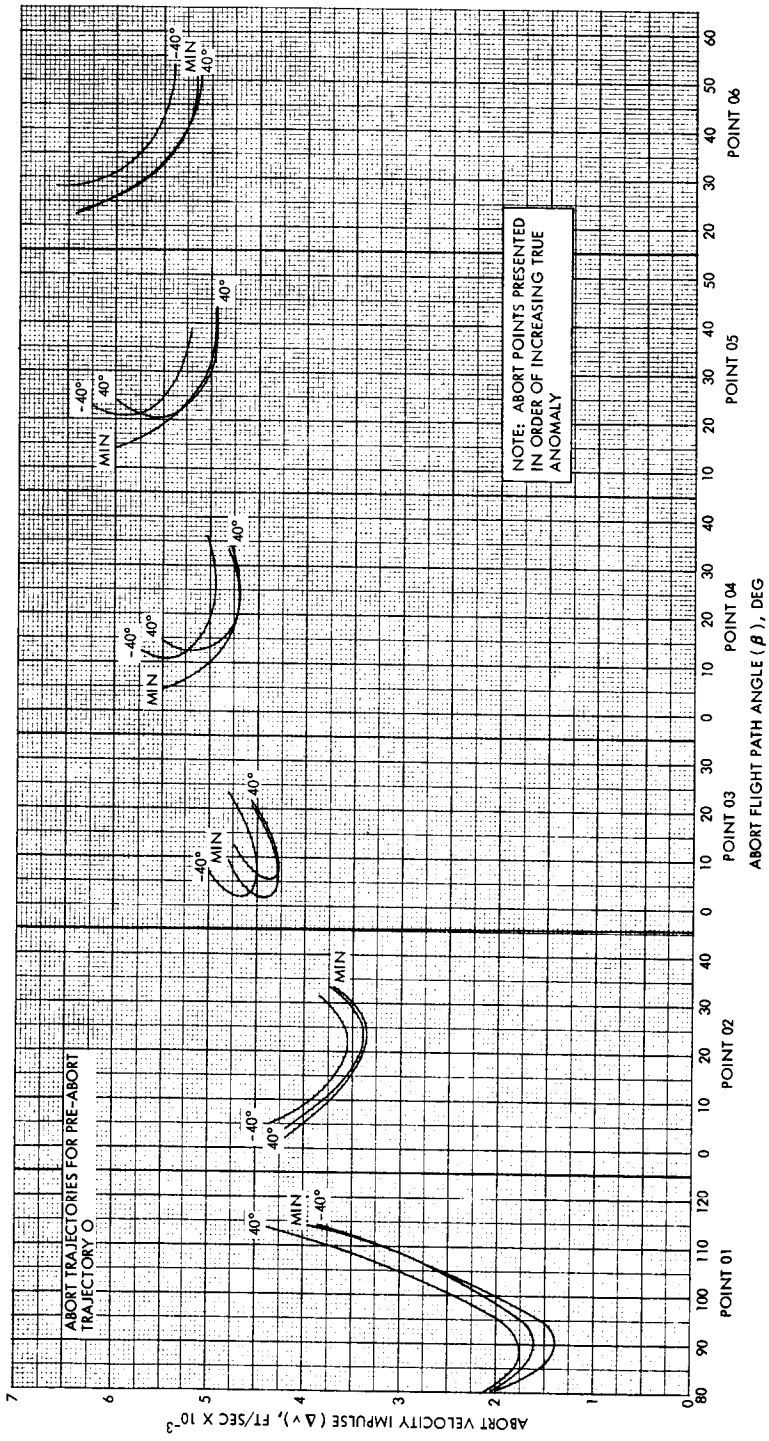

Figure 92. Abort Flight Path Angle (Pre-abort Trajectory O)

This document contains information affecting the national defense of the [redacted] dates within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which [redacted] to an unauthorized person is prohibited by law.

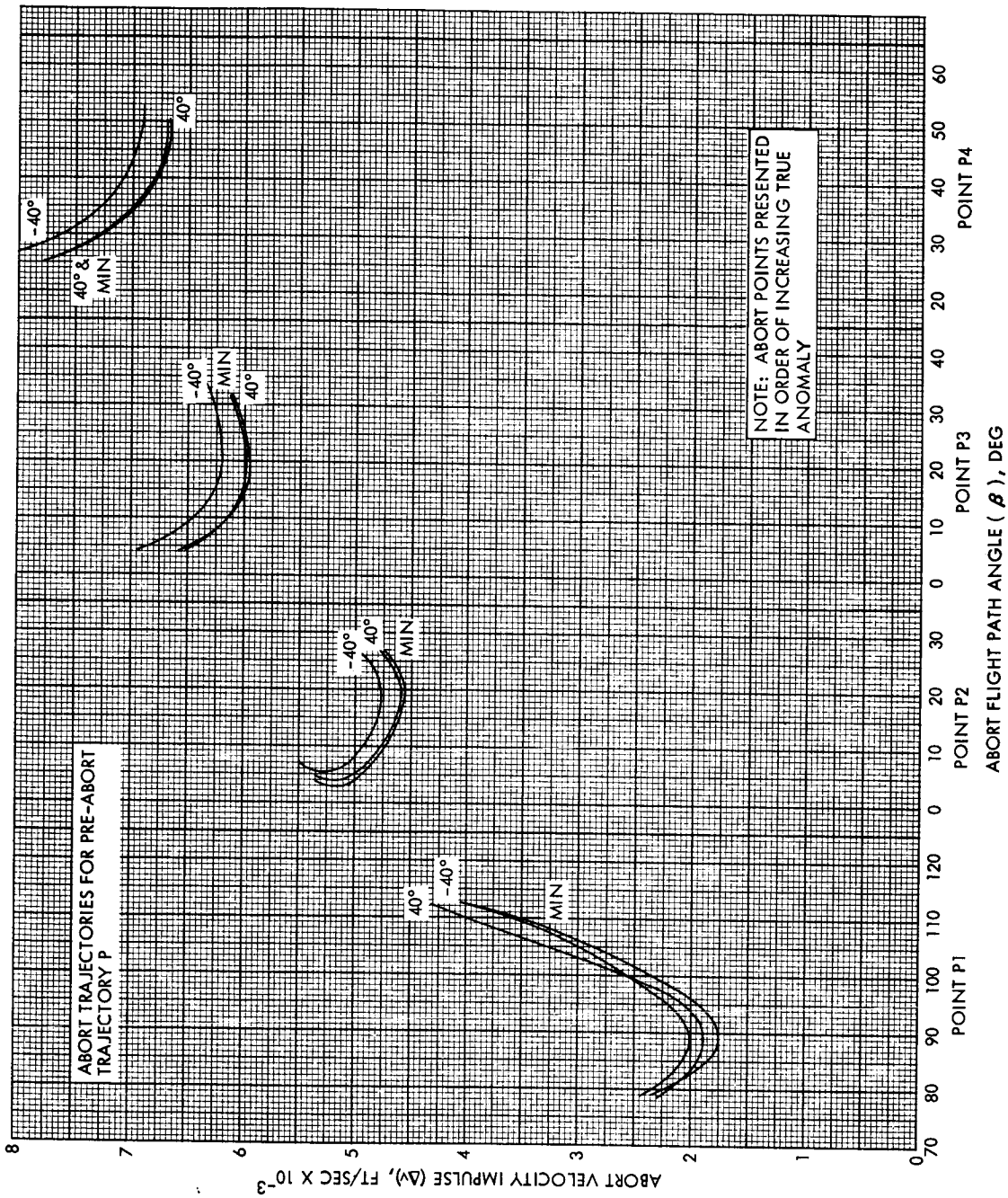

Figure 93. Abort Flight Path Angle (Pre-abort Trajectory P)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

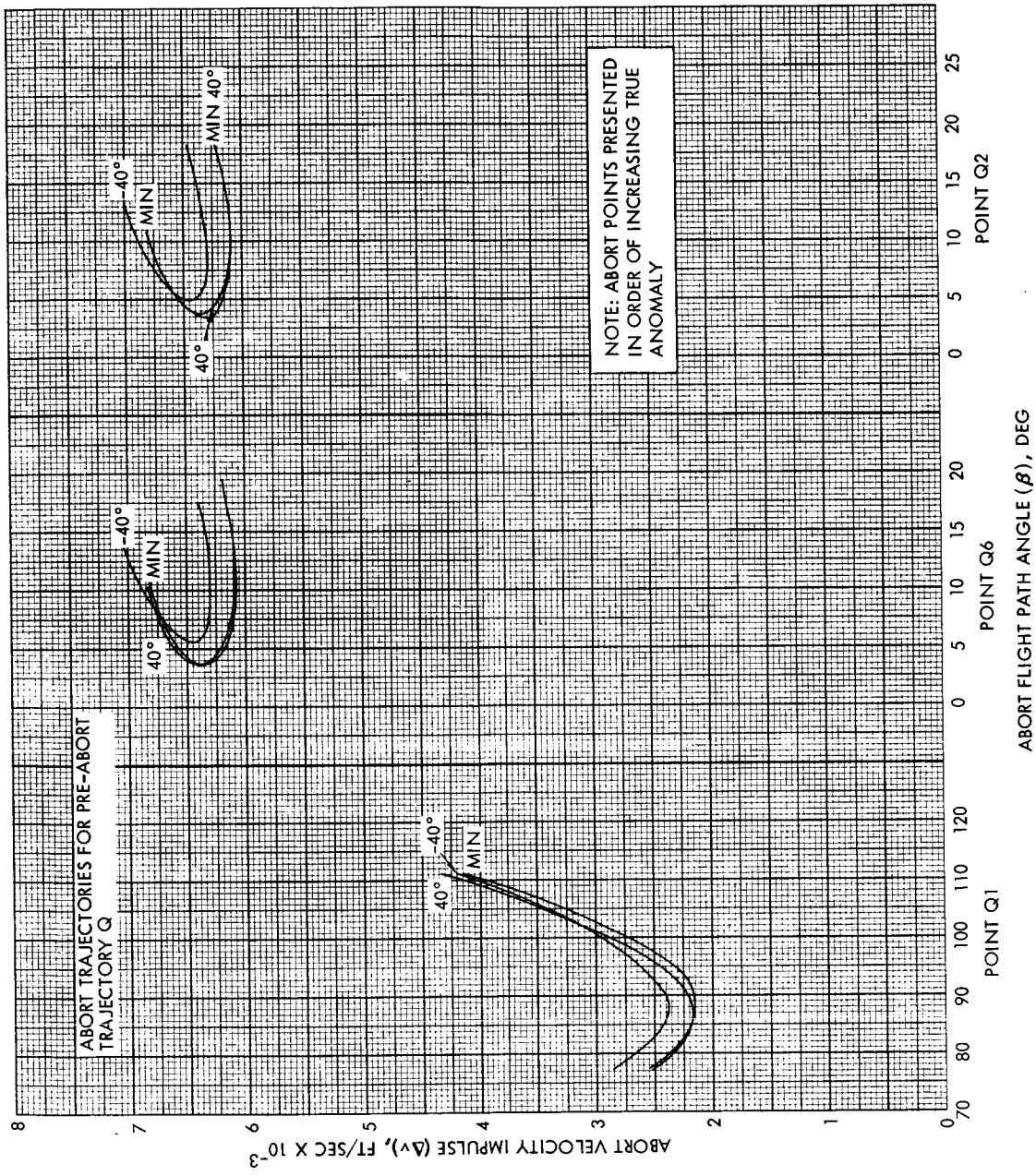

Figure 94. Abort Flight Path Angle (Pre-abort Trajectory Q)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

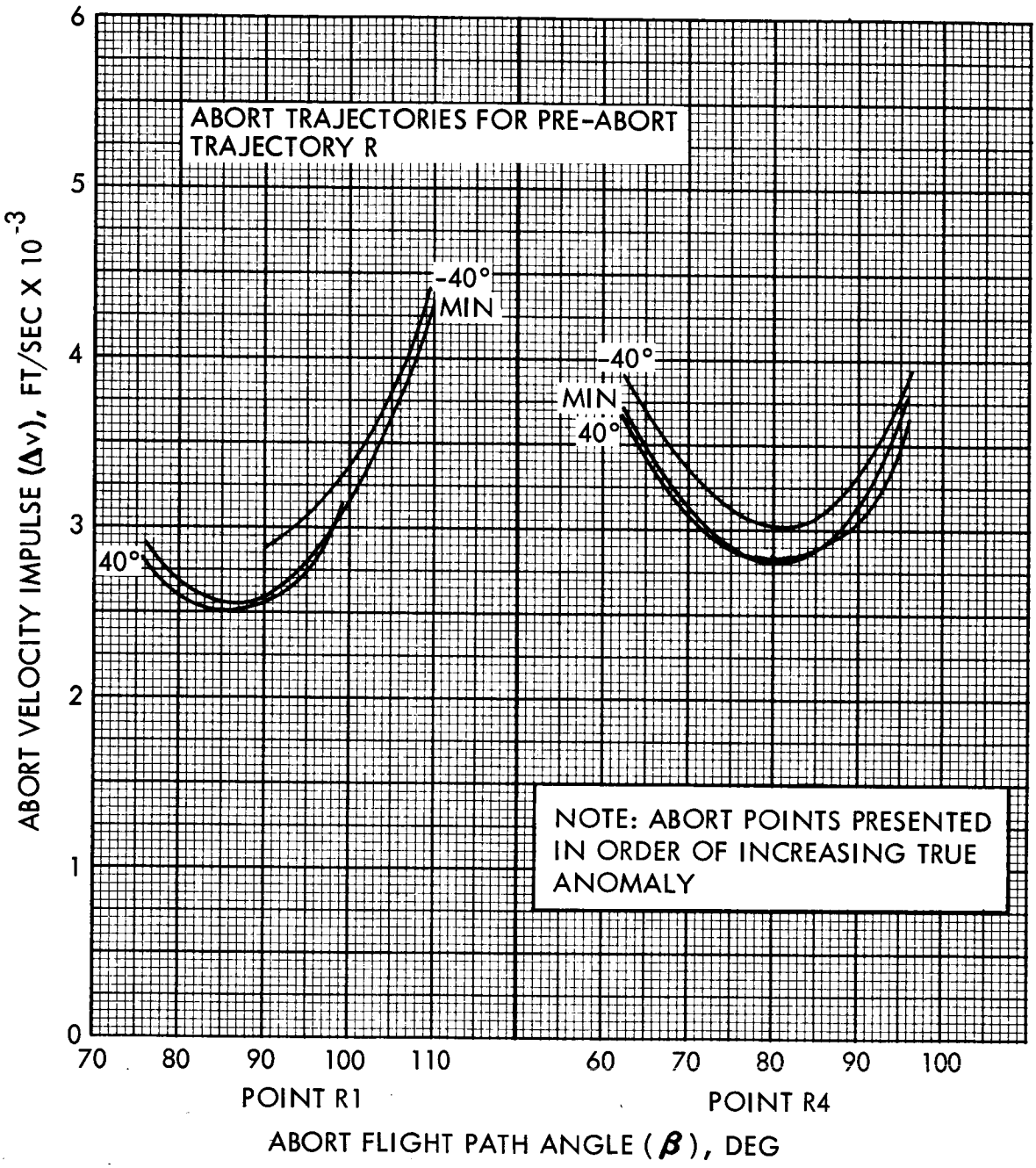

Figure 95. Abort Flight Path Angle (Pre-abort Trajectory R)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

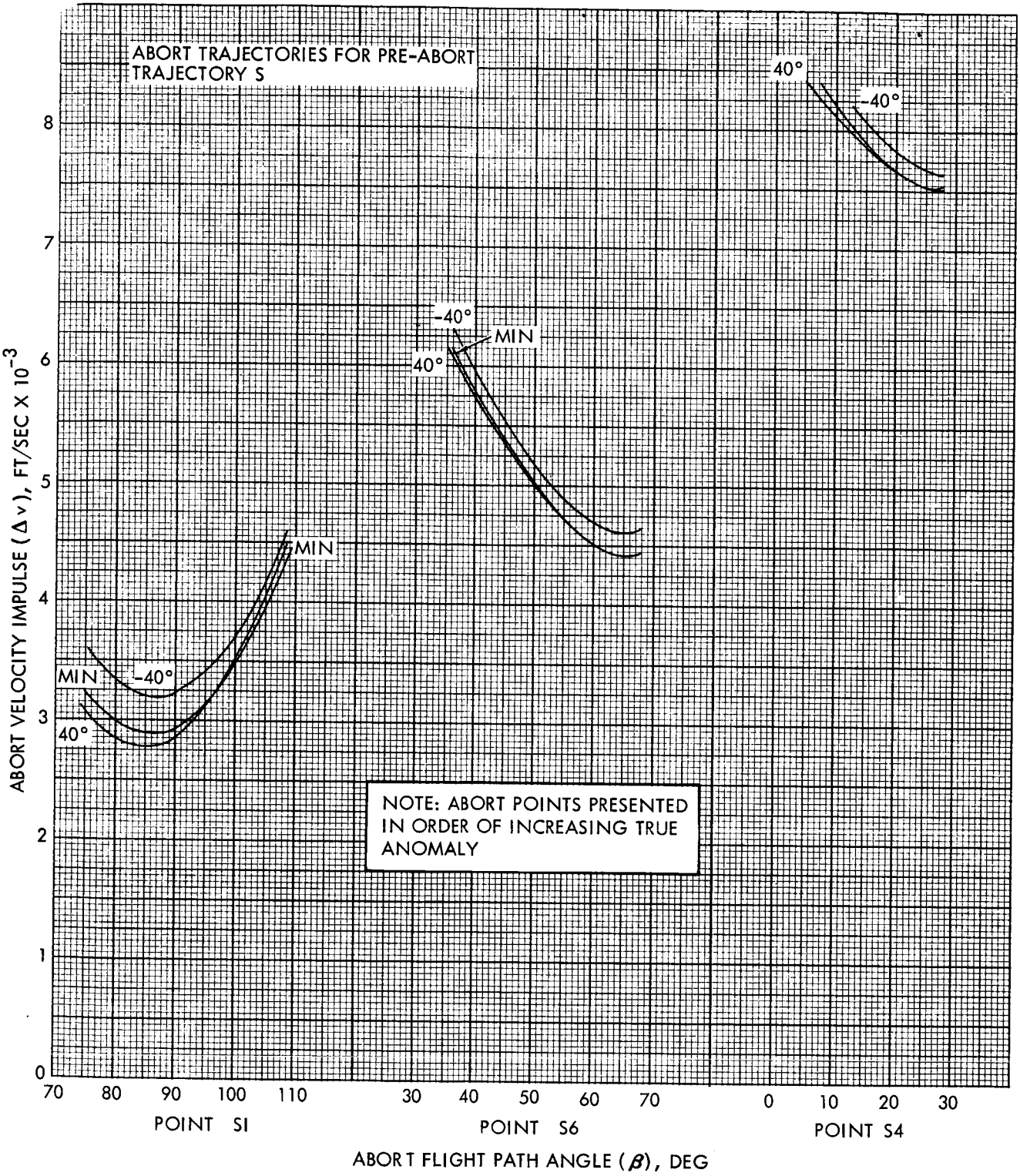

Figure 96. Abort Flight Path Angle (Pre-abort Trajectory S)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

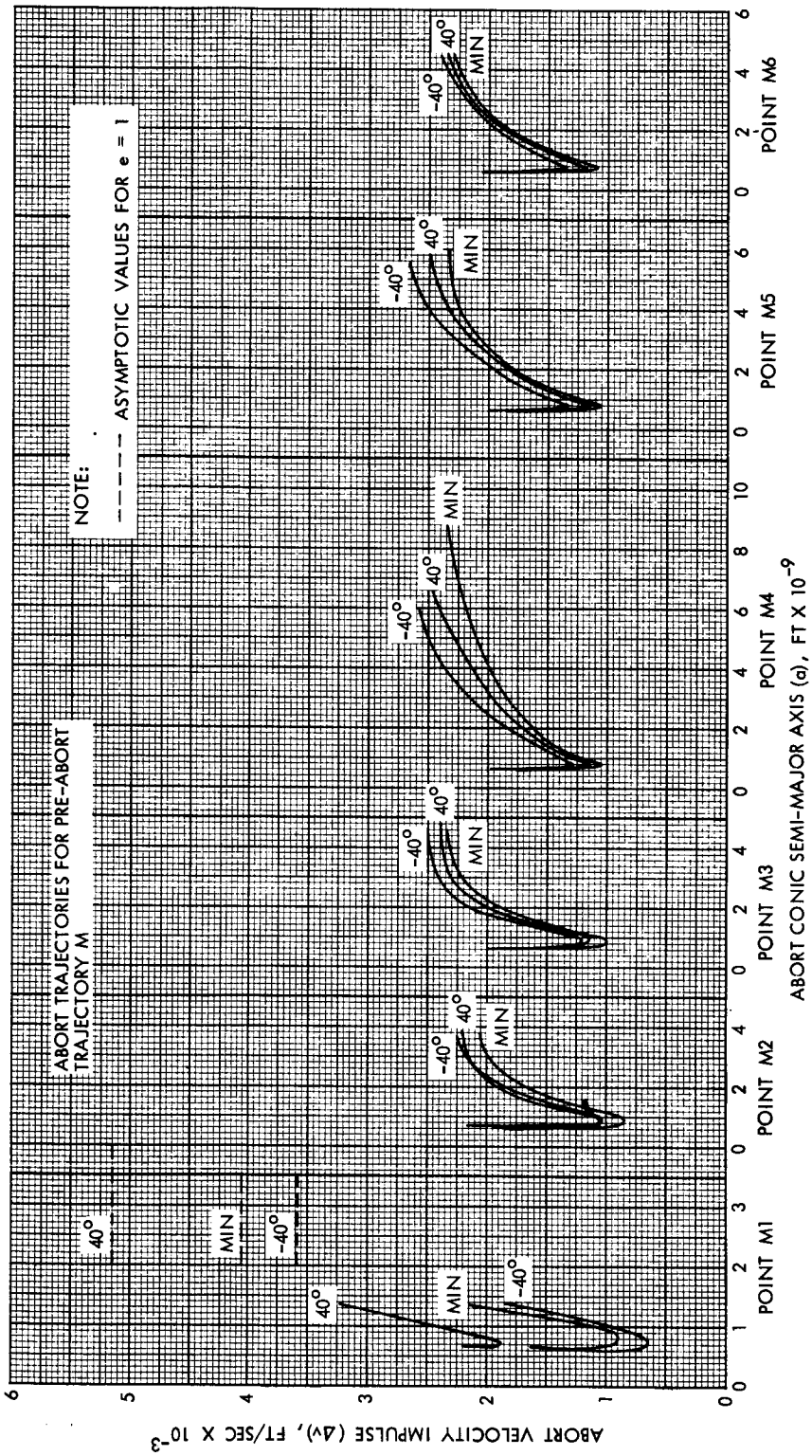

Figure 97. Abort Semi-major Axis (Pre-abort Trajectory M)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

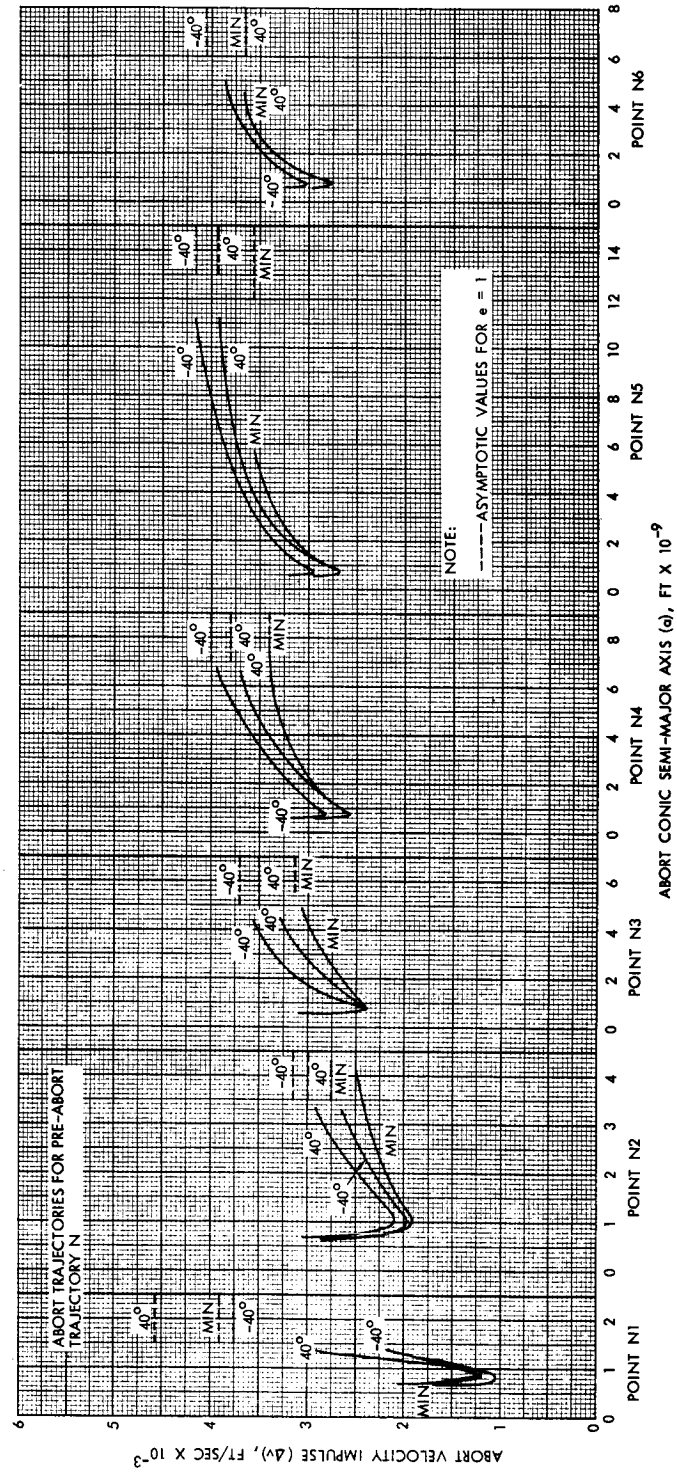

Figure 98. Abort Semi-major Axis (Pre-abort Trajectory N)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

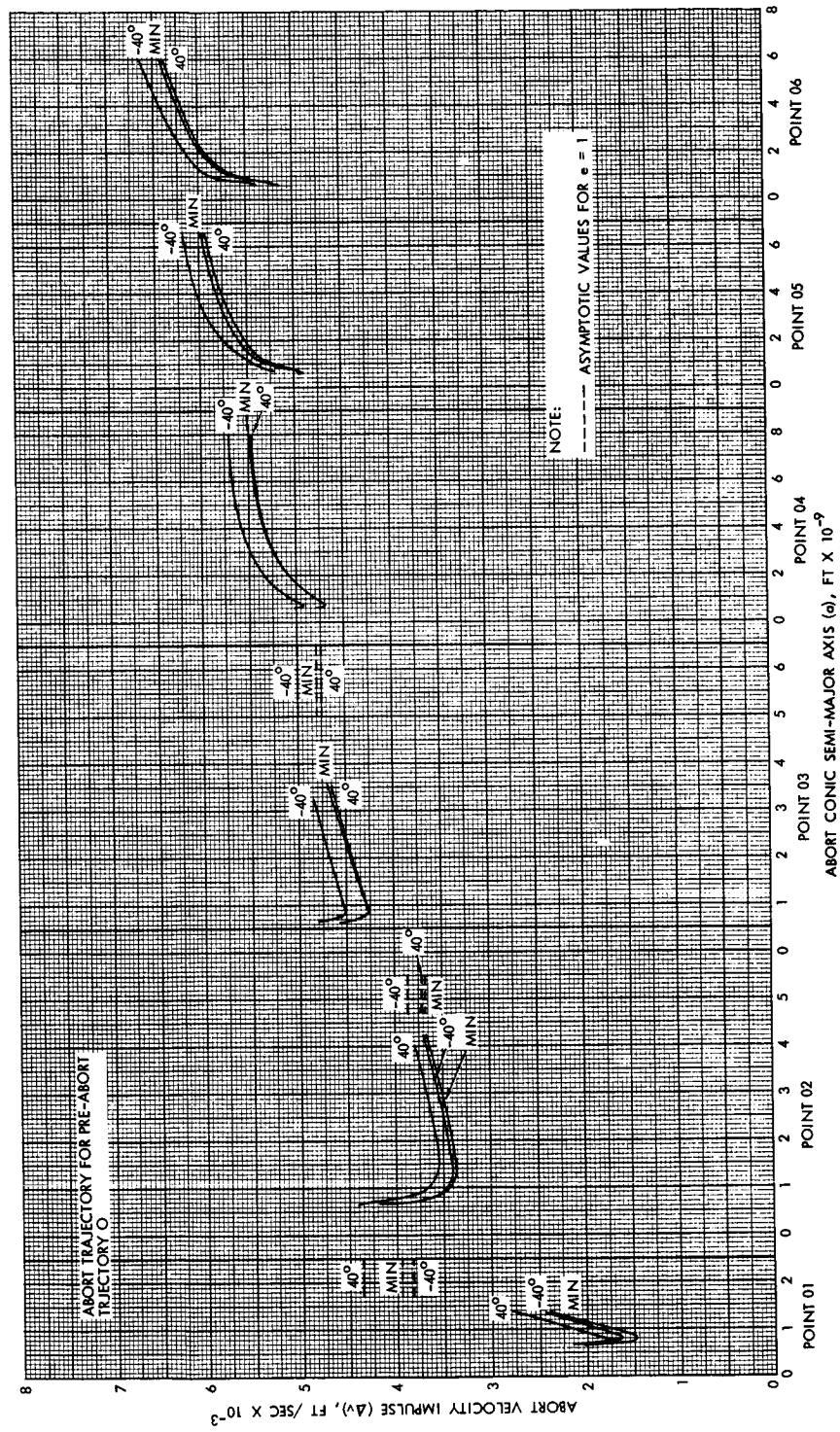

Figure 99. Abort Semi-major Axis (Pre-abort Trajectory O)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

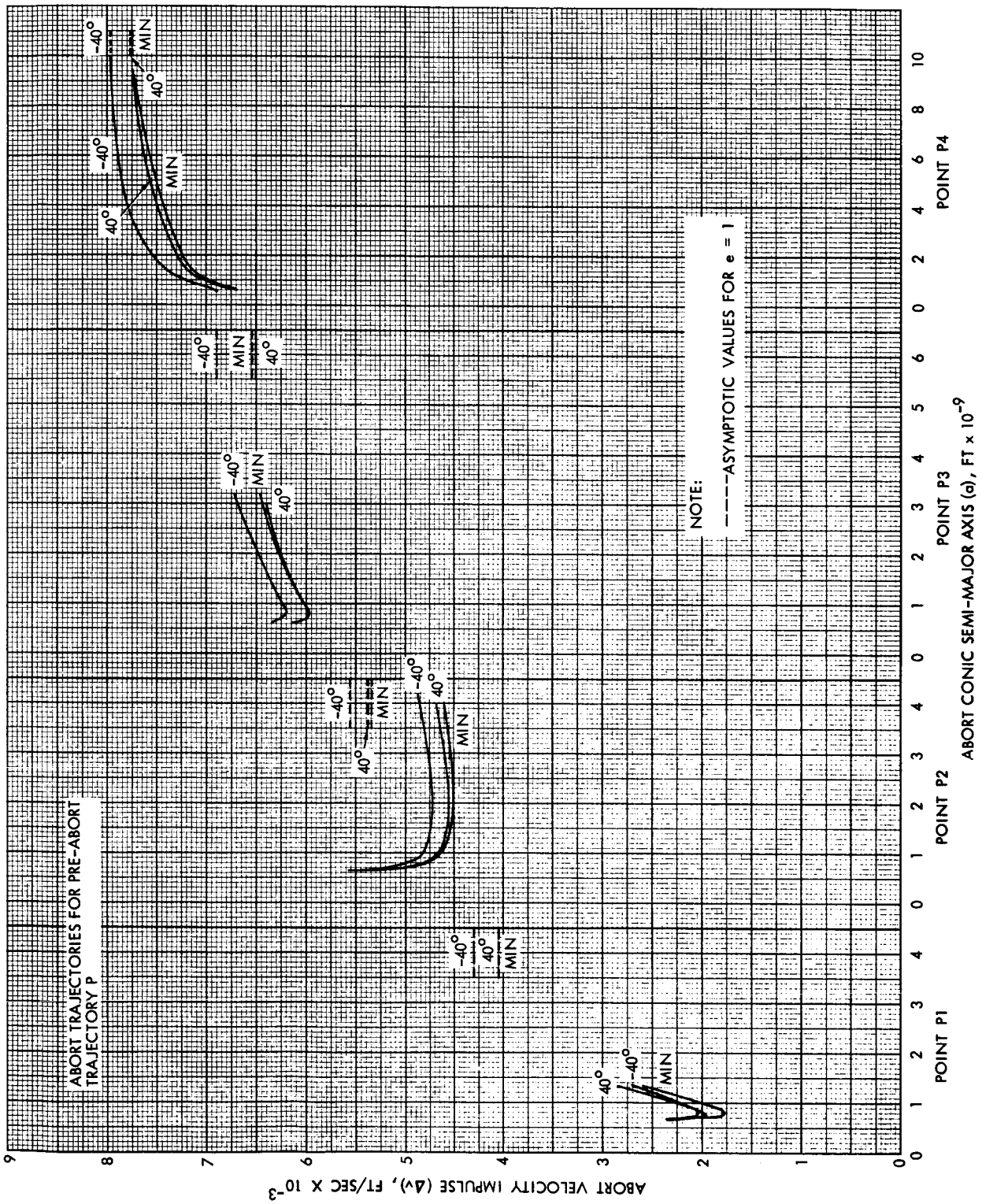

Figure 100. Abort Semi-major Axis (Pre-abort Trajectory P)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

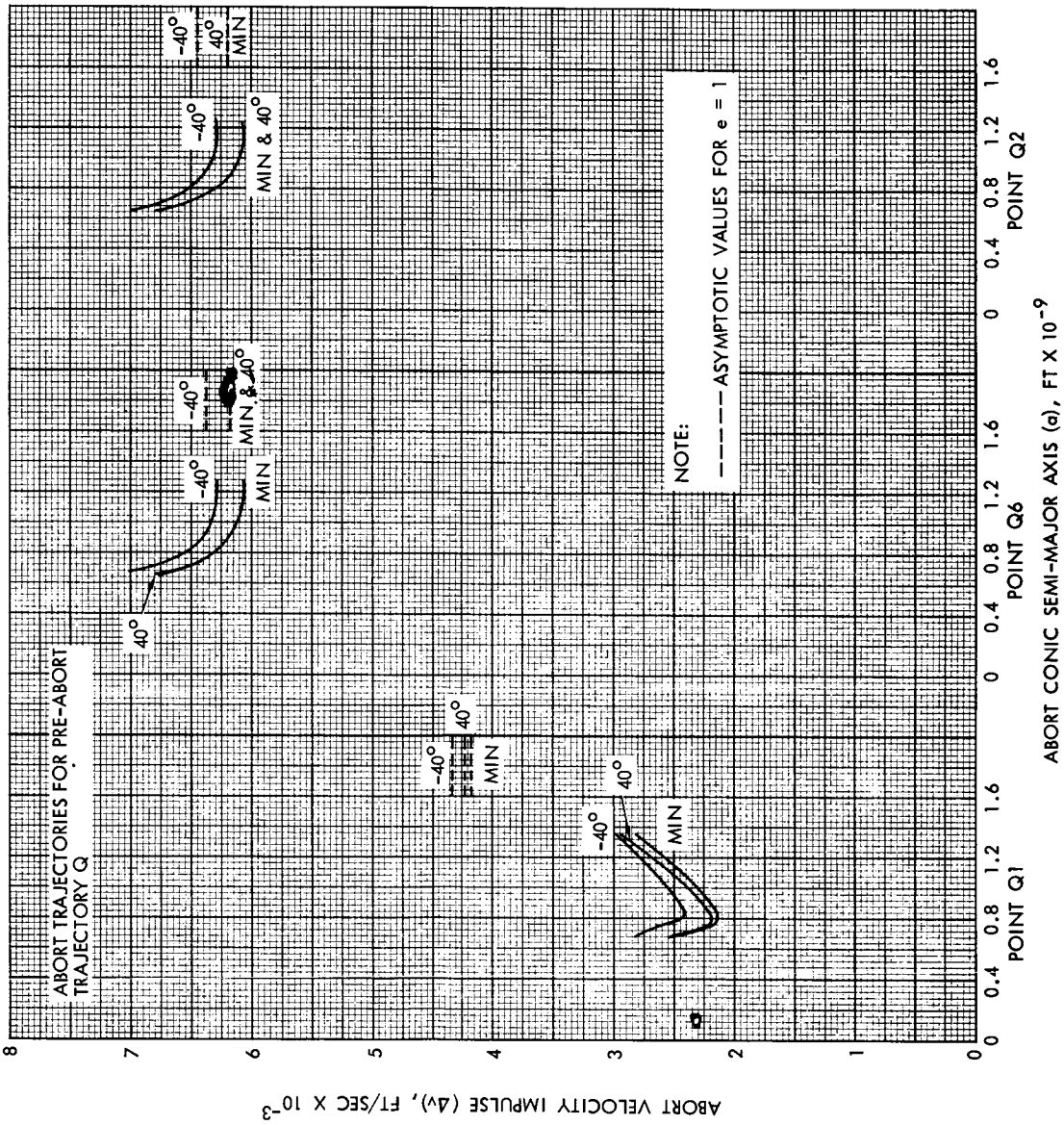

Figure 101. Abort Semi-major Axis (Pre-abort Trajectory Q)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

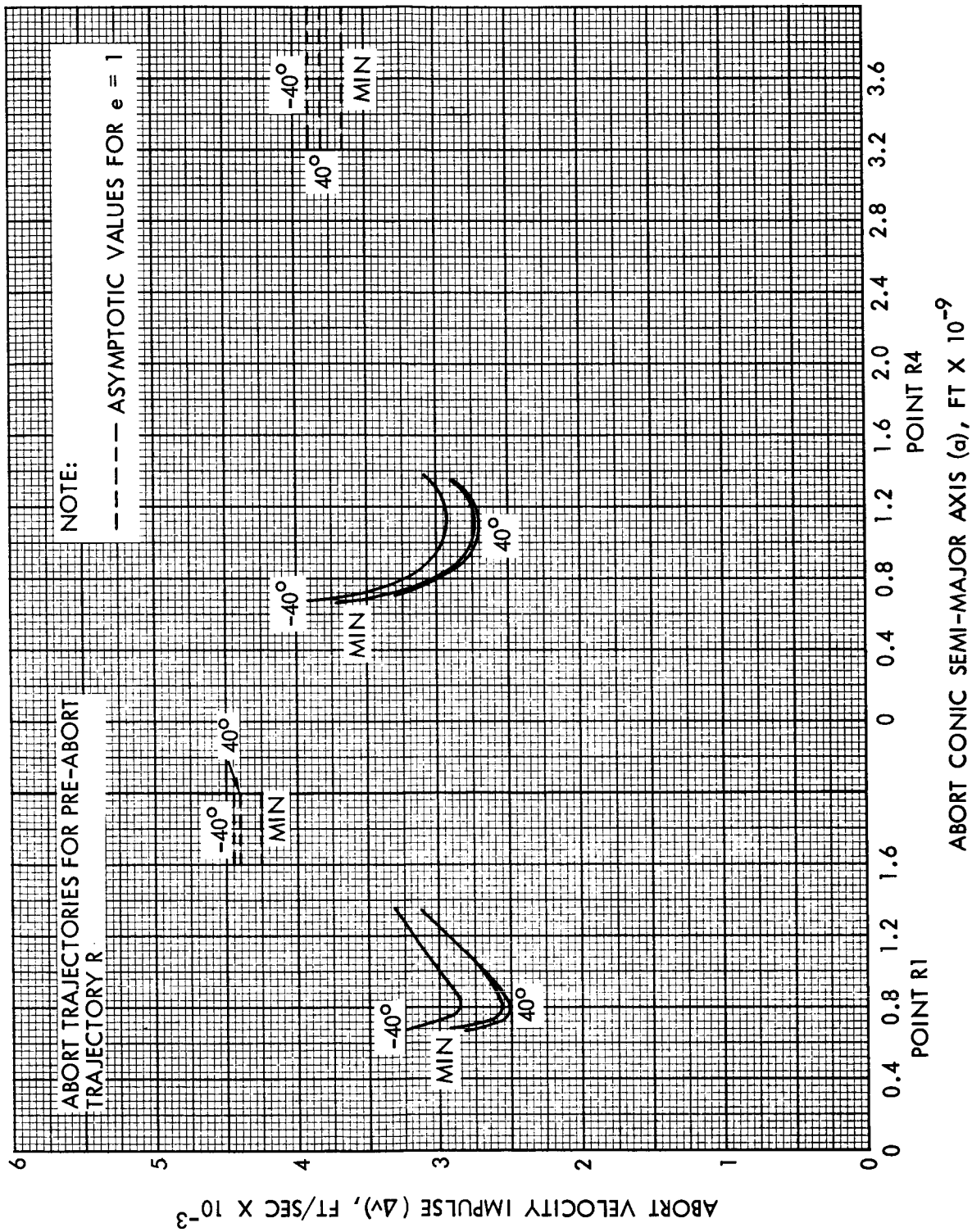

Figure 102. Abort Semi-major Axis (Pre-abort Trajectory R)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

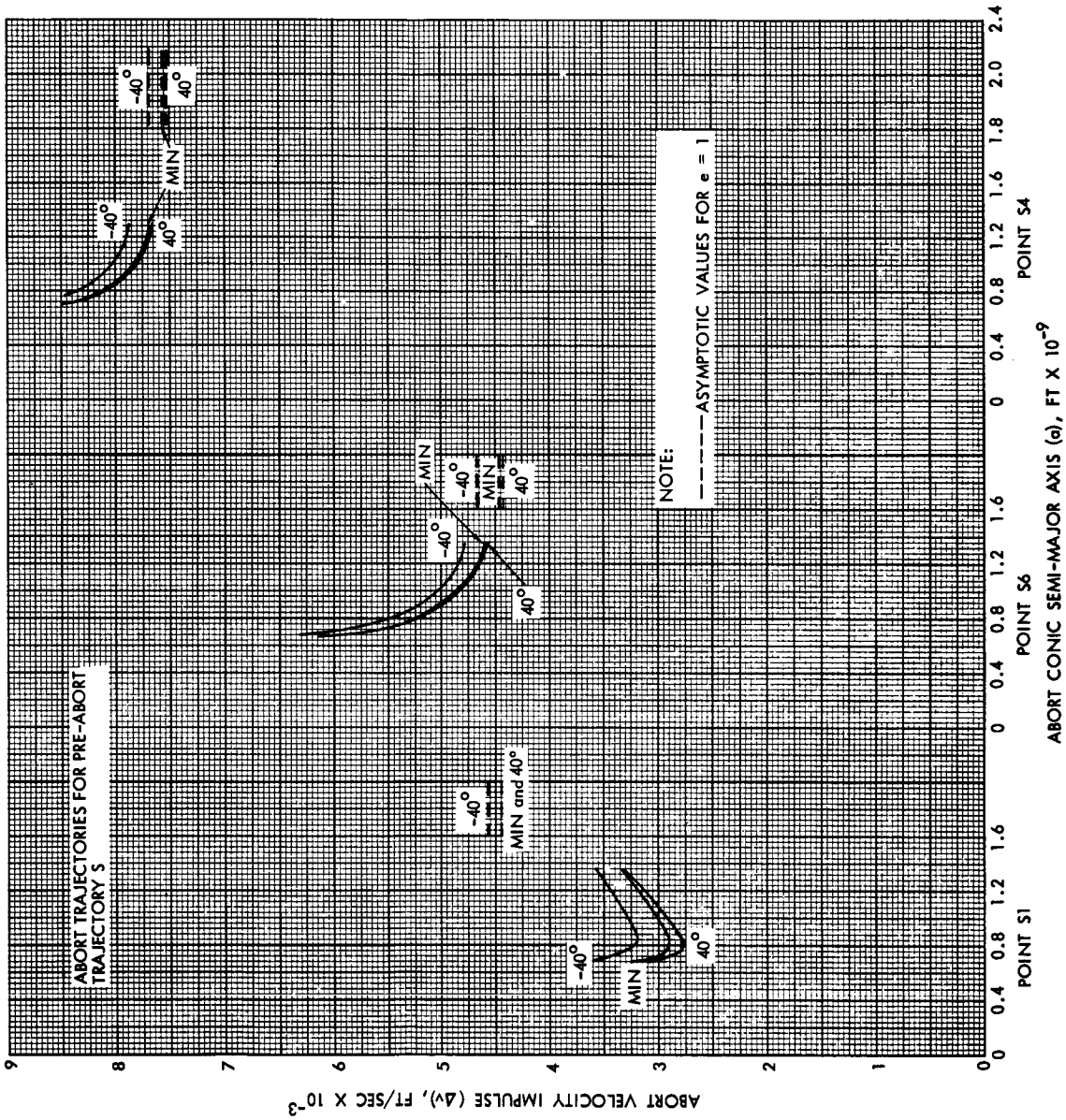

Figure 103. Abort Semi-major Axis (Pre-abort Trajectory S)

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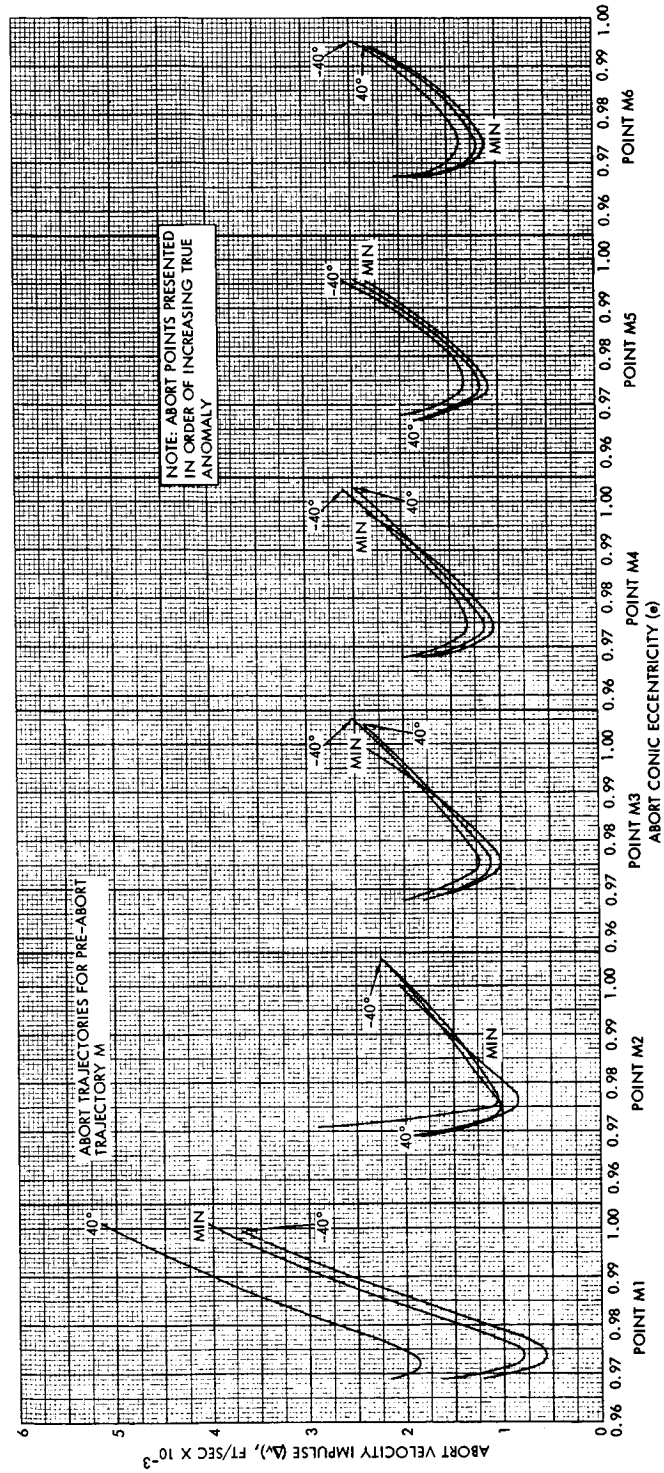

Figure 104. Abort Eccentricity (Pre-abort Trajectory M)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

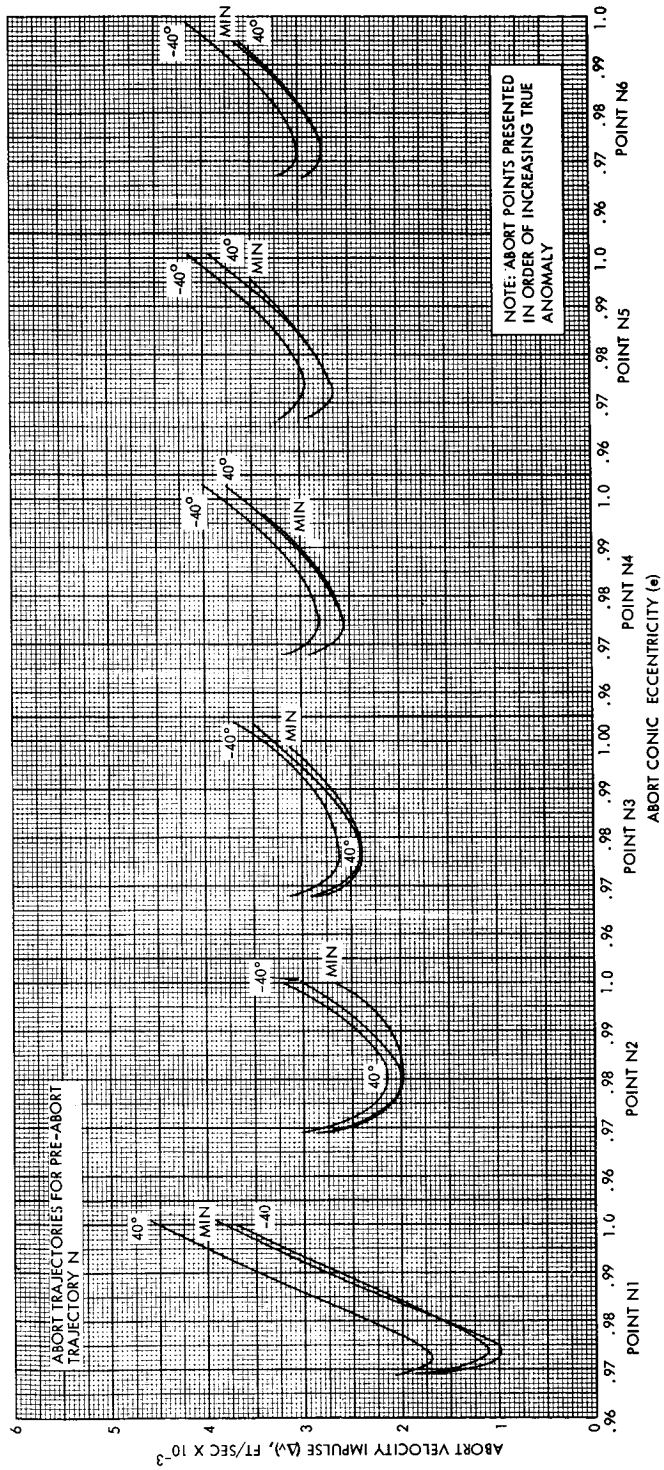

Figure 105. Abort Eccentricity (Pre-abort Trajectory N)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

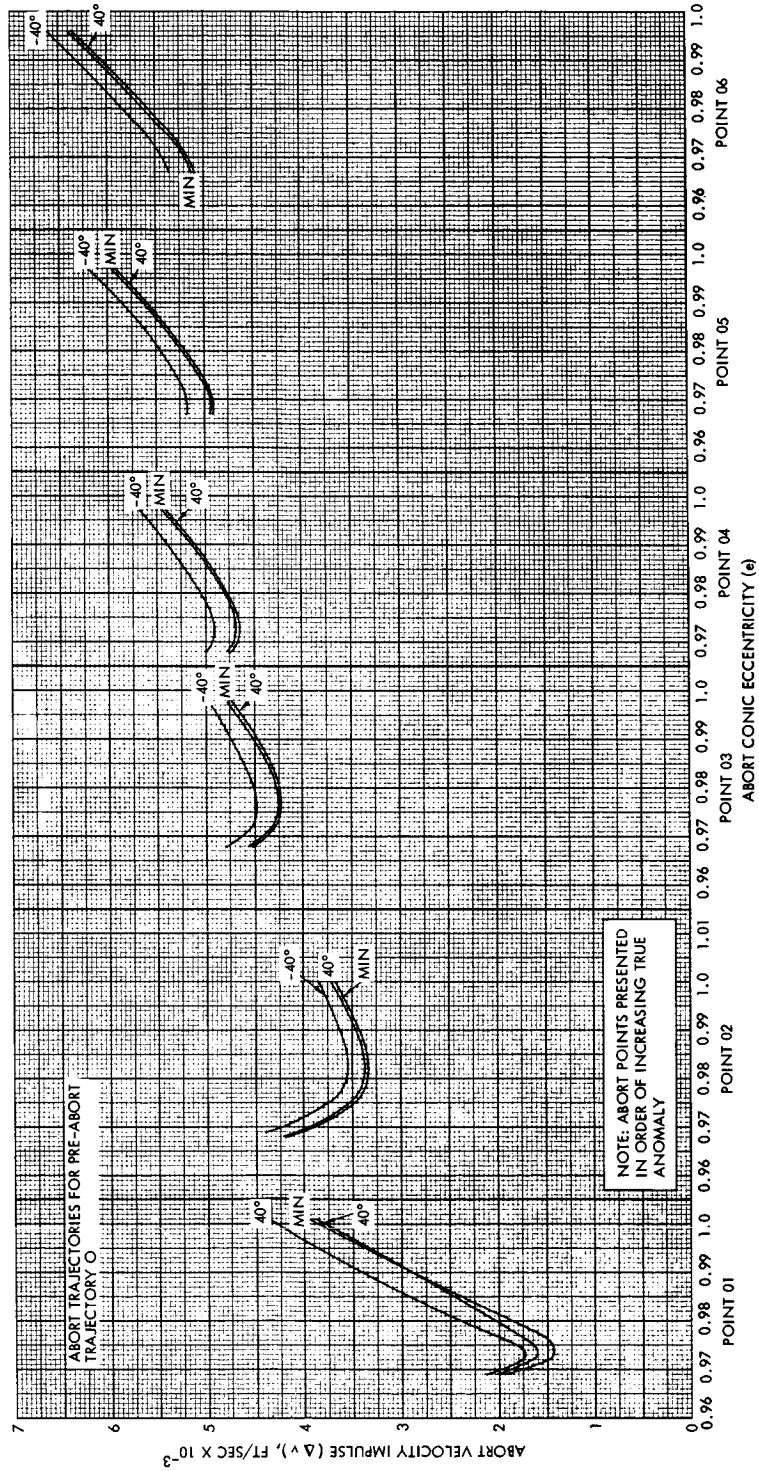

Figure 106. Abort Eccentricity (Pre-abort Trajectory O)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

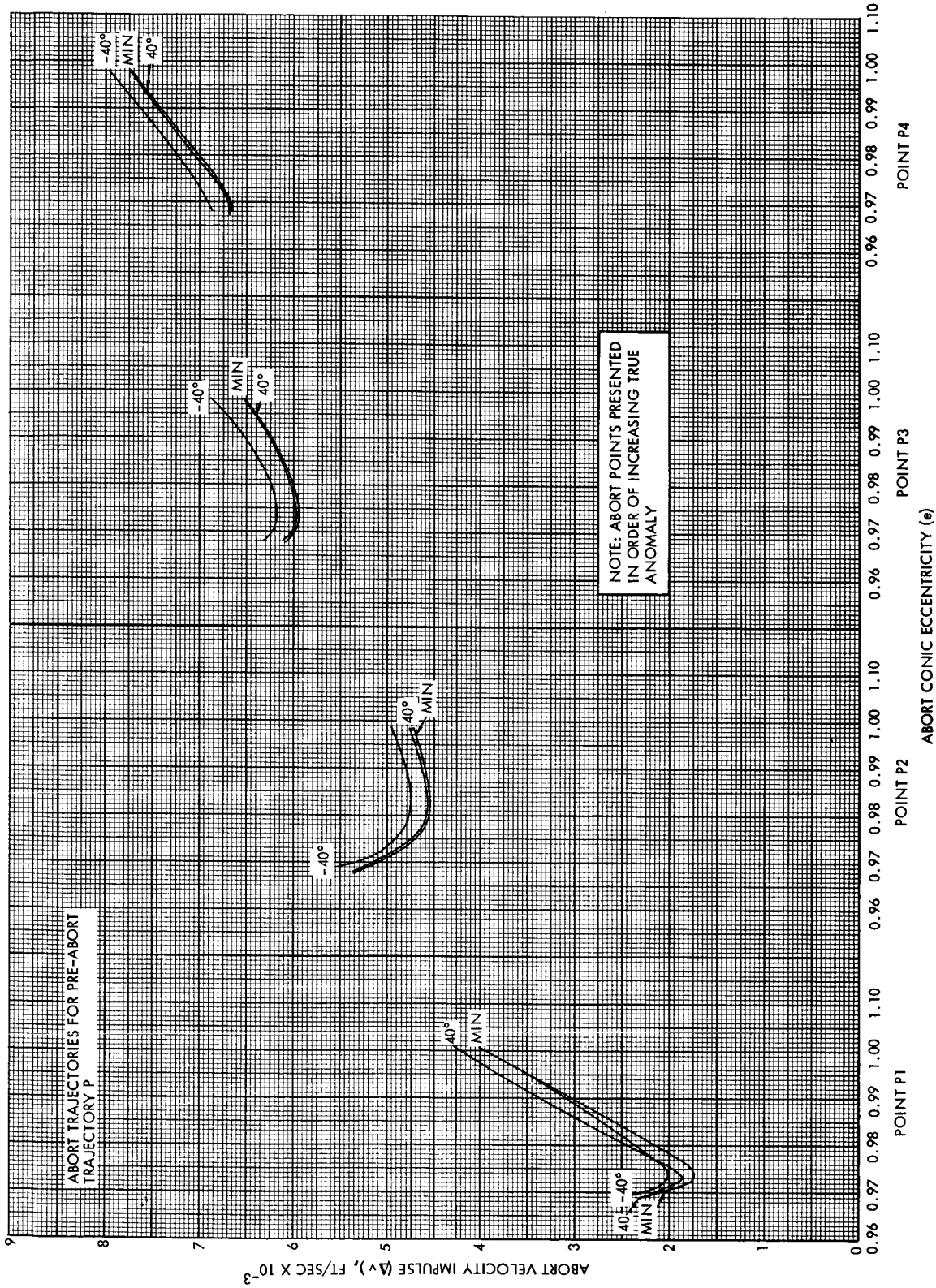

Figure 107. Abort Eccentricity (Pre-abort Trajectory P)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

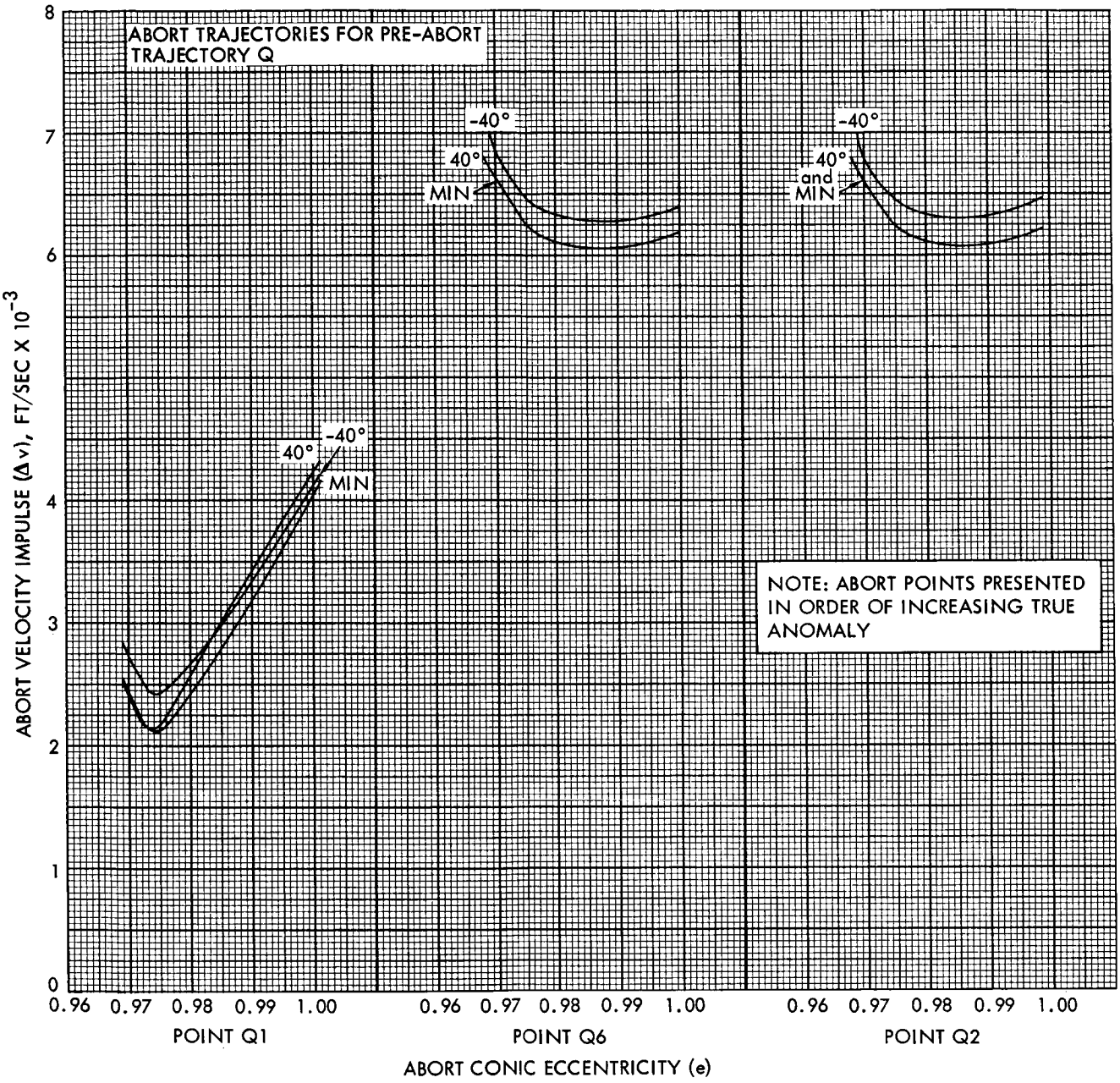

Figure 108. Abort Eccentricity (Pre-abort Trajectory Q)

This document contains information affecting the national defe[redacted] of the U[redacted] States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of [redacted] any manner to an unauthorized person is prohibited by law.

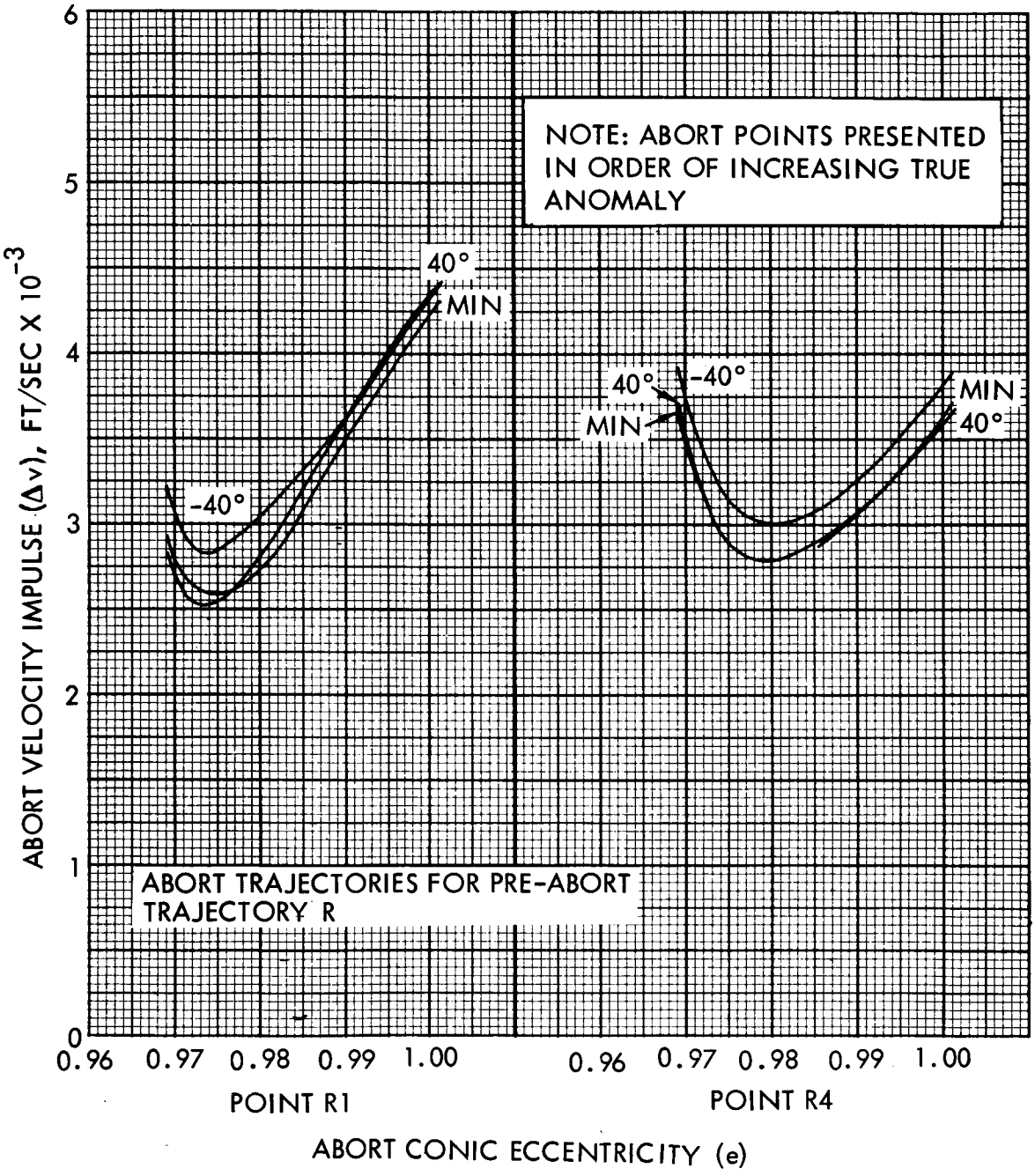

Figure 109. Abort Eccentricity (Pre-abort Trajectory R)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

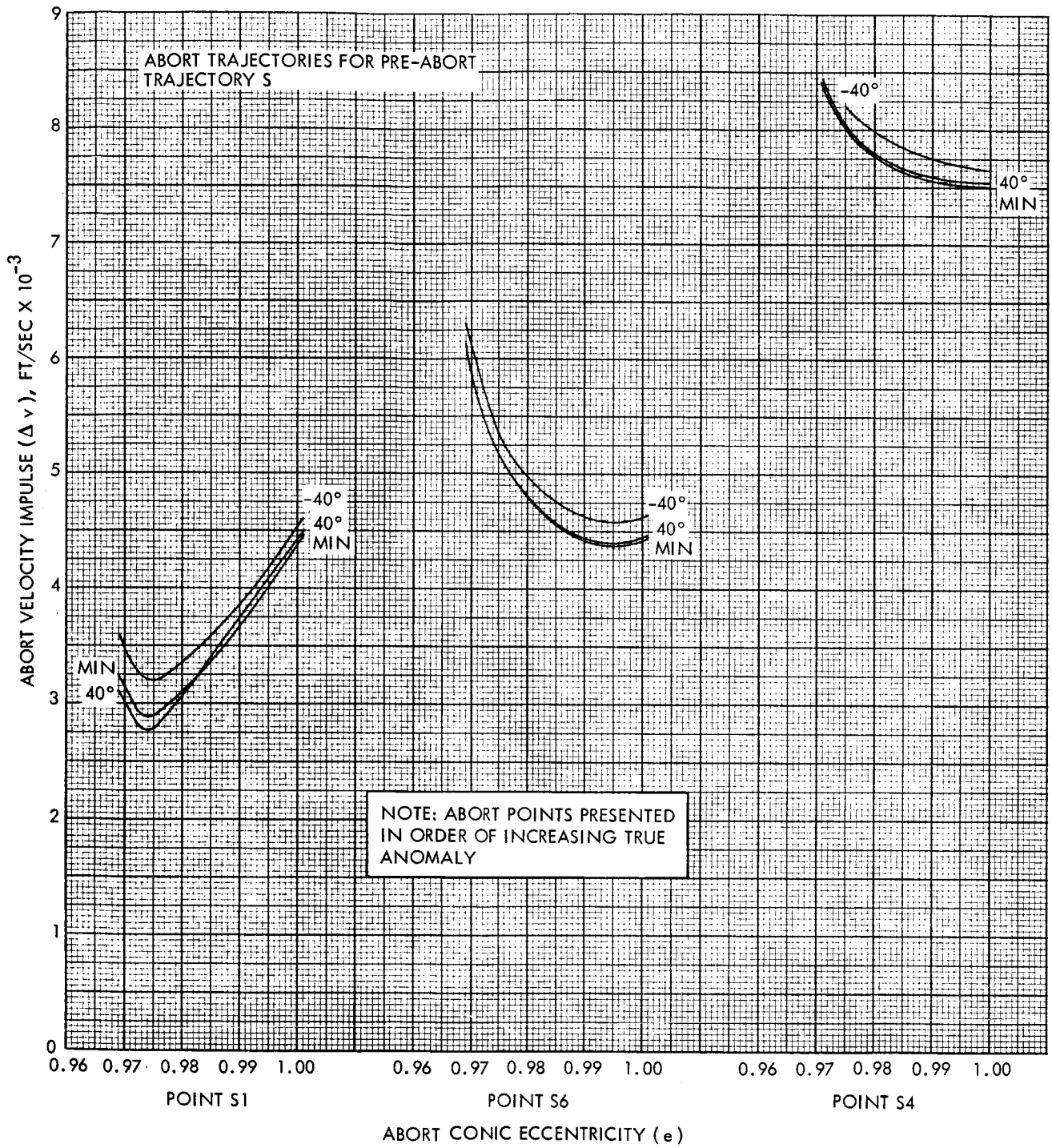

Figure 110. Abort Eccentricity (Pre-abort Trajectory S)

This document contains information affecting the national defense [redacted] States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of [redacted] manner to an unauthorized person is prohibited by law.

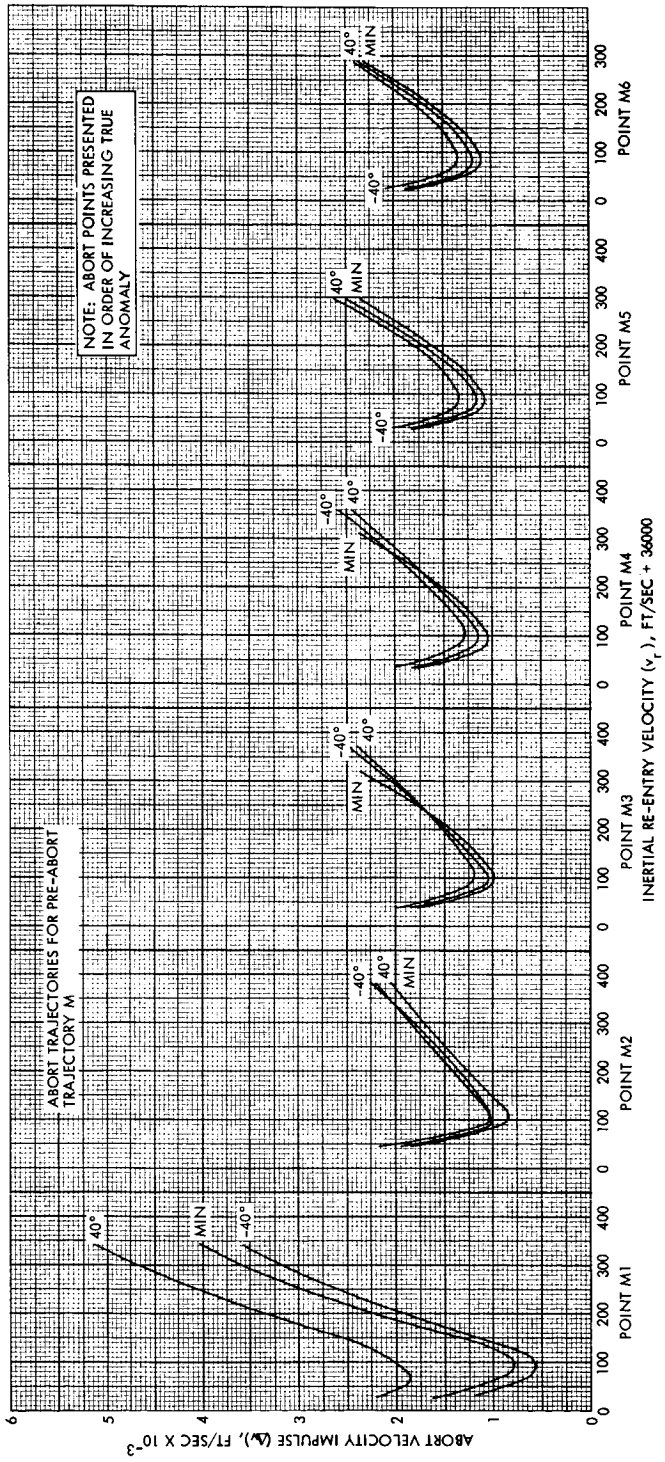

Figure 111. Abort Re-entry Velocity (Pre-abort Trajectory M)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

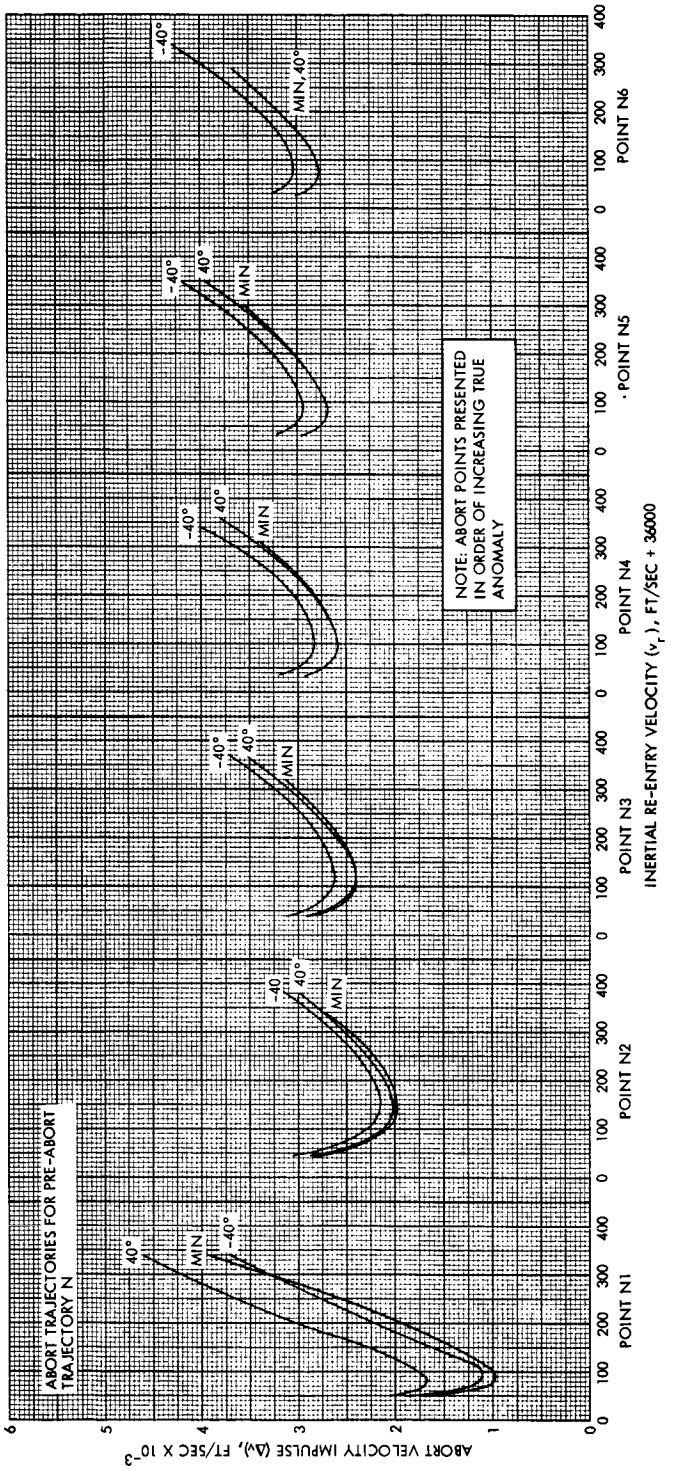

Figure 112. Abort Re-entry Velocity (Pre-abort Trajectory N)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of its contents in any manner to an unauthorized person is prohibited by law.

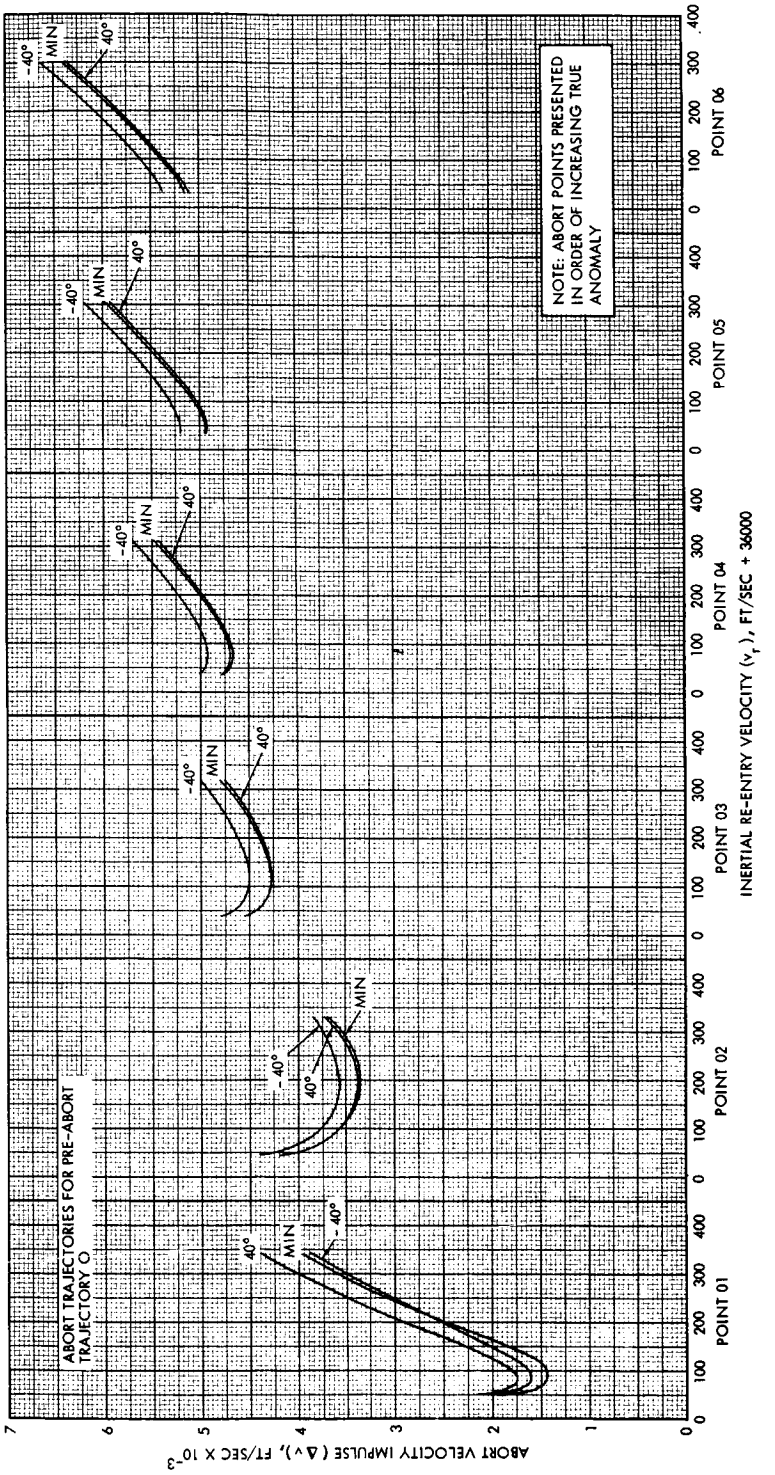

Figure 113. Abort Re-entry Velocity (Pre-abort Trajectory O)

This document contains information affecting the national defense of the [redacted] States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of wh[redacted]er to an unauthorized person is prohibited by law.

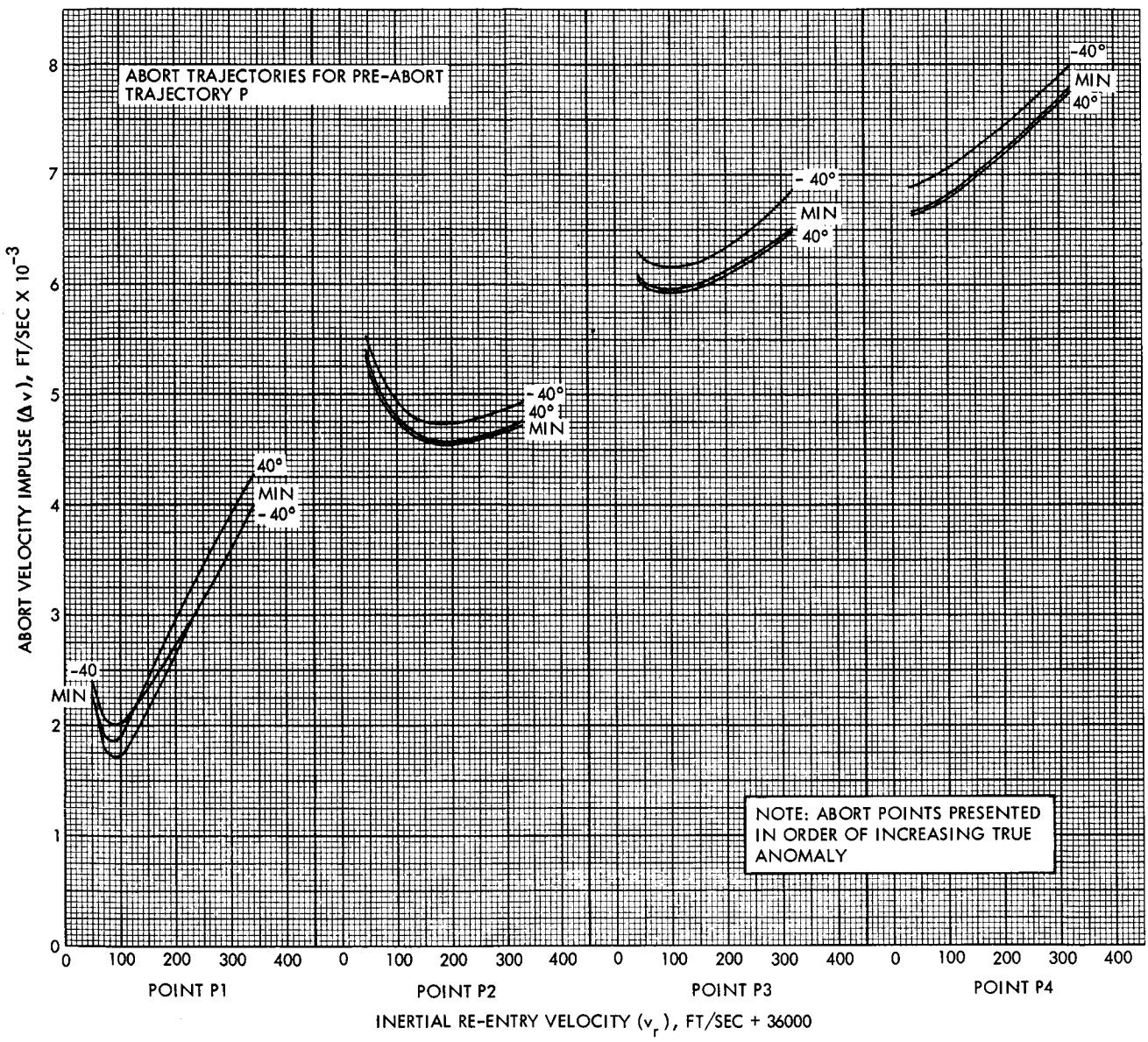

Figure 114. Abort Re-entry Velocity (Pre-abort Trajectory P)

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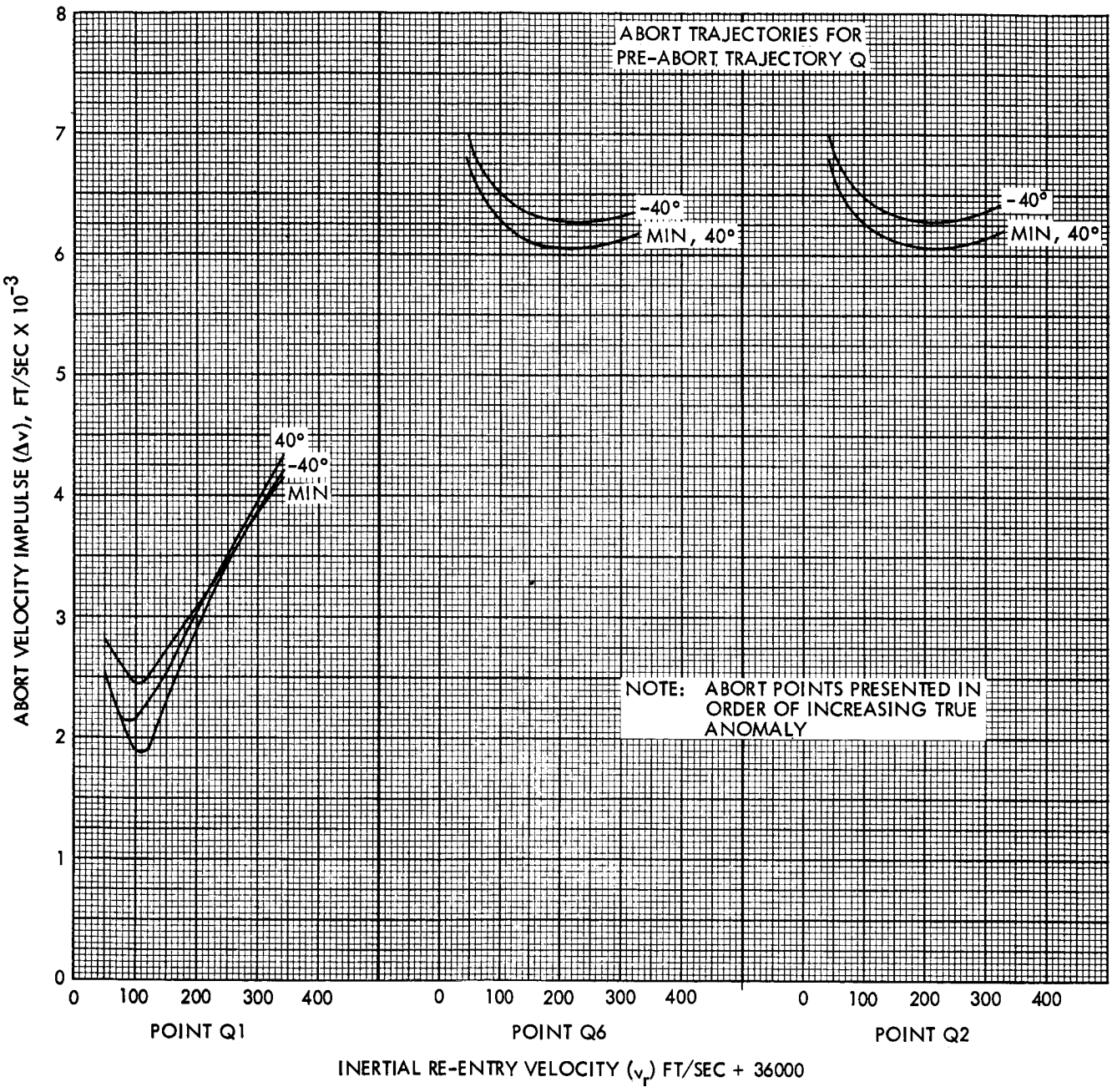

Figure 115. Abort Re-entry Velocity (Pre-abort Trajectory Q)

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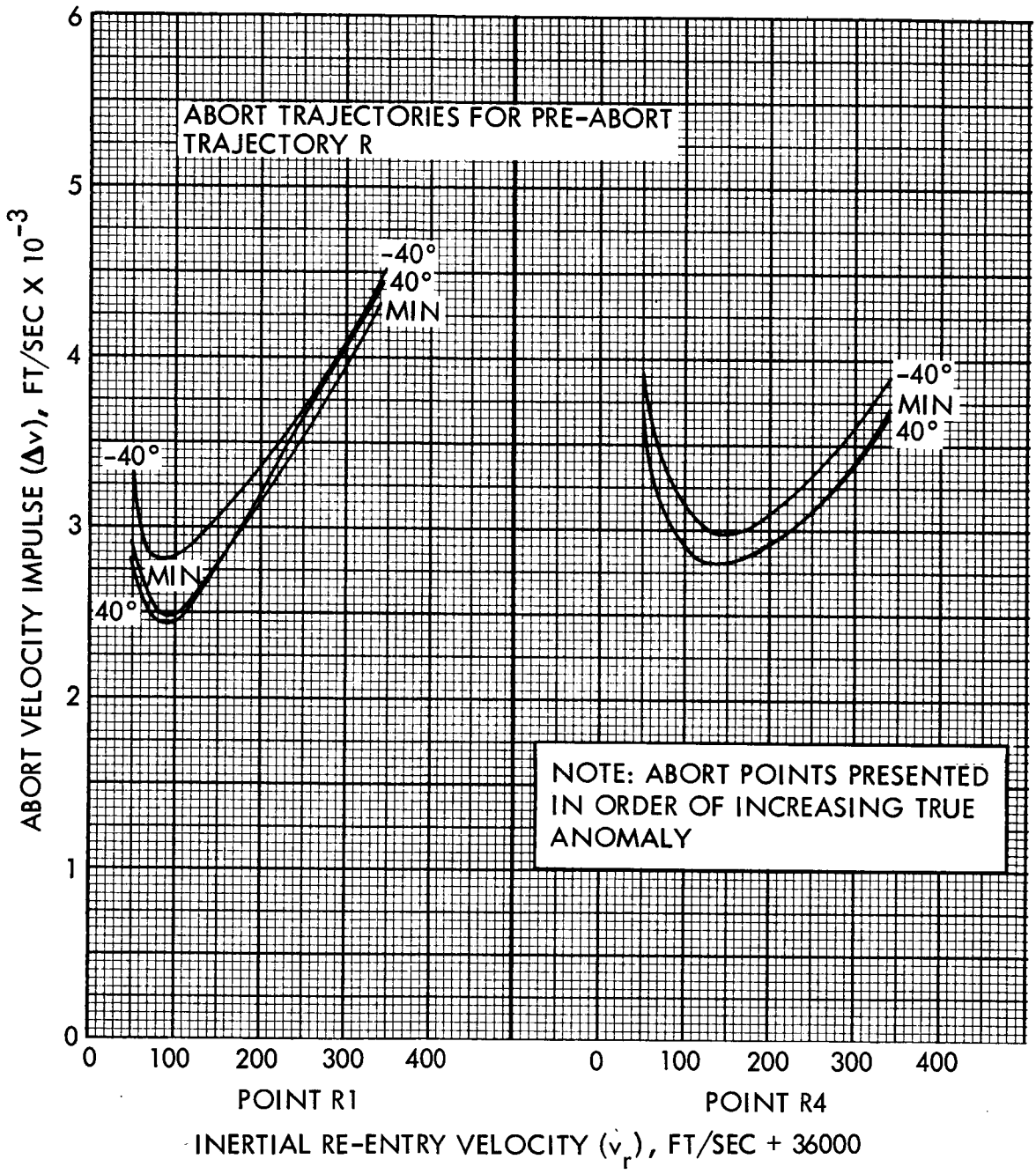

Figure 116. Abort Re-entry Velocity (Pre-abort Trajectory R)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

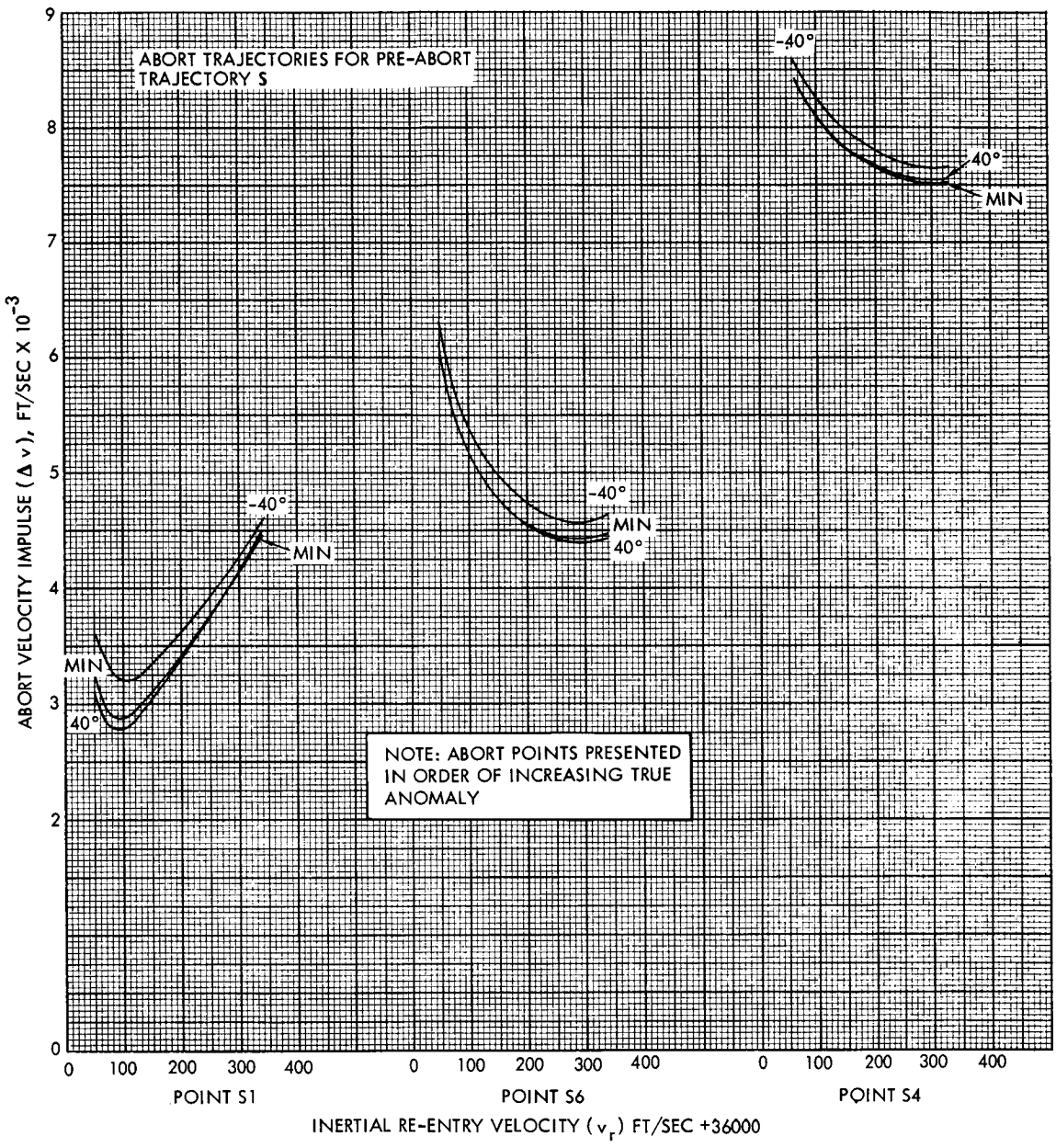

Figure 117. Abort Re-entry Velocity (Pre-abort Trajectory S)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

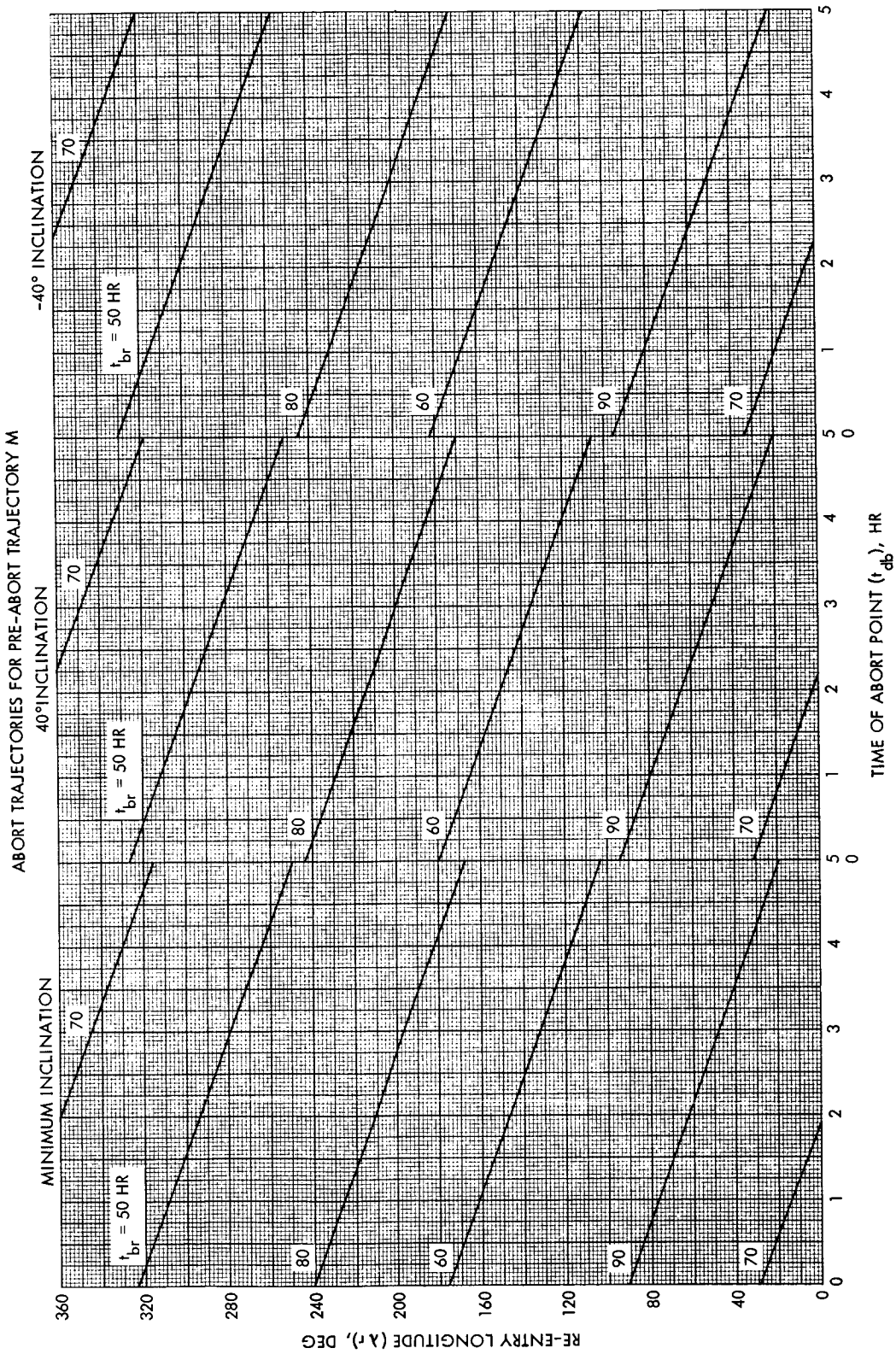

Figure 118. Abort Re-entry Longitude (Pre-abort Trajectory M)

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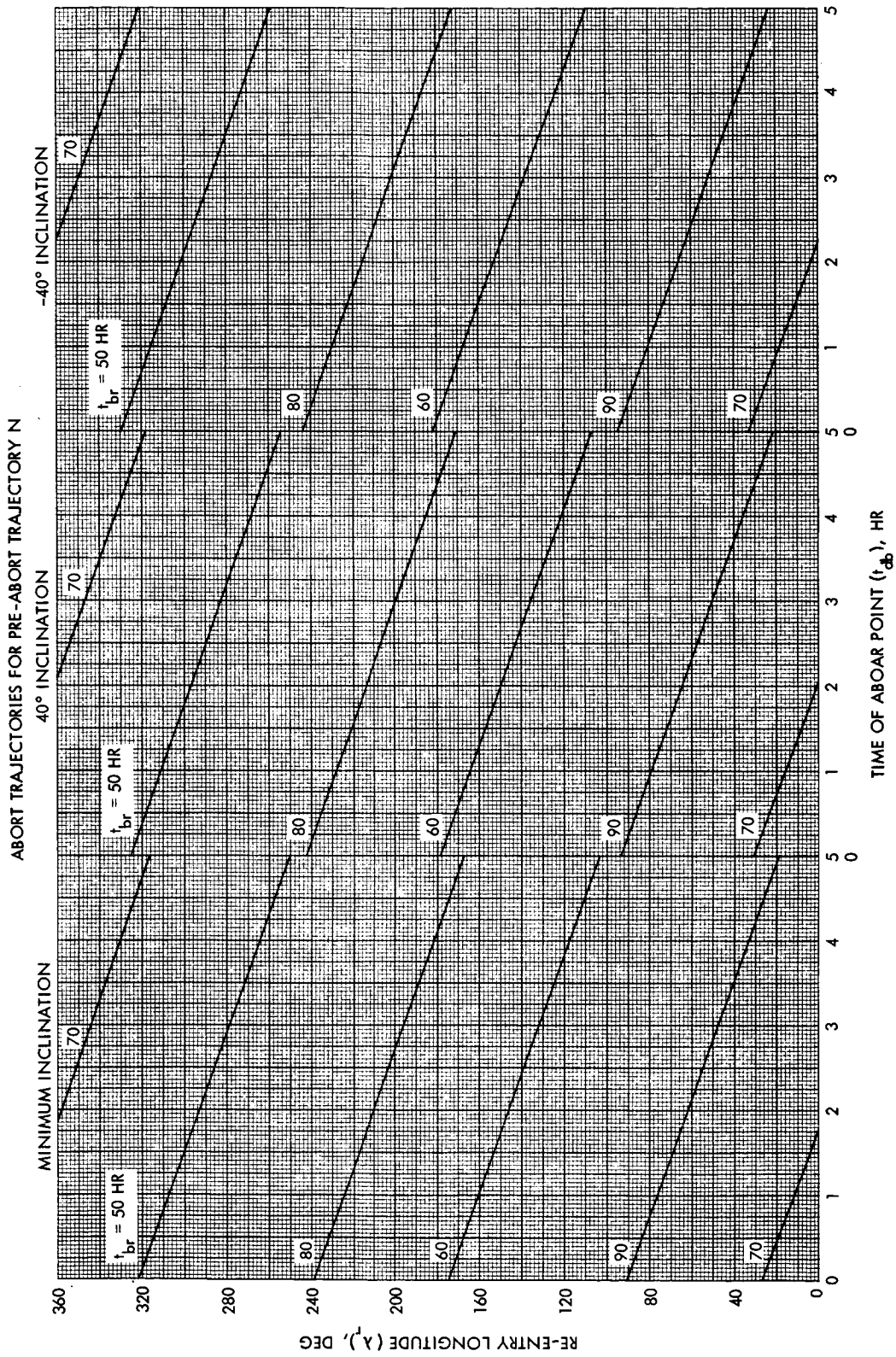

Figure 119. Abort Re-entry Longitude (Pre-abort Trajectory N)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

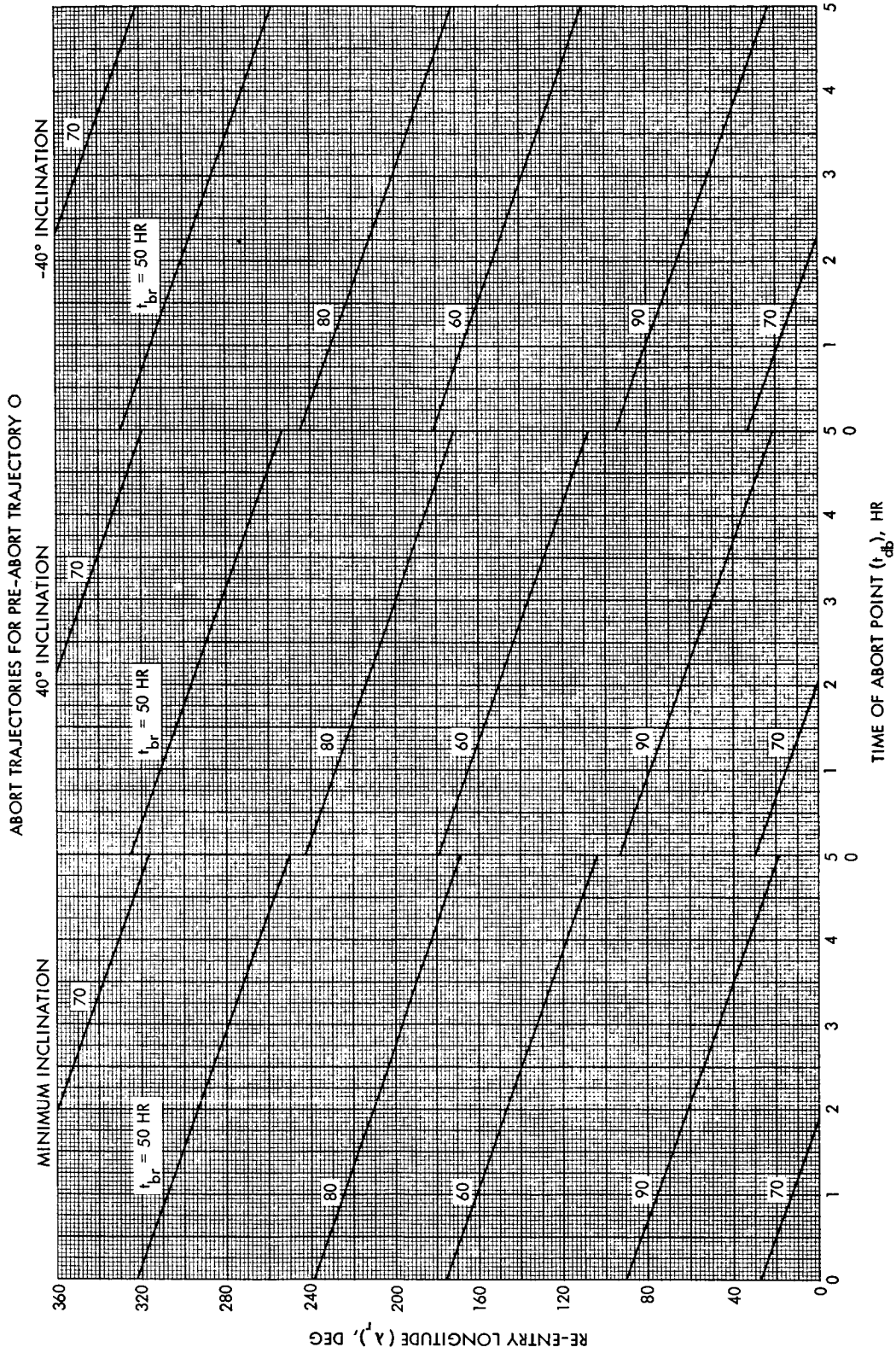

Figure 120. Abort Re-entry Longitude (Pre-abort Trajectory O)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

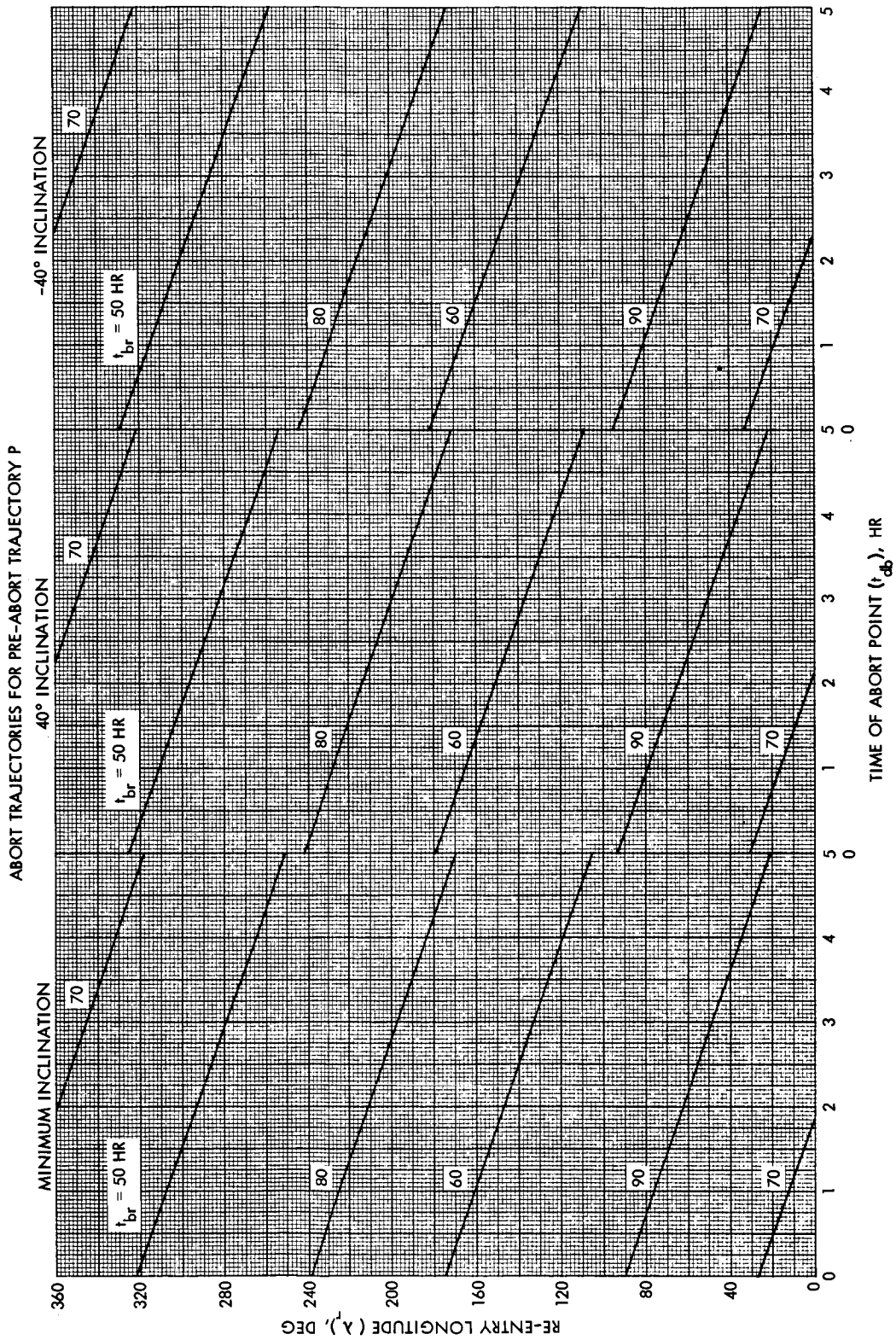

Figure 121. Abort Re-entry Longitude (Pre-abort Trajectory P)

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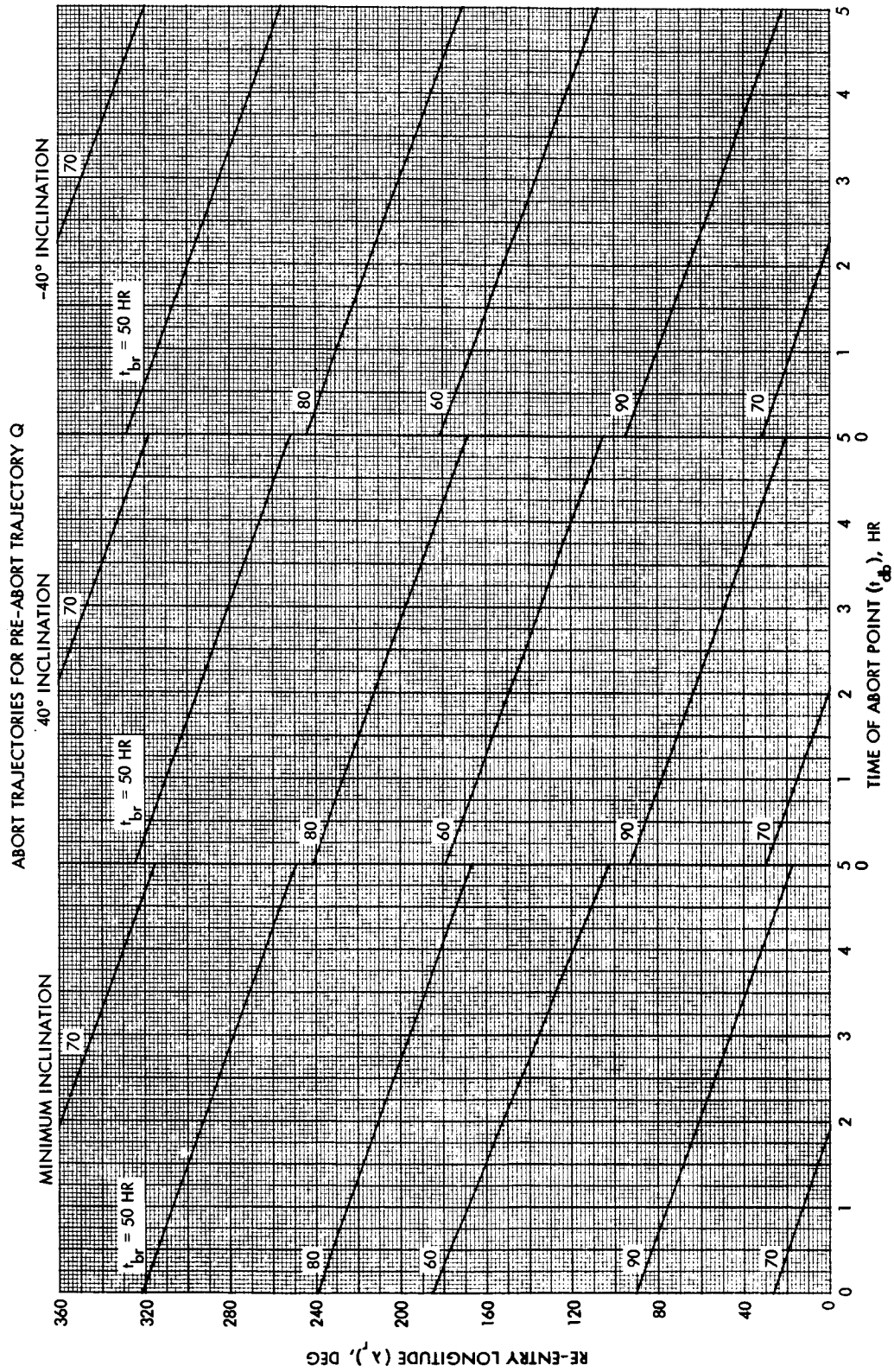

Figure 122. Abort Re-entry Longitude (Pre-abort Trajectory Q)

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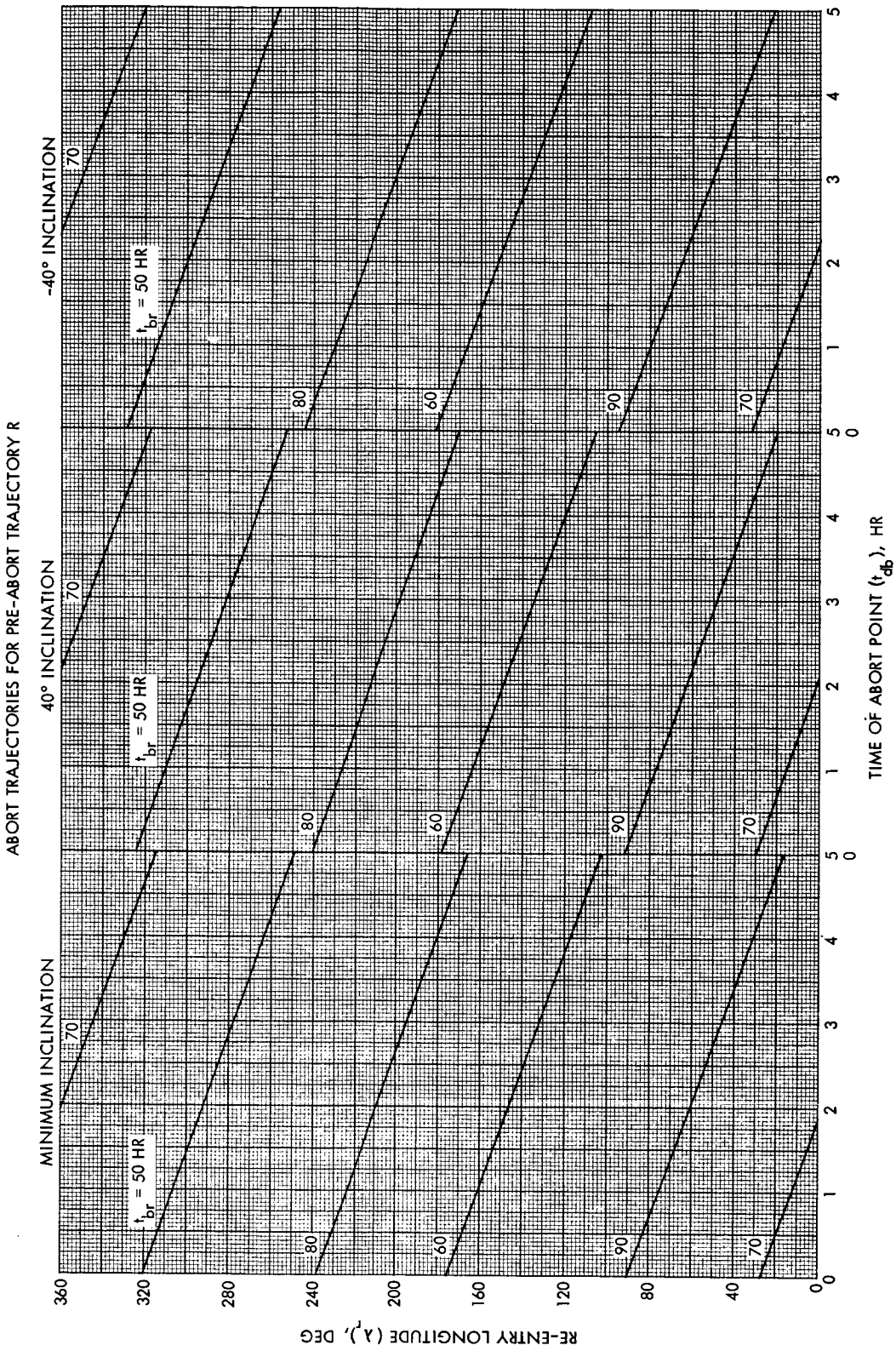

Figure 123. Abort Re-entry Longitude (Pre-abort Trajectory R)

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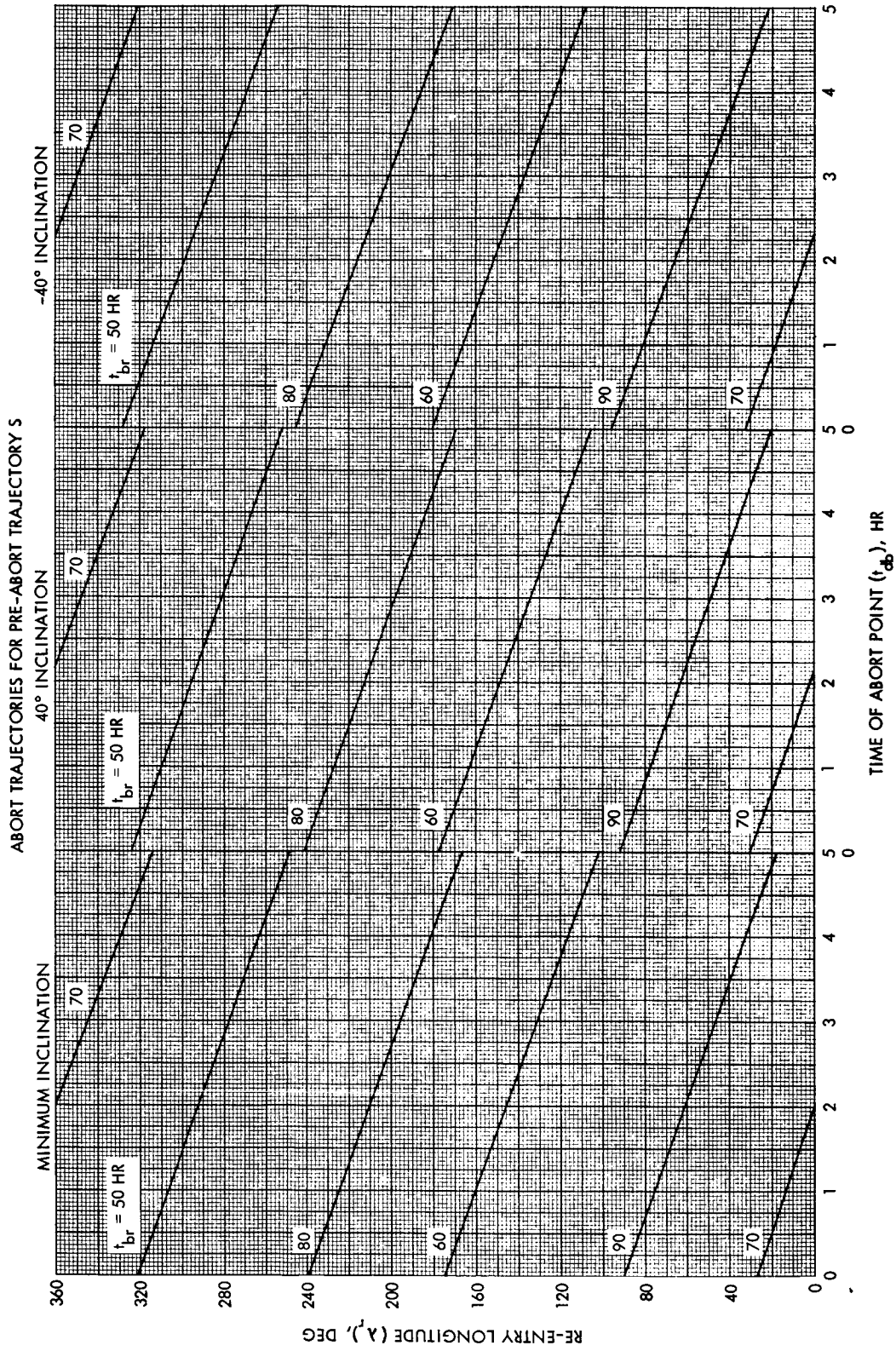

Figure 124. Abort Re-entry Longitude (Pre-abort Trajectory S)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

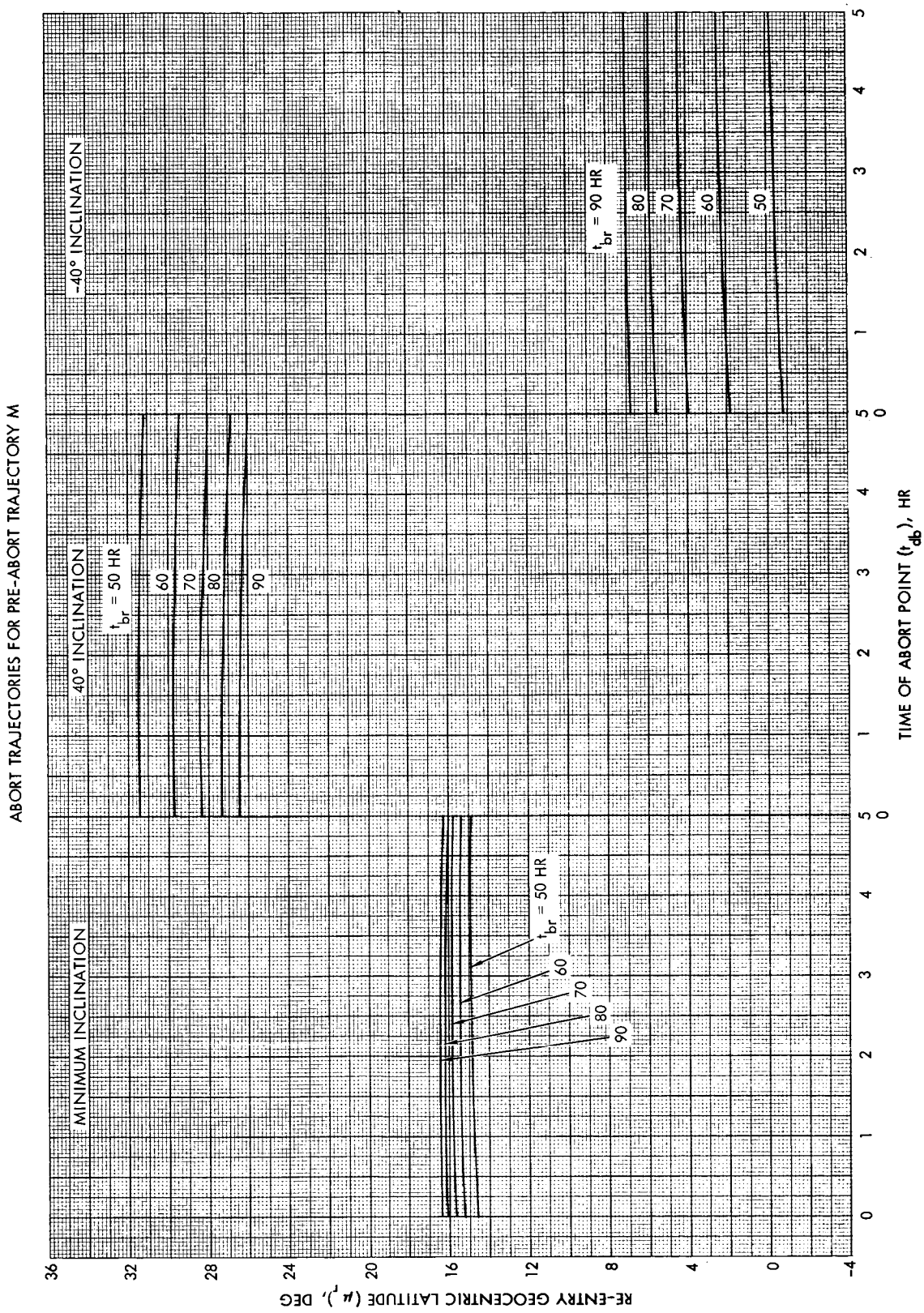

Figure 125. Abort Re-entry Latitude (Pre-abort Trajectory M)

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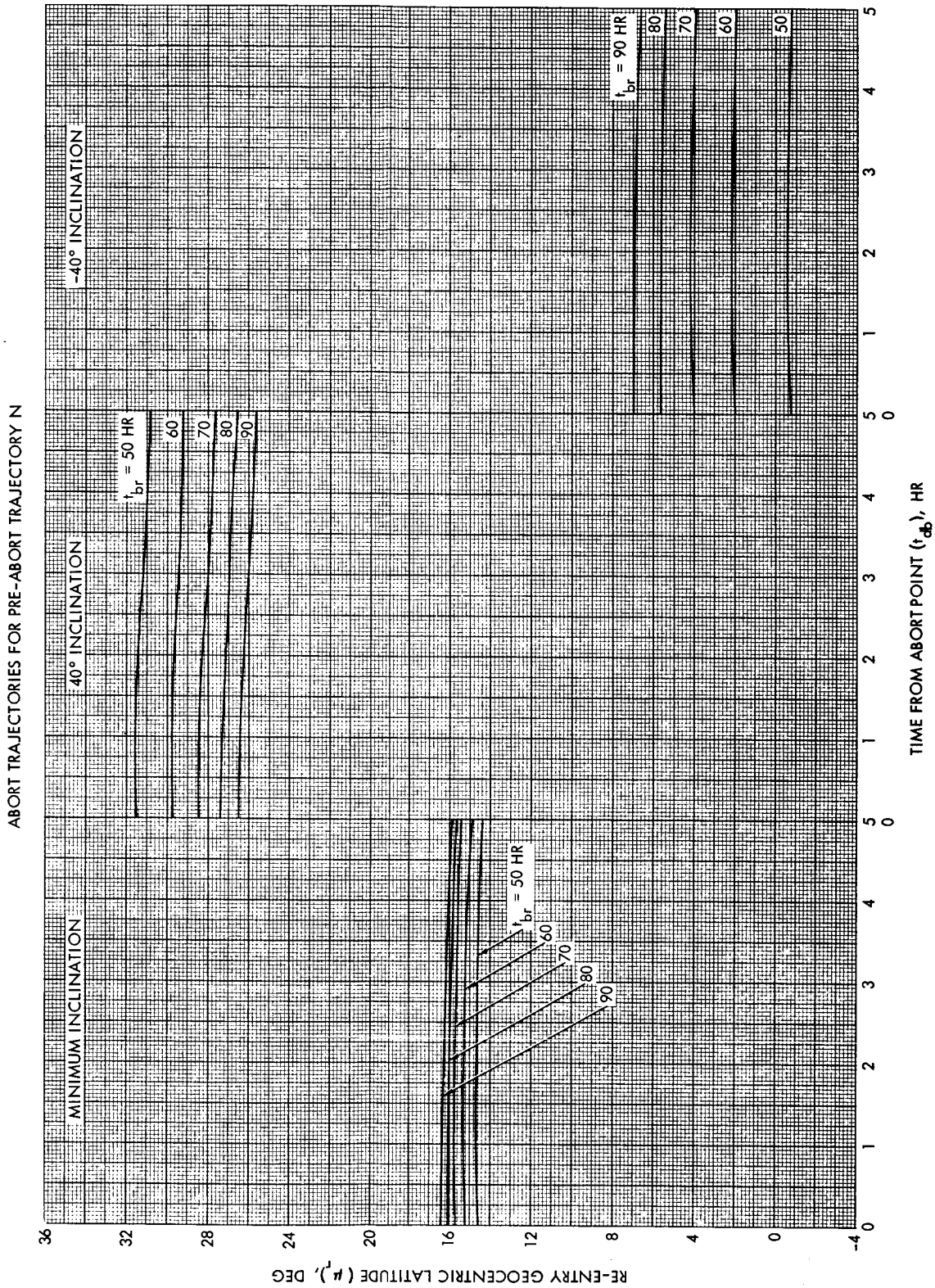

Figure 126. Abort Re-entry Latitude (Pre-abort Trajectory N)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

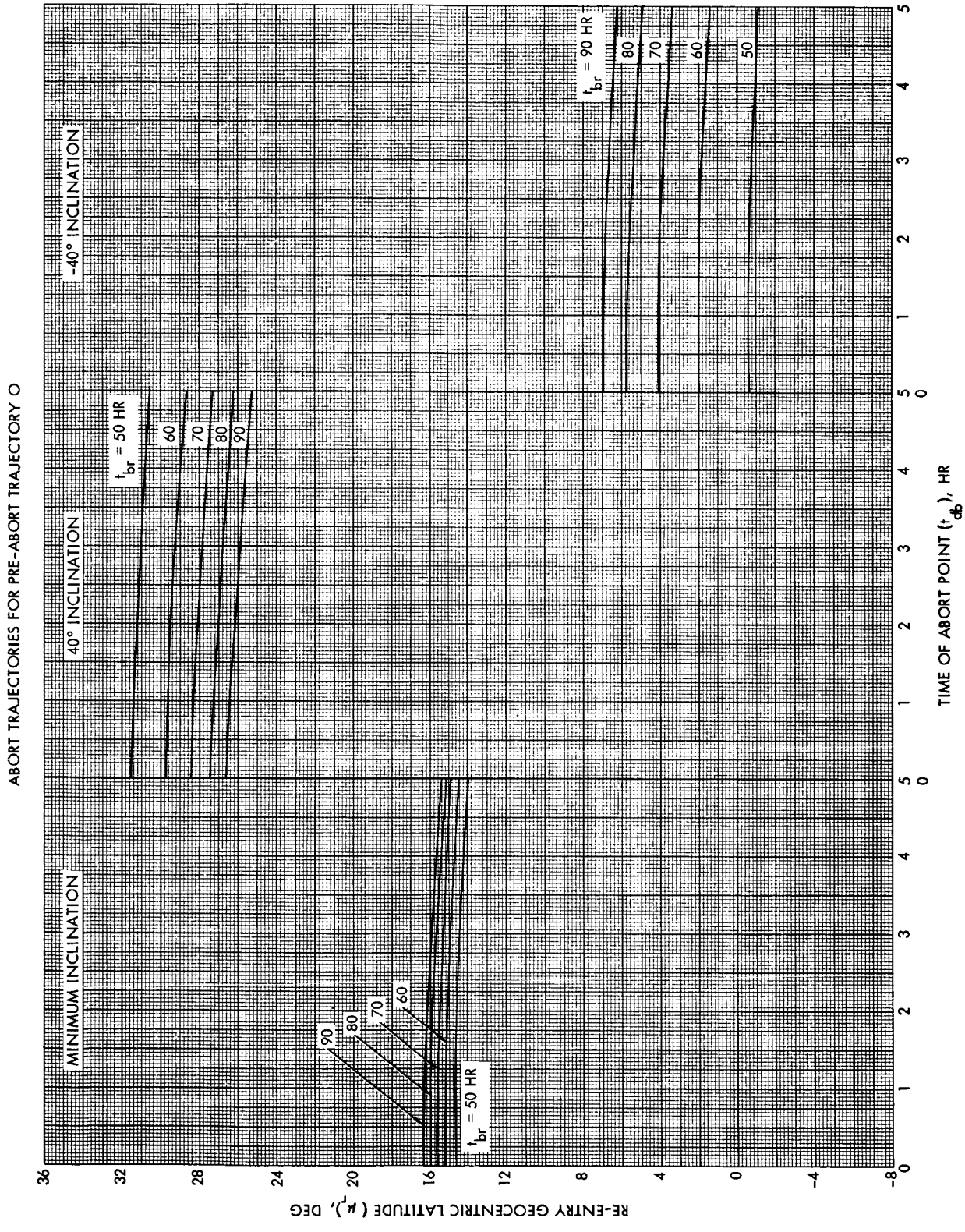

Figure 127. Abort Re-entry Latitude (Pre-abort Trajectory O)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

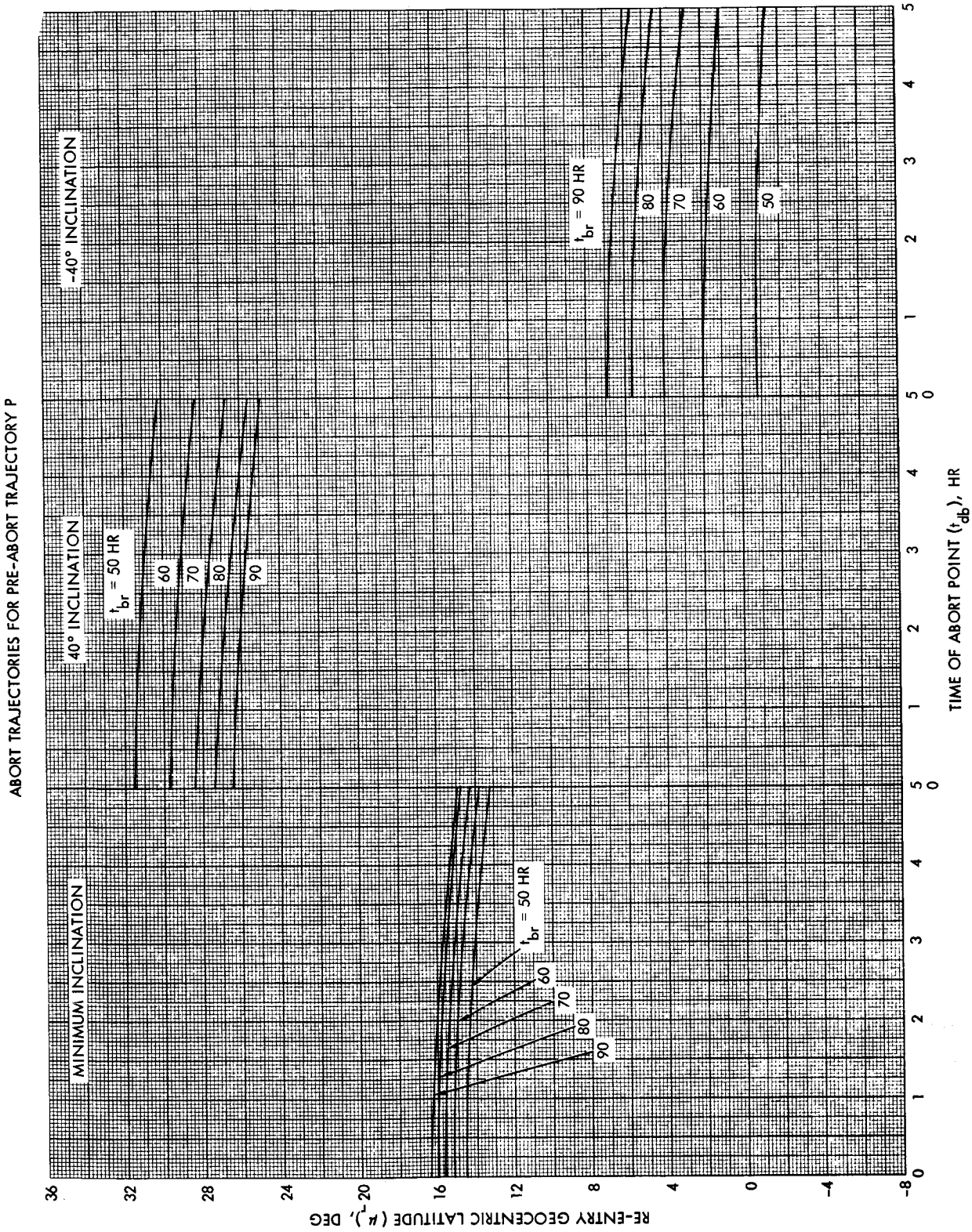

Figure 128. Abort Re-entry Latitude (Pre-abort Trajectory P)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

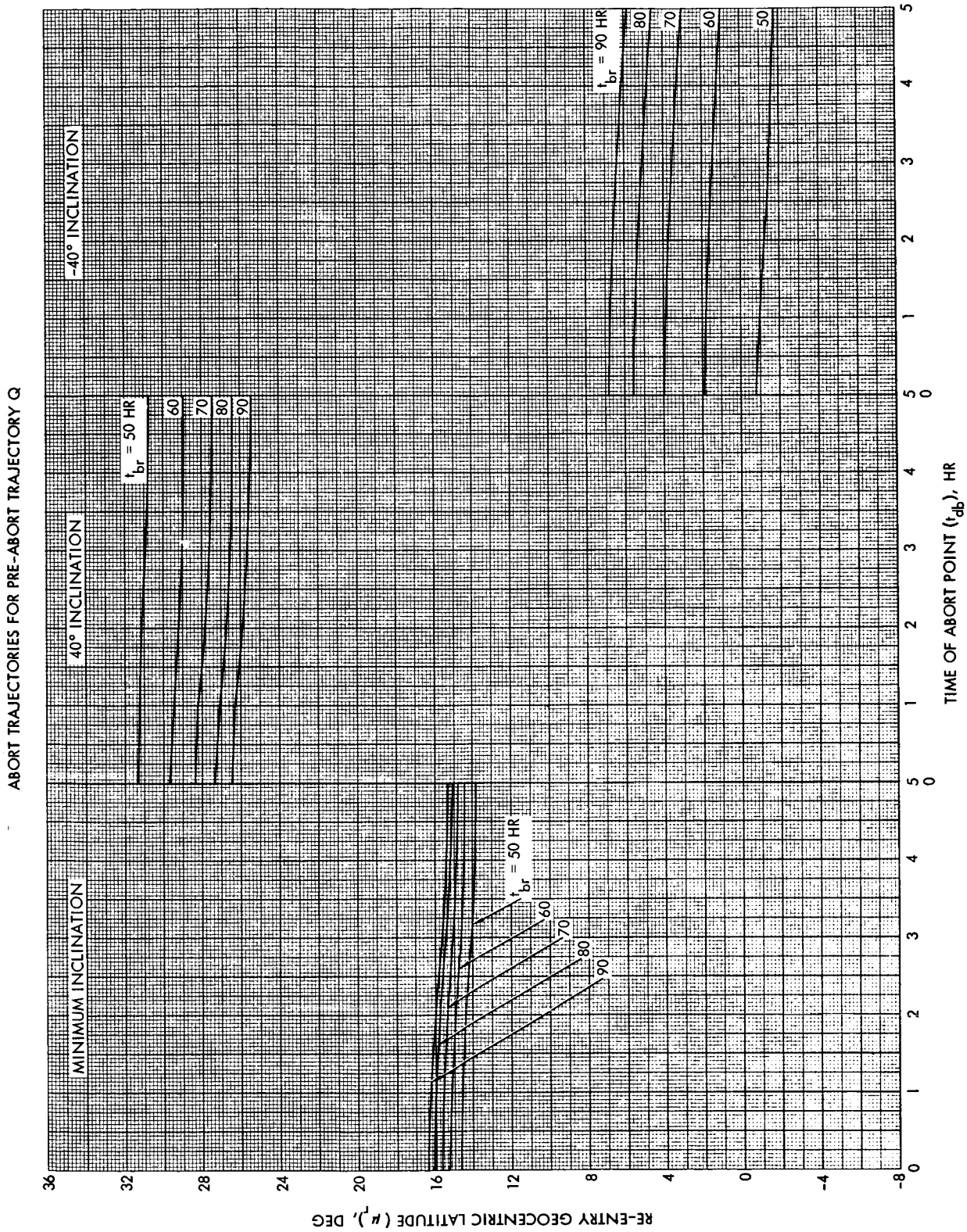

Figure 129. Abort Re-entry Latitude (Pre-abort Trajectory Q)

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

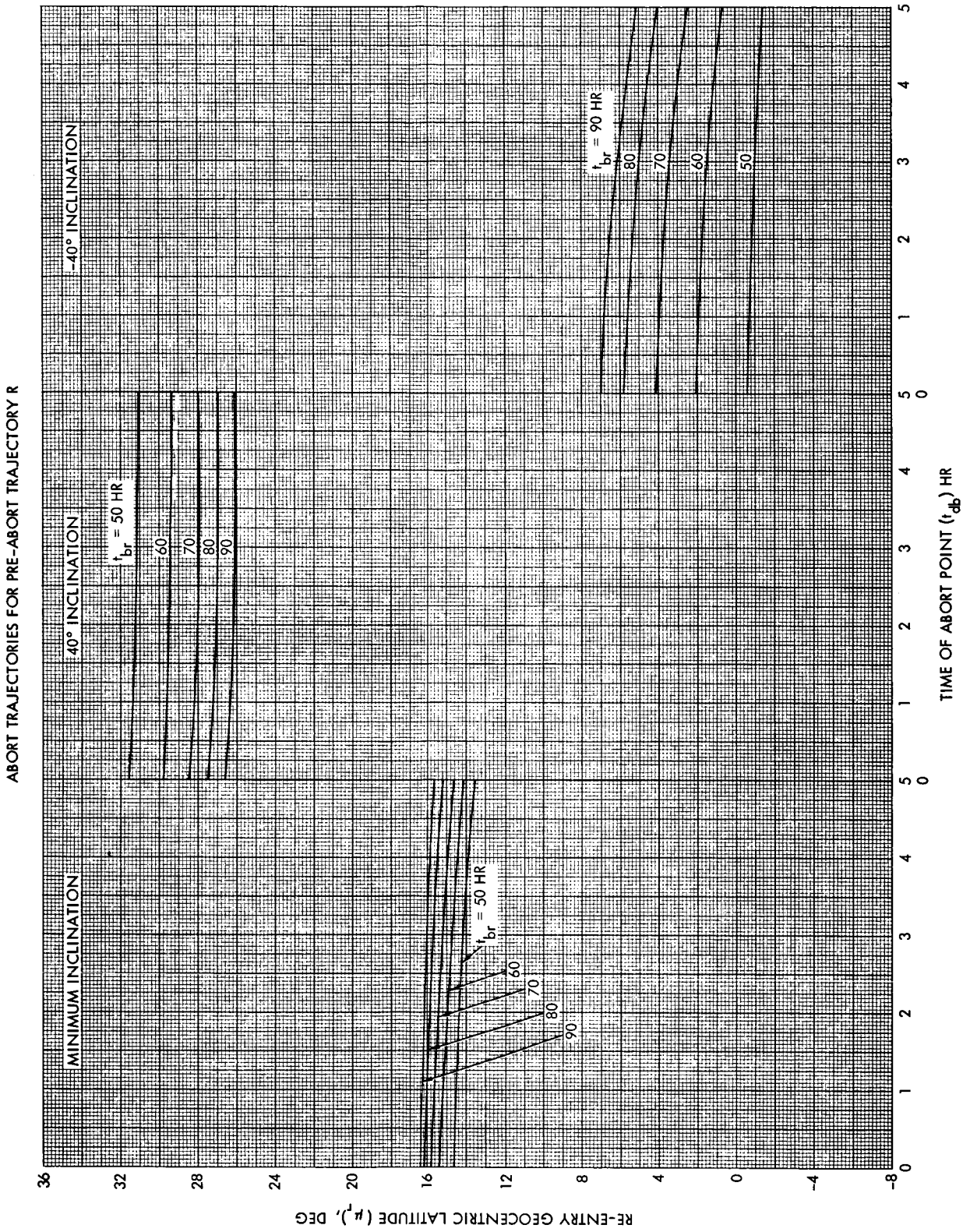

Figure 130. Abort Re-entry Latitude (Pre-abort Trajectory R)

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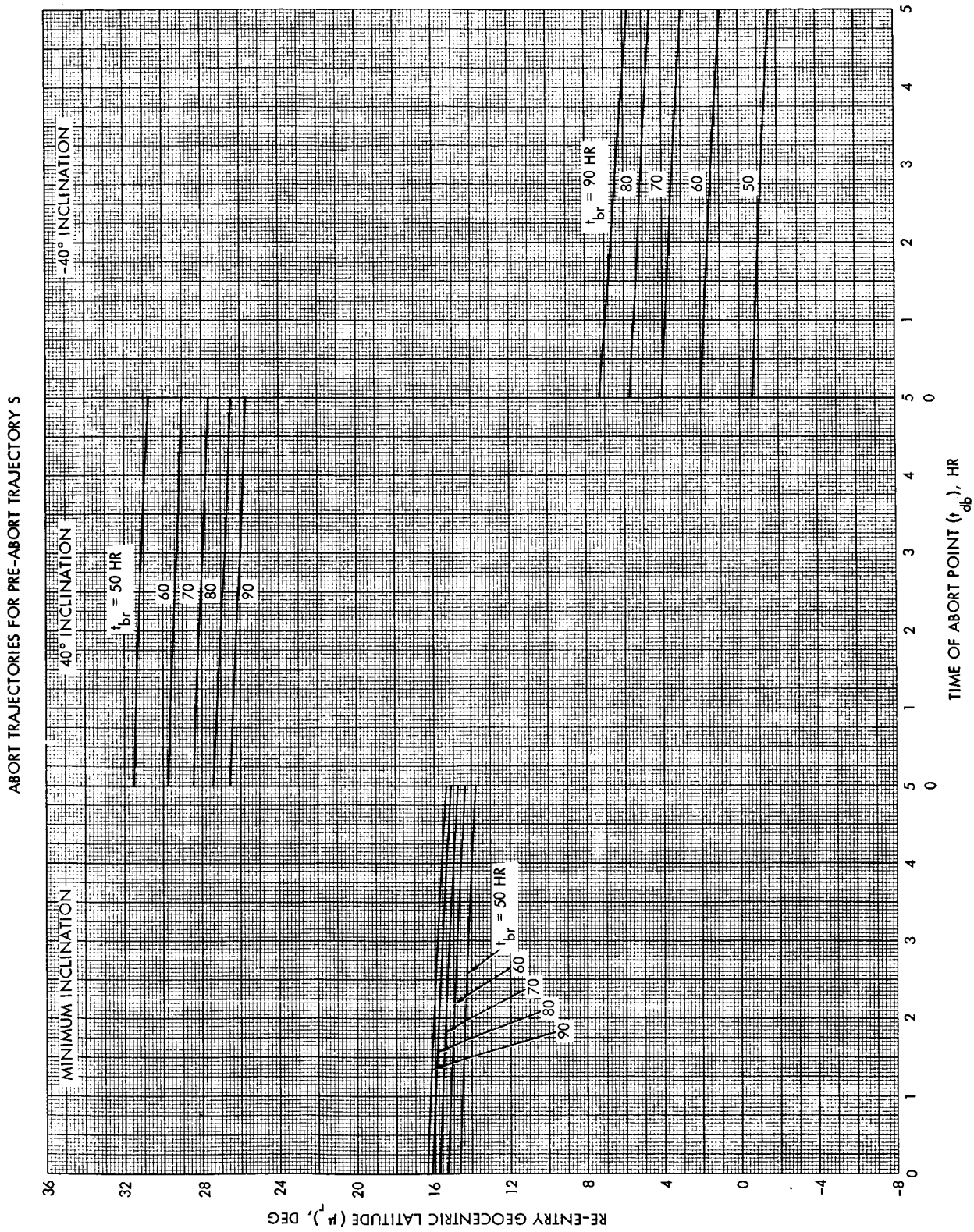

Figure 131. Abort Re-entry Latitude (Pre-abort Trajectory S)

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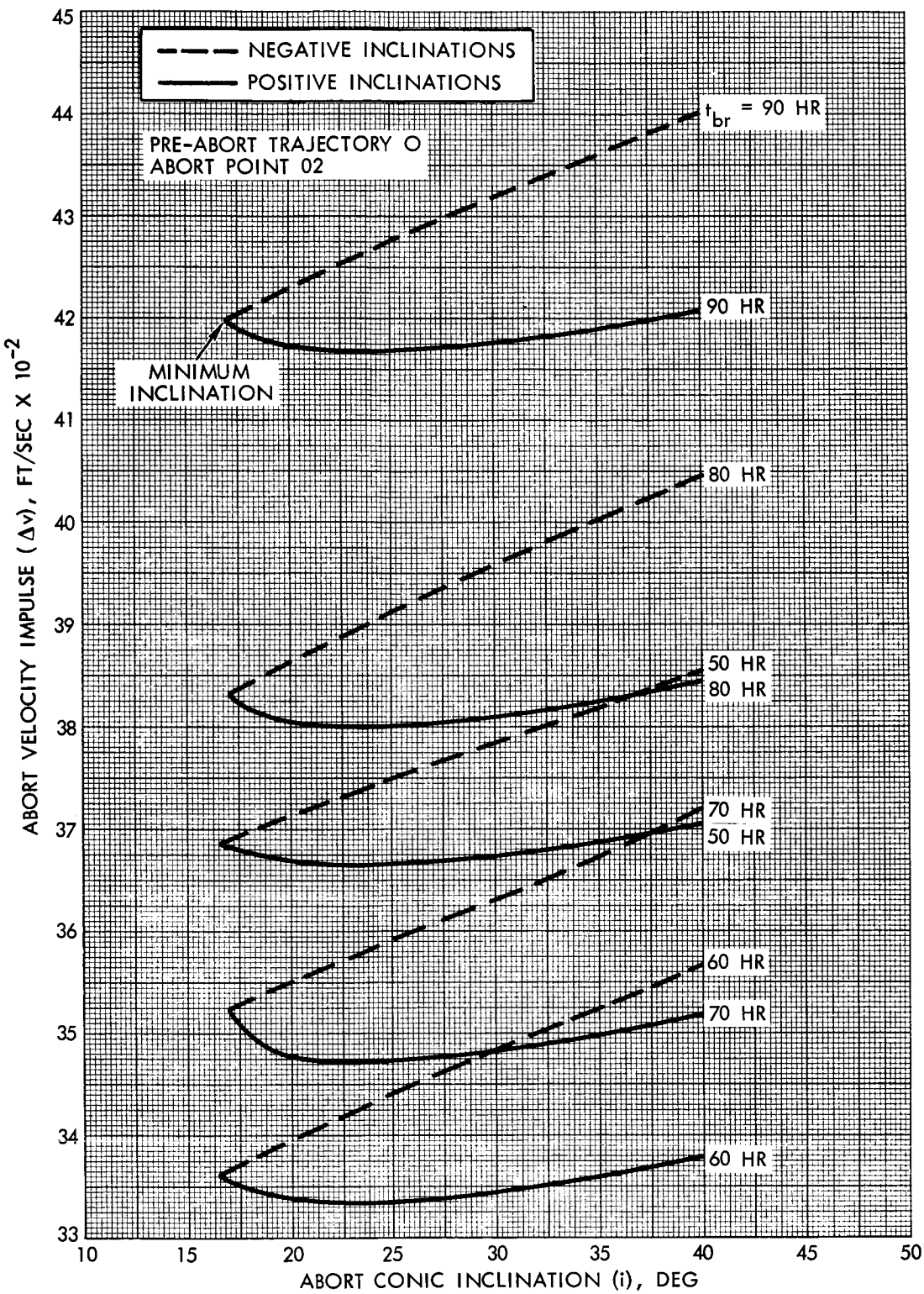

Figure 132. Abort Velocity Impulse versus Flight Time to Re-entry for Various Abort Trajectory Inclinations (Pre-abort Trajectory O, Point 02)

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C. Accuracy of the Analytic Programs

In order to evaluate the accuracy of the analytic programs used in generating these results, several check runs have been made with the integration program. For near earth aborts, three abort points on the reference trajectory were chosen for comparison; those at the distances of 2, 20 and 40 earth radii from the earth's center. (The reference trajectory penetrates the moon's sphere of action at approximately 55 earth radii.) At these three distances abort trajectories were found in the analytic program and the resulting abort position and velocity used in the integration program. The comparison of the re-entry conditions from both programs are shown in Table VI. It can be noticed that conditions are quite good for both distances of 2 and 20 earth radii. At 40 earth radii the re-entry flight-path angle and longitude show the greatest differences. In all cases the re-entry velocity generated by the analytic program is from 10 to 20 fps lower than the values from the integrating program. Although values are not shown, the variation in Δv required to cause the integrated trajectories to be acceptable would be negligible.

Similar comparisons have been made for the Analytic Lunar Return Program. As typical examples, pre-abort trajectories M and O have been chosen. In each case, the three abort points located at 1, 3 and 5 hours along these trajectories were considered and in all cases only the 70-hour flight times and the 40-degree return inclinations were used. Tables VII and VIII present the comparisons in the re-entry conditions for straight runs; i.e., integration of the analytic abort position and velocity to the re-entry point. Comparisons in time of flight and inclination are quite good, however, as expected from previous experience, the variation in re-entry flight-path angle, latitude and longitude are up to 15 degrees off.

In order to determine the variation in the abort conditions resulting from acceptable integrated trajectories, these cases were searched in to satisfy the required re-entry conditions. Variations in the abort velocity, flight-path angle, azimuth and velocity impulse are shown for these searched runs. The variation in impulse velocity is consistently near 40 fps.

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TABLE VI COMPARISON OF ANALYTIC AND INTEGRATED ABORT TRAJECTORIES (FROM THE REFERENCE TRAJECTORY)

Radial Distance (E. R.)	R = 2		R = 20		R = 40	
Velocity Impulse (ft/sec)	Δv = 13,300		Δv = 14,800		Δv = 13,300	
Flight Path Angle (deg)	β = 72		β = 167		β = 174	
	Analytic	Integrated	Analytic	Integrated	Analytic	Integrated
v_r (ft/sec)	30,043	30,064	36,287	36,304	36,979	36,991
β_r (deg)	96.4	96.4	96.4	96.6	96.4	99.8
t_{br} (hrs)	1.91	1.91	10.25	10.25	20.56	20.56
μ_r (deg)	27.4	27.6	28.4	28.6	28.0	28.6
λ_r (deg)	176.7	176.8	273.6	273.1	163.2	156.2

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[redacted]

TABLE VII COMPARISON OF ANALYTIC AND INTEGRATED ABORT TRAJECTORIES

40 DEGREE RETURN INCLINATION

(PRE-ABORT TRAJECTORY M)

		1 Hour* Analytic	1 Hour Integrated	3 Hour Analytic	3 Hour Integrated	5 Hour Analytic	5 Hour Integrated
Straight Runs	v_r (ft/sec)	36100	36113	36098	36101	36089	36089
	β_r (deg)	96.40	107.95	96.4	106.83	96.4	106.38
	t_{br} (hrs)	70.0	70.05	70.0	70.08	70.0	69.97
	λ_r (deg)	18.42	28.56	349.08	0.49	319.84	333.56
	μ_r (deg)	4.14	15.21	4.29	16.69	4.41	17.29
	i (deg)	40.0	39.55	40.0	38.94	40.0	37.75
Searched Runs	v_b (ft/sec)	5794	5800	4662	4676	4297	4317
	β_b (deg)	24.61	24.89	4.69	5.02	3.30	3.51
	A_b (deg)	284.99	284.32	276.99	274.26	146.45	152.97
	Δv (ft/sec)	-	40.6	-	35.5	-	38.4

* NOTE: This is the time from deboost to the abort point

[redacted]

[redacted]

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TABLE VIII COMPARISON OF ANALYTIC AND INTEGRATED ABORT TRAJECTORIES
40 DEGREE RETURN INCLINATION
(PRE-ABORT TRAJECTORY O)

		1 Hour* Analytic	1 Hour Integrated	3 Hour Analytic	3 Hour Integrated	5 Hour Analytic	5 Hour Integrated
Straight Runs	v_r (ft/sec)	36108	36111	36096	36098	36091	36090
	β_r (deg)	96.4	108.10	96.4	108.70	96.4	109.57
	t_{br} (hrs)	70.0	70.05	70.0	70.02	70.0	69.97
	λ_r (deg)	18.18	28.07	349.72	359.18	32.130	330.03
	μ_r (deg)	4.05	14.93	3.78	13.93	3.27	12.35
	i (deg)	40.0	39.69	40.0	39.80	40.0	40.11
Searched Runs	v_b (ft/sec)	6346	6358	5194	5198	4970	4971
	β_b (deg)	17.82	15.10	21.93	21.69	39.53	39.24
	A_b (deg)	272.93	277.16	124.34	125.31	119.92	120.51
	Δv (ft/sec)	-	42.7	-	39.4	-	41.1

* NOTE: This is the time from deboost to the abort point

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IV. CONCLUSIONS

The general velocity demand on the Apollo spacecraft has been calculated with respect to the possible abort paths emanating from an Apollo LOR mission reference trajectory and safely re-entering the earth's atmosphere. The study has been conducted with the aid of analytic (conic and patched conic) computer programs. Selected examples of these results have been checked for accuracy by numerical integration but all calculations and results are based on simple impulsive velocity addition at the abort points. The analysis has been addressed to the translunar injection, translunar free flight, and hyperbolic deboost phases of the mission plan.

Because a single reference trajectory has been used to describe the nominal behavior of the Saturn V and Apollo spacecraft, this abort analysis cannot be considered a thorough parametric study of all possible situations. However, several general conclusions can be stated with certainty.

1) There is sufficient Δv available for abort at any point on any pre-abort trajectory arising from premature S-IVB thrust cutoff, so long as the SM remains operable. In the case where, although the SM is inoperable, its propellant can be jettisoned before exercising the LEM stages, admissible abort points are restricted to be away from the vicinity of perigee. If SM propellant cannot be jettisoned, the abort points are restricted to be in the vicinity of apogee.

2) The time available to prepare for abort varies from a few minutes to many hours depending on the selection of an abort point on the translunar injection pre-abort trajectories. The time factor can be inconsequential by permitting multiple revolutions in the pre-abort trajectory.

3) Since the nominal translunar trajectory is such that the spacecraft would circumnavigate the moon and return safely to earth, no abort velocity impulse is theoretically necessary at any time. However, the time of flight to re-entry in this mode (138 hours) can be reduced by more than a factor of 10 by applying the Δv available. The reduction in flight time afforded is a strong function of Δv for small values and indicates a desirable minimum spacecraft configuration.

4) When returning to earth from pre-abort trajectories arising from failure of the Service Module propulsion during hyperbolic deboost at the moon, there is a preferred (from a fuel consumption standpoint) return time of flight. The Δv required rapidly increases

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for flight times shorter or longer than about 70 hours independent of pre-abort trajectory configuration. However, and of more significance, the minimum Δv occurs at the beginning of the pre-abort trajectories and indicates that early reaction is desirable. As opposed to the translunar injection pre-abort trajectories, many of the abort points in this region of the mission require that, as a minimum, the unused SM propellant be jettisoned prior to attempting abort and that the LEM descent stage be operable. This is particularly important for aborts due to failures in the last seconds of hyperbolic deboost when the pre-abort trajectory will be a tight orbit about the moon. In this case both LEM stages must be functioning or return is nearly impossible. The inclination of the return trajectory has essentially no influence on the velocity demand.

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   Volume 2 - Document No. 8408-6024-RC-000 (Conf.)

   Volume 3 - Document No. 8408-6025-RC-000 (Conf.)

   Volume 4 - Document No. 8408-6026-RC-000 (Conf.)

2. NASA Technical Report R-55, "An Analysis of the Corridor and Guidance Requirements for Supercircular Entry into Planetary Atmospheres," Dean R. Chapman, 1960.

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