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SANDIA SYSTEMATIC DECLASSIFICATION REVIEW	
1st Review Date: 1-03-96 Authority: ☐ ADC ☒ ADD Name: W. Layne 2nd Review Date: 1-15-96 Authority: ADD Name: K. D. Smith	Determination (Circle Numbers): 1. Classification Retained 2. Classification Changed to: U 3. Contains No DOE Classified Information 4. Coordinate With: 5. Contains UCAI? 6. Comments:

SCTM 328-61(91)

A METHOD FOR DETERMINING THE EFFECT OF PARAMETRIC PERTURBATIONS ON RE-ENTRY VEHICLE DECELERATION AND VELOCITY

H. A. Bennett, 9111

(Title is Unclassified)

SANDIA SYSTEMATIC DECLASSIFICATION REVIEW DOWNGRADING OR DECLASSIFICATION STAMP	
CLASSIFICATION CHANGED TO: U Emelda Sisch 05/23/96 PERSON CHANGING MARKING & DATE W. C. Layne 6-11-96 PERSON VERIFYING MARKING & DATE	AUTHORITY: K. D. Smith RECORD ID: 96SN006 DATED: 01-15-96

ABSTRACT

Expressions are developed which allow a quick assessment of the effects of perturbations in ballistic coefficient, atmospheric density, and re-entry angle on nominal values of re-entry vehicle deceleration and velocity. The accuracy of these expressions as compared with computer results is shown to be reasonable for values of ballistic coefficient greater than 1000 lb/sq ft.

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Case No. 13.917.10 UNCLASSIFIED November 1961

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TABLE OF CONTENTS

	Page
Purpose	5
Background	5
Analysis	5
Results of Analysis	7
Conclusions	7
LIST OF REFERENCES	24
APPENDIX	19

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LIST OF ILLUSTRATIONS

Figure		Page
1.	Drag Coefficient Versus Mach Number	8
2.	Deceleration and Velocity Versus Altitude	9
3.	Deceleration and Velocity Versus Altitude	10
4.	Pg/β K sin θ Versus Altitude	11
5.	Computer Results Compared with Simply Calculated Changes in Re-entry Deceleration for a 5-Percent Increase in Vehicle K	12
6.	Same for a 5-Percent Increase in Atmospheric Density	13
7.	Same for a 1-Degree Increase in Re-entry Angle	14
8.	Computer Results Compared with Simply Calculated Changes in Re-entry Velocity for a 5-Percent Increase in Vehicle K	15
9.	Same for a 5-Percent Increase in Atmospheric Density	16
10.	Same for a 1-Degree Increase in Re-entry Angle	17
11.	The Effect of Ballistic Coefficient on the Flight Path Angle	18

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A METHOD FOR DETERMINING THE EFFECT OF PARAMETRIC PERTURBATIONS ON RE-ENTRY VEHICLE DECELERATION AND VELOCITY

Purpose

The purpose of this study is to develop a simple means of determining the effect of parametric perturbations on re-entry vehicle deceleration and velocity. The parameters to be considered for perturbation effects are ballistic coefficient, atmospheric density, and flight-path angle.

Background

Considerable effort has been expended to develop inertial fuzing for re-entry vehicles. In general, an inertial fuze senses some function of vehicle deceleration or velocity to determine burst altitude. Consequently, the variance of such parameters strongly influences the ability of an inertial fuze to determine the desired burst altitude.

To evaluate a particular inertial fuze design it is necessary to determine the extent to which the fuzing parameters can vary for given conditions. One method of obtaining such information is to set up a computer program as in Reference 2 for re-entry trajectories and perturb all the factors which affect the fuzing parameters. However, this approach can consume large amounts of machine time and yield unnecessarily accurate results for feasibility studies.

A more attractive approach would be an analytic solution which allows a quick assessment of the effects of perturbations about a nominal set of trajectory conditions. A precise analytic solution, however, is not possible because of the variable nonlinear coefficients involved, such as atmospheric density and drag coefficients. Nevertheless, the insight provided by even an approximate analytic solution should be sufficient for any initial appraisal of a fuzing design.

Analysis

In this analysis of re-entry vehicle motion it is assumed that the earth and its atmosphere are stationary. Then, the equations of motion for the center of vehicle mass are as follows:

$$M\frac{dv}{dt} = -\text{drag} + W \sin \theta \tag{1}$$

$$MV \frac{d\theta}{dt} = W\left(\frac{V^2}{gr} - 1\right) \cos\theta + \text{lift} \tag{2}$$

where θ is the flight-path angle with respect to the local horizontal and is negative during re-entry.

Further simplification is possible without significant error, in most cases, by assuming the following, as in Reference 1:

1. A flat earth for short re-entry distances.
2. Lift can be neglected.
3. The gravitational effect can be neglected (not good for terminal velocity conditions).
4. Drag coefficient is constant.
5. Constant g.
6. Exponential atmospheric density.

Under these conditions the classic analytic expressions for vehicle velocity and deceleration are derived in the appendix.

To find the effect of parametric variations on both velocity and deceleration, the derived expressions were expanded in a Taylor series around the nominal values of the ballistic parameter (K), atmospheric density (ρ), and flight-path angle (θ). It should be noted that the original expressions for velocity and deceleration were derived assuming K and θ to be constant and ρ to be an exponential model throughout the trajectory. Consequently, any variations in these parameters will also be constant throughout the trajectory. For instance, if a 10-percent change in atmospheric density were introduced at 20,000 feet, the calculated result would reflect the effect of a 10-percent density change from re-entry to 20,000 feet. To allow these parameters to be variables of a general nature would prevent an analytic expression for velocity and deceleration.

Using only the first terms of the expansion, the following expressions were obtained to describe the effects of trajectory perturbations on vehicle velocity and deceleration, respectively:

$$\Delta V \cong \frac{V}{2}\left[\left(\frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta K}{K} - \left(\frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta\rho}{\rho} + \left(\frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta\theta}{\tan\theta}\right] \tag{3}$$

$$\Delta a \cong -a\left[\left(1 - \frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta K}{K} - \left(1 - \frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta\rho}{\rho} - \left(\frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta\theta}{\tan\theta}\right]; \tag{4}$$

[redacted]

Results of Analysis

Having derived approximate expressions for effects of perturbations, the next step is to compare the results of these simple expressions with those obtained from the computer solution of the original differential equations. Since the interest is in perturbation effects only, it is assumed that the nominal trajectory information will be available for numerical calculations.

In order to perform the numerical calculations, the following re-entry conditions were selected as nominal: 300,000 foot re-entry altitude, 21,500 ft/sec re-entry velocity, a re-entry angle of 20 degrees, and the ARDC 1959 standard atmosphere. Two vehicles with ballistic coefficients of 500 lb/sq ft and 1400 lb/sq ft were chosen to show the limitations of the simple perturbation expressions. **Figure 1** shows the drag coefficient curves used in the computer program for both these vehicles. Figures 2 and 3 show the corresponding nominal values of deceleration and velocity as a function of altitude for a point mass.

To facilitate the numerical analysis, the common factor $\rho g/\beta K \sin\theta$ in Equations 3 and 4 was evaluated using the nominal trajectory data obtained from the computer. Although contrary to some of the assumptions of the derivation, evaluating this factor from the nominal computer data improves the accuracy of the analytic expression. The principal benefit is in accounting for the Mach variation of the drag coefficient which is implicit in the computer data. Figure 4 shows a plot of this factor as a function of altitude for the following values of ballistic coefficient (K): 500, 1000, 1400, and 3000 lb/sq ft. The peaking in these curves is due primarily to the change in vehicle drag coefficient through the transonic velocities. Vehicles with high values of K do not decelerate enough to reach the transonic region.

The curves shown in Figure 4 were then used in conjunction with Equations 3 and 4 to calculate the variations in deceleration and velocity corresponding to the following perturbations: a 5-percent increase in ballistic coefficient and atmospheric density, and a 1-degree increase in re-entry angle. The results of these calculations and the computer program are given in Figures 5 through 10. For the case where K = 1400 lb/sq ft, the two methods agree very well. However, substantial errors are incurred when this simple method is used for values of K around or below 500 lb/sq ft. This situation is attributed to the neglect of gravitational effects. This neglect dictates a straight-line trajectory. Figure 11 shows that for a K of 500 lb/sq ft the nominal trajectory deviates considerably from a straight line. The trajectory approaches a straight line, however, as K increases and the accuracy of the analytic approximation improves.

Conclusions

The results of the numerical analysis indicate that the simple analytic expressions derived in this study are sufficiently accurate in many cases for an initial appraisal of the effects of trajectory perturbations. They particularly lend themselves to feasibility studies on vehicles with ballistic coefficients greater than 1000 lb/sq ft. However, their use can be extended to vehicles with lower ballistic coefficients provided the interest is in the upper altitude regions of the trajectory where gravitational effects can be neglected.

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FIGURE 1
DRAG COEFFICIENT VS MACH NUMBER

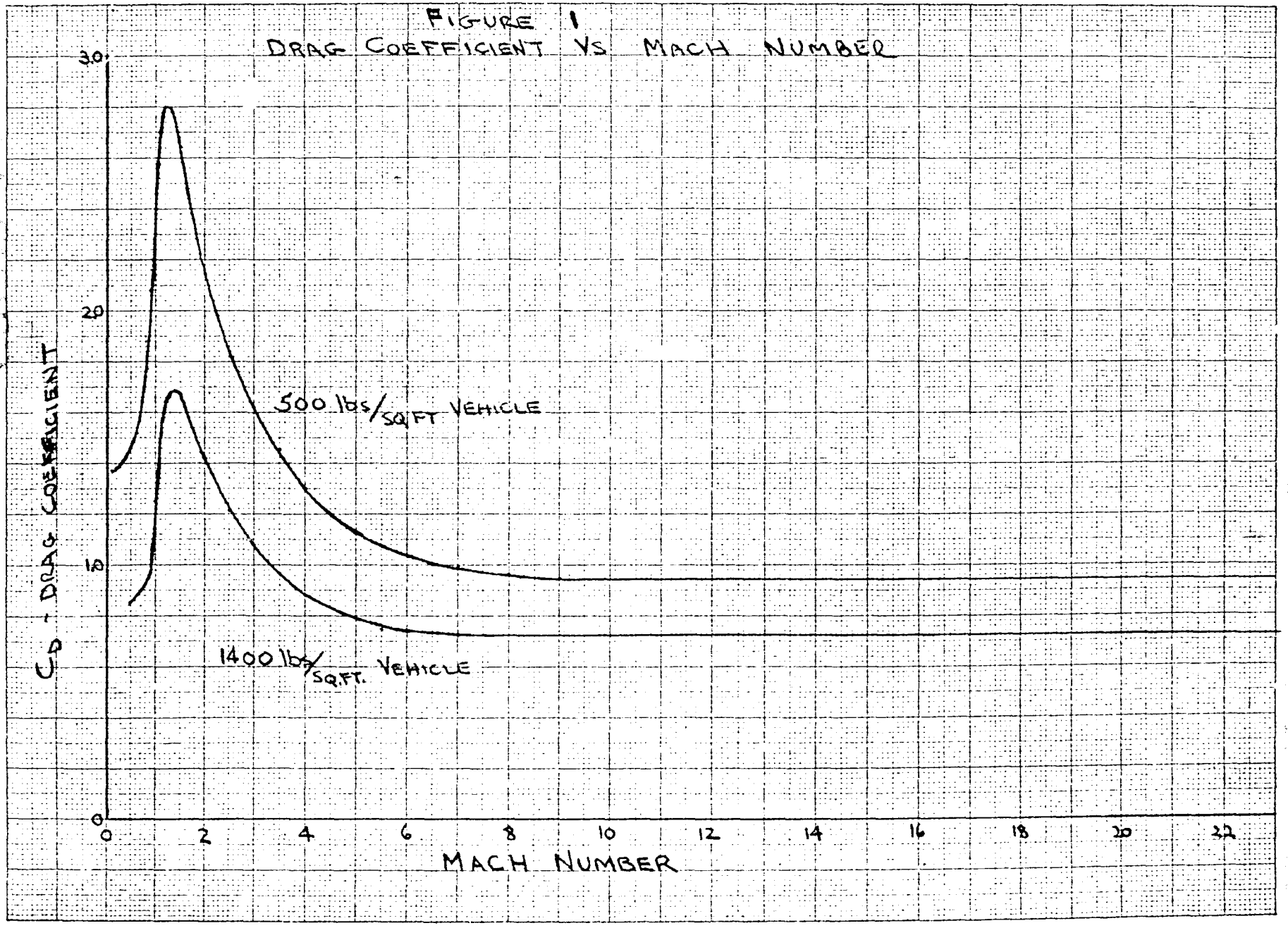

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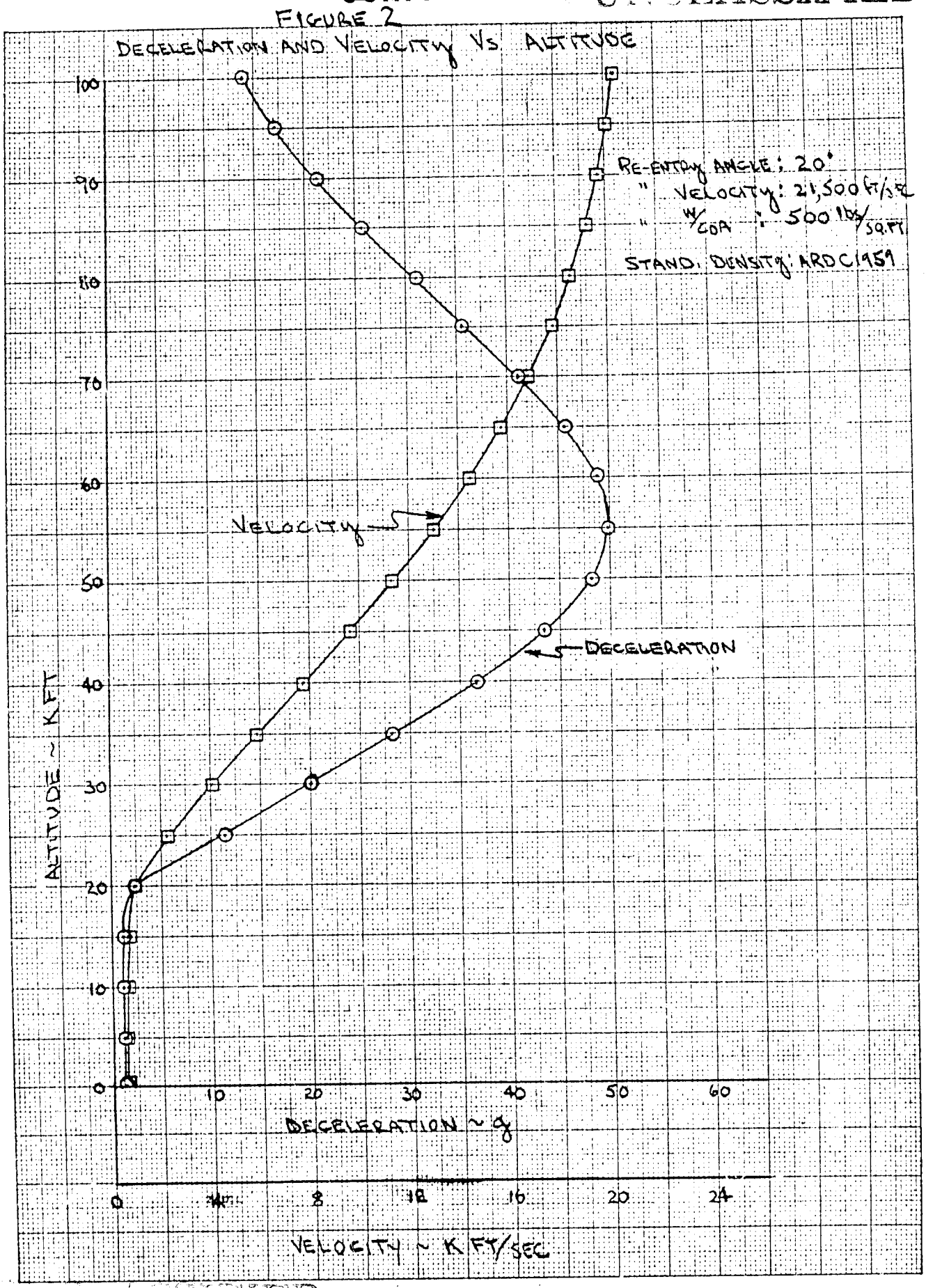
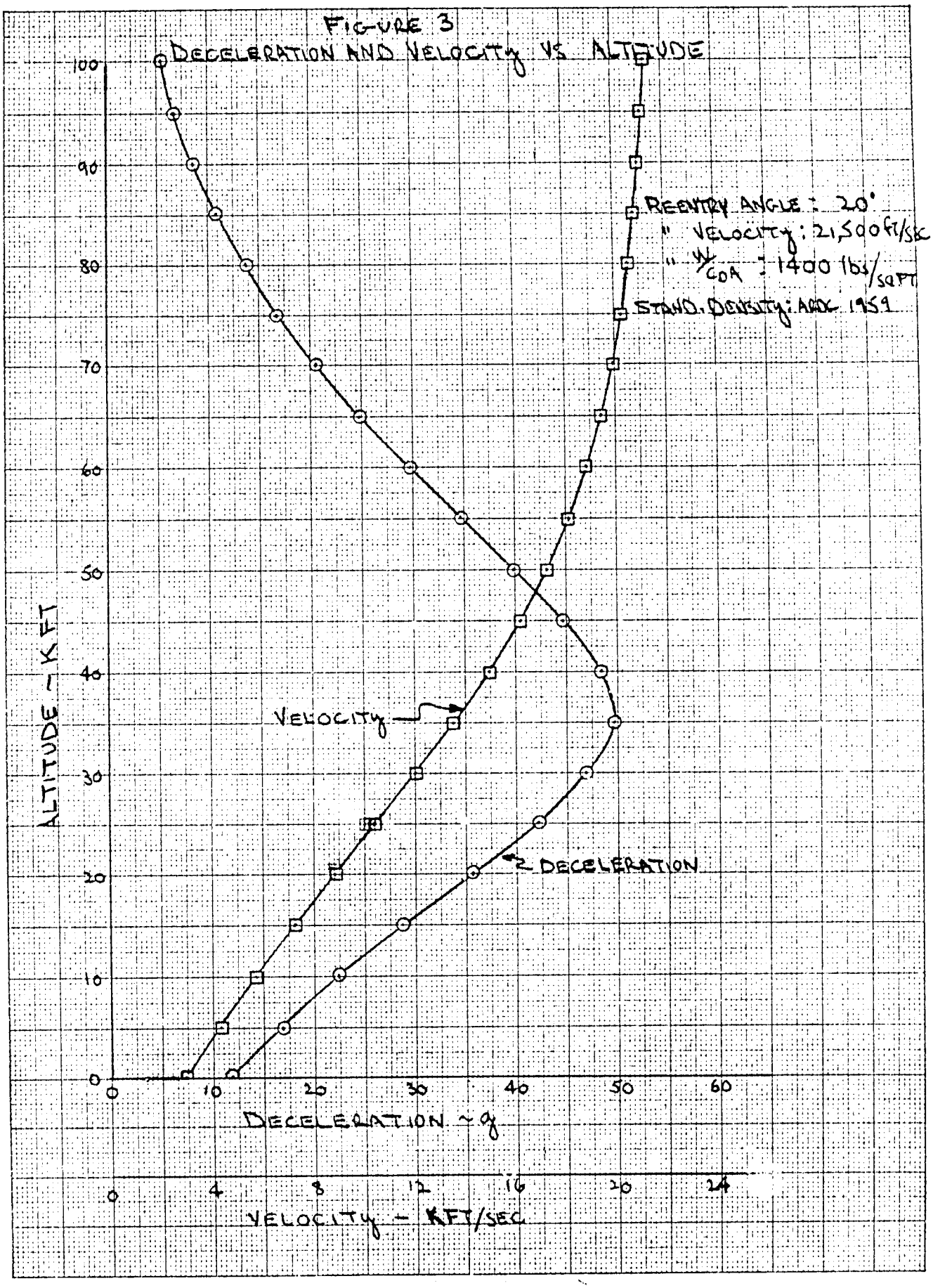
FIGURE 2


DECELERATION AND VELOCITY VS ALTITUDE
RE-ENTRY ANGLE: 20°
" VELOCITY: 21,500 FT/SEC
" W/CDA: 500 lbs/SQ.FT.
STAND. DENSITY: ARDC 1959
VELOCITY
DECELERATION
ALTITUDE ~ KFT
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
DECELERATION ~ g
0
4
8
12
16
20
24
VELOCITY ~ KFT/SEC

[redacted]



[redacted]

[redacted]

FIGURE 4

$\frac{\rho g}{\beta K \sin\theta}$ VS ALTITUDE

VALUES WERE TAKEN FROM COMPUTED TRAJECTORIES OF RE-ENTRY VEHICLES HAVING VALUES OF K = 500 lbs/SQ.FT.; 1000 lbs/SQ.FT.; 1400 lbs/SQ.FT.; 3000 lbs/SQ.FT.

RE-ENTRY ANGLE: 20°

" VELOCITY: 21500 FT/SEC

THE EXPRESSIONS BELOW FOR THE CHANGE IN DECELERATION AND VELOCITY SHOW HOW THE FACTOR $\frac{\rho g}{\beta K \sin\theta}$ IS UTILIZED

$$\Delta a \cong -g\left\{\left[1-\frac{\rho g}{\beta K \sin\theta}\right]\frac{\Delta K}{K}-\left[1+\frac{\rho g}{\beta K \sin\theta}\right]\frac{\Delta \rho}{\rho}-\left[\frac{\rho g}{\beta K \sin\theta}\right]\frac{\Delta\theta}{\tan\theta}\right\}$$

$$\Delta V \cong V\left\{\left[\frac{\rho g}{2\beta K \sin\theta}\right]\frac{\Delta K}{K}-\left[\frac{\rho g}{2\beta K \sin\theta}\right]\frac{\Delta \rho}{\rho}+\left[\frac{\rho g}{2\beta K \sin\theta}\right]\frac{\Delta\theta}{\tan\theta}\right\}$$

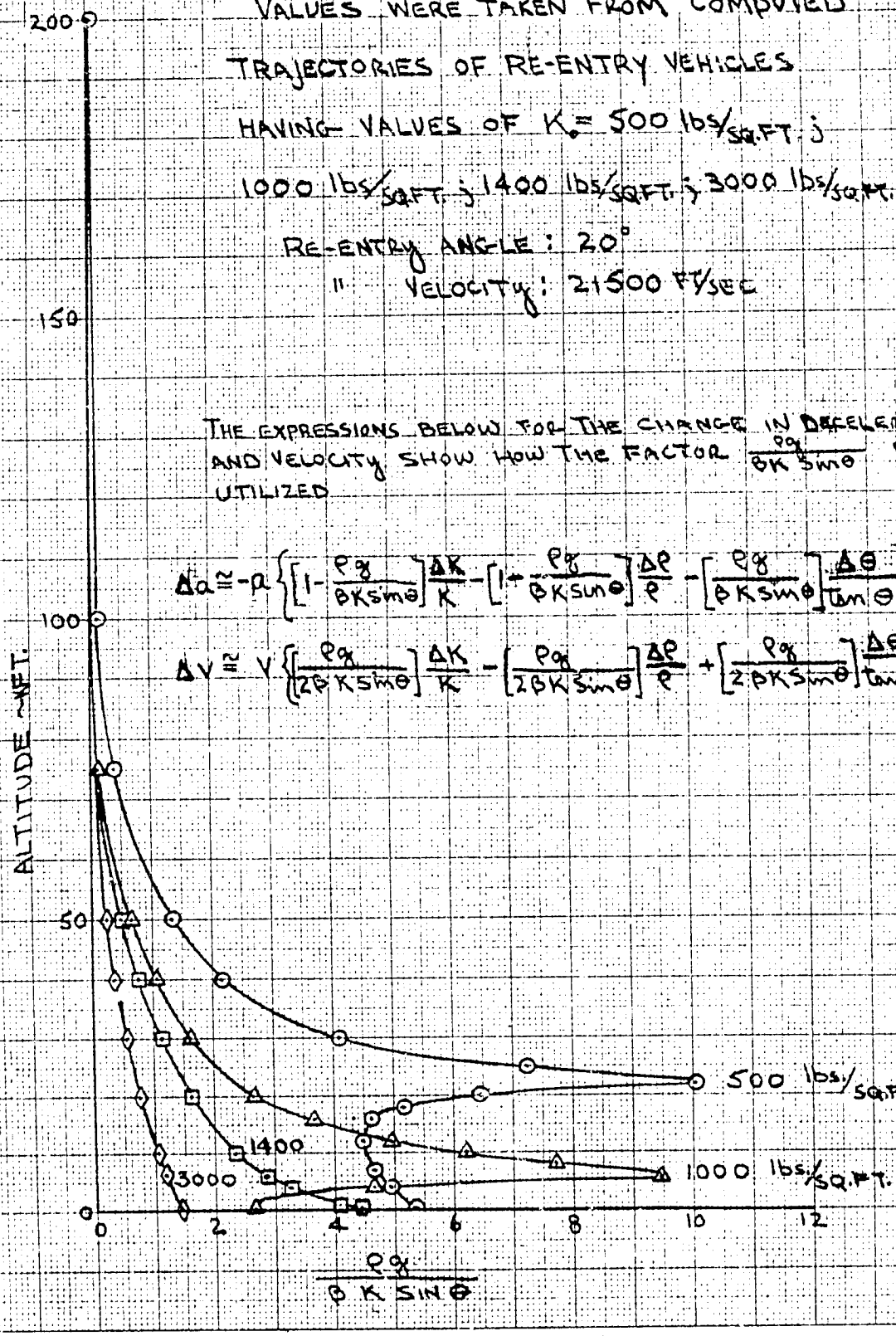


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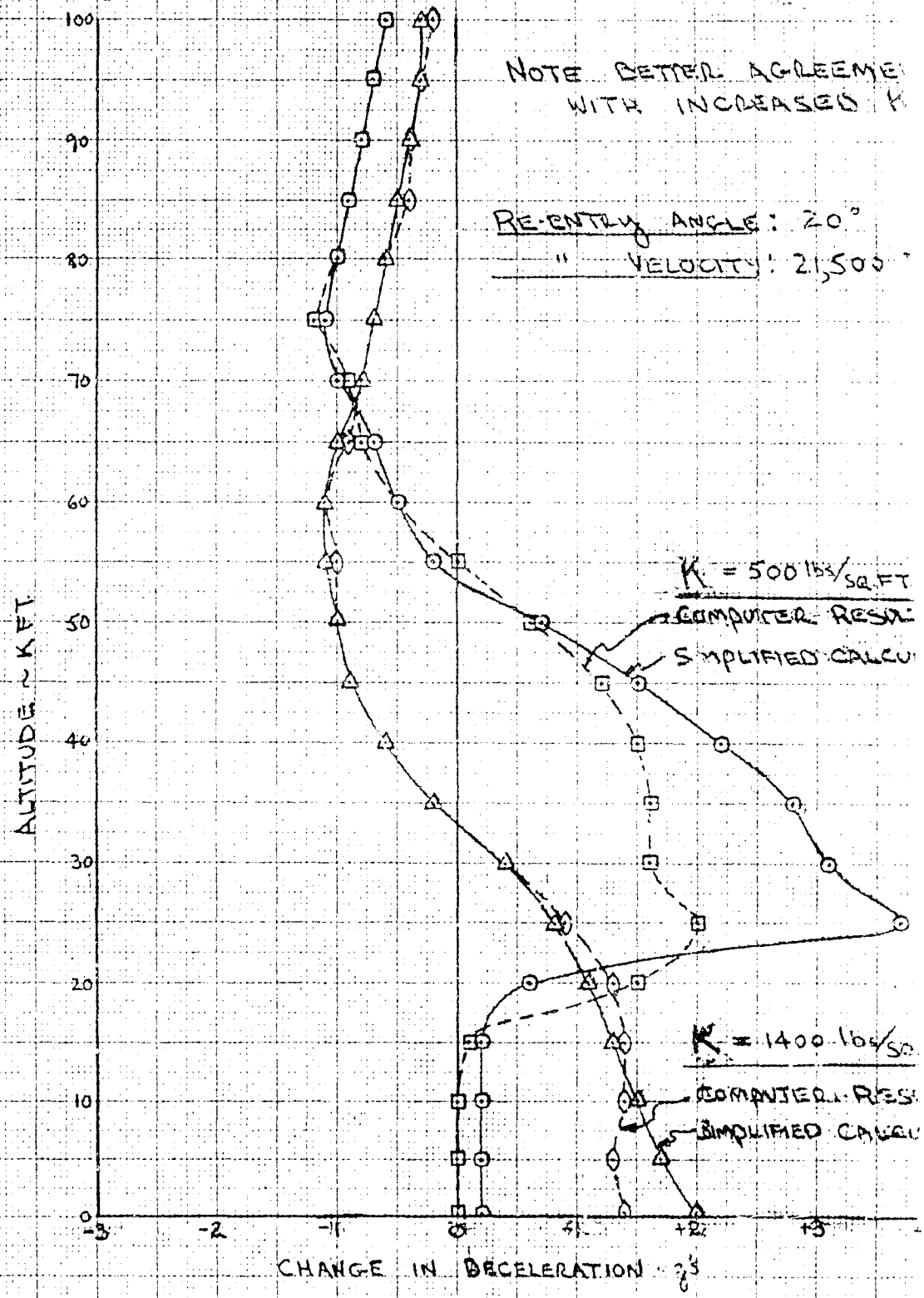
FIGURE 5

COMPUTER RESULTS COMPARED WITH SIMPLY CALCULATED CHANGES IN RE-ENTRY DECELERATIO FOR A 5% INCREASE IN VEHICLE K



[redacted]

[redacted]

FIGURE 6
COMPUTER RESULTS COMPARED WITH SIMPLY CALCULATED CHANGES IN RE-ENTRY DECELERATION FOR A 5% INCREASE IN ATMOSPHERIC DENSITY

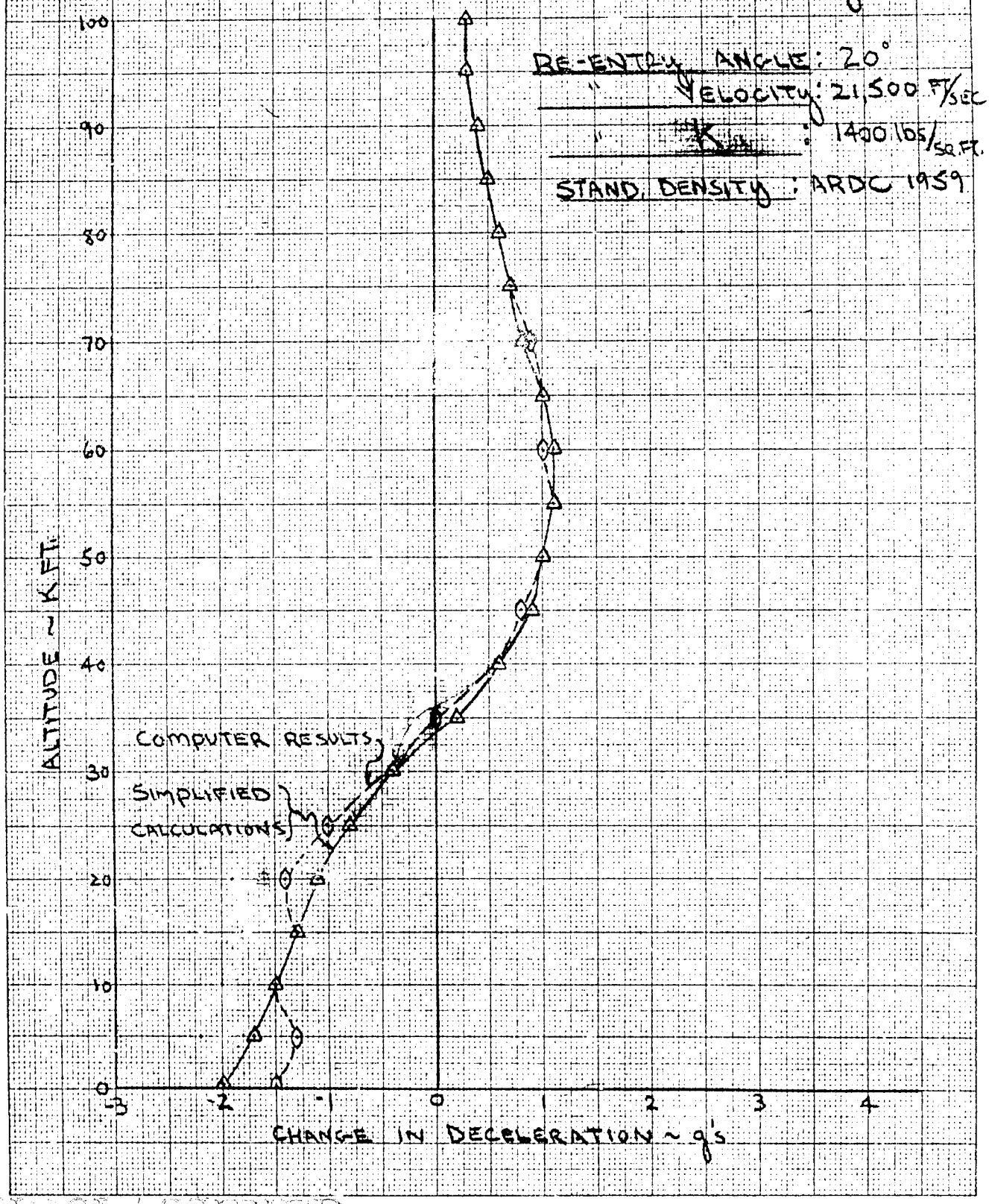


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FIGURE 7
COMPUTER RESULTS COMPARED WITH SIMPLY CALCULATED CHANGES IN RE-ENTRY DECELERATION FOR A ONE DEGREE INCREASE IN RE-ENTRY ANGLE

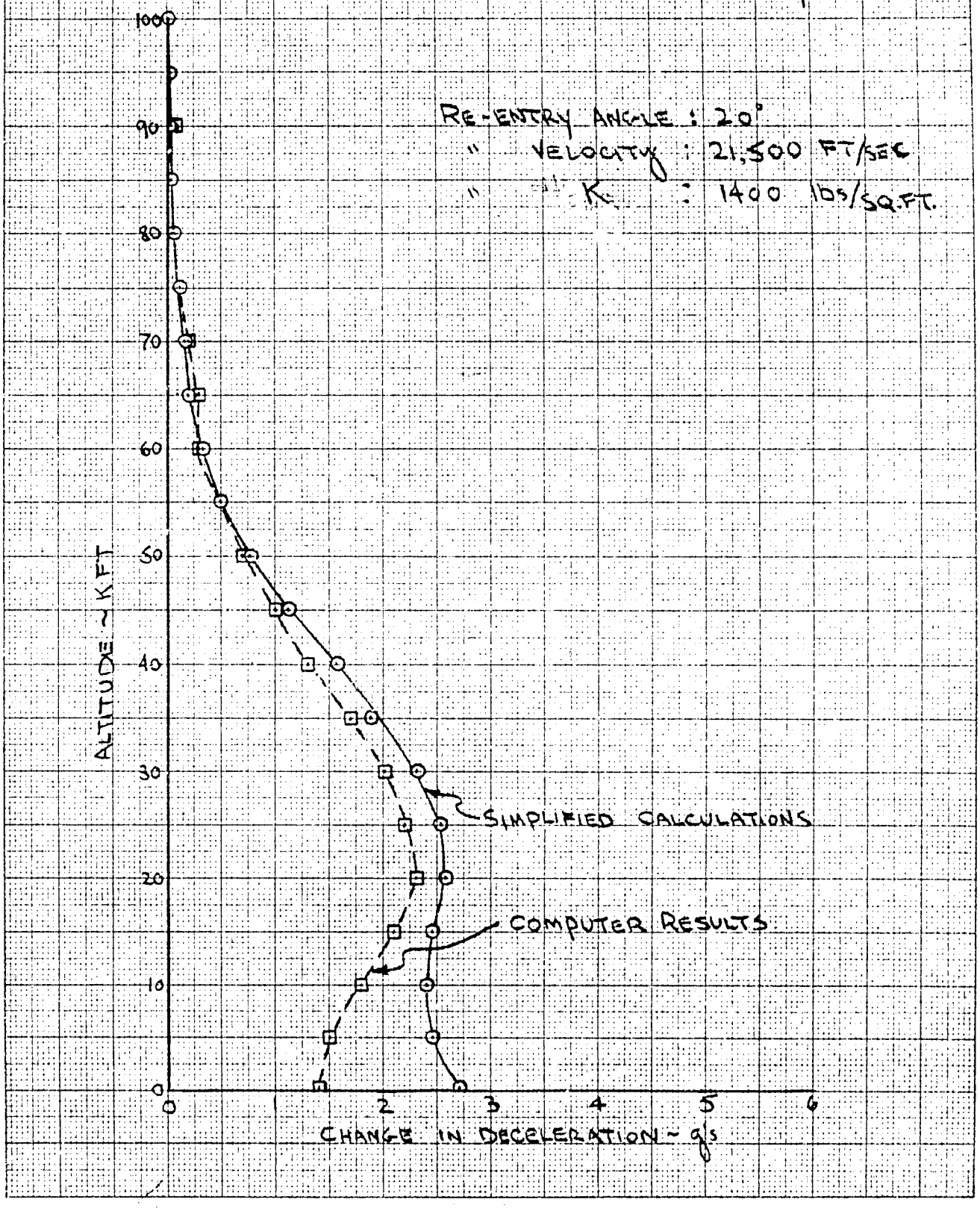

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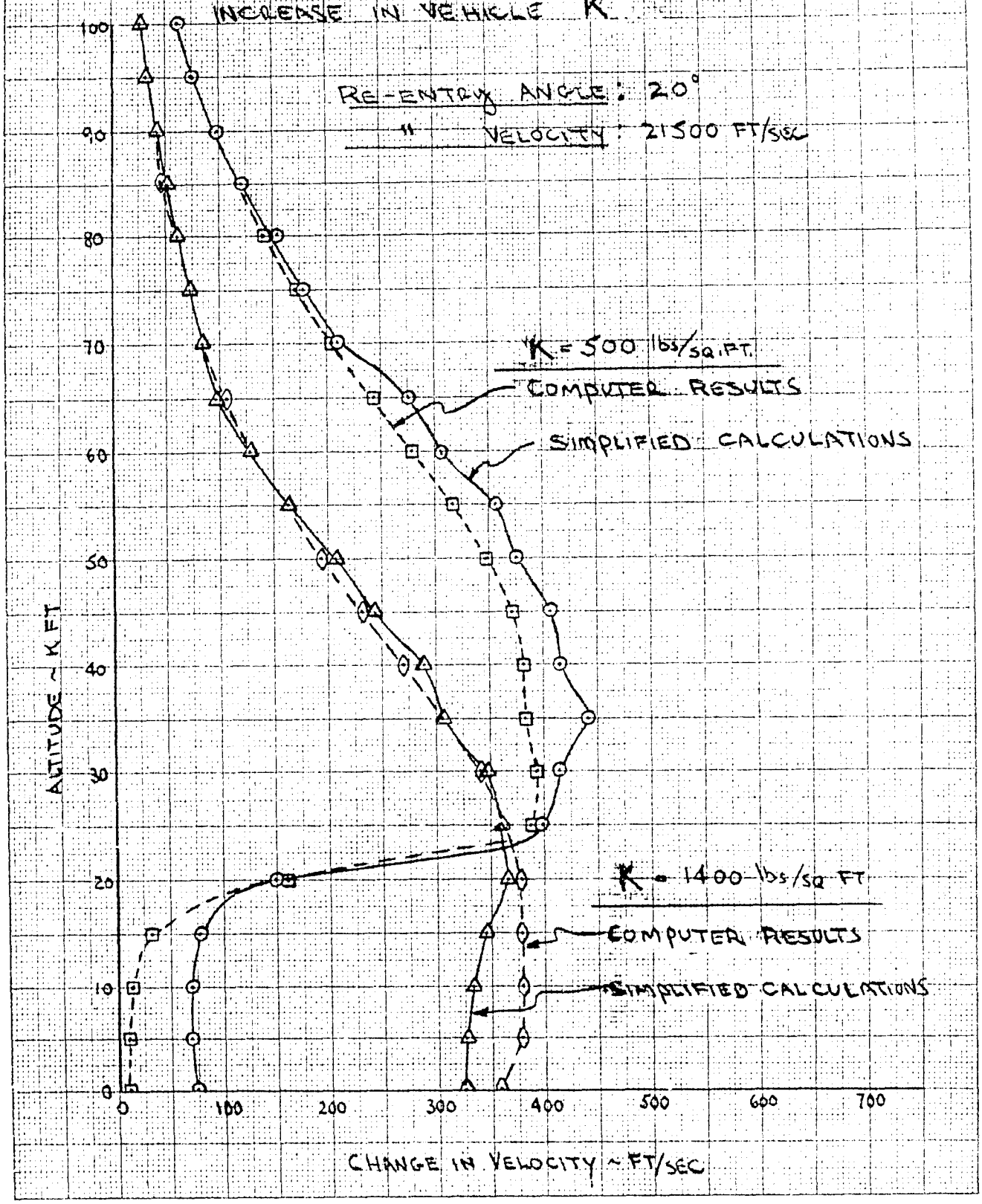
FIGURE 8

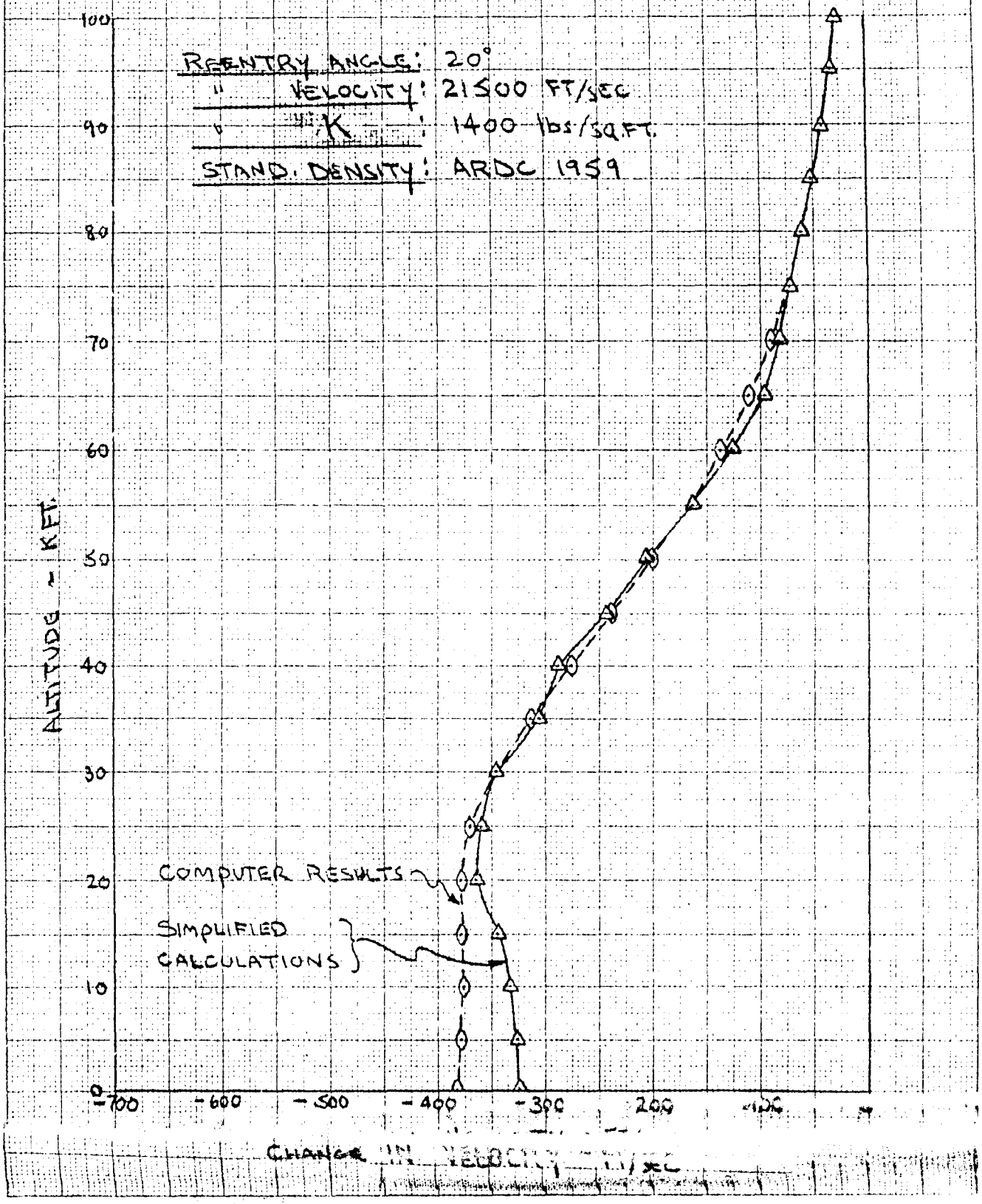
COMPUTER RESULTS COMPARED WITH SIMPLY CALCULATED CHANGES IN RE-ENTRY VELOCITY FOR A 5% INCREASE IN VEHICLE K



[redacted]

[redacted]

FIGURE 9
COMPUTER RESULTS COMPARED WITH SIMPLY CALCULATED CHANGES IN RE-ENTRY VELOCITY FOR A 5% INCREASE IN ATMOSPHERIC DENSITY



[redacted]

[redacted]

FIGURE 10
COMPUTER RESULTS COMPARED WITH SIMPLY CALCULATED CHANGES IN RE-ENTRY VELOCITY FOR A ONE DEGREE INCREASE IN RE-ENTRY ANGLE

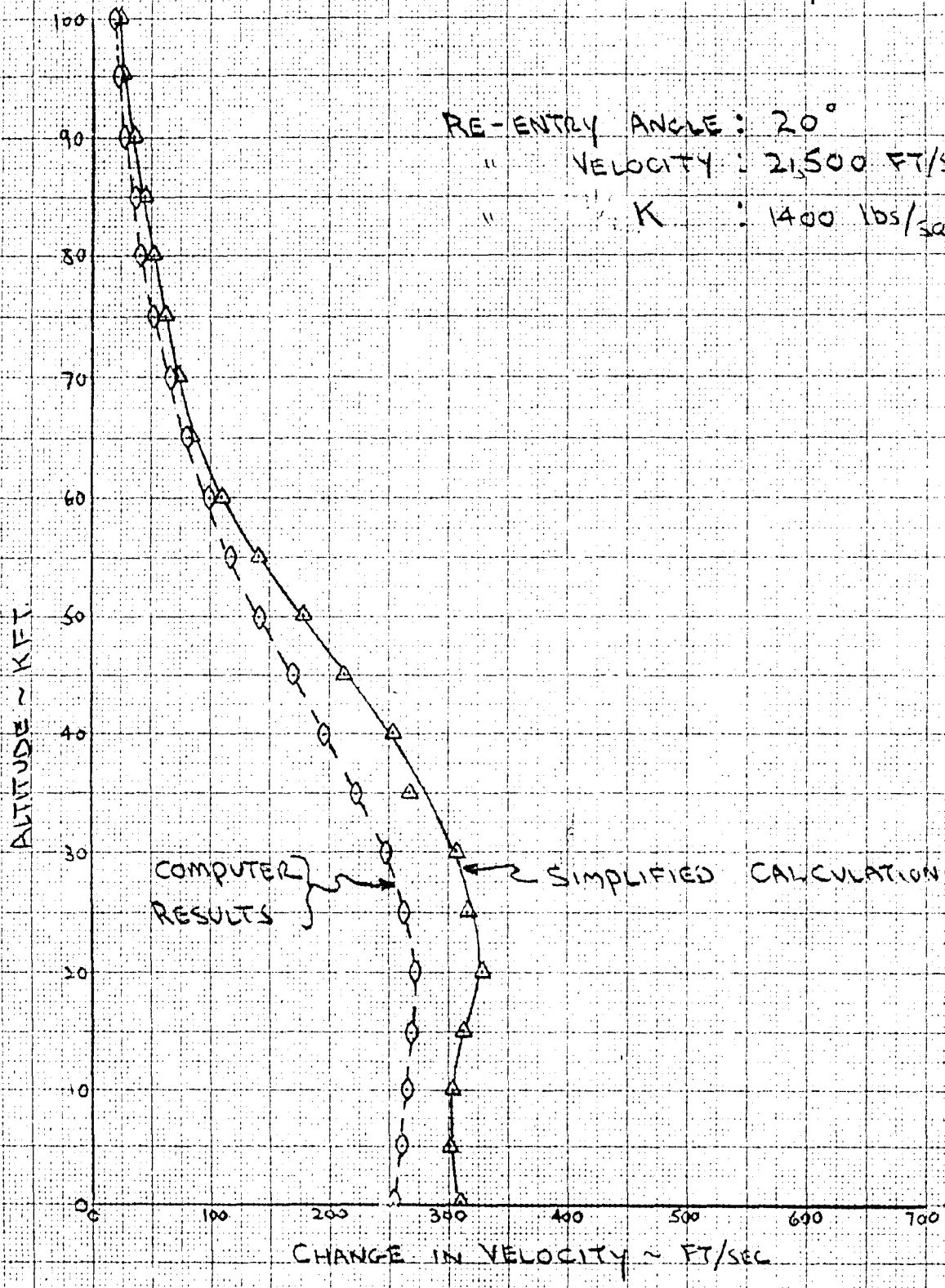


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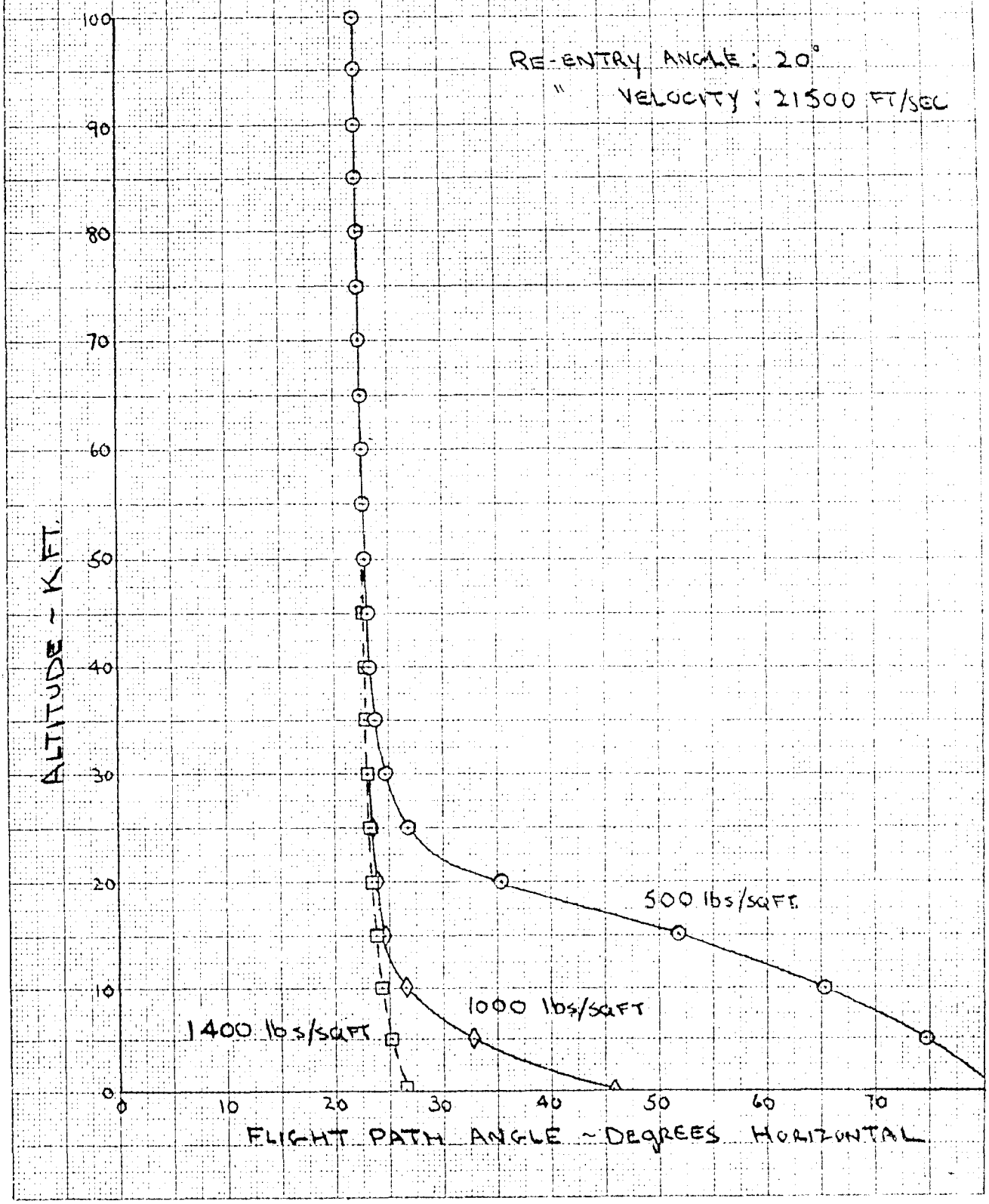
FIGURE 11

THE EFFECT OF BALLISTIC COEFFICIENT ON THE FLIGHT PATH ANGLE



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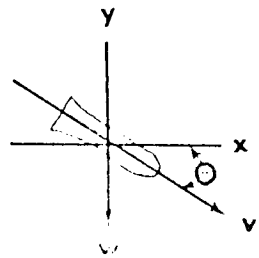
APPENDIX



The parametric equations of motion for the falling body with zero lift are:

$$M \frac{dv}{dt} = - 1/2\, \rho\, C_D A\, V^2 + W \sin \theta \qquad \text{(A-1)}$$

$$MV \frac{d\theta}{dt} = W \left(\frac{V^2}{gr} - 1 \right) \cos \theta \qquad \text{(A-2)}$$

where:

M = Mass of body - slugs

V = Speed - ft/sec

θ = Flight-path angle - radians

C_D = Drag coefficient

A = Body reference area ~ sq ft

ρ = Air density - slugs/ft^3

g = Acceleration of gravity ~ ft/sec^2

W = Weight of body - lbs

r = Radius from earth's center - ft

If the flight path is assumed to be a straight line, then Equation A-2 can be neglected for the present. This assumption is improved with increasing W/C_DA; i.e., for computer calculated trajectories with the following initial conditions:

$$V_o = 20{,}000 \text{ ft/sec}$$

$$\theta_o = 20 \text{ degrees}$$

$$y = 10{,}000 \text{ ft msl.}$$

For

W/C_DA	= 500 lb/sq ft	$\frac{d\theta}{dt}$	= 20.9×10^{-3} rad/sec
W/C_DA	= 1000 lb/sq ft	$\frac{d\theta}{dt}$	= 12.1×10^{-3} rad/sec
W/C_DA	= 1400 lb/sq ft	$\frac{d\theta}{dt}$	= 8.1×10^{-3} rad/sec
W/C_DA	= 3000 lb/sq ft	$\frac{d\theta}{dt}$	= 3.04×10^{-3} rad/sec.

Then Equation A-1 can be used to find an expression for the velocity:

$$\frac{dV}{dt} = -1/2 \frac{\rho g C_DA V^2}{W} + g \sin\theta \qquad \text{(A-3)}$$

$$\frac{dV}{dt} = -\frac{dV}{dy}\frac{dy}{dt} \qquad \text{(A-4)}$$

where $\frac{dy}{dt} = V \sin\theta$.

Substituting Equation A-4 into Equation A-3

$$-V \sin\theta \frac{dV}{dy} = -1/2 \rho g \frac{C_DA}{W} V^2 + g \sin\theta \qquad \text{(A-5)}$$

$$V \frac{dV}{dy} = \frac{g\rho C_DA}{2W \sin\theta} V^2 - g. \qquad \text{(A-6)}$$

If an atmospheric density model is assumed to be:

$$\rho = \rho_o e^{-\beta y}$$

where $\rho_o = 0.0034$ slugs/ft^3

$\beta = 1/22000$ per foot

y = altitude in feet

and the g term is neglected, then the differential Equation A-6 is solved as below by the separation of variables for constant θ and C_D.

$$\frac{dV}{V} = \frac{g\ C_D A\ \rho_o}{2W \sin\theta}\ e^{-\beta y}\ dy \tag{A-7}$$

$$\ln V \Big|_{V_o}^{V_y} = -\frac{C_D A\ \rho_o\ g}{2W\ \beta\ \sin\theta}\ e^{-\beta y}\Big|_{y_o}^{y} \tag{A-8}$$

where $e^{-\beta y_o} \simeq 0$ for $y_o = 300{,}000$ feet.

Therefore, an approximate expression for velocity is:

$$V_y = V_o \exp\left[-\frac{C_D A\ g\ \rho_o}{2W\ \beta\ \sin\theta}\ e^{-\beta y}\right]. \tag{A-9}$$

For the case where the range covered by the re-entry trajectory is small, the earth can be assumed flat ($r \to \infty$) in Equation A-2, and the resulting expression for deceleration can be obtained from combining Equation A-1 and Equation A-2.

$$\frac{dV}{dt} = -\frac{\rho V^2}{2}\left(\frac{C_D A}{M}\right) - V \tan\theta\ \frac{d\theta}{dt}\ . \tag{A-10}$$

Let $\frac{dV}{dt} = a$, $M = W/g$ and $W/C_D A = K$, then:

$$a = -V\left[\frac{\rho g\ V}{2K} + \tan\theta\ \frac{d\theta}{dt}\right]. \tag{A-11}$$

To find the effect of parametric variations on both velocity and deceleration, the expressions A-9 and A-11 are expanded in a Taylor series around the nominal value of the following parameters: the ballistic parameter K, atmospheric density, and flight path angle θ.

The general form of the Taylor series being:

$$f(x) = f(x_o) + f'(x_o)\ (x - x_o) + \frac{f''(x_o)}{2!}\ (x - x_o)^2 + \ldots$$

$$+ \frac{f^n\ (x_o)}{n!}\ (x - x_o)^n. \qquad \text{(A-12)}$$

Then the change due to parametric variation is:

$$f(x) - f(x_o) = f'(x_o)\ (x - x_o) + \frac{1}{2}\ f''\ (x_o)\ (x - x_o)^2 + \ldots\ . \qquad \text{(A-13)}$$

The expression for the change in velocity due to a change in K is:

$$\Delta V = \frac{\partial V}{\partial K}\ (K - K_o) + \ldots \qquad \text{(A-14)}$$

where $$\frac{\partial V}{\partial K} = \frac{V}{K}\left[\frac{\rho g}{2\beta K \sin\theta}\right].$$

For a change in ρ:

$$\Delta V = \frac{\partial V}{\partial \rho}\ (\rho - \rho_o) + \ldots$$

(A-15)

where $$\frac{\partial V}{\partial \rho} = -\frac{V}{\rho}\left[\frac{\rho g}{2\beta K \sin\theta}\right].$$

For a change in θ:

$$\Delta V = \frac{\partial V}{\partial \theta}\ (\theta - \theta_o) + \ldots$$

(A-16)

where $$\frac{\partial V}{\partial \theta} = \frac{V}{\tan\theta}\left[\frac{\rho g}{2\beta K \sin\theta}\right].$$

Combining Equations A-14, A-15 and A-16, an expression for ΔV is obtained:

$$\Delta V \cong \frac{V}{2}\left[\left(\frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta K}{K} - \left(\frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta\rho}{\rho} + \left(\frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta\theta}{\tan\theta}\right] \qquad \text{(A-17)}$$

In a similar manner, Equation A-11 can be expanded to find the effects on deceleration. However, for most cases Equation A-11 can be simplified as follows:

For V_o = 20,000 ft/sec

θ_o = 0.314 radian or 18 degrees

K_o = 1000 lbs/sq ft

y = 10,000 ft msl.

The following factors were numerically evaluated from computer calculated trajectories and compared:

$$\frac{\rho g V}{2K} = \frac{1.8 \times 10^{-3}\ (32.2)\ 1827}{2\ (370)} = 0.143$$

$$\frac{d\theta}{dt} \tan\theta = 15.7 \times 10^{-3}\ (0.516) = 0.0081 \quad .$$

Therefore (θ' tan θ) may be neglected and the first expansion terms of Equation A-11 are:

For a change in K,

$$\Delta a = \left[\frac{\rho g V^2}{2K^2} - \left(\frac{\rho g V}{K}\right)\frac{\partial V}{\partial K}\right]\Delta K; \tag{A-18}$$

For a change in ρ,

$$\Delta a = -\left[\frac{g V^2}{2K} + \left(\frac{\rho g V}{K}\right)\frac{\partial V}{\partial \rho}\right]\Delta\rho\ ; \tag{A-19}$$

For a change in θ,

$$\Delta a = -\left[\left(\frac{\rho g V}{K}\right)\frac{\partial V}{\partial \theta}\right]\Delta\theta. \tag{A-20}$$

Letting $\frac{\rho g V^2}{2K} = -a$, and substituting the expressions for $\frac{\partial V}{\partial K}$, $\frac{\partial V}{\partial \rho}$, $\frac{\partial V}{\partial \theta}$ in Equations A-17, A-18, and A-19, the resulting expression is obtained:

$$\Delta a = -a\left[\left(1 - \frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta K}{K} - \left(1 - \frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta\rho}{\rho} - \left(\frac{\rho g}{\beta K \sin\theta}\right)\frac{\Delta\theta}{\tan\theta}\right]. \tag{A-21}$$

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[redacted]

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2. Ortega, J. M., An IBM 704 Program for Calculating Theoretical Rocket Trajectories, SCTM 117-58(51), 1951.

[redacted]

[redacted]

No. & Class.	Title	Author	Abstract
85-61-54 SRD	Comments on a Lockheed Study of the Vulnerability of the Polaris Mark 2 Re-Entry Body at Low Altitudes (Title Unclassified; Abstract SDI)	R. T. Dillon, 5422	An examination of a Lockheed study of the vulnerability of the Polaris Mark 2 re-entry body to defensive measures below 20,000 feet leads to the conclusion that, at least for estimates of the effectiveness of conventional antiaircraft gunfire, the input assumptions are not realistic and the model used for estimation is deficient, even to the extent that the probabilities of kill reported for fragmenting shells are less than the probability of the shell making a direct hit on the re-entry body. In view of this it is believed that the Lockheed conclusion: "all efforts made to protect the Mark 2 re-entry body should be expended in the field of high altitude combat rather than that of low altitude." is not justified by their study.
110-61-51 UNCL	High Explosive Craters in Tuff and Basalt	Luke J. Vortman, 5112	Dimensions and surface velocities are presented for craters from thirteen 256-lb high-explosive shots detonated at six different depths in volcanic tuff. Crater dimensions, throw-out and air-blast suppression from three 40,000-lb charges buried at three depths in volcanic basalt are augmented by dimensions of craters from ten 1000-lb shots.
113-61-51 UNCL	Cratering with Row Charges	Luke J. Vortman, 5112	Preliminary information shows that craters from rows of charges are comparable to craters from line charges if the scaled spacing between charges is one plus the scaled depth of burst. The effect of greater spacing is explored.
130-61-51 UNCL	Photographic Instrumentation for the Teak and Orange Events	M. A. Palmer, 5113	Photographic instrumentation used for recording Teak and Orange events is described. A method of photographic photometry is reported more specifically. Streak cameras and high-speed framing cameras incorporating narrow-band-pass filters were used, and calibration techniques are described. A method for determining characteristic curves by "auto-calibration" was formulated. Each calibration curve was constructed with data obtained from the individual streak camera test film involved. The effect of light scatter within the Fastax streak camera was investigated and found to be significant.
152-61-54 UNCL	An AC Instrumentation System for Parameter Measurements of	F. M. McIver, 5434	A 400 cycle instrumentation complex for use with pulsed neutron irradiation of semiconductors is discussed. Included is a system for recording resistivity, carrier concentration, and mobility. A combination DC and 60 cycle photoconductivity system is discussed. Temperature control and recording systems are described.

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