WADC Technical Note 56-7

Escape From High Performance Aircraft

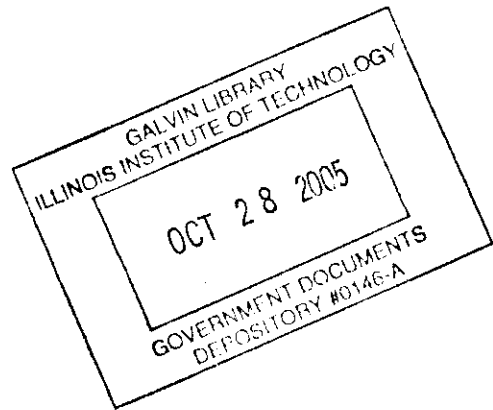JOHN W. GOODRICH, Captain, USAF

Plans Office
Directorate of Research

9 January 1956

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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ESCAPE FROM HIGH PERFORMANCE AIRCRAFT

1. PURPOSE

1.1 An objective analysis of the problem of escape from high performance aircraft is presented in terms of human tolerance to acceleration correlated with pertinent aerodynamic and physical factors. The maximum linear deceleration experienced during escape is computed for the conventional ejection seat system as a function of calibrated airspeed[1], altitude, and Mach number. The decay of deceleration is also computed as a function of altitude for a given initial calibrated airspeed. Correlation of these computed physical forces with human tolerance to acceleration reveals the critical human limitations associated with existing conventional ejection seats for successful escape from high performance aircraft. This study will aid in determining the scope of knowledge required to support escape systems research and development.

2. FACTUAL DATA

2.1 One aspect of the limitations of the ejection seat as a tolerable means of escape from high speed aircraft is the magnitude of linear deceleration caused by the airloads imposed on the ejected occupied seat as it enters the airstream. Human tolerance to acceleration has been fairly well defined as a result of the efforts of Dr. John P. Stapp, Holloman Air Development Center, Doctors Savely, Edelberg, and Henry of the Aero Medical Laboratory, WADC - and others. (References 1, 2, 3, and 4). The human tolerance to linear deceleration in relation to rate of on-set, magnitude, and duration for transverse g (in a stable escape system), as defined by the Biophysics Branch of the Aero Medical Lab, WADC, is presented in Fig. 1. The introduction of positive or negative g forces will lower the human tolerance depicted in Fig. 1. This study does not evaluate the effects of tumbling during escape, or the phenomena of the build-up to the initial peak deceleration (rate of on-set), and is limited to an analysis of a stable escape system.

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[1]Calibrated airspeed is defined as the indicated airspeed corrected for installation and instrument errors.

2.2   The maximum linear deceleration experienced by the occupied ejection seat as it enters the airstream is determined by the ratio of the drag to the weight of the occupied seat. There are three main variables affecting the magnitude of the g forces at various speeds. These are:

2.2.1   The exposed frontal area of the occupied seat normal to the airstream.

2.2.2   The weight of the occupied seat, and,

2.2.3   The variation of the drag coefficient with Mach Number.

In order to determine the airload imposed on the seat, a drag coefficient for the seat-man configuration must be found. Probably the most reliable drag data available for existing conventional ejection seat systems is that obtained from the MIT Wind Tunnel Report #69, January 1954. Data from the MIT report was used for this study, as shown in Fig. 2, which is a plot of drag coefficient (C_D) as a function of Mach number for a seat angle of attack of 10 degrees. This angle of attack of 10 degrees represents the attitude of the seat just as it clears the rails during ejection and is exposed to the full free stream velocity.

2.3   Using the values of C_D given by Fig. 2, the magnitude of the g force as a function of calibrated airspeed, altitude and Mach number, for a conventional ejection seat having a frontal area normal to the airstream of 6.5 sq.ft. and an occupied seat weight of 325 pounds, is shown in Fig. 3. The most significant fact to consider here is that the maximum linear acceleration is practically constant for a given calibrated airspeed regardless of altitude. The approximation may be made, without introducing too serious an error, that the maximum linear acceleration caused by ejecting into an airstream is constant for any given calibrated airspeed. Referring to Fig. 3, this means that the maximum linear acceleration experienced at M=1 at sea level is about the same magnitude as is experienced at M=2 at 39,000 feet. However, for a given escape system, even though the maximum g forces are equal for constant calibrated airspeeds, two other important factors must be considered in order to determine the tolerable limit of escape as a function of calibrated airspeed at extreme altitudes:

2.3.1   First, for a given ejection seat system at a constant calibrated airspeed, the rate of tumbling is increased with an increase in altitude because of the lower damping forces experienced in the less dense atmosphere. With an increase in altitude, at constant calibrated airspeed, the aerodynamic damping force which tends to reduce tumbling decreases. However, the force which produces the tumbling remains constant. The rate of tumbling for a given escape system at 40,000 feet approaches a rate double that experienced at sea level for the same calibrated airspeed.

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2.3.2 Secondly, as altitude increases for any given calibrated airspeed, the kinetic energy of the ejected occupied seat increases because the kinetic energy of the system is a function of the square of the true airspeed. The ratio of the increase in kinetic energy for a given calibrated airspeed at an altitude of 40,000 feet as compared to sea level conditions is approximately three to one. This three-fold increase in kinetic energy must be dissipated as a function of time in the less dense atmosphere at altitude. For this reason, it must be expected that the duration of the acceleration will increase with altitude. For a stable escape system, the relationship expressing g as a function of time may be derived from the basic force equation:

$$m \frac{dv}{dt} = -C_D A \frac{1}{2} \rho v^2 \qquad \text{(Eq. 2.1)}$$

Integrating this equation between proper limits, substituting, and solving for t reveals;

$$t = \frac{2W(v_0 - v)}{C_D A \rho g \; v_0 v} \qquad \text{(Eq. 2.2)}$$

where t is defined as the time required to go from v_0 to v and ρ would represent the density of the air at the altitude of ejection. Analog solutions of the above equation for the conventional ejection seat system used in the sample calculations for Fig. 3 were obtained between an initial and final calibrated airspeed at various altitudes to determine the curves for g versus time at various altitudes, shown in Fig. 4. An analysis of these results revealed that the decay of deceleration at various altitudes closely approximates the relationship

$$t_h \cong \frac{t_{SL}}{\sqrt{\rho / \rho_0}} \qquad \text{(Eq. 2.3)}$$

for a given g force, as shown in Fig. 4. For example, this simply means that it would take approximately twice as long for acceleration to decrease from 35 g to 10 g at 40,000 feet as it would at sea level. In this respect it is important to mention that duration of acceleration is considered just as important as magnitude when defining human tolerance to acceleration. The two factors cited above, tumbling rate and duration of acceleration, may be the limiting criteria for successful escape at extreme altitude rather than the more easily defined 35 g limit of linear deceleration described in Fig. 1.

2.4 Fig. 5 indicates the linear deceleration as a function of calibrated airspeed showing the effect of variation of the weight of the ejected occupied seat and the area normal to the airstream for values of C_D taken from Fig. 2. It can be seen from the equation defining

$$g = \frac{D}{W} = \frac{C_D A}{W} \left(\frac{1}{2} \rho v^2 \right) \qquad \text{(Eq. 2.4)}$$

that the maximum linear deceleration is directly proportional to the area

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normal to the airstream and inversely proportional to the weight of the ejected occupied seat. For the conventional ejection seat in common use today, the weight of the occupied ejection seat will vary from 300 to 360 pounds; and estimates of the area normal to the airstream for various ejection seat systems vary from 5 to 7.5 sq.ft. For any given set of ejection circumstances, the ratio of A/W may be determined, and designated as k so that the equation for g may be written as

$$g = k \, C_D \left(\tfrac{1}{2} \rho v^2 \right)$$

(Eq. 2.5)

The maximum g force is directly proportional to k, whose values for a conventional ejection seat system vary from about .014 to .025. The curve of Fig. 5 represents the contributing factor of ($C_D \tfrac{1}{2} \rho v^2$) in describing the relationship of g versus calibrated airspeed. The effect of the variation of k on the magnitude of the g forces is shown by the vertical lines at the left of the graph. To minimize the maximum linear deceleration, it is desirable to have as high an ejection weight as possible confined in the smallest practical frontal area in order to reduce the value of k to its most practical minimum. The important point to consider here is that the limiting 35 g linear deceleration may be expected within the range of calibrated airspeeds from 575 to 725 knots depending on the variables of A and W. For a given escape system, it is desirable to increase the weight of the ejected occupied seat to the maximum permissible value compatible with catapult and structural limitations in order to reduce the maximum g forces. However, the reduction in maximum g obtained by reducing the ratio of k is made at the expense of increased duration of acceleration. Duration of g forces as a function of t is most easily explained by referring to Equation 2.2 which clearly shows that t is inversely proportional to the ratio A/W. Here again, it is apparent that duration rather than magnitude may become the limiting criteria for exceeding the human tolerance curve defined by Fig. 1.

    2.5 Because of the number of variables involved, it is not possible to define a limitation of the ejection seat for successful escape in terms of a single value at calibrated airspeed. However, it is important to note that the maximum linear deceleration associated with conventional ejection seat systems increases sharply to significant magnitudes, relative to human tolerance, as the calibrated airspeed is increased above 550 knots. In order to indicate the seriousness of the problem, the rate of increase of the g forces as a function of calibrated airspeed may be determined as shown in Fig. 6. Here again it is assumed that the maximum force is constant for any given calibrated airspeed, and the computed g forces described in Fig. 3 are replotted as a function of speed on log-log paper. The result is a straight line with a slope of 2.47 to 1. From Fig. 6, showing the maximum g forces as the ordinate and the calibrated airspeed as the abscissa, an equation

for g may be written as

$$g = K \left(\frac{v}{100}\right)^{2.47}$$

<div align="right">(Eq. 2.6)</div>

where K is a constant for a given set of escape system conditions. This simply indicates that g increases as the 2.47 power of the velocity. The slope of this line is a function of the product of C_D times velocity squared. Because the nature of the variation of C_D with Mach number, as shown in Fig. 2, will be much the same for most of the conventional ejection seat systems, the slope of this line will always be near the value 2.47 to 1. In the Equation 2.6 the constant, K, is a function of the product of the ratio of A/W and the relative magnitude of the values for C_D. Changing the value of K simply shifts the curve to the right or to the left on this graph. The actual value of K in the Equation 2.6 would vary slightly for different ejection seat systems depending on the relative magnitude of C_D, which in turn depends on the relative aerodynamic cleanness of the ejection seat system. It is postulated that if the relationship of g versus v were plotted on Fig. 6 for most of the existing ejection seat systems, the actual computed values of g would all be in a relatively narrow band presenting a slope very near the value of 2.47 to 1. The important fact to consider here is that the slope of this line is such that a 15% increase in calibrated airspeed results in a corresponding increase in g forces of almost 50%. From this analysis it is reasonable to expect that the maximum linear decelerations experienced during ejections with existing ejection seat systems rapidly approach the limit of human tolerance (as defined in Fig. 1) as the speed of the aircraft at time of ejection is increased above 550 knots indicated airspeed.

2.6 A further indication of the seriousness of the problem may be realized by considering the maximum speed capability of the "Century Series" of fighter aircraft. The straight and level speed capability at maximum power is considerably less than the limiting permissible red-lined diving speed, and would represent a conservative estimate of performance capability. From the brief analytical approach described in this report, it seems quite obvious that the capability of the ejection seat as a means of successful escape is questionable in the "Century Series" fighters, which have a speed capability in excess of 600 knots calibrated airspeed.

2.7 Investigations aimed at solving the problem presented above include such things as the following:

2.7.1 Drogue chutes to slow the aircraft down to an acceptable escape speed.

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2.7.2 Thrust augmentation of the ejection seats in the direction of flight to reduce the initial deceleration at the expense of increased ram-air pressures.

2.7.3 Rocket thrust to increase the ejection velocity to insure tail clearance.

2.7.4 Increase ejection seat weight to reduce initial deceleration at the expense of increased duration of g forces.

2.7.5 Stabilization techniques for ejection seats.

A preliminary review of proposed solutions indicates there is no "quick-fix" solution apparent for the existing ejection seat systems. It is expected that optimization of some of the proposals resulting in a judicious compromise of decreased g forces at the expense of increased duration will allow a slight penetration into the present unsafe speed range with the current operational escape systems. The aerodynamic characteristics of a blunt object such as the ejection seat system will dictate a relatively high value for ($C_D A/w$). Therefore, this system will not lend itself for serious penetration into the extreme speed range of the "Century Series" fighters because of both magnitude and duration of g forces. However, an aerodynamically clean configuration as presented by an ogive type capsule would reduce the relative magnitude of C_D by a factor of as much as 4 or 5. The value of ($C_D A/w$) for the capsule would be such as to reduce the maximum linear deceleration by sufficient magnitude so that the duration of g forces would be insignificant relative to human tolerance. The aerodynamically clean capsule type of escape system could extend into and beyond the extreme speed range capability of the "Century Series" fighters and still not trespass human tolerance either in magnitude or duration of g forces.

3. SUMMARY

3.1 The information presented by this study may be summarized as follows for the conventional ejection seat system:

3.1.1 The maximum linear deceleration is essentially constant for a given calibrated airspeed regardless of altitude.

3.1.2 At constant calibrated airspeed the rate of tumbling increases with altitude and approaches a value proportional to the inverse of the square root of the density ratio.

3.1.3 At constant calibrated airspeed the duration of g forces is approximately proportional to the inverse of the square root of the density ratio.

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3.1.4 The maximum linear deceleration forces increase as the 2.47 power of the velocity.

3.1.5 The maximum linear deceleration rapidly approaches the limit of human tolerance as the speed of the aircraft at time of ejection is increased above 550 knots calibrated airspeed.

3.2 The aerodynamic and physical characteristics defined by the parameter (C_D $A\!/_W$) are such as to limit the usefulness of the conventional ejection seat system to the lower part of the speed range of the "Century Series" fighter. Only by optimization of these parameters, such as may be obtained by the use of a low drag capsule, can successful escape be expected in the extreme speed range capability of the "Century Series" aircraft and beyond.

Publication Review

This report has been reviewed and is approved.

Frederick Harris

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Chief, Plans Office
Directorate of Research

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2. Henry, J. P., Studies of the Physiology of Negative Acceleration. AF Technical Report Nr 5953, Oct 1950.

3. Savely, H. E., The Physiology of Escape. Paper presented at Symposium on Escape from High Performance Aircraft, ████t 55 (To be published)

4. Edelberg, R., Hydrostatic Effects of Combined Tumbling and Deceleration. Shock and Vibration Symposium, Supplement 22, 1955.
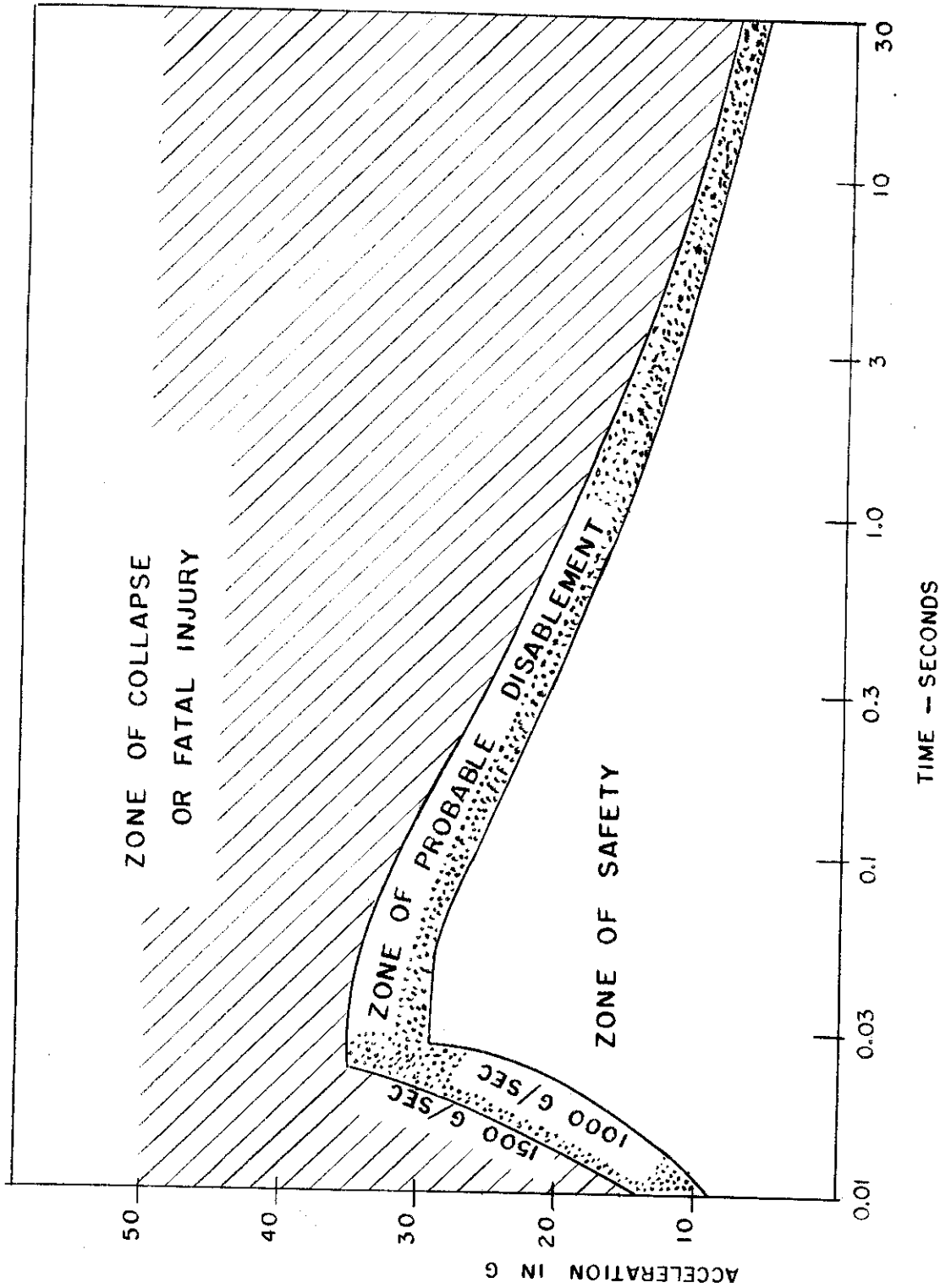
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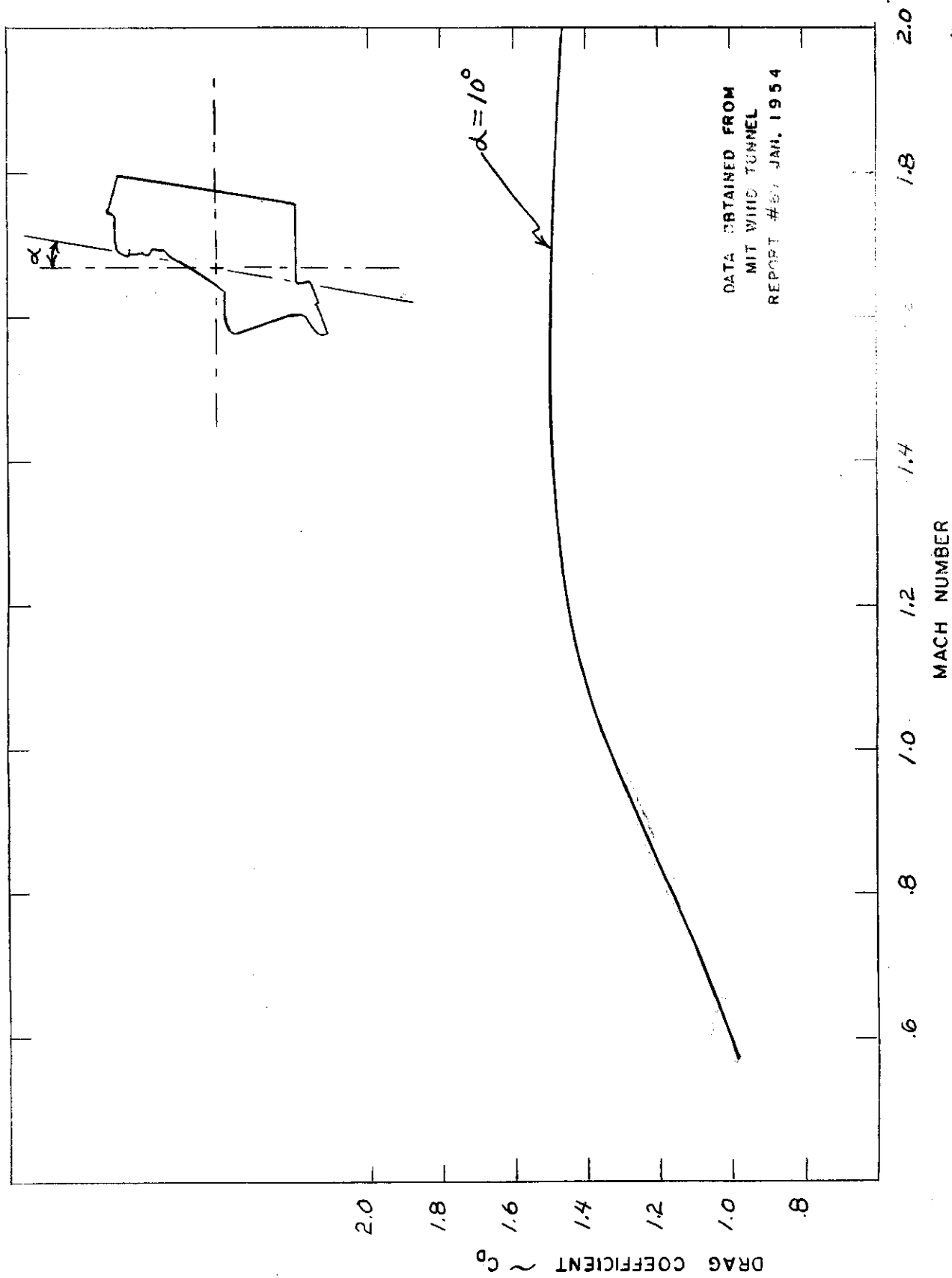Fig. 1. Limits of human tolerance for escape systems (Assuming transverse g in a stable system)
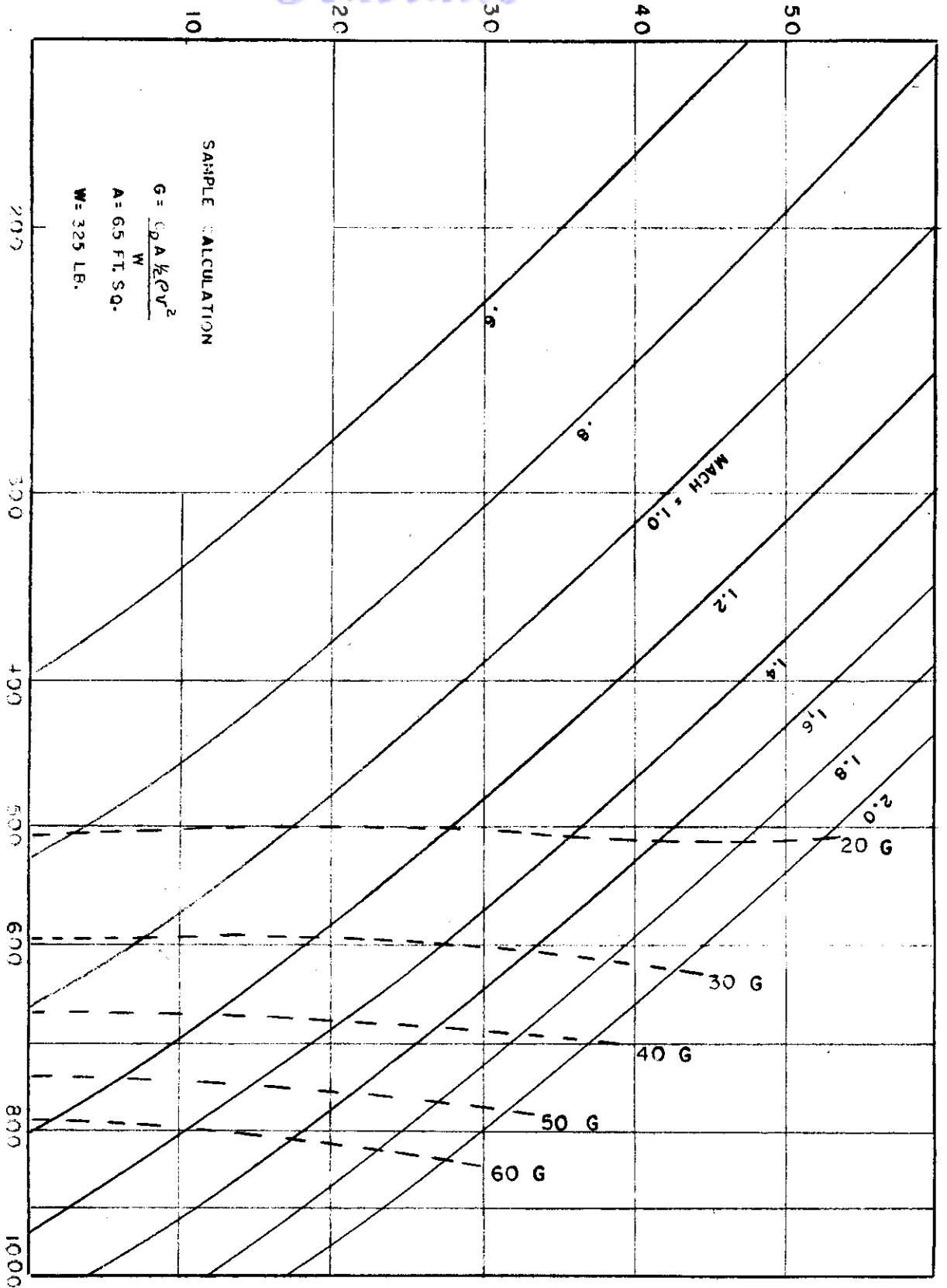
Fig. 2. Drag characteristics for conventional man-seat ejection seat

SAMPLE CALCULATION

$$G = \frac{C_D A \tfrac{1}{2} \rho v^2}{W}$$

A = 65 FT. SQ.

W = 325 LB.

MACH = 1.0

.9

.8

1.2

1.4

1.6

1.8

2.0

20 G

30 G

40 G

50 G

60 G

CALIBRATED AIRSPEED — KNOTS

Fig. 3. Magnitude of g force as a function of calibrated airspeed, altitude, and Mach number.
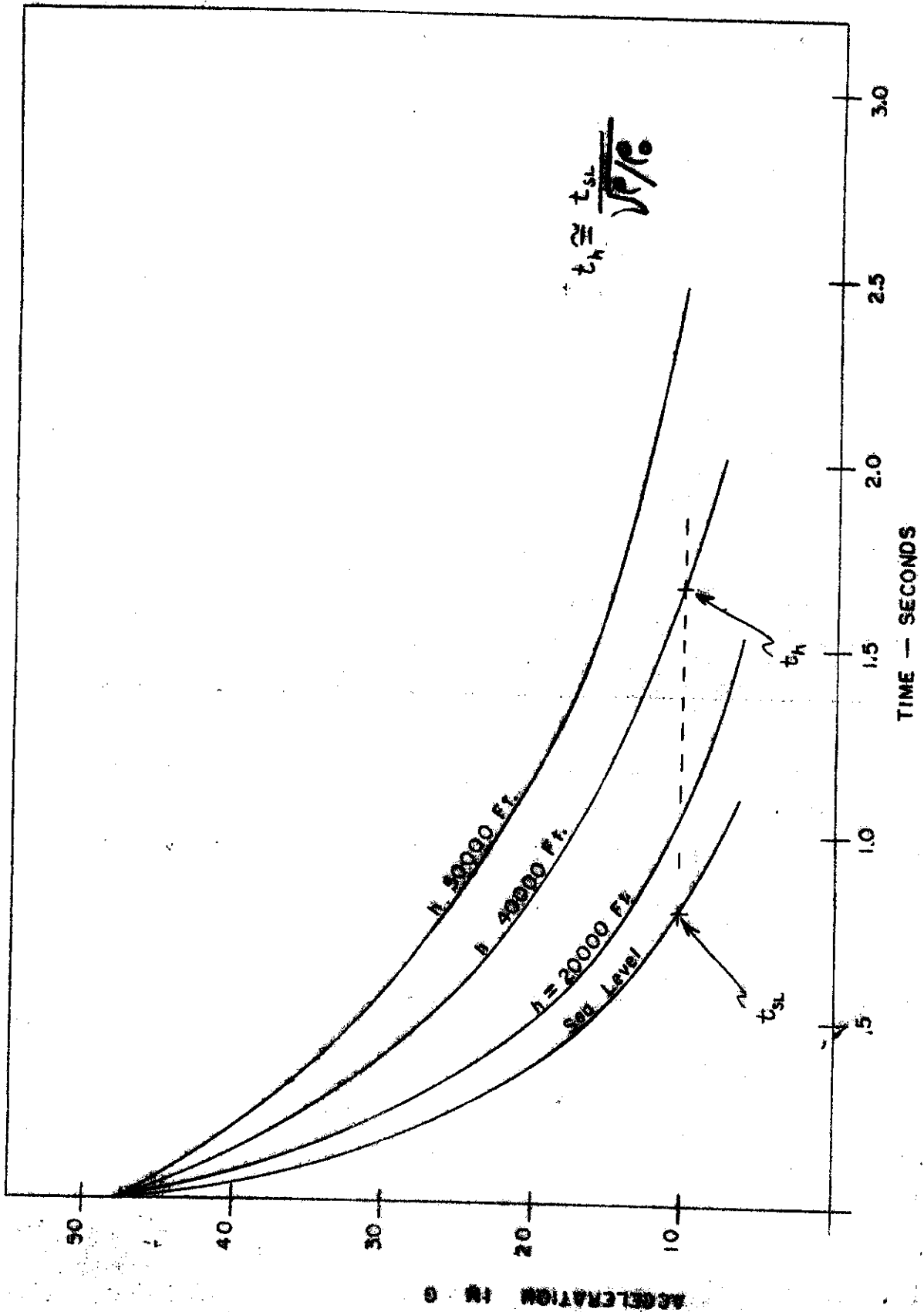
Fig. 4. Decay of deceleration as a function of altitude.
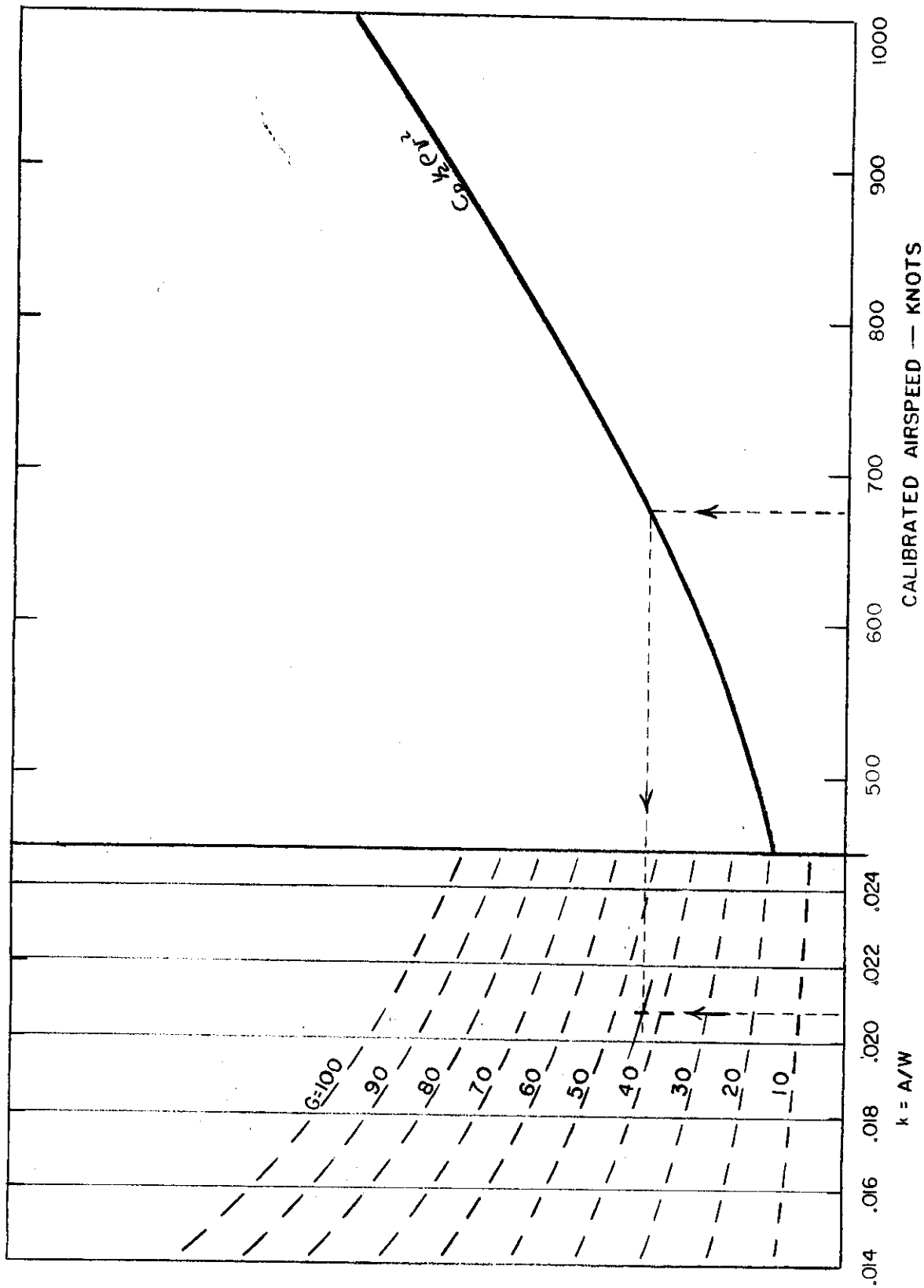
$$t_h \cong \frac{t_{sL}}{\sqrt{\rho/\rho_o}}$$

ACCELERATION IN G

TIME — SECONDS

h 50000 Ft.

h 40000 Ft.

h = 20000 Ft.

Sea Level

t_h

t_{sL}

Fig. 5. Linear deceleration as a function of airspeed showing effect of variation of k = A/W.

LINEAR DECELERATION — G

CALIBRATED AIRSPEED — KNOTS

CORRESPONDING G
FOR CENTURY SERIES
SPEED CAPABILITY

$$G = K\left(\frac{V}{100}\right)^{2.47}$$

2.47

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SPEED
CAPABILITY
CENTURY
SERIES
FIGHTERS

Fig. 6. Linear deceleration as a function of c librated airspeed.