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REPORT NO. 1349

DETERMINATION OF PERFORMANCE PARAMETERS FOR
FIN-STABILIZED FREE-FLIGHT MISSILES

by

Robert F. Lieske
Joseph W. Kochenderfer

December 1966

U. S. ARMY MATERIEL COMMAND
BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

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REPORT NO. 1349

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DETERMINATION OF PERFORMANCE PARAMETERS FOR
FIN-STABILIZED FREE-FLIGHT MISSILES

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REPORT NO. 1349

RFLieske/JWKochenderfer/bg
Aberdeen Proving Ground, Md.
December 1966

DETERMINATION OF PERFORMANCE PARAMETERS FOR FIN-STABILIZED FREE-FLIGHT MISSILES

ABSTRACT

The methods used by the Firing Tables Branch for the analysis of flight tests of fin-stabilized, free-flight missiles are outlined. Examples of obtaining thrust and aerodynamic drag from reduction of camera data with the aid of high speed computers are given. Determination of various performance parameters needed for the construction of firing tables is explained; some typical results are presented.

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TABLE OF SYMBOLS

Term	Definition	Unit
A_e	Area of jet exit	ft^2
AZ	Azimuth of line of fire (clockwise from North)	deg
$B(t)$	Transverse moment of inertia at time t	$lbm\text{-}ft^2$
C	Ballistic coefficient	lbm/in^2
d	Reference diameter of missile	ft
$\vec{E}$	Position of the missile with respect to spherical Earth surface	ft
F	Deceleration due to friction	ft/sec^2
$\vec{g}$	Acceleration vector due to gravity	ft/sec^2
g_0	Acceleration due to gravity (surface)	ft/sec^2
g_c	Constant used in the conversion of $lbf\text{-}sec^2/ft$ to lbm	$lbm\text{-}ft/lbf\text{-}sec^2$
$\vec{h}$	Angular momentum divided by $B(t)$	rad/sec
$h_{2\ell}$	h_2 at end of launch (t_ℓ)	rad/sec
$h_{3\ell}$	h_3 at end of launch (t_ℓ)	rad/sec
$\vec{H}$	Total angular momentum	$lbm\text{-}ft^2\text{-}rad/sec$
$\dot{\vec{H}}$	Rate of change of H	$lbm\text{-}ft^2\text{-}rad/sec^2$
I_{SP}	Specific impulse per unit of fuel mass	$lbf\text{-}sec/lbm$
I_{ST}	Total impulse at standard conditions	$lbf\text{-}sec$
K_D	Effective drag force coefficient	————
K_{D_B}	Drag force coefficient during thrust-on	————
K_{D_0}	Zero yaw drag force coefficient	————
K_{D_α}	Yaw drag force coefficient	$1/rad^2$
K_H	Damping moment coefficient	————

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TABLE OF SYMBOLS (Contd)

Term	Definition	Unit
K_L	Lift force coefficient	————
K_M	Overturning moment coefficient	————
K_S	Pitching force coefficient	————
L	Latitude of launch point	deg
m	Mass of missile	lbm
m (t)	Mass of missile at time t	lbm
$m_{t_{BST}}$	Mass of missile at end of thrust-on phase at standard conditions	lbm
m_f	Mass of fuel	lbm
$m_{f_{ST}}$	Mass of fuel at standard conditions	lbm
$\dot{m}$ (t)	Rate of change of mass at time t	lbm/sec
P_a	Static atmospheric pressure	lbf/ft²
P_e	Jet pressure at nozzle exit	lbf/ft²
PE	Probable error	————
PT	Propellant temperature	°F
QE	Quadrant elevation	m
r	Distance between center of Earth and projectile	ft
r_e	Distance from CG of missile to nozzle exit	ft
r_t	Distance from CG of missile to nozzle throat	ft
R	Radius of Earth	ft
t	Time	sec
t_B	Motor burnout time	sec
t_{BM}	Time from motor ignition until first motion	sec
t_{BMST}	Time from motor ignition until first motion at standard conditions	sec

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TABLE OF SYMBOLS (Contd)

Term	Definition	Unit
t_{BST}	Motor burnout time at standard conditions	sec
T	Thrust	lbf
T^*	Effective thrust	lbf
T_F	Thrust factor	————
$T_R(t)$	Thrust produced by motor at time t	lbf
$\vec{u}$	Velocity of missile with respect to ground	ft/sec
$\dot{\vec{u}}$	Acceleration of missile with respect to ground	ft/sec²
$\vec{v}$	Velocity of missile with respect to air	ft/sec
$\vec{w}$	Velocity of air with respect to ground	ft/sec
$\vec{x}$	Unit vector along longitudinal axis of missile	————
$\dot{\vec{x}}$	Rate of change of $\underline{x}$	rad/sec
$\vec{X}$	Position of missile with respect to ground-fixed coordinate system	ft
α	Yaw of missile	deg
$\vec{\Lambda}$	Coriolis acceleration due to rotation of Earth	ft/sec²
ρ	Air density (varies with altitude)	lbm/ft³
ϕ	Angle of elevation of launch	deg
Ω	Angular velocity of the Earth	rad/sec
.	Dot – when superscripted, eg. $\dot{u}$, denotes first derivative as a funtion of time – when appearing between vectors, eg $\underline{v} \cdot \underline{x}$, denotes a dot product	
×	Denotes cross product of vectors	

INTRODUCTION

The purpose of this report is to describe the methods used by the Ballistic Research Laboratories in determining performance parameters for fin-stabilized, free-flight missiles for use in generating firing tables. The work presented herein is derived from a simplified version of a general rigid body mathematical model described in BRL Report No. 1244.[1]*

FREE-FLIGHT MISSILE TEST PROGRAM

A firing program for production missiles is designed to determine the performance of a free-flight missile system. This program, or matrix, outlines the specific conditions of quadrant elevation (QE) and propellant temperature (PT) under which the rounds are fired. A typical matrix defining a test program is shown below.

Number of Missiles

QE (m)	PT (°F) −40	20	77	120
100	4	4	4	4
200	4	4	4	4
400	4	4	4	4
800	4	4	4	4

This array permits determination of motor performance as a function of propellant temperature, and launcher-missile performance as a function of quadrant elevation. The missiles are fired singly from at least two launchers.

The following data are collected for each round.

1. Missile pre-flight measurements
   a. Weight of components
   b. Center of gravity, with and without propellant
   c. Moment of inertia, with and without propellant

---

* *Superscript numbers denote references which may be found on page 29.*

d. Propellant temperature

e. Fuze setting

f. Warhead type

2. Missile in-flight measurements

   a. Positions, velocities, and accelerations from camera data

       (1) From ignition to clear of launcher at 100 frames per second

       (2) From launcher to point beyond maximum velocity at 30 frames per second

       (3) From maximum velocity to terminal event at 5 frames per second

   b. Roll data

3. Missile post-flight measurements

   a. Position of impact (range, height and deflection)

   b. Time of impact

4. Launcher measurements

   a. Tactical emplacement, before and after firing

   b. Quadrant elevation, before and after firing

   c. Azimuth of fire, before and after firing

   d. Survey of position, before and after firing

   e. Type and serial number

5. Meteorological measurements

   a. Winds

       (1) Recorded at five-second intervals at the launch site before, during, and after firing from 0 to 100 feet above the launcher

       (2) By balloon at a location and time as close to the launch site and firing time as possible

            (a) From 0 to 1000 feet above the launcher recorded at thirty-second intervals during ascent

            (b) From surface to a height greater than the expected maximum ordinate of the missile recorded at sixty-second intervals during ascent

   b. Atmospheric data (pressure, temperature and density)

       (1) At the launch site at the time of fire

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(2) By balloon at a location and time as close to the launch site and firing time as possible from surface to a height greater than the expected maximum ordinate of the missile recorded at sixty-second intervals during ascent.

REDUCTION OF FLIGHT TEST DATA FOR DRAG COEFFICIENT (K_D) AND THRUST (T) FORCES

The drag force and ultimately the drag coefficient and the thrust forces are determined by an inverse solution of the point-mass differential equations of motion. The drag force is obtained from the free-flight portion of the trajectory, and the thrust force is found from the boost phase. Two assumptions are made to carry out the latter phase.

1. The drag force during boost is small in comparison to the thrust force and is the same as that found for free-flight with estimated changes to the drag force to account for the presence of the jet.

2. An initial thrust curve is assumed along with the following equation to determine the mass flow rate.

$$(1.1) \quad \dot{m}(t) = -T_R(t)/I_{SP},$$

where

$\dot{m}(t)$ = Rate of change of mass at time t ,

$T_R(t)$ = Thrust produced by motor at time t and

I_{SP} = Specific impulse per unit of fuel mass.

The equations used for the determination of the drag and thrust forces are

$$(1.2) \quad K_D = -[(u_1 - w_1)(\dot{u}_1 + g_1 + \Lambda_1) + u_2(\dot{u}_2 + g_2 + \Lambda_2)$$
$$+ (u_3 - w_3)(\dot{u}_3 + g_3 + \Lambda_3)] \, m/\rho \, d^2 \, v^2 \quad \text{and}$$

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(1.3) $T = \{ [(u_1 - w_1)(\dot{u}_1 + g_1 + \Lambda_1) + u_2(\dot{u}_2 + g_2 + \Lambda_2) + (u_3 - w_3)$

$$(\dot{u}_3 + g_3 + \Lambda_3)] \, m(t)/g_c \, v + (\rho \, d^2 \, v^2/g_c) \, K_{D_B}$$

$$- (P_e - P_a) \, A_e \} \, (m_{f_{ST}}/m_f).$$

The approximation of the force of gravity is

(1.4) $\quad \underset{\sim}{g} = \left(-g_0 R^2/r^3\right) \begin{bmatrix} X_1 \\ X_2 + R \\ X_3 \end{bmatrix}$,

where $\quad r = [X_1^2 + (X_2 + R)^2 + X_3^2]^{\frac{1}{2}}$,

$g_0 = $ Value of gravity at point of launch,

$r = $ Distance between center of Earth and projectile,

$R = $ Radius of Earth, and

$X = $ Position of missile with respect to ground-fixed coordinate system .

The Coriolis acceleration due to rotation of the Earth is

(1.5) $\quad \underset{\rightarrow}{\Lambda} = \begin{bmatrix} -\lambda_1 \, u_2 - \lambda_2 \, u_3 \\ \lambda_1 \, u_1 + \lambda_3 \, u_3 \\ \lambda_2 \, u_1 - \lambda_3 \, u_2 \end{bmatrix}$.

For the Northern Hemisphere the λ's are defined by the following equations [for the Southern Hemisphere replace L by (-L)]:

$\lambda_1 \quad = \quad 2\,\Omega \cos L \sin AZ,$

$\lambda_2 \quad = \quad 2\,\Omega \sin L \text{ and}$

$\lambda_3 \quad = \quad 2\,\Omega \cos L \cos AZ,$

where $\quad AZ = $ Azimuth of line of fire (clockwise from North) ,

$L \quad = \quad$ Latitude of launch point and

$\Omega \quad = \quad$ Angular velocity of the Earth.

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The mass of the individual missile, the atmospheric conditions at time of firing and the reduced camera data provide the necessary inputs to solve Equations (1.2) and (1.3) for drag and thrust. Examples of the results of this method of reduction are presented as Figures 1 and 2.

The thrust-time history of a rocket motor as a function of propellant temperature is obtained by assuming a linear transformation of the standard propellant temperature thrust curve in time.
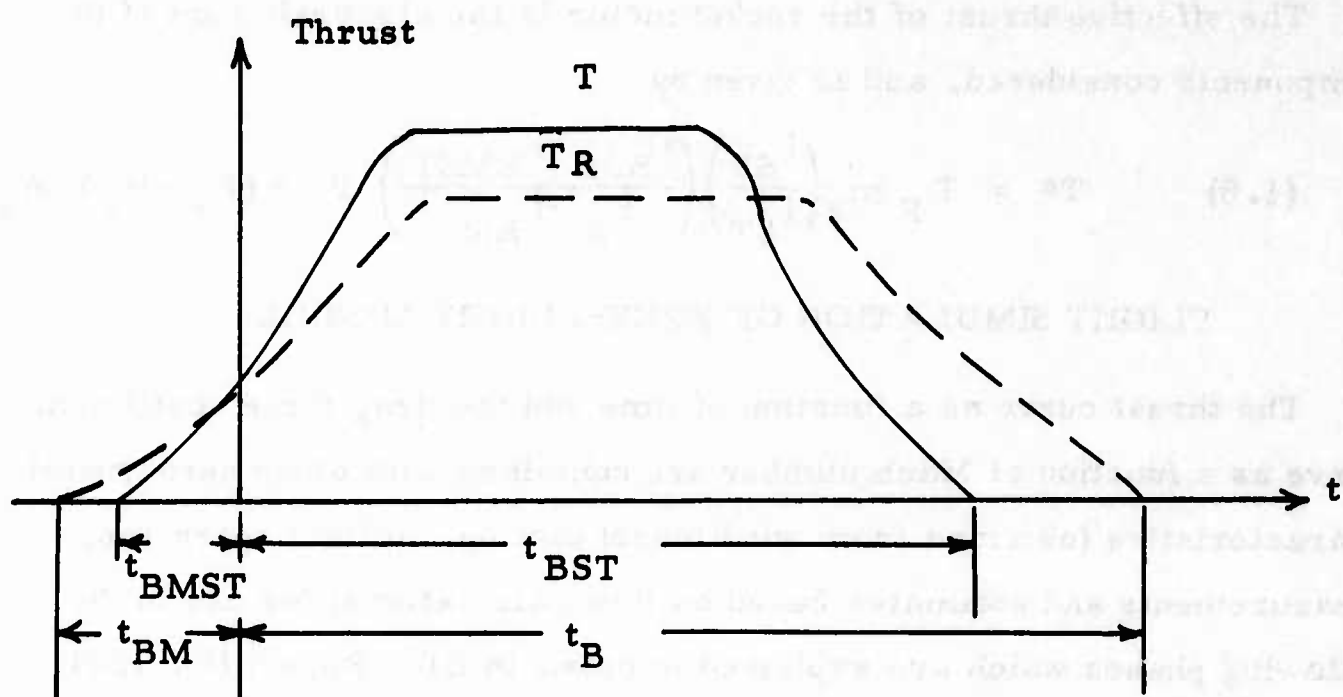
Let

$$(1.6) \quad T = f \left[(t - t_{BM}) \left(\frac{t_{BST} - t_{BMST}}{t_B - t_{BM}} \right) + t_{BMST} \right],$$

where   f [ ] indicates " a function of "

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The thrust of the rocket motor as a function of time may be linearly transformed, maintaining the same total impulse, by the following equation:

$$(1.7) \qquad T_R = m_f \left(\frac{I_{SP}}{I_{ST}}\right) \left(\frac{t_{BST} - t_{BMST}}{t_B - t_{BM}}\right) T.$$

The force due to jet pressure at the rocket nozzle is given by $P_e A_e$. The static atmospheric pressure produces a force equal to $-P_a A_e$. The total thrust contributed by pressure is then given by $(P_e - P_a) A_e$.

The effective thrust of the rocket motor is the algebraic sum of the components considered, and is given by

$$(1.8) \qquad T^* = T_F m_f \left(\frac{I_{SP}}{I_{ST}}\right) \left(\frac{t_{BST} - t_{BMST}}{t_B - t_{BM}}\right) T + (P_e - P_a) A_e.$$

FLIGHT SIMULATION OF FREE-FLIGHT MISSILES

The thrust curve as a function of time and the drag force coefficient curve as a function of Mach number are combined with other aerodynamic characteristics (obtained from wind tunnel testing, inflight spark range measurements and estimates based on flow calculations) for use in the following phases which are explained in detail in BRL Report No. 1244:[1]

1. Launching phase

$$(2.1) \quad \dot{\underset{\rightarrow}{u}} = \begin{bmatrix} \dfrac{g_c T^*}{m(t)} \cos \phi \quad \dfrac{-\rho d^2}{m(t)} K_{D_B} v^2 \cos \phi \\[2mm] - g_0 \sin \phi \cos \phi - F \cos^2 \phi \\ \rule{5cm}{0.4pt} \\ \dfrac{g_c T^*}{m(t)} \sin \phi \quad \dfrac{-\rho d^2}{m(t)} K_{D_B} v^2 \sin \phi \\[2mm] - g_0 \sin^2 \phi - F \cos \phi \sin \phi \\ \rule{5cm}{0.4pt} \\ 0 \end{bmatrix} .$$

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2. Boost phase (rigid projectile)

(2.2) $\dot{\vec{u}} = -\dfrac{\rho d^2}{m(t)} (K_{D_B} + K_{D_\alpha} \alpha^2) v \vec{v} + \dfrac{\rho d^2}{m(t)} K_L [v^2 \vec{x} - (\vec{v} \cdot \vec{x}) \vec{v}]$

$\qquad + \dfrac{\rho d^3}{m(t) B(t)} K_S v (\vec{x} \times \vec{H}) + \vec{g} + \vec{\Lambda} + \dfrac{g_c T^*}{m(t)} \vec{x}$,

(2.3) $\dot{\vec{H}} = \rho d^3 K_M v (\vec{v} \times \vec{x}) + \dfrac{\rho d^4}{B(t)} K_H v [(\vec{H} \cdot \vec{x}) \vec{x} - \vec{H}]$

$\qquad + \dfrac{(\dot{m}(t) r_e r_t)}{B(t)} [\vec{H} - (\vec{H} \cdot \vec{x}) \vec{x}]$ and

(2.4) $\dot{\vec{x}} = (\vec{H} \times \vec{x})/B(t)$.

3. Free-flight phase (point mass)

(2.5) $\dot{\vec{u}} = -(\rho\, m_{t_{BST}}/144\, m\, C) v \vec{v} + \vec{g} + \vec{\Lambda}$,

(2.6) $\vec{X} = \int_0^t \vec{u} \, dt$ and

(2.7) $\qquad \vec{E} = \begin{bmatrix} X_1 \\ X_2 + R - (R^2 - X_1^2)^{\frac{1}{2}} \\ X_3 \end{bmatrix}$.

In the interest of economy, flight simulations are carried out by two distinct, but combined, phases. The boost portion is simulated by the use of the rigid-body model mentioned above, and the point-mass model is used in the free-flight phase. Since any initial yawing motion of a fin-stabilized, free-flight missile is essentially damped out by motor burnout time, no degradation of result occurs from simulation of the free-flight phase with a point-mass model.

Individual missile weights and measures and the atmospheric conditions at the time of firing are used by the simulator with certain chosen variables to match the flight of the missile at two key points along the trajectory. These key points are obtained by the camera instrumentation and are

1. Velocity vector at a time shortly after motor burnout and
2. Range and height of terminal event.

The velocity vector is matched iteratively by

1. A multiplier (T_F) on thrust applied to the thrust curve to obtain the magnitude of the velocity vector and
2. Initial angular velocities in the vertical $(h_{3\ell})$ and horizontal $(h_{2\ell})$ planes at the time of launch to match the total angle of the velocity vector. These are merely pseudo rates to enable the simulator to match the missile attitude.

The range is matched iteratively by the simulator through the use of an inverse multiplier (C) on the drag curve.

Some additional comparisons are made to determine exactness of the simulation. These are

1. Velocity at end of launch,
2. Position of missile at time of match of velocity vector,
3. Position of missile and velocity vector at a point approximately 2 seconds beyond time of match of velocity vector,
4. Position of missile and velocity vector near maximum ordinate, and
5. Deflection and time of flight at terminal event.

When these comparisons are made to the degree of accuracy desired, the following performance parameters for a free-flight missile are obtained:

1. Effective drag force coefficient as a function of Mach number as determined from the drag reduction. (Fig. 3)
2. Thrust as a function of time as determined from the thrust reduction. (Fig. 4)

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3. Burning time of motor as a function of propellant temperature as determined from the thrust reduction. (Fig. 5)

4. Thrust factor (T_F) as a function of propellant temperature.
   (Fig. 6) This represents the effect of propellant temperature on the total impulse of the rocket motor; therefore, the observed probable error in thrust factor is representative of the probable error in impulse.

5. Initial angular velocities (h_{2_ℓ} and h_{3_ℓ}) as functions of quadrant elevation. (Figs. 7 and 8)

6. Ballistic coefficient (C) as a function of quadrant elevation. (Fig. 9)

On Figures 6 through 9 the solid line indicates the mean performance values of the particular parameter; whereas, the dashed lines present an idea of the dispersion of that parameter.

CONCLUSION

The methods described above have been used successfully to describe the Littlejohn and Honest John flight performance and in preparing adequate firing tables for those weapon systems.

ROBERT F. LIESKE   JOSEPH W. KOCHENDERFER

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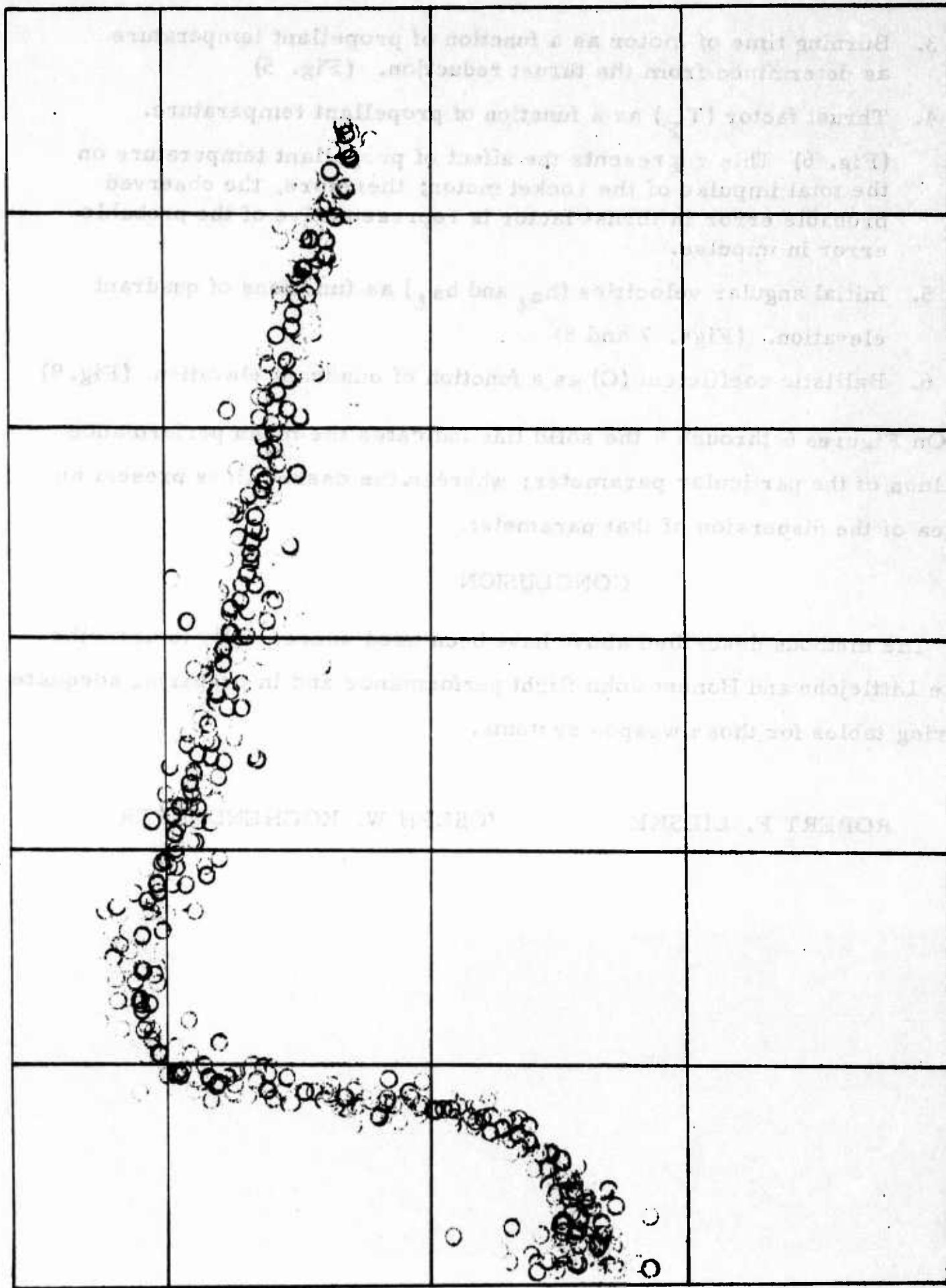Effective Drag Force Coefficient (K_D) vs Mach No.
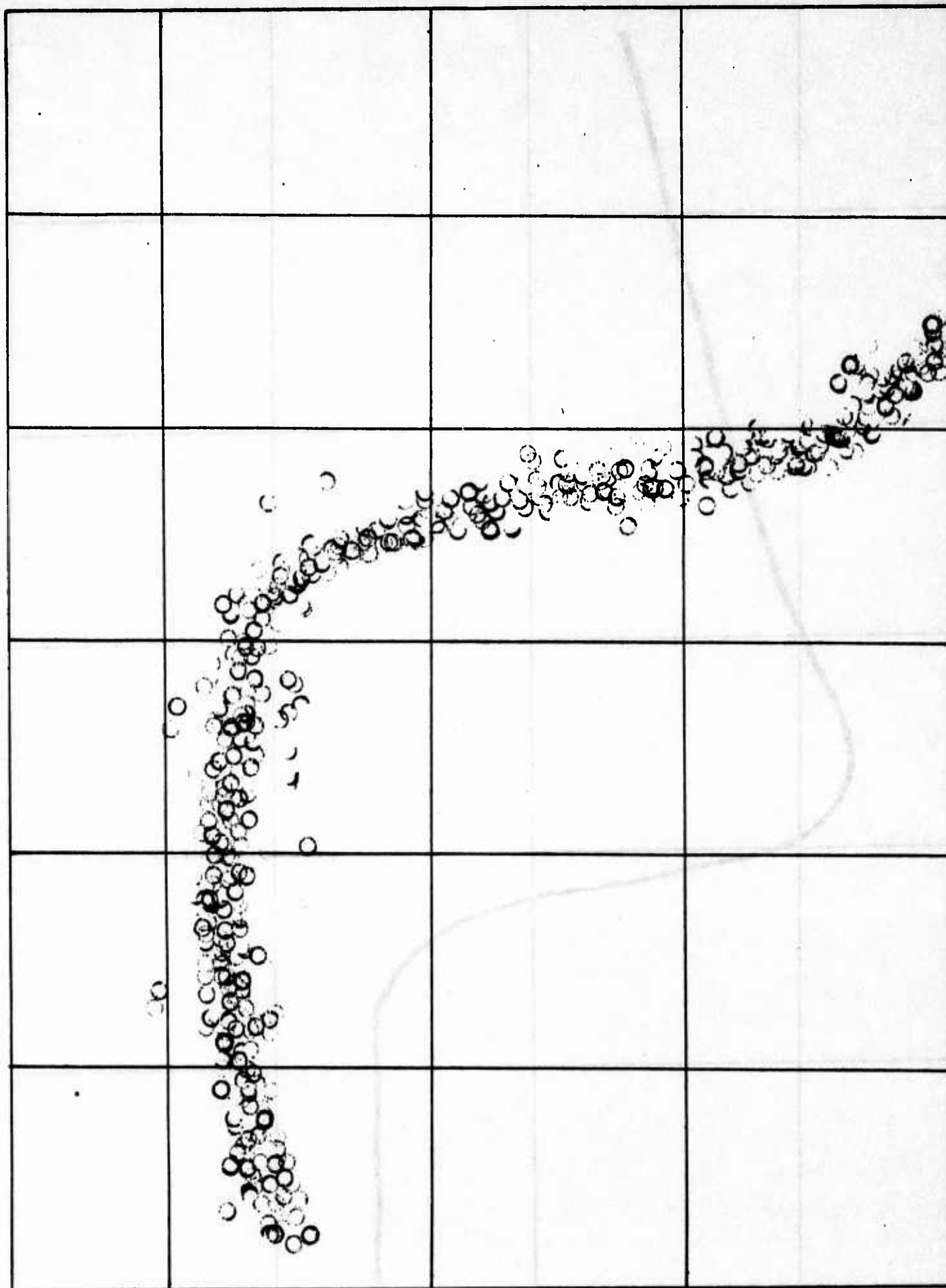
Figure 1

Mach No.

K_D

Thrust vs Time

Thrust

Time

Figure 2

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Drag Force Coefficient (K_{D_o}) vs Mach No.

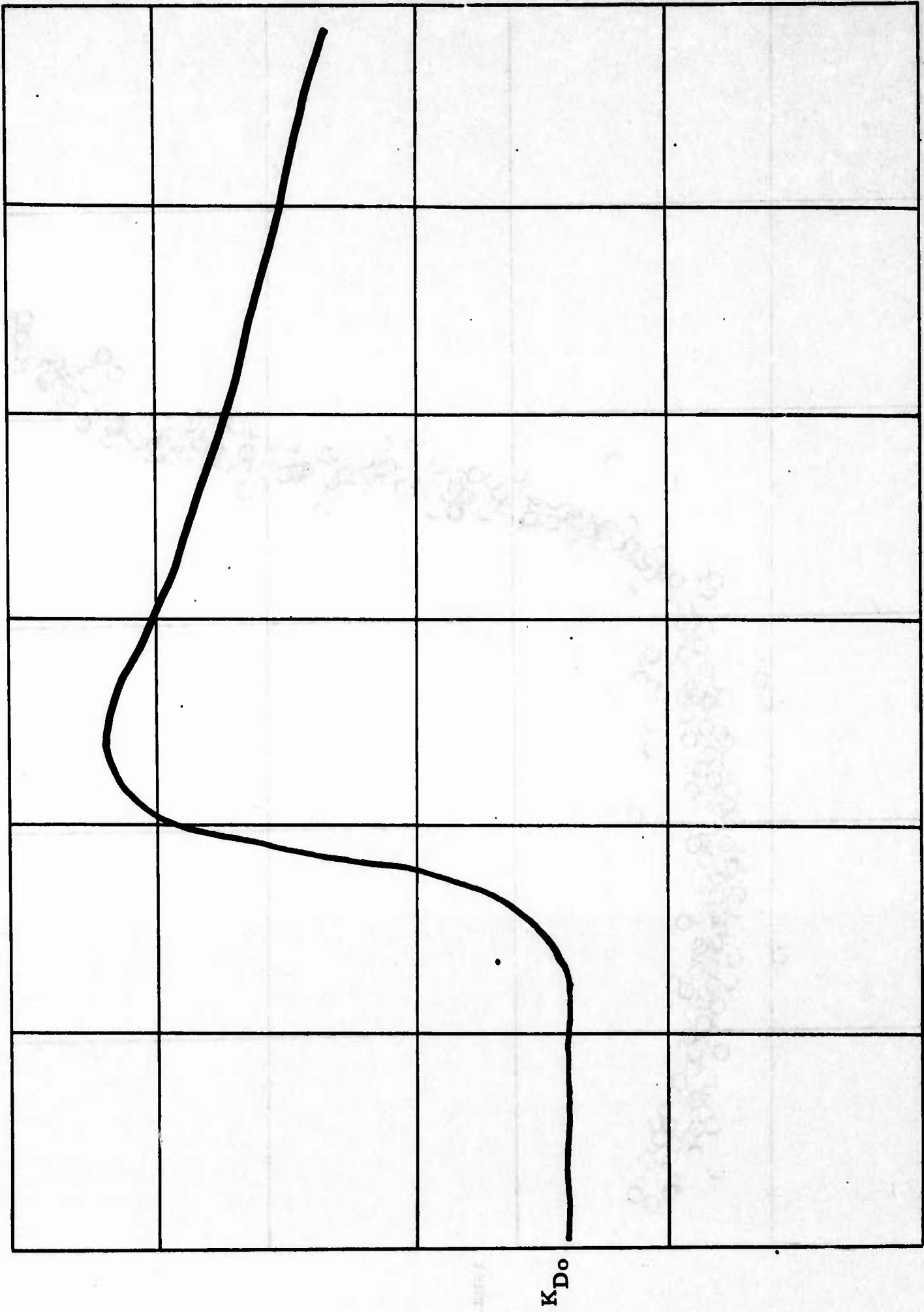K_{D_o}

Mach No.
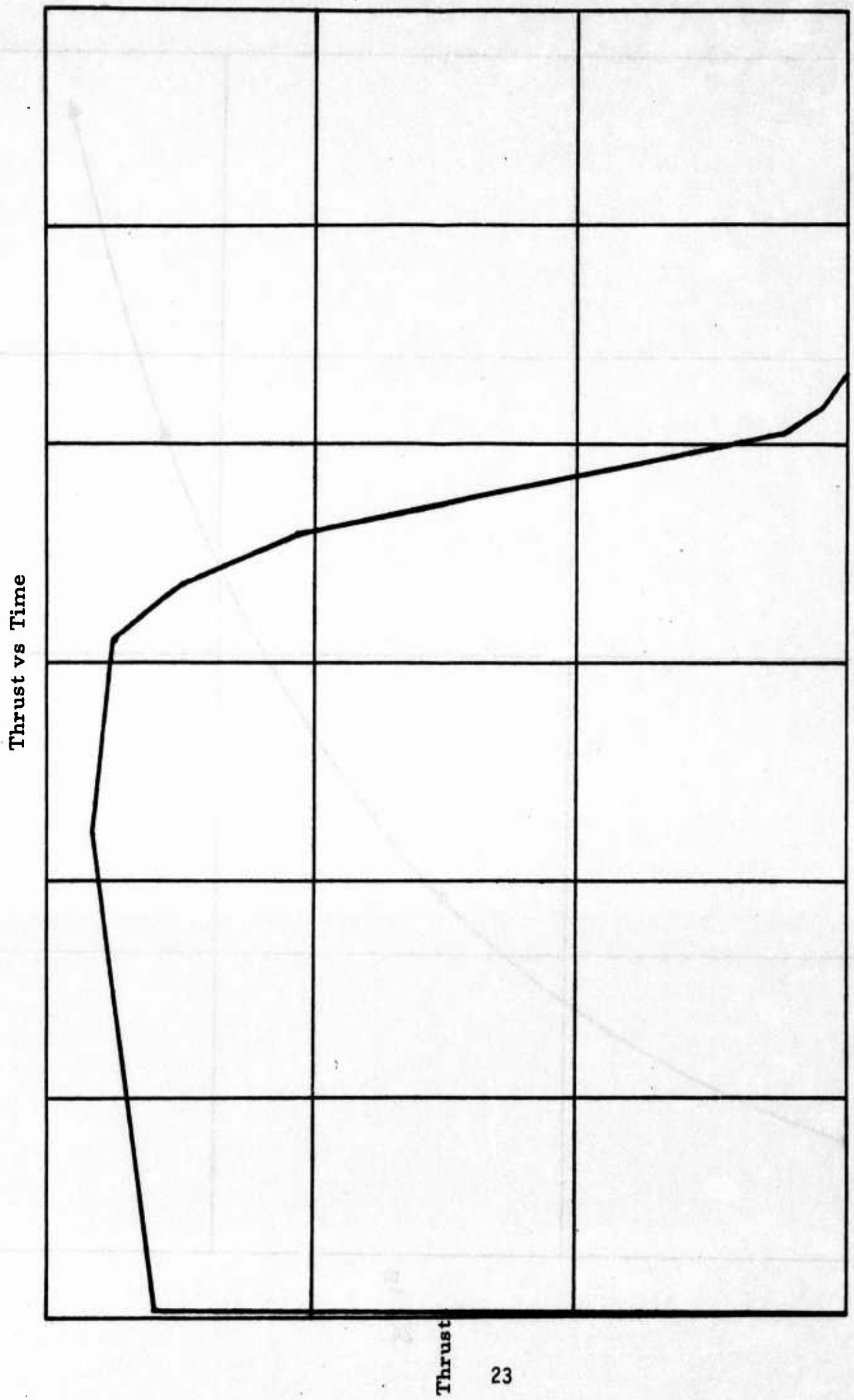
Figure 3

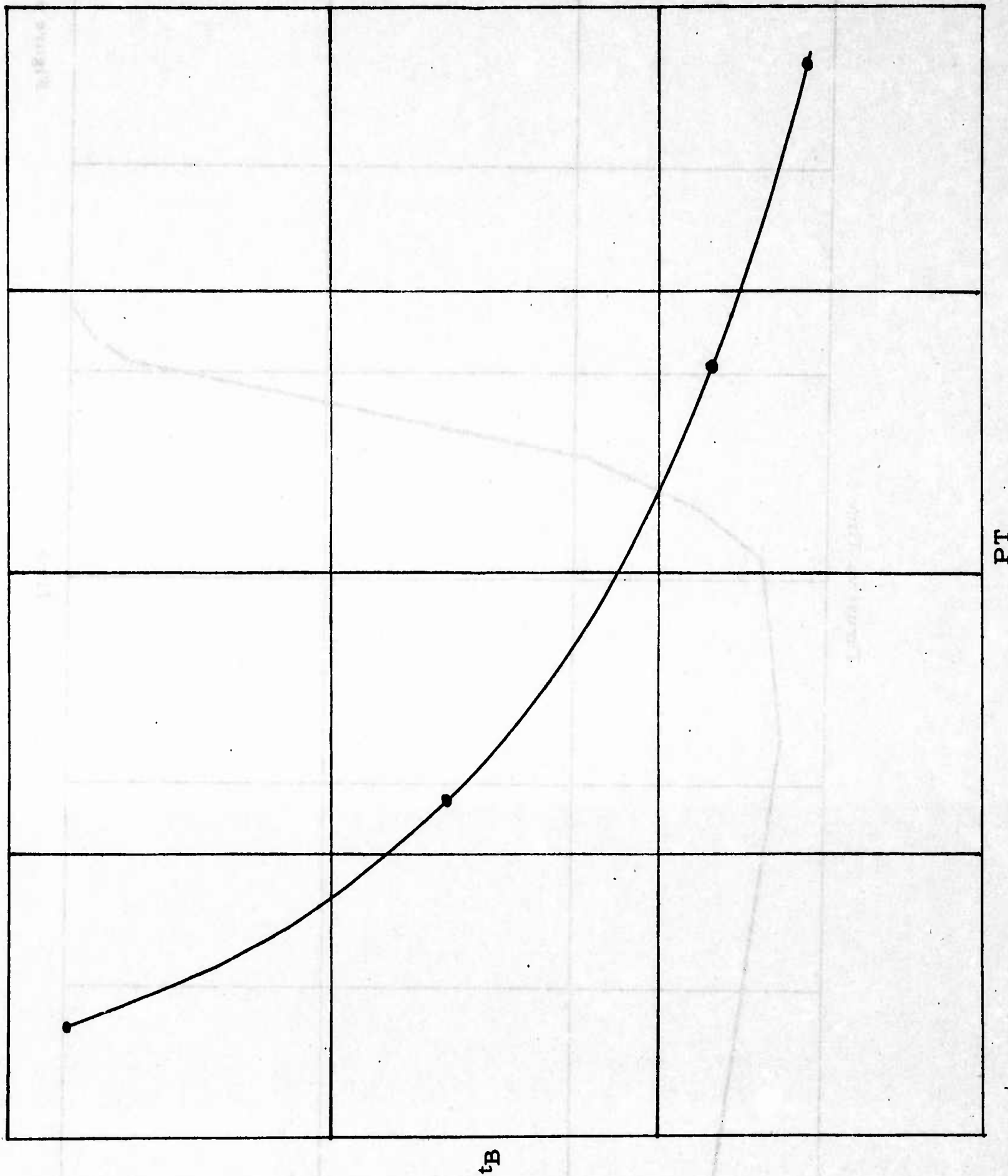22

Thrust vs Time

Thrust

Time

Figure 4

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Motor Burnout Time (t_B) vs Propellant Temperature (PT)

Figure 5
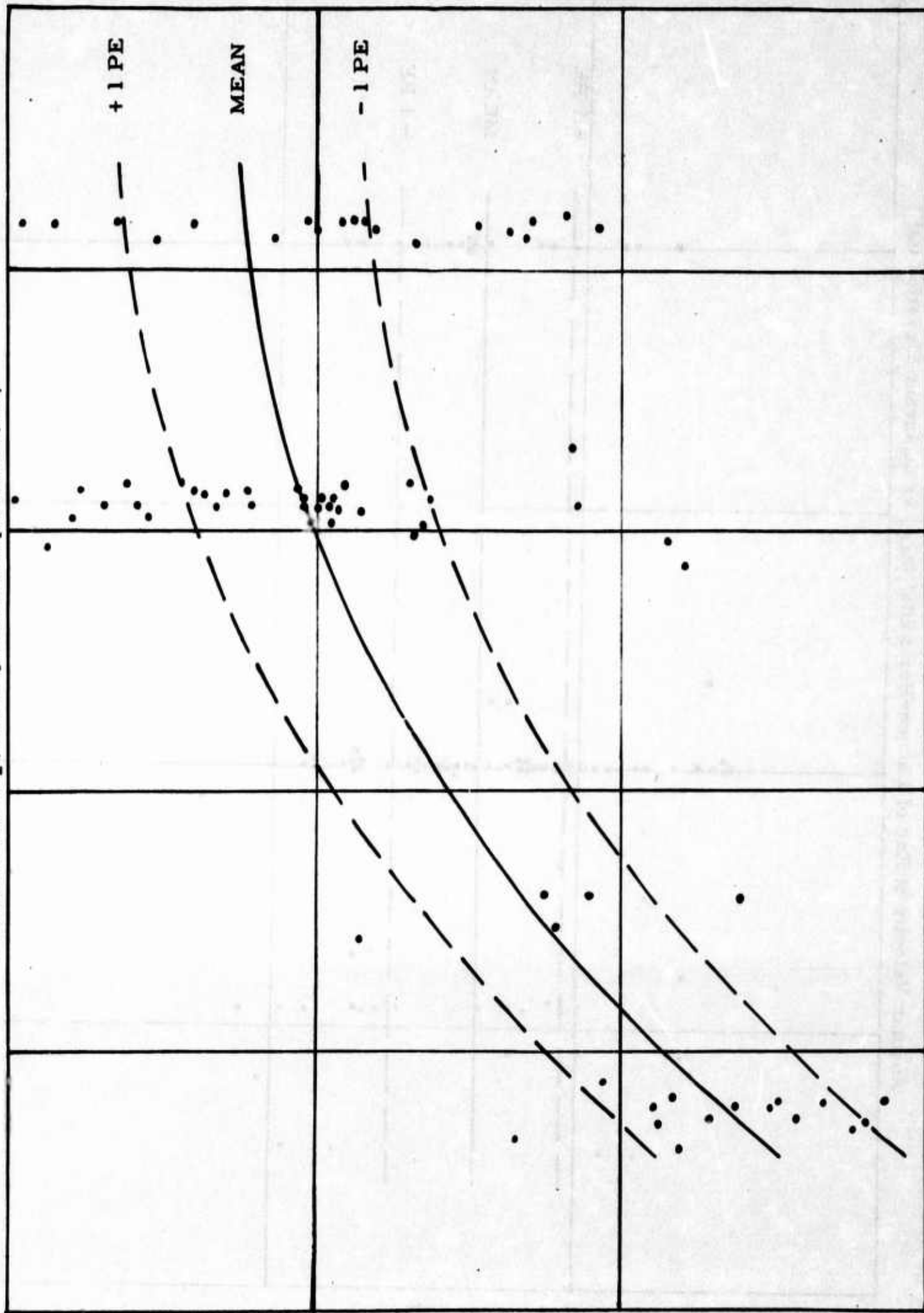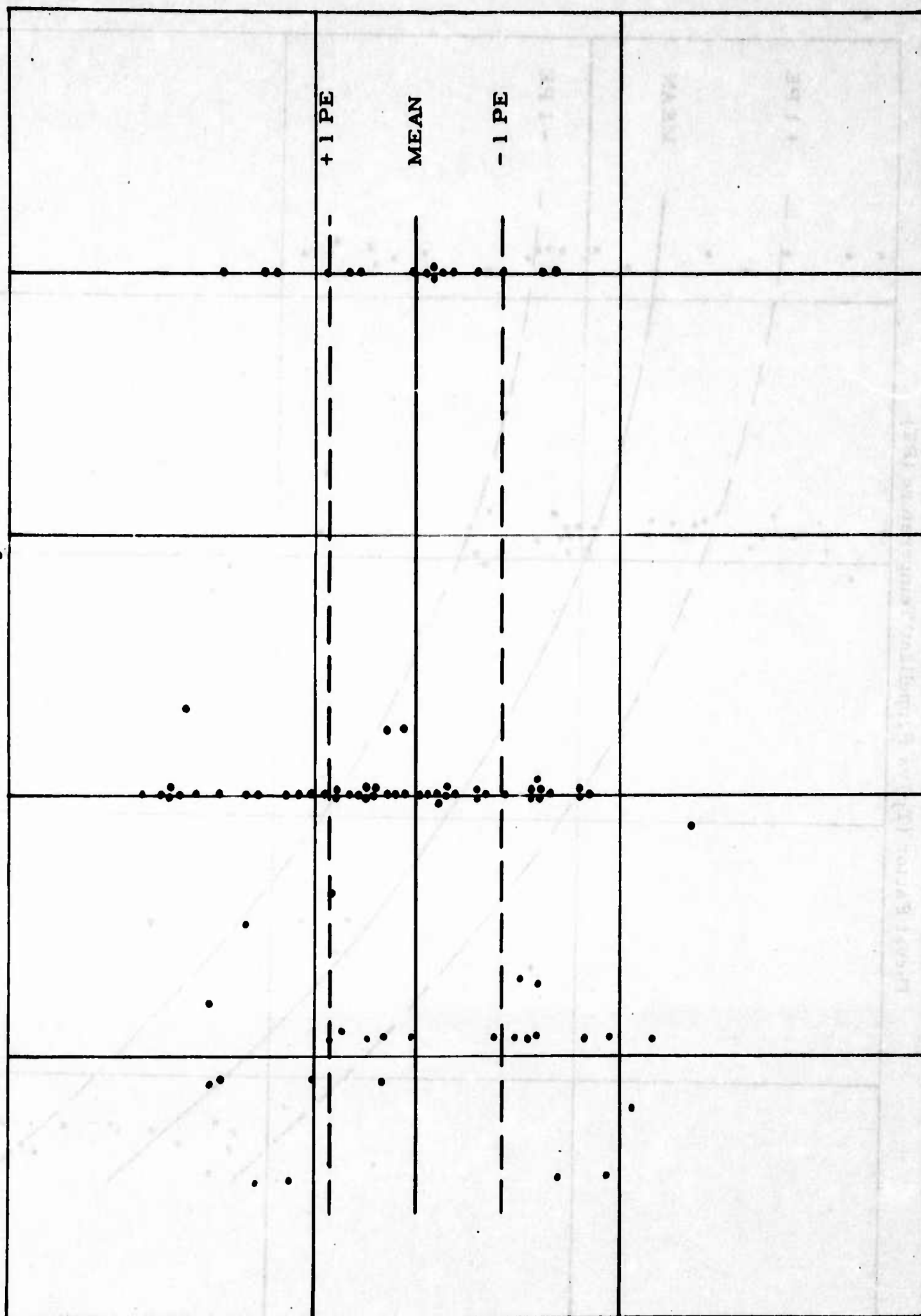
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Thrust Factor (T$_F$) vs Propellant Temperature (PT)

Figure 6

PT

T$_F$

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Angular Velocity at End of Launch-Horizontal ($h_{2\ell}$) vs Quadrant Elevation (QE)

+1 PE

MEAN

-1 PE

QE

$h_{2\ell}$

Figure 7

Angular Velocity at End of Launch–Vertical (h₃ℓ) vs Quadrant Elevation (QE)
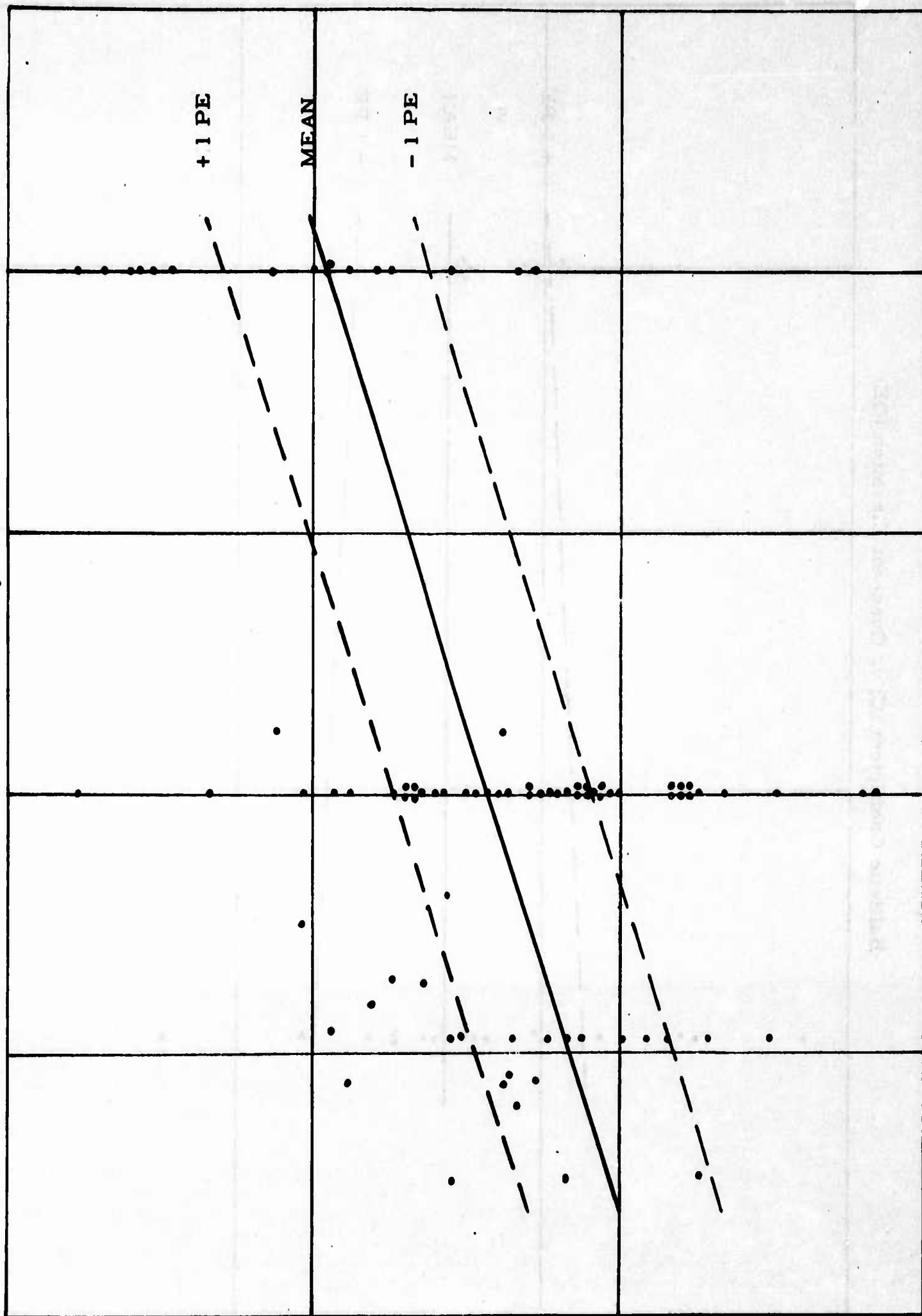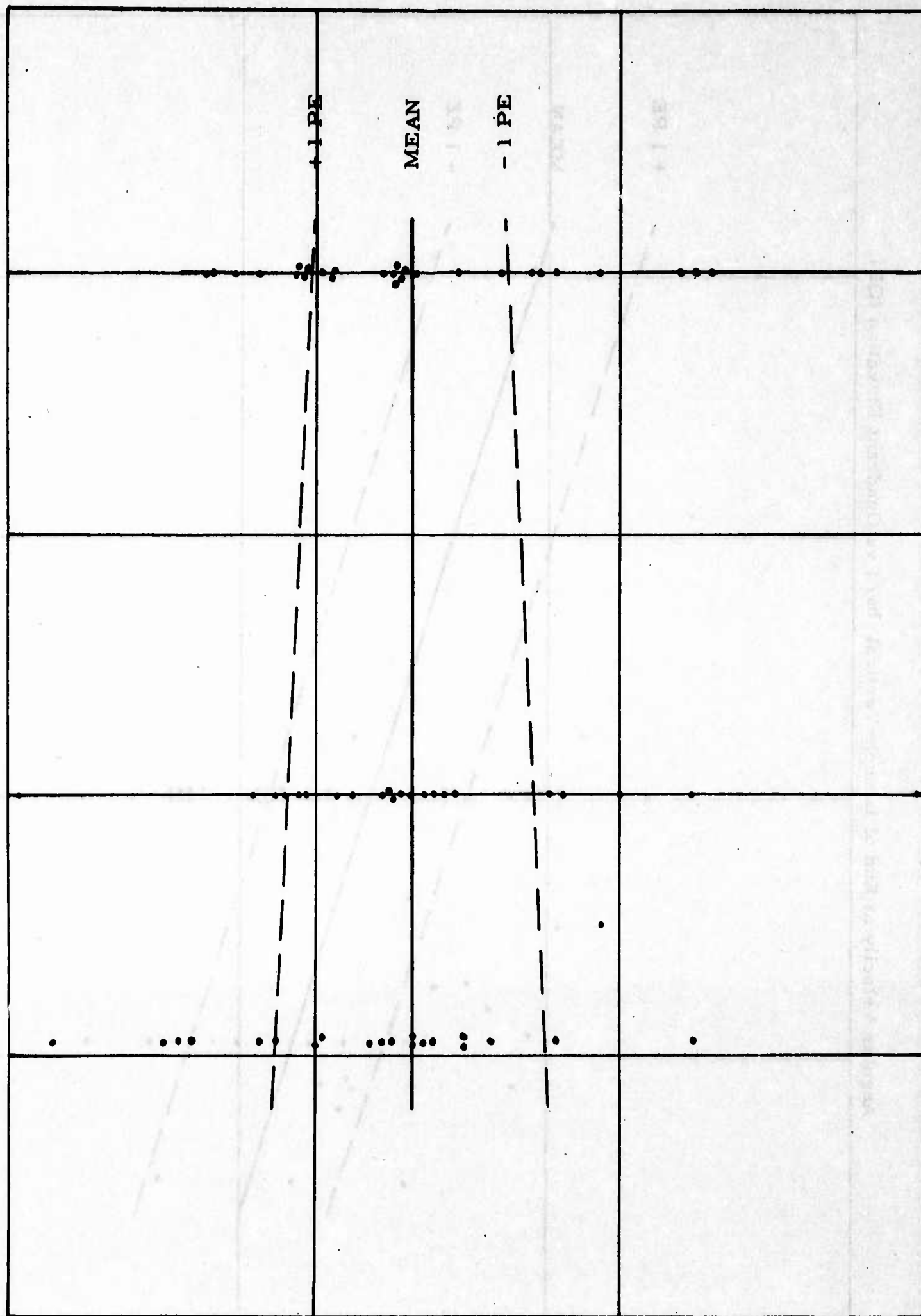
+1 PE

MEAN

−1 PE

QE

haℓ

Figure 8

Ballistic Coefficient (C) vs Quadrant Elevation (QE)

Figure 9

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REFERENCES

1. Lieske, R. F., and McCoy, R. L., Equations of Motion of a Rigid Projectile, BRL Report No. 1244, March 1964.

2. Rosser, B. J., Newton, R. R., and Gross, G. L. Mathematical Theory of Rocket Flight, New York and London, McGraw-Hill Book Company, Inc., 1947.

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   There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Idenfiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.