Copy No. 130

NASA PROGRAM APOLLO WORKING PAPER NO. 1203

HAZARDS ASSOCIATED WITH A LEM ABORT NEAR THE LUNAR SURFACE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

June 24, 1966

NASA PROGRAM APOLLO WORKING PAPER NO. 1203

HAZARDS ASSOCIATED WITH A LEM ABORT NEAR THE LUNAR SURFACE

Prepared by: Charles Teixeira

Charles Teixeira
AST, Mission Feasibility Branch

Authorized for Distribution:

Warren Gillespie, Jr.
for Maxime A. Faget
Director for Engineering and Development

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
June 24, 1966

CONTENTS

TABLES

FIGURES

HAZARDS ASSOCIATED WITH A LEM ABORT

NEAR THE LUNAR SURFACE

By Charles Teixeira

SUMMARY

A LEM abort near the lunar surface can be extremely hazardous during a portion of the descent due to the propellant remaining onboard the descent stage at staging. Subsequent impact of the descent stage with the lunar surface can rupture the propellant tanks prossibly resulting in propellant mixing and an explosion. Ensuing expansion of the products of detonation can result in high stagnation pressures and the ejection of a considerable number of fragments.

An indication of a malfunction requiring an immediate abort between 53.7 and 20.0 seconds of thrusting time until touchdown ($\approx$ 265 - 100 ft above lunar surface) will result in the ascent stage being subjected to pressures exceeding an assumed 5 psi pressure limit. An assumed probability of crew safety goal of .999 (entire flight) will be violated if an abort is performed between 65.0 and 20.0 seconds of thrusting time until touchdown (338-100 ft) due to the high probability of being hit by a fragment.

This exploratory study is intended to expose the possible hazards associated with an abort near the lunar surface. The advantages of a fuel dump in reducing or possibly eliminating the hazards are discussed.

INTRODUCTION

An abort during the final phase of the LEM's descent can involve hazards caused by the propellant onboard the descent stage when the stage impacts with the lunar surface. The hazards consist primarily of stagnation pressures and fragments. The purpose of the study was to define these hazards.

The procedure employed was to determine the ascent-descent stage separation at the time of the latter's impact with the lunar surface for various assumed malfunction times during a "nominal descent." The separations in conjunction with pressure-distance relationships enabled determination of the pressure experienced by the ascent stage as a function of the time of malfunction. An assumed pressure limit established the latest time a malfunction could be detected and not result in the assumed pressure limit being exceeded.

The probability of being hit by a fragment was determined on the basis of the ascent-descent stage separation in conjunction with the ratio of target to background area and the number of fragments anticipated.

SYMBOLS

a	=	acceleration, ft/sec^2
c	=	constant
A_{EFF}	=	effective area of target (ascent stage), ft^2
A_S	=	area of sphere of radius H ($= 4\pi H^2$), ft^2
g	=	gravitational acceleration (moon) = 5.14 ft/sec^2
H	=	ascent-descent stage separation at descent stage impact, ft
h	=	altitude above the lunar surface, ft
$\dot{h}$	=	vertical (descent) velocity, ft/sec
$\ddot{h}$	=	vertical acceleration, ft/sec^2
h_o	=	altitude at time of malfunction, ft
$\dot{h}_o$	=	vertical (descent) velocity at time of malfunction, ft/sec
$\dot{h}_1$	=	descent velocity at time of ascent-descent stage separation, ft/sec
K_1	=	cross sectional area of target, ft^2
K_2	=	perimeter of target, ft
K_3	=	surface area of donar, ft^2

m	=	mass, slugs
N	=	number of fragments
P_{CL}	=	probability of crew loss
P_{CS}	=	probability of crew safety (goal)
P_{EX}	=	probability of obtaining an explosion
P_{FAT}	=	probability that a hit by a fragment is fatal
P_{HIT}	=	probability of being hit by a fragment
P_S	=	stagnation pressure, psi
R	=	range, ft
R_o	=	range to intended landing point at time of malfunction
T	=	thrust, lbs
T_{GO}	=	thrusting time till touchdown, seconds
t	=	time, seconds
t_b	=	ascent stage engine burn time, seconds
t_d	=	staging time, time to detect failure, initiate an abort and achieve ascent-descent stage separation, seconds
t_H	=	time from abort initiation until descent stage impact, seconds
v_H	=	horizontal velocity, ft/sec
v_V	=	vertical velocity, ft/sec
W	=	weight, lbs
ρ	=	density, lbs/ft^3

DISCUSSION

A considerable quantity of hypergolic propellants (50-50 mixture of hydrazine and unsymmetrical dimethylhydrazine, nitrogen tetroxide oxidizer) will be onboard the descent stage at impact. Whether or not the propellant is released to the vacuum environment producing hazardous conditions depends on the severity of the stage's impact with the lunar surface.

Impact Conditions

The initiation of an abort will result in thrust termination of the descent engine and subsequent separation of the ascent and descent stages. The descent stage will follow a basically parabolic trajectory until impact with the lunar surface. The impact energy is a function of the initial conditions at staging which were determined from the "nominal" descent profile given in figures 1 through 4 (ref. 1) for the final 60 seconds ($\approx$ 305 ft) of descent. The impact energies are given in table I for staging times of 2.0 and 4.0 seconds.*

The high impact energies involved can be expected to result in severe structural damage to the descent stage for malfunction times of 20 seconds (until touchdown) or sooner. Even if the most liberal assumption were made, namely touchdown of the descent stage on its landing gear, the energies involved would be considerably above the gear's energy absorbing capability of approximately 20 000 ft-lbs/gear (design capability). (It is highly improbable that the stage will impact on its landing gear because of the angular rates which are likely to be induced at separation.) Consequently, for the purposes of this study, it was assumed that a malfunction requiring an abort at or before 20 seconds before touchdown ($\approx$ 100 ft) would result in sufficient structural damage to the descent stage to cause rupturing of the propellant tanks.

*The staging time (t_d) includes the time of detecting a failure, initiating an abort and achieving ascent-descent stage separation.

Propellant Hazards

The exposure of the hypergolic propellants to the vacuum environment will result in one of two possible events. Rapid boiling, evaporative cooling and freezing can occur at such a high rate that an explosive mixture cannot occur. This is particularly true if the propellant release is completely unconfined. If the propellants are released into a somewhat confined region, the evaporative cooling can suppress any immediate reaction and allow a detonable fuel-oxidizer mixture to accumulate. The latter situation can conceivably occur since the release will be caused by impact with the lunar surface and the surface together with the descent stage structure (debris) may provide the degree of confinement necessary to obtain an explosive mixture. It must be emphasized that a definite statement cannot be made concerning the possibility of obtaining an explosion due to the lack of data proving or disproving the possibility even under controlled conditions. In addition, there are the unknowns concerning the degree of confinement of the released propellants. For purposes of this study, it was assumed that an explosion would occur in order to consider what is presently believed to be a worst case.

Expansion of the products of detonation (or the hypergolic propellants themselves) to the vacuum environment can result in two basic hazards:

1. A gas "cloud" of high velocity and stagnation pressure

2. Tank and structural fragments as a result of the above.

Stagnation Pressures

Expansion of the products of detonation will be in the form of a gas "cloud". Any unreacted propellant will participate in the expansion in the form of crystalline particles. The influence of these crystalline particles on pressure, density, et cetera, are not known due to the lack of data and analytical techniques enabling its effects to be determined.

The expansion of the gas "cloud" will occur at high velocities (several thousand ft/sec) and will result in stagnation pressures $\left(P_s, \text{psi}\right)$ approximated by $\frac{1}{2} \rho V^2$ upon impingement on a surface normal to the flow. A surface parallel to the flow will not experience any pressure since the pressure arises solely from bringing the particles to rest.

The pressure exerted on a surface as a function of time will vary due to the changing cloud density. Analytical studies (refs. 2 and 3) have led to general density and pressure-time histories as shown in figure 5. The relatively slow rate of pressure buildup will not result in amplification factors common to the loading produced by a shock wave in the atmosphere. Therefore, the peak pressure was treated as a static pressure and it will be used as the loading criteria in this study. LEM pressure limits, particularly in terms of the pressure profiles in question, were not available at the time of the study. The study was performed assuming a limit of 5 psi.

In order to determine the stagnation pressure the ascent stage would experience, the following had to be determined:

1. The stagnation pressure as a function of distance from the center of expansion for propellant quantities corresponding to the assumed malfunction times.

2. The separation between the ascent and the descent stage at the time of the descent stage's impact with the lunar surface.

Knowledge of the ascent-descent stage separation at the time of the descent stage's impact (for various malfunction times) enables determination of the pressure experienced by the ascent stage from the pressure-distance relationships, which were obtained by using the procedure discussed in reference 3. The resulting stagnation pressure-distance curves are given in figure 6 for various assumed malfunction times. The quantity of propellant available at staging was determined from figure 7 for the descent profile of reference 1. In calculating the pressure-distance relationships, the propellant quantity was doubled to account for a hemispherical expansion rather than the spherical one assumed in reference 3.

The separation (H) between the ascent and the descent stages at the time of impact was determined for the initial conditions (altitude and velocity) at the time of malfunction for the nominal descent profile using the equations in Appendix A. The separation (H) is plotted in figure 8 for the staging times of 2.0 and 4.0 seconds. The separation (H) consists almost entirely of altitude since both the ascent and the descent stages have essentially the same horizontal velocity until impact. (The abort trajectory is a vertical thrusting one during the time span under consideration.) Figure 9 combines the results of figures 6 and 8 and gives the pressure the ascent stage would experience as a function of malfunction time. A malfunction at or after T_{GO} = 32.6 seconds (T_{GO} = thrusting time until touchdown) will result in pressures on the ascent stage exceeding 5 psi for a staging time of

2.0 seconds. A staging time of 4.0 seconds will result in excessive pressures for T_{GO} = 53.7 seconds or less. In arriving at these results, it was assumed that the gas cloud reached the ascent stage instantaneously. This is a reasonable assumption since the arrival times are generally less than .01 seconds due to the high cloud velocity and the relatively slow rate of separation of the ascent stage.

The pressures that the ascent stage would experience were also determined parametrically for various combinations of initial altitude and velocity at the time of malfunction. This will enable determination of the pressures experienced by the ascent stage for descent trajectories different from the one considered. The results are given in Appendix B.

Fragmentation

A proper analysis of the fragmentation hazards would require knowledge of the spectrum of fragments as to size, weight, dispersal pattern, et cetera. Such information is extremely difficult to obtain and was not available at the time of the study. As a result, a simplified approach was taken that based the probability of being hit by a fragment on an analysis using target area considerations.

The probability of being hit by a fragment $\left(P_{HIT}\right)$, assuming an abort is required and the descent stage is destroyed releasing the propellants, is given by:

$$P_{HIT} = N \frac{A_{EFF}}{A_S}$$

where

N = number of fragments

A_{EFF} = effective target area

A_S = area of sphere of radious H centered at the center of expansion

This simplified approach assumes the fragments are uniformly dispersed and are of the same size. The equation is defined in more detail in Appendix A.

The results of the above equation are plotted in figure 10 as a function of separation for various numbers of fragments. The number of fragments that can be produced is the big variable in the above equation. Work done by Dr. D. C. Gerneth suggests that a conservative (high) estimate of the number of fragments (N) is in the order of 500. Combining the results of figure 10 (N = 500) and figure 8, the probability of being hit was determined as a function of malfunction time for staging times of 2.0 and 4.0 seconds for the nominal descent trajectory of reference 1. The results are given in figure 11. In order to use figure 11, an acceptable probability of being hit must be determined. This can be accomplished in the following manner:

$$P_{CL} = 1 - P_{CS} = P_{EX} \times P_{HIT} \times P_{FAT}$$

assume:

P_{CS} = .9999 (portion of flight under consideration)

P_{EX} = .001

P_{FAT} = .50

$\therefore P_{CL}$ = .0001 = .0005 P_{HIT}

${P_{HIT}}_{allowable}$ = .20

For a staging time of 2.0 seconds, an abort between T_{GO} = 44.0 and 20.0 seconds would result in a probability of being hit by a fragment greater than .20 (20 percent). A staging time of 4.0 seconds results in a probability of a hit greater than .20 between T_{GO} = 65.0 and 20.0 seconds. (Below 20.0 seconds the impact energies were assumed to be insufficient to cause the propellants to be released to the environment.)

The probability of being hit by a fragment was also determined parametrically for various combinations of altitude and velocity. The results are given in Appendix B.

CONCLUDING REMARKS

A LEM abort during portions of the final phase of descent can be extremely hazardous if the descent stage propellants are allowed to mix and explode. An abort between 53.7 and 20.0 seconds (thrusting time to go until touchdown) will result in stagnation pressures greater than the assumed limit of 5 psi (4.0 second staging time). An abort between 65.0 and 20.0 seconds will result in a probability of being hit by a fragment of 20 percent or greater (4.0 second staging time). These hazardous conditions are not peculiar to the descent trajectory considered but would apply reasonably well to any practical trajectory in the altitude region considered.

The critical time spans are rather short and may not justify elaborate remedial action. However, the hazards do exist and must be either removed or accepted. A possible means of eliminating the hazards appears to be the elimination of the descent stage propellant prior to its impact on the lunar surface. A fuel dump could be initiated at abort initiation which would dump overboard the propellant at as high a rate as safely possible. The fuel dump would decrease and possibly eliminate the propellant available at impact. The hazards caused by the descent stage propellants would consequently be lessened and possibly eliminated.

REFERENCES

1. Cheatham, D. C.; and Price, T. G.: A Proposed LEM Descent Trajectory and Fuel Budget. MSC Internal Note No. 64-EG-29, Dec. 11, 1964.

2. Chemical Explosions in Space. Houston Research Institute, Feb. 1, 1965.

3. Hypergolic Explosion and Blast in a Vacuum. Atlantic Research Proposal, 1965.

4. LEM Familiarization Manual, LMA 790-1, Grumman Aircraft Engineering Corp., July 15, 1964.

5. Lutzky, M.: Explosions in Vacuum. NOLTR 62-19, Nov. 1962.

6. Payne, J. D.: Trajectory Profile for the LEM Powered Descent. MSC Memo, Apr. 30, 1965.

7. Personal Communication with Dr. D. C. Gerneth.

TABLE I. - KINETIC ENERGY OF DESCENT STAGE AT IMPACT

T_{GO}, sec	h_o, ft	$\dot{h}_o$, ft/sec	v_H ft/sec	At impact			
				v_V	v_H	KE_V, ft-lb	KE_H, ft-lb
60	305	6.35	55.5	55.75	55.50	372 000	368 000
50	245	5.71	45.0	50.81	45.0	309 000	242 000
40	190	5.25	32.0	45.00	32.0	242 000	122 500
30	140	~ 5.00	24.5	38.20	25.0	174 000	74 700
20	100	~ 5.00	0	31.35	0	117 500	0
10	50	~ 5.00	0	23.20	0	63 500	0

where: v_V and v_H determined from equations in Appendix A (free fall)

$KE = \frac{1}{2} mv^2$

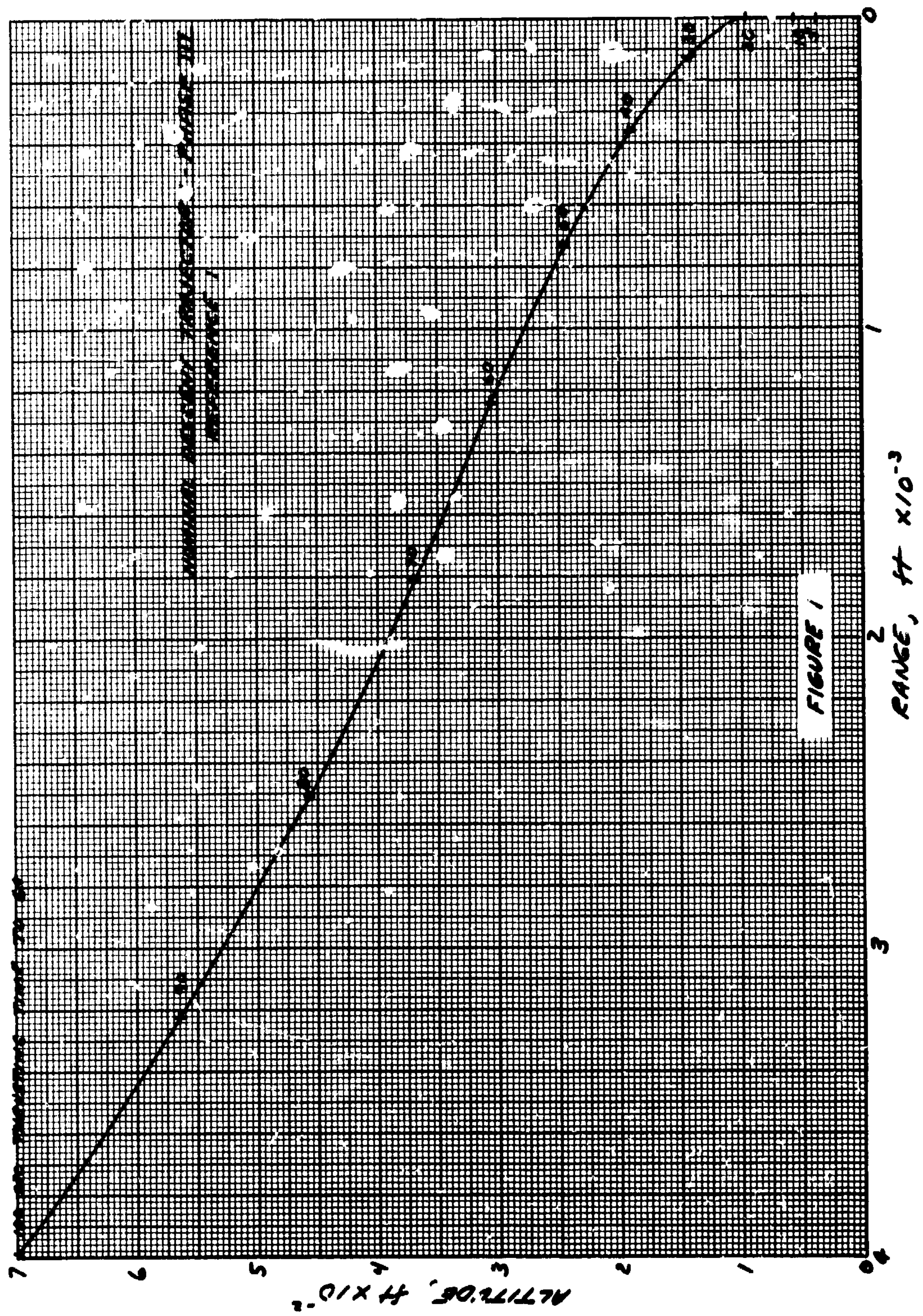


FIGURE 1

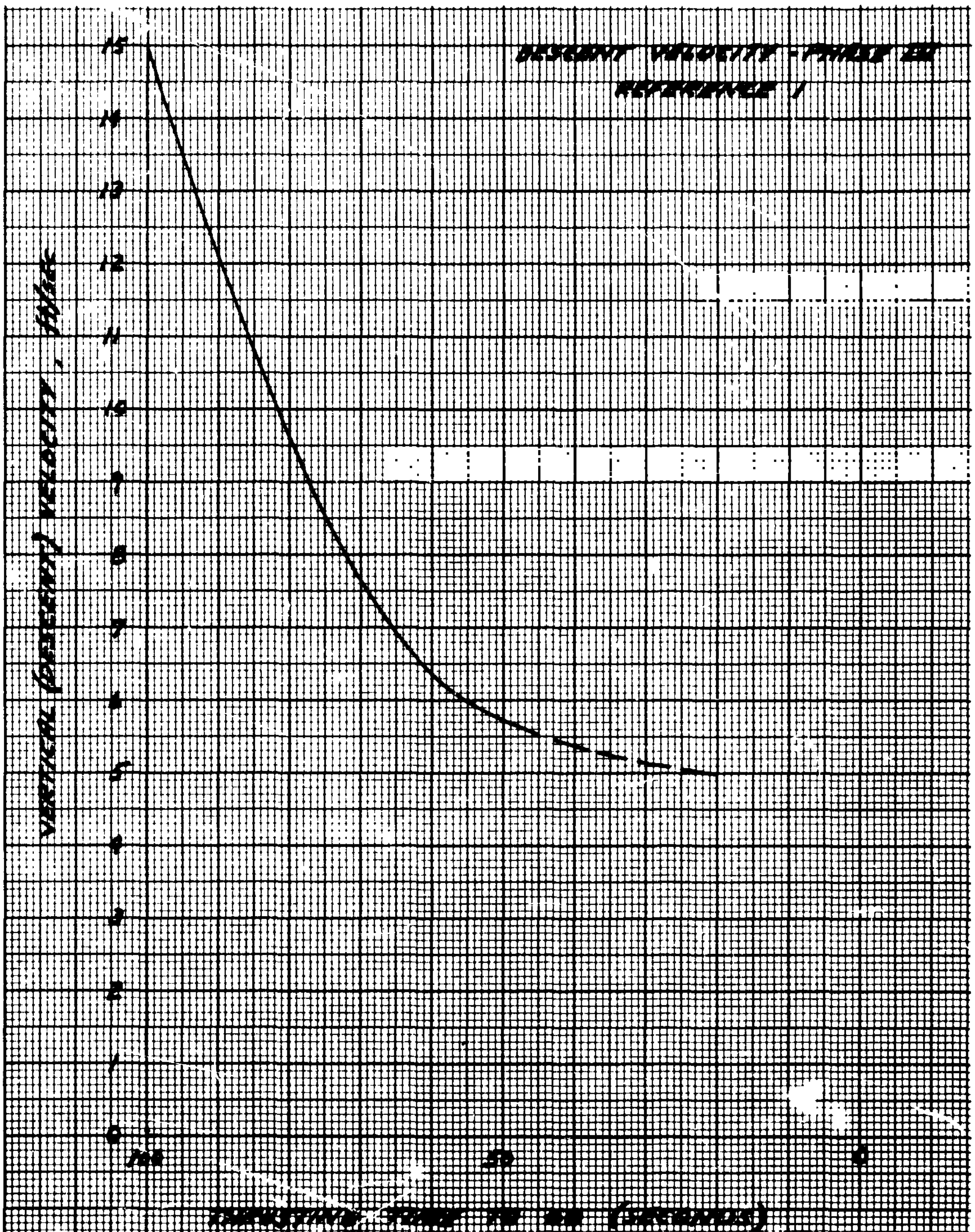

VERTICAL (DESCENT) VELOCITY, ft/sec
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
100
50
0

FIGURE 2

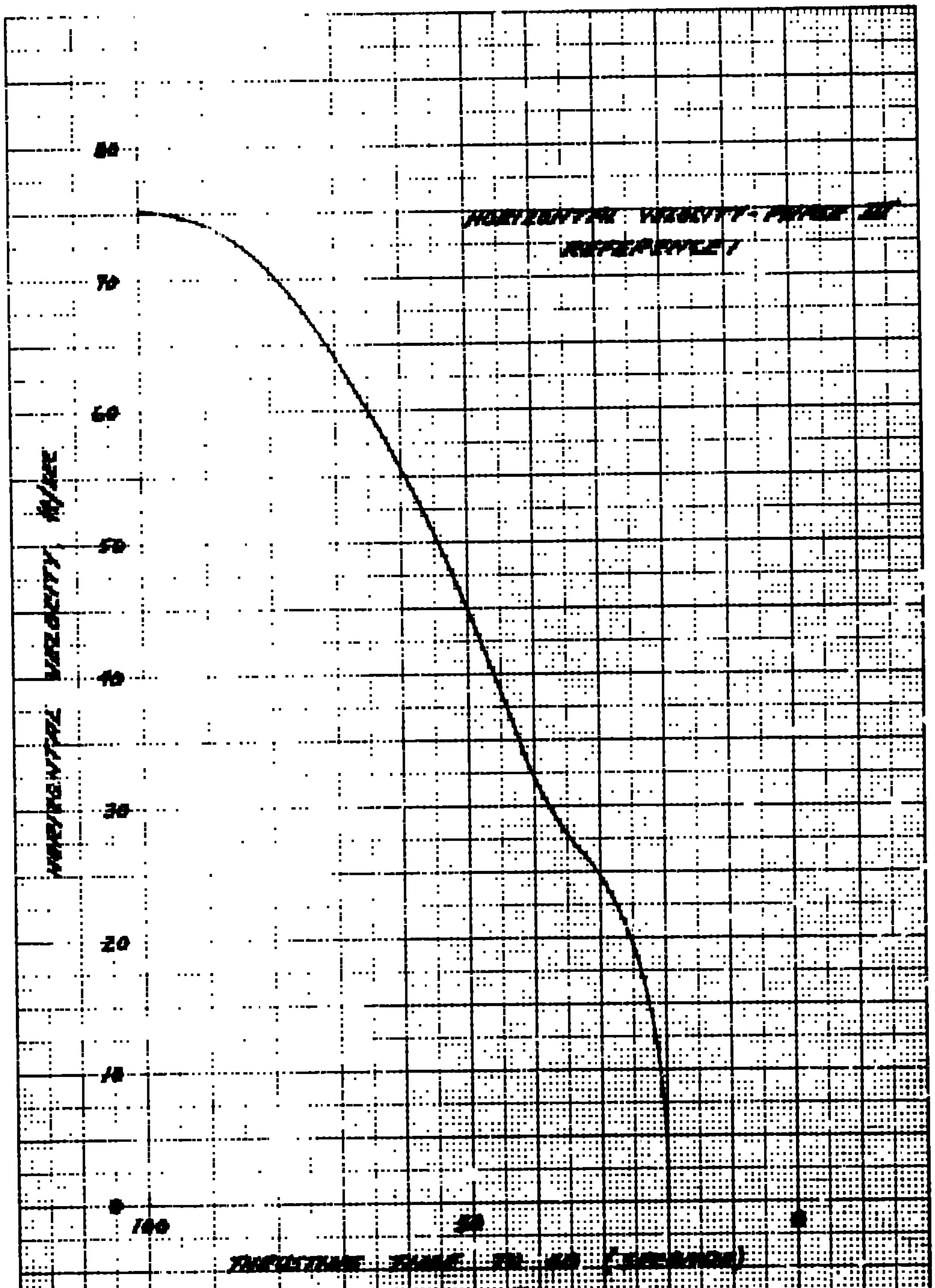


FIGURE 3

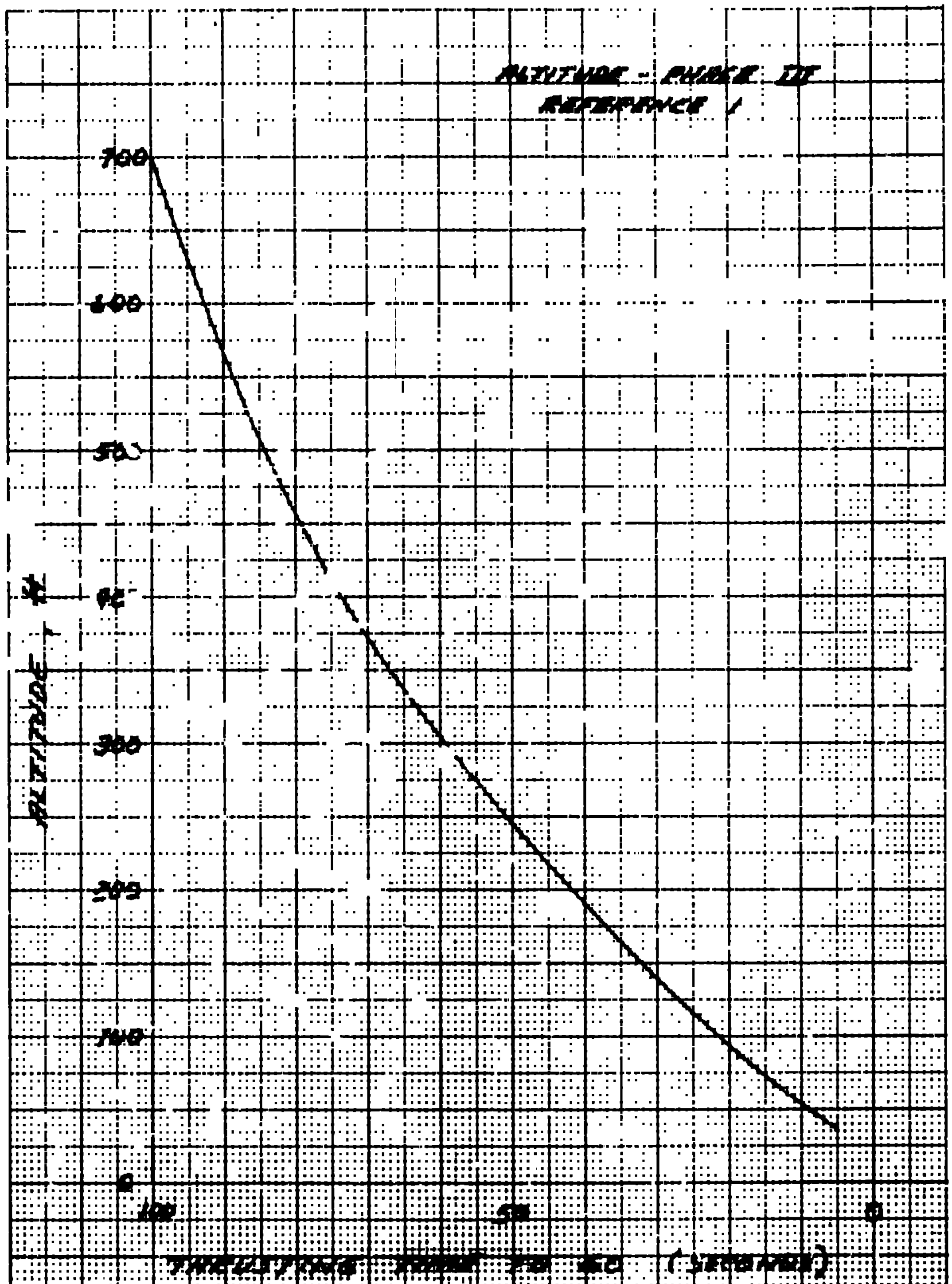

ALTITUDE - PHASE III
REFERENCE 1
ALTITUDE
700
600
500
400
300
200
100
0
100
50
0

FIGURE 4

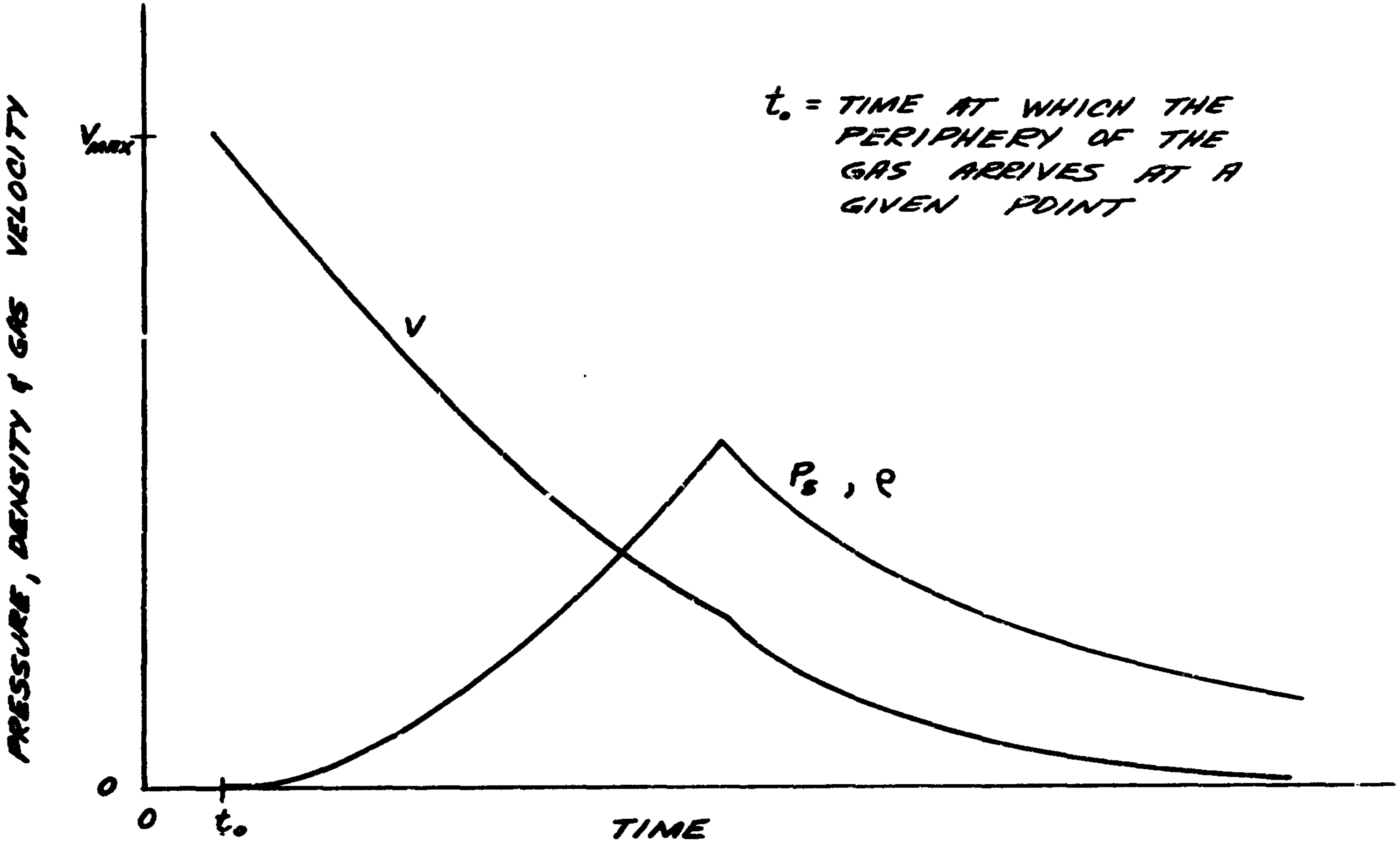


FIGURE 5. TIME PROFILE OF PRESSURE, DENSITY AND GAS VELOCITY

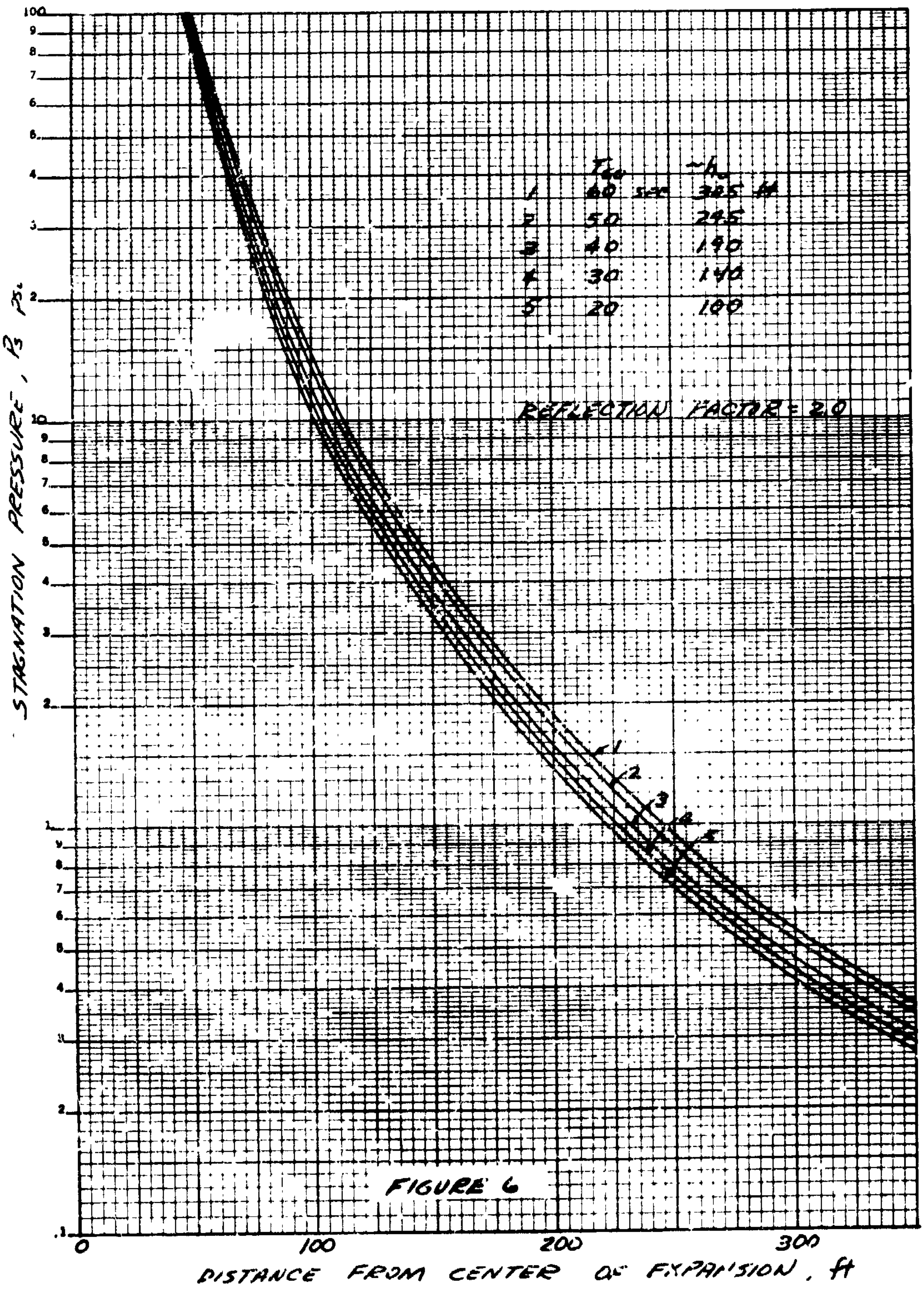

STAGNATION PRESSURE, P_3 psi
DISTANCE FROM CENTER OF EXPANSION, ft
T_{40} $\sim h_o$
1 60 sec 385 ft
2 50 245
3 40 190
4 30 140
5 20 100
REFLECTION FACTOR = 2.0
100
10
1
.1
0
100
200
300

FIGURE 6

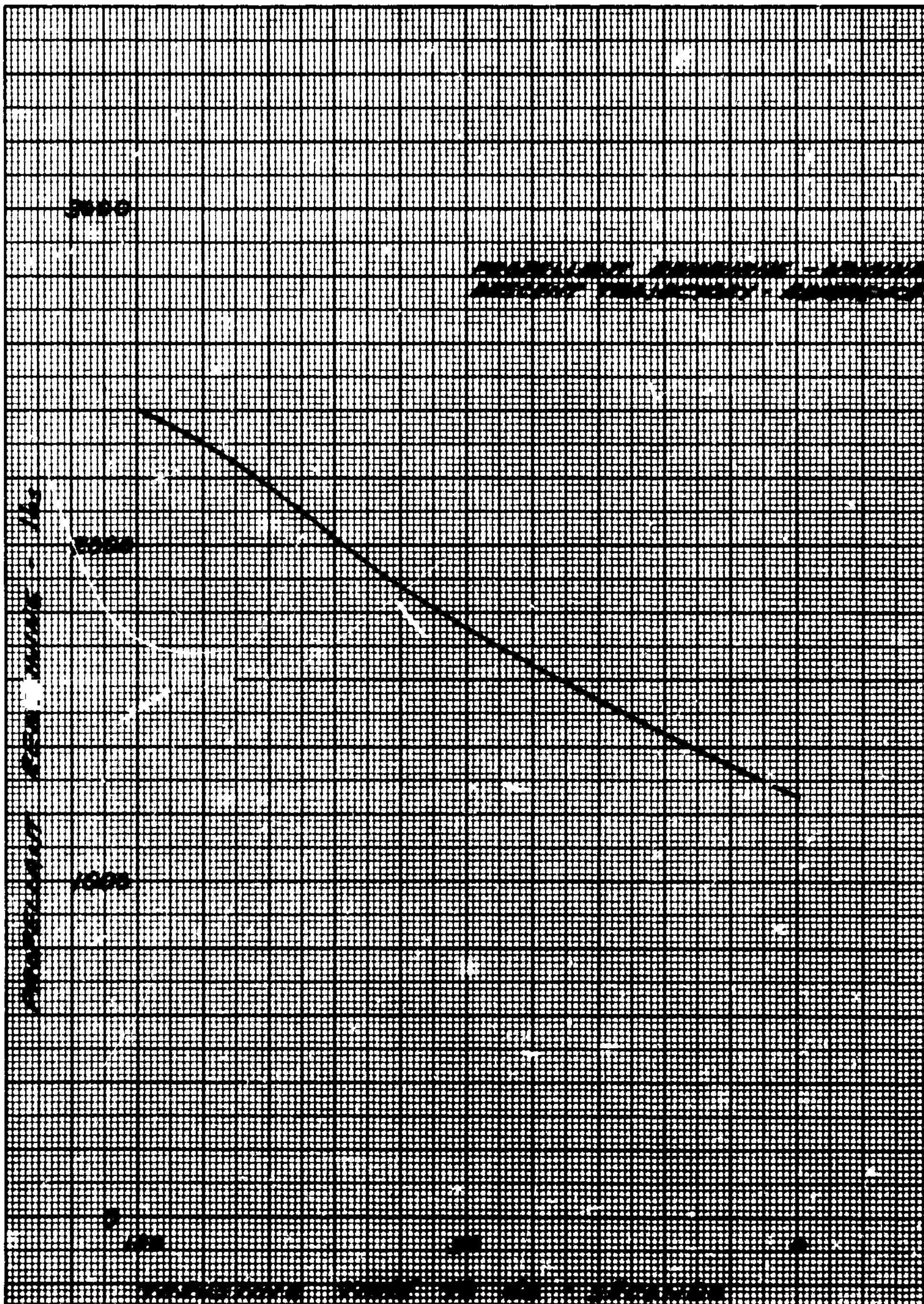


FIGURE 7

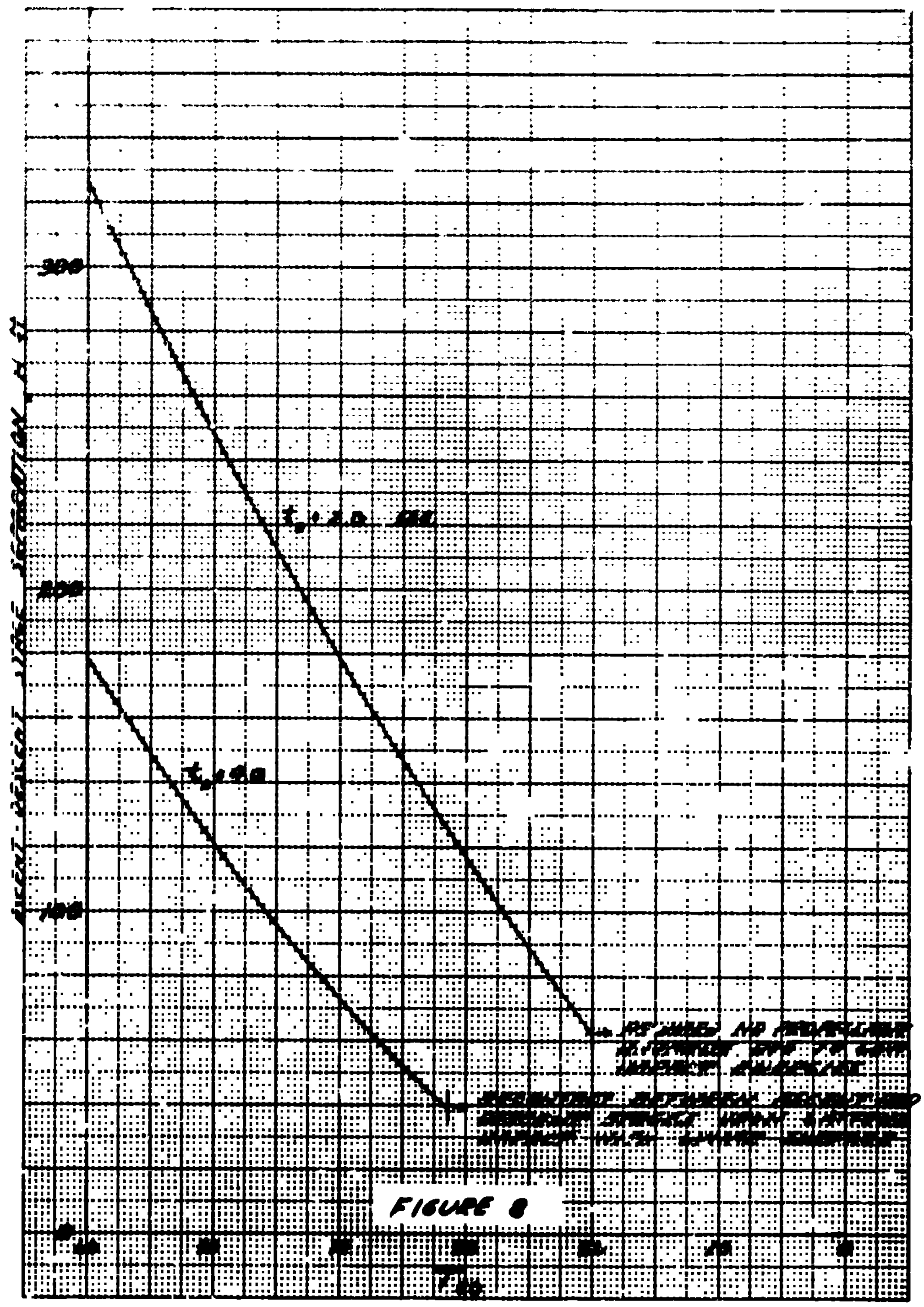


FIGURE 8

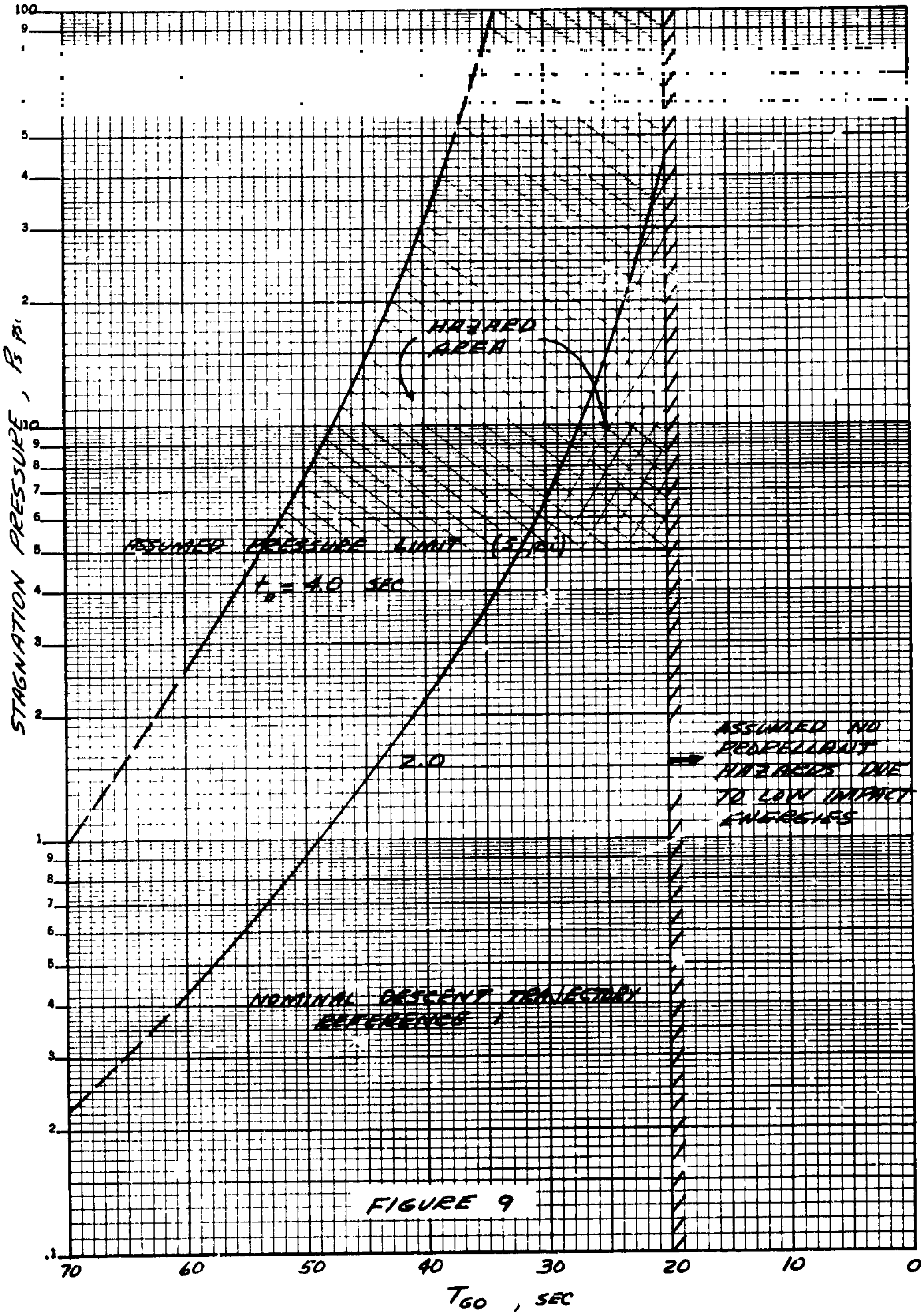

HAZARD AREA
ASSUMED PRESSURE LIMIT
t_B = 4.0 SEC
2.0
ASSUMED NO PROPELLANT HAZARDS DUE TO LOW IMPACT ENERGIES
NOMINAL DESCENT TRAJECTORY REFERENCE 1
STAGNATION PRESSURE, P_s PSI
T_{GO}, SEC

FIGURE 9

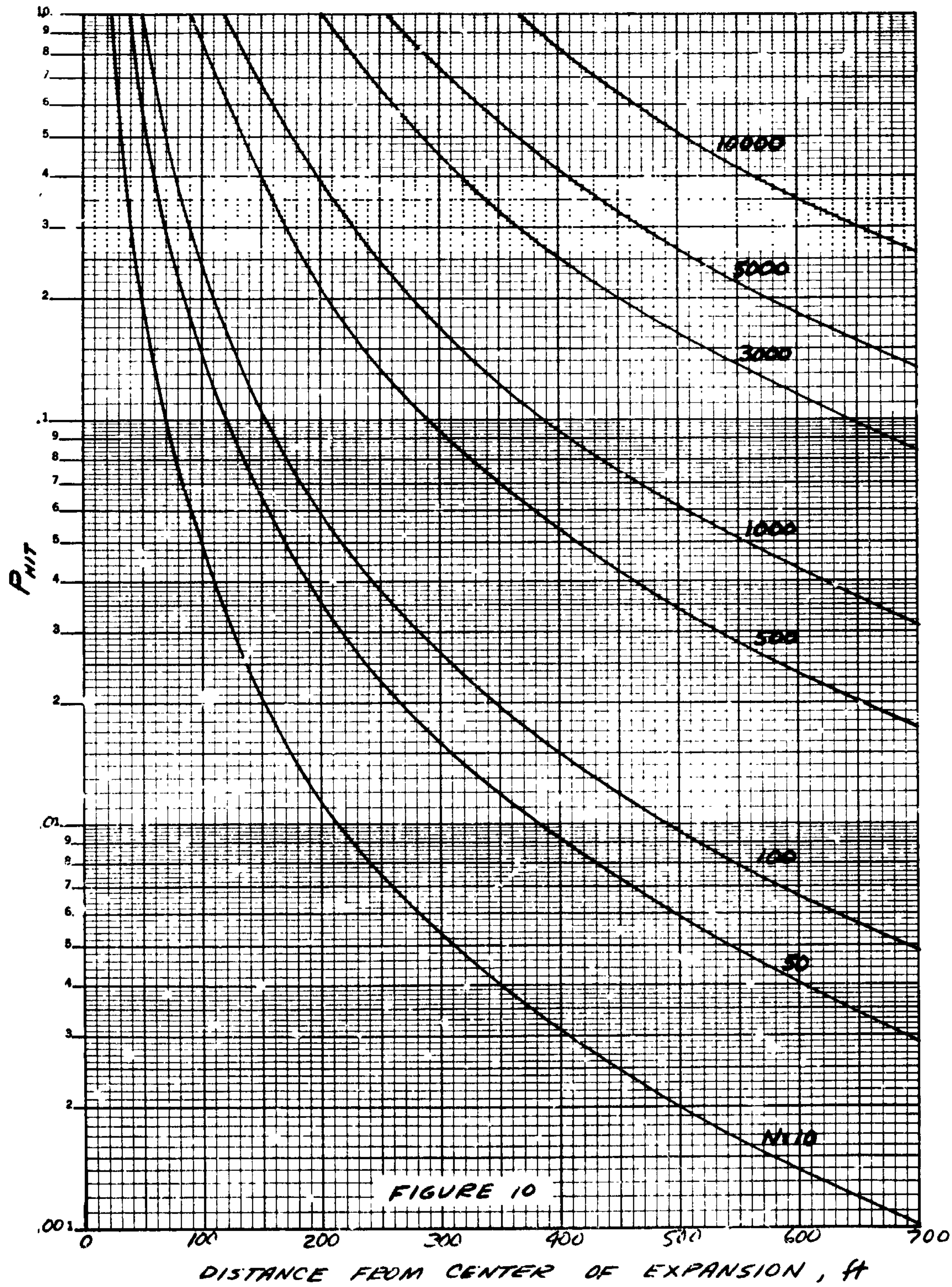

10.
9
8
7
6
5
4
3
2
.1
.01
.001
P_{HIT}
10000
5000
3000
1000
500
100
50
N=10
0
100
200
300
400
500
600
700
DISTANCE FROM CENTER OF EXPANSION, ft

FIGURE 10

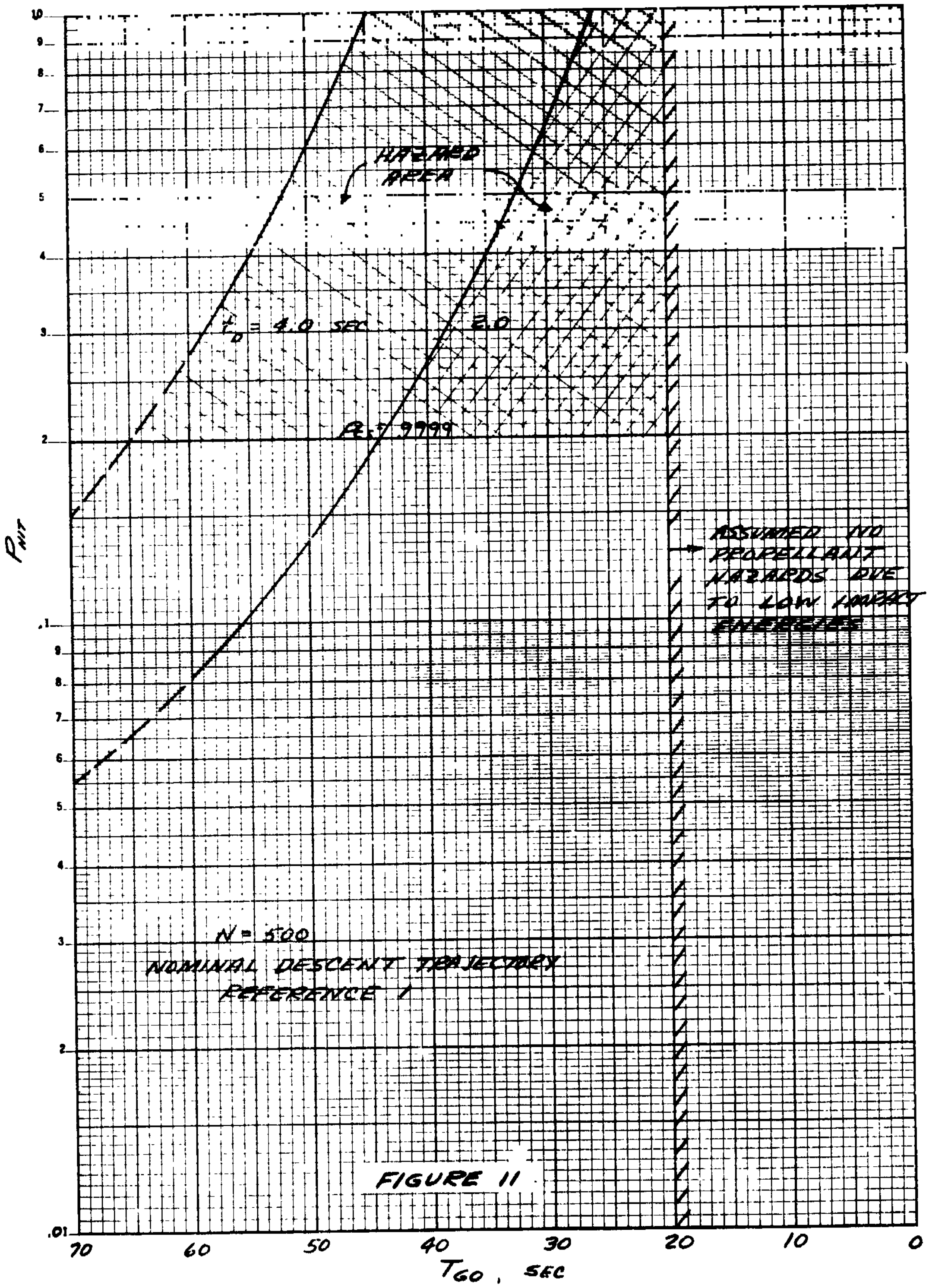
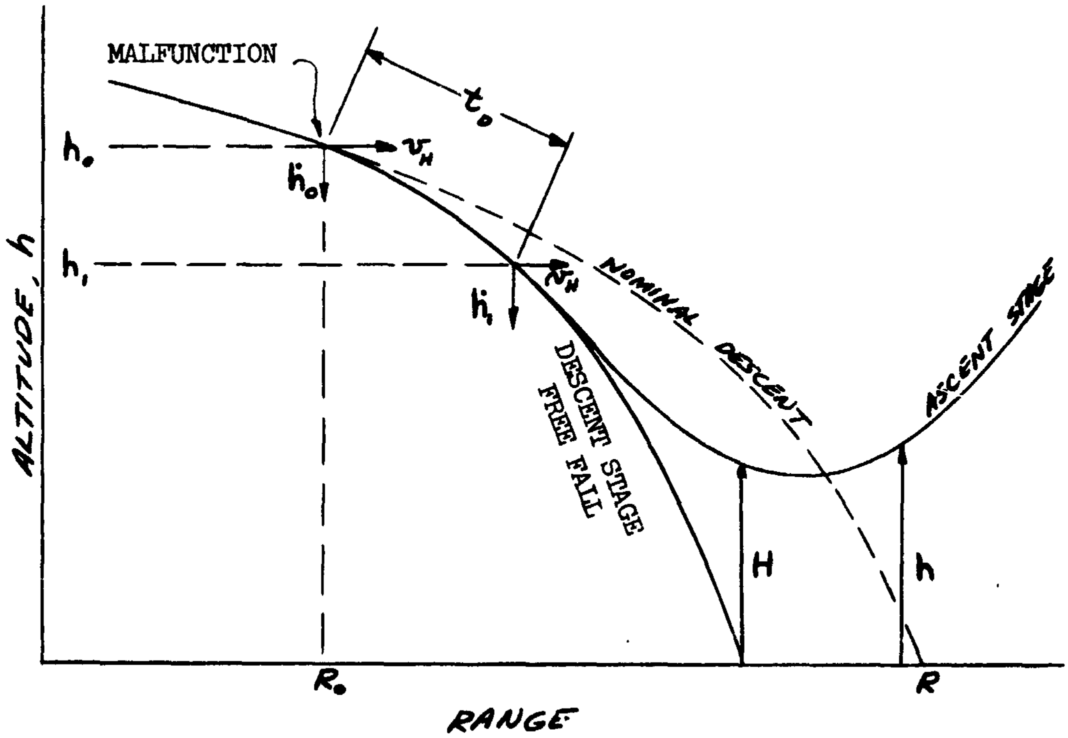

HAZARD AREA
T_D = 4.0 SEC
2.0
P_C = .9999
ASSUMED NO PROPELLANT HAZARDS DUE TO LOW IMPACT ENERGIES
N = 500
NOMINAL DESCENT TRAJECTORY
REFERENCE 1
P_{HIT}
T_{GO}, SEC
70
60
50
40
30
20
10
0
1.0
.1
.01

FIGURE 11

APPENDIX A

ASCENT - DESCENT STAGE SEPARATIONS

The basic equations of motion for constant acceleration were used to derive an expression for the ascent-descent stage separation (H) at the instant of the descent stage's impact with the lunar surface.



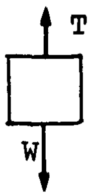
<u>Free fall</u>

$$h = \dot{h}_o t - \frac{1}{2} g t^2 + h_o$$

$$\dot{h} = \dot{h}_o - g t$$

$$R = v_H t - R_o$$

<u>Ascent</u>



$$m = \frac{W}{g}$$

$T = 3500$ lbs

$W \approx 10\,200$ lbs (earth)

$\approx 1\,640$ lbs (lunar)

$\frac{T}{W} = 2.13$ (lunar)

m = assumed constant (propellant expenditure assum. negligible)

t_B = burn time (ascent stage)

$t_o = o,\ \dot{h} = \dot{h}_1 = c$

$$T - W = ma$$

$$\frac{T}{W} - 1 = \frac{a}{g}$$

$$a = \ddot{h} = g\left[\frac{T}{W} - 1\right]$$

$$\dot{h} = \int_o^{t_B} \ddot{h}dt = g \int_o^{t_B} \left(\frac{T}{W} - 1\right) dt$$

$$= g\left(\frac{T}{W} - 1\right) t_B + c$$

$$\dot{h} = g\left(\frac{T}{W} - 1\right) t_B + \dot{h}_1$$

$$\dot{h} = 5.14\ (2.13 - 1)\ t_B + \dot{h}_1 = 5.81\ t_B + \dot{h}_1 \qquad \text{(A1)}$$

$$h = \int_o^{t_B} \dot{h}dt = \int_o^{t_B} \left(5.81\ t + \dot{h}_1\right) dt$$

$$h = 2.90\ t_B^{\ 2} + \dot{h}_1\ t_B + c$$

$$h = 2.90\ t_B^{\ 2} + \dot{h}_1\ t_B + h_1 \qquad t = o,\ h = h_1 = c \qquad \text{(A2)}$$

$$R = v_H\ t_B - R_1$$

To find H:

$$h = 0 = \dot{h}_o t_H - \frac{1}{2} g t_H^2 + h_o$$ (descent stage free fall)

$$t_H = \frac{-\dot{h}_o \pm \sqrt{\dot{h}_o^2 + 2\, g h_o}}{-g}$$ t_H = time from abort till impact

$$t_H = t_D + t_B$$ t_D = staging time

$$t_B = t_H - t_D$$

from (A2)

$$h = 2.90\, t_B^2 + \dot{h}_1 t_B + h_1$$

where

$$\dot{h}_1 = \dot{h}_o - g t_D$$

$$h_1 = \dot{h}_o t_D - \frac{1}{2} g t_D^2 + h_o$$

(conditions at ignition of ascent stage after free fall for t_D seconds)

$$\therefore h = 2.90\, t_B^2 + \left(\dot{h}_o - g t_D\right) t_B + \dot{h}_o t_D - \frac{1}{2} g t_D^2 + h_o$$

substituting $t_B = t_H - t_D$

$$H = 2.90 \left(t_H - t_D\right)^2 + \left(\dot{h}_o - g t_D\right)\left(t_H - t_D\right) + \dot{h}_o t_I - \frac{1}{2} g t_D^2 + h_o$$

The initial velocity induced on the descent stage by the ascent engine at staging is not considered in the above equation.

PROBABILITY OF BEING HIT BY A FRAGMENT

The probability of being hit by a fragment is given by:

$$P_{HIT} = N\frac{A_{EFF}}{A_s}$$

where

N = number of fragments

A_{EFF} = effective target area

A_s = area of sphere of radius H, = $4\pi H^2$

The effective target area $\left(A_{EFF}\right)$ is determined by the target geometry.

$$A_{EFF} = K_1 + 2K_2\sqrt{\frac{K_3}{\pi N}}$$

where

K_1 = cross sectional area of target, 144 ft^2

K_2 = perimeter of target, 48 ft

K_3 = surface area of the descent stage, plus tankage and bulkhead area, ≈ 810 ft^2

$$\therefore P_{HIT} = \frac{N}{4\pi H^2}\left(144 + 96\sqrt{\frac{810}{\pi N}}\right)$$

$$= \frac{N}{H^2}\left(11.48 + \frac{123}{N^{\frac{1}{2}}}\right)$$

APPENDIX B

The pressure and fragmentation hazards were determined for various combinations of initial altitude $\left(h_o\right)$ and vertical velocity $\left(\dot{h}_o\right)$ in order to evaluate the hazards for descent trajectories different from the one given in reference 1.

The procedure was to determine the ascent-descent stage separation (H) at the time of the latter's impact for combinations of h_o and $\dot{h}_o$ which did not violate the so-called "dead man's" curves. These curves specify the abort conditions which will result in recontact of the ascent stage with either the lunar surface or the descent stage (or its debris) when the latter impacts on the lunar surface. This area has been investigated previously (e.g., ref. 4). For reference purposes, a set of the so-called "dead man's" curves is given in figure B-1. These particular curves are based on the criteria of the ascent stage being able to arrest its vertical velocity by an altitude of at least 25 feet to avoid recontact with the descent stage.

The separation H for acceptable combinations of h_o and $\dot{h}_o$ are given in figures B-2 and B-3 for staging times of 2.0 and 4.0 seconds, respectively. Combining these results with those of figure 6 determined the stagnation pressures experienced by the ascent stage as a function of various combinations of h_o and $\dot{h}_o$. The results are given in figure B-4 and can be interpreted as "dead man's" curves. (In using figure 6, the thrusting time to go $\left(T_{GO}\right)$ was approximated by using the initial altitude $\left(h_o\right)$ versus T_{GO} of the "nominal" descent trajectory of reference 1.)

The fragmentation hazards were also determined parametrically as functions of various combinations of h_o and $\dot{h}_o$ by combining the results of figures B-2, B-3 and figure 10. The results are given in figure B-5 which gives the probability of being hit by a fragment $\left(P_{HIT}\right)$ as a function of the initial conditions at the time of malfunction. These results can also be interpreted as "dead man's" curves by establishing a maximum allowable P_{HIT}.

Figure B-6 summarizes the pressure and fragmentation hazards together with the nominal descent trajectory of reference 1.

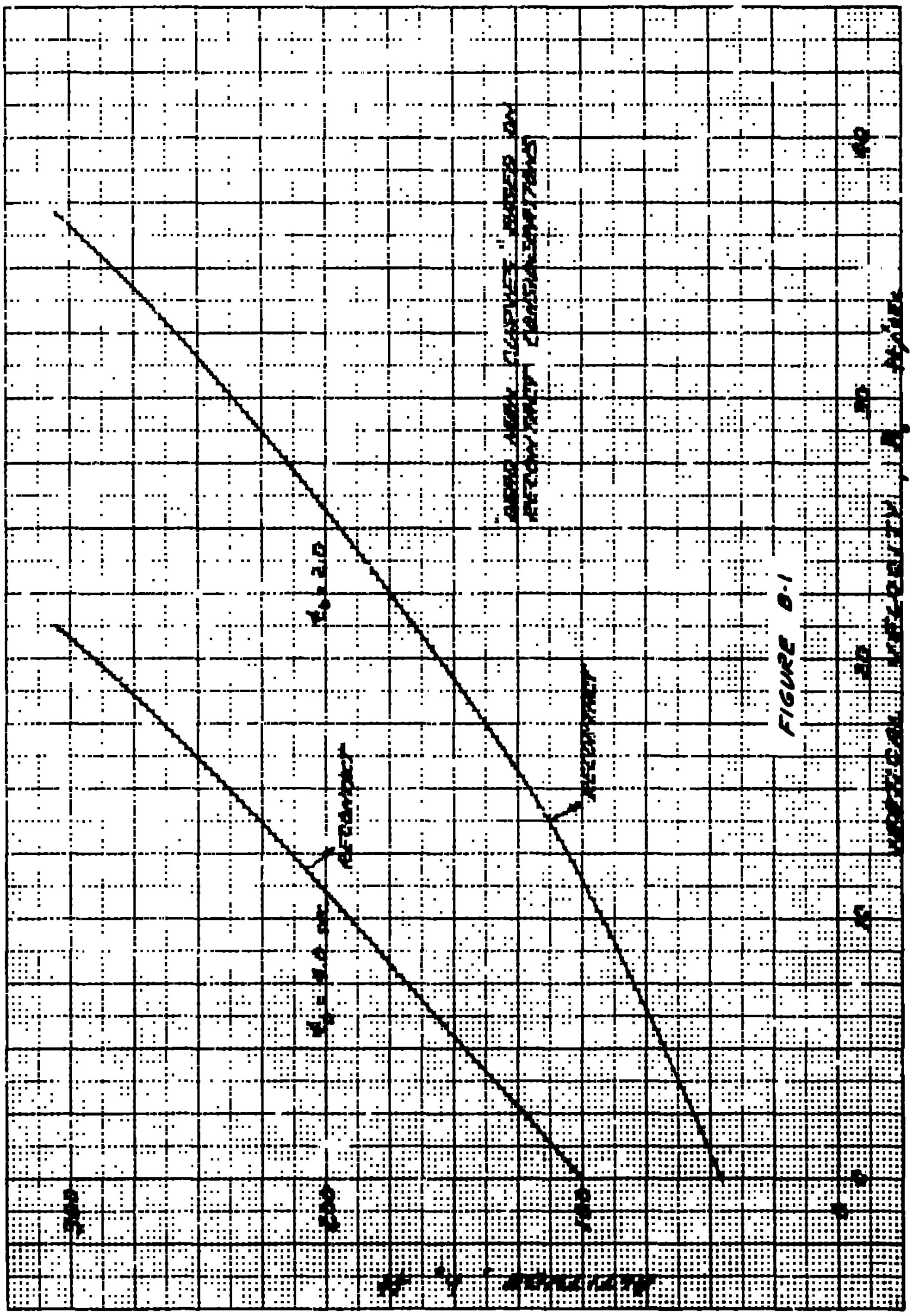


FIGURE B-1

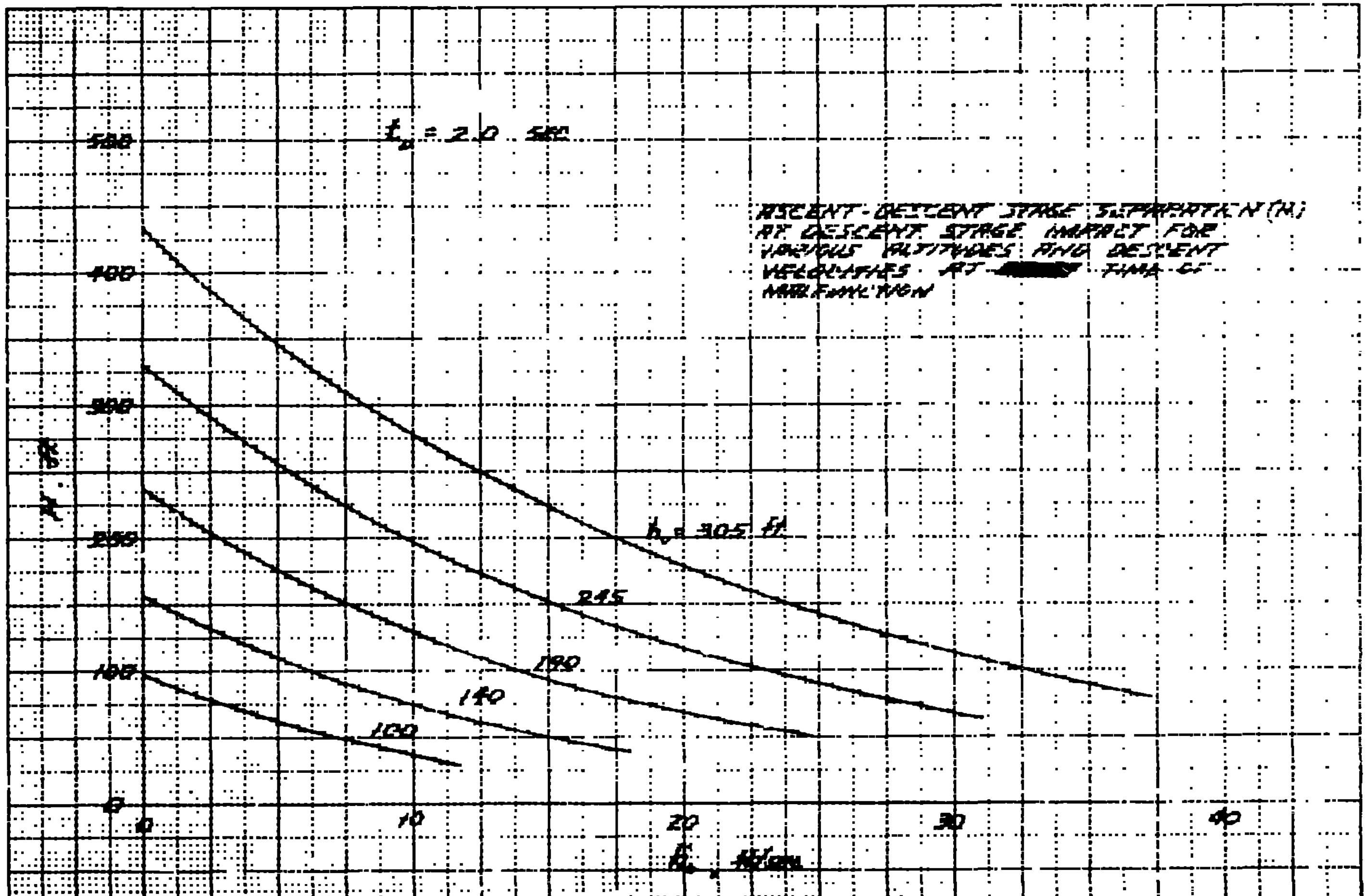

t_d = 2.0 sec
ASCENT-DESCENT STAGE SEPARATION (H)
AT DESCENT STAGE IMPACT FOR
VARIOUS ALTITUDES AND DESCENT
VELOCITIES AT [redacted] TIME OF
MALFUNCTION
500
400
300
200
100
0
0
10
20
30
40
h_o = 305 ft
245
190
140
100

FIGURE B-2

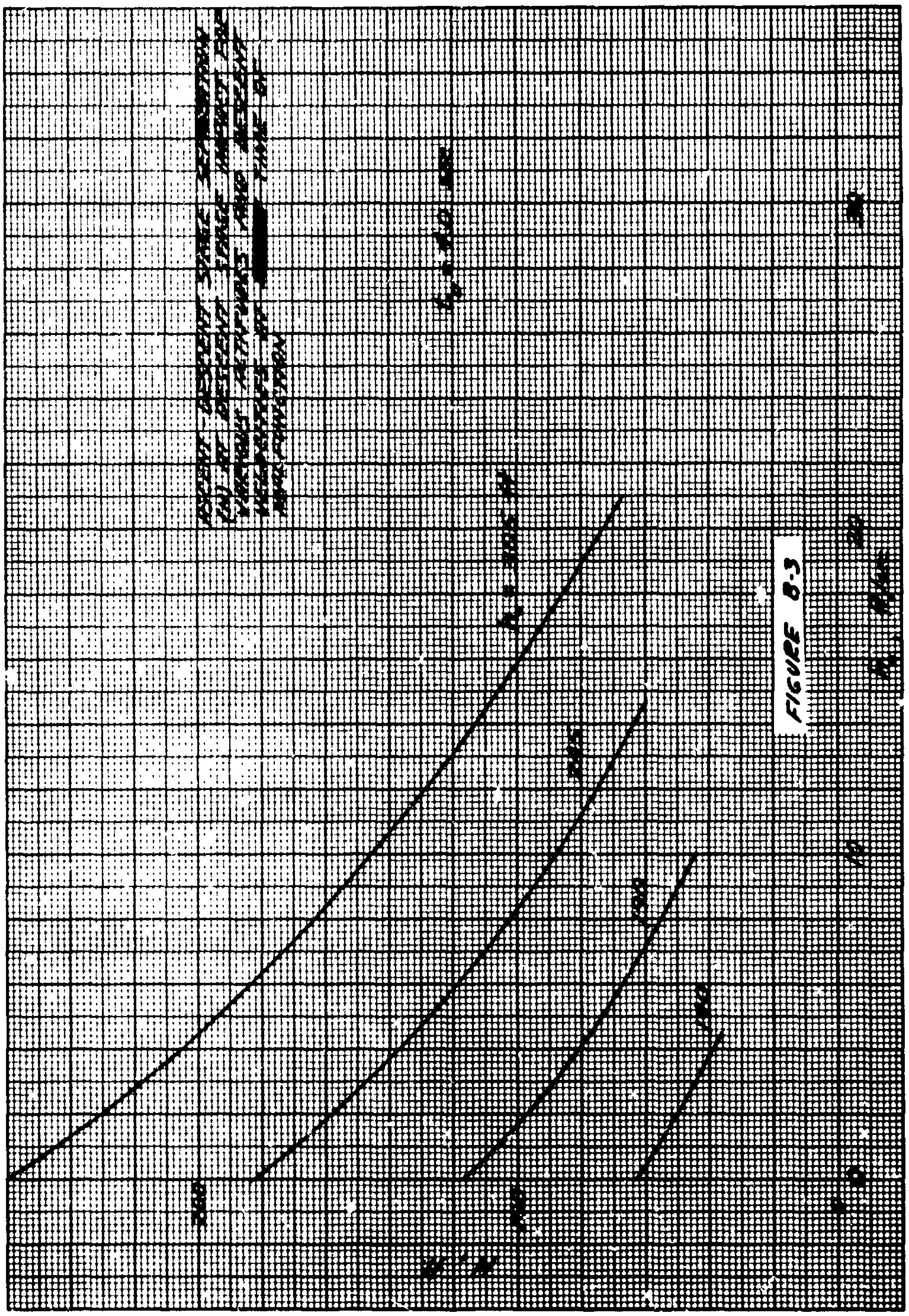


FIGURE B-3

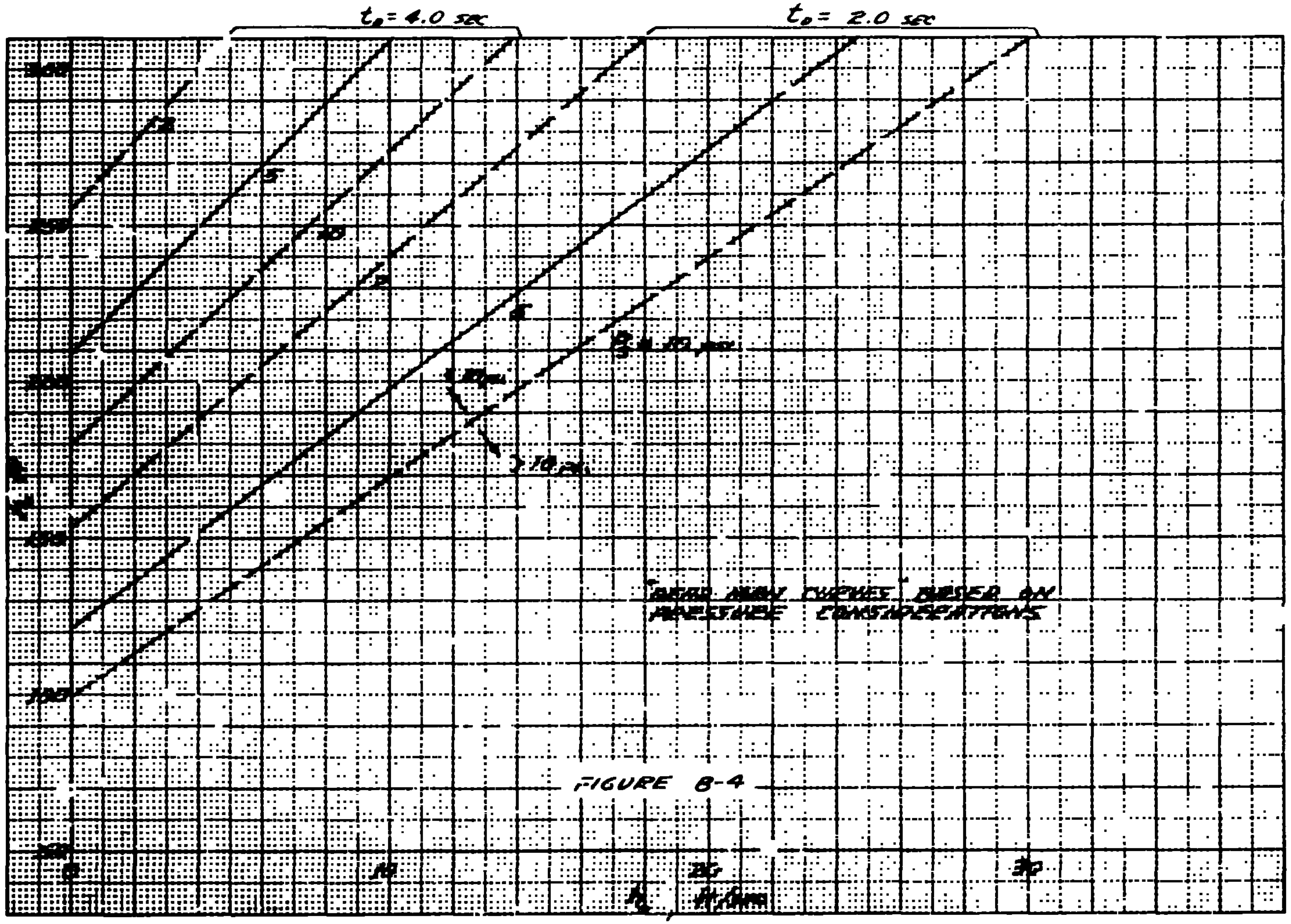
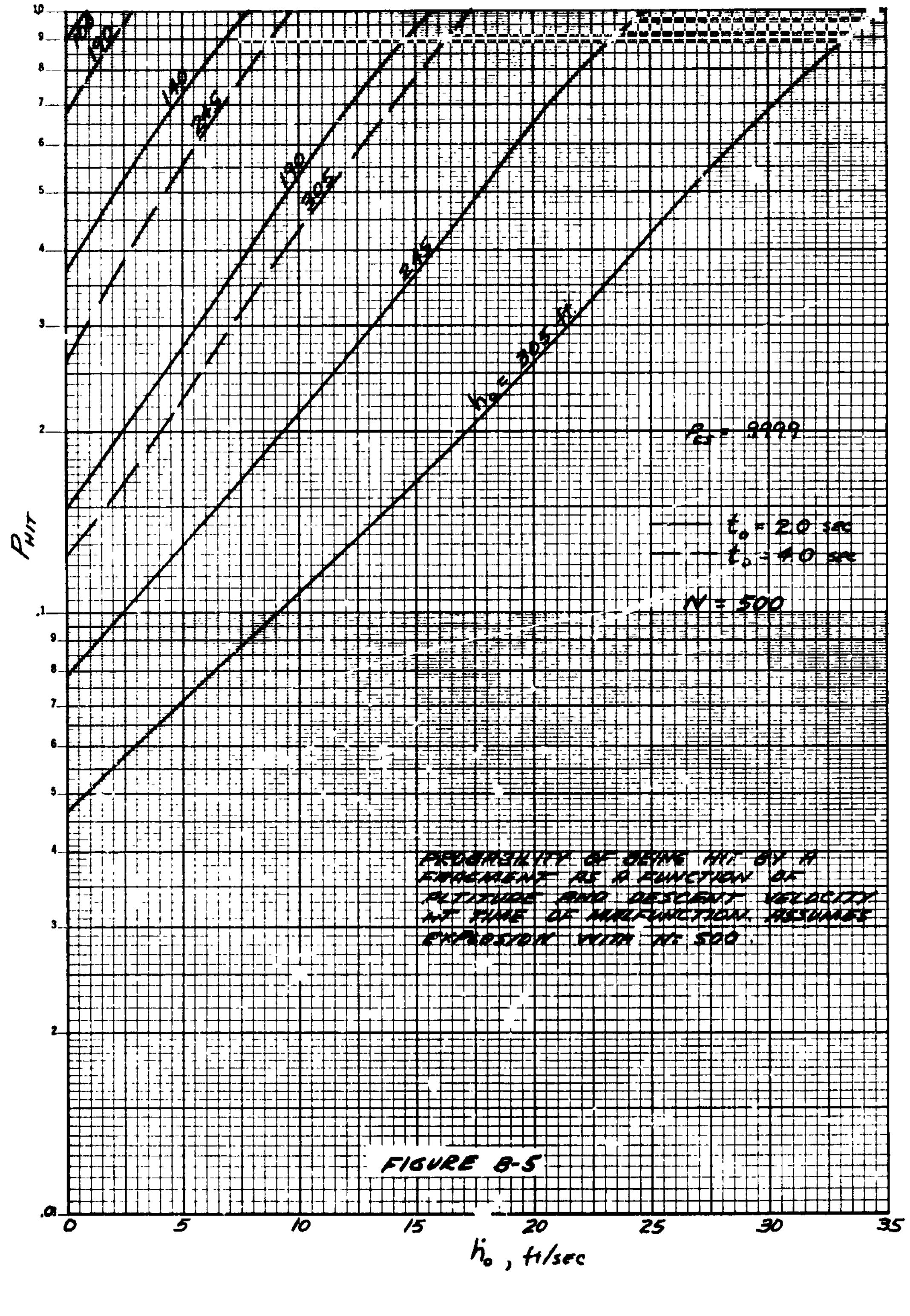


FIGURE B-4



P_HIT
ḣ₀ , ft/sec
0
5
10
15
20
25
30
35
.01
.1
1.0
140
190
245
h₀ = 305 ft.
t₀ = 20 sec
t₀ = 40 sec
N = 500
PROBABILITY OF BEING HIT BY A FRAGMENT AS A FUNCTION OF ALTITUDE AND DESCENT VELOCITY AT TIME OF MALFUNCTION. ASSUMES EXPLOSION WITH N: 500.

FIGURE B-5

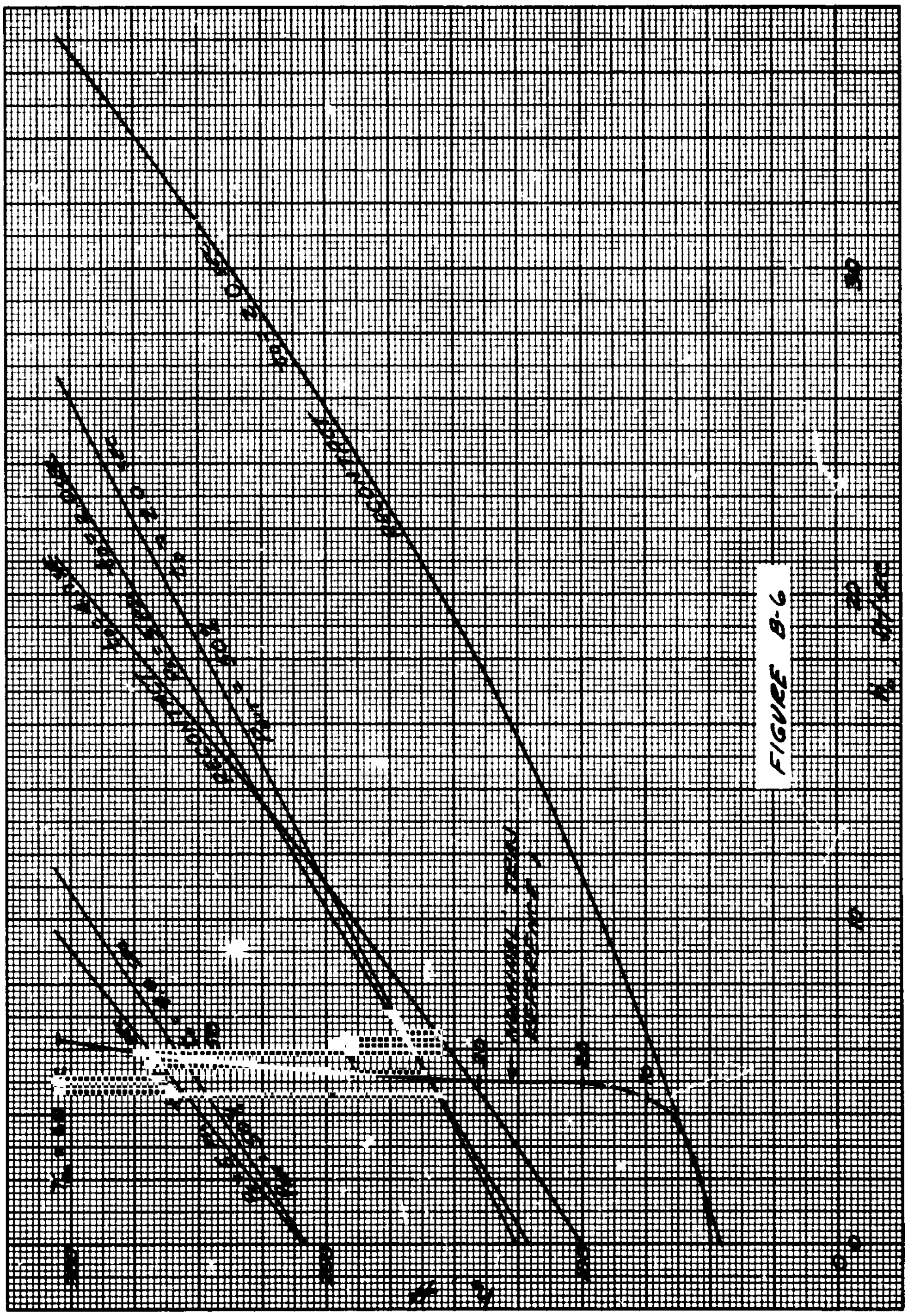


FIGURE B-6