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EFFECTS OF 1980 TECHNOLOGY ON WEIGHT OF A RECOVERY SYSTEM FOR A ONE MILLION POUND BOOSTER

by

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16. Abstract
This report presents the results of a study to evaluate the effects of 1980 technology on the weight of recovery systems capable of decelerating a one-million-pound booster to vertical velocities of 60 or 30 ft./sec. at sea level impact. The study assumed a nominal set of booster staging conditions and that there would be no constraints on parachute size, number or type. The study evaluated the effects of new materials that would be available by 1980 in addition to the effects of booster attitude during entry, various parachute staging methods, parachute reefing schemes, parachute-retro rocket hybrid systems, and the effects of dividing the booster into separate pieces for recovery. It was determined that for the systems considered, a hybrid parachute-retro-rocket recovery system would have the minimum weight. New materials now becoming available for parachute fabrication should result in a 37-percent reduction in hybrid recovery system weight for an impact velocity of 30 fps.

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PREFACE

The Space Shuttle system currently under development utilizes two solid rocket booster (SRB) vehicles which weigh on the order of 1.6×10^5 pounds. It is planned that these SRB vehicles will be recovered for reuse by conventional parachute systems. During the earlier design studies of possible Space Shuttle systems it was envisioned that much larger and heavier pressure fed boosters would be used. These larger boosters weighed on the order of one-million-pounds. Parachute systems for recovering these larger boosters were considered in these earlier studies, but were rejected because both the weight and the size of the parachute systems required was prohibitive. These decisions were based on the technology which existed in the early 1970's. In this study possible parachute type recovery systems were considered for a one-million-pound booster assuming a level of technology that could be available in 1980. This report contains the results of that study. The material is presented in the format in which it was prepared for oral presentations.

EFFECTS OF 1980 TECHNOLOGY ON WEIGHT OF A RECOVERY SYSTEM FOR A ONE MILLION POUND BOOSTER

PRESENTATION OUTLINE

- o STUDY GOAL AND ASSUMPTIONS
- o PARAMETERS AFFECTING WEIGHT
- o ALL-PARACHUTE RECOVERY SYSTEM
- o PARACHUTE-RETROROCKET RECOVERY SYSTEM
- o DIVIDING PAYLOAD INTO PIECES
- o L/D CONSIDERATIONS
- o CONCLUSIONS

Figure 1

SECTION I

STUDY GOAL AND ASSUMPTIONS

STUDY GOAL

EVALUATE THE EFFECTS OF 1980 TECHNOLOGY ON THE WEIGHT OF RECOVERY SYSTEMS CAPABLE OF DECELERATING A ONE MILLION POUND BOOSTER TO VERTICAL VELOCITIES OF 60 OR 30 FT/SEC AT SEA LEVEL IMPACT

Figure 2

STUDY ASSUMPTIONS

- Recovery system weight is in addition to the booster weight
- Booster size is assumed to be similar to pressure fed boosters of previous studies
- Range of staging conditions used

  Altitude 190,000 ± 10,000 ft
  Velocity 5,500 ± 500 ft/sec
  Flight path angle + 30 ± 5°

- No constraints on parachute size, number, or type

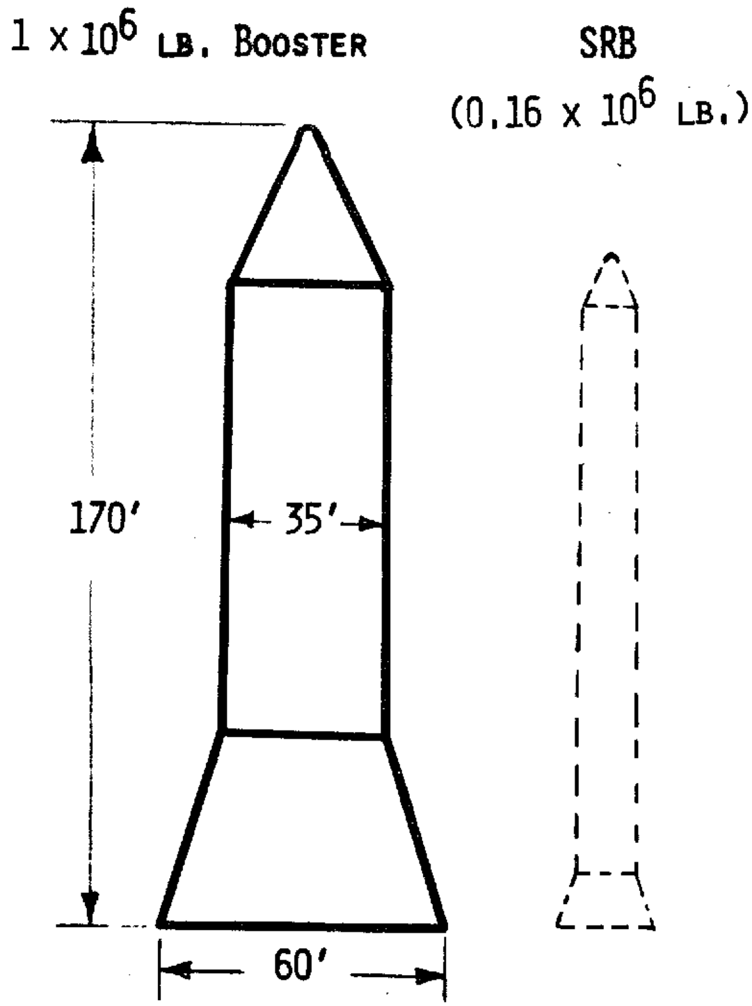

Figure 3

BOOSTER DRAG COEFFICIENT

One of the first requirements in designing a recovery system for a booster is to determine accurate trajectory data since this dictates the spectrum of decelerator system deployment conditions which must be considered. These trajectory calculations in turn require use of accurate values of booster drag coefficient as a function of Mach number. For the booster chosen for this study variations in drag coefficient with Mach number for two booster angles-of-attack are presented in figure 4. Both the drag coefficient curves shown are based on the cross sectional area of the booster when it is at 90 degrees to the flight path. As can be seen the booster has a much higher drag level at the high angle-of-attack flight attitude. The drag efficiency curves shown are based on a compilation and extrapolation of data from several sources for bodies ranging from short cylinders to cone-cylinder-flare shapes tested at the appropriate Mach numbers but at lower Reynolds numbers than the nominal booster trajectory would encounter. The drag coefficient data shown were used to determine the effect of booster drag on trajectory parameters, particularly the variation of dynamic pressure with altitude.

BOOSTER DRAG COEFFICIENT VS. MACH NUMBER

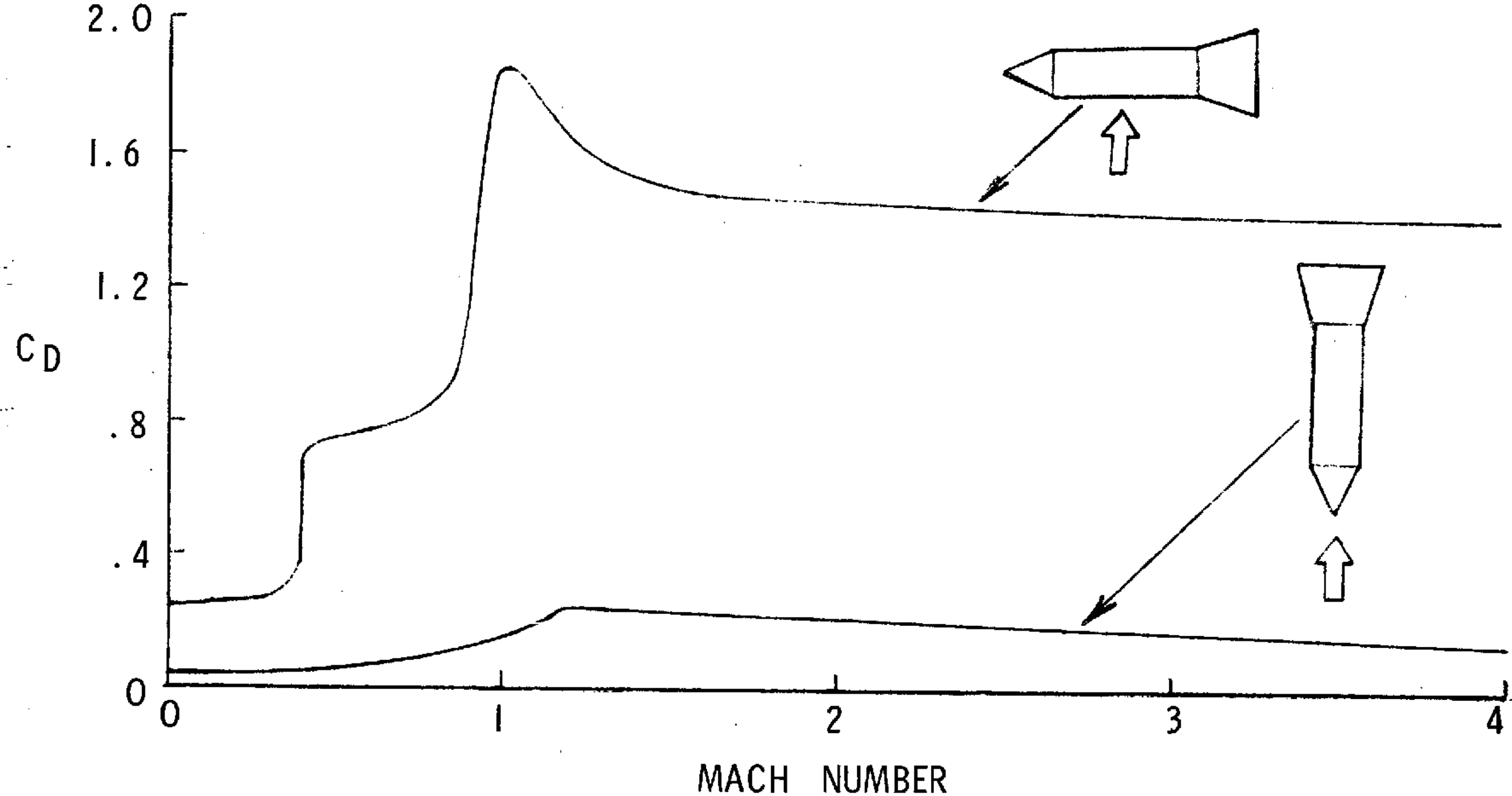

Figure 4

DYNAMIC PRESSURE

Using the drag coefficient data of figure 4 and the nominal booster staging conditions of figure 3, trajectory calculations have been carried out using point mass equations of motion. Results of these calculations for the variation of dynamic pressure with altitude for both zero and 90-degree angle-of-attack attitudes are presented in figure 5. Note that these are log-log scales and that we have indicated Mach number values along each flight path. For the nose first or zero angle-of-attack attitude the dynamic pressure reaches a level of about 12,000 psf at the 30,000 to 20,000 ft altitude level where we would normally be interested in deploying a final stage parachute recovery system. For the sideways or 90 degree angle-of-attack entry attitude the dynamic pressure is at a level of about 300 psf or less from 30,000 ft altitude and down. In addition, for the high angle-of-attack entry condition, the booster has decelerated to subsonic velocities from about 30,000 feet on down. Obviously, the high angle-of-attack entry is preferred from the deceleration standpoint and was used as the basis for the analysis presented herein.

EFFECT OF BOOSTER DRAG ON VARIATION OF DYNAMIC PRESSURE WITH ALTITUDE

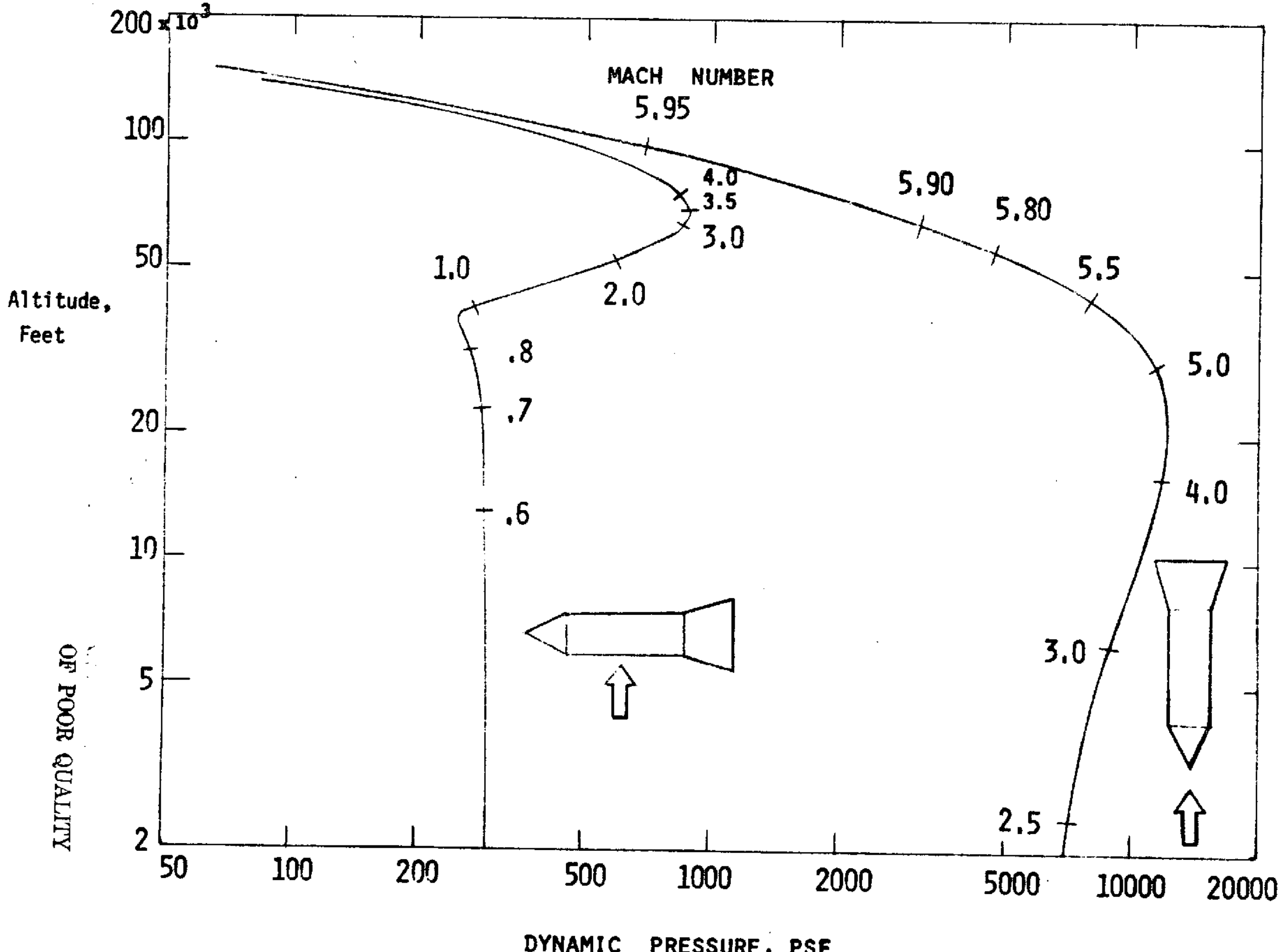

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Figure 5

EFFECT OF BOOSTER STAGING CONDITIONS

Figure 5 presented the dynamic pressure history for nominal staging conditions only. Clearly we need to examine the whole spectrum of staging conditions given in figure 3 to determine their effect on dynamic pressure levels in the altitude range being considered for parachute deployment. Figure 6 presents the dynamic pressure variation with altitude for the booster at the high angle-of-attack entry condition but with a change the dynamic pressure scale. The variations in trajectory shown are for the nominal trajectory and for the cumulative high and low differences in staging conditions that were listed in the study assumptions of figure 3. Note that variations in dynamic pressure for the different trajectories have essentially disappeared at 30, 000 ft. altitude and have disappeared completely at 20, 000 ft. altitude. Therefore, over the altitude interval of interest for parachute deployment the dynamic pressure level is essentially a constant value independent of variations in booster staging trajectory conditions over the range considered.

EFFECT OF BOOSTER STAGING CONDITIONS ON VARIATION OF DYNAMIC PRESSURE WITH ALTITUDE

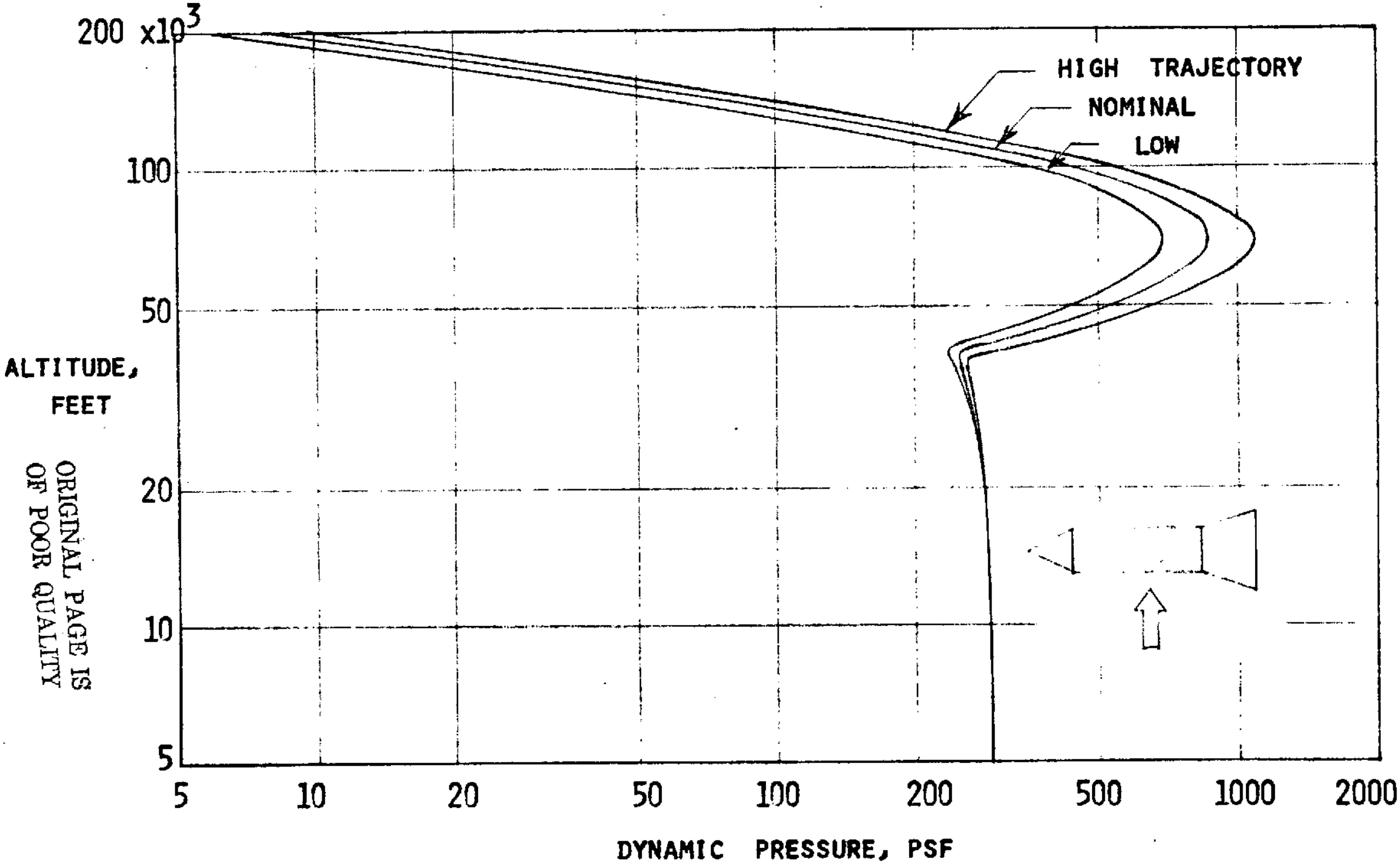

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Figure 6

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SECTION II

PARAMETERS AFFECTING WEIGHT

PARAMETERS AFFECTING THE WEIGHT OF A PARACHUTE RECOVERY SYSTEM

The design of a parachute system requires a knowledge of a number of technologies and the consideration of a number of parameters. Some of the most important parameters are listed in figure 7. Each of the individual items given are discussed on subsequent pages; of particular interest are items 1 and 3 which are most affected by new technology.

PARAMETERS AFFECTING THE WEIGHT OF A PARACHUTE RECOVERY SYSTEM

1. MATERIAL STRENGTH TO DENSITY RATIO
2. PARACHUTE DIAMETER AND CLUSTER NUMBER REQUIREMENTS
3. NUMBER OF REEFING STAGES
4. PARACHUTE DRAG EFFICIENCY
5. PARACHUTE DESIGN FACTORS
6. SUSPENSION SYSTEM LENGTHS-TRAILING DISTANCE REQUIREMENTS
7. DYNAMIC PRESSURE AT PARACHUTE DEPLOYMENT

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Figure 7

TENSILE PROPERTIES OF VARIOUS STRUCTURAL FILAMENTS

The tensile properties of various structural filaments, which could conceivably be considered for construction of parachute component parts, are presented in figure 8. The relationship between the strength to density ratio and the modulus of elasticity to density ratio for filaments of each type material is shown. Nylon, which is currently used for most parachute construction today, has both a low strength and a low modulus of elasticity ratio compared to the range of material data shown. Dacron, which is used today for some special parachute applications is in the same range as Nylon. On the right side of the figure we have some materials that are of interest for composite structures on aircraft and space vehicles. In the upper left corner of the figure are data on a new family of materials referred to as Fiber B and PRD-49. Filaments of these materials can easily be made into lines, cords, tapes, ribbons, webbings and fabrics as needed for parachute construction. Because the Fiber B and PRD-49 materials have such excellent tensile strength and a lower modulus of elasticity ratio we consider them to be our "1980 materials" for fabricating parachutes. As noted on the figure we have assumed that changing from Nylon to Fiber B and PRD-49 would provide a 2.2 increase in material strength to density ratio. Although Fiber B and PRD-49 are already being introduced into parachute systems in limited applications, there are still areas of technology development needed before these materials will be fully ready for use. These include the need for a complete evaluation of mechanical and environmental properties, development of seaming and joining techniques for fabrics, tapes, lines, etc., and an evaluation of the effects of the higher material modulus of elasticity on the dynamic loads encountered during the parachute deployment sequence.

TENSILE PROPERTIES OF VARIOUS STRUCTURAL FILAMENTS

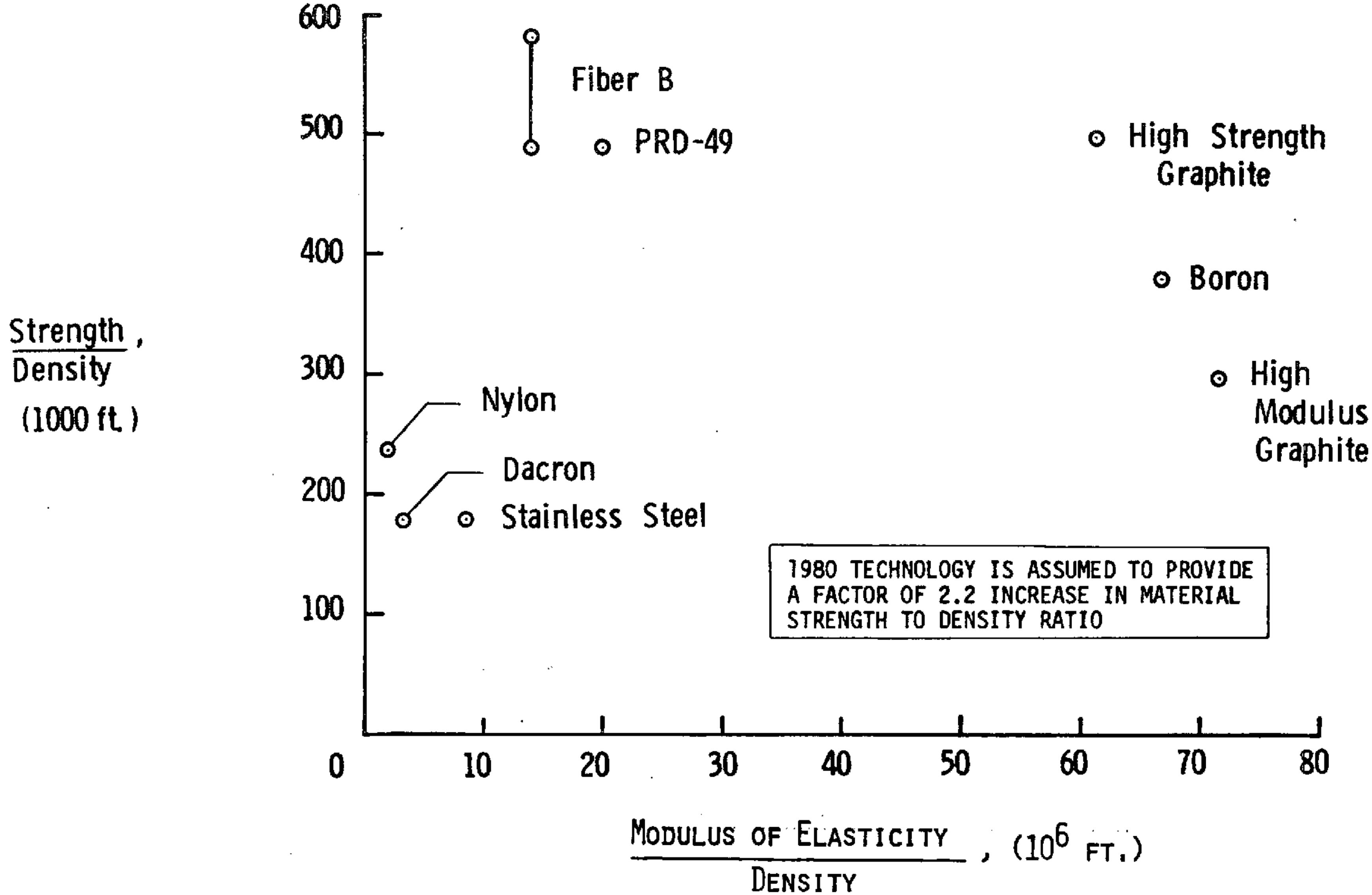


Figure 8

PARACHUTE DIAMETER AND CLUSTER NUMBER REQUIREMENTS

Figure 9 presents parachute diameter and cluster number requirements as a function of impact velocity for the recovery of a one million-pound parachute-payload system. The drag efficiency of the parachute system decreases as the number of parachutes in the cluster (N) increases as given by the expression for cluster C_{D_o} on the figure. The cluster C_{D_o} equation is based on a ribbon type individual-parachute C_{D_o} of 0.55. For this study we are interested specifically in impact velocities of 30 and 60 ft/sec as indicated by the dashed vertical lines on the figure. At an impact velocity of 60 ft/sec we have a choice of several parachute diameters and cluster number relationships. For instance a cluster of 5 parachutes of 350 ft diameter would provide the desired impact velocity of 60 ft/sec. There is less selection for an impact velocity of 30 ft/sec but a cluster of 7 or 10 parachutes of 540 to 600 ft diameter will do the job. As the required impact velocity decreases the parachute diameter and cluster number requirements increase rapidly.

PARACHUTE DIAMETER AND CLUSTER NUMBER REQUIREMENTS
(ALL PARACHUTE SYSTEM - RIBBON TYPE)

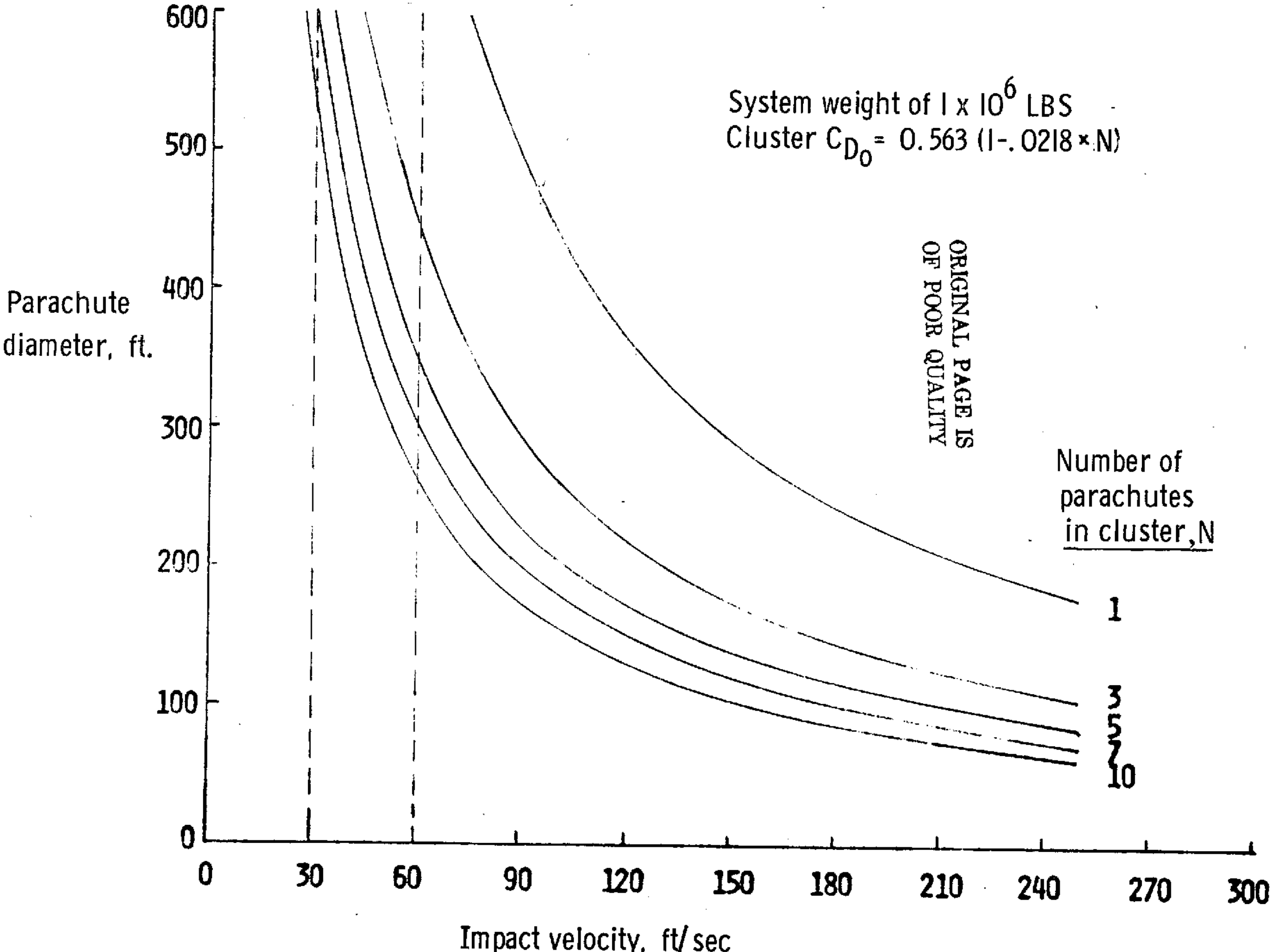


Figure 9

PARACHUTE OPENING LOAD CONTROL

The effects of reefing on parachute opening load are presented in figure 10. Parachute opening load (force) versus time curves are shown for three different kinds of parachute deployment methods. The upper force-time curve is typical of a parachute deployed with no reefing. The center force-time curve is typical of a parachute with two reefing stages and a final full open stage. The lower solid line is typical of what the force-time curve would be if a continuous disreefing system were used. The lower dashed line is the level at which the parachute force is equal to the system weight. This is the parachute force level during equilibrium descent conditions. Obviously a parachute system designed to withstand an unreefed deployment must be much stronger and therefore heavier than a parachute system with reefing capability. Many currently used parachute systems utilize 1 or 2 stages of reefing. Continuous disreefing systems have been used on an experimental basis and for special applications. The use of a continuous disreefing system for the recovery of a one million-pound payload would require the development of some new technology. Specifically a friction or servo system is needed which is capable of controlling the rate of parachute area increase such that a prescribed maximum force level is not exceeded. A significant amount of large scale testing of such a system would be required.

PARACHUTE OPENING LOAD CONTROL

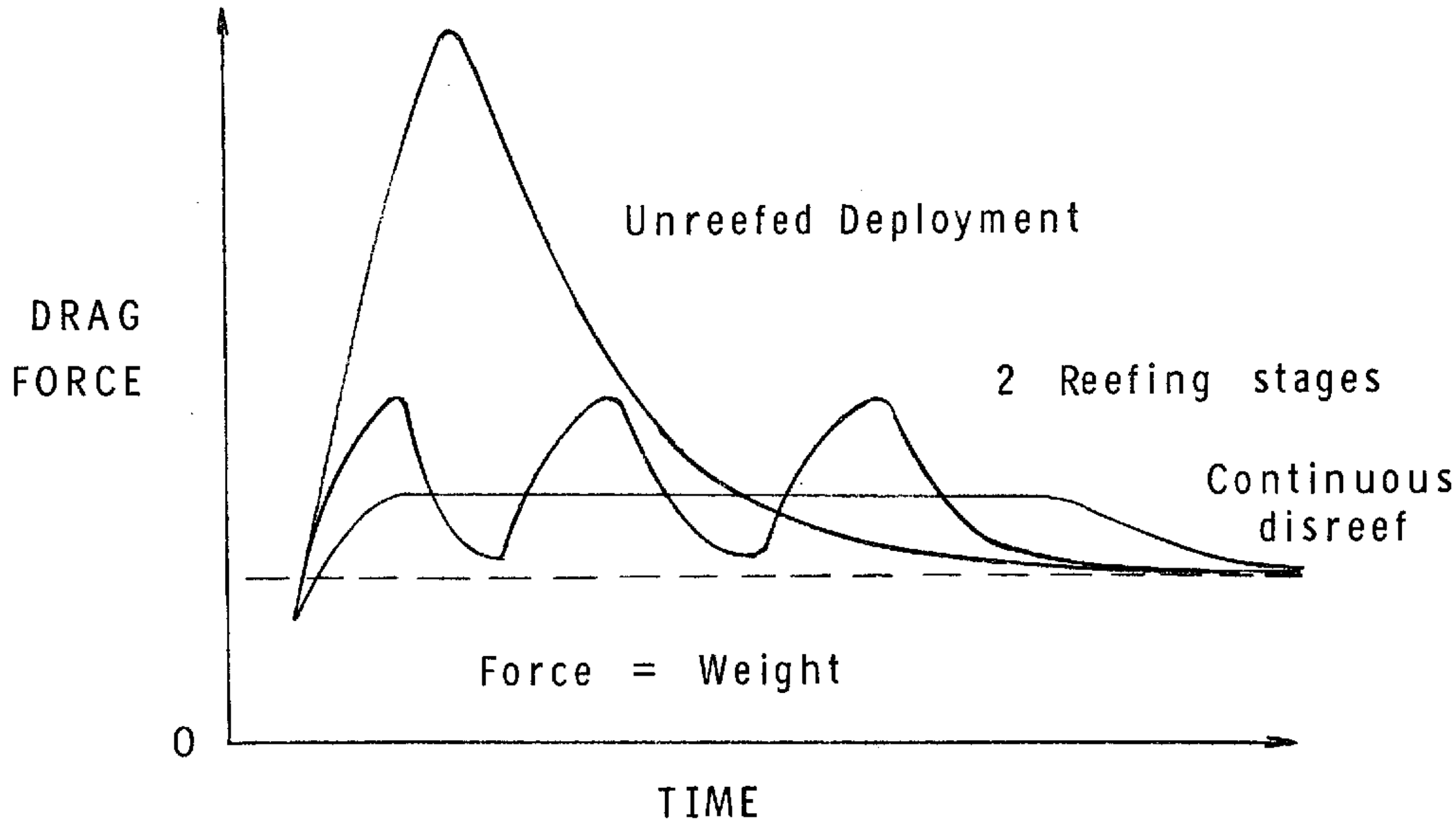


Figure 10

PARACHUTE DRAG EFFICIENCY

Figure 11 presents information showing how parachute drag coefficient, C_{D_o} , changes with equilibrium dynamic pressure levels and/or the terminal velocity at sea level. A C_{D_o} range for various parachute types is shown which breaks down into two general categories of parachutes (Solids and Ribbons). Most slotted and vented parachute types such as the ringsail parachute used on Apollo are included in the general category of solids as opposed to the more specific ribbon parachute category. If we choose to decelerate the booster to impact velocities of 30 or 60 ft/sec with an all parachute system we would be interested in solid type designs for the main parachutes. For a hybrid (parachute-retrorocket) system we would be interested in ribbon-type parachutes. We have also shown a point for a hypothetical 1980 parachute of reduced geometric porosity with an improved drag coefficient. Our studies indicate that although such an improved parachute would be smaller in diameter, it would be negligibly different in weight from the ribbon type parachute.

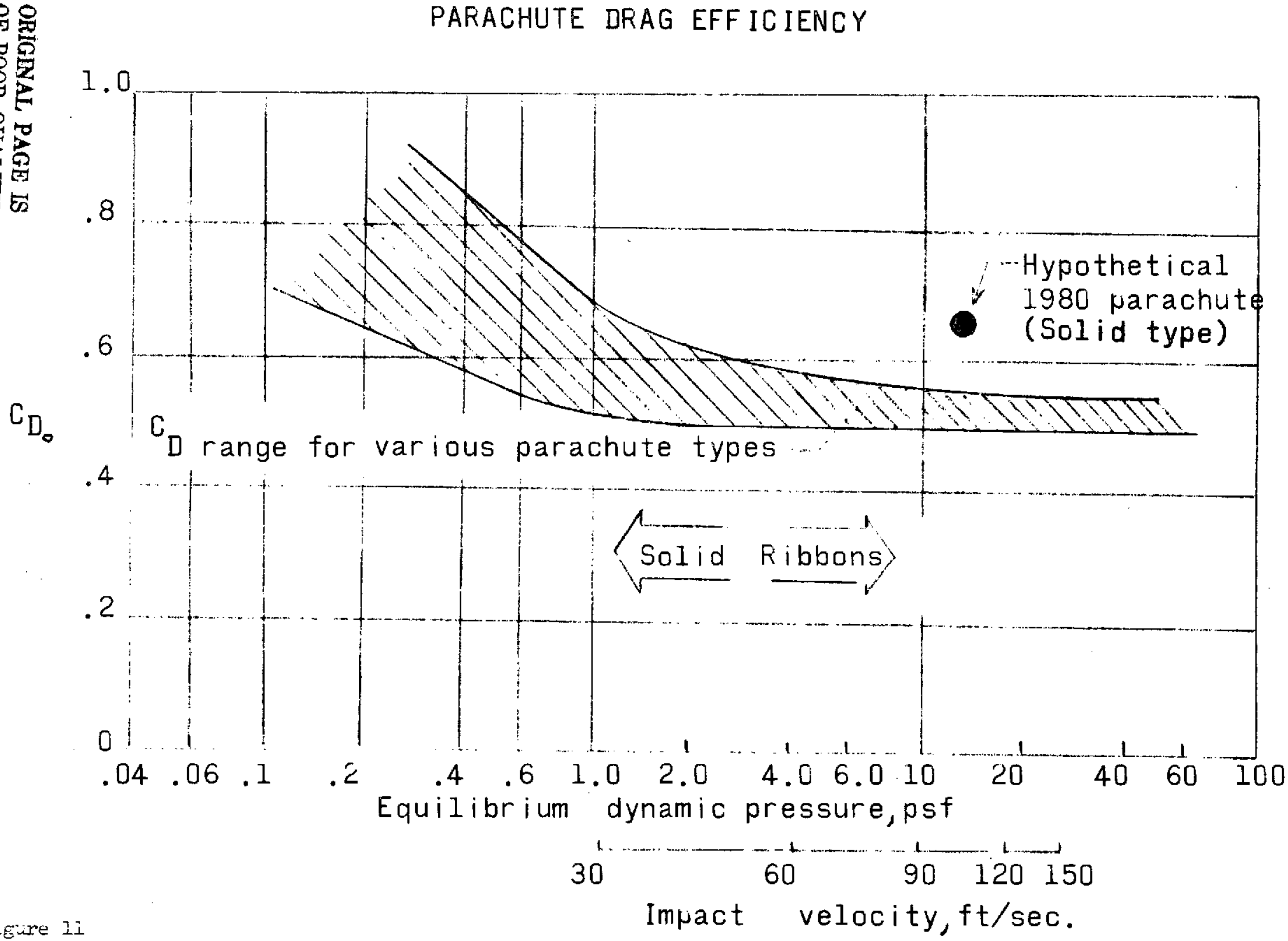

PARACHUTE DRAG EFFICIENCY
1.0
.8
.6
.4
.2
0
C_{D_o}
C_D range for various parachute types
Hypothetical
1980 parachute
(Solid type)
Solid
Ribbons
.04
.06
.1
.2
.4
.6
1.0
2.0
4.0
6.0
10
20
40
60
100
Equilibrium dynamic pressure, psf
30
60
90
120
150
Impact velocity, ft/sec.

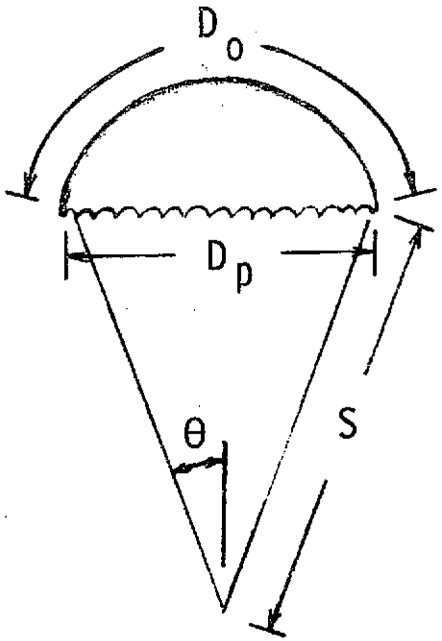
Figure 11

TYPICAL PARACHUTE DESIGN FACTORS

ITEM	SYMBOL	TYPICAL VALUES
SAFETY FACTOR	a	1.50
UNSYMMETRICAL LOADING FACTOR	b	1.05
SUSPENSION LINE CONVERGENCE ANGLE FACTOR	c	1.03
SEAM OR JOINT EFFICIENCY FACTOR	d	0.80
ABRASION DEGRADATION FACTOR	e	0.90
TEMPERATURE DEGRADATION FACTOR	f	0.90
DESIGN FACTOR	$\frac{abc}{def}$	2.50

Figure 12

SUSPENSION LINE LENGTH RELATION TO PARACHUTE TYPE



- o Parachute inflated diameter*, D_p, varies with canopy porosity (λ) and suspension line length (S) or pull angle (θ)

- o Suspension line length (S) to parachute nominal diameter (D_o) ratios vary typically from $S/D_o = 0.85$ for solid flat cargo parachutes to $S/D_o = 2.0$ for high porosity supersonic ribbon parachutes

* D_p is typically about 2/3 D_o

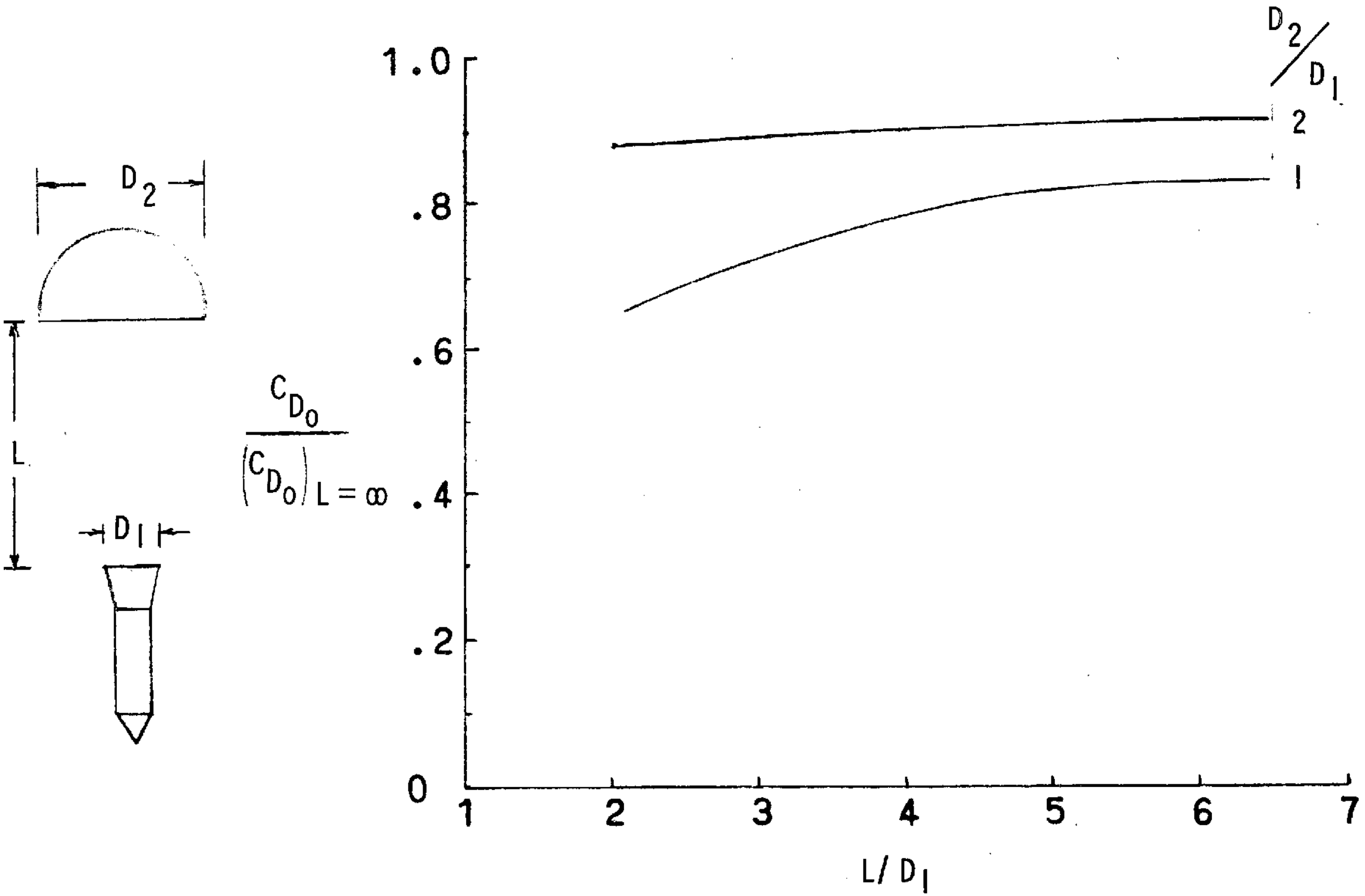
Sketch is correct for flat circular parachutes and approximately correct for most shaped gore parachutes

Figure 13

PARACHUTE TRAILING DISTANCE CONSIDERATIONS

Figure 14 presents typical parachute trailing distance considerations for minimization of drag loss for the parachute. The drag coefficient C_{D_o} of the parachute at a distance behind a forebody is ratioed to its C_{D_o} when the trailing distance is equal to infinity (i.e., no forebody body wake interference) and presented as a function of trailing distance in terms of maximum diameters of the primary body. Curves are shown for two secondary to primary body diameter ratios (D_2/D_1). Clearly, as the diameter of the trailing body increases the wake effects of the primary body become less. For the booster recovery study the trailing distance is of concern primarily when the parachutes are in the reefed mode. As indicated on the figure, typical trailing distance selections are in the range of 6 to 10 forebody diameters.

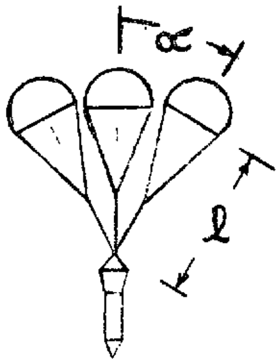
PARACHUTE TRAILING DISTANCE CONSIDERATIONS



Typical selection is L/D_1 = 6 to 10

Figure 14

SUSPENSION SYSTEM LENGTHS FOR VARIOUS CLUSTER NUMBERS



Maximum allowable α (parachute collapse point) varies with parachute type and porosity (λ)

α controlled by increasing suspension system length ℓ (riser + suspension line)

Typical cluster number-suspension system length relationships for subsonic parachute systems:

Cluster number, n	Suspension system length ratio, ℓ/D_o
1	1.00
3	1.50
5	1.75
7	2.00
10	2.25

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Figure 15

FACTORS INFLUENCING DEPLOYMENT DYNAMIC PRESSURE

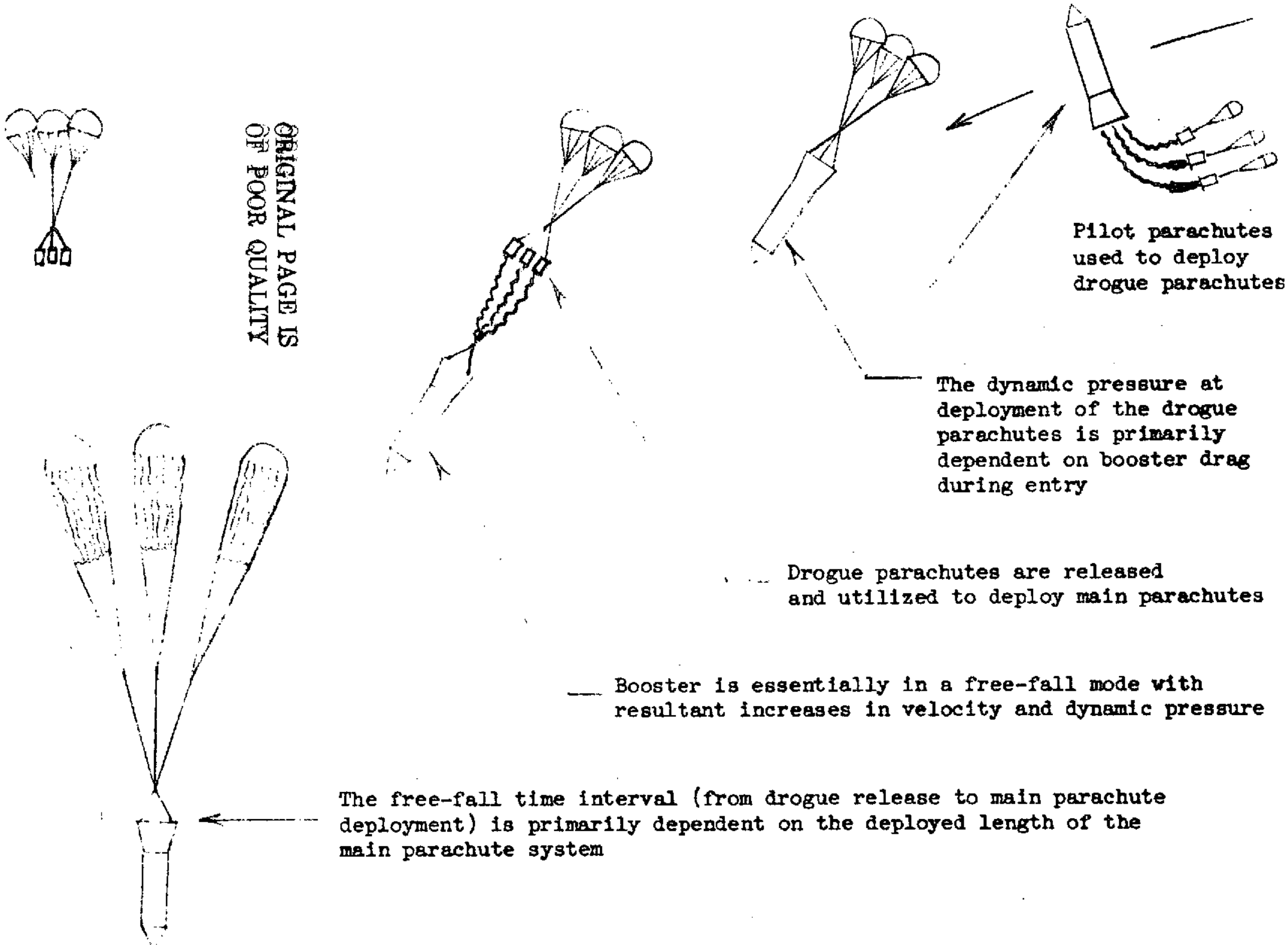

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Figure 16

PARACHUTE WEIGHT EQUATION*

PARACHUTE WEIGHT = WEIGHT OF RISERS AND SUSPENSION LINES + CANOPY FABRIC

$$= \frac{bq}{K_E} (C_{D_o} A)^{3/2} + c\, d_f\, (C_{D_o} A)$$

WHERE

q	FREE STREAM DYNAMIC PRESSURE	QUANTITIES UNAFFECTED BY 1980 MATERIALS TECHNOLOGY
C_{D_o}	DRAG COEFFICIENT	
A	REFERENCE AREA	
b, c	CONSTANTS DEPENDENT ON PARACHUTE GEOMETRY AND PERFORMANCE	
K_E	STRENGTH TO MASS RATIO OF SUSPENSION LINES	QUANTITIES AFFECTED BY 1980 MATERIALS TECHNOLOGY
d_f	CANOPY WEIGHT PER UNIT AREA	

* FROM NASA TN D-5535

Figure 17

EXPLANATION OF WEIGHT EQUATION CONSTANTS

$$b = \frac{K_D}{\pi^{1/2} \cos\theta} \cdot \frac{\bar{q}}{q} \cdot \frac{\rho \ell_s}{D_o} \cdot \frac{1}{K_e (C_{D_o})^{1/2}} , \quad c = \frac{K_c}{C_{D_o}} (1 - \lambda)$$

WHERE

K_D = THE PARACHUTE DESIGN FACTOR

θ = CONFLUENCE ANGLE OF THE SUSPENSION LINES

$\bar{q}/q$ = PARACHUTE OPENING SHOCK FACTOR

ρ = RATIO OF LENGTH OF SUSPENSION LINE LOOP TO LENGTH OF SUSPENSION LINE

ℓ_s = LENGTH OF SUSPENSION LINE

D_o = DIAMETER OF PARACHUTE

K_c = CONSTRUCTION EFFICIENCY FACTOR

C_{D_o} = DRAG COEFFICIENT

λ = GEOMETRIC POROSITY

Figure 18

NASA Langley

PARAMETER VALUES USED FOR PARACHUTE WEIGHT CALCULATIONS

PARAMETER	SYMBOL	VALUE USED
Parachute diameter	D_o	100 to 600 ft
Parachute design factor	K_D	2.9
Suspension line confluence angle	θ	20.5^o
Opening shock factor	$\bar{q}/q$	1.1
Suspension line strength to mass ratio	K_E	175,000 ft (Nylon) 385,000 ft (Fiber B)
Drag coefficient	C_{D_o}	0.55
Construction efficiency factor	K_C	1.25
Geometric porosity	λ	0.25
Suspension line length ratio	l_s/D_o	1.0
Riser length requirement	r/D_o	see below
Minimum required suspension system length	(l_s+r)	480 ft
Ratio of suspension line loop length to length of suspension line	ρ	$2 + \frac{1}{1+r/D_o}$

Riser length requirement, r/D_o:

m	1	3	5	7	10
r/D_o	0	0.50	0.75	1.00	1.25

Figure 19

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SECTION III

ALL-PARACHUTE RECOVERY SYSTEM

ALL-PARACHUTE RECOVERY SYSTEM

One possible decelerator system for recovery of heavy payloads is an all parachute recovery system. A schematic of how this system would operate is presented as figure 20. A high angle-of-attack entry is required to bring the booster to subsonic velocities and dynamic pressure levels reasonable for parachute deployment. An all-parachute recovery system would include drogue parachutes to provide deceleration before the main parachute system is utilized. The drogues would be deployed at an altitude of 30,000 ft, a velocity of 770 ft/sec and a dynamic pressure of 260 psf. To keep parachute opening forces down the drogue would have two reefing stages in addition to the full open stage. At about 20K ft, the drogue parachute would be released and used to deploy the main parachutes. The main parachutes would also have two stages of reefing and a full open stage. When the main parachutes are fully opened, they must be of sufficient size and number to decelerate the system to the desired sea level impact velocity.

ALL PARACHUTE RECOVERY SYSTEM

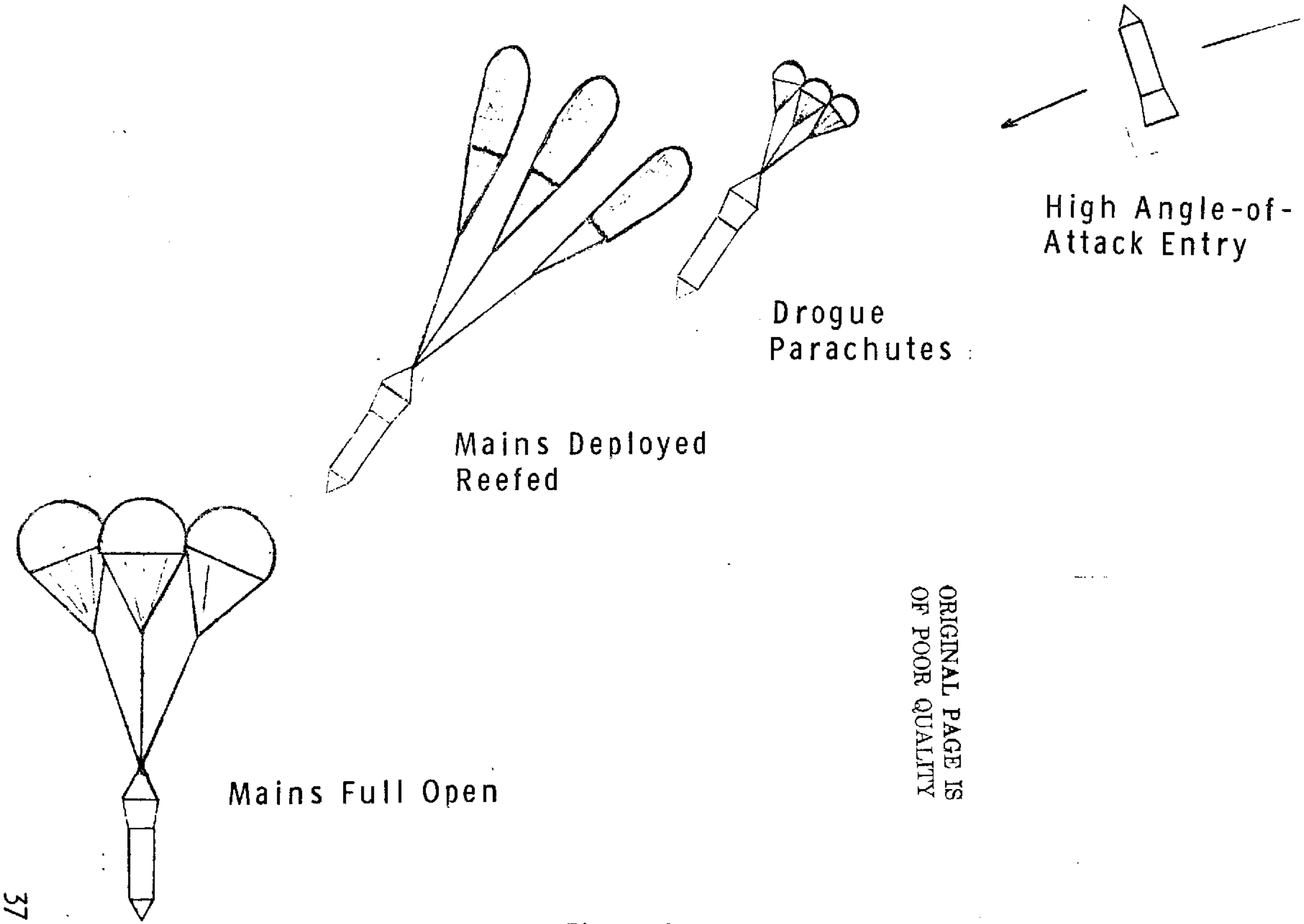

Figure 20

DYNAMIC PRESSURE CHANGES DURING THE ENTIRE PARACHUTE DEPLOYMENT SEQUENCE

The dynamic pressure changes which occur with the various stages of parachute deployment are presented in figure 21 for a typical all-parachute recovery system with a final impact velocity of 30 ft/sec. The drogue parachutes are first deployed at 30,000 ft altitude. The three drogue parachute deceleration stages bring the system to a dynamic pressure level of 10 psf at 20,000 ft altitude. At this time the drogue parachutes are released and used to deploy the main parachutes. Because the main parachutes are very large the booster dynamic pressure increases to a level of about 32 psf before the main parachutes develop sufficient drag area to slow the booster again. The three stages of main parachute deceleration bring the booster to an equilibrium dynamic pressure level of just over one psf which is equivalent to a velocity of 30 fps at sea level.

DYNAMIC PRESSURE CHANGES DURING PARACHUTE DEPLOYMENT SEQUENCES

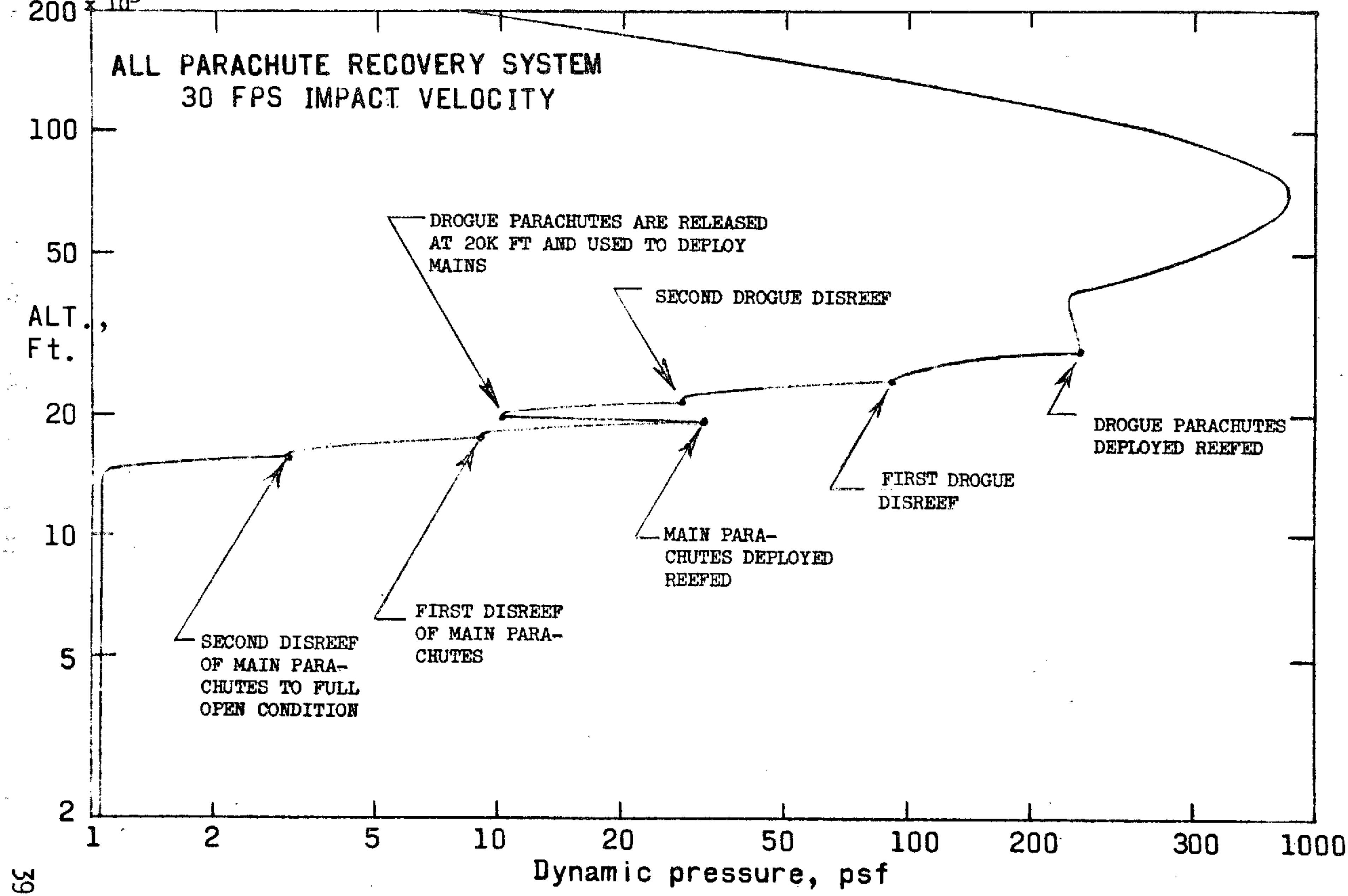

Figure 21

WEIGHT OF AN ALL PARACHUTE RECOVERY SYSTEM

A tabulation of estimated weights for all-parachute-recovery systems capable of decelerating a one million-pound booster to terminal velocities of either 60 or 30 ft/sec is presented in figure 22. The tabulated data indicate that a terminal velocity of 60 ft/sec can be attained for a decelerator system weight of about 67,000 pounds (27,000 pounds for drogue parachutes plus 40,000 pounds for the main parachutes). For an impact velocity of 30 ft/sec the weight of the drogue parachutes selected increases to 31,000 pounds. The number and diameter requirements of the main parachutes (10 each at 550 ft diameter) increases significantly as does the weight (135,000 pounds). Although drogue parachutes and main parachutes were used to achieve both of the listed impact velocities it will be shown later that the 60 ft/sec terminal velocity condition could have been achieved without drogue parachutes for about the same total declerator system weight. Although 1980 materials technology will probably be available, there are no programs to develop parachutes of sizes listed (D_o > 200 ft).

WEIGHT OF AN ALL PARACHUTE RECOVERY SYSTEM

(BASED ON 1980 MATERIALS TECHNOLOGY)

TERMINAL VELOCITY	DROGUE PARACHUTES	MAIN PARACHUTES	DECELERATOR SYSTEM WEIGHT	SYSTEM WEIGHT AT IMPACT
60 FT/SEC	3 EA 250 FT D_0 WT = 27,000 LB	5 EA 350 FT D_0 WT= 40,000 LB	67,000 LB	1,040,000 LB
30 FT/SEC	3 EA 300 FT D_0 WT = 31,000 LB	10 EA 550 FT D_0 WT = 135,000 LB	166,000 LB	1,135,000 LB

Figure 22

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SECTION IV

PARACHUTE-RETROROCKET RECOVERY SYSTEM

HYBRID (PARACHUTE-RETROROCKET) RECOVERY SYSTEM

A second recovery system concept which can be utilized is a hybrid (parachute-retrorocket) recovery system. Figure 23 presents a schematic showing how such a system would function. Again, a booster entry at a high angle-of-attack is required to decelerate the system to subsonic velocities and sufficiently low values of dynamic pressure. Then, at the parachute deployment altitude (20,000 ft for this study) the main parachutes would be deployed with 2 stages of reefing. With the parachute deployments occurring at about 20,000 ft, the main parachutes will reach the full open condition at about 17,000 ft. Shortly before touchdown the retrorockets would be fired to slow the booster to the desired impact velocity.

HYBRID (PARACHUTE-RETROROCKET) RECOVERY SYSTEM

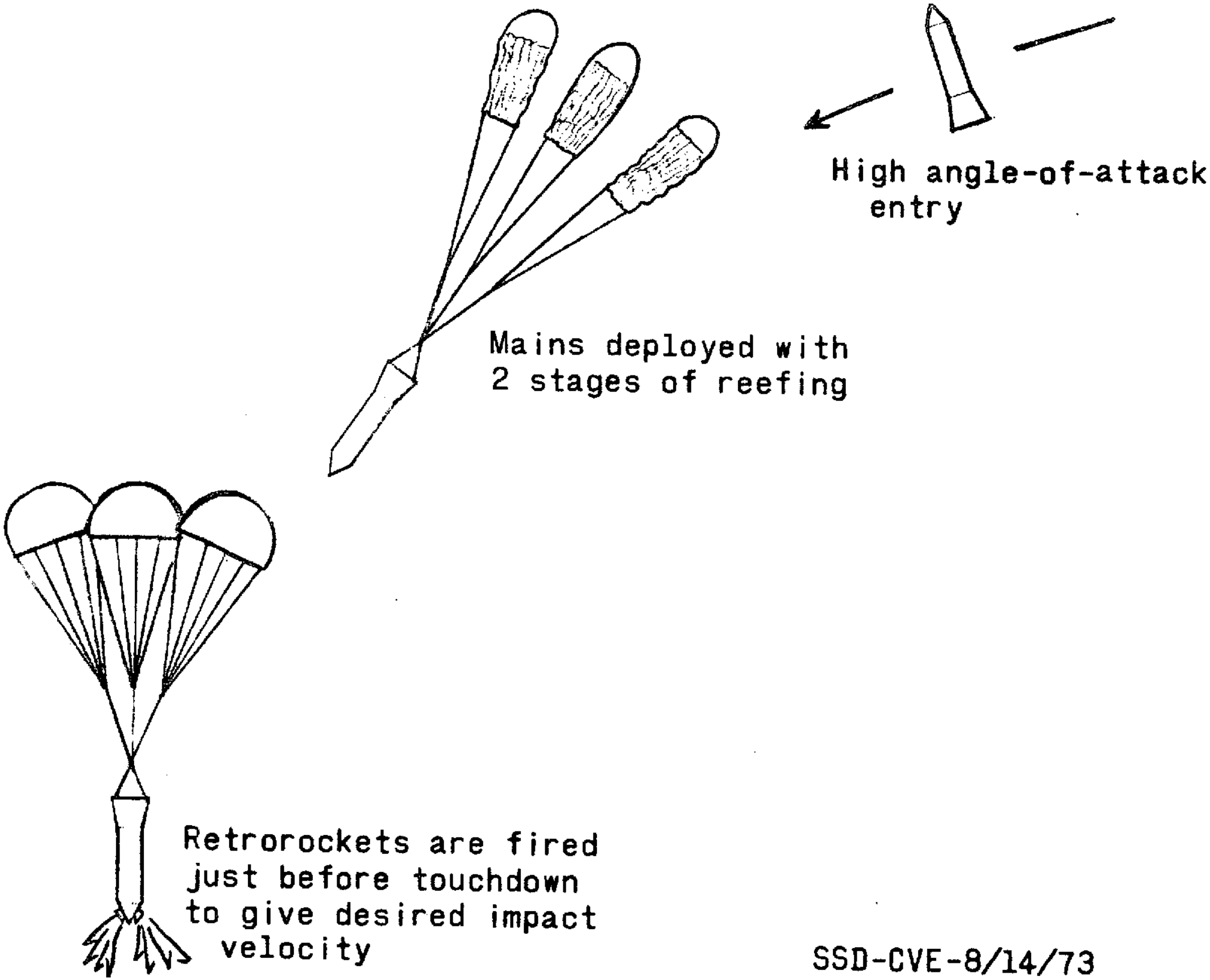

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Figure 23

HYBRID SYSTEM OPTIMIZATION

The reason for looking at a hybrid system is that it has a potential for providing a lighter weight recovery system than an all-parachute system. In fact, there is an optimum combination of parachute and retrorocket systems and the purpose of figure 24 is to demonstate how such an optimum system is determined.

The way in which the weight of parachute systems vary with the terminal velocity they provide is illustrated in the upper left hand corner of figure 24. Clearly as the impact velocity required goes down, the weight of the parachute system will rise very rapidly. For the present discussion an impact velocity of V_I will be specified which, for an all parachute system, yields the weight point labeled on the sketch in the upper left.

It has been determined that for low impact velocities a combined parachute-retrorocket decelerator system is often lighter in weight than an all parachute system. The sketch in the upper right hand corner indicates that the weight of a retrorocket system will vary almost linearly with the amount of velocity decrement it must provide. The factors which affect the slope of the retrorocket weight versus ΔV curve are indicated in figure 25; values of the parameters used in this study are listed in figure 26. If a retrorocket system is added to an all parachute system, we have the situation depicted in the sketch in the lower left hand corner. The parachute system chosen has a terminal velocity capability of V_T so that the retrorocket must provide a velocity decrement ΔV to bring the hybrid (retrocket-parachute) system to the desired impact velocity V_I. It is clear for the case illustrated that the hybrid system weight is less than the all parachute system weight.

If we go through this same process for a number of parachute systems along the parachute weight curve with terminal velocities greater than V_I, it will become evident that there is a minimum weight parachute-retrorocket combination. The sketch in the lower right depicts this process. The parachute system which will provide a terminal velocity of V_{T_1} when combined with a retrorocket to achieve an impact velocity of V_T yields a combined system weight of W_1. A second system is chosen such that the retrorocket weight curve (the dashed line) is tangent to the parachute weight curve. This parachute system has a terminal velocity capability of V_{T_2} and a combined system weight W_2. A third system is also indicated with a parachute terminal velocity of V_{T_3} and a weight W_3. The system determined by the point at which the retrorocket weight curve was tangent to the parachute weight curve, V_{T_2}, provides the minimum weight hybrid decelerator system. Conversely, every other parachute-retrorocket system will yield a total system weight greater than W_2. In the discussion to follow the minimum weight hybrid systems shown were determined by the procedure just described.

HYBRID SYSTEM OPTIMIZATION

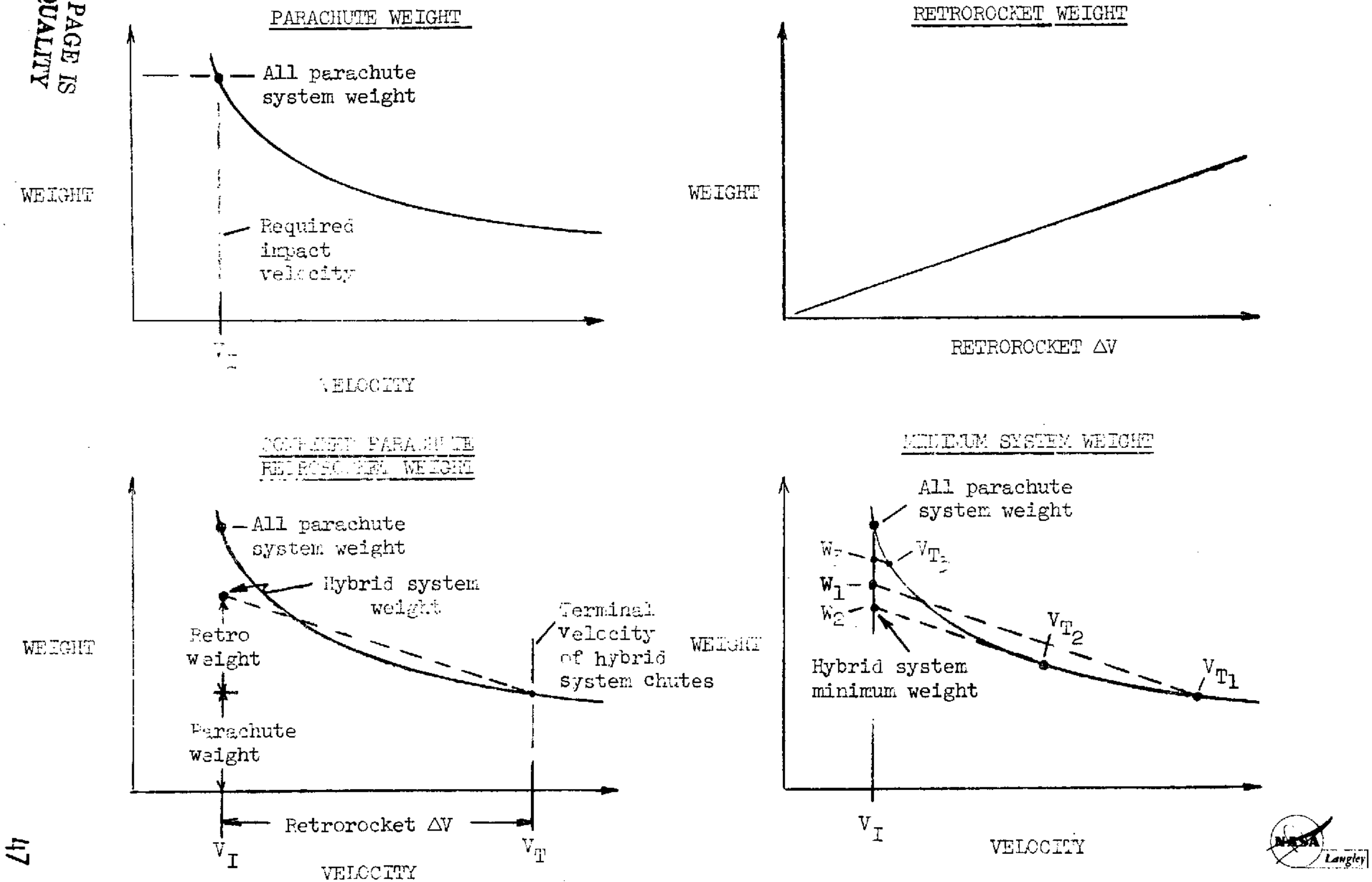

Figure 24

RETROROCKET REQUIREMENTS

Figure 25 presents the retrorocket requirements for a hybrid parachute retrorocket system. The retrorocket weight equation used in this analysis is presented on the left with an explanation of the terms used and also a presentation of the equation used to determine the required thrust time in seconds. On the right is a schematic showing the forces involved. Also given is the classical equation of the summation of forces equaling the mass times acceleration. Factors which influence the weight of a parachute system and the weight equation used were presented earlier.

RETROROCKET REQUIREMENTS

$$\text{Retrorocket weight} = \frac{(t)(T)}{(S.I.)(M.F.)}$$

where

t = thrust time, sec
T = thrust, lbs
S.I. = propellant specific impulse
M.F. = propellant mass fraction

$$W - T - D = \frac{W}{g}\frac{dV}{dt}$$

$$t = \frac{1}{g}\int_{V_{ignition}}^{V_{impact}} \frac{dV}{\left(\frac{T}{W} - 1\right) + \left(\frac{D}{W}\right)}$$

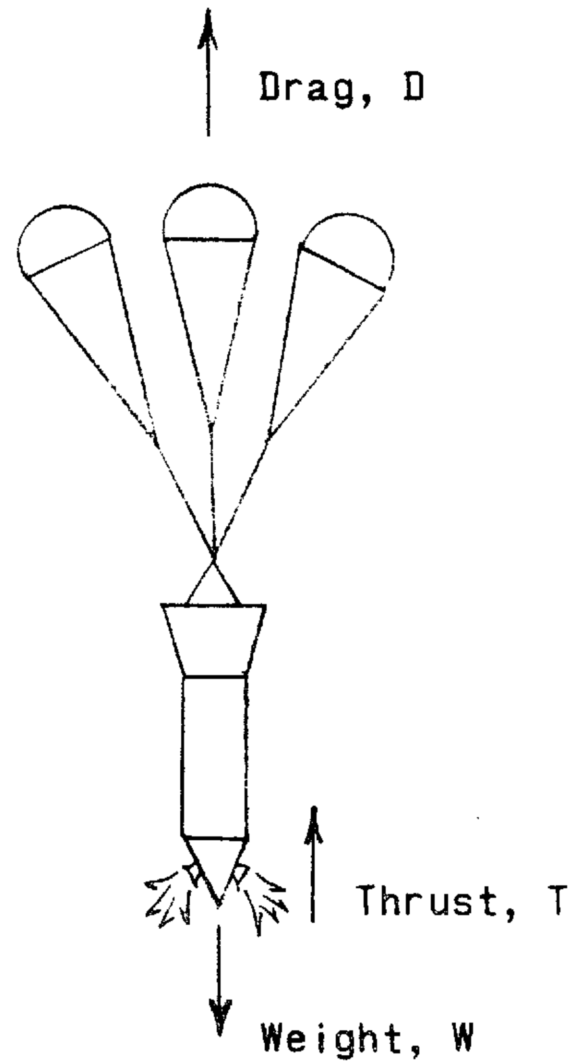

Figure 25

PARAMETER VALUES USED FOR RETROROCKET WEIGHT CALCULATIONS

PARAMETER	SYMBOL	VALUE USED
Ratio of retrorocket thrust to system weight	T/w	3
Propellant Specific Impulse, sec.	S.I.	250 (1973) 275 (1980)
Propellant Mass Fraction	M.F.	0.90 (1973) 0.92 (1980)

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igure 26

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DECELERATOR SYSTEM WEIGHT USING 1980 MATERIALS

Utilizing the technique described in connection with figure 24, a determination was made of a minimum weight hybrid decelerator system using 1980 materials for a cluster of 3 parachutes with 2 stages of reefing. Decelerator system weight is plotted versus impact velocity on figure 27 with tick marks denoting the parachute diameters associated with a number of points on the curve. Both the parachute weight curve and a minimum hybrid system weight curve are shown. The curves are tangent at a system velocity of just over 100 ft/sec. Three parachutes of 260-ft diameter are required to slow the system to this velocity for retrorocket ignition. At an impact velocity of 60 ft/sec the hybrid system weight would be on the order of 36,000 lbs. At 30 ft/sec impact velocity an additional 6,000 lbs of retrorocket weight are required bringing the total hybrid system weight to 42,000 lbs. A further decrease of 30 ft/sec to bring the impact velocity to 0 ft/sec will require the same retrorocket-weight increase as that used in going from 60 ft/sec to 30 ft/sec. Therefore, an impact velocity of 0 ft/sec can be obtained for a total system weight of about 48,000 lbs. The decelerator configuration of 3 parachutes with 2 stages of reefing just described has been used in subsequent discussion as the baseline or reference system.

DECELERATOR SYSTEM WEIGHT USING 1980 MATERIALS
(cluster of 3 parachutes with 2 stages of reefing)

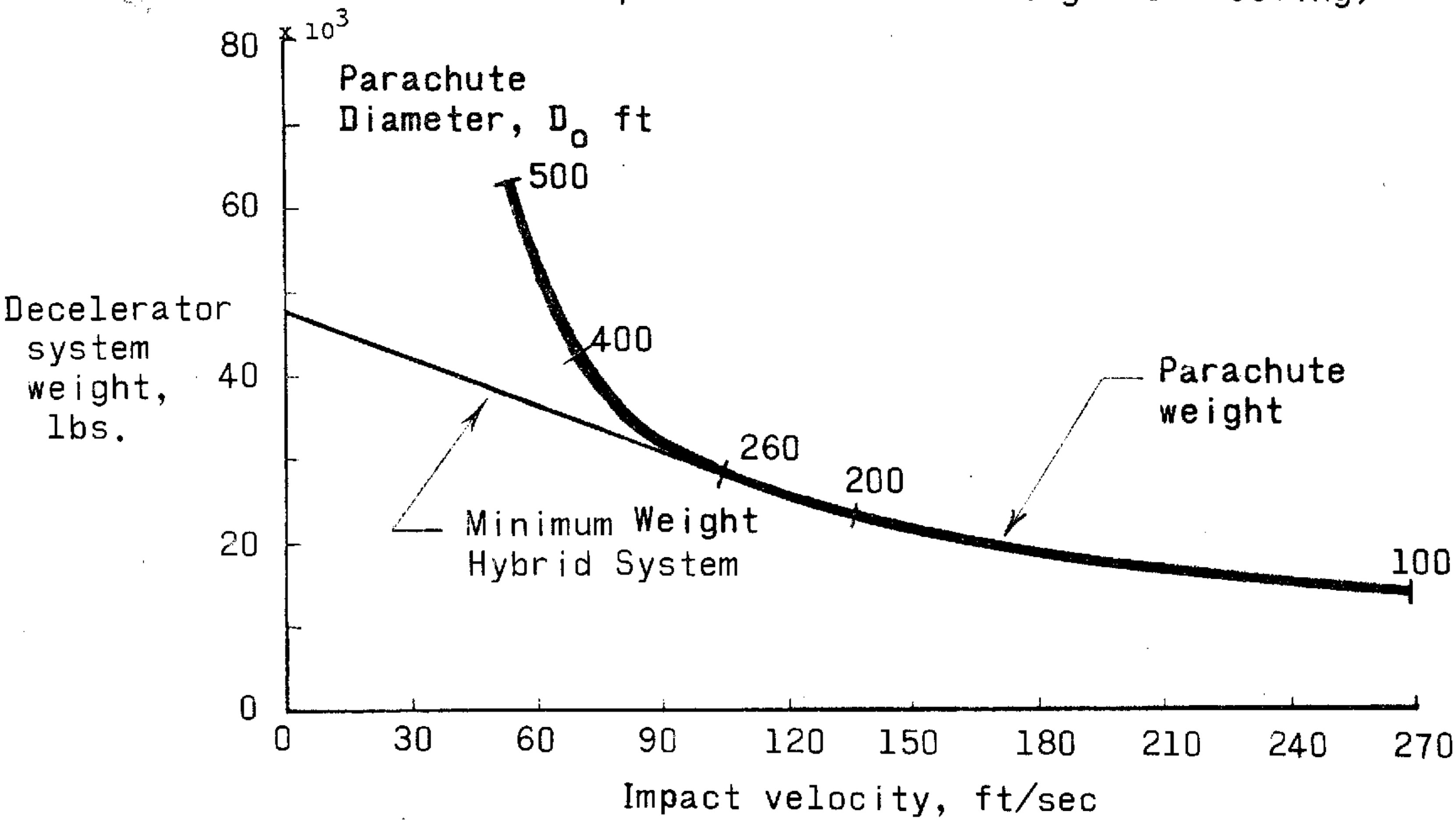

Figure 27

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GEOMETRY FOR A 1980 3-PARACHUTE SYSTEM

The decelerator system just described is obviously a very large one (parachute D_o = 260 ft). To give a better idea of the geometric relationships of the parachute and booster systems, a sketch of the 1980 3-parachute hybrid system is presented in figure 28. The 480-ft trailing distance shown on the figure was used throughout this analysis as a requirement to minimize wake effects of the booster, particularly for intervals where the parachutes are reefed to much smaller diameters. The parachute system shown is that which would be used for a hybrid system designed for impact velocities less than 100 ft/sec.

GEOMETRY FOR 3-PARACHUTE HYBRID SYSTEM (1980 MATERIALS TECHNOLOGY)

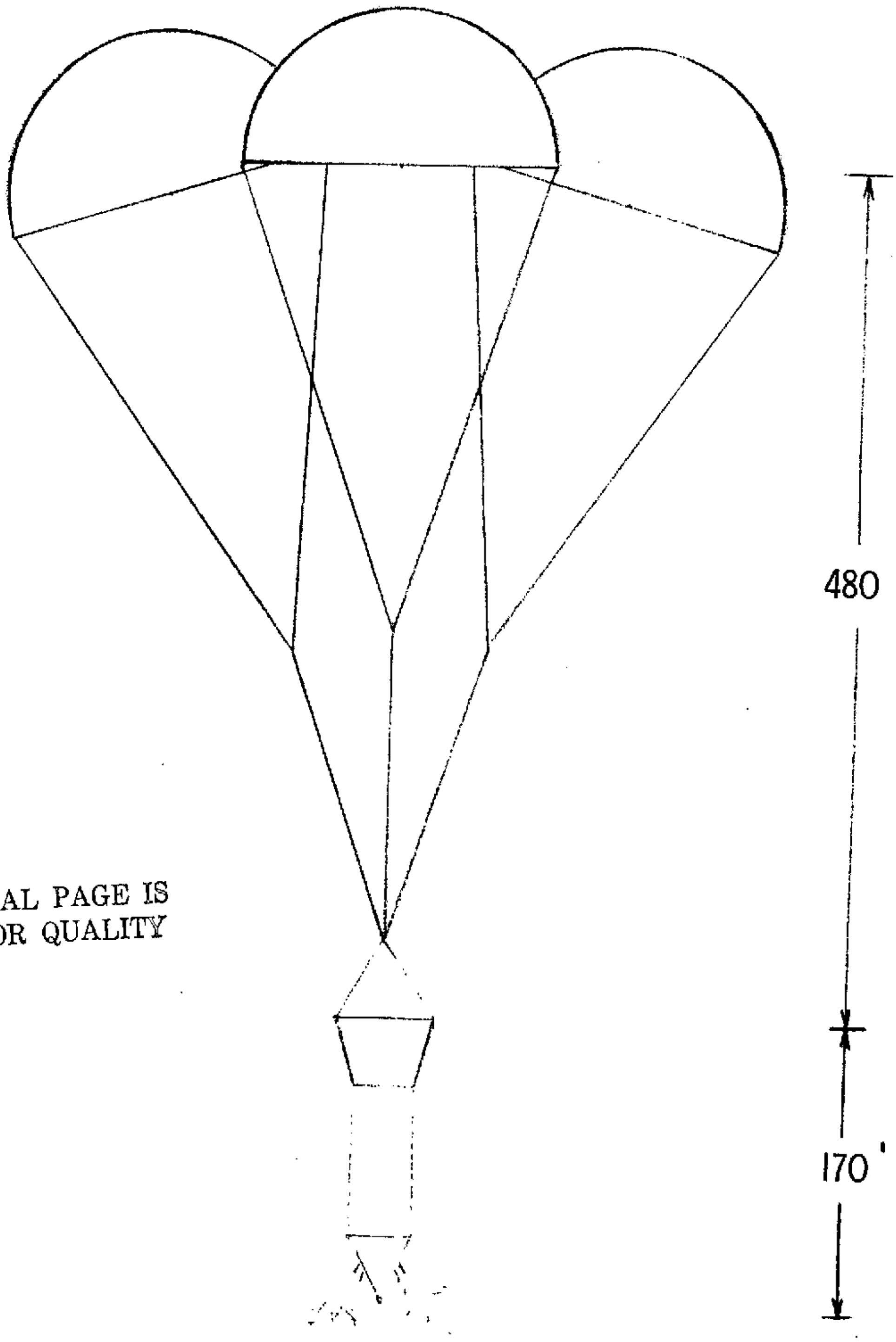


Figure 28

WEIGHT PENALTY FOR USING PARACHUTES SMALLER THAN OPTIMUM

It may be that parachutes greater than 200 ft diameter, such as required for our baseline system, may not constitute 1980 technology. In order to show the weight penalties sustained for using parachutes smaller than optimum, figure 29 is presented. In this figure the hybrid system weight is plotted as a function of the diameter of the parachutes used. As mentioned previously, the minimum weight system was achieved with 3 parachutes of 260-ft diameter each. For each of the impact velocity weight curves shown, the minimum weight is at the right hand end of each curve. Note that the curves are parallel and spaced about 6000 lbs apart. For any of these terminal velocities we could reduce the size of each of the parachutes by 100 ft, a change from using 260-ft diameter parachutes to using 160-ft diameter parachutes, for a weight penalty of about 4000 lbs. Further parachute size reductions would result in more significant weight increases as the system is getting further away from the optimum condition.

WEIGHT PENALTY FOR USING PARACHUTES SMALLER THAN OPTIMUM

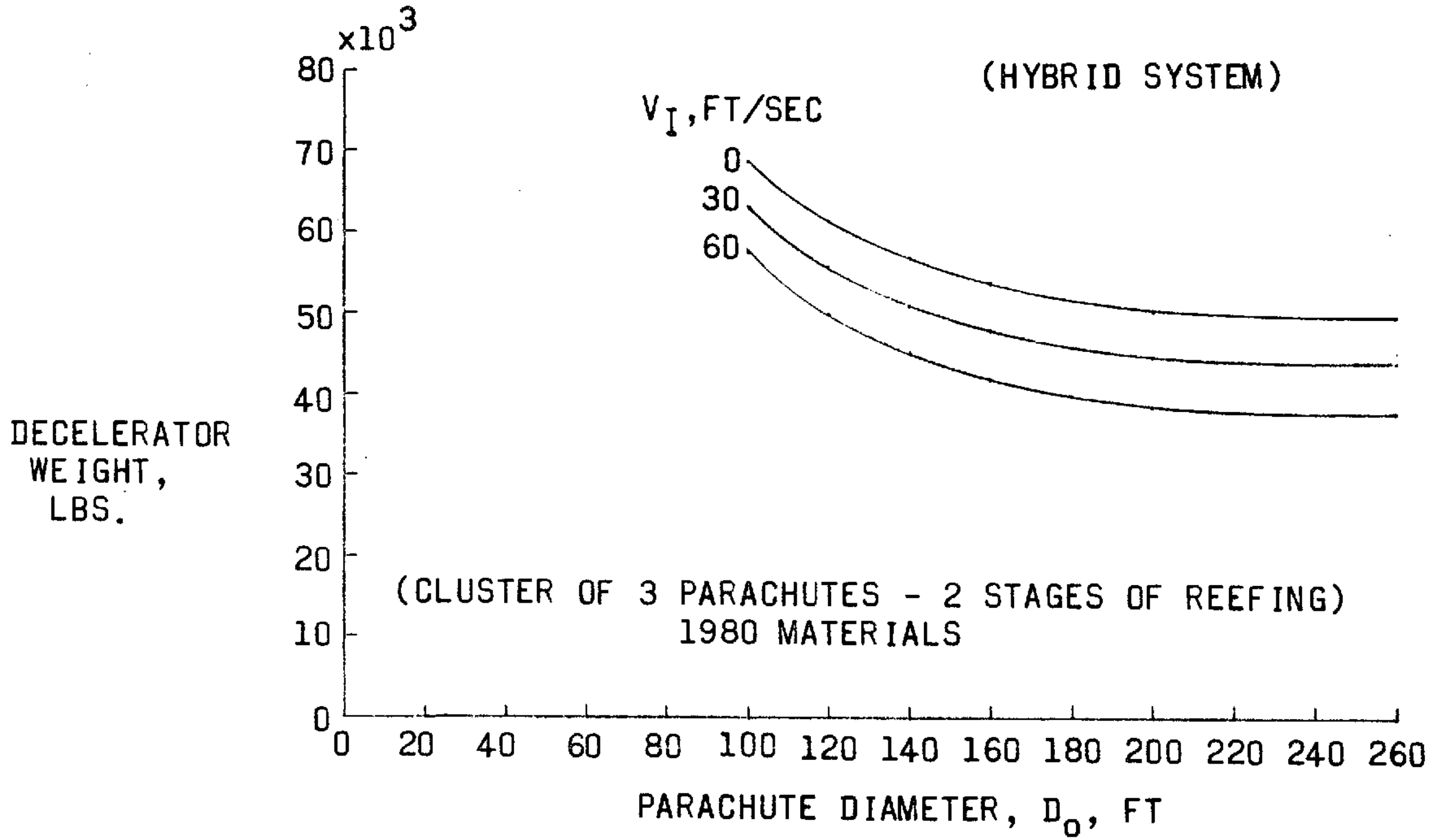


Figure 29

EFFECTS OF CLUSTERING ON PARACHUTE SYSTEM WEIGHT

Another way of reducing the size of the parachutes required is to go to a larger number of parachutes in the cluster. All previous figures presenting parachute weight for a hybrid system have been based on a cluster size of 3 parachutes. Figure 30 shows the changes in weight as the number of parachutes in a cluster is varied. The table included in the figure presents data used in establishing the curve shown. Note that significantly longer riser lengths were used for the larger cluster sizes to keep the total parachute trailing distance equal to 480 ft. The trailing distance is equal to the sum of the length of the suspension lines, which are one parachute diameter in length, plus the riser length. Minimum parachute system weights were obtained for systems with 3 to 5 parachutes but the differences in weight shown are not enough to justify selection of a cluster number based on weight alone. The weight vs cluster number curve shown is not universally applicable because of the somewhat unusual riser length requirements given.

EFFECTS OF CLUSTERING ON HYBRID PARACHUTE SYSTEM WEIGHT

(ALL CLUSTERS HAVE EQUAL DRAG AREA - 1980 MATERIALS)

(PARACHUTE TRAILING DISTANCE = 480 FT)

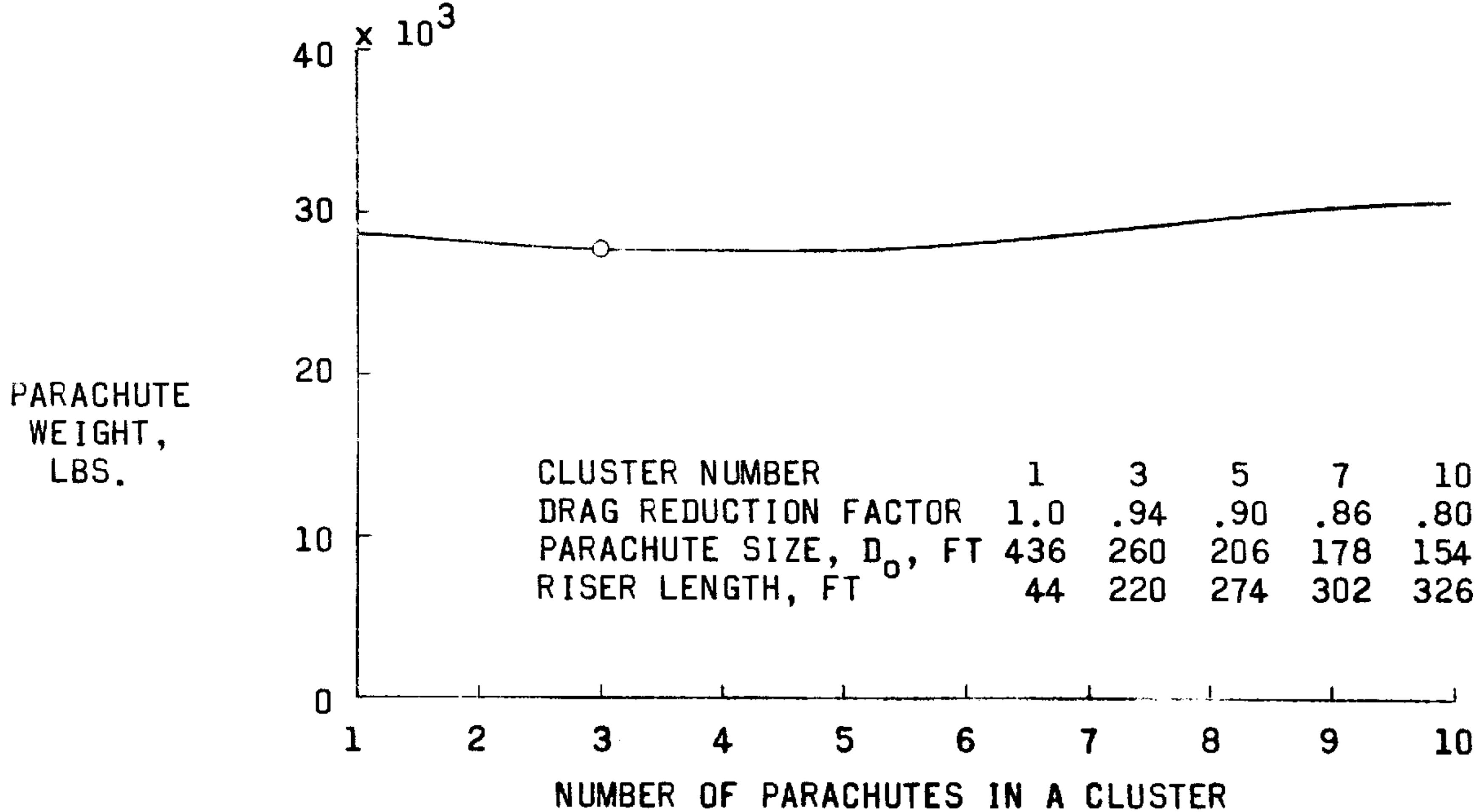


Figure 30

EFFECT OF 1980 TECHNOLOGY ON SYSTEM WEIGHT

The question of how much weight can be saved by using 1980 material technology and a 1980 retrorocket system for the recovery of a one million-pound payload is answered by figure 31. Decelerator system weight is presented as a function of impact velocity for both a 1973 system and a 1980 system. The major differences are the use of Fiber B type material, rather than Nylon, for fabrication of the parachute and small changes in retrorocket propellant specific impulse and casing weight efficiency for the retrorocket. A major difference resulting from using 1980 materials is that the optimum parachute size increases from 160 ft diameter for the 1973 system to 260 ft diameter for the 1980 system. We have already indicated on an earlier slide that bringing the 1980 parachute size back down to 160 ft diameter results in only a 4000 lb weight penalty for the 1980 system. At an impact velocity of 60 ft/sec the 1980 system results in a weight saving of 27,500 lbs (63,500 lbs vs. 36,000 lbs) which is more than a 43 percent reduction. At an impact velocity of 30 ft/sec the weight saving is slightly greater, approximately 28,300 lbs (69,000 lbs vs 41,700 lbs) but slightly less in terms of percentage of system weight, 41 percent. Potential 1980 technology has a major influence on decelerator system weight.

EFFECT OF 1980 TECHNOLOGY ON SYSTEM WEIGHT
(CLUSTERS OF 3 PARACHUTES WITH 2 STAGES OF REEFING EACH)

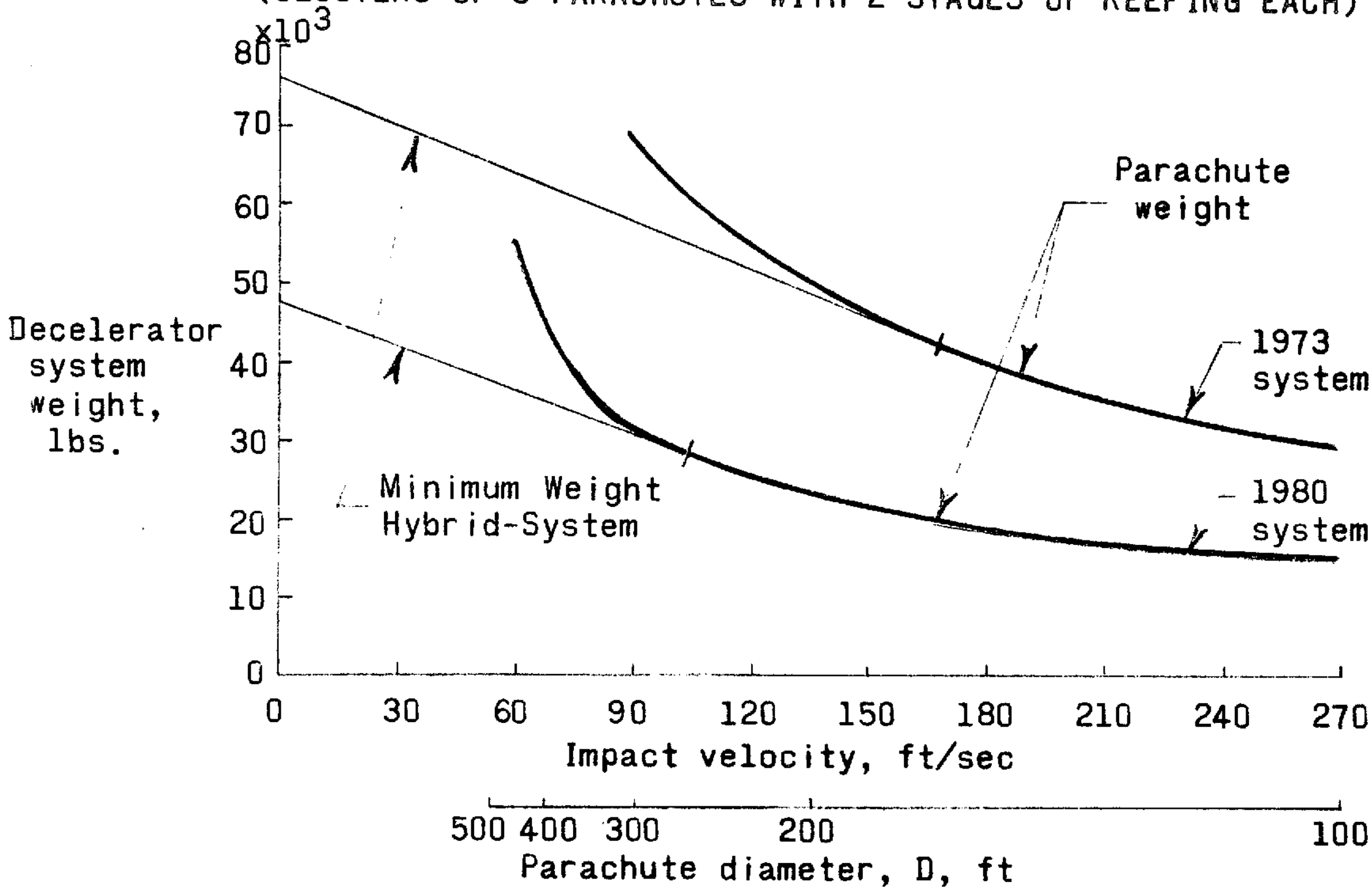


Figure 31

EFFECTS OF DROGUE PARACHUTES ON SYSTEM WEIGHT

An alternative way of saving recovery system weight in some instances is to use drogue parachutes. Figure 32 presents curves which show the effects of using drogue parachutes on parachute system weight. A decelerator system weight curve is presented as a function of terminal velocity for cluster of 3 parachutes using 1980 materials and 2 stages of reefing. This figure shows the same parachute weight and minimum hybrid system weight curves shown previously. In addition we show the weight curve for a parachute system using 3 each 120-ft diameter drogue parachutes for a preliminary deceleration phase prior to deploying the mains. The curves show that if the parachute system is used to bring the payload to a low enough terminal velocity there is a cross over point where the drogue parachutes have a weight advantage. However for a minimum weight hybrid system the use of drogue parachutes would result in a weight increase of about 4000 lbs.

EFFECTS OF DROGUE PARACHUTES ON SYSTEM WEIGHT
(CLUSTER OF 3 PARACHUTES --1980 MATERIALS - 2 STAGES OF REEFING)

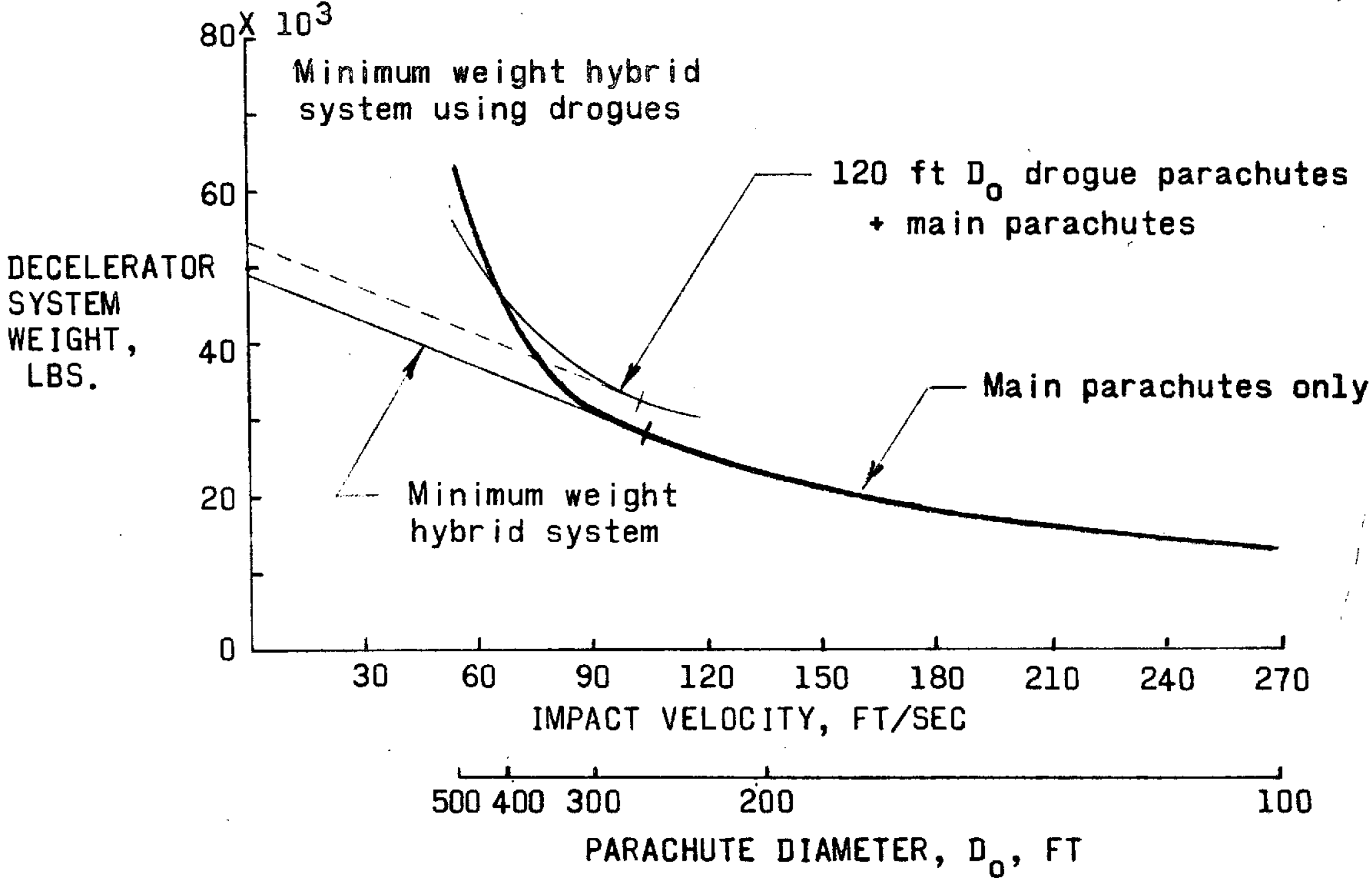
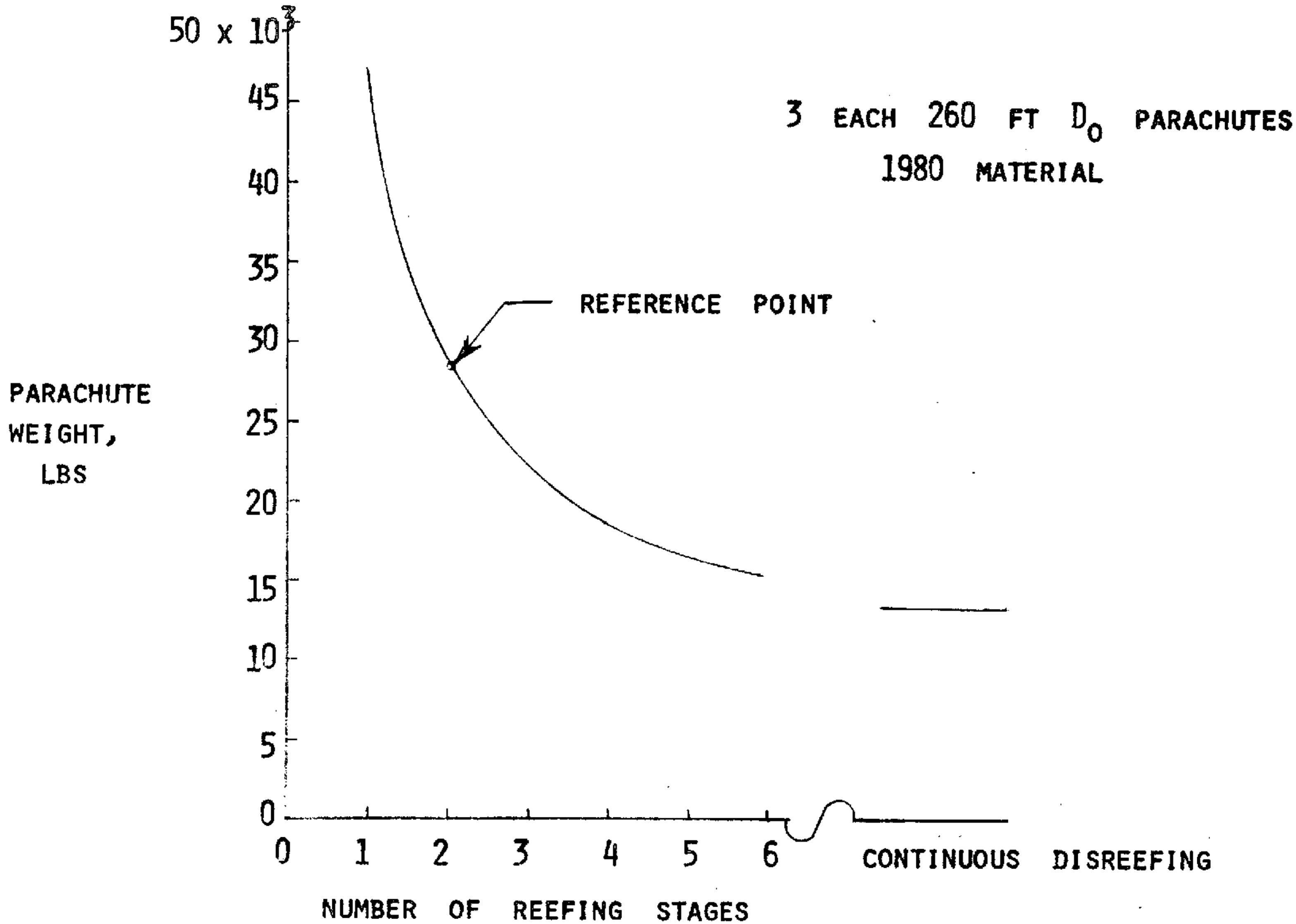


Figure 32

EFFECT OF REEFING STAGES ON PARACHUTE WEIGHT

The information presented so far has been for parachutes with two stages of reefing plus a full open stage. Figure 33 presents information on the effect of the number of reefing stages on parachute weight. We have plotted parachute weight versus the number of stages of reefing including data for a possible continuous disreefing system. Again, we have the reference point weight for the parachutes of the hybrid system shown. Obviously, there are significant weight advantages to be gained by going to a larger number of reefed stages. Our results to this point have been restricted to two reefed stages because that is about the useful limit of currently used powder train delay-pryotechnically activated reefing line cutters. We have however, taken a look at what continuous disreefing would do in terms of saving weight on a hybrid system as shown on the next figure.

EFFECT OF REEFING STAGES ON PARACHUTE WEIGHT



Figure

EFFECT OF 1980 TECHNOLOGY AND CONTINUOUS DISREEFING ON SYSTEM WEIGHT

Taking into account the additional parachute weight reduction possible with a continuous disreefing system, as shown in figure 33, a determination was made as to the combined effect of 1980 materials and continuous disreefing on a hybrid system. The results of this determination are presented in figure 34 along with the weight curves for a 1973 parachute and hybrid system plus the weight curves for a parachute of 1980 materials and the associated hybrid system. These latter curves have been presented in previous figures but are shown again for comparison purposes. Again, as the parachute weight curve is lowered the parachute size for an optimum system increases. For the parachutes of 1980 materials with continuous disreefing the retrorocket weight curve tangency point comes at a parachute diameter of 340 ft. This would bring the system down to 79 ft/sec. For a 60 ft/sec impact velocity it probably would be more practical to go to a slightly larger parachute and achieve the desired impact velocity with an all parachute system. At an impact velocity of 30 ft/sec the hybrid system weight would be down around 25,000 lbs. At an impact velocity of zero ft/sec the hybrid decelerator system weight would be about 30,000 lbs. We have not listed continuous disreefing as 1980 technology earlier because it is not clear that all of the weight savings shown could be realized even if the mechanics of a disreefing system could be accomplished. Therefore, this weight curve for a continuous disreefing parachute system should be considered more as a limit of potential weight savings. Obviously continuous reefing has the potential to save sufficient weight that the concept should be evaluated for any future heavy payload system.

EFFECT OF 1980 TECHNOLOGY AND CONTINUOUS DISREEFING ON SYSTEM WEIGHT
(CLUSTERS OF 3 PARACHUTES WITH 2 STAGES OF REEFING EACH)

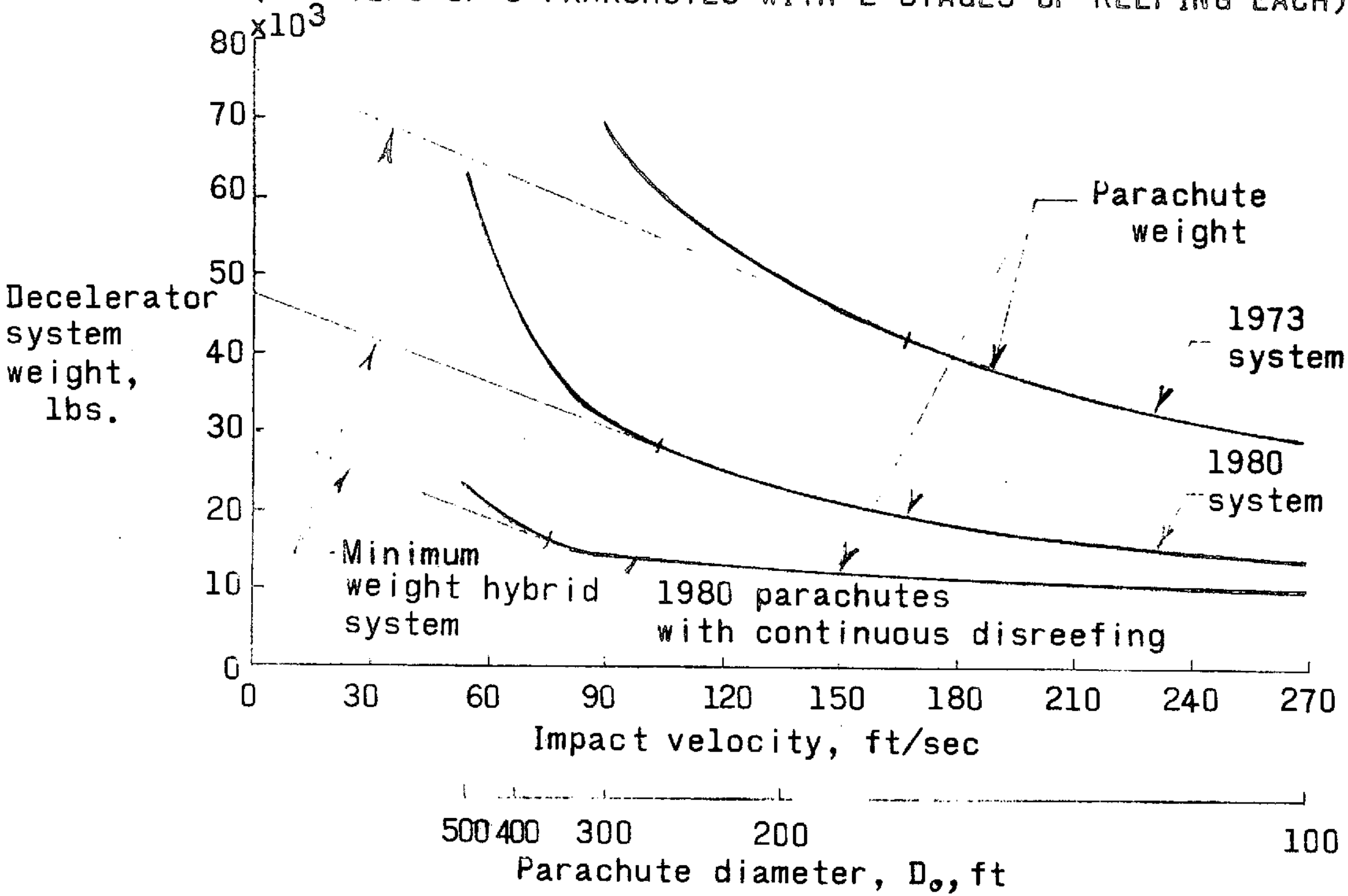


Figure 34

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SUMMARY OF ADVANCED TECHNOLOGY GAINS

If one considers all of the weight reductions that result from use of advanced technology for 1980 for impact velocities of 0 ft/sec as well as 30 and 60 ft/sec we have the combined results shown in bar graph form in figure 35. The highest level on each bar represents what the decelerator system weight would be using present (1973) technology. The next lower level represents system weight considering use of improved (1980) materials. The third level indicates improvements which would result from achieving the full potential weight savings of a continuous reefing system. The all other category includes such things as improved rocket propellant specific impulse, reduced rocket casing weights, improved parachute fabrication techniques and reduced parachute hardware weights.

It is evident from the figure that 1980 materials and continuous reefing result in significant weight savings for all three impact velocities listed, e.g., use of 1980 materials results in a reduction of 37 percent in hybrid recovery system weight for an impact velocity of 30 ft/sec. Advanced reefing techniques and other technology improvements provide an even greater percentage reduction.

SUMMARY OF ADVANCED TECHNOLOGY GAINS
(PARACHUTE-RETRO HYBRID SYSTEM)

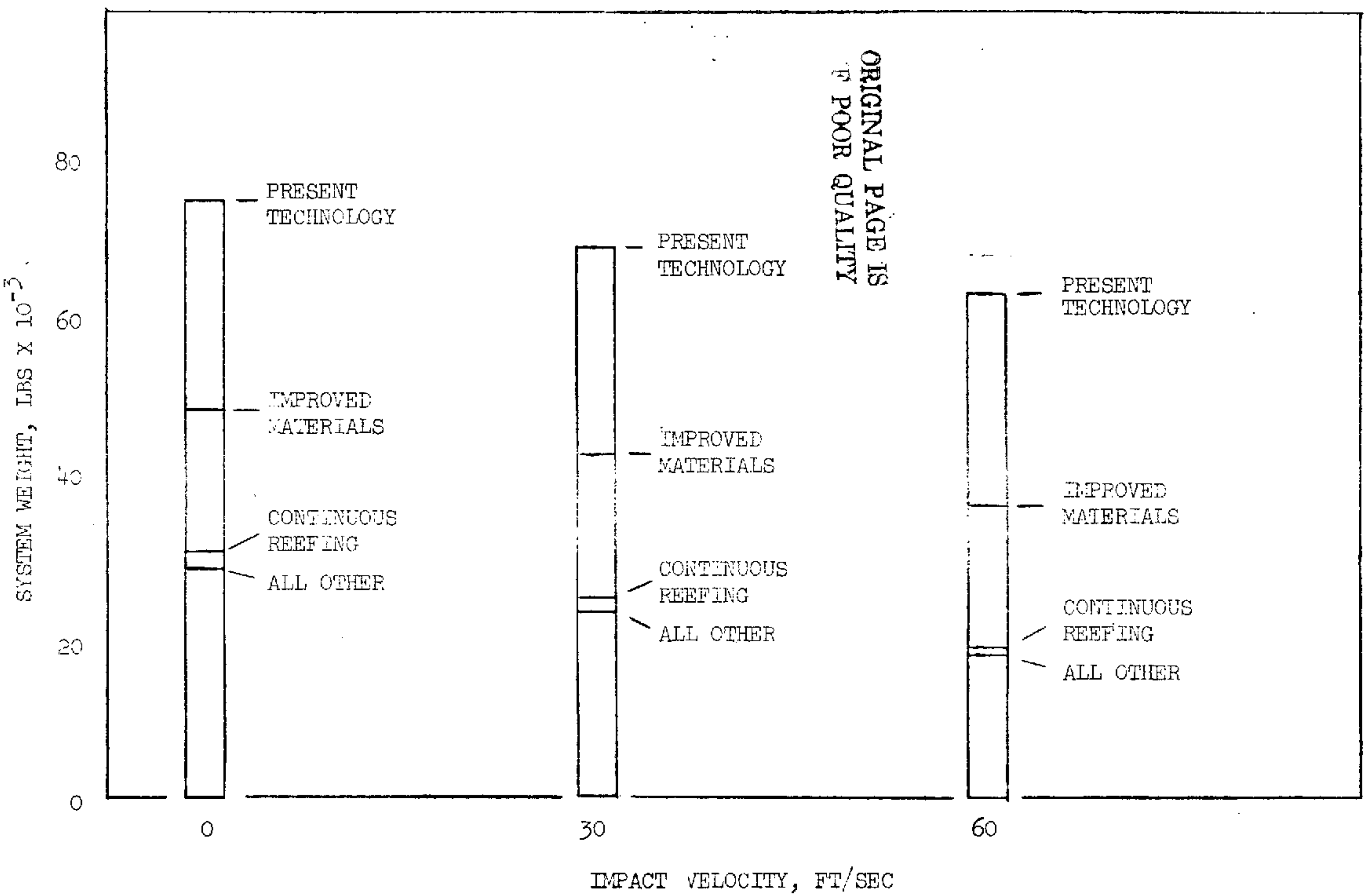

Figure 35

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SECTION V

DIVIDING PAYLOAD INTO PIECES

AND

L/D CONSIDERATIONS

EFFECT ON DECELERATOR SYSTEM WEIGHT OF DIVIDING PAYLOAD INTO N PIECES

Up to this point in the discussion we have been considering only a single one million-pound payload. However, if in the design of the booster system there is an option of using multiple stages in series or parallel, so that the booster could be divided into a number of pieces for recovery, substantial reductions in recovery system weight and parachute system size would result. Figure 36 presents the results of calculations made to determine the advantage of such a scheme. Plotted is the total decelerator system weight with N similar pieces ratioed to the weight for a single booster as a function of the number of pieces (N) the booster is divided into. The plot indicates there is a significant weight savings in using this approach since even for two pieces a 16 percent reduction is obtained. These weight savings result primarily from the rediced ballastic coefficient if the individual pieces. When the payload is broken into geometrically similar pieces the reduction is proportional to $1/(N)^{1/3}$ and for the situation where the length is maintained constant and only the diameter reduced, (no results shown) the reduction is proportional to $1/(N)^{1/2}$. A further advantage of dividing the payload into a number of separate pieces is that the size of the parachutes required are substantially reduced as indicated by the diameters given on the figure. No account is taken of any booster weight changes which may result from dividing it into a number of pieces.

HYBRID DECELERATOR SYSTEM WEIGHT REDUCTIONS RESULTING FROM DIVIDING PAYLOAD INTO N SIMILAR PIECES

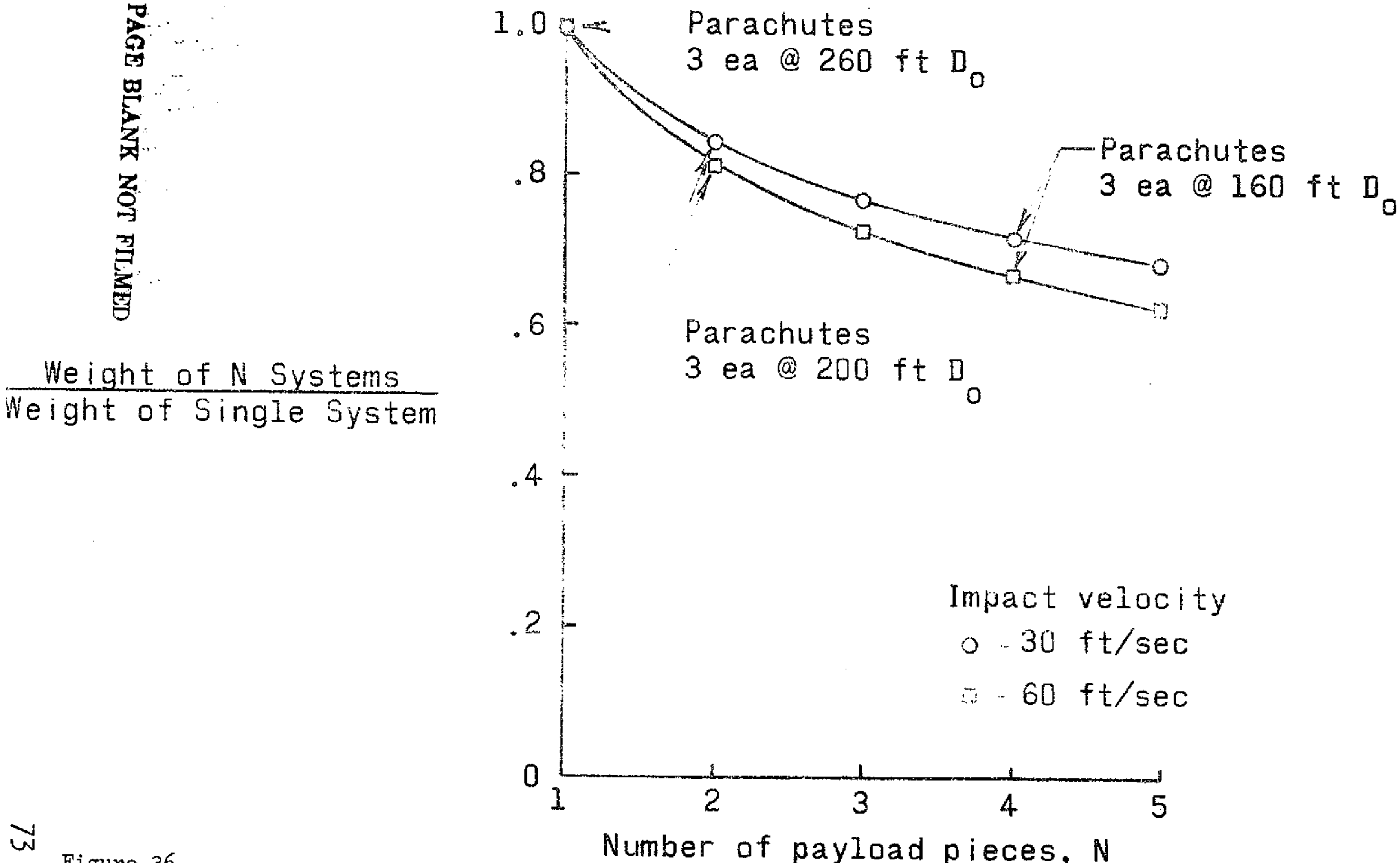


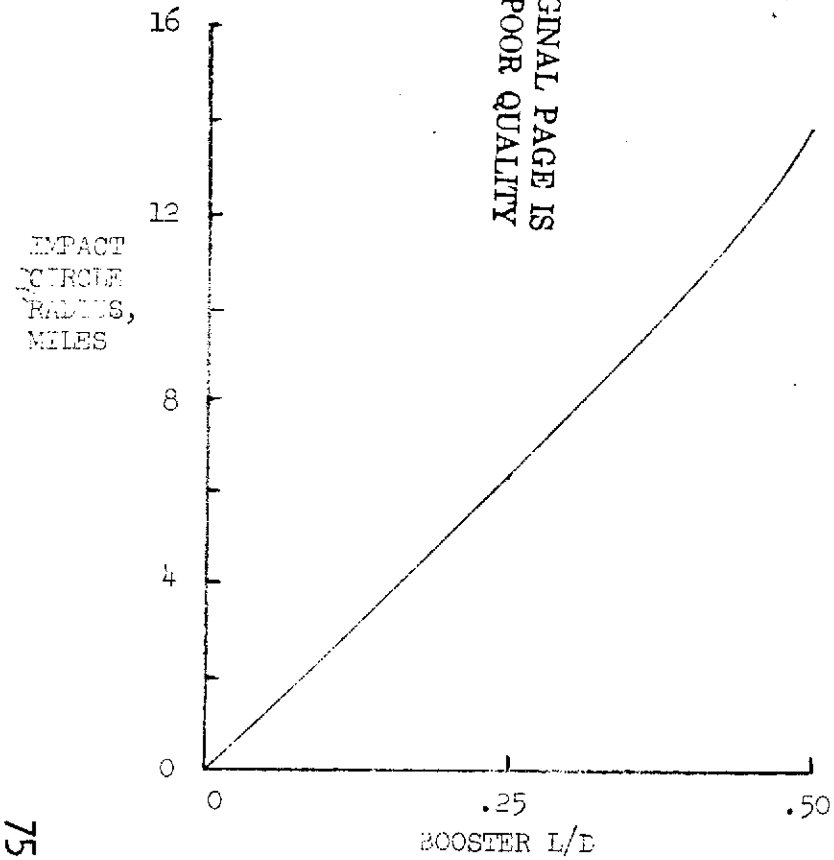
Figure 36

TARGETING CAPABILITY

An additional item investigated briefly was targeting capability. Figure 37 presents information on the targeting capability of both the booster by itself and the booster on the parachute from 20,000 ft on down to sea level. On the left side of the figure we have plotted range versus lift to drag ratio L/D for a booster over a trajectory interval from booster staging until the booster was down to an altitude of 20,000 ft. We show a potential range capability of up to 14 miles for an L/D of 0.50. The small table on the upper right lists the booster staging conditions used in the booster range figure on the left. In the lower right we present the potential range capability of the parachute system from an altitude of 20,000 ft down to sea level. Here the range capability at an L/D of 0.5 is only about 2 miles. It appears that any targeting capability should be accomplished using the booster rather than the parachute.

TARGETING CAPABILITY

BOOSTER FROM STAGING TO 20,000 FT



STAGING CONDITIONS	
Altitude	190,000 ft
Velocity	5500 ft/sec
Flight Path Angle	
Above Horizontal	30 deg

PARACHUTE FROM 20,000 FT

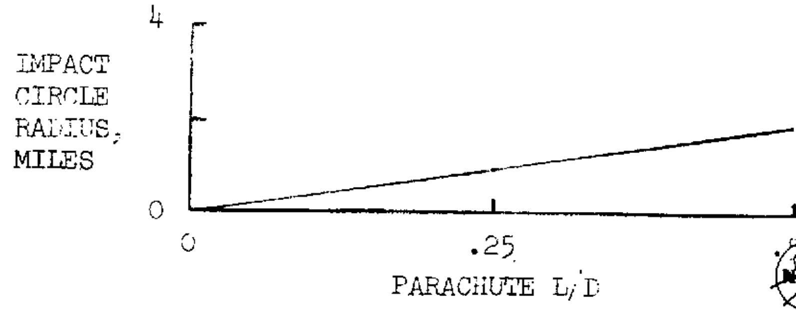


Figure 37

CONCLUSIONS

IT IS NECESSARY TO ORIENT BOOSTER AT HIGH ANGLES OF ATTACK IN ORDER TO REDUCE DEPLOYMENT DYNAMIC PRESSURES TO REASONABLE LEVELS.

THE MINIMUM WEIGHT SYSTEM FOR RECOVERY OF 10^6 POUNDS AT IMPACT VELOCITIES OF LESS THAN 100 FT/SEC IS A HYBRID (RETRO/PARACHUTE) SYSTEM.

ADVANCED MATERIALS OFFER SIGNIFICANT DECELERATOR SYSTEM WEIGHT SAVINGS, E.G., USE OF 1980 MATERIALS RESULTS IN A REDUCTION OF 37% IN HYBRID RECOVERY SYSTEM WEIGHT FOR AN IMPACT VELOCITY OF 30 FT/SEC.

ADVANCED REEFING TECHNIQUES OFFER ADDITIONAL WEIGHT SAVINGS BUT REALIZATION OF FULL THEORETICAL POTENTIAL MAY NOT BE ACHIEVABLE.

WEIGHT SAVINGS RESULTING FROM INCREASED ROCKET EFFICIENCY, REDUCED CASING WEIGHT, IMPROVED PARACHUTE FABRICATION TECHNIQUES AND PARACHUTE HARDWARE ARE SMALL COMPARED TO PARACHUTE MATERIAL AND REEFING BENEFITS.

CONCLUSIONS (CONTINUED)

LITTLE ADDITIONAL WEIGHT PENALTY IS INCURRED FOR REDUCING TERMINAL VELOCITY FROM 30 FT/SEC TO 0 FT/SEC FOR A HYBRID SYSTEM.

USE OF DROGUE STAGE IN ADDITION TO REEFED-MAIN STAGES DOES NOT PROVIDE ANY WEIGHT SAVINGS FOR A HYBRID SYSTEM.

SUBSTANTIAL DECELERATOR SYSTEM WEIGHT SAVINGS RESULT IF PAYLOAD CAN BE DIVIDED AND RECOVERED IN TWO OR MORE PIECES.

PARACHUTES OFFER LITTLE IN CROSS RANGE CAPABILITY; USE OF BOOSTER LIFT CAPABILITY AT HIGH ALTITUDES IS MORE EFFECTIVE.