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A MINIMUM WEIGHT ANALYSIS OF AEROSPACE VEHICLE RECOVERY SYSTEMS--ETC(U)
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② LEVEL II

A MINIMUM WEIGHT ANALYSIS OF AEROSPACE VEHICLE RECOVERY SYSTEMS

Recovery and Crew Station Branch
Vehicle Equipment Division

May 1977

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AIR FORCE FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This technical report has been reviewed and is approved for publication.

Stephen R. Mehaffie
STEPHEN R. MEHAFFIE
Project Engineer

Edwin R Schultz
EDWIN R. SCHULTZ, Chief
Recovery & Crew Station Branch
Vehicle Equipment Division

FOR THE COMMANDER

Ambrose B. Nutt
AMBROSE B. NUTT
Director
Vehicle Equipment Division

UNCLASSIFIED

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This report presents an algorithm for determining the minimum weight of an aerospace vehicle recovery system. The weight of the recovery system composed of parachute and impact attenuation subsystems is examined for the effects of advanced technologies including Kevlar materials and advanced attenuators. The vehicle description for input to the algorithm consisting of recovered weight, maximum acceleration, and characteristic length allows the algorithm to be applied to a large variety of aerospace vehicles and payloads. The algorithm provides optimized component weights and operating characteristics.

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FOREWORD

This report presents the derivation of an analytical technique for determining the minimum weight of an aerospace vehicle recovery system composed of a parachute subsystem and an impact attenuation subsystem. This report was prepared by the Recovery & Crew Station Branch, Vehicle Equipment Division, of the Air Force Flight Dynamics Laboratory (AFFDL/FER). The work was accomplished under Project 1964, "Recovery System Technology Application to RPVs", and Work Unit 19645001, "Packing Optimization Techniques". The work was performed from November 1974 to June 1975 and was in accordance with a Memorandum of Agreement (MOA) between the Remotely Piloted Vehicle System Program Office (RPV SPO), Aeronautical Systems Division, and the AFFDL dated 7 November 1974. This report was submitted by the author in March 1975.

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SECTION I

PURPOSE AND SCOPE OF ANALYSIS

1. PURPOSE

The purpose of this analysis is to provide the designer a mathematical technique for defining the minimum weight recovery system which can surface recover a remotely piloted vehicle (RPV). Additionally, the analysis can be applied to a variety of other payloads by reassessing the underlying assumptions involving the tradeoffs between the parachute and the impact attenuation subsystems.

2. BACKGROUND

Currently, most remotely piloted vehicles (RPV's) are recovered by the use of a Midair Retrieval System (MARS). This system involves using a helicopter to "catch" an RPV suspended under a parachute and return it to the ground safely. In a mission scenario where large numbers of RPV's are returning from combat missions simultaneously there may not be enough helicopters available to perform the MARS recoveries. Those RPV's which impact the ground require a surface recovery system which will allow a cost effective reuse of the vehicle. Since excess weight onboard an RPV degrades the mission-effectiveness of the vehicle, it is desirable to identify and define a minimum weight surface recovery system.

3. SCOPE

This analysis defines a recovery system as being composed of a parachute subsystem, an impact attenuation subsystem, and associated penalties.

The parachute subsystem components and weight parameters are examined in detail. A theoretical technique (Reference 1) for evaluating the efficiency of various conventional parachute canopy types is utilized. Gliding parachutes are not considered in this analysis. This analysis does consider the effect of improved parachute materials (para-aramide fiber) on the weight of the recovery system.

The impact attenuation subsystem components and weight parameters are discussed in a similar manner. This analysis considers only airbag concepts as comprising the state of the art but does postulate the effect of advanced attenuation concepts on the weight of the recovery system.

The penalties associated with having a parachute subsystem and an impact attenuation subsystem onboard an RPV while performing its combat mission are delineated.

This analysis represents an algorithm which can determine the minimum weight recovery system for a large variety of payloads using current (1975) state-of-the-art technology. Additionally, the algorithm will identify promising areas of advanced technology and predict the weight reduction effectiveness of a given technology advancement or the relative effect of several technology advancements.

SECTION II

RECOVERY SYSTEM DEFINITION

1. DEFINITION

An aerospace vehicle recovery system consists of those pieces of hardware which are essential to reduce the kinetic and potential energy of an airborne vehicle to zero relative to the earth's surface but which are not essential to the performance of the vehicle's combat mission.

2. COMPONENTS AND GROUPINGS

For the purposes of this analysis, those components which are defined above and which are schematically illustrated in Figure 1 will be grouped as follows:

a. Independent Components

1. Electronic logic circuitry for the command and control of the recovery system (includes battery)
2. Vehicle Riser

b. Parachute Subsystem

1. Main Recovery Parachute(s) (Canopy and suspension lines)
2. Main Recovery Parachute(s) Miscellaneous Hardware
3. Main Recovery Parachute(s) Deployment Bag
4. Main Recovery Parachute(s) Deployment Bag Container
5. Drogue Parachute (Canopy and Suspension Lines)
6. Drogue Parachute Miscellaneous Hardware
7. Drogue Parachute Deployment Bag
8. Drogue Parachute Deployment Bag Container

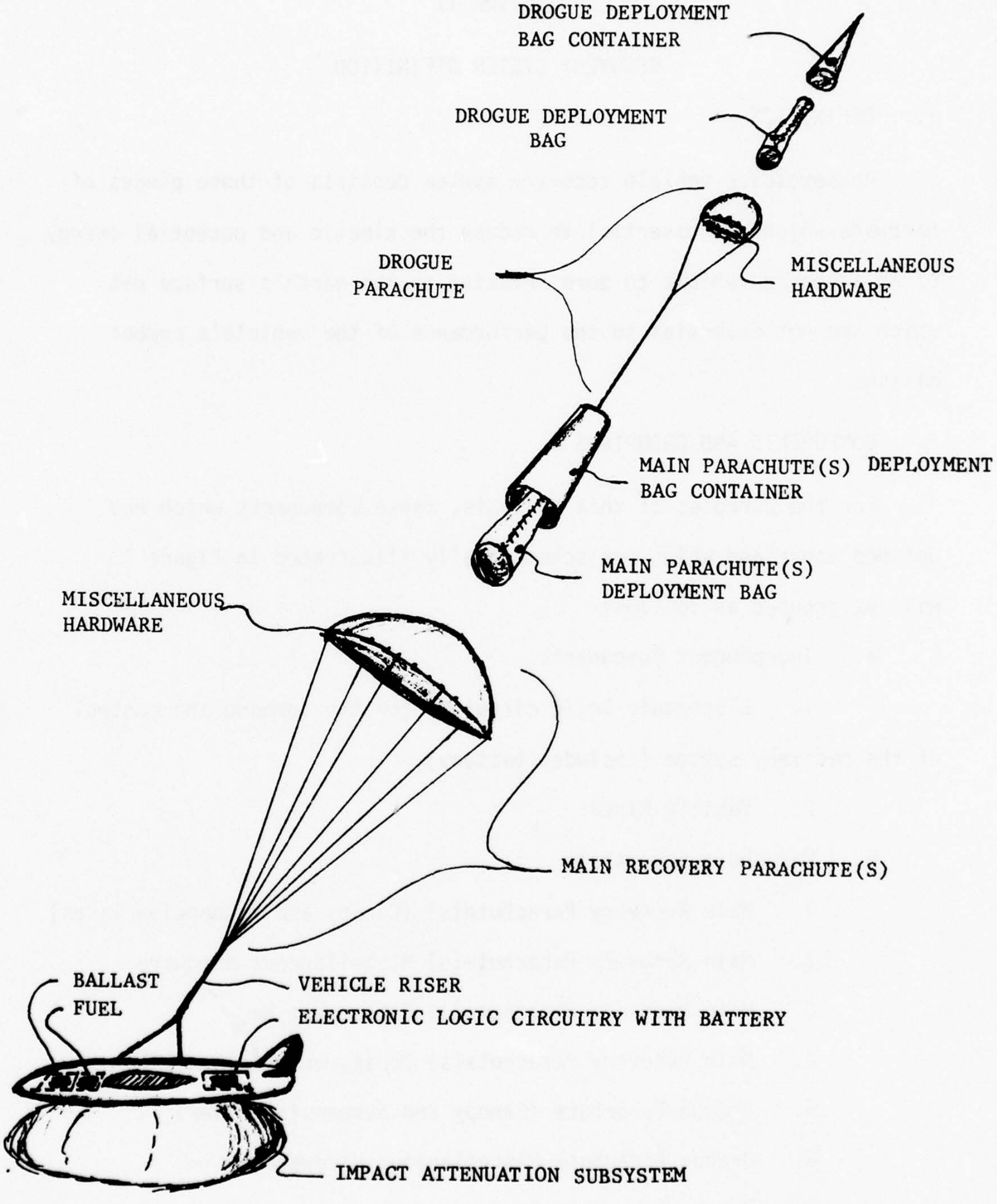

Figure 1. Schematic Recovery System and Associated Penalties

c. Impact Attenuation Subsystem

1. This subsystem will be treated generically and as such includes bags, hatch covers, plumbing, pressure bottles, etc.

d. Associated Penalties

1. Ballast required to compensate for the effect on the mission center of gravity (C.G.) of the addition of the recovery system.

2. Additional fuel required to carry the weight of the total recovery system throughout the mission.

None of these components are required for the accomplishment of a combat mission. Their presence onboard the vehicle during the mission represents a decrease in the combat effectivness of the vehicle.

SECTION III

RECOVERY SYSTEM USAGE AND REQUIREMENTS

It has been shown that the use of a recovery system imposes penalties on the mission effectiveness; why then have a recovery system? Historically, aerospace vehicle recovery systems have imposed weight penalties on the order of 5 - 15% of the gross take off weight (or gross launch weight for RPV's). This represents a significant reduction in the mission effectiveness. However, in the real world, mission effectiveness must be considered as complementary with cost effectiveness:

1. ADVANTAGES OF NOT HAVING A RECOVERY SYSTEM

(a) An additional 5 - 15% of the gross launch weight could be carried in the form of mission stores thus enhancing mission effectiveness.

(b) Penetration distance could be almost doubled because the vehicle would not have to return.

(c) Maintenance and repair operations could be simplified because all RPV's used would be new.

2. DISADVANTAGES OF NOT HAVING A RECOVERY SYSTEM

(a) Requires expenditure of a new RPV for every mission thus decreasing cost effectivness.

(b) Possible logistic problems under sustained high mission rate conditions.

3. ADVANTAGES OF HAVING A RECOVERY SYSTEM

(a) The vehicle is recovered intact and can be recycled.

4. DISADVANTAGES OF HAVING A RECOVERY SYSTEM

(a) Cost to develop and maintain the recovery system.

(b) Weight penalties on mission effectiveness.

The pros and cons of a mode of operation with and without a recovery system (as shown above) can be summarized as: Is the development, maintenance, and use of a recovery system cost effective? The remainder of this analysis assumes that a recovery system is desirable for the designer's application.

SECTION IV

MATHEMATICAL OPTIMIZATION

1. GENERAL

The mathematical optimization of the recovery system weight revolves around the vehicle kinetic energy at first ground contact. The drag area of the main recovery parachute(s) (C_DS) will be used as the independent variable. The weight of the recovery system will then be minimized against the variable C_DS. It will be shown that for a given set of design conditions there exists an optimum value of C_DS which results in a minimum weight recovery system.

2. ENERGY MAGNITUDES

The recovery system function is defined as the reduction of the kinetic and potential energies of an airborne vehicle to zero relative to the ground. The recovery system accomplishes this energy reduction through the sequential functioning of the two major subsystems consisting of the parachute subsystem and the impact attenuation subsystem. It is of interest to determine the relative amounts of energy each subsystem must dissipate.

To illustrate the relative allocation of energies, imagine an airborne vehicle whose weight (W) is 4000 pounds flying at a velocity (V) relative to the ground of 300 knots (503 feet/sec) at an altitude above ground (H) of 20,000 feet. The total kinetic and potential energy (E_T) of this vehicle relative to the ground is given by Equation 1.

$$E_T = 1/2 \frac{W}{g} V^2 + WH \qquad (1)$$

E_T = 15,714,845 ft-lbs (Kinetic) + 80,000,000 ft-lbs (Potential)

E_T = 95,714,845 ft-lbs (Total Energy)

The recovery system dissipates this total energy to zero by first using the parachute subsystem to slow the vehicle to some equilibrium descent velocity and then maintains a constant kinetic energy (equilibrium vertical velocity under the parachutes) during descent through altitude thus dissipating the potential energy. The impact attenuation subsystem then dissipates the kinetic energy resulting from the equilibrium descent velocity at ground impact.

In order to determine the relative allocation of energy dissipation between the two subsystems, assume that the equilibrium descent velocity prior to impact of this vehicle is 25 feet/sec (a typical order of magnitude descent velocity for recovery systems). In this analysis, the first ground contact of the vehicle (with recovery system) will be defined as the point of zero potential energy. Therefore, the impact attenuation subsystem is required to dissipate the kinetic energy resulting from the 25 feet/sec descent velocity. At first ground contact, this energy is given by Equation 2.

$$E = 1/2 \frac{W}{g} {V_v}^2 \qquad (2)$$

where:

E = Total energy at first ground contact. (The potential energy at first ground contact is zero by definition).

W = Weight of the vehicle (the weight of the recovery system is considered to be negligible compared to the suspended weight of the vehicle).

V_v = Equilibrium descent velocity of the vehicle suspended by the main recovery parachute(s)

Therefore the energy dissipated by the impact attenuation subsystem in this example is:

$$E = 1/2 \frac{4000}{(32.2)} (25)^2 \text{ ft-lbs}$$

$$E = 38{,}820 \text{ ft-lbs}$$

The allocation of the total energy (E_T) between the parachute subsystem and the impact attenuation subsystem in this example is:

The parachute subsystem dissipated:	95,676,025 ft-lbs
The impact attenuation subsystem dissipated:	38,820 ft-lbs
Total Energy (E_T) dissipated:	95,714,845 ft-lbs

The parachute subsystem is responsible for dissipating over 99.9% of the total energy and the impact attenuation subsystem is responsible for less than one-tenth of one percent of the total energy. However lopsided these energy allocations may appear, the impact attenuation subsystem cannot be ignored or deemed negligible. It will be shown mathematically that within the definition of a recovery system as used in this analysis there must exist an impact attenuation subsystem. In terms of a colloquial cliche, "It's not how far you fall, it's the sudden stop at the bottom."

3. DEFINITIONS OF COEFFICIENTS AND CONSTANTS

In order to determine a minimum recovery system weight it is necessary to express the weights of the hardware components in a mathematical form. The following definitions will be used in this analysis.

a. C_1 - The term "C_1" will be used as a constant value (i.e. not a function of the independent variable C_DS). It will represent the weight in pounds of the independent components (i.e. the vehicle riser and the logic circuitry weights).

b. C_2 - The term C_2 will be used to represent the weight, in pounds, of the parachute subsystem per square foot of drag area.

Weight of the parachute subsystem = $C_2\ (C_DS)$ (3)

c. C_3 - The term "C_3" is used to represent the system specific energy absorption of an impact attenuation subsystem. As such it is the amount of energy in ft-lbs which can be absorbed per pound of impact attenuation subsystem. It is used as a coefficient in Equation 4.

Weight of the Impact Attenuation Subsystem = E/C_3 (4)

4. RECOVERY SYSTEM WEIGHT EQUATIONS

a. General

The total weight of a recovery system as defined and delineated in Section II is shown in words in Equation 5 and transformed into symbolism in Equation 6.

> The Recovery system weight is equal to the weight of the independent components plus the weight of the parachute subsystem plus the weight of the impact attenuation subsystem plus the weight of the associated penalties. (5)

Or in mathematical symbols (Reference Equations 3 and 4):

$$\text{Recovery System Weight} = C_1 + C_2\ (C_DS) + \frac{E}{C_3} + \text{Penalties} \qquad (6)$$

b. Working Equation

This analysis will assume that the weights of the associated penalties will be minimized when the weights of the independent components, the parachute subsystem, and the impact attenuation subsystem are minimized (see Section V). This assumption allows a reduced weight equation (Equation 7) to be written.

$$\text{WEIGHT} = C_1 + C_2\,(C_D S) + E/C_3 \qquad (7)$$

where WEIGHT = The weight of the recovery system minus the associated penalties.

5. OPTIMIZATION OF "WEIGHT"

In order to minimize WEIGHT it is necessary to examine the conditions at first ground contact of the vehicle as shown in Figure 2.

The assumption will be made that any horizontal velocity component and the resulting horizontal component of the kinetic energy is taken into account in the design of the impact attenuation subsystem. Only the vertical kinetic energy will be considered in the WEIGHT optimization. This assumption is rationalized in Section VIII with the end result that the numerical values for C_3 reflect this assumption. At first ground contact the energy is

$$E = 1/2\,\frac{W}{g}\,V_v 2 \qquad (2)$$

for the vehicle in equilibrium vertical descent under its main recovery parachutes, the vertical velocity (V_v) can be rewritten as in Equation 8:

$$V_v 2 = \frac{2W}{\rho(C_D S)} \qquad (8)$$

where: ρ = density of air at impact altitude

$C_D S$ = drag area of the main recovery parachutes (used as the independent variable in this analysis)

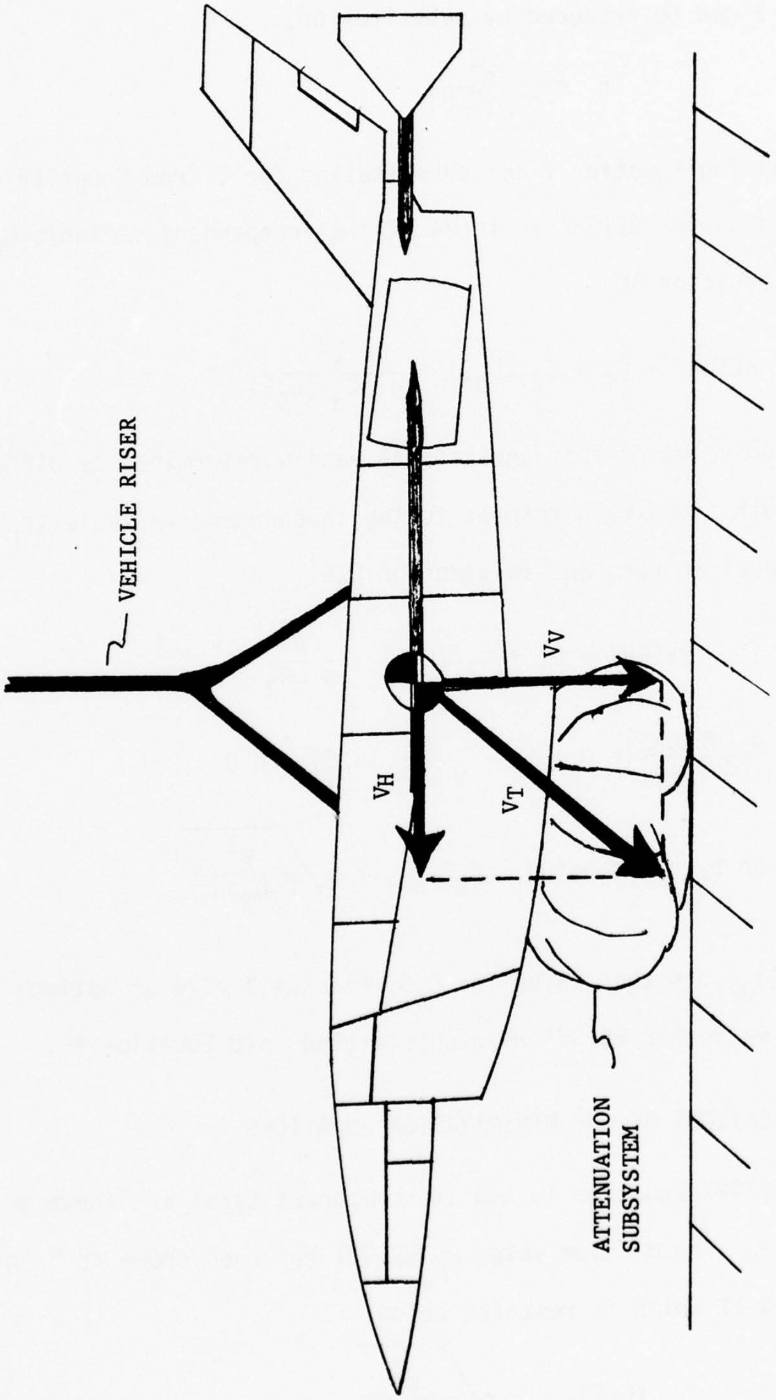

Figure 2. First Ground Contact

Since both Equations 2 and 8 are true at first ground contact, Equation 9 can be produced by substitution.

$$E = \frac{W^2}{g\ \rho (C_D S)} \qquad (9)$$

Recalling Equation 7 and substituting for E from Equation 9 gives an expression for WEIGHT in terms of the independent variable $C_D S$ as shown in Equation 10.

$$\text{WEIGHT} = C_1 + C_2\ (C_D S) + \frac{W^2}{g\ \rho C_3\ (C_D S)} \qquad (10)$$

The minimum value of this equation is easily determined by differentiating both sides with respect to the independent variable $(C_D S)$ then setting equal to zero and solving for $C_D S$.

$$\text{i.e. WEIGHT} = C_1 + C_2\ (C_D S) + \frac{W^2}{g\ \rho C_3}\ (C_D S)^{-1} \qquad (10)$$

$$\frac{d\ (\text{WEIGHT})}{d\ (C_D S)} = 0 + C_2 - \frac{W^2}{g\ \rho C_3}\ (C_D S)^{-2} = 0$$

$$\text{or by rearranging, } (C_D S)_{OPT} = \sqrt{\frac{W^2}{C_2 C_3 g \rho}} \qquad (11)$$

where $(C_D S)_{OPT}$ is that value for $C_D S$ which will give an optimum (minimum) value for WEIGHT when substituted into Equation 10.

6. IMPLICATIONS OF THE MINIMIZATION EQUATIONS

The WEIGHT Equation 10 and its component terms are shown graphically in Figure 3. The minimum value of WEIGHT has been shown to be given by Equation 11 which is restated below.

$$(C_D S)_{OPT} = \sqrt{\frac{W^2}{g\ \rho C_2 C_3}} \qquad (11)$$

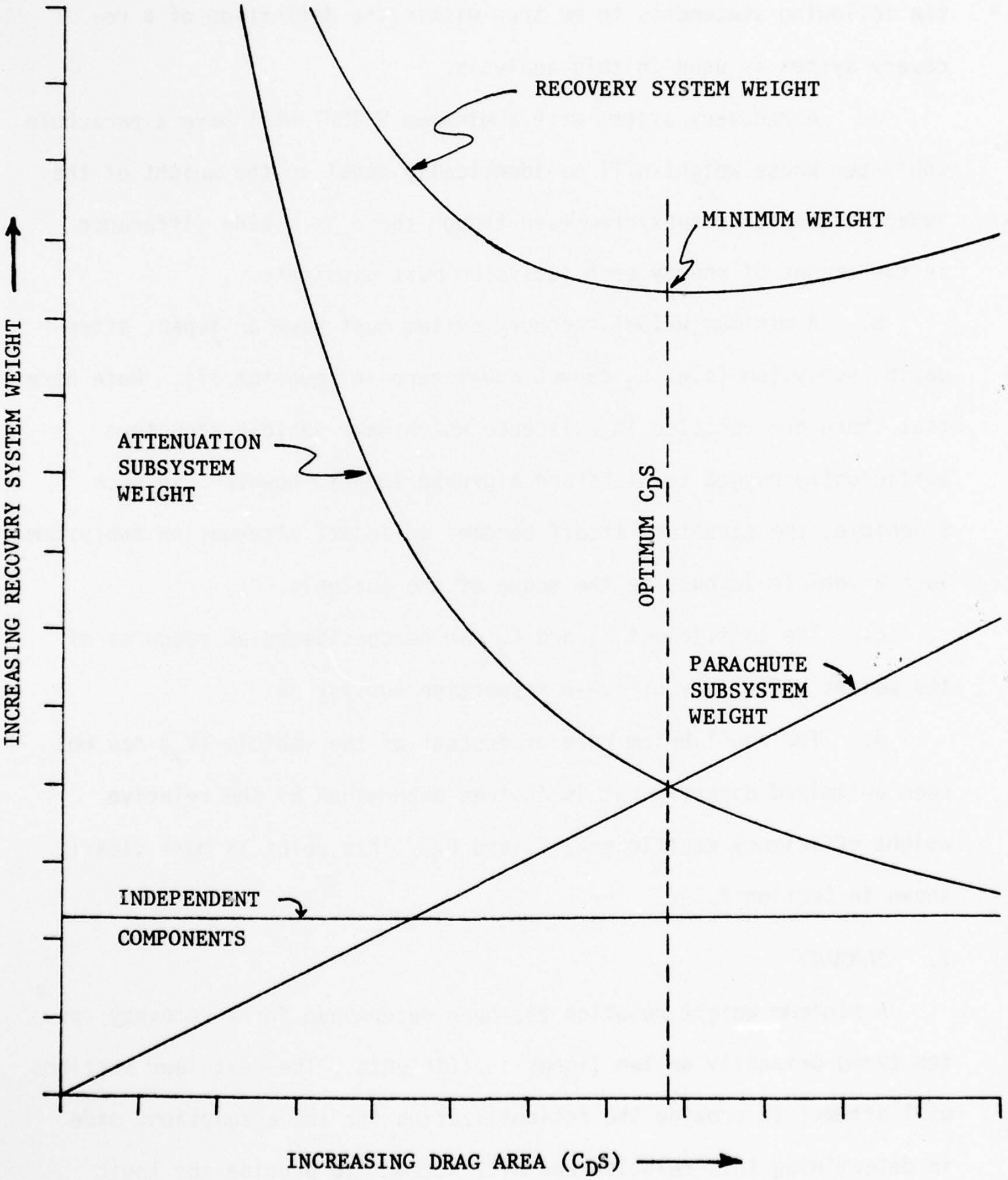

Figure 3. Generalized Optimization Curves

Examining either Equation 10, Figure 3, or Equation 11 will show the following statements to be true within the definition of a recovery system as used in this analysis.

a. A recovery system with a minimum WEIGHT will have a parachute subsystem whose weight will be identically equal to the weight of the impact attenuation subsystem even though there is a wide difference in the amount of energy each subsystem must dissipate.

b. A minimum WEIGHT recovery system must have an impact attenuation subsystem (i.e. C_3 cannot equal zero in Equation 11). Note here that there are vehicles in existence which have vehicle structure sufficiently rugged to withstand a ground impact, however, in such a vehicle, the structure itself becomes an impact attenuation subsystem. Such a vehicle is outside the scope of the analysis.

c. The coefficient C_2 and C_3 can be considered as measures of the weight efficiency of their respective subsystems.

d. The equilibrium rate of descent of the vehicle (V_v) has not been optimized directly but is instead determined by the relative weight efficiency coefficients C_2 and C_3. This point is more clearly shown in Section X.

7. SUMMARY

A minimum weight relation has been determined for a recovery system based primarily on two linear coefficients. The next four sections will attempt to provide the rationalization for the assumptions made in determining this relation and will attempt to provide the logic necessary to determine numerical values for the coefficients.

SECTION V

PENALTIES ASSOCIATED WITH A RECOVERY SYSTEM

It was shown in Section II that at least two penalties are associated with a recovery system (i.e. additional fuel and additional ballast). In Section IV however, the weights of these penalties were not included in the minimizing equations. This section will explain the reasoning behind the exclusion of these penalty weights from the minimizing equations.

1. FUEL PENALTY

The fuel penalty can be considered as the weight of the fuel required to carry the weight of the recovery system throughout the combat mission.

To assess this penalty requires a complex analysis of the aerodynamic efficiency and propulsion system efficiency of the specific vehicle under consideration. Such a complex analysis can be avoided by reasoning that if the WEIGHT was zero pounds, then there would be no fuel penalty and as the WEIGHT increased the fuel penalty would also increase. i.e.,

$$\text{Fuel Penalty} \propto \text{WEIGHT} \tag{12}$$

Therefore, if WEIGHT is minimized it follows that the fuel penalty will be minimized.

2. BALLAST PENALTY

Typically, aerospace vehicles are required to maintain the vehicle center of gravity (C.G.) within a narrow range of fuselage stations for aerodynamic stability. The ballast requirements will be affected by two different recovery system design conditions:

(1) Vehicle designed with a recovery system

(2) Vehicle designed without a recovery system and later retrofitted.

a. Vehicle Designed with a Recovery System

For vehicles where the recovery system is integral from the drawing board stage, the ballast required to offset the recovery system should be zero. The designer, given the recovery system weight, has the freedom to choose the locations of the recovery system components and other vehicle components not associated with the recovery system in such a manner that the addition of recovery system associated ballast is not required. In this case, the ballast weight is zero.

b. Vehicle Designed without a Recovery System

For the case where the aerospace vehicle is already designed (and possibly in operational usage) the addition of a recovery system may require the addition of ballast to maintain the C.G. within flying requirements. In this case, the weights of the individual recovery system components are the same as previously determined but now the locations of those components are restricted because of the frozen design requirements of the nonrecovery system components. Thus, the location more than the weight of the recovery system components dominates the requirements for the addition of ballast.

As was the case in the fuel penalty discussed above, an assessment of the ballast penalty would require a complex analysis of the particular vehicle under consideration. Again, if the recovery system WEIGHT were zero, then there would be no ballast penalty and as the WEIGHT increased, the ballast penalty would increase proportionally, Equation 13:

$$\text{Ballast Penalty} \propto \text{WEIGHT} \tag{13}$$

Therefore if WEIGHT is minimized, the ballast penalty will be minimized.

3. APPLICATION TO A VEHICLE

In the course of applying the algorithm being developed in this analysis to an actual vehicle where the proportionality equations are known (Equations 12 and 13) then these two penalties should be included as part of the recovery system total weight. Under the definition of a recovery system stated in Section II, these two penalties are indeed part of a recovery system. These penalties have been treated summarily in this analysis because specific vehicle details are not available for assessment.

SECTION VI

INDEPENDENT COMPONENTS

The electronic logic circuitry and the vehicle riser were grouped as "independent" components in Section II. It will now be argued that the weights of these components are relatively independent of the variable C_DS. It will be shown that the weights of these components are influenced more by design considerations than by the drag area of the main recovery parachutes (the independent variable C_DS).

1. ELECTRONIC LOGIC CIRCUITRY

The electronic logic circuitry is composed of command circuits, control circuits, a power supply, and mounting brackets.

a. Command

The command functions of the logic circuitry are (1) the initiation of the recovery system and (2) the termination of the recovery system. The first command function has a reliability related requirement that the recovery system shall be capable of initiation and capable of functioning in the event of total loss of vehicle power. This requirement for an independent operating capability dictates an additional power source (e.g. a battery). Typically, the signal to the command circuit to initiate recovery is either command from a remote manned control center or through internal sensors and internal logic. The second command function of the logic circuitry is the release of the parachute system after surface impact. This is done to prevent the dragging of the vehicle (and subsequent damage) by the main recovery parachute(s) and surface winds. Disconnecting the parachute subsystem from the vehicle requires that sensors be located onboard the vehicle capable of reliably sensing when the vehicle has impacted (either on land or water). A large variety of sensors have been used and tested and all share the features of closing a switch when subjected to some stimulus characteristic of surface impact of the vehicle. The physical ground disconnect hardware is activated by the closing of this switch. Since the ground disconnect device is required to separate the parachute forces from the vehicle, it must be designed to carry the parachute inflation forces. This constraint may be interpreted as implying that the weight of the ground disconnect device is a function of the maximum force of the parachute and hence of C_DS. However, the weight function in this relation is very insensitive being on the order of 1 pound for every 5000 square feet of C_DS. The weight of the ground disconnect is more closely dependent on the physical size of the webbing, the allowable pin diameter for joint efficiency and the metallic alloys and heat treatments utilized. For this analysis, the weight relationship of the ground disconnect versus parachute size is considered negligible.

The command functions have necessitated the inclusion of both initiation and termination sensors and hardware and an independent power supply in the electronic logic circuitry of the recovery system.

b. Control

The control functions of the logic circuitry are typically the staging of different parachute deployments so as to maintain a predetermined force level and/or a trajectory. However, the control functions of the logic circuitry do not include reefing control of individual parachutes (see Section VII). The control circuitry uses timing and/or altitude sensing mechanisms to signal the release of the next stage parachute. The times for actuation are determined from extensive trajectory/airspeed analysis and are preset before recovery system initiation. Control of trajectory and subsequent ground impact location accuracy is achieved by minimizing the time exposed to surface winds. Typically, this is accomplished by an altimeter (either radar or pressure) delaying the deployment of the main recovery parachute(s) until some preselected minimum altitude. This attempts to minimize the duration of the vehicle being exposed to the somewhat random surface winds while descending at a slow velocity under the main recovery parachutes.

The control functions require the inclusion of timers, altimeters, and the associated hardware into the electronic logic circuitry of the recovery system.

c. Power Supply and Mounting Brackets

The power supply and the mounting bracketry associated with the electronic logic circuitry frequently account for a majority of the weight of the electronic logic circuitry.

The power supply used for the independent functioning of the recovery system is commonly in the form of a battery. The battery size and weight is determined by the anticipated power requirements and by the type of battery selected (e.g. lead-acid, nicad, potassium hydroxide, etc.). Although the power requirements are determined by the complexity of the command and control circuitry it is argued that the type of battery selected is a more important factor in the battery weight. This analysis will assume that the weight of the battery is independent of the variable C_DS and instead is controlled by the selection of the battery type.

The weight of the mounting bracketry is also included under the definition of a recovery system. This bracketry includes the battery mounts as well as the mountings for the command and control circuitry. The strength and hence the weight of these mountings is controlled by their location and geometry within the vehicle and by the maximum allowable accelerations of the vehicle. Therefore, the weight of the mounting brackets will be assumed independent of the variable C_DS.

d. Example Weight Breakdown

A breakdown of the weights of the electronic logic circuitry as used in the RPRV-F-16 research vehicle serves to illustrate a typical weight allocation.

Electronic Logic Circuitry Weight for the RPRV-F-16 Vehicle

Battery	35 Pounds
Command and Control Circuits	15 Pounds
Mounting Bracketry	5 Pounds
TOTAL	55 Pounds

It should be noted that in this example, the weights of the power supply (battery) and the mounting bracketry account for almost three-fourths (73%) of the total weight of the electronic logic circuitry.

e. Weight of the Electronic Logic Circuitry

The term "C_1" was defined as representing the weight of the electronic logic circuitry and the weight of the vehicle riser. The factors controlling the weight of the electronic logic circuitry have been examined and can best be summarized as: The level of technology used in the electronic logic circuitry most directly controls the circuitry weight. In this analysis, the weight of the electronic logic circuitry will be considered as a constant value supplied by the vehicle designer. As such, it will be included in the recovery system WEIGHT optimization but will not be optimized independently. It will be shown later that the weight of the electronic logic circuitry is a significant portion of the recovery system WEIGHT and perhaps merits future attention.

2. VEHICLE RISER

The purpose of the vehicle riser is to connect the main recovery parachute to the vehicle attachment points in such a manner as to control the pitch/roll attitude of the vehicle in a manner most suited for the impact attenuation subsystem.

a. Construction Efficiency

A conventionally constructed riser consists of several plys of woven nylon webbing banded together and attached to the vehicle and the main recovery parachute by means of round pins. The weight per foot of riser can be approximated by Equation 14.

$$\text{Wgt}/_{\text{foot of Riser}} = \frac{(\text{maximum force})\ (\text{Factor of Safety})}{\left[\dfrac{\text{Breaking Strength}/_{\text{Ply}}}{\text{Wgt}/_{\text{Foot of one Ply}}}\right]} \qquad (14)$$

or in symbolic format:

$$\text{Wgt}/_{\text{foot of Riser}} = \frac{(W)\ (g\ \max)\ (K_D)}{k_c} \qquad (14)$$

where

W = Vehicle Weight (Equation 2), pounds

g max = maximum allowable acceleration of the vehicle in g's (dimensionless)

K_D = Design Safety Factor, includes margin of safety and joint efficiences. A dimensionless value of 2.3 will be used in this analysis (Reference 2)

k_c = Webbing weave efficiency which is the rated minimum breaking strength of one ply of webbing divided by the weight per foot of the webbing. Units are lb/(lb/ft) or ft.

Examining Equation 14 indicates that the only parameter that the designer of the vehicle riser may alter is the webbing weave efficiency, k_c. In order to determine the most efficient common nylon webbing for a particular application, the designer must choose the most efficient combination of weaves and number of plys required to satisfy the vehicle attachment point geometry. Table 1 lists the webbing weave efficiencies for a variety of nylon webbings.

TABLE 1

WEBBING WEAVE EFFICIENCIES

From MIL-W-4088G

Type	Weight (oz/yd)	Strength (lbs)	k_c(ft)
I	0.28	500	85714
II	0.42	600	68571
III	0.52	800	73846
IV	1.2	1800	72000
VI	1.15	2500	104347
VII	2.35	5500	112340
VIII	1.6	3600	108000
IX	4.0	9000	108000
X	3.7	8700	112864
XII	0.85	1200	67764
XIII	2.9	6500	107586
XIV	0.8	1200	72000
XV	1.25	1500	57600
XVI	2.0	4500	108000
XVII	1.15	2500	104347
XVIII	2.05	6000	140487
XIX	4.1	10000	117073
XX	3.25	9000	132923
XXI	1.7	3600	101647
XXII	3.5	9500	130285
XXIII	3.7	12000	155675
XXIV	2.25	5500	117333
XXV	1.5	4500	144000
XXVI	4.9	15000	146938
XXVII	2.9	6500	107586

From MIL-W-27657A

Type	Weight (oz/yd)	Strength (lbs)	k_c(ft)
I	0.9	3000	160000
II	1.25	4000	153600
III	1.65	6000	174545
IV	2.40	8700	174000
V	2.40	9000	180000
VI	2.70	10000	177777

The top ten most efficient webbings of Table 1 are ranked by their relative efficiency in Table 2.

TABLE 2

HIGH EFFICIENCY WEBBINGS

Webbing	Type	Weight (oz/yd)	Breaking Strength (LB)	k_c(ft)	Order of Performance
MIL-W-27657A	V	2.40	9000	180000	1
MIL-W-27657A	VI	2.70	10000	177777	2
MIL-W-27657A	III	1.65	6000	174545	3
MIL-W-27657A	IV	2.40	8700	174000	4
MIL-W-27657A	I	0.9	3000	160000	5
MIL-W-4088G	XXIII	3.7	12000	155675	6
MIL-W-27657A	II	1.25	4000	153600	7
MIL-W-4088G	XXVI	4.9	15000	146938	8
MIL-W-4088G	XXV	1.5	4500	144000	9
MIL-W-4088G	XVIII	2.05	6000	140487	10

The top five high efficiency webbings appear to be of sizes (3,000 - 10,000 pounds breaking strength) such that a designer would have sufficient latitude in matching the breaking strength to the number of riser legs required for vehicle pitch/roll attitude control. For this analysis, a value of k_c of 170,000 ft will be used as a representative of good riser construction techniques.

b. Weight of the Vehicle Riser

The total weight of the vehicle riser is then a function of the length of the riser given the construction technique and the maximum force. The length of the riser however, is a complex function of the aerodynamic flow characteristics of the vehicle as a forebody to the parachute and the geometrical arrangement of the vehicle and parachute attachment points. In order to resolve this difficulty, this analysis will assume that the length of the vehicle riser is equal to the length of the vehicle. This assumption is a rough rule of thumb but is in the ballpark for aerospace vehicle recovery systems. This assumption will be used in this analysis with the condition that if the actual vehicle riser length is known, then it will be used in lieu of the assumed vehicle length. The weight of the vehicle riser is expressed in Equation 15 which is obtained by multiplying Equation 14 by the vehicle length.

$$\text{Vehicle Riser Weight (lbs)} = \frac{(W)\ (g\ \text{max})\ (K_D)\ (\text{Vehicle length})}{k_c} \qquad (15)$$

or substituting numerical values; $(K_D = 2.3;\ k_c = 170{,}000\ \text{ft})$;

$$\text{Vehicle Riser Weight (lbs)} = \frac{(W)\ (g\ \text{max})\ (\text{Vehicle length})}{73{,}900} \qquad (15)$$

3. WEIGHT OF THE INDEPENDENT COMPONENTS (C_1)

The term C_1 is used to represent the weight of the independent components. It is the combined weight in pounds of the electronic logic circuitry and the vehicle riser. The weight of the electronic logic circuitry is considered to be a constant value with respect to the independent variable C_DS. The weight of the vehicle riser is determined by the vehicle's weight, length, and maximum acceleration and is also considered to be a constant with respect to the independent variable C_DS. The preceding argument allows Equation 16 to be written expressing the weight in pounds of the independent components.

$$C_1 = (\text{Weight of Logic Circuitry}) + \frac{(W)\ (g\ \max)\ (\text{Vehicle Length})}{73{,}900} \tag{16}$$

This relationship will be used in the WEIGHT optimization subject to all the assumptions made in its derivation.

SECTION VII

PARACHUTE SUBSYSTEM

This analysis is concerned with the performance requirements of the parachute subsystem only at the point of first ground contact (termination of the parachute subsystem operation). The weight and physical description of the parachute subsystem is also dictated by the performance requirements at initiation and during the subsystem functioning. The desired vehicle recovery envelope and maximum allowable force on the vehicle determine the number of parachutes and reefing stages. This wide variety of parameters may result in a parachute subsystem consisting of a single unreefed parachute or many different parachutes with multiple stages of reefing. For the purposes of this analysis, a two parachute subsystem with each parachute having a single reefing stage will be considered. Therefore, the parachute subsystem consists of the following components:

MAIN STAGE	1. Main Recovery Parachute 2. Main Recovery Parachute Miscellaneous Hardware 3. Main Recovery Parachute Deployment Bag 4. Main Recovery Paracute Deployment Bag Container
DROGUE STAGE	5. Drogue Parachute 6. Drogue Parachute Miscellaneous Hardware 7. Drogue Parachute Deployment Bag 8. Drogue Parachute Deployment Bag Container

It is argued that this two parachute, singly reefed subsystem is the most typical arrangement to be found in aerospace vehicle recovery systems. However, the designer should be aware that alternate configurations may exist which may satisfy a specific application (e.g. the parachute subsystem could consist of a single parachute with multiple reefings). The technique for analysis developed in this section should still be applicable in all but the most exotic of design configurations.

1. OVERVIEW OF ANALYSIS TECHNIQUE

This section will show that the weight of the miscellaneous hardware (both stages) is a direct function of the weight of the parachute. The weight of the deployment bag (both stages) is a direct function of the weight of both the parachute and the miscellaneous hardware and the packing density. The weight of the deployment bag container (both stages) also is considered to be a direct function of the combined weights of the parachute, miscellaneous hardware, and deployment bag as well as the packing density. The weight of the parachute will be shown to be a function of the independent variable, C_DS and can be optimized by stage (main versus drogue). A summation of the individual component weights will give a relation between the weight of the parachute subsystem and the variable C_DS.

2. MISCELLANEOUS HARDWARE FOR BOTH MAIN AND DROGUE PARACHUTES

In addition to the basic fabric component weights of a simply reefed parachute there must be added the weights of several miscellaneous hardware and fabric components. These components are individually of almost negligible weight but collectively represent a significant percentage of the parachutes weight. Considering the parachute weight to include only the canopy and suspension lines down to a single or multiple confluence point, then the weights of the following items must be included in the parachute subsystem weight for both the main and drogue parachutes.

1. Reefing lines
2. Reefing rings
3. Reefing line cutters
4. Reefing line cutter arming lanyards
5. Reefing line cutter protection pockets
6. Canopy stowage break ties
7. Suspension line stowage break ties
8. Riser connector linkages
9. Canopy stretch out break ties
10. Release knife assemblies
11. et cetera

While each of these items weigh on the order of ounces or less, collectively they have been approximated as totaling on the order of 6% of the parachute weight (Reference 3).

$$\text{Weight of the miscellaneous hardware} = 0.06 \text{ (Weight of the Parachute)} \qquad (17)$$

Equation 17 will be assumed to apply to both the main and drogue stage parachutes.

3. DEPLOYMENT BAG WEIGHT

The deployment bag is used to pack the parachute in such a manner so as to provide reliable deployment. The bag is designed to provide the necessary pressure on the parachute to maintain the pack density. In addition, the bag protects the parachute during ground handling and transportation. The weight of the deployment bag is a function of the total volume of the bag and the packing density (hence bag force required) of the parachute. Since volume represents a penalty onboard aerospace vehicles, a maximum practical packing density of 40 pounds per cubic foot will be assumed for nylon parachutes.

Operational experience with deployment bags designed and tested for use with packing densities on the order of 40 lb/ft^3 indicates the bag weight is on the order of 6% of the total weight of its contents.

$$\text{Weight of the Deployment bag} = 0.06\,(\text{Wgt of the Parachute}) + 0.06\,(\text{Wgt of Misc. hardware})$$

or substituting from Equation 17 and simplifying;

$$\text{Weight of the deployment bag} = 0.0636\,(\text{Weight of the parachute}) \tag{18}$$

Equation 18 will be assumed to apply to both the main and drogue parachute deployment bags.

4. DEPLOYMENT BAG CONTAINER WEIGHT

When installed in a vehicle, the parachute, it's associated hardware, and it's deployment bag are typically housed in a metal container which attaches to the vehicle airframe. This container serves to carry the flight loads imposed by the mass of the parachute (including associated hardware and deployment bag) and the acceleration environment during vehicle maneuvers. The container may also be a primary load path during some or all of the recovery system functioning. The weight of the container is a function of the total volume of the container and whatever load paths are incorporated in its design. The integral load paths and their associated weight penalties on the container design are a function of the geometry of the aerospace vehicle and the location of the stowed parachute in that vehicle. Since the location and geometry are unknown in this analysis, past experience will be used to make the following assumption. It will be assumed that the weight of the parachute deployment bag container is on the order of 5 pounds per cubic foot of volume of the packed parachute. For the assumed packing density of 40 pounds per cubic foot, the weight of the deployment bag container can be written as Equation 19.

$$\text{Weight of the Deployment bag container} = 5\left(\frac{\text{Lbs}}{\text{Ft}^3}\right)(\text{Container Volume}) \tag{19}$$

$$\text{Container Volume} = \frac{\left[\begin{array}{l}\text{Weight of the Parachute} + \\ \text{Weight of the misc. hardware} + \\ \text{Weight of the deployment bag}\end{array}\right]}{\text{Packing density}}$$

or by inserting numbers, substituting Equations 17 and 18 and simplifying:

$$\text{Weight of the deployment bag container} = 0.1404\,(\text{Weight of the parachute}) \tag{19}$$

Equation 19 will be assumed to apply to both the main and drogue stage containers.

5. WEIGHT OF THE MAIN RECOVERY PARACHUTE

a. The Designers Problem

Given the required performance characteristics of the main recovery parachute, the designer is tasked with selecting the type of parachute to be used. (e.g. ringslot, solid flat circular, conical, etc.) Not only must the designer consider the relative drag area efficiencies (square feet of drag area per pound of parachute weight) but he must also consider opening shock factors, minimum reefing ratios, complexity, costs, reliability, oscillations, etc.

b. Approach to the Problem

In order to select the best parachute for his application, the designer will first determine as much information as possible concerning the intended application and will then utilize some (or all) of the following techniques in his selection process.

1. Studying flight test data
2. Performing theoretical analysis
3. Consulting with experts
4. Engineering intuition

The point is that there is no clear method to select a parachute type and that therefore, "THE BEST PARACHUTE" does not exist. No single type of parachute can be rated "best" in all applications. The designer must decide which type of parachute appears best for his specific application. In this analysis, a theoretical analysis will be used in order to determine the best drag area efficiency between parachute types. Flight test data will be used as the basis for performance values for that parachute type and engineering intuition will be exercised to maintain reasonableness. This process uses these techniques as a basis for selection of the parachute type. It should be recognized that alternate techniques may be used to arrive at different conclusions.

c. Theoretical Selection of Parachute Type

An analysis of and a technique for analysis of the relative efficiency of different types of parachutes has been developed and documented in A Structural Merit Function for Aerodynamic Decelerators by Messrs. Anderson, Bohen, and Mikulas of the NASA Langley Research Center (Reference 1). This report defines a function representing decelerator efficiency which takes into consideration both aerodynamic and structural parameters. By applying this merit function to a variety of candidate parachutes, a minimum weight parachute type may be identified and the parachute weight to produce a required C_DS value may be quantified. Anderson, et al, showed that the parameter of m/C_DS is a proper merit function for decelerators if presented as a function of the single parameter $q\ (C_DS)^{1/2}$ and that for a given value of $q\ (C_DS)^{1/2}$ the decelerator having the lowest numerical value of m/C_DS will be the most efficient. The parachute types which were considered as candidates for the minimum weight main recovery stage parachute were:

1. Solid Flat Circular
2. Ringsail
3. Conical
4. Tri-Conical
5. Disc - Gap - Band

The application of the structural merit function to these parachute types is somewhat laborious and is contained in Appendix A. The results of the structural merit function application is that the ringsail parachute is the most weight efficient of the parachutes examined.

d. Weight Relation of a Ringsail Parachute

In order to obtain a realistic relationship for the numerical value of parachute weight per square foot of C_DS, the available flight test data covering measured values of C_DS and parachute weight (W_p) is presented in Table 3 (Reference 3).

TABLE 3

RINGSAIL FLIGHT TEST DATA FOR MAIN RECOVERY PARACHUTE APPLICATIONS

D_o (ft)	q_{max} (psf)	Average measured C_DS/W_p (ft^2/lb)	Number of Tests
56.2	57	50.2	14
63.1	76	57.4	77
128.8	64	51.3	1

The flight tests documented in Table 3 represent a reasonably sized sample (92 tests total), with a reasonably wide range in nominal diameters and with a reasonably small variation in the average measured values of C_DS/W_P. Therefore, this analysis will assume that a value of 50 square feet of effective drag area (C_DS) per pound of parachute weight is a reasonable value for a ringsail parachute used as a main recovery stage parachute.

$$\text{Weight of the main recovery parachute (lbs)} = C_D S/50 \qquad (20)$$

This equation will be used as the basis for determining the weight of the main recovery parachute and hence the weights of the components of the main stage of the parachute subsystem.

6. WEIGHT OF THE DROGUE PARACHUTE

The weight of the drogue stage parachute will be assessed by determining a reasonable weight efficiency and then estimating the size of the drogue parachute based on the size and type of the main recovery parachute. Although this technique is not rigorous from a performance analysis viewpoint, it is an adequate approximation for a weight analysis.

a. Selection and Weight Relationship of a Drogue Parachute

The selection of the type of parachute to be used in this analysis was also based on the structural merit function (Appendix A) used to select the type of parachute for the main stage. The results were again that the ringsail parachute was the most weight efficient of the parachutes examined in this analysis and in the referenced report (Reference 3).

In order to determine a realistic weight relation for a Ringsail Parachute used as a drogue, the flight test data presented in Table 4 (Reference 3) was examined.

TABLE 4

RINGSAIL FLIGHT TEST DATA FOR DROGUE PARACHUTE APPLICATIONS

D_o (ft)	q_{max} psf	Average measured C_DS/W_p (ft^2/lb)	Number of Tests
29.6	542	22.8	9
40.5	410	31.2	5
41.0	422	42.3	33

The flight test data presented in Table 4 represents a medium sized sample of tests (47 total) with nominal diameters considered to be large for normal drogue applications and with a wide spread in the measured values of C_DS/W_P. This analysis will assume that a value of 20 square feet of effective drag area (C_DS) per pound of parachute is a reasonably conservative value for a Ringsail Parachute used as a drogue parachute. Although this assumption appears tenuous, it can be rationalized since the weight efficiency is the only parameter used in this analysis describing the drogue parachute. Other parachute types (ribbon, hemisflow, ringslot, etc.) could be considered as having the assumed weight efficiency of 20 ft^2/lb. The selection of a ringsail drogue canopy is a result of the selection process chosen and the analytical techniques utilized in that process.

b. Size of the Drogue Parachute

The required effective drag area of the drogue parachute, $(C_DS)_{DROGUE}$, can be approximated by assuming that at transition to the main recovery parachute the equilibrium dynamic pressure is equal to the maximum dynamic pressure for the reefed deployment of the main recovery parachute. Therefore, for the drogue parachute at equilibrium conditions:

$$W = (q\ \text{max})(C_D S)_{\text{DROGUE}} \tag{21}$$

and for the maximum dynamic pressure (q max) at which the main recovery parachute may be deployed in the minimum reefed condition without violating the maximum allowable acceleration limitations of the vehicle

$$q\ \text{max} = \frac{(W)\ (g\ \text{max})}{(R_R)_M\ (X_R)_M\ (C_D S)_{\text{MAIN}}} \tag{22}$$

where $(R_R)_M$ = minimum reefing ratio of the main recovery parachute which is reported to be 5% for the Ringsail (Reference 3)

$(X_R)_M$ = reefed opening shock factor for the main recovery parachute, which is reported to be 1.1 for the Ringsail (Reference 3)

by substituting for q max in Equation 22 from Equation 21 the following relationship expressing the size of the drogue parachute in terms of the size of the main recovery parachute can be written

$$(C_D S)_{\text{DROGUE}} = \frac{(R_R)_M\ (X_R)_M}{g\ \text{max}}\ (C_D S)_{\text{MAIN}} \tag{23}$$

This approximation of the required size of the drogue parachute will be used in this analysis to predict the weight characteristics of the drogue parachute. The performance characteristics of the drogue parachute should not be based on this simplified approximation.

c. Weight of the Drogue Parachute

The weight efficiency (20 ft^2/lb) and the size of the drogue parachute can be combined in Equation 24 to represent the weight of the drogue parachute as a function of the independent variable C_DS (or $(C_DS)_{MAIN}$) as used in this analysis.

$$\text{Weight of the Drogue Parachute} = \frac{(R_R)_M\ (X_R)_M}{20\ (g\ max)}\ (C_DS) \qquad (24)$$

7. WEIGHT OF THE PARACHUTE SUBSYSTEM

The weight of the parachute subsystem is the combined weight of all the components as discussed above. The weights of the components will be assessed by individual parachute and then combined into the weight relation of the parachute subsystem.

a. Weight of the Main Parachute Stage

The weight relation for the main parachute stage is the sum of the weight relations developed for the main recovery parachute and its miscellaneous hardware, deployment bag, and container.

$$\text{Weight of the main recovery parachute} = (C_DS)/50 \qquad (20)$$

$$\text{Weight of the main parachute misc. hardware} = 0.06\ (\text{Wgt of the main parachute}) \qquad (17)$$

$$\text{Weight of the main parachute deployment bag} = 0.0636\ (\text{Wgt of the main parachute}) \qquad (18)$$

$$\text{Weight of the main deployment bag container} = 0.1404\ (\text{Wgt of the main parachute}) \qquad (19)$$

Summing up these weight relations and simplifying yields the weight relation of the main parachute stage of the parachute subsystem, (Equation 25) as a function of C_DS.

$$\text{Weight of the main parachute stage} = 0.02528\ C_DS \qquad (25)$$

b. Weight of the Drogue Parachute Stage

The weight relation for the drogue parachute stage of the parachute subsystem is the sum of the weight relations for the drogue parachute and its miscellaneous hardware, deployment bag, and container.

$$\text{Weight of the Drogue parachute} = \frac{(R_R)_M\ (X_R)_M}{(20)(g\ \text{max})}\ (C_DS) \qquad (24)$$

Weight of the Drogue misc hardware = 0.06 (Wgt of the drogue parachute) (17)

Weight of the Drogue deployment bag = 0.0636 (Wgt of the drogue parachute) (18)

Weight of the deployment bag container = 0.1404 (Wgt of the drogue parachute) (19)

Summing up these weight relations and simplifying the numerical values (as shown) gives Equation 26.

$$\text{Weight of the drogue stage} = \frac{0.0632\ (R_R)_M\ (X_R)_M}{(g\ \text{max})}\ (C_DS) \qquad (26)$$

By using the previous values of 5% for the maximum allowable reefing ratio $(R_R)_M$ of the main recovery parachute (Ringsail) (Reference 3) and 1.1 for the reefed opening shock factor $(X_R)_M$ (Reference 2) of the main recovery parachute allows Equation 27 to relate the weight of the drogue stage as a function of the maximum allowable accelerations of the vehicle (g max) and the independent variable C_DS.

$$\text{Wgt of the drogue stage} = \frac{0.003476}{(\text{g max})} (C_DS) \qquad (27)$$

c. Weight of the Parachute Subsystem

The weight relation for the parachute subsystem is the sum of the weight relations of the main and drogue stages.

$$\text{Weight of the main stage} = 0.02528\ C_DS \qquad (25)$$

$$\text{Weight of the drogue stage} = \frac{0.003476}{(\text{g max})}\ C_DS \qquad (27)$$

Summing these relations gives Equation 28, expressing the weight of the parachute subsystem as a function of the maximum allowable accelerations of the vehicle (g max) and the independent variable C_DS.

$$\text{Weight of the parachute subsystem} = (0.02528 + \frac{0.033476}{\text{g max}})\ C_DS \qquad (28)$$

or referencing Equation 3 from Section IV-3;

$$C_2 = (0.02528 + \frac{0.003476}{\text{g max}}) \qquad (29)$$

This value for C_2 will be used in the optimization of the recovery system WEIGHT (Reference Equation 7).

SECTION VIII

IMPACT ATTENUATION SUBSYSTEM

1. GENERAL

The purpose of the impact attenuation system is to reduce the kinetic energy of the vehicle from some initial value to zero relative to the ground. The initial value of the kinetic energy is partially determined by the rate of descent of the main recovery parachute/vehicle. Although the drag area of the main recovery parachute directly determines the vertical velocity, there are horizontal kinetic energy components which the impact attenuator must dissipate. Although a systematic detailed analysis of the component weights of an impact attenuation subsystem is desirable, such an analysis is considered beyond the scope of this weight optimization analysis. A summary review of the design parameters which are to be considered in an impact attenuation subsystem will be discussed. For the purposes of this analysis, an argument will be presented in which the actual impact attenuation subsystem weight is directly related to the vertical velocity induced kinetic energy vector measured at the instant of first ground contact.

2. IMPACT CONDITIONS

The kinetic energy of the vehicle's center of gravity relative to the ground which the attenuation subsystem must dissipate is composed of the following components:

a. The kinetic energy due to the vertical velocity of the main recovery parachute and vehicle in equilibrium descent.

b. The kinetic energy due to the horizontal glide velocity of the main recovery parachute and vehicle in equilibrium descent.

c. The kinetic energy relative to the ground induced by the surface wind velocity.

The attitude of the vehicle with respect to the ground and hence the attitude of the impact attenuation subsystem is composed of the following components:

a. The oscillation of the main recovery parachute/vehicle combination (parachute center axis) with respect to the horizontal.

b. The orientation of the vehicle with respect to the parachute center axis (vehicle hang angle).

c. The attitude of the local terrain with respect to the horizontal as well as the nature of the terrain.

The vehicle is assumed to be descending in equilibrium descent under the main recovery parachute. While the vehicle is being suspended by the vehicle riser both the pitch and roll rates of the vehicle relative to the parachute center axis are assumed to be zero. It is also assumed that the vehicle yaw rate with respect to either the parachute center line axis or the ground is so small as to be negligible and will be considered as zero in this analysis. These impact conditions are shown in Figure 4.

3. SIMPLIFYING ASSUMPTION

For the purposes of this analysis, the weight of the impact attenuation subsystem will be considered as a function of the design vertical kinetic energy component only. The additional kinetic energy components such as the wind velocity, gusts, thermals, downdrafts,

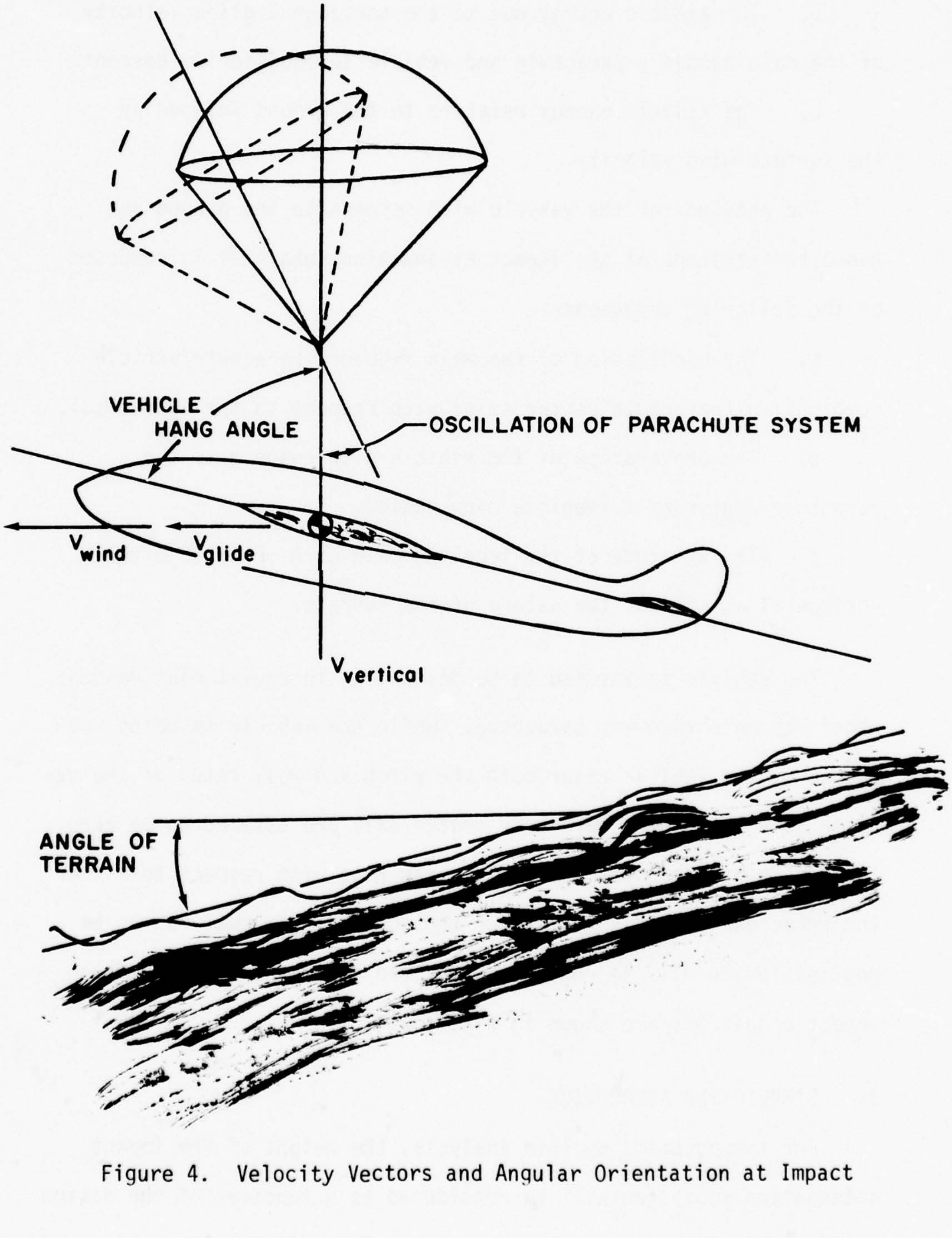

Figure 4. Velocity Vectors and Angular Orientation at Impact

and parachute perturbations from some nominal equilibrium condition are largely unknown. The many variables associated with the vehicle attitude relative to the ground such as the nature of the immediate terrain, vehicle yaw angle relative to the horizontal velocity vector, etc., are also unknown. However, in the weight of an actual impact attenuation subsystem all of these unknowns are reflected in a heavier system than would be predicted based upon laboratory tests. This analysis will examine actual impact attenuation systems and determine their system specific energy absorbtion (SSEA) based on the vertical kinetic energy they were designed for. In this way, the SSEA values will reflect the weight penalties of the unknown impact conditions. These unknown impact conditions and their effect on the SSEA will be dealt with as "...and other conditions being equal." By maintaining this postulate, it is believed that realistic values for the weight of an impact attenuation subsystem can be predicted. This is a large assumption and a discussion of some of the unknown parameters being dealt with in this manner is warranted.

4. KINETIC ENERGY COMPONENTS

It can readily be seen that the total velocity of the vehicle is some function of the vertical and horizontal velocities (glide angle) of the main recovery parachute and the prevailing surface wind. If it were possible it would be desirable to so align the parachute horizontal velocity vector so as to cancel out or minimize the wind vector when viewed from a ground fixed coordinate system. At the present time, this is considered as being beyond the state-of-the-art of conventional (low glide ratio) parachutes and an assessment of the hi-glide parachutes is beyond the scope of this analysis. Therefore, it is assumed that the horizontal angular relationship between the parachute horizontal velocity vector and the surface wind vector is random. They (the two vectors) may reinforce or cancel out each other in a random, unknown fashion. In order to reduce the possibility of reinforcement and thereby gain some measure of control of the horizontal component of the kinetic energy vector, it is desirable to utilize a system which has a very small or zero glide angle. The characteristics of the Ringsail type of canopy meet this requirement; although this require- was not one of the input functions or parameters to the efficiency evaluation of main recovery parachutes. Therefore, the remaining horizontal kinetic energy component is assumed to be attributable to the surface wind velocity. This velocity vector is completely random and may be large and unsteady, therefore, the wind component of the kinetic energy is placed in the category of "...all other conditions being equal."

It should be noted that for a passive type attenuation system which operates by the use of a vertical displacement (stroke) that at first ground contact there is a remaining potential energy equal to the weight of the vehicle times the stroke. It has been assumed in this analysis that (a) the parachute system will dissipate nearly all of this energy during the movement through the stroke distance and/or (b) this potential energy (or remainder of the potential energy) is small and can be considered negligible in comparison with the kinetic energy. This assumption should be checked however in the case of very low velocities with very long deceleration attenuation strokes.

5. ANGULAR ORIENTATION

The angular orientation of the vehicle with respect to the ground is determined by a minimum of three independent parameters:

1. Parachute oscillation relative to horizontal
2. Vehicle orientation relative to parachute axis
3. Terrain orientation relative to horizontal

The parachute oscillation parameter can be minimized by selection of a very stable parachute system. It again happens that the Ringsail canopy exhibits good stability characteristics. Oscillations have been reported to be typically less than ± 10° and frequently less than ± 5° in some flight test programs. Stability of many parachute canopies can be brought to this level by clustering two or three canopies to achieve stability in oscillation at the expense of aerodynamic efficiency. The oscillation parameter therefore can be assumed to be controllable down to a level of ± 10° or less.

The vehicle pitch orientation with respect to the parachute system centerline axis is determined by the location of the center of gravity of the vehicle when suspended and by the riser geometry. Vehicle pitch attitude can be controlled to approximately ± 5°, however, it is difficult to improve beyond this point due to manufacturing difficulties in maintaining tolerance of fabric risers. It is beyond the state-of-the-art of conventional parachutes to orient the vehicle yaw angle with respect to the ground. Therefore, all angles are conical in nature.

The orientation of the terrain with respect to the horizontal is beyond the control of the recovery system designer. If the recovery is premeditated, it may be possible to choose a "level" field but in an emergency, anything may occur. Even in a "level" field the actual orientation may be several degrees due to local variations such as rocks, drywashes, gullies, tree stumps, etc.

For the purpose of this analysis, these attitude considerations will be classed as "...all other conditions being equal" as regards the weight of an impact attenuation subsystem.

6. SYSTEM SPECIFIC ENERGY ABSORPTION

The usage of a System Specific Energy Absorbtion (SSEA) should not be confused with the SEA of a material or an idealized laboratory concept. In the laboratory SEA's of 20,000 $\frac{\text{ft-lbs}}{\text{lb}}$ are not considered unusual for many materials. The airbag concept can be laboratory tested and demonstrated to have an SEA value of more than 3000 $\frac{\text{ft-lbs}}{\text{lb}}$. But when these materials, concepts, etc., are incorporated into a realistic system subject to large conical loading vectors, angular misorientation, imperfect terrain (rock, etc.) and are designed for everyday operational usage, then these large values of SEA of the material no longer represent the SSEA of the system. For this analysis, the approach taken will be to examine realistic systems which have been designed and/or tested for conditions of service which maintain the postulate of "...all other conditions being equal." The SSEA of these systems will be considered as a realistic SSEA for a future system when measured as a direct function of kinetic energy due to the vertical velocity with "...all other conditions being equal." Airbag systems have been selected so as to provide a range of kinetic energy levels coupled with a spread in the mass and velocities involved. The results are shown in Table 5.

It is assumed as realistic that an airbag attenuation system designed for use with an aerospace vehicle recovery system will have a system specific energy absorbtion rate of approximately 300 $\frac{\text{ft-lbs}}{\text{lb}}$ based on the vertical velocity with all other conditions being equal. Again as technology increases this assumption may be reopened to question.

TABLE 5

ATTENUATOR SYSTEM STATISTICS (REFERENCE 4)

Payload Wgt. at Impt. Lb.	Vertical Velocity fps	System Weight W_s	Application	SSEA (K.E./W_s) or C_3	Reference
3544 Lbs	20	98	Drone Rec.	224	TRA XR72-12
8025 Lbs	31.5	251	B-1	345*	Goodyear
506 Lbs	75	136	Planetary Lander	325	NASA TND-5326

* Test Data Indicated a 70%, Energy Attenuation Efficiency

7. IMPACT ATTENUATION SUBSYSTEM WEIGHT RELATION

The weight relation for the impact attenuation subsystem was defined in Section IV and has been discussed in this section. From this Section IV, the weight relation is:

$$\text{Weight of the impact attenuation subsystem} = \frac{E}{C_3} \qquad (4)$$

where E is the vertical kinetic energy at first ground contact as given in Equation 9.

$$E = \frac{W^2}{g\,\rho\,(C_D S)} \qquad (9)$$

In this section, it is shown that the System Specific Energy Absorbtion is the same as the coefficient defined as C_3 and that a realistic numerical value for this parameter is 300 (ft-lbs)/lb. That is for every 300 foot pounds of vertical kinetic energy at design impact conditions, the impact attenuation subsystem will weigh one pound.

Using these equations and assumptions, the weight of the impact attenuation subsystem can be written as Equation 30.

$$\text{Weight of the impact attenuation subsystem} = \frac{W^2}{300\ \rho\ g\ (C_D S)} \qquad (30)$$

As technology advances, the SSEA of 300 (ft-lbs)/lb may be changed and the above assumptions re-examined.

SECTION IX

MINIMUM WEIGHT ALGORITHM

1. GENERAL

An algorithm which can be used to predict the minimum WEIGHT of an aerospace vehicle recovery system has been developed. This algorithm examines the weight buildup of the components of the recovery system but does not include the weight penalties of the vehicle fuel and ballast requirements. This algorithm is based on a number of assumptions which should be re-examined as regards any given specific application. The application parameters which are required to begin the algorithm are (1) the vehicle recovery weight, (2) the maximum acceleration (or force constraint) which the vehicle can withstand, and (3) some characteristic dimension of the vehicle (fuselage length).

These three application parameters and a good understanding of the assumptions inherent in this algorithm will allow a designer to predict the minimum WEIGHT recovery system required for his application.

2. INDEPENDENT COMPONENTS (C_1)

The independent components were defined as consisting of the electronic logic circuitry (including battery) and the vehicle riser (Reference Section II and VI).

The weight of the electronic logic circuitry was argued as being relatively independent of the variable C_DS. It is assumed in this algorithm that the electronic logic circuitry weight is determined and provided to the recovery system designer by an outside source and therefore this component's weight is treated as a constant value in the algorithm.

The weight of the vehicle riser was argued in Section VI to be a function of the construction techniques used and the vehicle geometry. The weight of the vehicle riser was approximated by Equation 15 (shown below) for a riser using conventional nylon webbings.

$$\text{Vehicle Riser Weight} = \frac{(W)\ (g\ \text{max})\ (\text{Vehicle Length})}{73{,}900}\ (\text{Lbs}) \qquad (15)$$

If a more accurate approximation were available, it would be advantageous to use it as this approximation is based on "ball park" style assumptions (see Section VI).

3. PARACHUTE SUBSYSTEM (C_2)

The parachute subsystem was defined in Sections II and VII as consisting of the following components:

A. Main Recovery Parachute
B. Main Recovery Parachute Miscellaneous Hardware
C. Main Recovery Parachute Deployment Bag
D. Main Recovery Parachute Deployment Bag Container
E. Drogue Parachute
F. Drogue Parachute Miscellaneous Hardware
G. Drogue Parachute Deployment Bag
H. Drogue Parachute Deployment Bag Container

These components represented a two parachute system (main and drogue) with each parachute stage employing single reefing. Such an arrangement (although common) must be based on a detailed performance analysis which is outside the scope of this algorithm.

The selection of the type of canopy to be used for the drogue and main parachutes (see Section VII and Appendix A) as well as the material and construction techniques determine the weight of the parachutes. In this analysis, an assumption was made that a nylon Ringsail canopy used for the main recovery parachute will yield an optimum weight efficiency of 50 square feet of effective drag area for every pound of parachute weight (canopy and suspension lines). When the nylon Ringsail canopy was examined for use as a drogue parachute, it was assumed that a value of 20 ft^2 of effective drag area per pound of drogue parachute was realistic.

The miscellaneous hardware associated with a simply reefed parachute was assessed as comprising an additional 6% of the parachute (canopy and suspension lines) weight. The deployment bag weight was also assessed at an additional 6% of the parachute weight. It is assumed that these assessments apply to both the main recovery and drogue parachutes.

The weight of the metallic deployment bag container is strongly influenced by the vehicle design and was assumed to weigh 5 pounds per cubic foot of inclosed volume. This was related to the variable C_DS by assuming a parachute pack density of 40 pounds per cubic foot for nylon parachutes. Again, this container weight relationship was assumed to apply to both the main recovery and drogue parachutes including the deployment bags and associated miscellaneous hardware.

4. IMPACT ATTENUATION SUBSYSTEM (C_3)

The weight of the impact attenuation subsystem was assumed to be directly related to the design vertical kinetic energy of the vehicle at first ground contact. A heuristic analysis (see Section VIII) resulted in a System Specific Energy Absorbtion value of 300 ft-lbs of vertical kinetic energy absorbtion for every pound of impact attenuation subsystem weight. This assumption is based on impact attenuation systems employing airbags which have been subjected to full scale testing. As technology progresses, this assumption should be reopened for examination in a more rigorous manner.

5. VEHICLE APPLICATION PARAMETERS

The parameters which are required to describe a given application for this algorithm are (1) the vehicle recovery weight, (2) the maximum acceleration, and (3) a characteristic dimension. The vehicle recovery weight has been used as a constant value and does not include the weight of the recovery system. The maximum vehicle acceleration (or maximum force for a constant vehicle weight) is used in the vehicle riser considerations and has not been considered from a strict parachute performance viewpoint. The characteristic dimension of the vehicle is utilized as indicative of the vehicle riser weight and is not critical to the algorithm.

6. MINIMIZATION OF WEIGHT

The WEIGHT of the recovery system is given by Equation 10 (shown below) once the numerical values for C_1, C_2, and C_3 have been determined and their underlying assumptions satisfied.

$$\text{WEIGHT} = C_1 + C_2(C_DS) + \frac{W^2}{g\ \rho\ C_3\ (C_DS)} \tag{10}$$

The minimum value of WEIGHT for a specific application is obtained when the optimum value of C_DS is inserted in Equation 10. This value of (C_DS) is obtained from Equation 11 (Ref. Section IV)

$$(C_DS)_{opt} = \sqrt{\frac{W^2}{g\ \rho\ C_2C_3}} \tag{11}$$

These two relations will give a minimum recovery system WEIGHT value for a specific application. As an indication of the value of the underlying assumptions, it is desirable to break out the weights of the individual components of the recovery system. Additionally, by examining the individual components an indication of the performance of the minimized WEIGHT recovery system can be obtained and examined for realism.

7. COMPONENT WEIGHT BREAKDOWN AND DESCRIPTION

The weight of the recovery system components and an indication of some of the performance parameters can be identified as follows:

a. Independent Components

(1) Electronic Circuitry

The weight of the electronic logic circuitry was assumed to be a given value (not subject to change) provided by an outside source.

(2) Vehicle Riser

The weight of the vehicle riser was assessed in Section VI and is given by Equation 15 for a nylon riser using good construction techniques.

$$\text{Vehicle riser weight} = \frac{(W)\ (g\ max)\ (\text{Vehicle length})}{73{,}900}\ (\text{Lbs}) \qquad (15)$$

b. Parachute Subsystem

(1) Main Recovery Parachute

The weight of the main recovery parachute based on the optimum value of C_DS was assessed in Section VII and is given by Equation 20 for a nylon ringsail parachute.

$$\text{Main Recovery Parachute Weight} = \frac{(C_DS)_{opt}}{50}\ (\text{Lbs}) \qquad (20)$$

By assuming a drag coefficient (C_D) of 0.78 for a ringsail canopy (Reference 2) the surface area (S) may be determined from $(C_DS)_{opt}$ and hence the diameter of the main recovery parachute may be approximated by the geometric relation of $S = 1/4\ \pi D^2$.

(2) Main Recovery Parachute Miscellaneous Hardware

The weight of the miscellaneous hardware associated with the main recovery parachute was assessed in Section VII and given by Equation 17.

$$\text{Miscellaneous hardware weight} = 0.06\ (\text{Weight of the Parachute}) \qquad (17)$$

(3) Main Recovery Parachute Deployment Bag

The weight of the deployment bag for the main recovery parachute was assessed in Section VII and is given by Equation 18 for an assumed pack density of 40 lbs/ft^3.

$$\text{Deployment Bag Weight} = 0.0636\ (\text{Weight of the Parachute}) \tag{18}$$

(4) Main Recovery Parachute Deployment Bag Container

The weight of the metallic container for the main recovery parachute deployment bag was assessed in Section VII and is given by Equation 19 for an assumed pack density of 40 lbs/ft^3.

$$\text{Container Weight} = 0.1404\ (\text{Weight of the parachute}) \tag{19}$$

(5) Drogue Parachute

The weight of the drogue parachute (canopy and suspension lines) was assessed in Section VII and is given by Equation 24 for a nylon ringsail canopy.

$$\text{Drogue Parachute Weight} = \frac{(R_R)_M (X_R)_M (C_D S)_{opt}}{(20)(g\ max)} \tag{24}$$

where: $(R_R)_M$ = The minimum reefing ratio of the main recovery parachute and was assumed to have a value of 0.05 for a ringsail parachute (Reference 3).

$(X_R)_M$ = Opening shock factor of the main recovery parachute and was assumed to have a value of 1.1 for a ring sail parachute (Reference 3).

The diameter of the drogue parachute can be approximated by using Equation 23 to obtain the effective drag area of the drogue parachute and then assuming a coefficient of drag (C_D) of 0.78 (Reference 2).

$$(C_D S)_{DROGUE} = \frac{(R_R)_M \ (X_R)_M \ (C_D S)_{opt}}{(g \ max)} \tag{23}$$

With the assumed C_D, the diameter of the drogue parachute can be approximated using $S = 1/4 \ \pi D^2$ in the same manner as was used for the main recovery parachute.

(6) Drogue Parachute Miscellaneous Hardware

The weight of the miscellaneous hardware associated with the drogue parachute was assessed in Section VII and is also given by Equation 17.

Miscellaneous hardware weight = 0.06 (Weight of the parachute) (17)

(7) Drogue Parachute Deployment Bag

The weight of the drogue parachute deployment bag was assessed in section VII and is also given by Equation 18 for an assumed Pack density of 40 lbs /ft^3.

Deployment Bag Weight = 0.0636 (Weight of the Parachute) (18)

(8) Drogue Parachute Deployment Bag Container

The weight of the metallic container for the drogue parachute was assessed in Section VII and is given by Equation 19 for an assumed pack density of 40 lbs/ft^3.

$$\text{Container Weight} = 0.1404\ (\text{Weight of the Parachute}) \tag{19}$$

c. Impact Attenuation Subsystem

The weight of the impact attenuation subsystem was assessed in Section VIII and is given by Equation 30 where a

$$\text{Impact Attenuation Subsystem Weight} = \frac{W^2}{C_3\ g\ \rho\ (C_D S)\text{opt}} \tag{30}$$

value for C_3 of 300 (ft-lb)/lb has been assumed realistic for a conventional impact attenuation subsystem.

d. Associated Penalties

The ballast and fuel penalties have not been quantified in this minimization of a recovery system WEIGHT. Nevertheless, these two penalties do comprise a portion of the total recovery system weight as defined in Section II.

e. Performance Description

Two of the performance parameters most commonly used in describing a recovery system are the vertical velocity and impact kinetic energy.

(1) Vertical Velocity

The vertical velocity of the aerospace vehicle descending under the main recovery parachute under equilibrium, steady state conditions can be approximated by Equation 8 (Reference Section IV for assumptions concerning suspended weight)

$$V_v = \sqrt{\frac{2\,W}{\rho\,(C_D S)_{opt}}} \tag{8}$$

(2) Impact Kinetic Energy

The vertical kinetic energy at impact is given by Equation 9 (reference Section IV).

$$E = \frac{W^2}{g\,\rho(C_D S)_{opt}} \tag{9}$$

This is the kinetic energy (vertical) for which the impact attenuation subsystem is designed.

8. SUMMARY OF ALGORITHM

The algorithm presented above will enable a designer to predict the minimum weight of a recovery system for an aerospace vehicle. However, that predicted weight will only be as valid as the assumptions underlying the algorithm. This algorithm has been developed primarily based on an aerospace vehicle similar to a remotely piloted vehicle of the general Firebee class of airframes. When applying this algorithm to alternate vehicles, a thorough understanding of both the explicit and implicit assumptions underlying this algorithm is recommended.

SECTION X

APPLICATION OF THE MINIMUM "WEIGHT" ALGORITHM

1. GENERAL

The minimum WEIGHT algorithm can be used to determine both the minimum WEIGHT of a recovery system using conventional technology and the minimum WEIGHT of a recovery using advanced (or hypothesized) technologies. A typical set of vehicle parameters are arbitrarily chosen and the algorithm applied using conventional technology. Using this example as a baseline, the effects of improved materials and other advanced concepts on the minimum WEIGHT of a recovery system may be identified.

The vehicle parameters chosen for this example are:

Vehicle weight (W) = 3000 Lbs,
Vehicle maximum acceleration (g max) = 10 g's,
Vehicle length = 20 ft.

It will be assumed that the vehicle designer has allocated 50 pounds for the electronic logic circuitry (including battery) and that the vehicle is of the same general class of airframes upon which the algorithm was based.

The four applications of the algorithm to be examined involve a conventional parachute subsystem and an advanced materials (para-aramide fibers) parachute subsystem as well as a conventional and an advanced impact attenuation subsystem. The four cases under investigation are shown in Table 6.

TABLE 6

ALGORITHM APPLICATIONS

	Parachute Technology	Attenuator Technology
Case #1	Conventional	Conventional
Case #2	Advanced	Conventional
Case #3	Conventional	Advanced
Case #4	Advanced	Advanced

By graphically summing up the four cases examined the effect of advancing technology is readily evident.

2. CASE #1, CONVENTIONAL PARACHUTE/CONVENTIONAL ATTENUATOR

a. Independent Components (C_1)

The weight of the electronic logic circuitry was given as 50 Lbs. The weight of the vehicle riser is obtained from Equation 15 for a conventional nylon webbing.

$$\text{Vehicle Riser Weight (Lbs)} = \frac{(3000 \text{ Lbs})\ (10 \text{ g's})\ (20 \text{ Ft})}{73{,}900 \text{ Ft}} \tag{15}$$

$$\text{Vehicle Riser Weight (Lbs)} = 8.119 \text{ Lbs}$$

The value for C_1 is therefore given by Equation 16:

$$\begin{aligned} C_1 &= 50 + 8.119 \text{ Lbs} \\ C_1 &= 58.119 \text{ Lbs} \end{aligned} \tag{16}$$

b. Parachute Subsystem (C_2)

The weight coefficient of the parachute subsystem using conventional nylon ringsail canopies is given by Equation 29, Reference Section VII.

$$C_2 = (0.02528 + \frac{0.003476}{10g's})$$

$$C_2 = 0.025628\ \text{ft}^2/\text{lb} \tag{29}$$

c. Impact Attenuation Subsystem (C_3)

It was shown in Section VIII that for a conventional impact attenuator system, a realistic value for the SSEA (or C_3) is 300 ft-lb/lb.

d. WEIGHT Minimization

The equation for the WEIGHT of the recovery system for this case may be written (Reference Equation 10)

$$\text{WEIGHT} = 58.119 + 0.025629\ (C_DS) + \frac{W^2}{300\ g\ \rho(C_DS)} \tag{10}$$

where: ρ = 0.002378 slugs/ft^3 at sea level

C_1 = 58.119 lbs

C_2 = 0.025628 lbs/ft^2

C_3 = 300 ft-lbs/lb

g = 32.2 ft/sec^2

W = 3000 lbs

Determining the optimum value of C_DS by using Equation 11 and substituting values gives:

$$(C_DS)_{opt} = \sqrt{\frac{(3000)^2\ \text{ft}^4}{(32.2)(0.002378)(0.025628)(300)}} \tag{11}$$

$$(C_DS)_{opt} = 3910\ \text{ft}^2$$

Thus the optimum effective drag area for the main recovery parachute in this case is 3910 ft^2. Substituting this value of $(C_DS)_{opt}$ for C_DS in the WEIGHT equation gives

$$\text{WEIGHT} = 58.119 + 0.025628\,(3910) + \frac{3000^2}{(300)(0.0765)(3910)} \qquad (10)$$

$$\text{WEIGHT} = 258.62 \text{ Lbs}$$

This is the minimum WEIGHT recovery system for the example application using a conventional parachute subsystem and a conventional impact attenuation subsystem.

e. Recovery System Description and Weight Breakdown

The weights of the individual components of this optimized recovery system are shown in Table 7. The detailed calculations are omitted here, but are as given in Section IX.

TABLE 7

COMPONENT BREAKDOWN FOR CASE #1

Conventional Parachute/Conventional Attenuator

Component	Weight
Electronic Logic Circuitry	50.00 Lbs
Vehicle Riser	8.12 Lbs
Main Recovery Parachute	78.20 Lbs
Main Recovery Parachute Misc. Hardware	4.69 Lbs
Main Recovery Parachute Deployment Bag	4.97 Lbs
Main Recovery Parachute Deployment Bag Container	10.97 Lbs
Drogue Parachute	1.07 Lbs
Drogue Parachute Miscellaneous Hardware	0.06 Lbs
Drogue Parachute Deployment Bag	0.068 Lbs
Drogue Parachute Deployment Bag Container	0.150 Lbs
Impact Attenuation Subsystem	100.29 Lbs
Ballast Penalty	not calculated
Fuel Penalty	not calculated
Total WEIGHT	258.58

Description	Value
Main Recovery Parachute (C_DS)	3910 ft^2
Main Recovery Parachute Diameter (approx.)	79.8 ft
Drogue Parachute C_DS	21.5 ft^2
Drogue Parachute Diameter (approx.)	5.9 ft
Equilibrium Vertical Velocity with Main Recovery Parachute (S.L.)	25.4 ft/sec
Kinetic Energy at Impact	30,060 ft-lbs

This case is shown graphically in Figure 5.

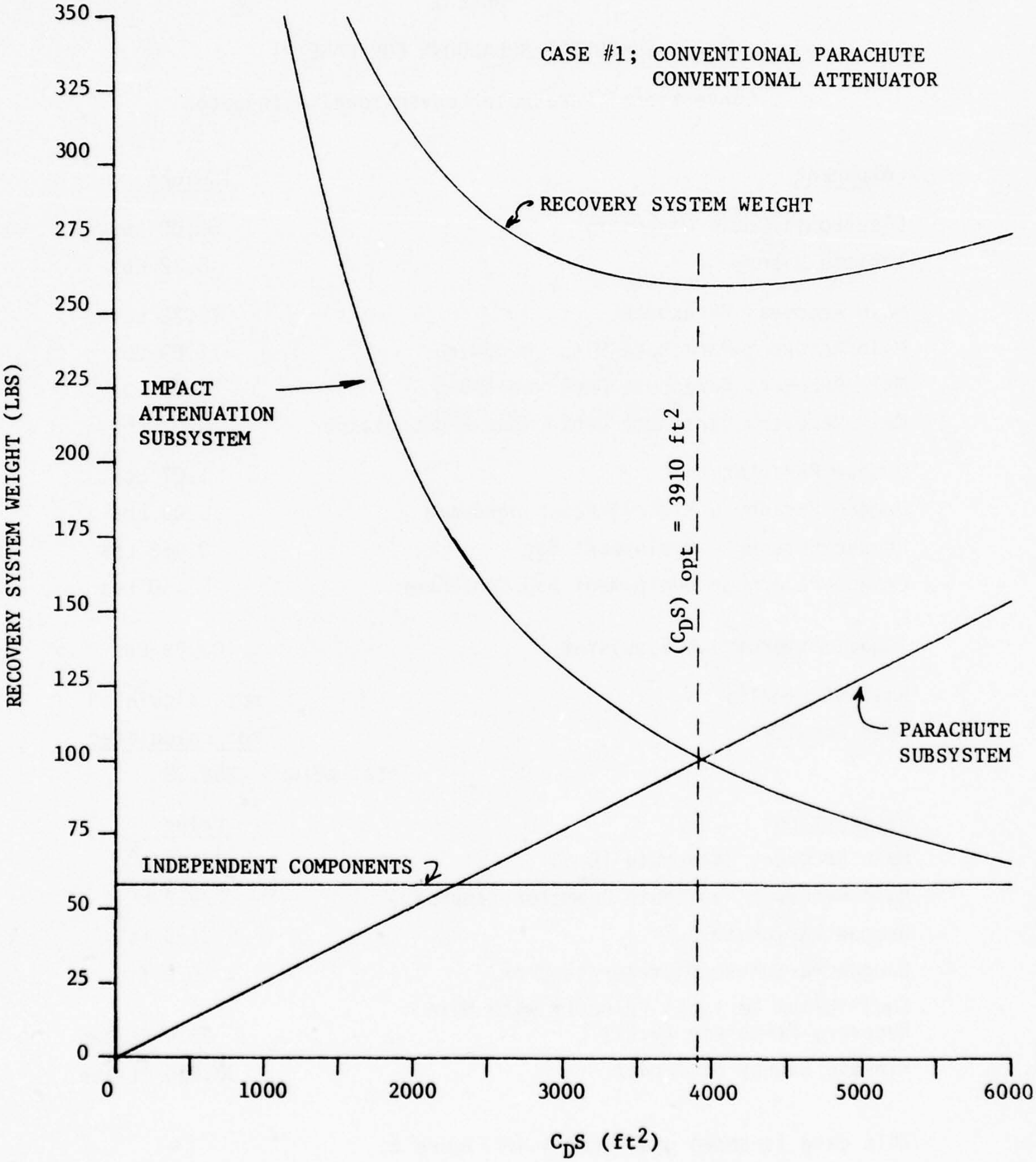

Figure 5. Case #1 WEIGHT Relation

3. CASE #2, ADVANCED PARACHUTE/CONVENTIONAL ATTENUATOR

a. General

Recent developments in improving parachute fabrics indicate that an advanced material may be highly suited to the needs of the parachute designer. At the present time, para-aramide fiber is undergoing extensive test and evaluation to develop a family of webbings, tapes, cords and fabrics which in their strength properties closely duplicate historical nylon weavings. The apparent advantages over nylon are lighter weight at a given breaking strength, and a higher density than nylon. These advantages should yield higher pack densities and hence less volume. In this case, the effect of an advanced system replacing the conventional nylon system will be examined. It will be assumed that for a nylon weave of a given strength the para-aramide fiber replacement will weigh only half as much. The nylon parachutes are currently being pressure packed to approximately 40 pounds per cubic foot or approximately 56% of its ultimate density of 71 pounds per cubic foot. It will be assumed that para-aramide fiber material can also be pressure packed to 56% of its ultimate density of 90 pounds per cubic foot for a pack density of approximately 51 pounds per cubic foot. With these assumptions and using the same vehicle parameters as before the algorithm can be applied to an advanced parachute/conventional attenuator case.

b. Independent Components (C_1)

The weight of the electronic logic circuitry will not be affected by the introduction of the advanced material and hence will remain at 50 pounds.

The weight of the vehicle riser will be affected by the introduction of the Kevlar material. Referencing Section VI Equation 15, it can be seen that the effect of the advanced material will be to double the weave efficiency (k_c) of the webbing utilized for the vehicle riser. If the safety factor (K_D) remains unchanged then the weight of the advanced vehicle riser may be written:

$$\text{Advanced Vehicle Riser Weight} = \frac{(W)\ (g\ max)\ (\text{Vehicle Length})}{(2)(73{,}900)} \quad (15)$$

or by substituting values;

$$\text{Advanced Vehicle Riser Weight} = \frac{(3000)(10)(20)}{(2)(73{,}900)} \quad (15)$$

Advanced Vehicle Riser Weight = 4.06 pounds

Therefore the value of C_1 for the inclusion of para-aramide fiber material in the vehicle riser is

$$\begin{aligned} C_1 &= 50.00 + 4.06 \text{ pounds} \\ C_1 &= 54.06 \text{ pounds} \end{aligned} \quad (16)$$

c. Parachute Subsystem

(1) Main Recovery Parachute

For the case of a nylon ringsail parachute, it was assumed that 50 square feet of effective drag area could be produced for every pound of parachute weight (canopy plus suspension lines). It will be assumed that by introducing para-aramide fiber that 100 square feet of drag area can be produced per pound of parachute weight (equal strength (size) at half the weight). Therefore, Equation 20 can be rewritten for an advanced parachute as:

$$\text{Advanced Main Recovery Parachute Weight} = \frac{C_D S}{100} \qquad (20)$$

(2) Main Recovery Parachute Miscellaneous Hardware

The weight of the miscellaneous hardware associated with the main recovery parachute will not in itself be changed by the introduction of para-aramide fiber. The bulk of this weight component is in metallic elements and the total weight is expected to remain the same, in order to maintain this weight the percentage allotted to this hardware will be doubled. Equation 17 can be written as:

$$\text{Advanced Miscellaneous Hardware Weight} = 0.12\ (\text{Weight of the Parachute}) \qquad (17)$$

(3) Main Recovery Parachute Deployment Bag

The weight of the deployment bag for the main recovery parachute was assessed as being 6% of the weight of the parachute. Since the parachute weight reflects the introduction of para-aramide fiber this relation is expected to remain the same. Therefore, Equation 18 is changed to reflect the new percentage allocated to miscellaneous hardware:

$$\text{Main Recovery Parachute Deployment Bag Weight} = (0.0672)\ (\text{Weight of the Parachute}) \qquad (18)$$

(4) Main Recovery Parachute Deployment Bag Container

The weight of the metallic container for the main recovery parachute deployment bag was assessed as being 5 pounds per cubic foot of enclosed volume. It was assumed that an advanced material main recovery parachute could be high density packed to a density of 51 pound/ft^3 as opposed to nylons 40 pounds/ft^3. This increased density should result in a reduction in volume (hence weight) of the container by a factor of 0.78 (40/51). Therefore the container weight (Equation 19) can be written:

$$\text{Deployment Bag Container} = (0.78)(0.1404)(\text{Weight of the Parachute}) \tag{19}$$

(5) Drogue Parachute

It was assumed in Section VII that a nylon ringsail parachute used as a drogue would produce approximately 20 square feet of effective drag area for every pound of parachute weight. Following the same reasoning as used for the main recovery parachute, it appears reasonable that an advanced material drogue should produce 40 ft^2 of drag area per pound of parachute. Therefore Equation 24 can be written as:

$$\text{Drogue Parachute Weight} = \frac{(R_R)_M\,(X_R)_M\,(C_DS)_M}{(40)(g\ \text{max})} \tag{24}$$

(6) Drogue Parachute Miscellaneous Hardware

The weight of the miscellaneous hardware associated with the Drogue Parachute is not subject to change directly by the inclusion of advanced material. Therefore, the percentage allotment will be doubled (reference the treatment of the main recovery parachute miscellaneous hardware) as expressed below:

$$\text{Miscellaneous Hardware Weight} = (0.12)(\text{Weight of the Parachute}) \qquad (17)$$

(7) Drogue Parachute Deployment Bag

The weight of the drogue parachute deployment bag is a percentage of the parachute weight which already reflects the inclusion of advanced material and therefore the relation (Equation 18) will be the same as for the main recovery parachute deployment bag.

$$\text{Drogue Parachute Deployment Bag Weight} = 0.0672\ (\text{Weight of the Parachute}) \qquad (18)$$

(8) Drogue Parachute Deployment Bag Container

The weight of the metallic container housing the drogue parachute will be affected by the decreased volume required due to advanced material in the same manner as the main recovery parachute deployment bag container. Therefore Equation 19 is written:

$$\text{Deployment Bag Container} = (0.78)(0.1404)(\text{Weight of the Parachute}) \qquad (19)$$

(9) Summation of the Parachute Subsystem Weight

The effect of introducing para-aramide fiber into the parachute subsystem has been assessed and is reflected in the weight relations of the individual components of the parachute subsystem.

The individual weight relations must be summed up to obtain a value for C_2 which reflects the advancements of fiber research. Therefore, in a manner similar to Section VII:

(a) Weight Main Recovery Parachute Stage

Weight main recovery parachute = $C_DS/100$ (20)

Weight main parachute misc. hardware = (0.12) (Wgt. of the Par.) (17)

Weight main parachute deployment bag = (0.0672) (Wgt. of the Par.) (18)

Weight main deployment bag container = (0.1095) (Wgt. of the Par.) (19)

Summing up and simplifying gives the weight relation of the main recovery parachute stage (Reference Equation 25)

Weight of the main stage = 0.0129 (C_DS) (25)

(b) Weight Drogue Parachute Stage

$$\text{Weight drogue parachute} = \frac{(R_R)_M\ (X_R)_M\ (C_DS)_M}{40\ (g\ max)} \qquad (24)$$

Weight drogue misc. hardware = 0.12 (Wgt. of the Par.) (17)

Weight drogue deployment bag = (0.0672)(Wgt. of the Par.) (18)

Weight drogue deployment bag container = (0.1095)(Wgt. of the Par.) (19)

Using the same reefing ratio and opening shock factor for the main recovery parachute as before (0.05 and 1.1 respectively) and then summing and simplifying gives:

Weight of the Drogue Stage = 0.000178 (C_DS) (26)

(c) Parachute Subsystem Weight

The weight relation for the advanced materials parachute subsystem weight is obtained by summing the main and drogue stage weight relations and is expressed in this case as:

Weight of the parachute subsystem = 0.0130 (C_DS)

or for advanced material $C_2 = 0.0130\ \text{lb/ft}^2$ (29)

(d) Impact Attenuation Subsystem

The impact attenuation subsystem will be assessed as unaffected by the introduction of advanced material and will retain a value of 300 ft-lbs/lb for C_3.

(e) Minimum WEIGHT relation

The equation of the WEIGHT of a recovery system using an advanced parachute subsystem with a conventional attenuation subsystem can now be written (Reference Equation 10)

$$\text{WEIGHT} = 54.06 + 0.0130\,(C_DS) + \frac{W^2}{(300)(g)(\rho)(C_DS)} \qquad (10)$$

where $\rho = 0.002378\ \text{slugs/ft}^3$ @ Sea Level

$C_1 = 54.06\ \text{lbs}$

$C_2 = 0.0130\ \text{lbs/ft}^2$

$C_3 = 300\ \text{ft-lbs/lb}$

$g = 32.2\ \text{ft/sec}^2$

$W = 3000\ \text{lbs}$

Inserting these values into the optimized C_DS relation (Reference Equation 11) gives

$$(C_DS)_{opt} = \sqrt{\frac{(3000)^2\ ft^4}{(32.2)(0.002378)(0.0130)(300)}} \qquad (11)$$

$$(C_DS)_{opt} = 5490\ ft^2$$

Substituting this value of $(C_DS)_{opt}$ into the WEIGHT relations yields the minimum recovery system weight for Case #2.

$$\text{WEIGHT} = 54.06 + 0.0130(5490) + \frac{3000^2}{(300)(0.0765)(5490)} \qquad (10)$$

$$\text{WEIGHT} = 196.86\ \text{Lbs}$$

This is the minimum WEIGHT for the example case using an advanced parachute subsystem with a conventional impact attenuation subsystem.

(f) Recovery System Description and Weight Breakdown

A breakdown of the recovery system component weights and performance description is given in Table 8. The method of calculation is the same as presented in Section IX except where the weight relationships have been modified to reflect the properties of para-aramide fiber in this example Case #2. This case is shown graphically in Figure 6.

TABLE 8

COMPONENT BREAKDOWN FOR CASE #2

Advanced Parachute/Conventional Attenuator

Component	Weight
Electronic Logic Circuitry	50.00 Lbs
Vehicle Riser	4.06 Lbs
Main Recovery Parachute	54.90 Lbs
Main Recovery Parachute Misc. Hardware	6.58 Lbs
Main Recovery Parachute Deployment Bag	3.69 Lbs
Main Recovery Parachute Deployment Bag Container	6.01 Lbs
Drogue Parachute	0.75 Lbs
Drogue Parachute Miscellaneous Hardware	0.09 Lbs
Drogue Parachute Deployment Bag	0.05 Lbs
Drogue Parachute Deployment Bag Container	0.08 Lbs
Impact Attenuation Subsystem	71.43 Lbs
Ballast Penalty	not calculated
Fuel Penalty	not calculated
Total WEIGHT	197.64 Lbs

Description	Value
Main Recovery Parachute $(C_DS)_{opt}$	5490 ft^2
Main Recovery Parachute Diameter (approx.)	94.7 ft
Drogue Parachute C_DS	30.2 ft^2
Drogue Parachute Diameter (approx.)	7.02 ft
Equilibrium Vertical Velocity with Main Recovery Parachute (S.L.)	21.4 ft/sec
Kinetic Energy at Impact	21,430 ft-lbs

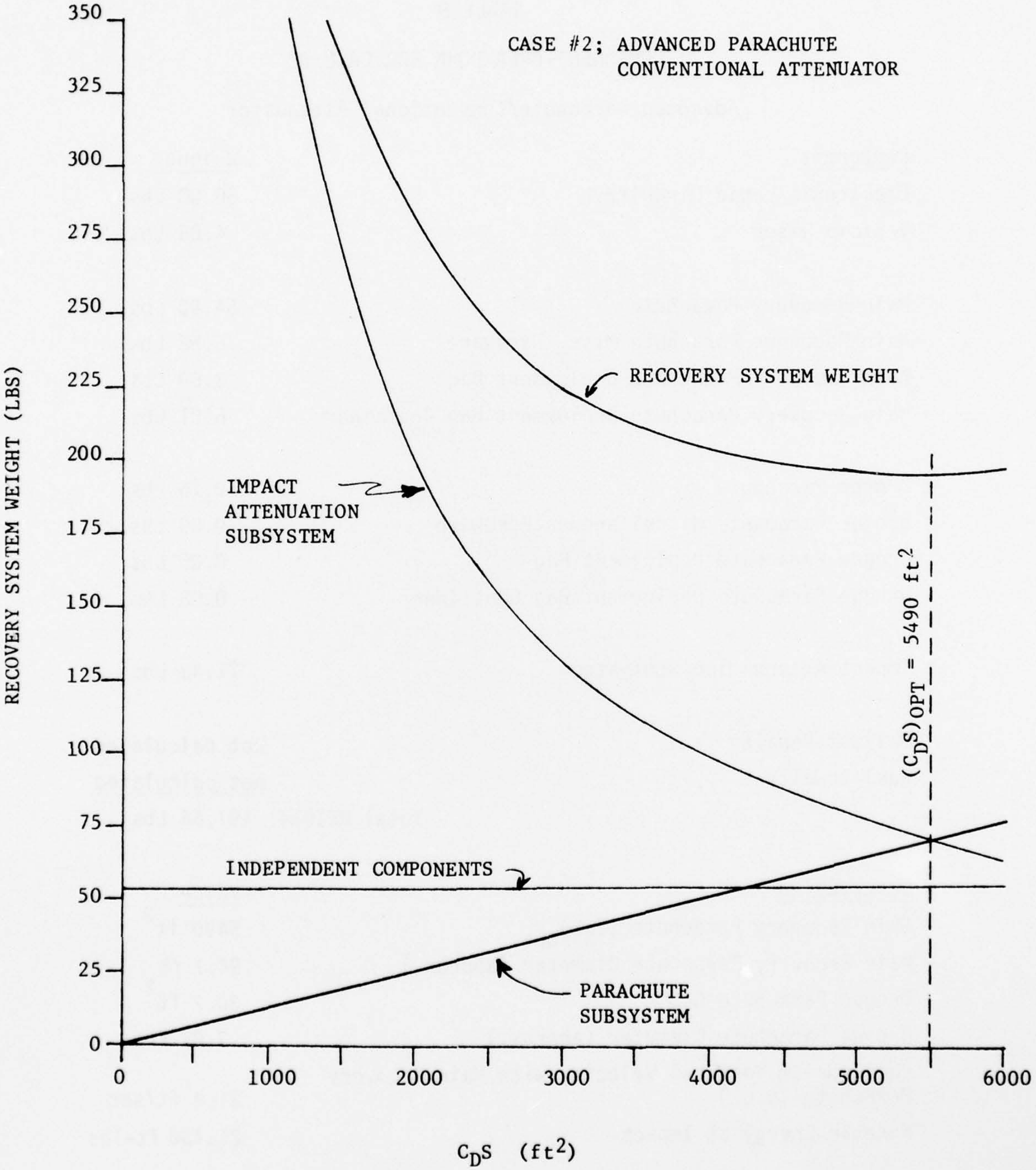

Figure 6. Case #2 WEIGHT Relation

4. CASE #3, CONVENTIONAL PARACHUTE/ADVANCED ATTENUATOR

(a) General

The conventional impact attenuation subsystem was shown to have a System Specific Energy Absorbtion (SSEA or C_3) of 300 foot-pounds per pound of subsystem weight. Now consider a hypothetical advanced impact attenuation subsystem whose SSEA is on the order of 600 foot-pounds per pound of subsystem weight. The parachute subsystem will be the conventional nylon as was used in Case #1.

(b) Independent Components (C_1)

In this case, the value for C_1 will be the same as was obtained in Case #1.

Therefore $C_1 = 58.119$ Lbs

(c) Parachute Subsystem (C_2)

Again in this case, the value for C_2 will be the same as was obtained in Case #1.

Therefore $C_2 = 0.025628\ \text{Lb/ft}^2$

(d) Impact Attenuation Subsystem

A hypothetical advanced impact attenuation subsystem has been proposed whose SSEA (or C_3) value is 600 ft-lbs per pound of subsystem weight, therefore:

$$C_3 = 600\ \text{ft-lbs/lb}$$

(e) Minimum WEIGHT Relation

Using the above values for the three coefficients, the WEIGHT relation can be written (Reference Equation 10) for Case #3.

$$\text{WEIGHT} = 58.119 + 0.025628\ (C_DS) + \frac{W^2}{600\ g\ \rho\ (C_DS)} \tag{10}$$

where: $\rho = 0.002378$ slugs/ft^3 at sea level

$C_1 = 58.119$ lbs

$C_2 = 0.025628$ lbs/ft^2

$C_3 = 600$ ft-lbs/lb

$g = 32.2$ ft/sec^2

$W = 3000$ lbs

Inserting these values into the optimized C_DS relation (Reference Equation 11) gives:

$$(C_DS)_{opt} = \sqrt{\frac{(3000)^2 \text{ ft}^4}{(32.2)(0.002378)(0.025628)(600)}} \qquad (11)$$

$$(C_DS)_{opt} = 2765 \text{ ft}^2$$

Substituting this value for $(C_DS)_{opt}$ into the WEIGHT relation yields the minimum WEIGHT for Case #3.

$$\text{WEIGHT} = 58.119 + 0.025628\,(2765) + \frac{(3000)^2}{(600)(0.0765)(2765)}$$

$$\text{WEIGHT} = 199.89 \text{ Lbs}$$

Thus a value at 199.89 pounds is the minimum WEIGHT for the recovery system in this case using a conventional parachute subsystem and an advanced impact attenuation subsystem.

(f) Recovery System Description and Weight Breakdown

A breakdown of the recovery system component weights and performance description is given in Table 9. The method of calculation is the same as presented in Section IX allowing for the hypothesized advanced impact attenuation subsystem. This case is shown graphically in Figure 7.

TABLE 9

COMPONENT BREAKDOWN FOR CASE #3

Conventional Parachute/Advanced Attenuator

Component	Weight
Electronic Logic Circuitry	50.00 Lbs
Vehicle Riser	8.12 Lbs
Main Recovery Parachute	55.30 Lbs
Main Recovery Parachute Misc. Hardware	3.32 Lbs
Main Recovery Parachute Deployment Bag	3.52 Lbs
Main Recovery Parachute Deployment Bag Container	7.76 Lbs
Drogue Parachute	0.76 Lbs
Drogue Parachute Misc. Hardware	0.05 Lbs
Drogue Parachute Deployment Bag	0.05 Lbs
Drogue Parachute Deployment Bag Container	0.11 Lbs
Impact Attenuation Subsystem	70.91 Lbs
Ballast Penalty	not calculated
Fuel Penalty	not calculated
Total WEIGHT	199.90 Lbs

Description	Value
Main Recovery Parachute $(C_DS)_{opt}$	2765 ft^2
Main Recovery Parachute Diameter (approx.)	67.2 ft
Drogue Parachute (C_DS)	15.2 ft^2
Drogue Parachute Diameter (approx.)	5.0 ft
Equilibrium Vertical Velocity with Main Recovery Parachute (S.L.)	30.2 ft/sec
Kinetic Energy at Impact	42,550 ft-lbs

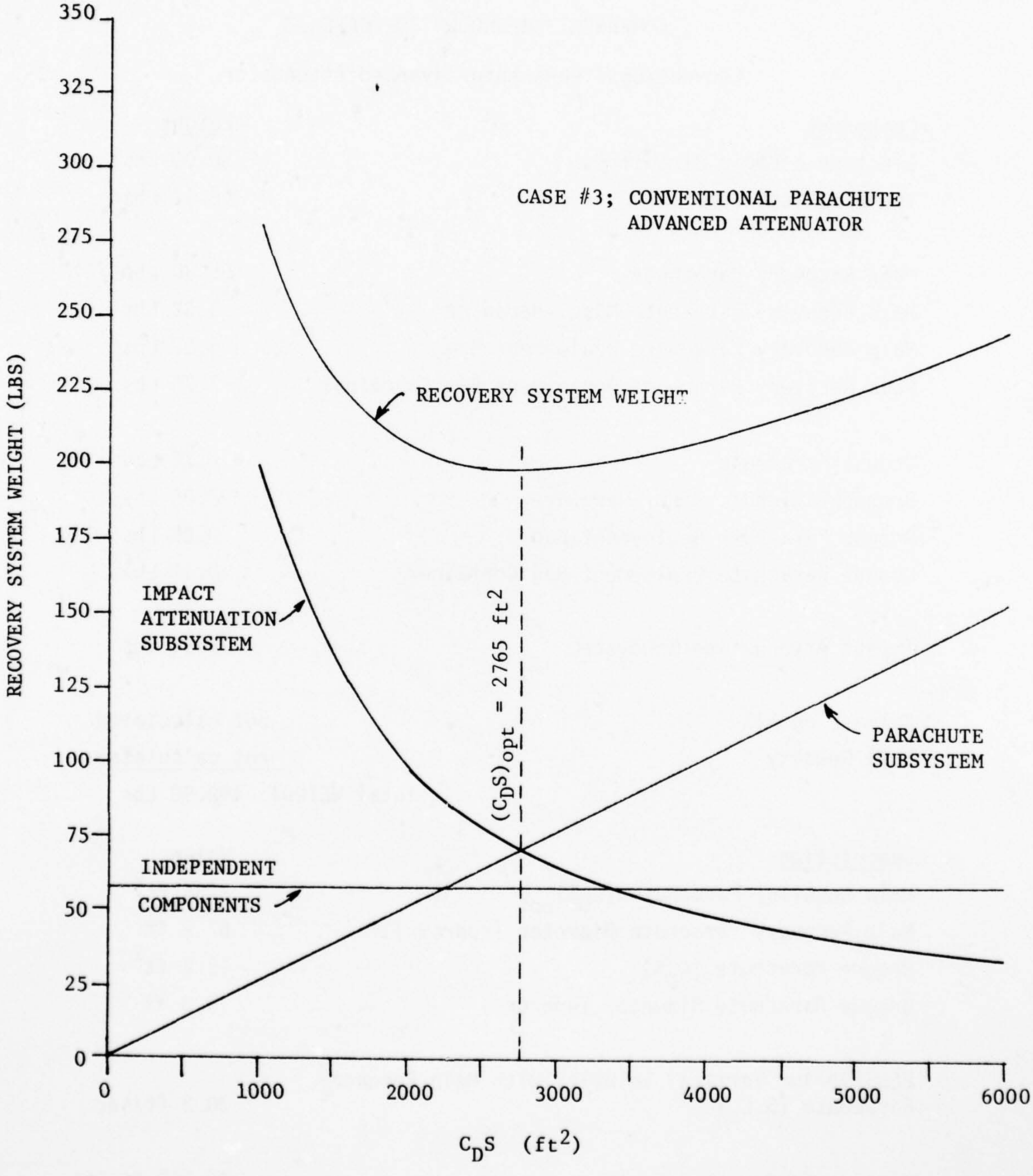

Figure 7. Case #3 WEIGHT Relation

5. CASE #4, ADVANCED PARACHUTE/ADVANCED ATTENUATOR

(a) General

This case will examine the effect on the recovery system WEIGHT of combining an advanced parachute subsystem with an advanced impact attenuation system. As such this Case #4 represents a degree of technology which is currently beyond the state-of-the-art of recovery systems. The examination and derivation of the three coefficients has been previously done in Case #2 for the independent components and the parachute subsystem and in Case #3 for the hypothetical impact attenuation subsystem.

(b) Independent Components (C_1)

The value of C_1 for the independent components which reflects the incorporation of para-aramide in the vehicle riser was developed in Case #2 and can be applied directly to this case.

There C_1 = 54.06 Lbs

(c) Parachute Subsystem (C_2)

The development of the value for C_2 which reflects the incorporation of advanced material into the parachute subsystem was done in Case #2 and can be applied directly to this case. Therefore:

$$C_2 = 0.0130 \text{ Lb/ft}^2$$

(d) Impact Attenuation Subsystem (C_3)

The assumption of a value for C_3 which reflects an advanced impact attenuation subsystem was made in Case #3 and can be applied directly to this case. Therefore: C_3 = 600 ft-lbs/lb.

(e) Minimum WEIGHT Relation

The WEIGHT relation for Case #4 combining an advanced parachute subsystem with an advanced impact attenuation subsystem can be written as (Reference Equation 10):

$$\text{WEIGHT} = 54.06 + 0.0130\ (C_DS) + \frac{W^2}{600\ g\ \rho(C_DS)} \qquad (10)$$

where ρ = 0.002378 slugs/ft^3 at sea level

C_1 = 54.06 lbs

C_2 = 0.0130 lbs/ft^2

C_3 = 600 ft-lbs/lb

g = 32.2 ft/sec^2

W = 3000 lbs

Substituting these values into the optimized C_DS relation (Reference Equation 11) gives

$$(C_DS)_{opt} = \sqrt{\frac{(3000)^2\ \text{ft}^4}{(32.2)(0.002378)(0.0130)(600)}} \qquad (11)$$

$$(C_DS)_{opt} = 3882\ \text{ft}^2$$

Inserting this value for $(C_DS)_{opt}$ into the WEIGHT relation gives the minimum WEIGHT for the recovery system in Case #4.

$$\text{WEIGHT} = 54.06 + 0.0130\ (3882) + \frac{(3000)^2}{(600)(0.0765)(3882)}$$

$$\text{WEIGHT} = 155.03\ \text{Lbs}$$

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A MINIMUM WEIGHT ANALYSIS OF AEROSPACE VEHICLE RECOVERY SYSTEMS--ETC(U)
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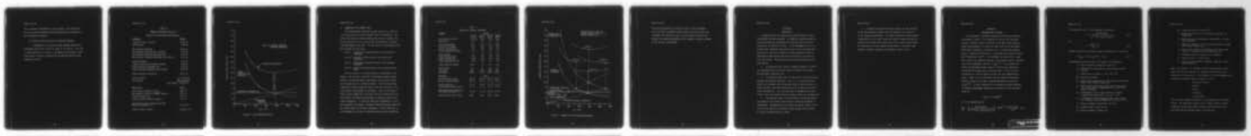

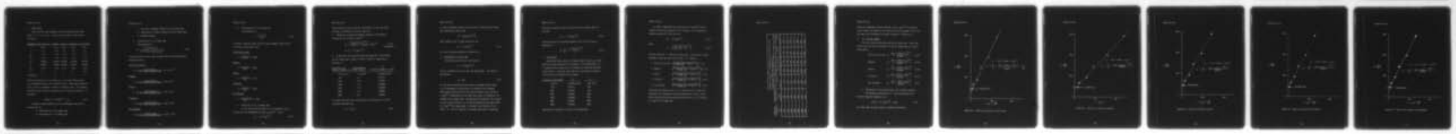

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Thus a recovery system WEIGHT of 155.03 pounds is the minimum for this case using an advanced parachute subsystem and an advanced impact attenuation subsystem.

(f) Recovery System Description and Weight Breakdown

A breakdown of the recovery system component weights and performance description is shown in Table 10 for Case #4. This case is shown graphically in Figure 8. The method of calculation is the same as used in Section IX modified by the advanced material based assumptions Case #2.

TABLE 10

COMPONENT BREAKDOWN FOR CASE #4

Advanced Parachute/Advanced Attenuator

Component	Weight
Electronic Logic Circuitry	50.00 Lbs
Vehicle Riser	4.06 Lbs
Main Recovery Parachute	38.82 Lbs
Main Recovery Parachute Misc. Hardware	4.66 Lbs
Main Recovery Parachute Deployment Bag	2.61 Lbs
Main Recovery Parachute Deployment Bag Container	4.25 Lbs
Drogue Parachute	0.53 Lbs
Drogue Parachute Miscellaneous Hardware	0.06 Lbs
Drogue Parachute Deployment Bag	0.04 Lbs
Drogue Parachute Deployment Bag Container	0.06 Lbs
Impact Attenuation Subsystem	50.50 Lbs
Ballast Penalty	not calculated
Fuel Penalty	not calculated
Total WEIGHT	155.59 Lbs

Description	Value
Main Recovery Parachute $(C_DS)_{opt}$	3882 ft^2
Main Recovery Parachute Diameter (approx.)	79.6 ft
Drogue Parachute C_DS	21.4 ft^2
Drogue Parachute Diameter (approx.)	5.9 ft
Equilibrium Vertical Velocity with Main Recovery Parachute (S.L.)	25.5 ft/sec
Kinetic Energy at Impact	30,300 ft-lbs

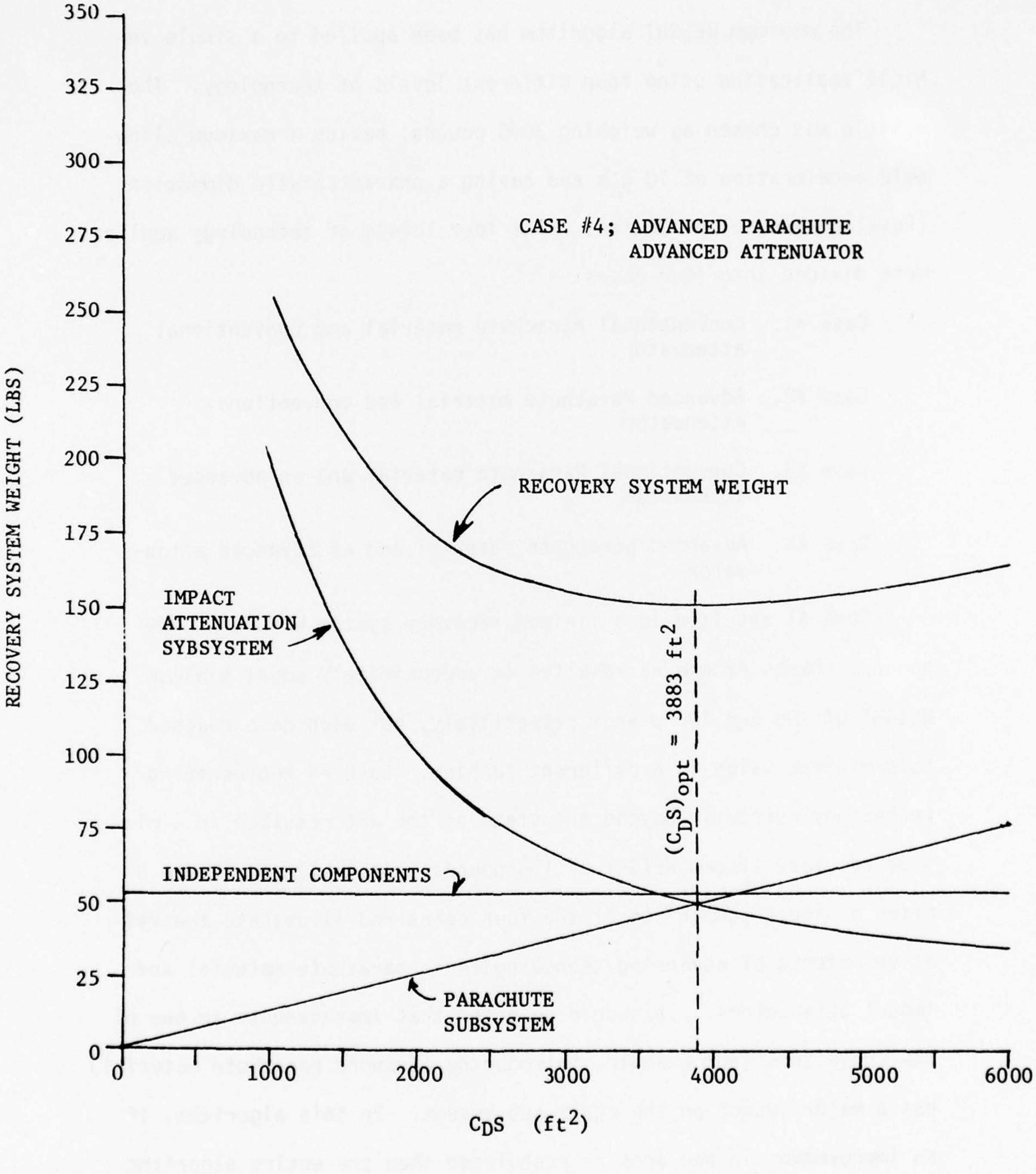


Figure 8. Case #4 WEIGHT Relation

6. SUMMATION OF THE EXAMPLE CASES

The minimum WEIGHT algorithm has been applied to a single vehicle application using four different levels of technology. The vehicle was chosen as weighing 3000 pounds, having a maximum allowable acceleration of 10 g's and having a characteristic dimension (fuselage length) of 20 feet. The four levels of technology applied were divided into four cases:

Case #1. Conventional Parachute material and conventional attenuator

Case #2. Advanced Parachute material and conventional attenuator

Case #3. Conventional Parachute material and an advanced attenuator

Case #4. Advanced parachute material and an advanced attenuator

Case #1 resulted in a minimum recovery system WEIGHT of 259 pounds. Cases #2 and #3 resulted in approximately equal minimum WEIGHT of 198 and 200 pounds respectively, but each case reached this minimum value in a different fashion. Case #4 representing technology currently beyond the state of the art resulted in a minimum recovery system WEIGHT of 156 pounds. Table 11 and Figure 9 offer a direct comparison of the four cases and illustrate the relative effects of advancing technologies in parachute material and impact attenuators. It should be noted that improvements in one of the subsystems (for example, introducing advanced parachute material) has a major impact on the other subsystems. In this algorithm, if an improvement in one area is postulated then the entire algorithm

TABLE 11

COMPARISON OF TECHNOLOGY ADVANCEMENTS

Component	Weight			
	Case #1 conv/conv	Case #2 adv/conv	Case #3 conv/adv	Case #4 adv/adv
Electronic Logic Circuitry	50.00 Lbs	50.00	50.00	50.00
Vehicle Riser	8.12	4.06	8.12	4.06
Main Recovery Parachute	78.20	54.90	55.30	38.82
Main Rec P Misc Hardware	4.69	6.58	3.32	4.66
Main Rec P Deployment Bag	4.97	3.69	3.52	2.61
Main Rec P Deploy Bag Container	10.97	6.01	7.76	4.25
Drogue Parachute	1.07	0.75	0.76	0.53
Drogue Parachute Hardware	0.06	0.09	0.05	0.06
Drogue P Deployment Bag	0.068	0.05	0.05	0.04
Drogue P Deploy Bag Container	0.150	0.08	0.11	0.06
Impact Attenuation Subsystem	100.29	71.43	70.91	50.50
Ballast Penalty	N/A	N/A	N/A	N/A
Fuel Penalty	N/A	N/A	N/A	N/A
Total WEIGHT	258.58	197.64	199.90	155.59

Description	Value			
Main Rec Parachute $(C_DS)_{opt}$	3910 ft^2	5490 ft^2	2765 ft^2	3882 ft^2
Main Rec P Diameter (approx.)	79.8 ft	94.7 ft	67.2 ft	79.6 ft
Drogue Parachute C_DS	21.5 ft^2	30.2 ft^2	15.2 ft^2	21.4 ft^2
Drogue Parachute Diameter (Approx.)	5.9 ft	7.0 ft	5.0 ft	5.9 ft
Equilibrium Vertical Velocity with Main Recovery Parachute (S.L.)	25.4 FPS	21.4 FPS	30.2 FPS	25.5 FPS
Kinetic Energy at Impact (ft-lbs)	30060	21430	42550	30300

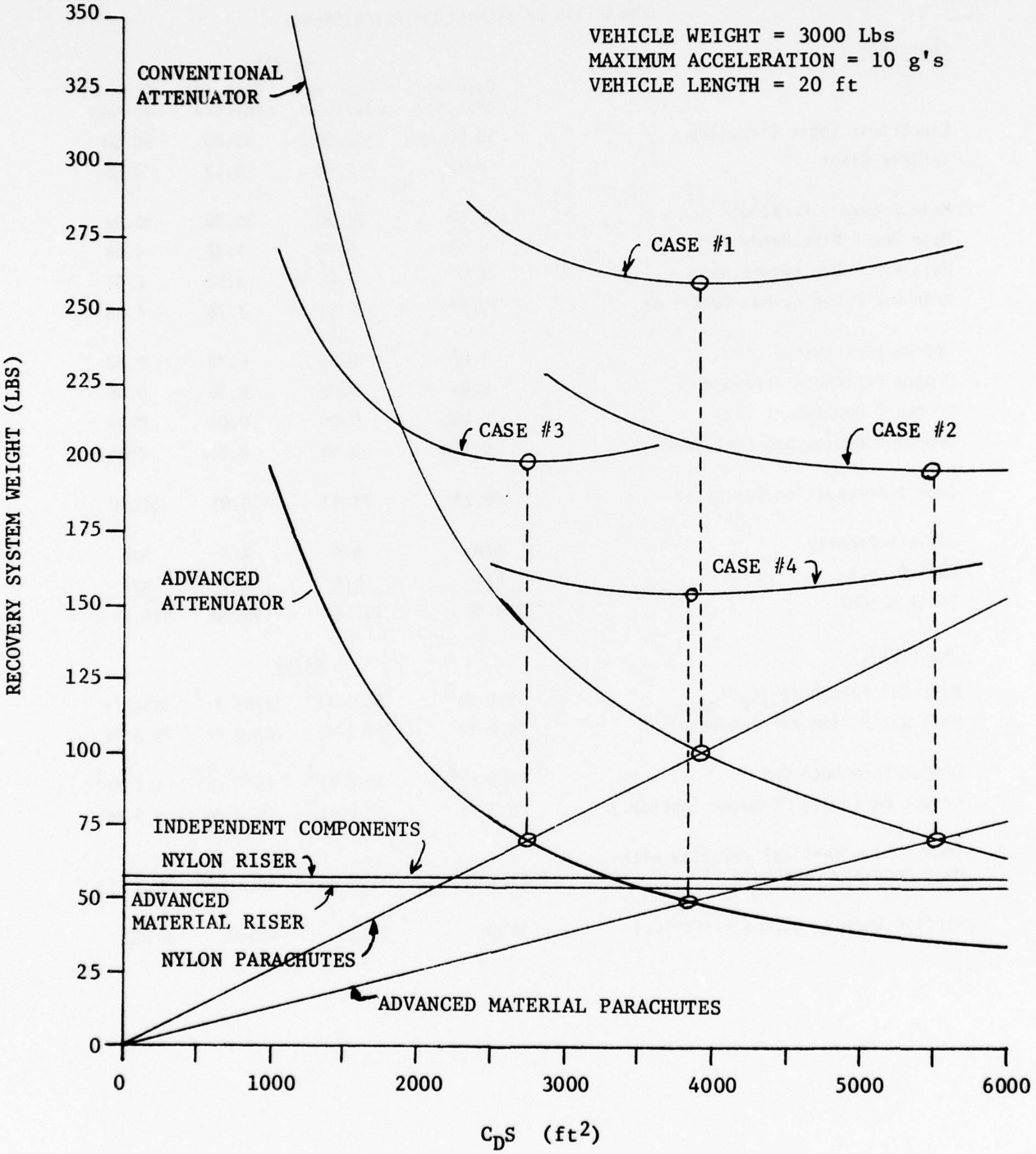


Figure 9. Comparison of Technology Advancements

should be reconsidered for the total effect of the improvement. Also, note that as advanced concepts reduce the total recovery system WEIGHT, the electronic logic circuitry weight (primarily the battery) has remained unchanged and thus becomes a larger percentage of the recovery system WEIGHT.

SECTION XI

CONCLUSIONS

A broad algorithm for predicting the optimum vehicle recovery system WEIGHT has been presented. The WEIGHT as determined does not include the penalties associated with additional ballast and fuel required for the vehicle's mission. In the development of this algorithm, many assumptions both explicit and implicit have been made. The basis for, and the limitations of those assumptions should be understood in depth before applying the algorithm to any given vehicle application. The conclusions which are drawn concerning this algorithm are:

a. The algorithm lends itself to comparing advances in different technologies and the relative input on recovery system weight and performance characteristics.

b. The algorithm lends itself to the solution of minimum weight problems with boundary conditions. That is, if a vertical descent velocity of no greater than 20 feet per second is specified by an external condition, then the algorithm may still be applied by appropriate considerations. Or an existing piece of hardware may be specified in lieu of an optimal design to enhance logistical considerations.

c. The electronic logic circuitry becomes a larger percentage (by weight) of the recovery system weight as advanced technology is incorporated. Development work to minimize the weight penalty of the circuitry and especially the battery weight becomes more desirable in the more advanced recovery systems.

d. In general the parachute system accounts for more than 99% of the total mechanical energy to be dissipated but only about 2/5 of the recovery system weight. The impact attenuation system although responsible for a very small (relative) amount of energy dissipation, accounts for an equal share (about 2/5) of the recovery system weight. The remaining 1/5 of the recovery system weight is relatively independent of whatever parachute and attenuator system is used.

APPENDIX A

STRUCTURAL MERIT FUNCTION

In this appendix a theoretical decelerator efficiency evaluation is presented in detail. This technique for analysis was developed by Messrs. Anderson, Bohen, and Mikulus of the NASA Langley Research Center and documented in "A Structural Merit Function For Aerodynamic Decelerators" (Reference 1) Anderson, et al., selected the parameter $m/C_D S$ as a measure of efficiency as it represents the weight per square foot of drag areas (lb/ft^2). This parameter was shown to be a proper merit function for comparing canopies if the comparison was at a constant value of the independent variable "$q\ (C_D S)^{1/2}$". This variable represents the deployment dynamic pressure (infinite mass conditions) multiplied by the square root of the drag area. As such it can be interpreted as a relative measure of the total force generated by a canopy. (Note it is not the actual force as normally defined which would be $q\ (C_D S)(X)$ but rather an abstracted measure of the force $q\ (C_D S)^{1/2}$). In brief, Anderson, et al, derived a suitable technique for comparing aerodynamic decelerator efficiencies in the functional format of:

$$m/C_D S = F\ (q\ (C_D S))^{1/2}$$

or in the expanded form of:

$$\frac{m}{C_D S} = \left[\frac{(K_D)(X)(\rho_R)(L_s)}{(\pi)^{1/2}(\cos\theta)(D_o)(k_c)(C_D)^{1/2}}\right] q(C_D S)^{1/2} + \frac{(K_c)(1-\lambda_g)d_f}{C_D} \qquad (A-1)$$

by allowing "b" and "c" to be constants with values of

$$b = \frac{(K_D)(X)(\rho_R)(L_S)}{(\pi)^{1/2}(\cos\theta)(D_o)(k_c)(C_D)^{1/2}} \qquad \text{(A-2)}$$

and

$$C = \frac{(K_C)(1-\lambda_g)}{C_D} \qquad \text{(A-3)}$$

shortens the writing of the merit equation (Equation A-1) to the form

$$(m/_{C_D}S) = (b)(q\ (C_DS)^{1/2}) + c\ (d_f) \qquad \text{(A-4)}$$

The parameters and terms used in this analysis are defined as:

m = mass of canopy and suspension lines (lb)

C_D = coefficient of drag based on a nominal area S dimensionless

S = nominal area of canopy, $S = 1/4\ \pi\ D_o^2\ (ft^2)$

C_DS = drag area of canopy

K_D = Design factor accounting for seam and joint efficiencies (deals with strength of materials)

K_C = Canopy construction factor accounting for excess material in seam overlap, thread mass, etc. (deals with weight of canopy)

k_f = strength/mass ratio of fabric material (breaking strength/foot)/(Weight/ft^2) units are in "ft"

k_c = strength/mass ratio of webbing, cords, lines, tapes, etc. (breaking strength)/(Weight/ft) units are in "ft"

F_S = nominal strength of suspension lines (lb)

f_a = allowable fabric stress (lb/ft)

D_o = Nominal Diameter of canopy (ft)

d_f = canopy mass per unit area (lb/ft^2)

X = opening shock factor at infinite mass conditions, dimensionless

q = dynamic pressure at deployment (interpreted as infinite mass conditions)

L_s = length of suspension line from confluence point to canopy skirt (used as equal to D_o)

ρ_R = Ratio of the length of the suspension line loop to the length of the suspension line (used equal to 3)

θ = Confluence angle of suspension lines (degrees)

λg = geometry factor (1-cloth area/S)

ψi = used as a dummy (interim) parameter, subscript i designates canopy type

Note: The parameter "d_f" although explicitly defined above is mathematically implicitly defined in a somewhat obtuse derivation presented later in the analysis. This analysis will seek to comparatively evaluate five different types of canopies, to wit;

Solid Flat Circular,
Ringsail,
Conical,
Triconical,
Disc-Gap-Band,

for use as main recovery parachutes in an aerospace vehicle recovery system. This theoretical analysis will be used to select a type of canopy but, owing to the nature of theory, empirical data will be used regarding the selected canopy in the main text.

1. INPUT VALUES

Values for the input parameters have been obtained from references 1, 2, 4, 5, 6, and 7. The values to be used in this presentation are:

Parameter	Solid Flat Circ.	Ringsail	Conical	Triconical	Disc-Gap-Band
θ	20.5°	20.5°	18.9°	25.0°	18.0°
X	2.0	1.05	1.8	1.8	1.8
K_D	2.91	2.91	2.91	2.91	2.91
K_C	1.25	1.25	1.25	1.25	1.25
k_f*	60,000	60,000	60,000	60,000	60,000
k_c	100,000	100,000	100,000	100,000	100,000
C_D	0.75	0.78	0.72	0.85	0.85
λg	0	0	0	0	0.05
$(\rho_R)(L_S)/D_o$	3	3	3	3	3

*Values calculated for k_f are based on 1.1 oz nylon ripstop and for k_c are considered typical for suspension lines. Additional background for k_f values is contained in Table 1 of the main text. The constants and values to be inserted in Equation A-4 will now be calculated. For reference,

$$(m/C_DS) = b\ q\ (C_DS)^{1/2} + c\ d_f \tag{A-4}$$

In order to reduce confusion in this presentation the order of business will be:

a. Calculation of "b" by canopy type

b. Calculation of "c" by canopy type

c. Derivation (somewhat lengthy) of d_f by canopy type

d. Substitution into Merit Equation (A-4) by canopy type

e. Graphical Summary

a. Calculation of "b" by Canopy Type

From Equation A-2;

$$b = \frac{(K_D)(X)(\rho_R)(L_S)}{(\pi)^{1/2}(\cos\theta)(D_o)(k_c)(C_D)^{1/2}} \qquad \text{(A-2)}$$

using the values from the input parameter table and substituting by canopy type gives:

Solid Flat Circular

$$b = \frac{(2.91)(2.)(3)}{(1.77)(.9366)(100{,}000)(0.866)} = 12.16 \times 10^{-5}$$

Ringsail

$$b = \frac{(2.9)(1.05)(3)}{(1.77)(.9366)(100{,}000)(0.883)} = 6.26 \times 10^{-5}$$

Conical

$$b = \frac{(2.91)(1.8)(3)}{(1.77)(.946)(100{,}000)(0.848)} = 11.06 \times 10^{-5}$$

Triconical

$$b = \frac{(2.91)(1.8)(3)}{(1.77)(.906)(100{,}000)(0.922)} = 10.62 \times 10^{-5}$$

Disc-Gap-Band

$$b = \frac{(2.91)(1.8)(3)}{(1.77)(.9510)(100{,}000)(0.922)} = 10.12 \times 10^{-5}$$

b. Calculation of "C" by Canopy Type

From Equation A-3

$$C = \frac{K_c\ (1-\lambda g)}{C_D} \qquad \text{(A-3)}$$

as before, using the values from the input parameter table and substituting by canopy type gives:

Solid Flat Circular

$$C = \frac{1.25\ (1-0)}{0.75} = 1.6666$$

Ringsail

$$C = \frac{1.25\ (1-0)}{0.78} = 1.6025$$

Conical

$$C = \frac{1.25\ (1-0)}{0.72} = 1.7361$$

Triconical

$$C = \frac{1.25\ (1-0)}{0.85} = 1.4705$$

Disc-Gap-Band

$$C = \frac{1.25\ (1-0.05)}{0.85} = 1.3970$$

c. Derivation of "d_f" by Canopy Type

In this derivation the objective is to determine "d_f" as a function of the independent variable $q\ (C_D S)^{1/2}$. That is

$$d_f = f\ (q\ (C_D S)^{1/2}) \qquad \text{(A-5)}$$

The derivation of this functional relationship utilizes two input relations; one theoretical and one empirical.

1. Theoretical relationship between suspension line breaking strength and the variable $q\ (C_DS)^{1/2}$

$$F_S = \left[\frac{(K_D)(X)(\pi)(C_D)^{1/2}}{(\cos\theta)\qquad(4)}\right] \cdot q\ (C_DS)^{1/2} \qquad \text{(A-6)}$$

(Reference 1)

$$\text{or } F_S = f\left(q\ (C_DS)^{1/2}\right)$$

2. An empirical relationship between the suspension line strength and the canopy fabric weight is given in Table 7-6, page 376 of Reference 2.

Suspension Line Breaking Strength (F_S)	Canopy Material Weight (Nylon)	d_f $(oz/Yd^2)(0.006944) = Lb/ft^2$
375 Lbs min.	1.1 oz/Yd^2	0.007639 Lb/ft^2
550	1.6	0.011111
1500	2.25	0.015625
2300	3.5	0.024306
4000	4.75	0.032986
6000	7.0	0.048611
9000	14.0	0.097222

This empirical table lists seven points of a curve which is of the functional notation form

$$d_f = G\ (F_S) \qquad \text{(A-7)}$$

so that if Equation A-6 were to be written in functional form these two relationships would yield

$$d_f = G\left[f(q(C_D S)^{1/2})\right]$$

which combined into a single function as per .

$$d_f = f\ (q(C_D S)^{1/2}) \qquad \text{(A-5)}$$

will give the desired objective (Equation A-5)

2. EXPLANATION OF CALCULATIONS

The detailed calculation of the function

$$d_f = f\ (q(C_D S)^{1/2})$$

will be presented for each of the five canopy types. The relation (definition)

$$f_a = d_f k_f \qquad \text{(A-8)}$$

will be used to determine seven values of allowable fabric stress (f_a) corresponding to seven values of suspension line strength. Additionally Equation A-6 will be used to determine seven values of $q\ (C_D S)^{1/2}$ corresponding to the same seven values of suspension line strength but by canopy type. By equating the suspension line strength, the set of seven values of f_a can be correlated with the seven values of $q\ (C_D S)^{1/2}$ per canopy type. A straight line function (of the form $y = a + bx$) will then be fit to these seven sets of coordinate resulting in equations (one for each of the five canopy types) of the form

$$f_a = a + b\,(q(C_DS)^{1/2}) \qquad \text{(A-9)}$$

which may easily be transformed (Equation A-8) into the form of Equation A-5.

$$d_f = \frac{f_a}{k_f} = \frac{a + b(q(C_DS)^{1/2})}{k_f} \qquad \text{(A-10)}$$

3. CALCULATIONS

Determining seven values of allowable fabric stress (f_a) corresponding to seven suspension line strengths is straightforward if it is assumed that the value of k_f is constant for the seven different canopy fabrics. Using the input empirical relationships, Equation A-8 and a value of 60,000 ft for k_f gives.

Suspension Line Strength	d_f	f_a
375 Lbs	0.007639 Lb/ft^2	458 Lb/ft
550	0.011111	666
1500	0.015625	937
2300	0.024306	1458
4000	0.032986	1979
6000	0.048611	2916
9000	0.097222	5833

note that this relation is for all five canopy types.

In order to determine the seven values of q $(C_DS)^{1/2}$ corresponding to the seven suspension line strengths it is convenient to redefine Equation A-6 into the form:

$$F_S = \psi_i(q(C_DS)^{1/2}) \qquad \text{(A-11)}$$

where

$$\psi_i = \left(\frac{(K_D)(X)}{\cos\theta}\right)\left(\frac{(\pi)(C_D)^{1/2}}{4}\right) \qquad \text{(A-12)}$$

with the subscript "i" indicating canopy type. Calculation of these constants, using the input table values, is as follows.

$$\psi \text{ Solid Flat Circular} = \left(\frac{(2.91)(2)}{0.9366}\right)\left(\frac{(3.14)(0.75)^{1/2}}{4}\right) = 4.77$$

$$\psi \text{ Ringsail} = \left(\frac{(2.91)(1.05)}{0.9366}\right)\left(\frac{(3.14)(0.78)^{1/2}}{4}\right) = 2.55$$

$$\psi \text{ Conical} = \left(\frac{(2.91)(1.8)}{0.9460}\right)\left(\frac{(3.14)(0.72)^{1/2}}{4}\right) = 4.16$$

$$\psi \text{ Triconical} = \left(\frac{(2.91)(1.8)}{0.9063}\right)\left(\frac{(3.14)(0.85)^{1/2}}{4}\right) = 4.72$$

$$\psi \text{ Disc-Gap-Band} = \left(\frac{(2.91)(1.8)}{0.9510}\right)\left(\frac{(3.14)(0.85)^{1/2}}{4}\right) = 4.50$$

Using these calculated values of ψ_i in Equation A-11 and the same suspension line strengths as were used previously in the f_a calculation gives the following tabulated relations for f_a as a function of q $(C_DS)^{1/2}$ by canopy type.

Suspension Line Strength (F_S) (Lb)	Corresponding Fabric Stress (f_a) (Lb)/(ft)	Values of $q(C_DS)^{1/2}$ Corresponding to F_S and hence f_a by canopy type (Reference Equation A-11)				
		Solid Flat Cir = 4.77 (Lb)/(ft)	Ringsail =2.55 (Lb)/(ft)	Conical =4.16 (Lb)/(ft)	Triconical = 4.72 (Lb)/(ft)	Disc-Gap-Band = 4.50 (Lb)/(ft)
375	458	79	147	90	79	83
550	666	115	215	132	117	122
1500	937	315	587	360	318	333
2300	1458	482	900	552	487	511
4000	1979	838	1565	961	847	889
6000	2916	1258	2348	1441	1271	1333
9000	5833	1887	3522	2162	1906	2000

These five tabulated relations between f_a and $q\ (C_DS)^{1/2}$ are plotted, curve fitted, and reduced to the numerical form of Equation A-10 by canopy type in the following five graphs (Figures A-1 through A-5).

4. "d_f" FUNCTION SUMMARY

Five "d_f" functions have been derived by canopy type. These functions are of the form of Equation A-10 and are summarized (for convenience) below.

Solid Flat Circular $$d_f = \frac{300 + 2.0848\ q(C_DS)^{1/2}}{60{,}000} \qquad \text{(A-13)}$$

Ringsail $$d_f = \frac{350 + 1.0928\ q\ (C_DS)^{1/2}}{60{,}000} \qquad \text{(A-14)}$$

Conical $$d_f = \frac{375 + 1.7633\ q\ (C_DS)^{1/2}}{60{,}000} \qquad \text{(A-15)}$$

Triconical $$d_f = \frac{400 + 1.9811\ q\ (C_DS)^{1/2}}{60{,}000} \qquad \text{(A-16)}$$

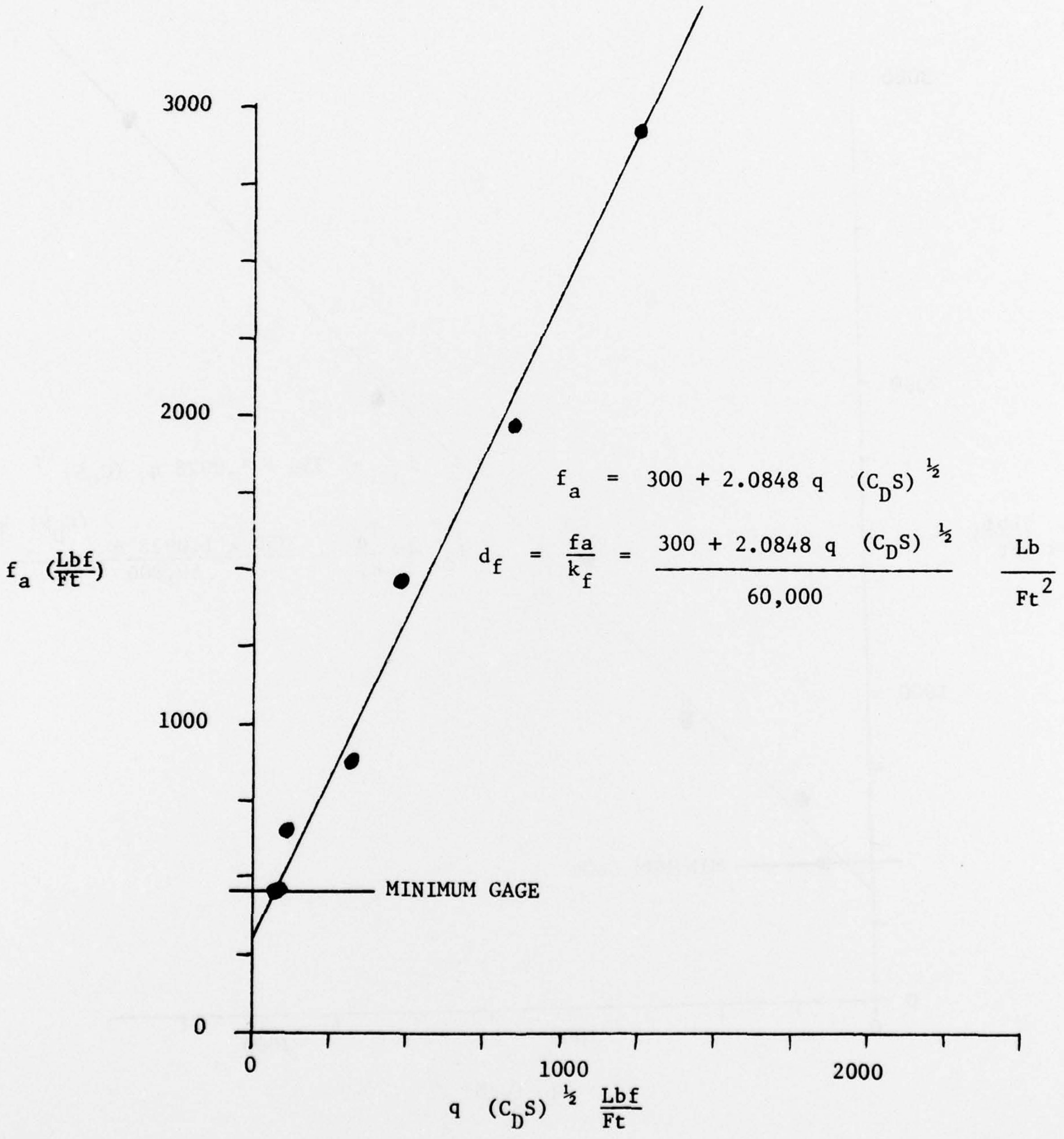
Disc-Gap-Band $$d_f = \frac{385 + 1.9062\ q\ (C_DS)^{1/2}}{60{,}000} \qquad \text{(A-17)}$$

d. Substitution of Calculated Values into the Merit Equation

The foregoing calculations will now be substituted into the merit equation (Equation A-4):

$$m/C_DS = b\ (q\ (C_DS)^{1/2}) + c(d_f) \qquad \text{(A-4)}$$

by canopy types and then plotted in graphical comparison.



$$f_a = 300 + 2.0848\ q\ (C_D S)^{\frac{1}{2}}$$

$$d_f = \frac{fa}{k_f} = \frac{300 + 2.0848\ q\ (C_D S)^{\frac{1}{2}}}{60{,}000} \quad \frac{Lb}{Ft^2}$$

Figure A-1. Explicit d_f Function, Flat Circular

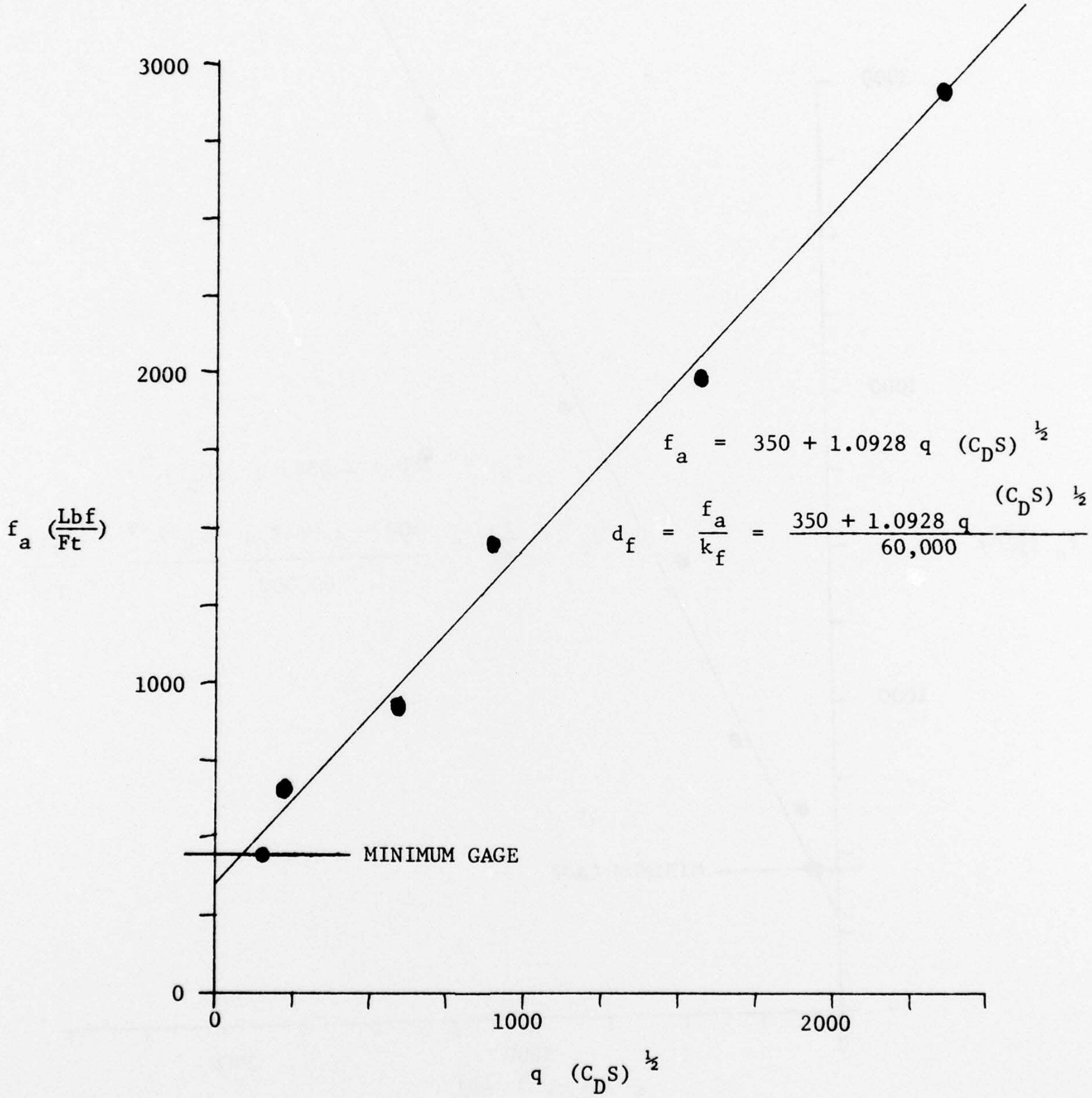
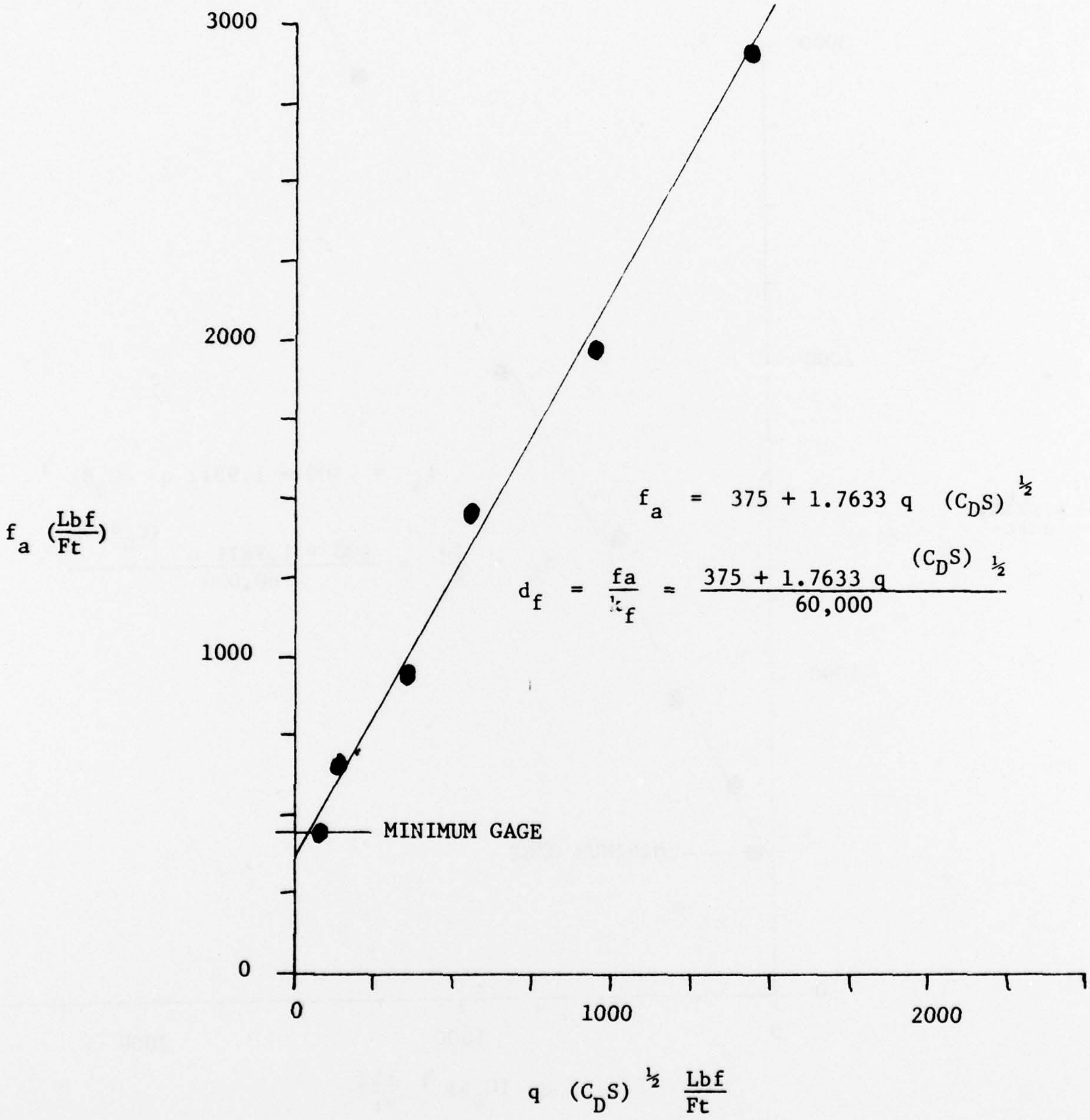


Figure A-2. Explicit d_f Function, Ringsail



$$f_a = 375 + 1.7633\, q\, (C_D S)^{1/2}$$

$$d_f = \frac{fa}{k_f} = \frac{375 + 1.7633\, q\, (C_D S)^{1/2}}{60{,}000}$$

Figure A-3. Explicit d_f Function, Conical

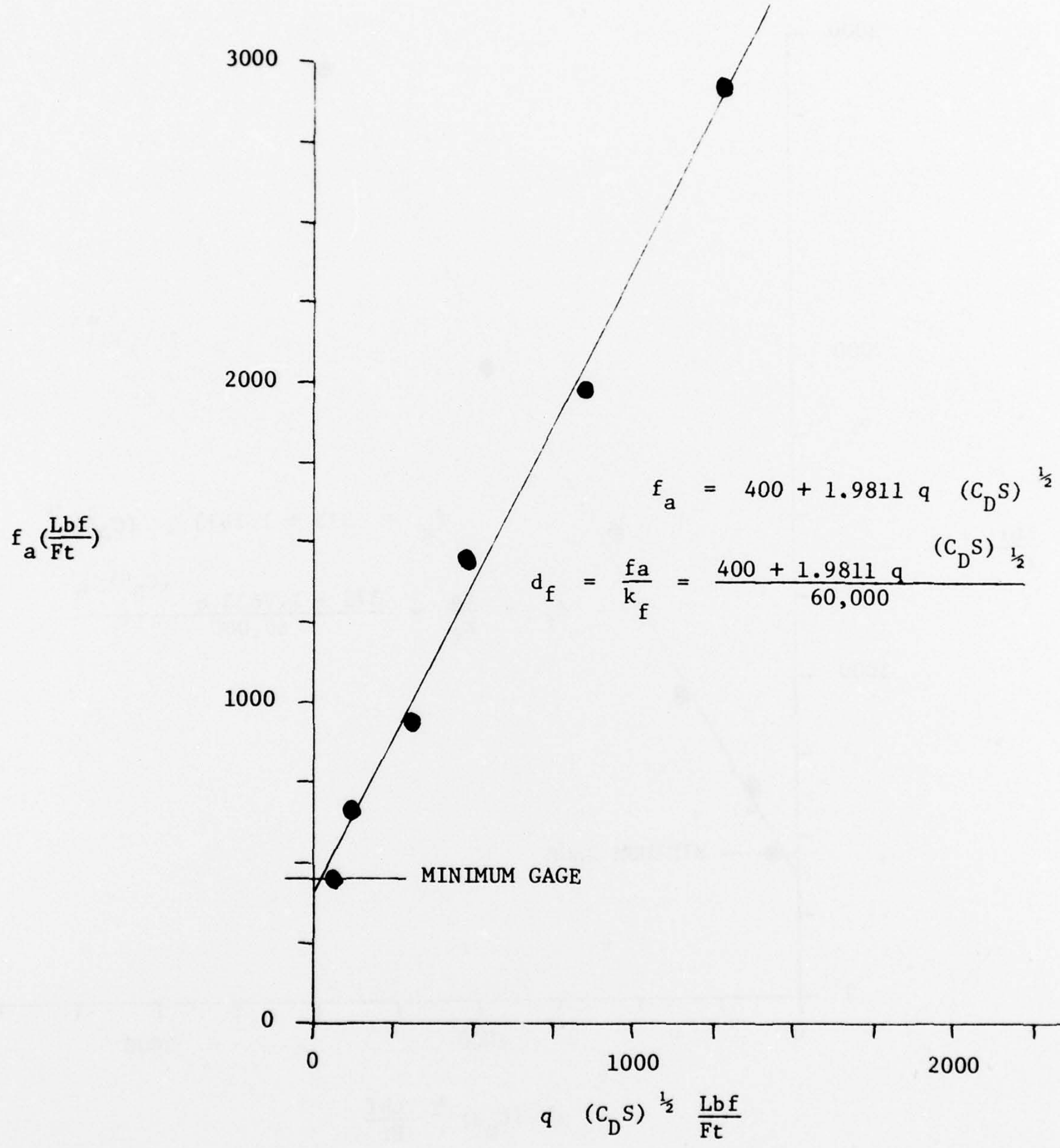


Figure A-4. Explicit d_f Function, Triconical

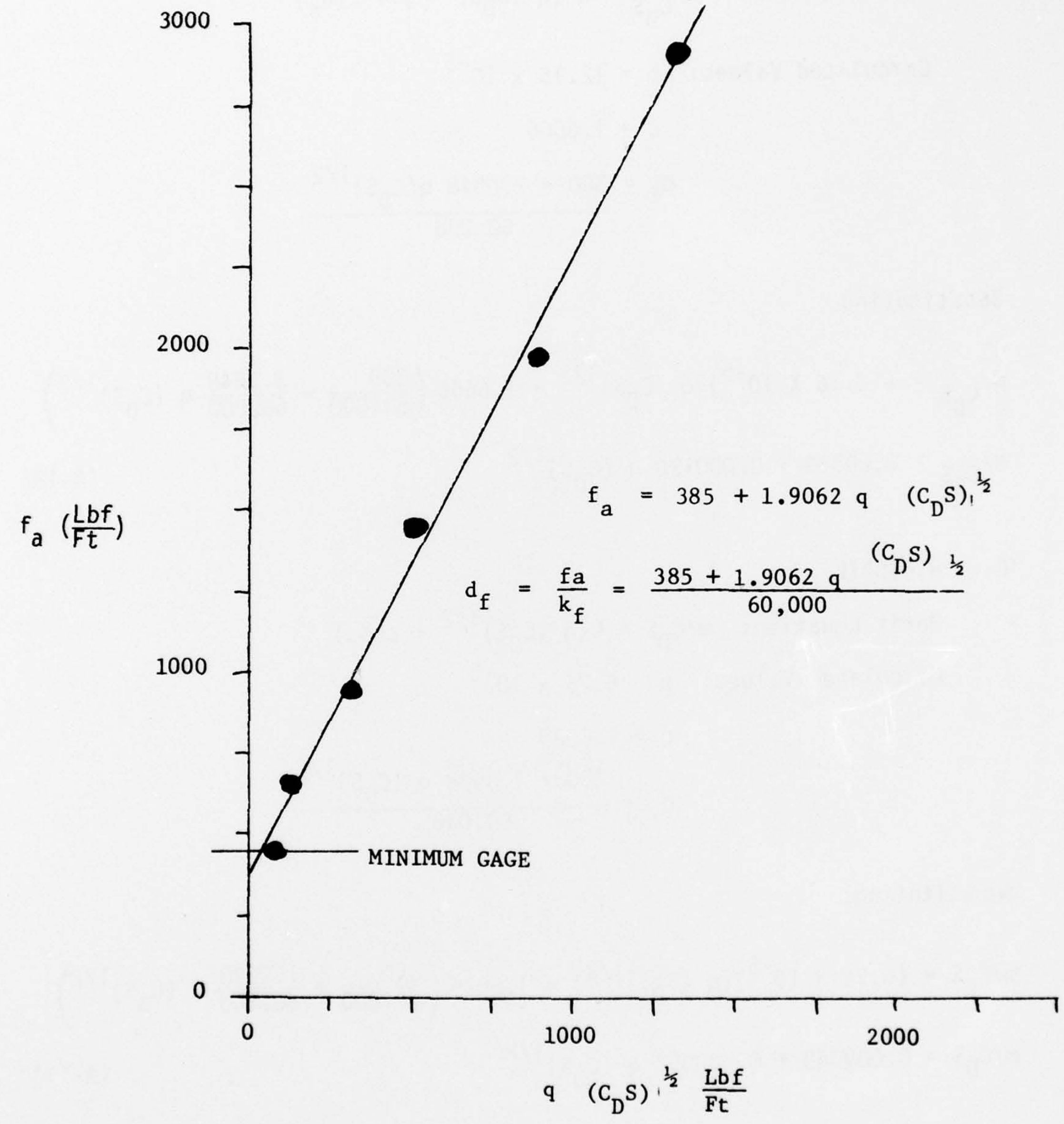


Figure A-5. Explicit d_f Function, Disc-Gap-Band

5. SOLID FLAT CIRCULAR

Merit Equation: $m/_{C_DS} = b\ (q\ (C_DS)^{1/2}) + c(d_f)$

Calculated Values: $b = 12.16 \times 10^{-5}$

$c = 1.6666$

$$d_f = \frac{300 + 2.0848\ q(C_DS)^{1/2}}{60{,}000}$$

Substituting:

$$m/_{C_DS} = (12.16 \text{ X } 10^{-5})\ q\ (C_DS)^{1/2} + 1.6666 \left(\frac{300}{60{,}000} + \frac{2.0848}{60{,}000}\ q\ (C_DS)^{1/2}\right)$$

$$m/_{C_DS} = 0.00833 + 0.000180\ q\ (C_DS)^{1/2} \tag{A-18}$$

6. RINGSAIL

Merit Equation: $m/C_DS = b(q\ (C_DS)^{1/2} + c(d_f)$

Calculated Values: $b = 6.26 \times 10^{-5}$

$c = 1.6025$

$$d_f = \frac{350 + 1.0928\ q\ (C_DS)^{1/2}}{60{,}000}$$

Substituting:

$$m/C_DS = (6.26 \text{ X } 10^{-5})(q\ (C_DS)^{1/2}) + 1.6026 \left(\frac{350}{60{,}000} + \frac{1.0928}{60{,}000}\ q\ (C_DS)^{1/2}\right)$$

$$m/C_DS = 0.009349 + 0.000092\ q\ (C_DS)^{1/2} \tag{A-19}$$

7. CONICAL

Merit Equation: $m/_{C_DS} = b\ (q\ (C_DS)^{1/2}) + c(d_f)$

Calculated Values $b = 11.06 \times 10^{-5}$

$$c = 1.7361$$

$$d_f = \frac{375 + 1.7633\ q\ (C_DS)^{1/2}}{60{,}000}$$

Substituting:

$$m/C_DS = (11.06 \times 10^{-5})\ q\ (C_DS)^{1/2} + 1.7361 \left(\frac{375}{60{,}000} + \frac{1.7633}{60{,}000}\ q\ (C_DS)^{1/2}\right)$$

$$m/C_DS = 0.010851 + 0.000162\ q\ (C_DS)^{1/2} \qquad \text{(A-20)}$$

8. TRICONICAL

Merit Equation: $m/C_DS = b\ (q\ (C_DS)^{1/2}) + c(d_f)$

Calculated Values: $b = 10.62 \times 10^{-5}$

$$c = 1.4705$$

$$d_f = \frac{400 + 1.9811\ q\ (C_DS)^{1/2}}{60{,}000}$$

Substituting:

$$m/C_DS = (10.62 \text{ X } 10^{-5})\ q\ (C_DS)^{1/2} + 1.4705\left(\frac{400}{60{,}000} + \frac{1.9811}{60{,}000}\ q\ (C_DS)^{1/2}\right)$$

$$m/C_DS = 0.009803 + 0.000155\ q\ (C_DS)^{1/2} \qquad \text{(A-21)}$$

9. DISC-GAP-BAND

Merit Equation: $m/C_DS = b\ (q(C_DS)^{1/2}) + c(d_f)$

Calculated Values: $b = 10.12 \times 10^{-5}$

$$c = 1.397$$

$$d_f = \frac{385 + 1.9062\ q\ (C_DS)^{1/2}}{60{,}000}$$

Substituting:

$$m/C_DS = (10.12 \text{ X } 10^{-5})\ q\ (C_DS)^{1/2} + 1.397\left(\frac{385}{60{,}000} + \frac{1.9062}{60{,}000}\ q\ (C_DS)^{1/2}\right)$$

$$m/C_DS = 0.008964 + 0.000146\ q\ (C_DS)^{1/2} \qquad \text{(A-22)}$$

The five merit equations have been calculated against values of q $(C_DS)^{1/2}$ in the following table to facilitate graphical comparison.

m/C_DS By Canopy Type from Equations A-18 through A-22

$q(C_DS)^{1/2}$	Solid Flat Cir.	Ringsail	Conical	Triconical	Disc-Gap-Disc
10	0.0101	0.0102	0.0124	0.0113	0.0103
20	0.0119	0.0111	0.0140	0.0129	0.0118
50	0.0173	0.0139	0.0189	0.0175	0.0162
100	0.0263	0.0185	0.0270	0.0253	0.0235
200	0.0443	0.0277	0.0432	0.0408	0.0381
500	0.0983	0.0553	0.0918	0.0873	0.0819
1000	0.1883	0.1013	0.1728	0.1648	0.1549
2000	0.3683	0.1933	0.3348	0.3198	0.3009
5000	0.9083	0.4693	0.8208	0.7848	0.7389
10000	1.8083	0.9293	1.6300	1.5598	1.4689
20000	3.6083	1.8493	3.2508	3.1098	2.9289
50000	9.0083	4.6093	8.1108	7.7598	7.3089

The plots of the five canopy merit functions are shown in Figure A-6. From this figure it can readily be seen that the Ringsail canopy has the lowest value of m/C_DS at the same q $(C_DS)^{1/2}$ when compared to the other four canopy types. The conclusion of this analysis is that the Ringsail canopy is the most efficient in terms of parachute weight per square foot of drag area when evaluated by this theoretical analysis.

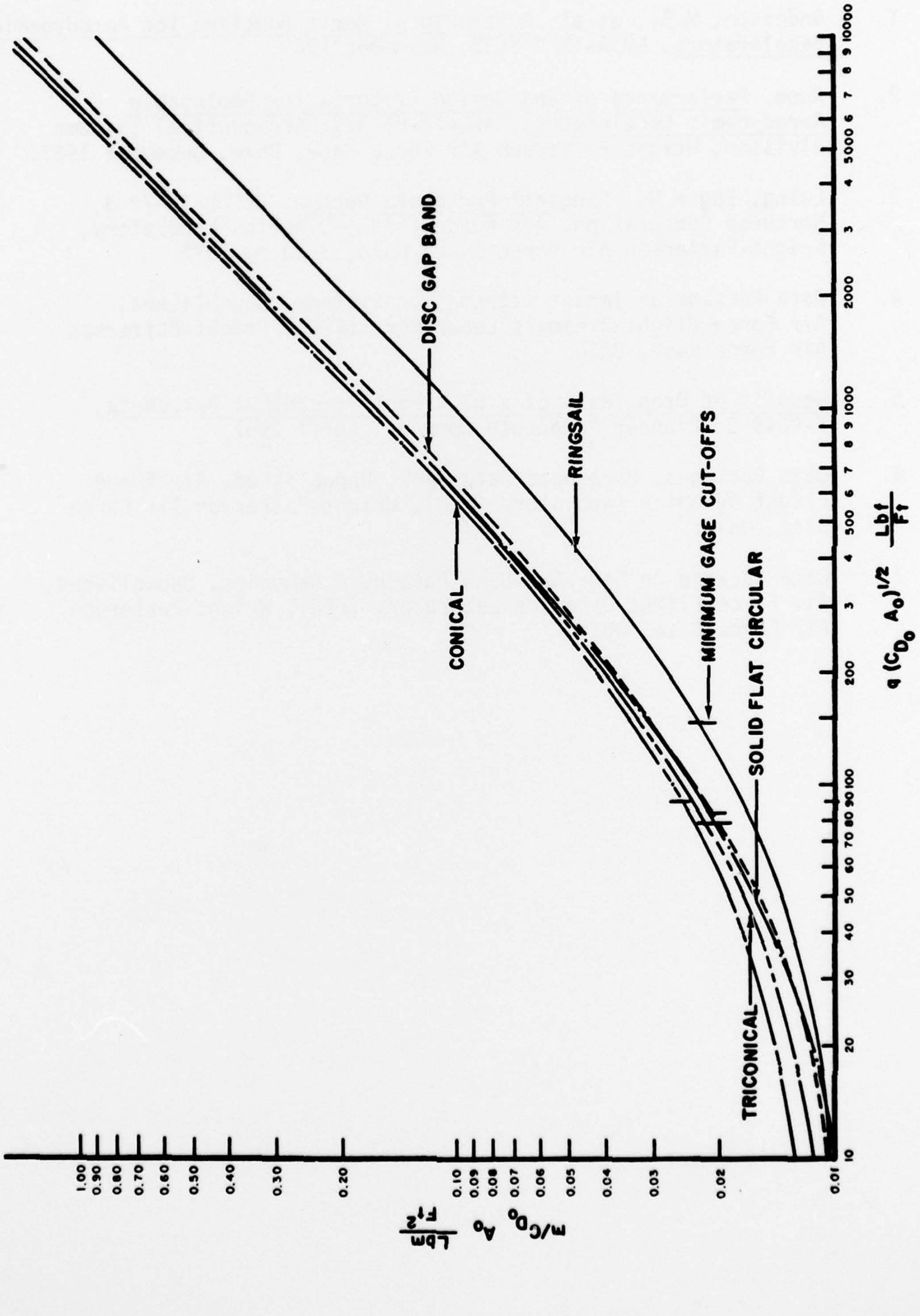


Figure A-6. Evaluation of Canopy Efficiencies

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