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STUDY OF HEAVY EQUIPMENT AERIAL DELIVERY AND RETRIEVAL TECHNIQUES

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et al

THE LOCKHEED-GEORGIA COMPANY
(A DIVISION OF LOCKHEED AIRCRAFT CORPORATION)
MARIETTA, GEORGIA

TECHNICAL REPORT No. AFFDL-TR-66-97

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AIR FORCE FLIGHT DYNAMICS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This final Technical Documentary Report was prepared by the Lockheed-Georgia Company, Marietta, Georgia, in compliance with requirements of Contract No. AF 33(615)-2989, Project Number 6065, Task Number 606509. The report describes analytical studies conducted between 1 July 1965 and 1 August 1966.

This study was sponsored by the Air Force Flight Dynamics Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio. Mr. Reinhold Gross of the Recovery and Crew Station Branch served as the Air Force Program Manager.

The program at the Lockheed-Georgia Company was the responsibility of the Advanced Concepts Department, Mr. R. H. Lange, Manager. Mr. E. L. White, Jr. served as the Project Leader. Staff members who contributed significantly to the program include C. E. Bronn, J. S. Coates, B. M. Crenshaw, J. E. Fletcher, B. H. Lightfoot, J. C. Muehlbauer, R. G. Smethers, F. H. Stokes, and R. F. Sturgeon, Jr.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

SOLOMON R. METRES
Acting Chief, Recovery & Crew Station Branch
Vehicle Equipment Division
Air Force Flight Dynamics Laboratory

ABSTRACT

Analytical studies were conducted for the purpose of defining optimum systems for the aerial delivery of payloads in the 35,000 to 70,000-pound range and the aerial retrieval of payloads in the 3,000 to 10,000-pound range. A generalized approach was utilized in the analysis and evaluation of candidate systems for both functions. Included in the study was a definition of requirements for each operational phase, the development of criteria for concept classification and selection, feasibility analyses of candidate concepts, and a comparison of operational characteristics of delivery and retrieval concepts. Selected concepts were employed in the formulation of complete systems, for which detailed performance analyses and evaluations were conducted. Conclusions formed on the basis of the analytical study are presented.

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LIST OF SYMBOLS

a	length (general)
A	area (general)
b	length (general)
c	effective parachute cloth porosity
C	constant (general)
C_D	drag coefficient
C_L	lift coefficient
C_M	pitching moment coefficient
c_p	specific heat
C_Q	torque coefficient
C_T	thrust coefficient
$\bar{c}$	mean aerodynamic chord
d	diameter
d_o	nominal diameter for aerodynamic decelerator
d_p	projected diameter for aerodynamic decelerator
D	drag force
e	subscript: extraction
E	energy (general)
F	force (general)
g	acceleration of gravity subscript: gust
h, H	altitude (general)
h_a	aircraft altitude
h_d	altitude at beginning of descent phase
h_r	altitude at beginning of recovery phase
i	subscript: impact

LIST OF SYMBOLS (Cont'd)

i_T	tail incidence angle
I	moment of inertia
i_μ	ultimate safety factor
k	radius of gyration
K	material constant
l	length (general)
l_c	cargo floor length
L	lift force
L'	turbulence scale length
L_D	rotor disk loading
m	mass slugs
M	Mach number moment (general)
n	load factor
n_o	initial load factor; initial thrust/weight ratio
o	subscript: initial
p	pressure; power
P	probability (general), impulse
P_e	engagement probability
q	dynamic pressure
r	radius
S	surface area of aerodynamic decelerator (general); stress
S_w	aircraft wing area
s	deceleration stroke
s_o	initial vertical height of deceleration system
T	temperature (general); tension, thrust

LIST OF SYMBOLS (Cont'd)

t	time
t_c	cycle time
t_f	parachute filling time
u, U	gust velocity
U	free-stream velocity component along the stability x-axis
v, V	velocity (general)
v_a	aircraft velocity
v_b	rotor tip speed
$\bar{v}_e$	mean extraction velocity
Δv_e	velocity increment during extraction
v_d	velocity at beginning of descent phase
v_r	velocity at beginning of recovery phase
v_i	velocity at beginning of impact phase
v_t	terminal velocity
V	volume
w_s	wing loading
W	weight (general)
W_a	aircraft weight
W_c	useful payload weight
W_e	extraction phase system weight
W_d	descent phase system weight
W_r	recovery phase system weight
W_i	impact phase system weight
x, X y, Y z, Z	coordinates
α_{frl}	angle of attack of fuselage reference line

LIST OF SYMBOLS (Cont'd)

β	angle (general)
γ	flight path inclination angle, specific gravity
δ_e	elevator deflection angle
ϵ	strain
μ	sliding friction coefficient
η	viscosity, ratio (general)
ϕ	inclination angle of cargo retrieval line
θ	airplane attitude angle, tether line inclination
ρ	density (general)
ρ_o	density of air at sea level
σ	ratio of air densities, standard deviation
ω	angular velocity

I - INTRODUCTION

Techniques for the aerial delivery, retrieval, and redeployment of cargo and equipment continue to acquire increased significance as a means for providing the support and necessary technical flexibility in the conduct of various types of conflicts, including limited war and counterinsurgency operations. In this respect the past ten years have been characterized by a rapid rate of growth in the load carrying capability of military cargo aircraft. Operational cargo aircraft in this category include both the C-130 and C-141 aircraft, which have maximum payload capabilities of 45,000 pounds and 70,000 pounds respectively. The C-5A, which is currently under development, will have a maximum design payload capability of 260,000 pounds.

In order to take advantage of the heavy cargo carrying capability of these aircraft, and in the interests of providing a maximum degree of flexibility in the delivery and retrieval of heavier unit loads, developmental and flight test programs are being continually implemented in this area. To date these programs have demonstrated the feasibility of delivering by airdrop unit loads weighing over 41,000 pounds. Lesser loads, weighing up to 20,000 pounds, have been delivered in ground proximity by parachute extraction. Program plans include development of the means for delivery of unit loads up to 30,000 pounds by this method. Ground-to-air retrieval has been demonstrated with a maximum payload weight of 3000 pounds.

While these programs have produced significant improvements, both in the areas of cargo aerial delivery and ground-to-air retrieval, the maximum capabilities of these military cargo aircraft, in this respect, have not yet been fully realized. Improved drop accuracy is required of current aerial delivery techniques at the high end of the demonstrated capability. The feasibility of aerial delivery and ground-to-air retrieval of loads considerably heavier than those demonstrated to date has yet to be investigated. In the interests of obtaining maximum utilization of operational aircraft considered to be in the United States Air Force inventory through the year 1975, the Air Force Flight Dynamics Laboratory established and sponsored the study program documented herein. The purpose of the study is to develop technological concepts for the aerial delivery of military equipment in the weight category between 35,000 and 70,000 pounds and to develop techniques for the purpose of retrieving, towing, or boarding into an aircraft in flight, ground stationed equipment in unit loads weighing from 3000 to 10,000 pounds.

The study assumes utilization of the C-141 and the C-5A aircraft for cargo aerial delivery and the C-130, C-141, C-5A and a V/STOL aircraft for the purpose of cargo ground-to-air retrieval. To insure comprehensive results, an operations research approach is employed early in the study to provide guidance in the classification and compilation of airdrop and retrieval concepts. Feasibility analyses are conducted in which the characteristics of each concept are determined and compared to the performance requirements in each phase of the delivery and retrieval sequence. The most promising systems are selected and subjected to a detailed analysis to project performance capabilities in terms of pertinent system parameters. Data obtained from these analyses are utilized in conjunction with analyses of system operational characteristics to permit an evaluation of the selected delivery and retrieval systems. A cost-effectiveness study is conducted to establish the relative value of cargo retrieval by fixed wing aircraft in comparison with VTOL aircraft. Major results and implications of the study are summarized and conclusions are presented.

II – AERIAL DELIVERY SYSTEMS

CRITERIA FOR CONCEPT CLASSIFICATION

The systematic investigation of aerial delivery system concepts requires a set of logical criteria for description and classification of the various possible concepts. As a preface to the development of these criteria, definitions are given for the fundamental terms which are used, along with an outline of the logic under which combinations of these terms are accepted or rejected in the concept formulation process.

Operational Phases

Reduced to fundamental physical terms, the basic functions which must be performed by an aerial delivery system involve the imparting of a sequence of metered and timed impulses to the drop cargo such that its velocity is changed from the airplane flight speed to zero during the time period the cargo is displaced from the airplane to the target drop point on the ground. The magnitude of the total impulse, which is the sum of the individual impulses in the sequence, depends on the drop conditions as expressed in terms of flight speed and drop altitude and on the type of trajectory desired for the drop cargo.

From an analytical standpoint, it is advantageous to associate the various impulse increments in the sequence with distinctly different operational phases. These phases are extraction, descent, recovery and impact.

The Extraction Phase comprises all events which occur while the cargo maintains direct physical contact with the airplane into which it originally was loaded.

The Descent Phase covers all events occurring from the end of the extraction phase until such time as devices are activated for the express purpose of reducing the cargo velocity to a tolerable, specified ground impact value.

The Recovery Phase comprises all events associated with reduction of the vertical components of the cargo velocity to a specified, tolerable impact value. It terminates upon ground contact of the cargo or the shock-absorbing device provided for the cargo. It does, however, include ground contact of sensing devices which may be used to activate operation of pre-impact velocity-reducing systems.

Under certain operational conditions (e.g., in very low altitude airdrop situations) the descent and recovery phases tend to coalesce into a single phase.

The Impact Phase comprises all events which occur between the first instant of physical ground contact of shock absorbing devices attached to the cargo and the instant at which the cargo has come to rest on the ground.

Reaction Modes

The impulse increments associated with each of the operational phases are generated by action forces having their points of application located at the cargo. From a concept classification standpoint, analysis of the behavior of the action forces is unprofitable, since the results of such an analysis at best only would lead to a classification of cargo trajectories.

A set of workable classification principles can however be derived from answers to the following questions:

- Where is the reaction to the impulse-generating action force generated
- How is the reaction force itself generated
- What are the characteristics of the link which connects the reaction force generating source with the point of application of the action force

In order to avoid ambiguity in the derivation of classification principles, the following convention was adopted:

> The term "reaction force" is only used in conjunction with the reaction force generating source. At all other points along the load paths of the system, the forces are considered to be "action forces" whether these load paths terminate at the cargo or not.

In the following, the derivation and coding of classification principles on the basis of this approach will be outlined in detail.

Location of the Reaction Points: There are only four possible separate and conceptually different locations for a reaction force generating source.

They are:

- The airplane from which the cargo is dropped
- The air
- Impulse propellant
- The ground

The first of these is self explanatory.

The second, characterizes all concepts wherein the reaction to the impulse-generating force acting on the drop cargo ultimately is transmitted to the surrounding air by whatever means, except through the airplane initially carrying the drop cargo.

"Impulse propellant" characterizes all concepts relying on the reaction of high speed jets for generation of the impulse increment.

Finally, "The ground," characterizes all concepts in which the cargo impulse increment is generated by forces whose reactions ultimately are transferred to specific locations on the ground.

Origin of Reaction Forces: The next step in the derivation of classification principles is concerned with the different ways in which the reaction forces can be generated.

A convenient point of departure for this examination is afforded by the fact that imparting various impulse increments to the drop cargo implies the performance of associated amounts of mechanical work. It is a basic principle of physics that the performance of mechanical work involves the transformation of energy from one form to one or several other forms. A broad classification can be obtained by noting that certain energy forms are available as part of the natural environment for all operational phases. All other energy forms must be provided either by means of a subsystem capable of converting a naturally available energy form into the desired one, or by a subsystem comprising both an independent energy source and the means for extracting mechanical work from the energy form contained in the source.

The energy forms which are naturally available throughout all operational phases are kinetic energy of cargo and airplane and gravitational energy. All other energy forms which are provided for conversion in order to generate reaction forces must conform to the general requirement of being available in latent form.

The various principles for generating reaction forces by means of conversion of available basic energy forms are illustrated in Figure 1. Conversion of kinetic energy for the purpose of generating reaction forces can occur in three basically different ways:

- o Aerodynamic action
- o Sliding friction action
- o Mechanical deformation action

In the aerodynamic action mode, a pressure field is generated by interaction of an aerodynamic shape with a fluid in motion. The reaction force is generated by the aerodynamic shape itself which, accordingly, defines the location of the reaction point. Useful work is performed on the cargo by forces transmitted to it by whatever structural means are used to connect the aerodynamic shape with the cargo including configurations which also involve the airplane. Energy is dissipated at a rate which depends on the magnitude of the reaction force and the rate of motion of the aerodynamic shape in a reference frame at rest relative to the fluid.

In the sliding friction action mode, a reaction point must be provided. The reaction point can be fixed either relative to the cargo, or relative to the inertial reference frame in which the cargo is moving. The amount and rate of energy dissipation is equal to the amount and rate of useful work performed on the cargo.

In the mechanical deformation action mode, a reaction point must again be provided, fixed either relative to the cargo or relative to the inertial reference frame in which the cargo is moving. The reaction force performs work which will either be dissipated by inelastic deformations or which will be stored as elastic strain energy in the case of elastic deformation. Storing of elastic energy can be utilized to increase the impulse increment provided by the energy conversion mode.

Conversion of gravitational energy can be used to generate reaction forces in only two basically different ways:

- o Buoyancy action
- o Direct action

In the buoyancy action mode, both the reaction point and the reaction force reside in the buoyant body. Action forces must be transmitted to the cargo by structural connections. The useful work done is stored as potential energy in the buoyant body.

In the direct action mode, a reaction point must be provided permitting a component of the cargo weight to furnish the required impulse increment.

Conversion of latent energy to provide the reaction force can occur in either of two basically different ways:

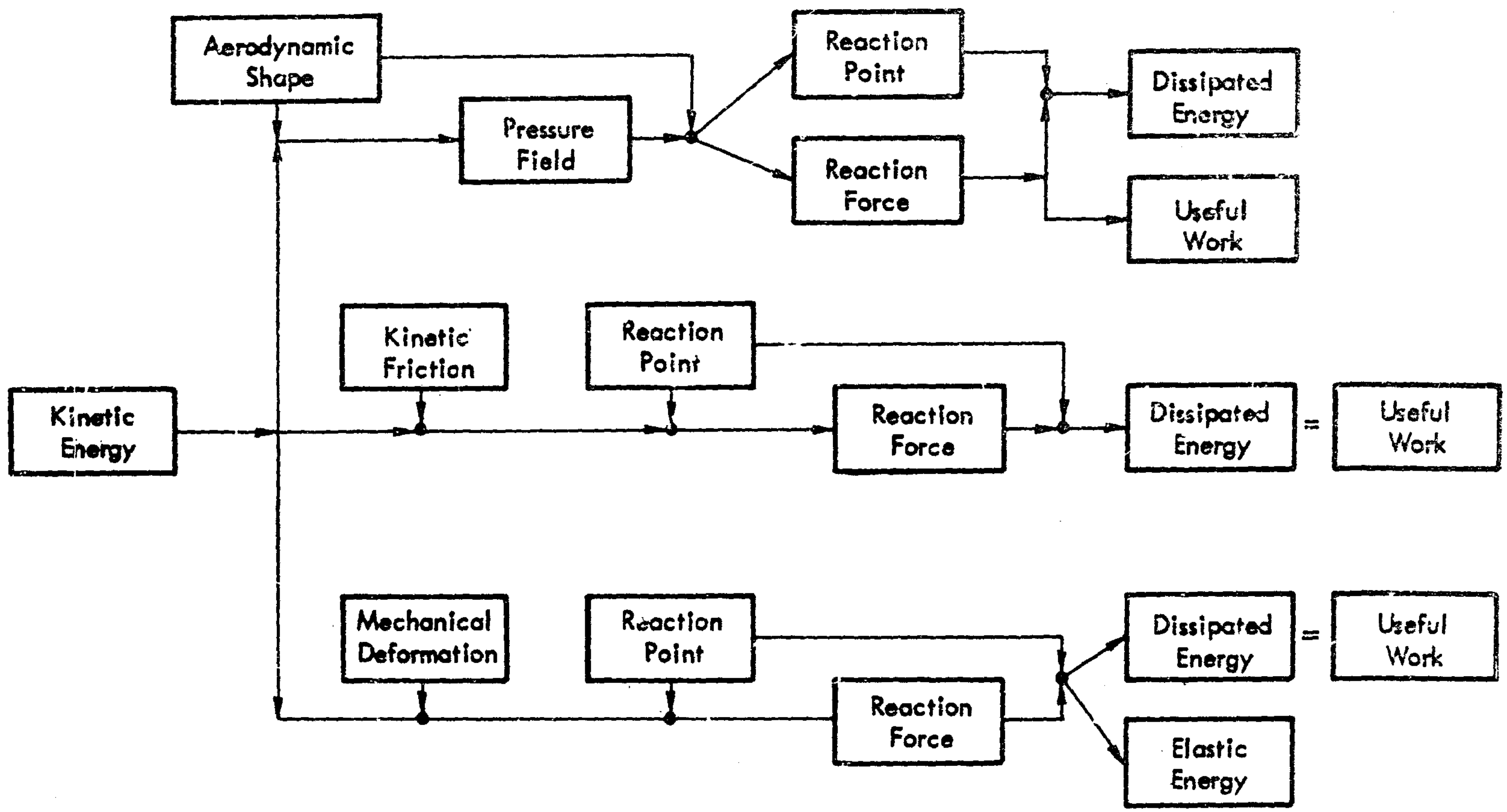
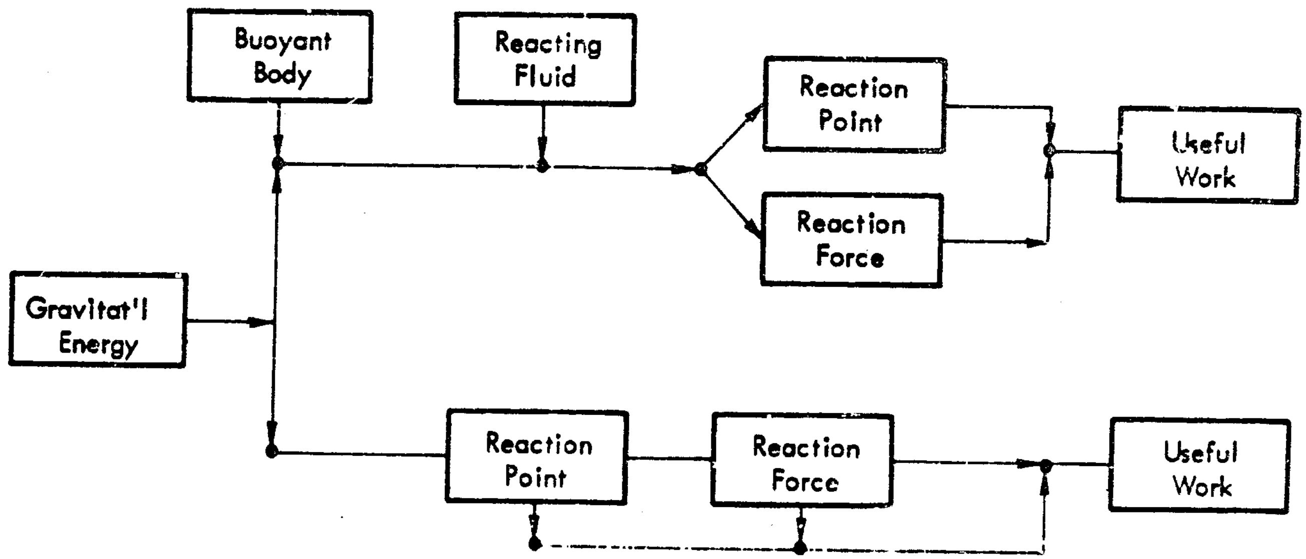


Figure 1 – Reaction Force Generating Principles



Figur· · continued

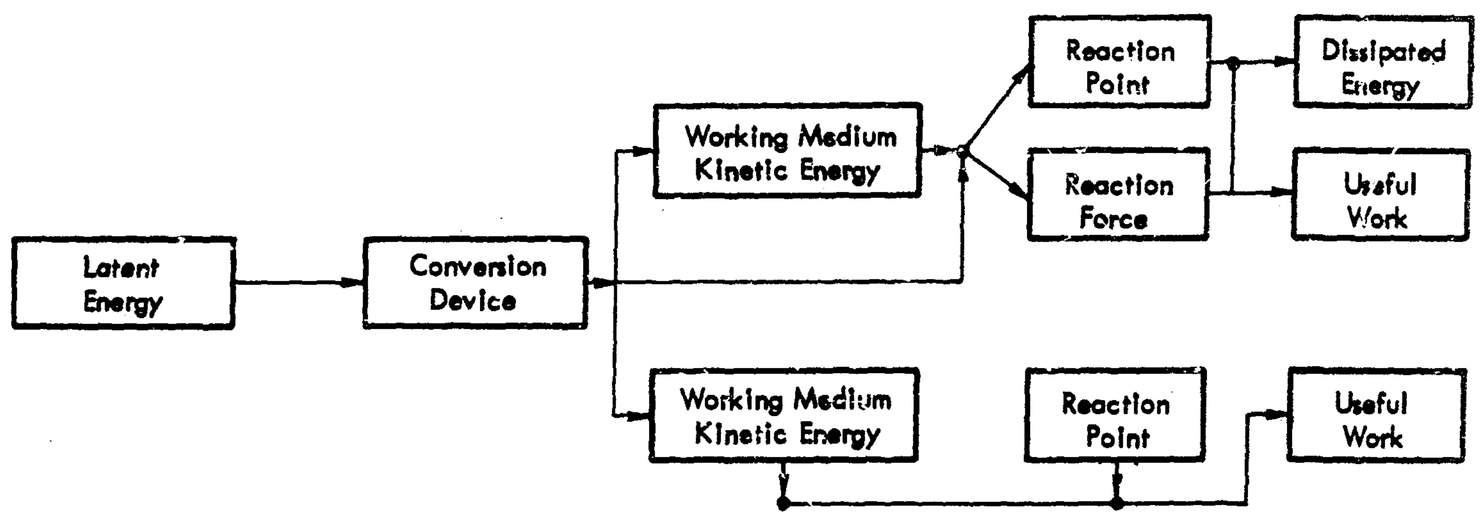


Figure 1 continued

- o Impulse action
- o Direct action

In the impulse action mode, the latent energy is converted to kinetic energy in a working medium which may include, but is not limited to, combustion gases produced in the conversion process. The impulse action mode includes conversion processes leading to shaft power input on a propeller or rotor shaft causing transmission of kinetic energy to air influenced by the propeller or rotor. The reaction point is defined by the location of the device which performs the final conversion to working-medium kinetic energy.

The direct action mode requires a specific location of the reaction point from which mechanical work is performed on the cargo by such means as are most convenient and efficient for converting the type of latent energy under consideration.

Figure 2 presents a summary of the various available energy conversion principles along with the constraints on reaction point locations. There are two types of constraints. One type is associated with the energy conversion principle and fixes the reaction point location in the conversion device, as explained above. The other type is associated with operational aspects and limits the selection of reaction point location from operational standpoints.

Force-link characteristics: The force link characteristics are tied intimately to the physical configuration of particular systems. In order to retain a sufficient level of generality of the derived classification principles, it was necessary to constrain the considerations to simple characteristics of the network through which the action forces are distributed from the reaction force generating source. These can be expressed in terms of:

- o Action force load path branching
- o Action force effectiveness ratio

The first characteristic expresses the property of the concept that the reaction force may be opposed by several components of action force, each being transmitted along its own load path which need not terminate at the cargo. The second characteristic can be expressed numerically as the ratio between the magnitudes of the action force component applied to the cargo, and the total reaction force.

In a sum, the force-link characteristics represent an efficiency index whose basic value may change in steps between different concepts depending on the extent of action force load path branching, and continuously between different systems within the same concept group depending on the variations in action force effectiveness achieved.

Classification according to the principles derived above from consideration of force-link characteristics are in general only applicable when a concept has been spelled out in considerable systematic detail. For this reason, and also because the classification characteristics according to these principles are rather synomymous with the relative values of system weight ratio (system weight/cargo weight) they are not included in the general concept classification system.

Energy Form/Reaction Point Constr't (General) / Conversion Principle	Kinetic		Gravitational		Latent		Operational Constraint on Reaction Point Location
	Inherent	Free	Inherent	Free	Inherent	Free	
Aerodynamic	✓						The Air
Kinetic Friction		✓					The Ground
Mech'l Deformation		✓					The Ground
Buoyancy			✓				The Air
Direct Action				✓		✓	The Airplane
Impulse Action					✓		The Impulse Medium

Note: "Inherent" denotes that the reaction point is inseparable from the energy conversion device

"Free" denotes that the specific reaction point location must be selected in the system design process and does not need to coincide with the energy conversion device

Figure 2 - Energy Conversion Principles and Constraints on Reaction Point Locations

Identification and coding of reaction modes: The information contained in Figure 2 has been consolidated and rearranged as shown in Figure 3. In this figure, a specific reaction mode is defined as a combination of one or more energy conversion principles with specific reaction point locations. The combinations were assigned arbitrary code numbers in order to simplify the analytical manipulations presented subsequently. In Figure 3, a distinction was drawn between a "pure" aerodynamic conversion principle and a mixed principle involving both aerodynamic and buoyancy devices. The reason that the buoyancy principle is presented only in combination with aerodynamic energy conversion is that in practical applications, a significant amount of motion of the buoyant body must be expected. The aerodynamic energy conversion associated with this motion can be expected to contribute significantly to the magnitude of total reaction force generated.

The kinetic friction and mechanical deformation principles were combined as one reaction mode, since both derive the reaction force from kinetic energy conversion, and both are constrained to reaction point locations on the ground for aerial delivery concepts.

Concept Classification Matrix

If the assumption is made that each of the five reaction modes shown in Figure 3 can be utilized singly or in combination with one, two, or all four of the remaining reaction modes in all operational phases of the drop sequence, a generating matrix for all possible groups of airdrop system concepts can be established as shown in Figure 4. These concept groups can be considered as the trunks of a number of concept family trees. The limbs and branches for each family tree will emerge from consideration of various available means for generating the reaction forces along with different configurations of the action force transmission paths.

The total number of different possible airdrop concept groups is 923,521.

In order to reduce this formidable array of concept groups to a manageable size, a search has been made for a set of generally applicable exclusion principles. These principles would serve to identify and reject matrix element combinations which, in conjunction with specified drop conditions, would lead to one of the following consequences:

- Requirements for transgression of the state-of-the-art with respect to knowledge of physical laws and principles.
- Incompatibility or conflict with currently accepted standards for safe cargo aircraft operation.
- Requirements for transgression of the state-of-the-art with respect to technological applications of established physical law and principles.
- Intermittent subsystem operation.
- Lack of operational flexibility.

These rejection principles can be applied at any level in the analysis, and are characterized by a decreasing definiteness of their rejecting powers. The reason for this is as follows:

The body of known physical laws and principles constitutes a very stable system which very infrequently is subject to modifications and changes. It is, therefore, very easy to decide with confidence whether a particular matrix element combination satisfies the first rejection principle.

ENERGY CONVERSION PRINCIPLE	REACTION POINT LOCATION	REACTION MODE CODE NO.
Aerodynamic	The Air	(1)
Aerodynamic and Buoyancy	The Air	(2)
Direct Action	The Airplane	(3)
Kinetic Friction and/or Mech Deformation	The Ground	(4)
Impulse Action	The Impulse Medium	(5)

Figure 3 – Reaction Mode Identification and Coding

REACTION MODE CODE # / OPERATIONAL PHASE	(1)	(2)	(3)	(4)	(5)
EXTRACTION					
DESCENT					
RECOVERY					
IMPACT					

Total number of possible different combinations

$$N_{CT} = \left[\sum_{r=1}^{r=5} \frac{5!}{r!(5-r)!} \right]^4 = 923521$$

Figure 4 - Airdrop Concept Classification Matrix

The concept of what constitutes safe cargo aircraft drop operation is ultimately derived from operational experience with proven systems. A particular system will be assessed as safe if it exhibits a low malfunction rate in operation along with fail-safe features which prevent occasional system malfunctions from endangering the safety of the aircraft. Although malfunction rates for any system can usually be reduced to acceptably low levels by concerted developmental efforts, past experience indicates that certain systems will never-the-less be lacking fail-safe features. Matrix element combinations which are judged to exhibit this characteristic as an inherent property will be rejected.

Finally, technological applications of established physical laws and principles are subject to a more or less continuous process of development and refinement, partly under pressure of operational needs and requirements and partly due to individually exercised curiosity and inventiveness. The acceptance/rejection criterion must, in this case, be formulated in terms of probability of achieving the required state-of-the-art advances within a stated, sufficiently short, time span. A judgment of this nature, however correct when initially made, must be subject to periodic reviews.

The next step is to examine the total number of basic concept groups in the light of the acceptance/rejection criteria outlined previously.

For that purpose, two matrices are prepared. One of these pertains to concept combinations suitable for drop altitudes $\leq$ 10 feet, while the other pertains to concept combinations suitable for drop altitudes $>$10 feet. This altitude was selected as a discriminating value, since it corresponds to a free fall impact velocity of $\approx$ 26 feet-per-second.

Results of this filter process carried out in Tables I and II are shown in Figure 5, where rejected matrix element combinations are crossed out. Application of this filter brings the number of physically possible concept family trees down to 225. This number is still excessive, as it includes a number of combinations which do not allow for the fact that the various operational phases must follow one another in a regular sequence. By taking this fact into consideration, the following logical rule is obtained for generating concept family trees by combination of matrix elements:

> An impulse reaction mode used in any concept-generating combination must appear in the earliest operational phase where it is applicable, except from the extraction phase, and must be assumed active throughout its entire range of applicability.

This rule prevents formation of obviously nonsensical combinations which would permit intermittent appearances of a particular impulse reaction mode in a sequence of operational phases.

Reference 1 directs the scope of the study toward investigation of concepts possessing the needed technical flexibility to comply with a broad range of operational situations. This requirement serves to eliminate from further study all concepts which can operate only under very specialized conditions. Typical of concepts within this category are those relying on fixed ground installations for performing the necessary functions in the various operational phases, particularly when ground-based extraction equipment is utilized. Also included in this category are concepts requiring obstacle-free approach and departure paths approximating airport dimensions for the drop zone.

OPERATIONAL PHASE \ REACTION MODE CODE #	(1)	(2)	(3)	(4)	(5)
EXTRACTION	✓	✗	✓	✗	✗
DESCENT	✓	✓	✗	✗	✓
RECOVERY	✓	✓	✗	✗	✓
IMPACT	✗	✓	✗	✓	✗

Figure 5 - Screened Concept Classification Matrix

TABLE I

IMPULSE REACTION MODE COMBINATION FILTER (h $\leq$ 10 feet)

Reaction Mode Combination Code No.	Reaction Point Location	Unsuitable Operational Phase (s)	Reason For Rejection	Potential Appl. In Operational Phase(s)
(1) Aerodynamic	The Air	Impact	Implies consistent touch-downs at zero Velocity which is beyond the State-of the-Art	Extraction Descent Recovery
(2) Aerodynamic and Aerostatic	The Air	Extraction	Buoyancy Force component perpendicular to required extraction force direction	Descent Recovery Impact
(3) Direct Action	The Airplane	Descent Recovery Impact	A/C Pitching moment reactions cannot be accommodated. Transmission devices for action force and moments beyond State-of-the-Art	Extraction
(4) Kinetic Friction and/or Mechical Deformation	The Ground			All
(5) Impulse Action	Impulse Propellant	Extraction Impact	Implies discharge of impulse propellant inside or very close to A/C - Undesirable from flight safety standpoint. Implies consistent touch-downs at zero velocity - beyond the State-of-the-Art	Descent Recovery
(1,3)		Descent Recovery Impact	Reason as for (3), above	Extraction

TABLE I (Cont'd)

Reaction Mode Combination Code No.	Reaction Point Location	Unsuitable Operational Phase(s)	Reason for Rejection	Potential Appl. in Operational Phase(s)
(1, 4)				All
(1, 5)		Extraction Impact	Same reason as (5), above	Descent Recovery
(2, 3)		Extraction Descent Recovery Impact	Same reasons as for (2) and (3), above	None
(2, 4)		Extraction	Same reason as for (2) above	Descent Recovery Impact
(2, 5)		Extraction	Same reason as for (2) and (5), above	Descent Recovery Impact
(3, 4)		Descent Recovery Impact	Same reasons as for (3) and (5), above	Extraction
(3, 5)		Extraction Descent Recovery Impact	Same reasons as for (3) and (5), above	None

TABLE I (Cont'd)

Reaction Mode Combination Code No.	Reaction Point Location	Unsuitable Operational Phase(s)	Reason for Rejection	Potential Appl. In Operational Phase(s)
(4,5)		Extraction	Same reason as for (5), above	Descent Recovery Impact

TABLE II

IMPULSE REACTION MODE COMBINATION FILTER ($h > 10$ feet)

Reaction Mode Combination Code No.	Reaction Point Location	Unsuitable Operational Phase(s)	Reason for Rejection	Potential Appl. In Operational Phase(s)
(1) Aerodynamic	The Air	Impact	Implies consistent touch-downs at zero velocity which is beyond the State-of-the-Art	Extraction Descent Recovery
(2) Aerodynamic & Aerostatic	The Air	Extraction	Buoyancy force component perpendicular to required extraction force direction	Descent Recovery Impact
(3) Direct Action	The Airplane	Descent Recovery Impact	A/C pitching moment reactions cannot be accommodated. Transmission devices for action forces beyond State-of-the-Art	Extraction
(4) Kinetic Friction and/or Mech'l Deformation	The Ground	Extraction Descent Recovery	Physical realization of mechanism beyond State-of-the-Art	Impact
(5) Impulse Action	Impulse Propellant	Extraction Impact	Implies discharge of impulse propellant inside or very close to A/C - undesirable from flight safety standpoint. Implies consistent touch-downs at zero velocity.	Descent Recovery
(1,3)		Descent Recovery Impact	Reason as for (3), above	Extraction

TABLE II (Cont'd)

Reaction Mode Combination Code No.	Reaction Point Location	Unsuitable Operational Phase(s)	Reason for Rejection	Potential Appl. in Operational Phase(s)
(1,4)		Extraction Descent Recovery	Reason as for (4), above	Impact
(1,5)		Extraction Impact	Reason as for (5), above	Descent Recovery
(2,3)		Extraction Descent Recovery Impact	Reason as for (2) and (3), above	None
(2,4)		All	Implies ground-based equipment, not compatible with operational flexibility concept	None
(2,5)		Extraction	Same reason as (2) and (5), above	Descent Recovery Impact
(3,4)		All	Same reason as (3) and (4), above	None
(3,5)		All	Same reason as (3) and (5), above	None
(4,5)		Extraction Descent Recovery	Same reason as (4) above	Impact

Results of the application of these screening criteria are shown in Figure 6. Each column in the matrix identifies the basic features of a large family or group of related airdrop system concepts. There are in all 21 such groups, sub-divided into 3 basic groups, which have been assigned the arbitrary basic group numbers 01, 02 and 03. Basic group no. 01 contains all concept groups which achieve cargo extraction as a result of some form of aerodynamic reaction.

Basic group no. 02 contains all concept groups achieving cargo extraction by means of some form of direct action force reacted in the airplane, and basic group no. 03 contains all concepts utilizing a combination of aerodynamic reaction and airplane-reacted direct action force for cargo extraction.

Within each basic group, individual concept groups have been assigned arbitrary numbers ranging from 1 through 7. Inspection of Figure 6 reveals that corresponding group numbers for each of the basic groups possess identical reaction made combinations for the descent, recovery and impact phases. This implies that the number of essentially different concept groups is reduced to 7, when conceptual differences in reaction modes for the extraction phase along with differences between concepts in the action force linkage are disregarded.

Criteria for Concept Selection

The very large number of logically possible concepts, each containing varying numbers of systems exhibiting different conceptual realizations of the reaction mode combinations characterizing the particular sub-group, precludes an exhaustive analysis of all possible concepts. However, if attention is focussed initially on selected specimens from the least complex concept groups, information will be gained which can be carried over into the evaluation of more complex systems. A further argument in favor of this approach is based on the generally accepted fact that an increase in complexity is justified only when necessary to correct performance deficiencies inherent in systems of lesser complexity.

This argument was used to exclude tethered concepts such as the "LAAD" and the "Trolley" concepts which are characterized by poor force-link characteristics compared with the simpler basic systems.

Operational Phase	Concept Group No./Reaction Mode Combination													
	Basic Group #01							Basic Group #02						
	01.1	01.2	01.3	01.4	01.5	01.6	01.7	02.1	02.2	02.3	02.4	02.5	02.6	02.7
Extraction	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(3)	(3)	(3)	(3)	(3)	(3)	(3)
Descent	(1)	(2)	(2)	(5)	(1)	(2)	(2)	(1)	(2)	(2)	(5)	(1)	(2)	(2)
Recovery	(1)	(2)	(2)	(5)	(1,5)	(2,5)	(2,5)	(1)	(2)	(2)	(5)	(1,5)	(2,5)	(2,5)
Impact	(1,4)	(2)	(2,4)	(5,4)	(1,5,4)	(2,5)	(2,5,4)	(1,4)	(2)	(2,4)	(5,4)	(1,5,4)	(2,5)	(2,5,4)

Operational Phase	Concept Group No./Reaction Mode Combination						
	Basic Group #03						
	03.1	03.2	03.3	03.4	03.5	03.6	03.7
Extraction	(3, 1)	(3, 1)	(3, 1)	(3, 1)	(3, 1)	(3, 1)	(3, 1)
Descent	(1)	(2)	(2)	(5)	(1)	(2)	(2)
Recovery	(1)	(2)	(2)	(5)	(1,5)	(2,5)	(2,5)
Impact	(1,4)	(2)	(2,4)	(5,4)	(1,5,4)	(2,5)	(2,5,4)

Note: (3, 1), (1,5) Etc. denote mixed modes

Reaction Mode Coding:

Energy Conversion Mode	Reaction Point Location	Code No.
Aerodynamic	The Air	(1)
Aerodynamic & Aerostatic	The Air	(2)
Direct Action	The Airplane	(3)
Kinetic Friction & Mech'l Deformation	The Ground	(4)
Impulse Action	The Impulse Medium	(5)

Figure 6 - Airdrop System Concept Classification Groups

FORMULATION OF CONCEPTS

The classification system developed in the previous section was used as a guide to compile concepts for performing the functions required in the various operational phases of an airdrop sequence. The compilation was based on the literature survey and analysis conducted earlier in the study by study team members and is of a sampling rather than of an exhaustive nature. A separate listing of conceptual ideas which only differ in the matter of minor technical detail was avoided. The principal purpose was to achieve complete coverage of the spectrum of classification groups presented in the previous section.

The results of the compilation are shown tabulated in Table III.

A few observations can be made on the formation of complete concepts by combination of subsystem concepts for the various successive operational phases:

- o Where a particular reaction mode combination is applicable in several successive operational phases, considerations of system simplicity and weight economy will tend to favor concepts which permit the functions in all operational phases concerned to be performed by the same components. In addition, for a combination of different subsystems to be competitive, the added concept complexity must be offset by real improvements, either in performance or in added operational flexibility.

- o For the range of drop altitudes considered in this study, selection of particular impact phase subsystem concepts has a negligible influence on the selection of subsystem concepts for any of the earlier operational phases. The essential characterization of a complete airdrop concept is accordingly described by specification of the subsystems for the extraction, descent, and recovery phases.

TABLE III

FORMULATION OF AERIAL DELIVERY CONCEPTS

Operational Phase	Reaction Mode	Concept Description	May Appear in Classification Groups
Extraction	(3)	Inclined Plane	02.1-02.7, 03.1-03.7
	(3)	Catapult	02.1-02.7, 03.1-03.7
	(1)	Parachute	01.1-01.7, 03.1-03.7
	(1)	Extraction Aircraft	01.1-01.7, 03.1-03.7
Descent and Recovery	(1)	Parachute	01.1, 01.5, 02.1, 02.5, 03.1, 03.5
		L/D Parachute	
		Paracone	
		Ballute	
		Parawing	
		Rigid Glider	
	(1)	Windmilling Rotor	01.1, 01.5, 02.1, 02.5, 03.1, 03.5
	(5)	Powered Rotor	01.4-01.7, 02.4-02.7, 03.4-03.7
	(2)	Balloon	01.2, 01.3, 01.6, 01.7, 02.2, 02.3, 02.6, 02.7, 03.2, 03.3, 03.6, 03.7
	(2)	Paravulcoon	01.2, 01.3, 01.6, 01.7, 02.2, 02.3, 02.6, 02.7, 03.2, 03.3, 03.6, 03.7
	(5)	Turbojet	01.4-01.7, 02.4-02.7, 03.4-03.7
	(5)	Rocket	01.4-01.7, 02.4-02.7, 03.4-03.7
Impact	(4)	Displacement Type Hydraulic Shock Absorber	All, Except 01.2, 02.2, 03.2
		Displacement Type Pneumatic Shock Absorber (Air Bag)	
		Turbulent Drag Hydr. Brake	
		Viscous Drag Hydr. Brake	
		Mechanical Friction Brake	
		Controlled Structural Collapse	
	(4)	Soil Deformation	

ANALYSIS OF CONCEPT FEASIBILITY

To provide a basis for the selection of optimum concepts for complete aerial delivery systems, the concepts formulated in the previous section are analyzed with respect to the following operational phases:

- o Extraction
- o Descent and Recovery
- o Impact

The results for the concepts are presented in the order outlined in Table III. Each concept is analyzed only to the depth necessary to assess concept feasibility. Promising concepts are investigated in somewhat greater detail to permit comparison with other candidate concepts.

In the final part of this section, concept characteristics are summarized and evaluated. Based on these evaluations, concepts are selected for each phase, and two complete aerial delivery systems are formulated.

Extraction Phase

The extraction phase of aerial delivery comprises all events which occur while the cargo maintains direct physical contact with the airplane into which it was originally loaded. Characteristic of the extraction phase is a requirement for the generation of large forces to accelerate the cargo at a high rate. Physical systems compatible with extraction phase requirements may utilize forces derived from a stored energy source, gravitational interactions, or aerodynamic interactions.

The basic requirement of a system intended for cargo extraction is the capability of accelerating the cargo at a rate compatible with constraints imposed by operational characteristics of the aircraft. A complete analysis of aircraft limitations is presented in Appendix A for the employment of C-141 and C-5A aircraft in the aerial delivery of payloads in the 35,000 to 70,000 pound range. Since requirements for extraction from the C-141 are significantly more stringent than those related to the C-5A, feasibility analyses of candidate extraction systems are based on these requirements. Figure 7 shows minimum average values of extraction load factor required to hold the airplane pitch response below the 2.5 flight load factor level as a function of aircraft velocity and cargo weight. The minimum required extraction load factor boundaries increase markedly with increasing flight speed and increasing cargo weight.

In addition to specific operational requirements, there are a number of operational characteristics which are desirable in cargo extraction systems. Such characteristics include minimization of the following quantities:

- o System weight
- o System volume
- o Modification of aircraft

In the feasibility analyses which follow, evaluation of candidate extraction concepts is based on comparisons of weight, volume, and operational characteristics for systems capable of satisfying minimum extraction load factor requirements.

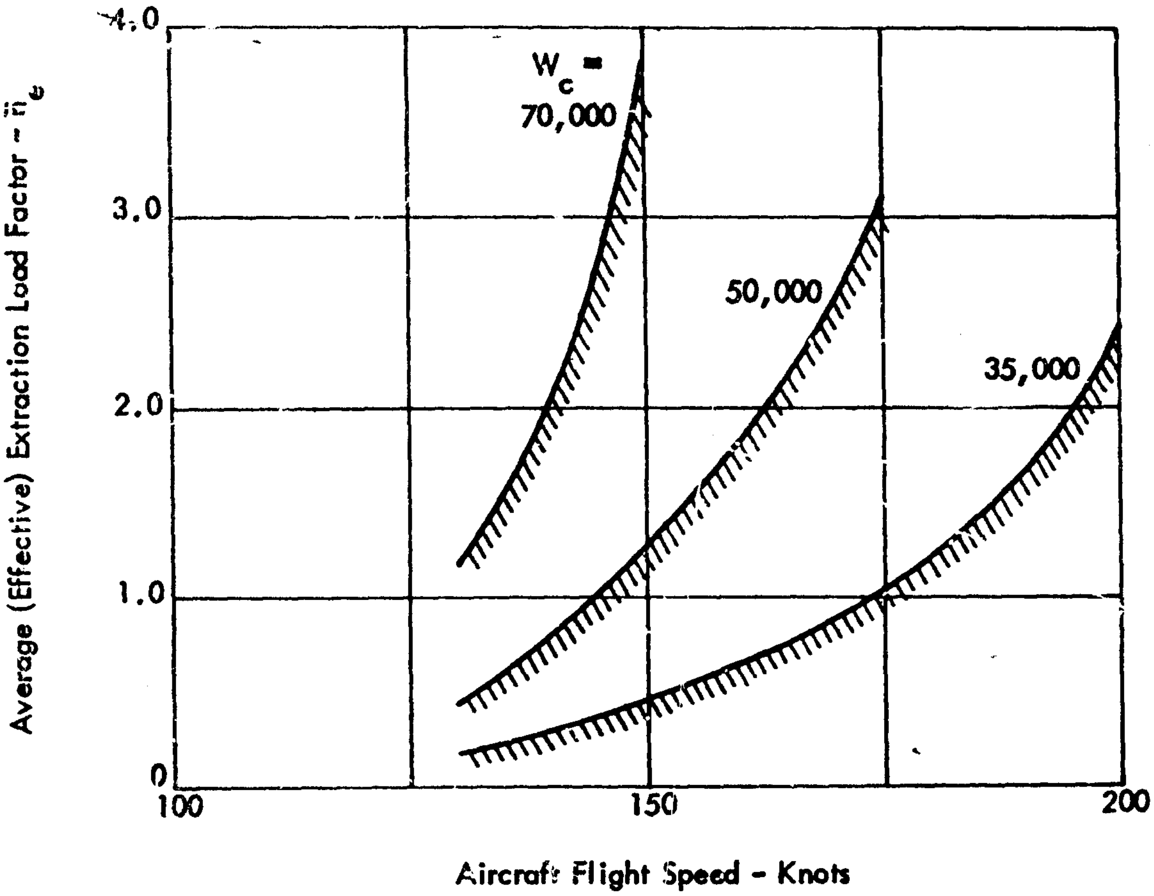


Figure 7 - Required Average Extraction Load Factor for Delivery from C-141 for Flight Load Factor Response ≤ 2.5 with 10 Feet/Second Gust Velocity

Inclined Plane

General - The inclined plane concept for cargo extraction utilizes a reaction force generated by gravitational action. Extraction is achieved by changing the aircraft pitch attitude to provide a rearward-downward inclination of the cargo floor along which the cargo is accelerated to the exit.

Results and Conclusions - Employment of this concept is restricted to aircraft speeds greater than 166 knots for 35,000-pound cargo loads and to speeds greater than 191 knots for 50,000-pound loads. Cargo weights of 70,000 pounds cannot be extracted by this method. Due to the limited range of applicability, this concept is not considered to be suitable for cargo extraction except as a possible emergency jettison technique.

Analysis - The inclined plane concept was investigated for application to the C-141 aircraft. Application of this concept is limited by the elevator control power required to counteract the upsetting pitching moment generated by the displacement of the drop cargo during extraction. The pitching moment is represented by pitching moment coefficient increments. The elevator pitch control is given by a constant value, $\Delta C_M = -.520$ (Reference 2) representing the change in airplane pitching moment coefficient by elevator deflection from the up elevator angle required to trim out a stall angle of attack, or design load factor, to a full down position.

The upsetting pitching moment coefficient increment due to cargo displacement is

$$\Delta C_M = \frac{n \cdot W_c \cdot \Delta x}{q \cdot S_w \cdot \bar{c}} \qquad (1)$$

where n is the trimmed flight load factor at cargo release and Δx is the maximum displacement of the cargo during extraction.

Results of the investigation are shown in Figure 132 of Appendix A. The concept can be used only at speeds where the elevator pitching moment coefficient increment numerically equals or exceeds the upsetting pitching moment coefficient increment. As shown in Figure 132, this restricts operation of this concept to speeds greater than 166 knots for 35,000-pound cargo weights and to speeds greater than 191 knots for 50,000-pound cargoes. Cargo weights of 70,000 pounds cannot be extracted by this method.

The lower set of curves in Figure 132 shows the gross extraction load factors obtainable with this concept. The values shown do not include effects of rolling or sliding friction of the drop cargo.

Due to limited range of applicability, this concept is not feasible for any application other than emergency cargo jettison.

Catapult

General - The catapult extraction concept utilizes a power unit or energy storage device with appropriate linkage, push rod, screw, or cable mechanisms to apply force to the cargo and accelerate it along the cargo floor and out of the aircraft. Figure 8 illustrates a representative system.

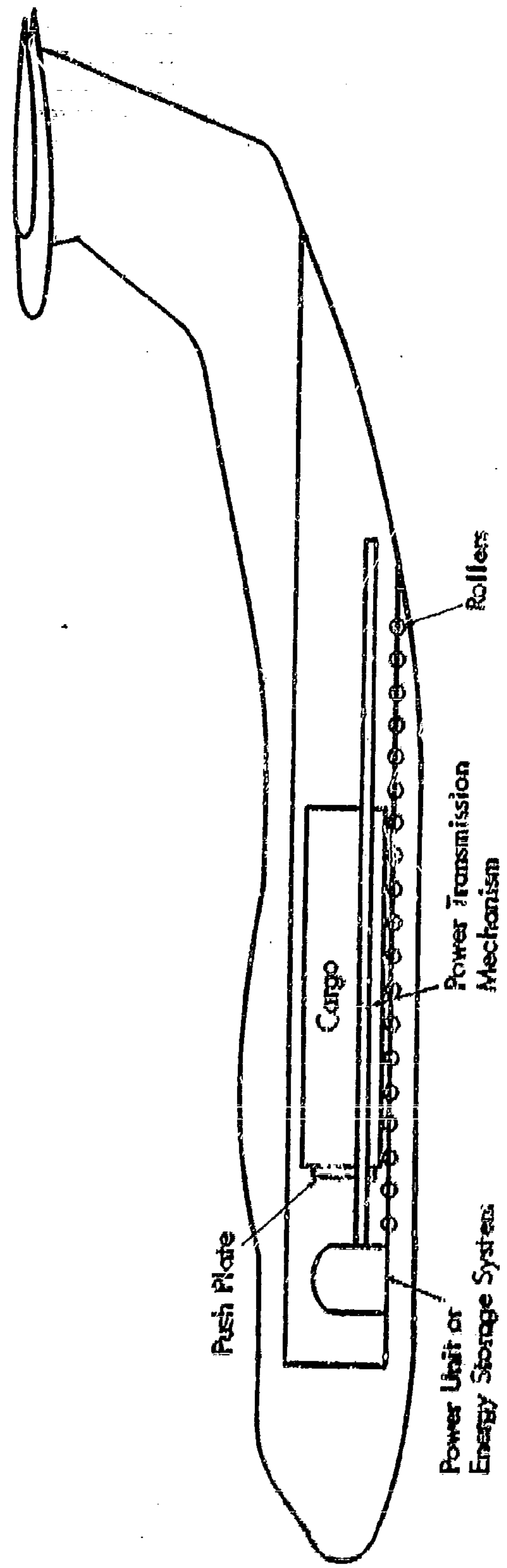


Figure 8 - Catapult Extraction Concept

Results and Conclusions - Satisfaction of the minimum extraction load factor requirement of 1.2 for extraction of a 70,000-pound cargo from the C-141 requires a power source of about 9300 horsepower. It is estimated that the weight of such a power source and the associated power transfer mechanism would be on the order of 14,000 pounds. For catapults designed for employment in low altitude delivery systems, in which the cargo is extracted at high velocity and allowed to fall without vertical retardation, power and weight requirements are higher by a factor of about 20 than those described above.

Catapults are not considered to be suitable for use in the extraction of heavy cargo loads due to excessive power requirements, excessive weight requirements, and the requirement for major modification of the aircraft.

Analysis - The power necessary to accelerate a weight W_c at a constant rate $\bar{n}_e \cdot g$ for a distance x is given by

$$P = W_c \cdot \bar{n}_e \sqrt{2 \cdot \bar{n} \cdot g \cdot x} \tag{2}$$

In the extraction of a 70,000-pound cargo from a C-141, a minimum $\bar{n}_e$ of 1.2 is required. The distance over which the cargo is accelerated is approximately 50 feet. Under these conditions, a catapult power source of 9300 horsepower is required.

Without restricting the catapult extraction concept to a specific design, it is difficult to establish an accurute system weight. However, it is not unreasonable to assume a ratio of 1.5 pounds per horsepower for a catapult power source and the associated power transfer mechanism. On this basis, the extraction system weight is approximately 14,000 pounds, excluding weight added by the structural modification of the aircraft. This weight requirement does not compare favorably with that of parachute extraction systems in common use.

Requirements for catapult extraction systems designed for low altitude aerial delivery are much more stringent than those described above. For an aircraft velocity of 220 feet/second and a residual cargo velocity of 50 feet/second after extraction, an average extraction load factor of 8.9 is required. In this system, the catapult power source must be capable of a 192,000 horsepower output. The system weight corresponding to such an extraction system is on the order of 300,000 pounds. These power and weight requirements are obviously not compatible with aerial delivery operations.

Parachute

General - The operation of parachute cargo extraction systems is based on a reaction force generated by aerodynamic action. Drag forces obtained by trailing one or more parachutes of the required size from the delivery aircraft are used for cargo extraction. Parachute extraction systems have been employed for the extraction of cargo weights up to 42,000 pounds (Reference 3).

Results and Conclusions - A 70,000-pound cargo can be extracted from a C-141 using one 73-foot diameter ring-slot parachute or three 35-foot diameter ring-slot parachutes. Weight of the complete parachute extraction system for this cargo weight is about 700 pounds. Parachute extraction systems are feasible for use over the complete range of cargo weights considered in this study.

Analysis - For aerodynamic drag-generating devices, the peak value of the extraction load factor may be appreciably higher than the average value for the deceleration period. The ratio of maximum to average load factor is given by

$$\frac{n_{max}}{\bar{n}_e} = \left[1 - \frac{\Delta v}{v_a} + \frac{1}{3}\left(\frac{\Delta v}{v_a}\right)^2\right]^{-1} \qquad (3)$$

where

$$\Delta v = \left[2\,\bar{n}_e\, g\, l_c\right]^{1/2} \qquad (4)$$

Figure 9 illustrates the relation between $n_{max}/\bar{n}_e$ and $\Delta v/v_a$. The ratio of peak-to-average load factor provides a basis for the sizing of any aerodynamic drag-generating device used for cargo extraction.

The following expression for the weight of a parachute extraction system, including line weight, was developed from the opening shock force relations and parachute materials data given in Reference 4.

$$W_e = \frac{.0038\,(n_{max}\, W_c)^{3/2}}{v_a} \qquad (5)$$

This weight estimation is based on flat canopy parachutes using a drag coefficient of 0.75, and allows for an opening shock factor of 2.0 and a safety factor of 2.195. It is anticipated that other canopy configurations possessing different values of C_D and opening shock characteristics may be preferable for specific applications. However, for the purpose of establishing reference data for comparison with other types of cargo attraction systems, the flat canopy configuration provides results of sufficient accuracy. Values obtained through the use of this relation demonstrate close conformity with currently available weights data as presented in Reference 4. Figure 10 describes generalized extraction parachute weights as a function of aircraft velocity.

By using the data presented in Figures 7, 9, and 10, it is possible to determine the weights of parachute extraction systems for specific cargo weights, aircraft speeds, and extraction load factors. Figure 11 shows the ratio of extraction system weight to cargo weight as a function of aircraft velocity with cargo weight as a parameter. Extraction system weights shown in this figure are those corresponding to minimum required average load factors as described in Figure 7, for a cargo floor length of 50 feet.

The data presented in Figure 11 are independent of the aircraft altitude at the time of extraction and may therefore be utilized in conjunction with any combination of concepts for the descent and recovery phases of the aerial delivery operation. As indicated by Figure 11, parachute extraction system weight requirements are relatively modest throughout the range of cargo weights under consideration.

Extraction Aircraft

General - The extraction aircraft concept completes the cargo delivery operation in addition to the cargo extraction function. This concept requires the use of two airplanes, one to carry the cargo to the drop zone and the second to extract and deliver the cargo. Figure 12 illustrates the extraction aircraft concept.

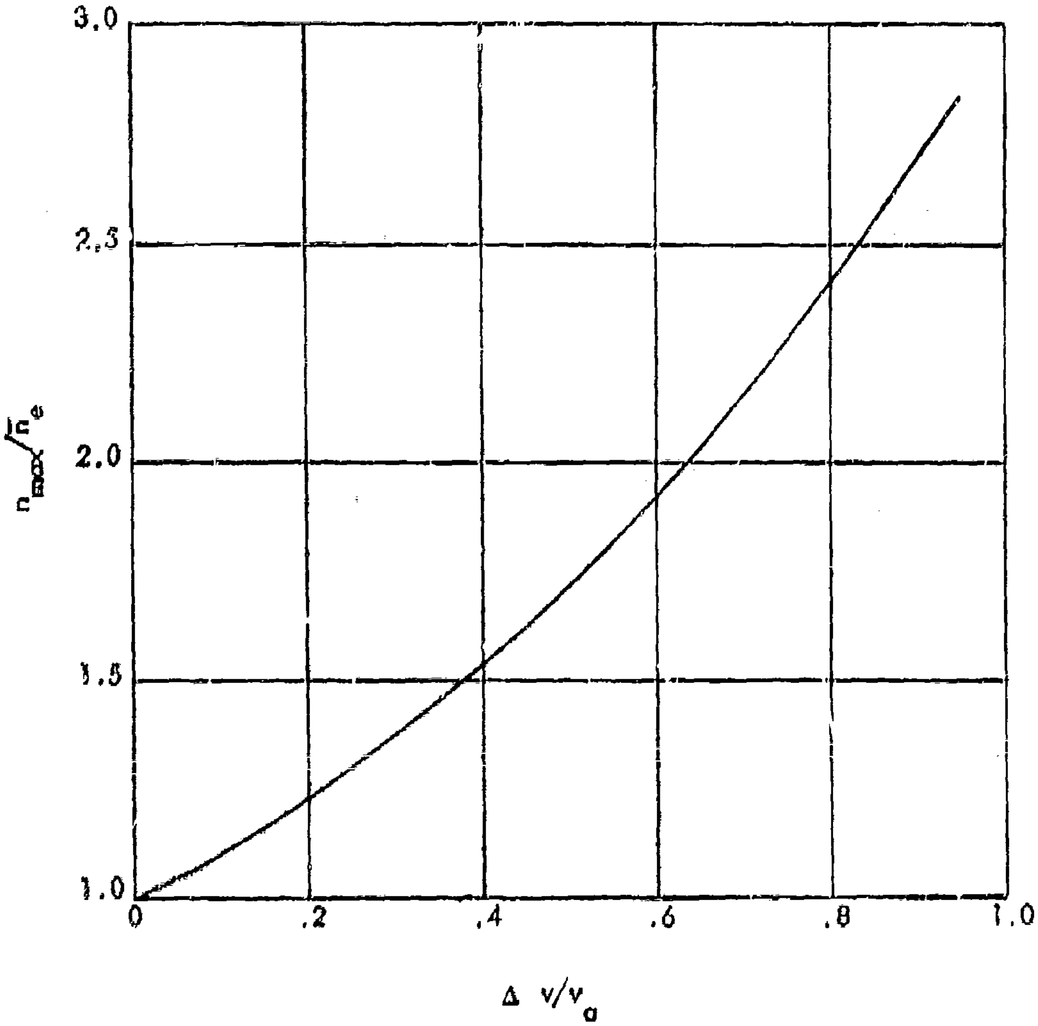


Figure 9 - Peak Extraction Load Factor Ratio for Aerodynamic Drag Devices

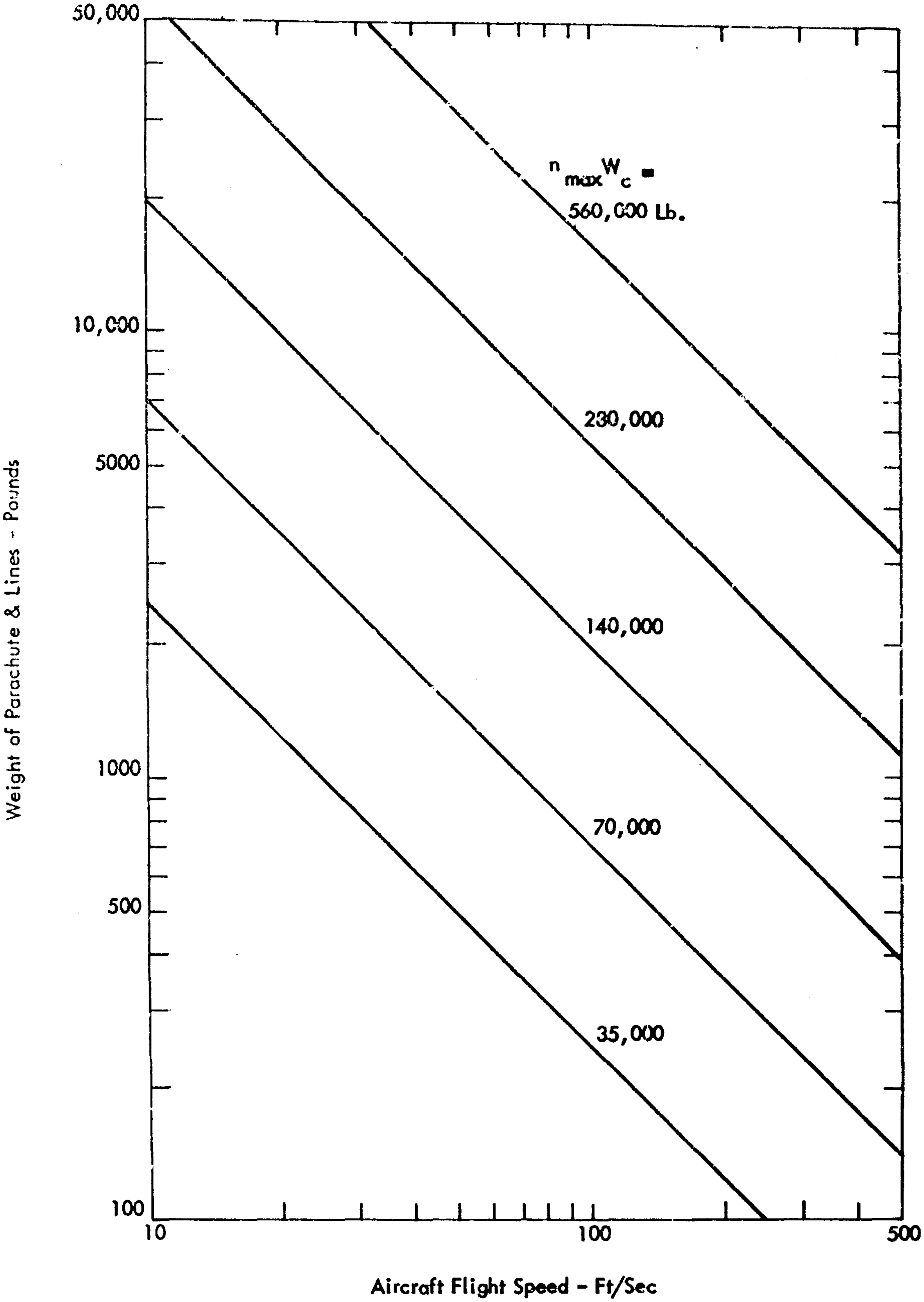


Figure 10 - Generalized Parachute Weights

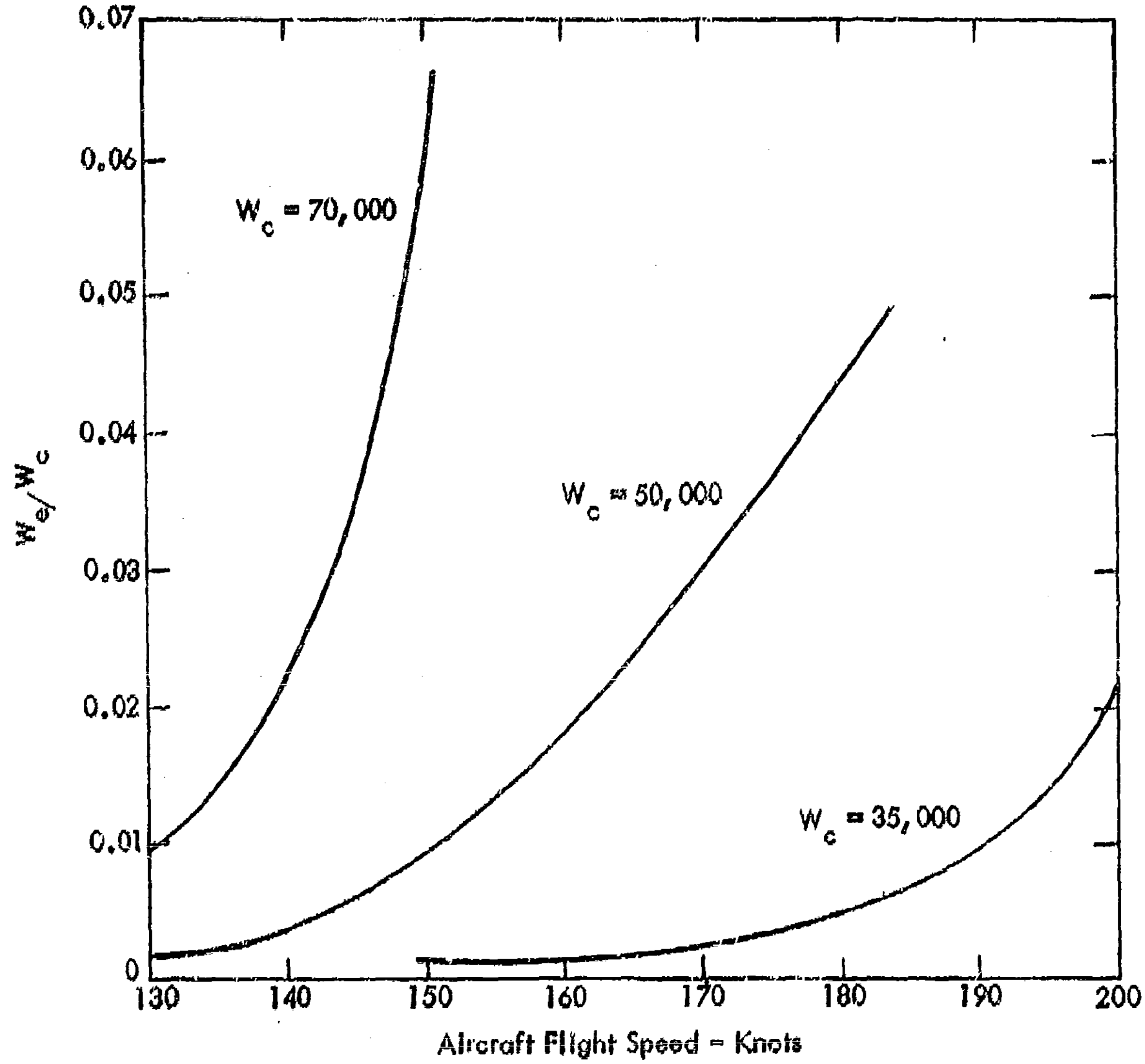


Figure 11 - Extraction Phase Weight Ratios for Parachutes

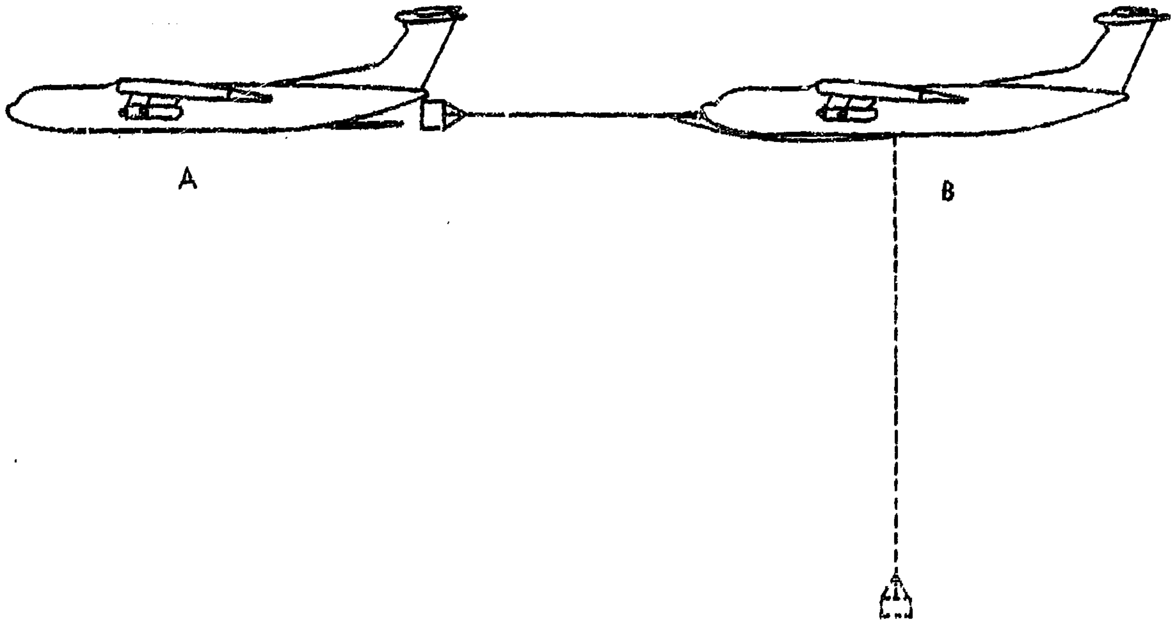


Figure 12 - Extraction Aircraft Concept

In operation, Airplane A carries the cargo to the drop zone. During the approach to the drop zone, Airplane A extends a drogue connected to the cargo. A probe on the nose of Airplane B connected to a line makes contact with the drogue, connects to it, and detaches from the nose to permit pivoting below the center-of-gravity of Airplane B. At the appropriate time, Airplane A accelerates and Airplane B decelerates, extracting the cargo from Airplane A at the required rate. Under the influence of gravity, the cargo drops earthward, swinging as a pendulum pivoted at Airplane B. With the proper choice of altitude, airspeed, and line length, it is theoretically possible to deliver the cargo to the ground at zero velocity.

Results and Conclusions - For the delivery of a 70,000-pound cargo, the delivery airplane must have the capability to support a load greater than 210,000 pounds. The maximum extraction load factor attainable with this concept is on the order of 0.5. Thus, this concept cannot be employed when the C-141 is to be used as either the cargo or the delivery aircraft. For these reasons, in addition to major aircraft modifications required, it is concluded that such a concept is not compatible with aerial delivery operations.

Analysis - Neglecting aerodynamic drag on the cargo and the weight of the supporting line, the tension in the line is given by

$$T = 3\, W_c \sin \theta \tag{6}$$

where θ is the angle between the line and the aircraft flight path. At $\sin \theta = 1$, when the cargo reaches the ground, the tension is equal to three times the cargo weight. For a 70,000-pound cargo, the tension is 210,000 pounds. This tension requires a 1.5-inch diameter high strength cable and an aircraft with a capacity similar to that of the C-5A. The load carrying capacity of the C-141 is inadequate for this operation.

It is estimated that the maximum extraction load factor attainable due to the relative accelerations of the two aircraft is approximately 0.5. Since a minimum load factor of 1.2 is required for the extraction of a 70,000-pound payload from the C-141, this concept does not permit use of that aircraft for the cargo aircraft.

Thus, the extraction aircraft concept requires the use of two aircraft of the C-5A class for the extraction and delivery of a single cargo package in the 35,000 pounds to 70,000 pounds weight range. Both aircraft would require modification to accommodate high concentrated loading. This concept is not considered to be suitable for use in aerial delivery operations involving drop cargo weights in the range covered by this study.

Descent and Recovery Phases

The descent phase of aerial delivery includes all events which occur from the end of the extraction phase until such time as devices are activated for the express purpose of reducing the cargo velocity to a specified ground impact value. The recovery phase comprises all events associated with reduction of the cargo velocity from the descent value to the specified impact value. This phase terminates upon ground contact of the cargo or the shock-absorbing devices provided for the cargo. The recovery phase includes ground contact of sensing devices which are used to activate preimpact velocity-reducing systems.

Characteristics of systems suitable for use in the descent and recovery phases are generally similar and may be identical under some conditions. Initiation of the recovery phase is precisely defined only in aerial delivery systems utilizing more than one decelerating stage or system during the cargo descent. In general, if a distinct recovery phase is included in the operation of an aerial delivery system, the recovery subsystem is designed to decelerate the cargo at a high rate immediately before ground impact.

The basic requirement of systems utilized during the descent and recovery phases is the generation of an impulse increment of sufficient magnitude to decelerate the cargo to an acceptable impact velocity. The magnitude of the total impulse required is a function of the cargo weight, aircraft flight speed and altitude, characteristics of the extraction system, and the type of trajectory desired for the cargo. The rate at which the impulse is imparted to the cargo varies appreciably among systems, but must be applied in a manner which satisfied cargo impact velocity requirements.

Optimum descent and recovery systems will in general possess features which tend to minimize the following quantities:

- o System weight
- o System volume
- o Required deployment altitude
- o Drop area size requirement
- o Wind sensitivity
- o Sensitivity to variations in initial velocity for both the descent and the recovery phases

The performance of any descent control device is basically determined by the following:

- Cargo weight
- Cargo velocity upon initial activation of the descent control device
- Terminal, or steady state descent velocity of the drop cargo in the descent phase
- Altitude change during the descent phase

In accordance with the definition of operational phases, the initial conditions for the descent phase are identical with the conditions prevailing upon cargo exit from the airplane. These conditions are determined by the airplane flight speed and the acceleration experience of the cargo during the extraction phase.

For airplanes requiring specific relations between drop cargo weight and extraction load factor in order to avoid exceeding structural limitations in the ensuing flight load factor excursion, such as the C-141 airplane with drop cargo weights in the 35,000 - 70,000 pounds range, this leads to a quite definite set of relations between initial cargo descent velocity, airplane speed at cargo extraction and drop cargo weight. This relation can be written

$$v_d = v_a - \Delta v_e = f(W_c) \tag{7}$$

The relation is illustrated in Figure 13, which was prepared using data from Figure 8. The range of possible initial velocities depends strongly on the cargo weight and decreases rapidly with increasing cargo weight. These data serve in part to limit the velocity increments associated with the descent phase. For the purpose of this investigation, the terminal descent velocity was varied parametrically in order to define a range of possible velocity changes during the descent phase.

The descent altitude changes were also varied parametrically. For promising descent control system concepts, the weight efficiency was evaluated in terms of the ratio W_d/W_c as a function of the descent terminal velocity v_r, cargo exit velocity v_d, and cargo weight W_c, and also as a function of descent altitude change Δh, terminal or steady state descent velocity v_r, and cargo weight W_c.

Recovery phase performance requirements are identified by the following:

- Cargo weight
- Initial velocity at recovery
- Final recovery velocity
- Altitude loss during recovery.

For the purpose of evaluating system weight efficiency data for the recovery phase, a fixed value of 25 feet/second was selected for the final recovery velocity, while the initial recovery velocity was varied parametrically along with the cargo weight.

Parachute

General - Aerial delivery systems capable of satisfactorily accommodating cargo weights up to 35,000 pounds are currently operational. These systems utilize various parachute configurations for cargo deceleration in the descent and recovery phases. A singular advantage of parachutes is that they are amenable to clustering as required for the delivery of heavy cargoes.

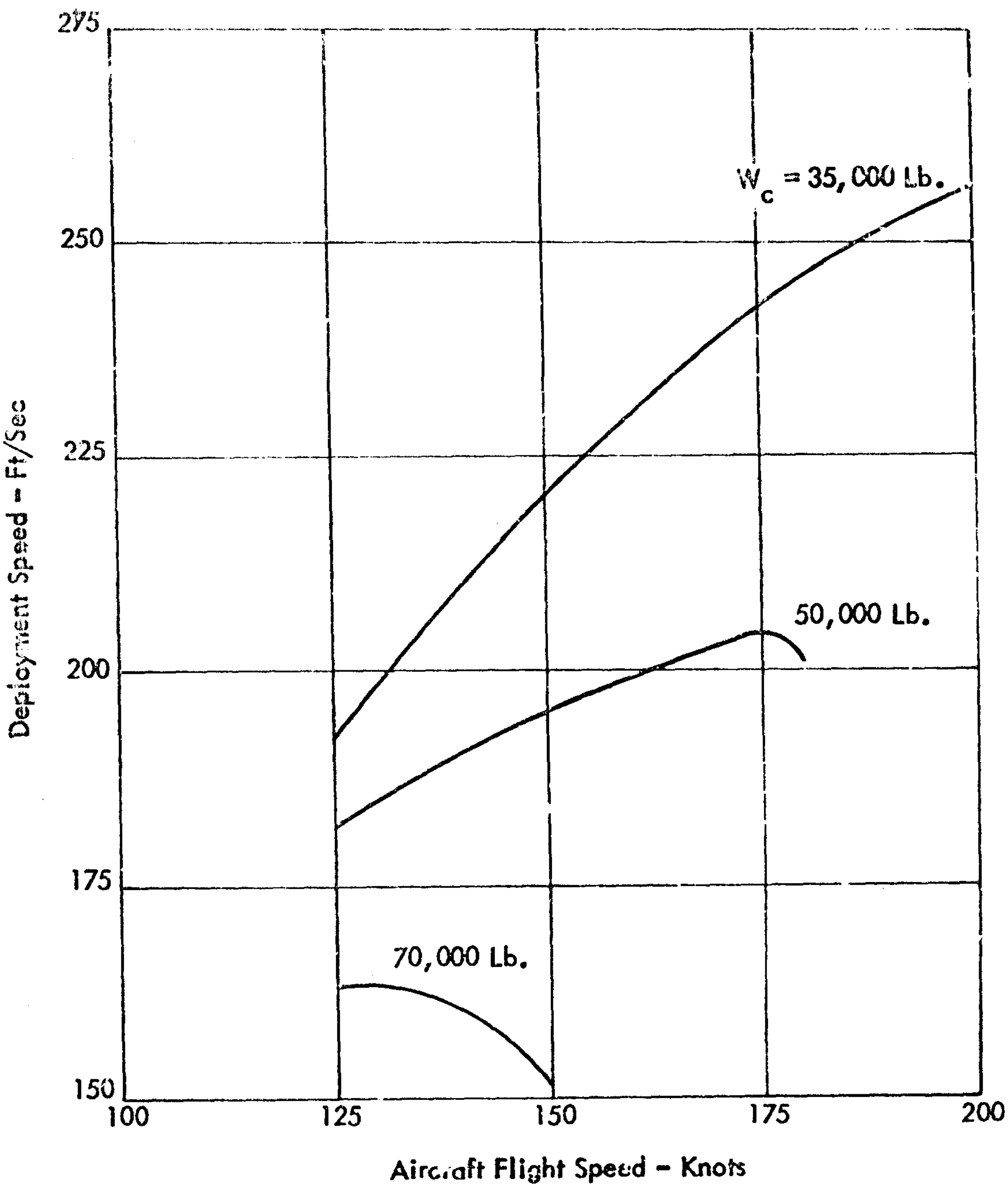


Figure 13 - Descent Control Device Deployment Speed versus Aircraft Flight Speed - C-141 Aircraft

Results and Conclusions - Using parachutes for cargo deceleration in both the descent and recovery phases, a parachute system weight of 3300 pounds is required for the delivery of a 70,000-pound cargo at an impact velocity of 25 feet/second. Although clustering of parachutes is required for heavy cargo weights, parachute systems are compatible with the aerial delivery of cargoes in the 35,000 to 70,000-pound range.

The finite parachute inflation time, which increases with increasing parachute size, and the attendant altitude loss during the inflation period limits the use of parachutes for final recovery of cargoes in this weight range to drop altitudes of approximately 1200 feet.

Analysis - It is not possible to obtain an accurate closed-form solution to calculate the weight of parachute deceleration systems. Therefore, a computer program was developed to calculate the weight of a single parachute, or a cluster of parachutes, given the payload weight, deployment speed and altitude, and terminal speed. The program also computes the parachute filling time and altitude loss during inflation.

Parachute weight ultimately depends on the amount of cloth and cord used, and the type of cloth, which is a function of the maximum stress that the material must withstand. The maximum stress is usually expressed in terms of opening shock factor, which is the maximum load factor during canopy inflation. This shock factor is found using the method presented in Reference 4, in which the assumption is made that during inflation the drag area of the canopy increases linearly with respect to time.

The following equations describe the instantaneous velocity of the cargo-parachute combination and the final filled volume of the parachute for a vertical drop situation:

$$\frac{dv}{dT} = -\frac{22.5\,v}{A' + 22.5T} - \frac{B' \cdot t_f \cdot T \cdot v^2}{A' + 22.5T} + \frac{A' \cdot g \cdot t_f}{A' + 22.5T} \tag{8}$$

$$V = \frac{d_o^2}{\pi}\, t_f \int_0^1 \left\{\left[(1 - T)\,(T^{4/3}) - 2\,cT\,(1 - T)\right] \cdot v \right\} \cdot dT \tag{9}$$

where

$$A' = 10^5\, W_c / \sigma\, g d_o^3$$

$$B' = 120\,(C_D S)_{max} / d_o^3$$

c = effective cloth porosity

$T = t/t_f$

In the solution of these equations, it is necessary to assume a value of t_f, numerically integrate the first equation to obtain v, and compare the value of v calculated from the second equation with the known canopy volume. This procedure is repeated until consistent results are obtained. The maximum load factor, (dv/dT) max, and the parachute filling time, t_f, may then be computed.

An empirical method for determining the strength requirements of a canopy is presented in Reference 4. The basicassumption is that the number of gores equals the integral part of $d_o \div 3.0$. This method has been extended with the further assumption that suspension line length equals d_o. By using an empirical correlation of the strength of nylon materials currently in use with the corresponding material weight, the following equation was derived to determine the weight of canopy cloth and suspension lines for flat canopy parachute systems:

$$W_d = \left(\frac{6.59 \times 10^{-5}\, d_o^2}{d_o + 3} + 1.83 \times 10^{-5}\, d_o\right) W_c \left[\left(\frac{dv}{dT}\right)_{max} / g t_f - 1\right] \qquad (10)$$

An automatic computer program for numerical solution of these equations was developed, and the relations were explored parametrically. This exploration covered weights data along with recovery altitude losses during inflation from initial deployment as well as from a 2% reefed condition.

The inflation altitude losses were of the order of 440 feet for inflation from initial deployment, and 425 - 430 feet for inflation from the initially reefed condition. The total minimum altitude loss during descent and recovery was obtained by adding to the inflation altitude loss main canopy deployment altitude loss of $\sim$ 750 feet. This increment allows for canopy extraction as well as for an alignment of cargo and canopy along a 55° - 60° inclination to the horizon.

Figure 14 describes the parachute system weight ratio as a function of terminal velocity with cargo weight as a parameter. As indicated by this figure, parachute system weights are of acceptable magnitude for the ranges of cargo weights and terminal velocities under consideration. For example, the parachute system weight is about 3300 pounds for the delivery of a 70,000-pound cargo at a terminal velocity of 25 feet/second.

L/D Parachute

General - The L/D parachute is a self-inflating, gliding, and steerable parachute designed to develop high aerodynamic lift during gliding descent. To improve the aerodynamic characteristics, the canopy is usually constructed of low porosity material. Flaps or canopy deflections can be utilized for glide and turn control. The general configuration of an L/D parachute is shown in Figure 15.

Results and Conclusions - Because L/D parachutes cannot be clustered, the single parachute size becomes extremely large for the delivery of heavy payloads. A canopy diameter of 175 feet is required to deliver a 70,000-pound cargo at an equilibrium descent velocity of 25 feet/second. System weight ratios of L/D parachutes are somewhat higher than those for conventional parachutes for equal descent velocities. Based on these considerations, in addition to the higher complexity of L/D systems, it is concluded that L/D parachutes offer no significant advantage over conventional parachute delivery systems.

Analysis - The essential features of L/D parachute glide performance are illustrated by the velocity diagram shown in Figure 16. The length of the radius vector from the origin of the graph to points on the curve represents the resultant velocity along the flight path, with horizontal and vertical component values given along the abscissa and ordinate axes respectively.

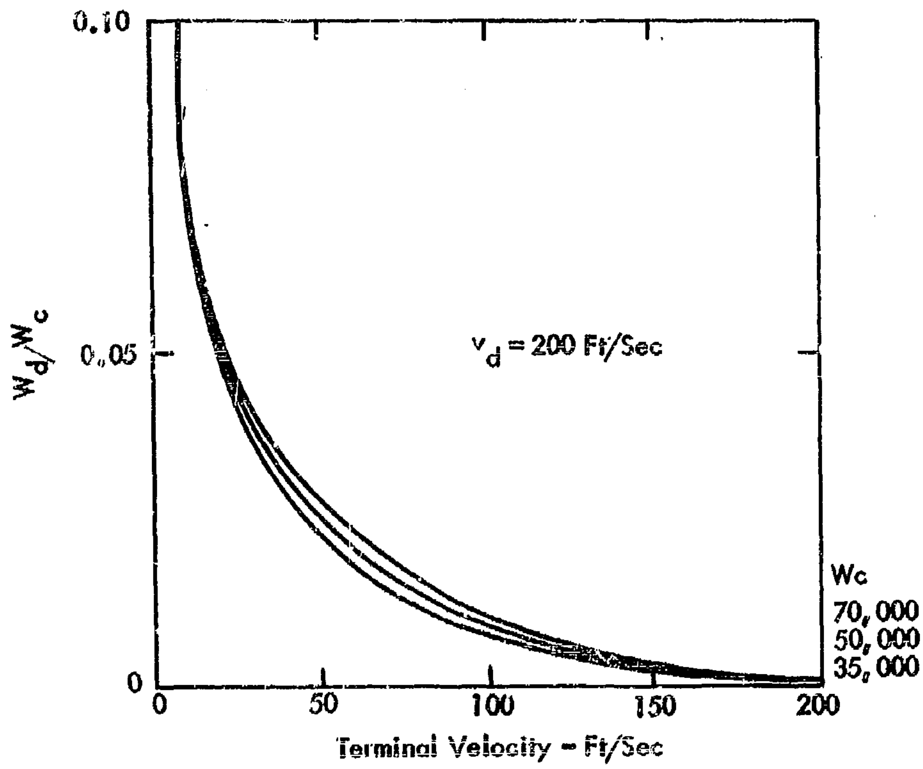


Figure 14 - System Weight Ratio - Parachute

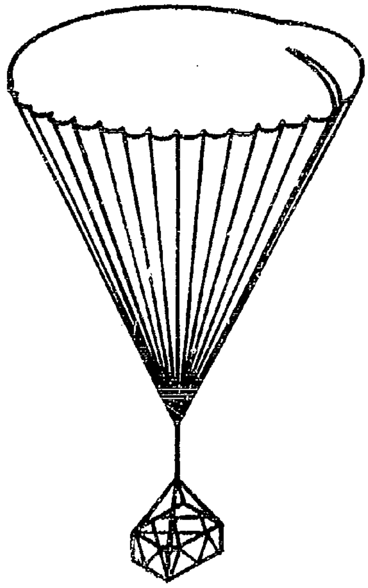


Figure 15 - L/D Parachute Delivery Concept

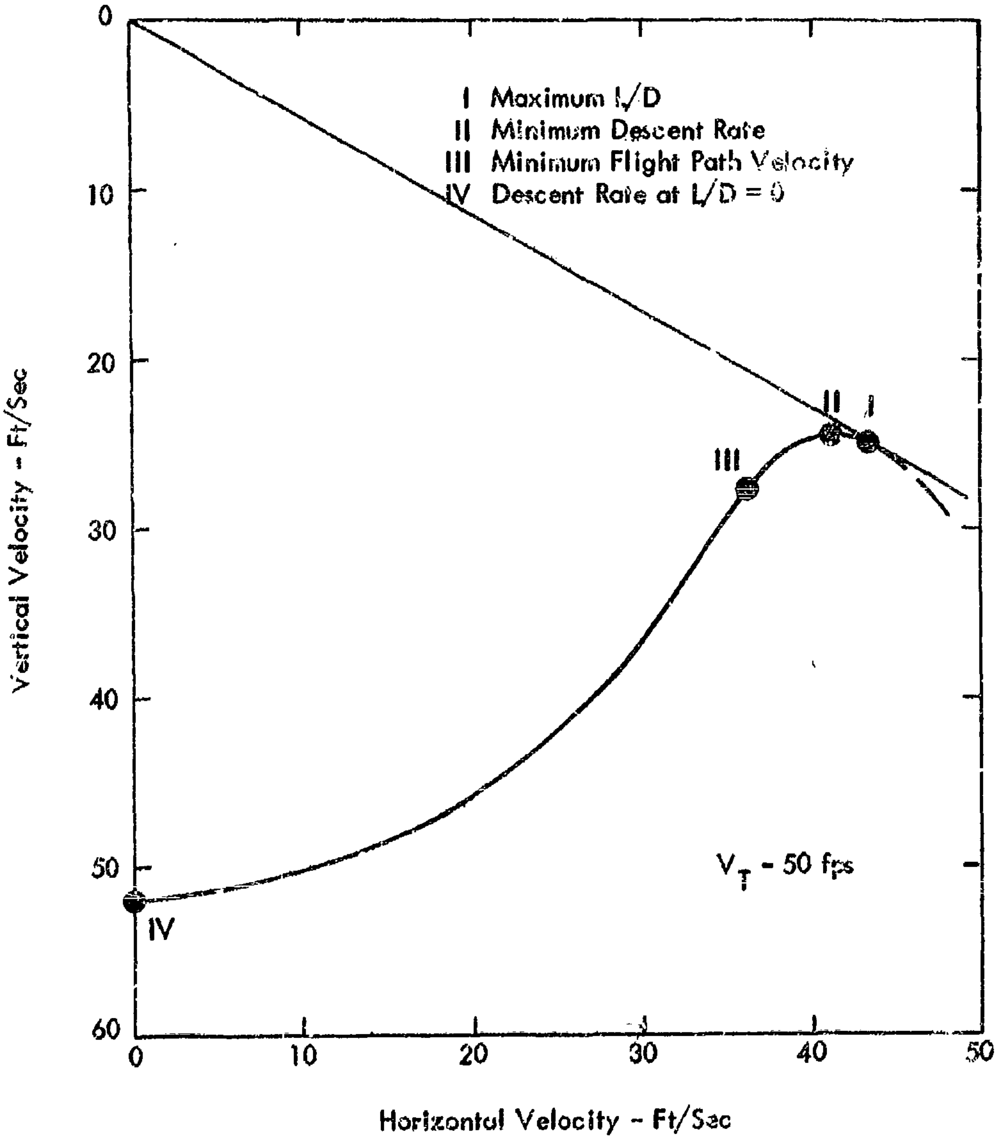


Figure 16 - Steerable Parachute Glide Relations

Four points of major interest have been denoted by Roman numerals on the curve:

- I denotes the flight condition for max L/D
- II denotes the flight condition for minimum descent velocity
- III denotes the condition for minimum flight path velocity ($C_R = (C_L^2 + C_D^2)^{1/2} = C_{R_{max}}$)
- IV denotes, finally, the flight condition for zero horizontal velocity ($C_L/C_D = 0$)

Figure 16 is based on typical values for lift and drag coefficients attained in model tests for the Northrop Ventura "Cloverleaf" type of L/D parachute. The data, as adjusted to a flight path velocity of $\sim$ 50 fps, are shown in Table IV below.

TABLE IV

Aerodynamic Characteristics of L/D Parachute

Condition	C_L	C_D	C_R	L/D
$L/D = (L/D)_{max}$	.85	.5	.985	1.73
$C_L = C_{L_{max}}$	.95	.64	1.15	1.48
L/D = 0	0	.9	.9	0

Tests with L/D parachutes have shown them capable of performing max L/D glides with excellent stability, and also to descend in the L/D = 0 condition with moderate stability.

Utilization of the glide performance capabilities of L/D parachute delivery systems hinges critically on the existence of a steering capability. This capability can be achieved by a turning control system which aligns the glide path with the desired direction of travel. Turning control can be exercised by means of either differential flap adjustments or by differential tip deflections. In addition, means for controlling the glide slope are highly desirable. This type of control can also be arranged, and is achieved by either adjustments of symmetrically arranged flaps or simply by symmetrical canopy deflections.

The weight of L/D parachute delivery systems, exclusive of control gear, depends basically on the forces experienced during the inflation period. These weight relations were explored in the same computer program which was used for evaluation of conventional parachutes, assuming that L/D parachutes generally will be deployed and inflated in the L/D = 0 condition. In accordance with available technical data on the subject, a drag coefficient of 0.9 and a porosity of 0.025 was used throughout this investigation.

The parachutes were sized for 35,000, 50,000 and 70,000 pounds drop cargo weights, and for descent velocities at $L/D = (L/D)_{max}$ ranging from 10 to 75 fps. In all cases a velocity at deployment of 200 fps was assumed.

Results of these investigations are shown in Figure 17.

Comparison of Figure 17 with the corresponding data for conventional parachutes given in Figure 14 indicates that weight ratios are generally somewhat higher for L/D parachutes than

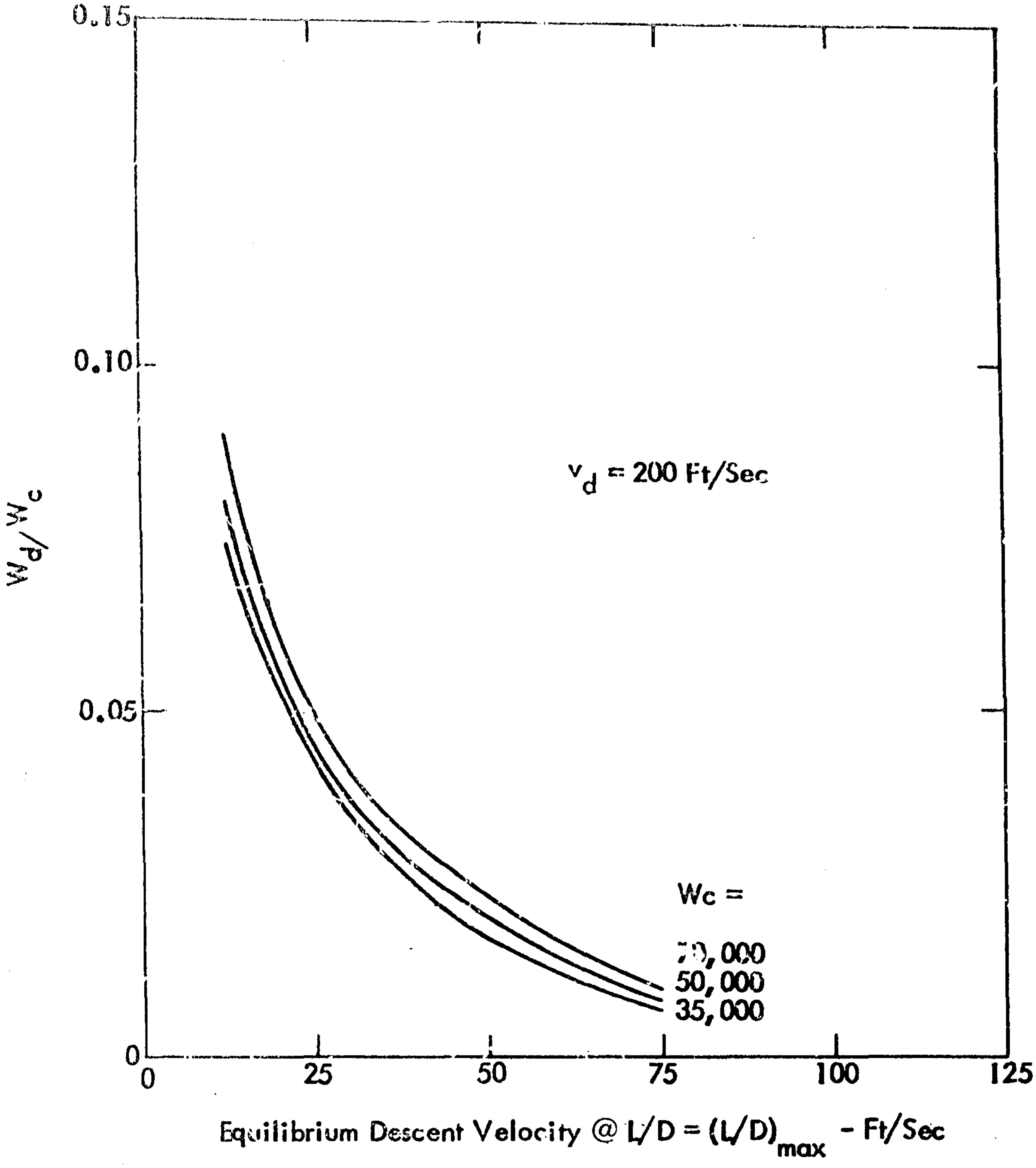


Figure 17 - System Weight Ratio - L/D Parachute

for conventional configurations. For the recovery of a 70,000-pound payload at a terminal vertical velocity of 25 feet/second, the system weight ratio for a conventional parachute is 0.047. For an L/D device the weight ratio is 0.05 under maximum lift conditions, with a horizontal velocity component of 41 feet/second.

Figure 18 shows the diameter of L/D parachutes as a function of terminal vertical velocity with cargo weight as a parameter. Diameters up to 175 feet are required for recovery of a 70,000-pound cargo at an equilibrium descent velocity of 25 feet/second under $L/D = (L/D)_{max}$ conditions. Due to aerodynamic considerations and control problems, L/D parachutes cannot be clustered for the delivery of heavy payloads. Therefore, the size of individual parachutes becomes quite large for heavy cargo weights. In addition, a larger inventory of different size L/D parachutes is required to accommodate the varying payload weights, whereas a smaller number of standard conventional parachutes can be clustered for a given payload.

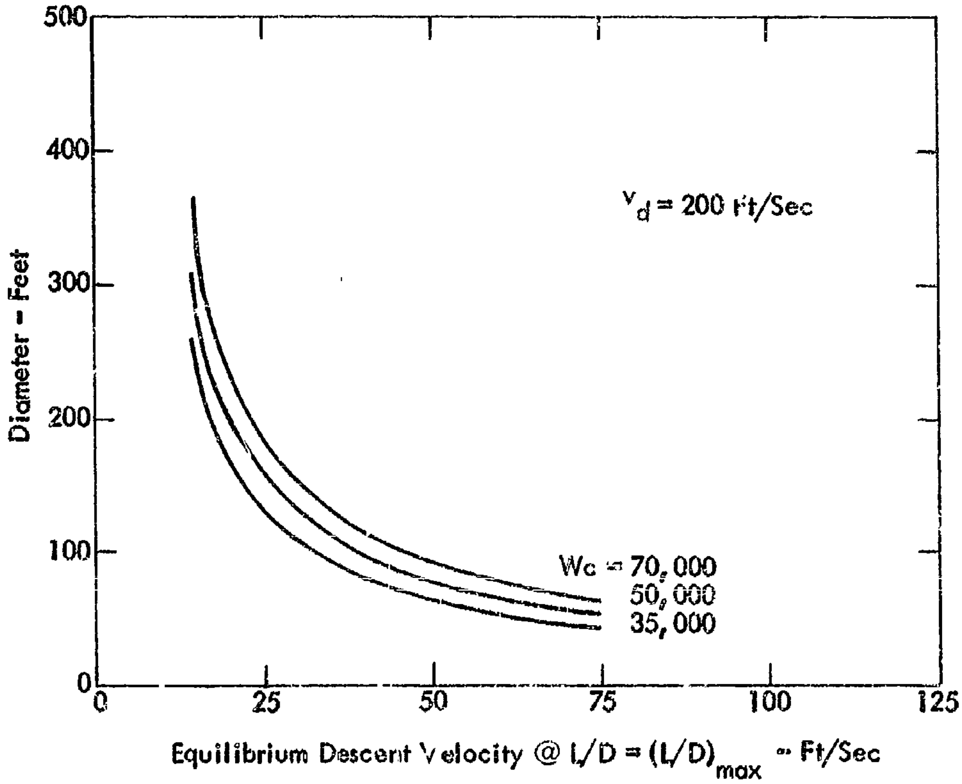


Figure 18 - L/D Parachute Diameter versus Equilibrium Descent Velocity

The glide capabilities inherent in L/D parachute systems appear to offer attractive operational advantages such as offset delivery, guide-in descent, reducing impact point scatter, and pre-impact terminal flight path control, reducing the probability of post-impact cargo toppling. These advantages can only be realized, however, by augmenting the system with quite sophisticated and highly reliable guidance and control systems. For high altitude delivery, the advantages are further considerably tempered by the variability of the wind structure at the different levels in the atmosphere which generally prevails in high wind conditions. The same arguments tend to reduce the value of the pre-impact terminal flight path control feature, unless the control system response times can be made sufficiently short.

Finally, the extended glide times which are associated with the limitations on permissible vertical impact velocity tend to increase the exposure of the dropcargo to enemy action, by comparison with systems utilizing a high speed descent mode for high level delivery.

As a result of the large sizes required along with considerations of probable complexity of an operational system, including the need for large variation in stock sizes in inventory, it is concluded that L/D parachutes offer no significant advantage over conventional parachutes for the majority of aerial delivery operations.

Ballute

General - The inflatable-balloon decelerator or ballute is a blunt body aerodynamic decelerator fabricated from material of very low porosity. Ballutes are deployed behind the cargo to be decelerated and inflated by ram air or pressure bottles. Figure 19 illustrates the configuration of a spherical ballute. Other rotational symmetric shapes may also be used, including cones with the apex pointing upstream.

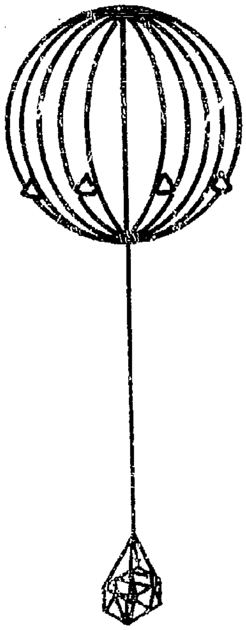


Figure 19 - Ballute Delivery Concept

Results and Conclusions - The ballute is essentially a decelerating device suitable for deployment at and deceleration from high supersonic speeds. At speeds in the range necessary for the aerial delivery of frangible cargoes, the drag characteristics of ballutes are inferior to common types of parachutes. Weights of ballute descent systems are greater than those of parachutes by factors ranging up to 2.63 and cannot be used effectively at the velocities required in the recovery phase. Ballutes do not represent efficient decelerating devices for the aerial delivery of heavy cargo weights. They do have a potential area of application as cargo extraction systems for aerial delivery.

Analysis - The feasibility of ballutes, including both ram-air-inflated and pressure-gas-inflated of all shapes, for heavy cargo delivery systems was examined from two different aspects. The first aspect concerned the performance as a braking device permitting steady state descent at an equilibrium speed suitable for ground impact. The second aspect concerned the performance as a decelerating device being deployed and active in the speed regime between aircraft flight speed and permissible ground impact velocity.

For the steady state descent performance, the drag coefficient affords the basic figure of merit. Extrapolation of drag data given in Reference 4 indicates values for the drag coefficient (based on projected area) of the order of 0.5 for the speed regime of interest in this connection ($M < .05$). By comparison, a flat circular canopy conventional parachute has a drag coefficient $C_{D_o} = 0.75$ (based on constructed area), or a $C_{D_p} \cong .75/(.7)^2 = 1.53$ based on the fully inflated projected area.

In order to achieve a descent performance for the ballute which would be comparable with that of conventional parachutes, the projected ballute diameter would have to be

$$D_{pb} = (1.53/(.5)^{1/2})D_{pp} = 1.75\,D_{pp}$$

where D_{pp} denotes the projected diameter of the fully inflated conventional parachute.

The cloth area required for the ballute would be approximately $(2)\cdot(1.75)^2 \cong 6$ times that required for the conventional parachute.

The performance characteristics of the ballute as a decelerating device operating in a regime of varying airspeeds bracketed by the deployment speed $\approx$ aircraft flight speed and the equilibrium descent speed, is a function of several factors.

Principal of these are:

- o The deceleration distance
- o The peak value of the deceleration load factor
- o The shape of the time history curve for the deceleration load factor
- o The system weight.

The deceleration distance is essentially a function of the shape of the time history curve for the deceleration load factor.

When this curve is known, the deceleration distance can be evaluated from the expression

$$s_d = v_o \cdot t + 1/2\,gt^2 - \int_{t=o}^{t=t} dt \int_{t=o}^{t=t} dn(t)dt \qquad (11)$$

for a vertical deceleration, where

s_d = deceleration distance - ft

v_o = initial velocity - ft/sec

g = gravitational acceleration - ft/sec^2

$n(t)$ = deceleration (drag) load factor at time t

t = time - seconds

It would appear that the ballute possesses greater potential for controlled inflation and drag modulation than the conventional parachute, particularly when forced inflation by stored gas rather than ram-air-inflation is used. For the purpose of analysis, it is assumed that ballutes can be clustered as conventional parachutes without serious deterioration of the aggregate drag. For a 70,000-pound cargo, a cluster of eight ballutes, each with a projected diameter of 173 feet will yield the required equilibrium descent speed of 25 feet/second.

The volume of each ballute will be $\sim$ 2,700,000 ft^3, assuming an approximate spherical shape. (The volume does not change significantly by changing to a conical-hemispherical shape.) Assuming forced inflation by air stored in 3.8ft^3 fiberglass gas bottles under 2000 psi, the number of bottles required for inflation of one ballute is $2.7 \cdot 10^6/3.8 \cdot (2000/14.7)$ = 5220 bottles. If inflation is carried out at higher altitudes, the number of required bottles is reduced, but hardly below a number approaching 1500 per ballute. At a weight per bottle of 20 pounds, the weight of the complete system will exceed by a factor of about 3.5 the weight of the payload, based upon the lower extimated number of bottles.

With ram-air inflation, these weight penalties need not be incurred. On the other hand, the potential for a well-modulated inflation is also greatly reduced, leading either to drag load factor time-histories which are not greatly different from parachutes, or to generally lower drag load factors and considerably extended deceleration distances.

If peak deceleration load factors of the same order of magnitude as occur for conventional parachutes are assumed, the critical hoop tension stress in the ballute canopy cloth will be of the order $\left(\frac{C_{D_p \text{ Ballute}}}{C_{D_p \text{ Parachute}}}\right)^{1/2}$ times that for the parachute. This amounts to a reduction factor of $\left(\frac{.5}{1.53}\right)^{1/2}$ = 0.572 per unit cloth area.

This reduction is, however, more than compensated by the required increase in cloth area for the ballute, leading to a ballute canopy weight of about (.572) (6) = 3.4 times that for a comparable flat canopy parachute system. This corresponds to a total system weight factor of 2.6 - 2.7. This does not include allowance for possible requirements for less permeable cloth material for ballute canopy construction.

Since the ballute does not compare favorably with parachute descent systems on the basis of weight and does not appear to offer any obvious compensatory advantages, it is concluded that such systems are not employed optimally in aerial delivery operations for the cargo weight ranges encompassed by this study. One potential application would be as extraction device, where modulated ram-air-inflation at flight speed should offer no technical difficulty, and where precise timing and control of the inflation process would be to great advantage.

Paracone

General - The paracone is an aerodynamic drag device in the form of an open cone of gas-inflated material which envelops the cargo during descent. Stability of the paracone is achieved by obtaining the proper relationship between the center of gravity and the center of pressure. When the paracone impacts on the ground, the forces are absorbed by compression of gases within the point of the cone, through a mechanism similar to that used by air-bag decelerators. The paracone configuration is illustrated in Figure 20, and described in detail in Reference 6.

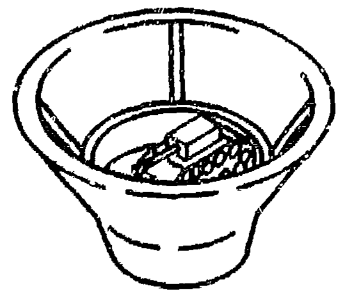


Figure 20 - Paracone Delivery Concept

Results and Conclusions - For a given terminal velocity, the projected area and corresponding weight required for paracones is greater than that required for parachutes. Since paracones cannot be used in clusters, the size of paracones for delivery of heavy cargo weights at low terminal velocities presents severe operational problems. Paracones are not suitable for use in the aerial delivery of cargo weights in the 35,000 to 70,000-pound range.

Analysis - Drag characteristics of paracones are inferior to those of parachute decelerating devices. The drag coefficient of an inverted cone is approximately 0.4, while representative parachutes have drag coefficients of 0.75. Therefore, for a given cargo weight and terminal velocity, the projected area of a paracone is almost two times greater than the nominal area of a parachute.

Figure 21 illustrates paracone diameter as a function of terminal velocity with cargo weight as a parameter. Required paracone diameters are somewhat greater than those described in this figure, due to the omission of paracone weight in computations. However, even this conservative approach indicates that paracone size becomes excessive for acceptable impact velocities. For example, a paracone diameter of almost 600 feet is required for the delivery of a 70,000-pound cargo at 25 feet/second. The fact that paracones cannot be clustered results in excessive dimensions for heavy cargo weights at reasonable impact velocities.

Paracones are inherently less efficient than parachutes on a weight basis due to their physical configuration. While a parachute canopy is subjected to tensile loading which maintains the proper canopy shape, a paracone is subjected to bending stresses which tend to deform the configuration and reduce the drag area. Therefore, provision for adequate rigidity in the paracone is necessary, with an attendant weight penalty. Since paracones are deployed by force inflation, such systems must also incorporate gas stored under high pressure. This results in further weight ratio degradation due to the weight of the inflation system and the requirement for gas-tight material for paracone construction.

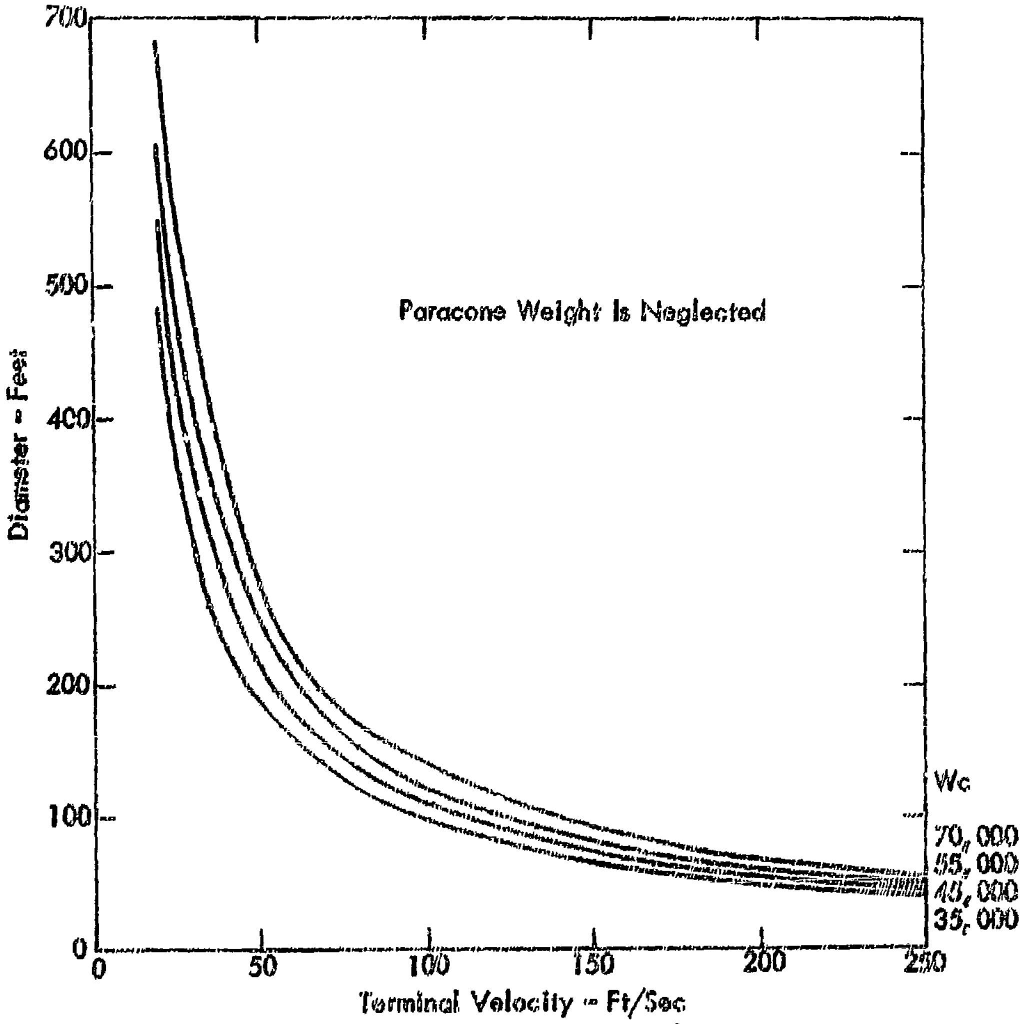


Figure 21 - Paracone Diameter versus Terminal Velocity

Paracones do not appear to offer any advantages over more conventional systems for the aerial delivery of heavy cargo weights.

Parawing

General – The tethered parawing aerial delivery concept is illustrated in Figure 22. In operation, the parawing is deployed behind the aircraft and allowed to achieve a trail distance, under constant tow line load, equal to slightly more than the aircraft height above the drop zone. As this trail distance is achieved, the cargo, connected to the parawing by a second or pendulum line, is ejected from the aircraft and drops on a modified trajectory as dictated by parawing lift and forward speed. For the drop speeds of interest, in order to take advantage of the parawing lift force to reduce vertical velocity at impact, drop heights on the order of 1,000 feet are required.

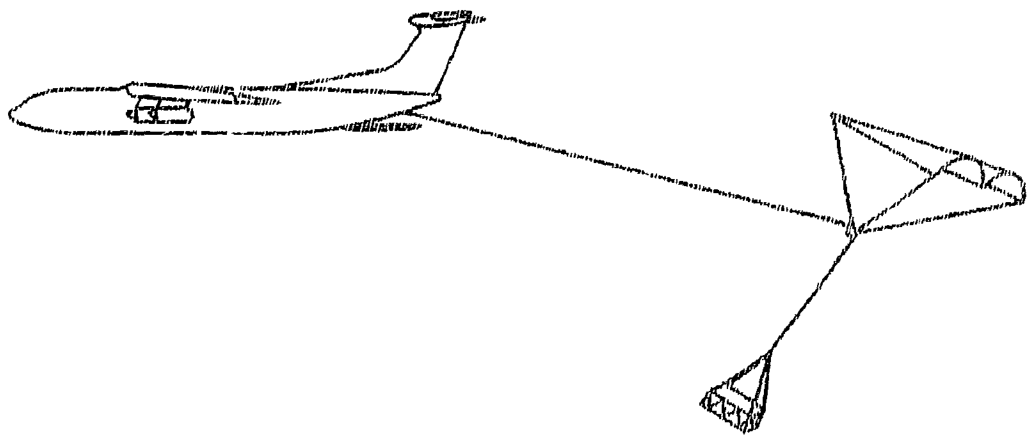


Figure 22 – Parawing Delivery Concept

Results and Conclusions – Keel length requirements for parawings range up to 80 feet for the delivery of a 70,000-pound cargo. The deployment of parawings of this size from an aircraft presents a difficult operational problem.

Parawings within the current state of the art cannot be towed in an unloaded condition at speeds greater than 87 knots, and are thus unsuitable for use with modern cargo aircraft.

Analysis – A parawing configuration having equal-length leading edges and keel was chosen for analysis. This configuration, with a 45-degree flat planform sweep and a 50-degree in-flight sweep, gives maximum area for a given keel length. For this parawing configuration, keel length requirements range from 56 feet for a 35,000-pound cargo weight up to 80 feet for a 70,000-pound cargo weight.

The deployment of a parawing of this size from the towing aircraft cargo compartment requires that the basic wing structure be collapsible and either folding or telescoping for convient stowage in the aircraft cargo compartment. Gradual deployment is required to maintain attitude control, since any tendency for the wing to stall can result in a sudden loss of stability and consequent severe oscillatory motions. The development of techniques to permit deployment of the wing to full flight planform while avoiding a kiting behavior is a major problem.

Parawings possess a limited range of useable lift coefficients. References 7 through 12 indicate that parawings are subject to fabric flutter and buffeting with subsequent loss of stability, below an angle of attack of about 20 degrees. For parawings of the type under consideration, the lift coefficient at this angle of attack is about 0.6. The maximum lift coefficient is about 1.2. This corresponds to a ratio between maximum and minimum speeds at 1.0g flight load factor of $(1.2/0.6)^{1/2} = 1.41$. The maximum L/D is between 5.0 and 6.0 and occurs at the minimum useable lift coefficient of 0.6.

An assessment was made of the maximum practical wing loading for a parawing capable of being deployed from a stored condition in the cargo aircraft. For the purpose of analysis, the wing booms were assumed to be rigidized by inflation. Each boom was considered to have two load suspension points located such as to minimize the bending loads. The diameter/length ratio for the booms were assumed as .05. With these assumptions, the maximum wing surface loading $w_{s_{max}}$ could be expressed as

$$w_{s_{max}} = 12100\, P_i \left(\frac{d_b}{l_k}\right)^3 \tag{12}$$

where

$w_{s_{max}}$ = maximum parawing surface loading (including gust and/or maneuvering load factor), pounds/ft^2

P_i = boom inflation pressure, pounds/in^2

d_b/l_k = ratio of boom diameter/boom length

The maximum inflation pressure P_i depends on the allowable hoop tension stress in and the material thickness of the boom. A good grade of nylon cloth for parachutes possesses breaking stress of 12,000 psi in accordance with data from Reference 4. In consideration of the requirement for stowage folding, boom material thickness would probably be limited to about 0.12-0.15 in.

Assuming a safety factor on boom pressurization of 2.0, the permissible inflation pressure becomes

$$P_i = \frac{12000}{2.0} \cdot \frac{2t}{d_b} = \frac{12000}{.05 \cdot l_k} \cdot t$$

For the keel length of 80 feet one obtains

$$P_i = 30 - 37.5 \text{ pounds/in}^2$$

and

$$w_{s_{max}} = 45 - 56 \text{ pounds/ft}^2$$

Considering that the maximum wing surface loading must include ultimate safety factor along with maneuver and/or gust load factor allowance, a design value for the wing loading is obtained as

$$w_s = \frac{w_{s_{max}}}{1u \cdot n} \tag{13}$$

$$w_s = \frac{45 - 56}{1.5 \cdot 2.5} = 12 - 15 \text{ pounds/ft}^2$$

Using these values in the relation,

$$\frac{L}{S_w} = \frac{1}{2} \rho v^2 C_L \tag{14}$$

the maximum towing speed for parawings is calculated to be about 87 knots. This value is well below the stalling speed of the aircraft under consideration.

The difficulties encountered in deploying a tethered parawing from a cargo aircraft are a direct consequence of not being able to attain stable flight while the parawing is in an unloaded condition. That is, the angle of attack cannot be reduced enough to maintain stable flight. Suppose that g loading can be increased so that stable flight is always maintained; that is, the angle of attack is greater than 20°. Then $C_L = 0.6$ and, if the tow speed is taken as 150 knots, $W/S_w = 45$ lb/ft^2. This value is a threefold increase in the state of the art in wing loading.

These results indicate that the use of parawings tethered to modern cargo aircraft is not a satisfactory method for the aerial delivery of heavy cargo weights.

Fixed Wing Gliders

General - Fixed rigid wing gliders were utilized for the delivery of cargo and personnel during World War II. Typical cargo gliders were the Horsa and the Hamilcar which had payload capabilities of 6,900 and 16,000 pounds, respectively.

Results and Conclusions - Typical cargo gliders exhibit stall speeds of about 40 knots, lift-to-drag ratios of about 10, and payload-to-gross-weight ratios ranging from 0.20 to 0.47. Weights of gliders capable of delivering payloads in the range under consideration range from 75,000 pounds to 150,000 pounds. Such vehicles are too expensive to be considered expendable and therefore have landing and retrieval requirements, in terms of both size and surface characteristics, similar to those of powered aircraft of the same cargo class. There appears to be no advantage in using fixed rigid wing gliders for delivery of heavy payloads.

Analysis - The ratio of payload weight to gross weight for fixed wing gliders previously used for the delivery of cargo and personnel ranges from 0.20 to 0.47. For the most favorable ratio of 0.47, gross weights of gliders suitable for the delivery of payloads between 35,000 and 70,000 pounds range from 75,000 pounds to 150,000 pounds.

Clear area requirements for landing and braking fixed wing gliders are similar to those for powered cargo aircraft of equal capacity. Similar requirements exist for retrieval of the glider since such an aircraft is not expendable and is not amenable to disassembly for recovery by surface transport.

Since a glider requires a trained crew, is dependent upon a powered aircraft for delivery and retrieval, and has less versatility than a powered aircraft, there is no operational advantage in utilizing a glider in preference to a powered aircraft for the delivery of heavy payloads.

Windmilling Rotor

General - A windmilling rotor, illustrated in Figure 23, is a multibladed helicopter-type rotor which provides aerodynamic retardation in autorotative descent. Previously utilized for recovery of relatively small payloads, windmilling rotors provide features and capabilities for high speed and high "g" deployment, initial retardation and stabilization, drag force modulation, usable L/D glide, maneuverability during descent, and terminal flare for low impact velocities.

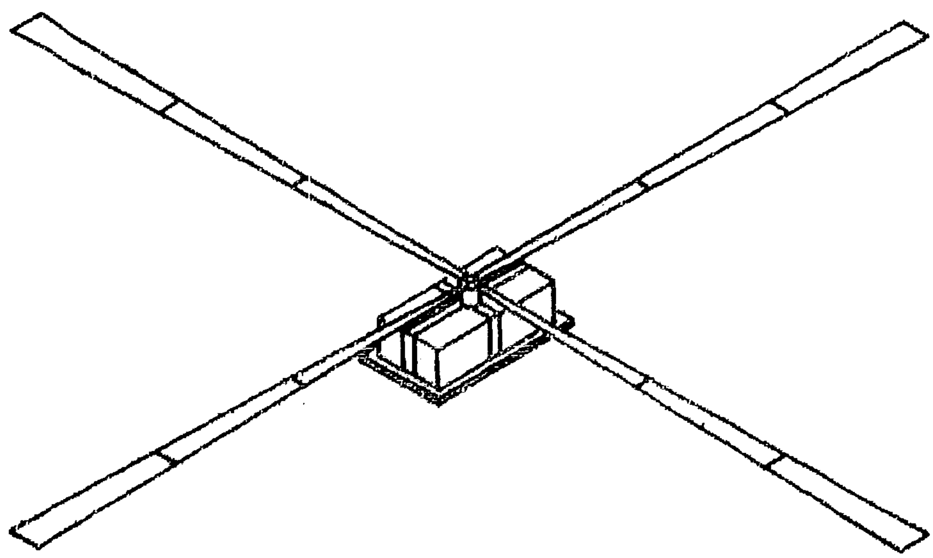


Figure 23 - Windmilling Rotor Delivery Concept

Results and Conclusions - For the recovery of a 70,000-pound cargo weight at an impact velocity of 25 feet/second, a rotor diameter of almost 300 feet is required. Rotors of such dimensions and the associated mechanism required for deployment and control are not compatible with aerial delivery operations involving the aircraft under consideration.

Analysis - In common with most aerodynamic systems, the performance of a windmilling rotor is defined by the following expression:

$$D = \frac{1}{2} \rho v_t^2 \quad C_D S \tag{15}$$

in which C_D is the rotor drag force coefficient and v_t is the terminal velocity of the system.

The system achieves a constant terminal velocity when D is equal to the total system weight. Neglecting the weight of the rotor system, the rotor disk area required for delivery of a cargo weight W_c is given by

$$S = \frac{2 W_c}{\rho v_t^2 C_D} \tag{16}$$

with a diameter of

$$d = \left[\frac{8\, W_c}{\pi \rho v_t^2 C_D} \right]^{1/2} \tag{17}$$

Reference 6 indicates that a drag coefficient of 1.4 is near the maximum attainable for such a device. Therefore, for recovery of payloads in the weight range from 35,000 to 70,000-pounds at a velocity of 25 feet/second, rotor diameters ranging from approximately 210 to 300 feet are required. These values represent ideal minima since the rotor weights were neglected, the most favorable drag coefficient assumed, and the drag loss due to coning of the blades omitted.

The problems inherent in the aerial storage and deployment of such a rotor system are obvious. Since the rotor diameter far exceeds the maximum cargo compartment dimension of aircraft under consideration, rotor blades would be required to fold or telescope. The weight of the rotors and associated deployment mechanism would be prohibitive for rotors having adequate rigidity and an acceptable solidity ratio.

It is concluded that the employment of windmilling rotors for the delivery of cargo weights in the range under consideration is not feasible.

Powered Rotor

General - The powered rotor delivery concept effects cargo deceleration and control of the cargo descent rate through the use of a powered, multibladed helicopter-type rotor.

Results and Conclusions - Recovery of drop cargo in the weight range from 35,000 to 70,000-pounds at an impact velocity of 25 feet/second requires rotor diameters ranging from 75 to 106 feet and power sources ranging from 4500 to more than 9000 horsepower. The weight of these systems varies from approximately 5000 to 10,000 pounds. It is concluded that powered rotor systems are impractical for the delivery of heavy payloads on the basis of rotor size, power, and weight requirements.

Analysis - In powered rotor decelerators, minimum rotor size and power are required for a system which rapidly decelerates the payload to the desired terminal velocity and maintains that velocity throughout the descent. The approach utilized in this analysis assumed a constant descent rate of 25 feet/second, which is the desired terminal velocity. Since more power and a somewhat larger rotor are needed for initial deceleration of the cargo, the requirements specified in this analysis are minimal.

The radius of the rotor required to maintain a constant descent velocity is given by

$$r = \left[\frac{W_c}{\pi L_D} \right]^{1/2} \tag{18}$$

The highest disk loading which can reasonably be assumed for this application is eight. Based on a cargo weight of 70,000 pounds, the rotor diameter required for a constant descent velocity is 106 feet. Since this exceeds the cargo compartment size of the aircraft under consideration, rotor blades would be required to fold or telescope. The rotor blade extension system would present difficult design problems, since the rotor is large and must be extended while acceleration to operational speed.

The horsepower required for a rotor decelerating system is given by

$$P = \frac{C_Q}{C_T} \; T \, v_b / 550 \tag{19}$$

where

$$C_Q = \frac{Q}{\rho \pi r^3 (\omega r)^2} \tag{20}$$

$$C_T = \frac{T}{\rho \pi r^2 (\omega r)^2} \tag{21}$$

For a thrust of 70,000 pounds and a limiting rotor tip velocity of 600 feet/second, $C_T = 9.35 \times 10^{-3}$. A typical variation of C_T with C_Q for a hovering helicopter indicates that the corresponding C_Q is 1.1×10^{-3} (Reference 13).

Based on these values, about 9000 horsepower are required for such a deceleration system. This represents a minimum value, since design power would be determined by the requirement for decelerating the descent speed to the desired level after acquiring operational rotor speed.

The weight of a power source of this magnitude is between 4000 and 5000 pounds. The total system weight including the transmission, rotor blades, support structure, and subsystems is estimated to approach 10,000 pounds. The corresponding weight ratio is 0.14.

As a result of the rotor size, horsepower, and weight requirements, powered rotor systems are not considered to be feasible for use in the aerial delivery of heavy cargo.

Balloon

General - The balloon delivery concept utilizes a helium-filled balloon, which combines aerodynamic drag and buoyancy forces to decelerate the cargo.

Results and Conclusions - For descent at a constant velocity of 100 feet/second, system weight ratios for helium-filled balloons range from 0.45 to 0.55 for cargo weights between 35,000 and 70,000 pounds. Comparable values for parachute systems are between 0.007 and 0.01. Considering contributions of the envelope material required to withstand aerodynamic forces, helium gas and bottles, and component values and accessories, the total system weight is excessive for aerial delivery operations.

Analysis - The weight of a balloon envelope with adequate strength to withstand aerodynamic loading corresponding to a velocity of 200 feet/second at sea level was estimated from Reference 6.* To account for suspension lines, values, and accessories, a factor of 1.5 was assumed, giving

$$W_1 = 8.78 \times 10^{-5} \, d^{3.48} \tag{22}$$

*The Paravulcoon Recovery System by A. J. Oberg and R. A. Pohl.

In common applications, a balloon is filled with helium on the ground and used to lift a small payload. The heavy helium containers, from which the balloon is filled, remain on the ground. In aerial delivery applications, the helium containers must be considered as a part of the system weight. If the helium is stored in fiberglass gas bottles the weight of the bottles is given by

$$W_2 = 3.88 \times 10^{-2} d^3 \text{ , where } d = \text{balloon diameter in ft} \tag{23}$$

and the helium weight is

$$W_3 = 5.84 \times 10^{-3} d^3 \tag{24}$$

For a spherical helium-filled balloon at sea level and 32°F, the lift and drag are given by

$$L = 3.46 \times 10^{-2} d^3 \tag{25}$$

$$D = \frac{1}{8} \rho v_t^2 C_D \pi d^2 \tag{26}$$

Therefore, the total decelerating force is

$$F = 3.46 \times 10^{-2} d^3 + \frac{1}{8} \rho v_t^2 C_D \pi d^2 \tag{27}$$

Figure 24 describes balloon system weight as a function of terminal velocity and cargo weight for a C_D value of 0.5. As indicated by this figure, balloon deceleration systems cannot be employed for achieving terminal velocities required for the recovery of heavy cargo weights. As decelerators during the descent phase, balloons are much less efficient on a weight basis than parachute systems. For descent at a constant velocity of 100 feet/second, weight ratios for a 70,000-pound cargo are 0.55 and 0.01, respectively, for balloon and parachute systems.

Paravulcoon

General - The paravulcoon is a hot-air balloon which utilizes aerodynamic drag in addition to buoyancy forces for deceleration of a payload. The system consists of a balloon envelope with a large opening in the base and a heat generating system. At the time of deployment, the balloon is inflated by ram air. After inflation, heat is added to the air through the opening in the base until the desired gas temperature is achieved. The heating rate can be controlled to obtain the desired descent rate. Paravulcoons are best suited for use when a payload is to be decelerated to near-zero terminal velocity or suspended for a long period of time. The paravulcoon is illustrated in Figure 25.

Results and Conclusions - Due to the relatively long time required for envelope inflation and heating the air, deployment of paravulcoon decelerating systems is limited to altitudes above 10,000 feet. Paravulcoon system weight is about twice that of parachute systems for terminal velocities greater than 10 feet/second. Below such a terminal velocity, paravulcoon systems are more efficient than parachutes. However, system weight ratios at these low terminal velocities are very high.

Analysis - Since paravulcoon envelope inflation occurs gradually, opening shock effects and attendant payload load factors are considerably lower than those for parachute decelerators.

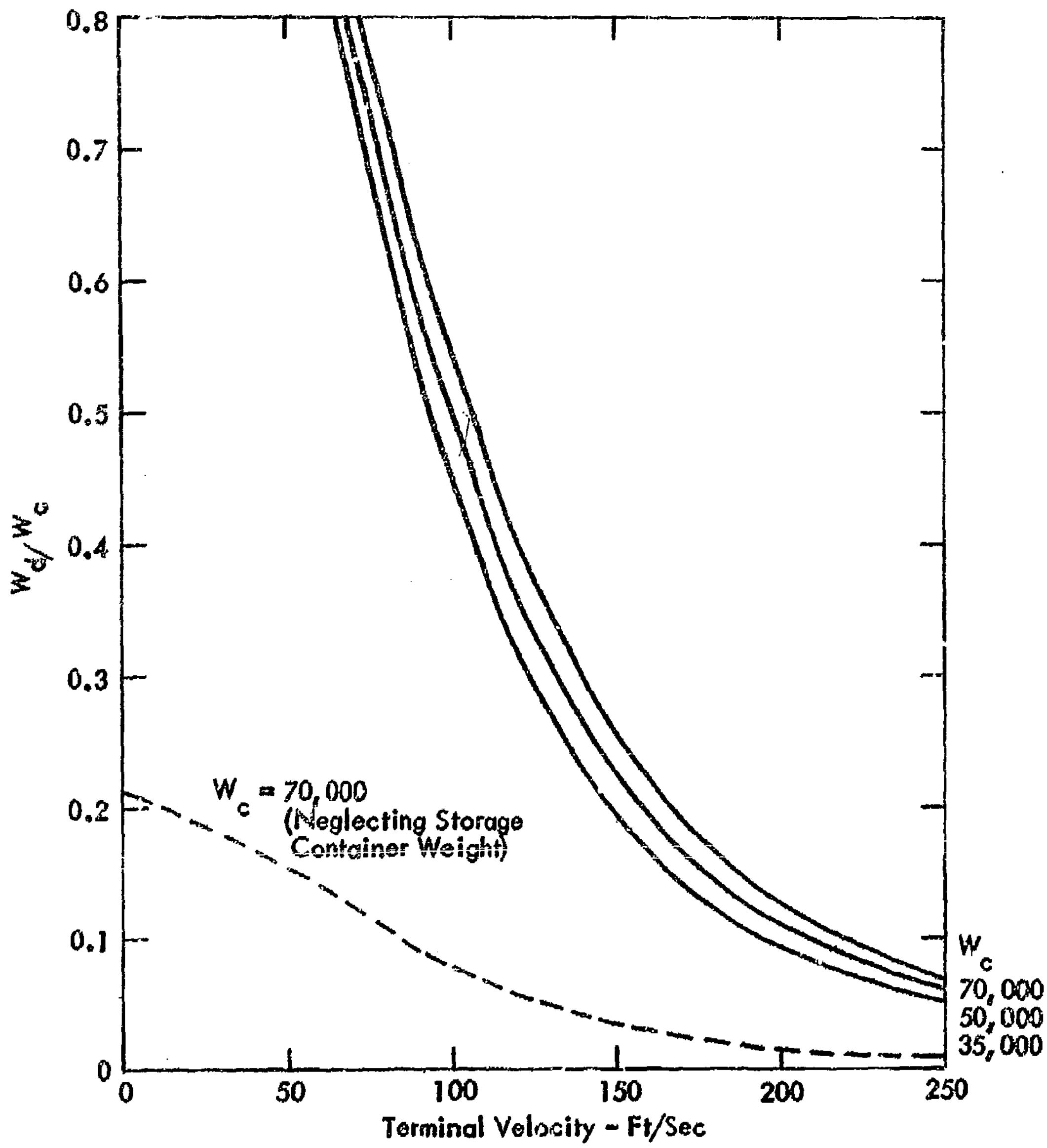


Figure 24 - System Weight Ratio - Helium Balloon

After inflation is complete, from 120 to 160 seconds are required for heating the air to the operating temperature. As a result of the relatively long inflation time and the extended heating time, deployment of the paravulcoon must occur at altitudes above 10,000 feet.

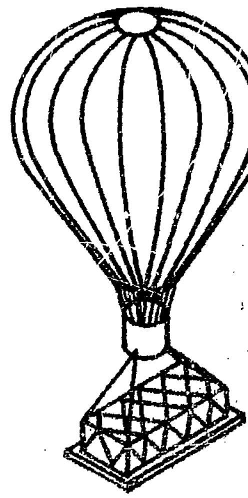


Figure 25 – Paravulcoon Delivery Concept

The weight of a paravulcoon envelope is given in Reference 6, and approximated by

$$W_1 = 5.85 \times 10^{-5} d^{3.48} \tag{28}$$

Using a relation similar to that derived for parachutes, the line weight is given by

$$W_2 = 9.6 \times 10^{-5} \frac{W_c^{3/2}}{\rho v_t^2} \tag{29}$$

The initial heating rate required in Btu/second is approximately equal to the payload weight in pounds. Using propane, the fuel weight is

$$W_3 = 6 \times 10^{-3} W_c \tag{30}$$

From an analysis of a detailed paravulcoon design, it was determined that the weight of the burner, gas tankage, and miscellaneous accessories is approximately $0.5\ W_1$. The total weight of the paravulcoon system is, therefore

$$W_d = 8.76 \times 10^{-5}\ d^{3.48} + 9.6 \times 10^{-5}\ \frac{W_c^{3/2}}{\rho v_t^2} + 6 \times 10^{-3}\ W_c \tag{31}$$

The lift generated at sea level by a paravulcoon with an average internal air temperature of 250°F is

$$L = 1.08 \times 10^{-2}\ d^3 \tag{32}$$

Since the paravulcoon drag is

$$D = \frac{1}{8}\ \rho\ v_t^2\ C_D\ \pi\ d^2 \tag{33}$$

the total decelerating force is

$$F = 1.08 \times 10^{-2}\ d^3 + \frac{1}{8}\ \rho\ v_t^2\ C_D\ \pi\ d^2 \tag{34}$$

By equating decelerating force and cargo weight, it is possible to determine the diameter of the paravulcoon as a function of terminal velocity. The preceding weight equations permit calculation of paravulcoon system weight when these quantities are known.

Figure 26 illustrates paravulcoon system weight as a function of terminal velocity with cargo weight as a parameter. These data are based on a drag coefficient of 0.50 for the paravulcoon. For a 70,000-pound cargo and a terminal velocity of 25 feet/second, the paravulcoon system weight ratio is 0.10, compared to 0.047 for a parachute deceleration system. Only for terminal velocities lower than 10 feet/second is the paravulcoon system more efficient on a weight basis than a parachute system.

Turbojet

General - This concept is based on the use of high performance turbo-jet or fan-jet engines for deceleration of the cargo to an acceptable velocity. The decelerating engines may be attached directly to the cargo platform or suspended by a drogue parachute above the cargo. In either configuration, the engine exhaust is directed in a manner to avoid flame damage to suspension lines and the cargo.

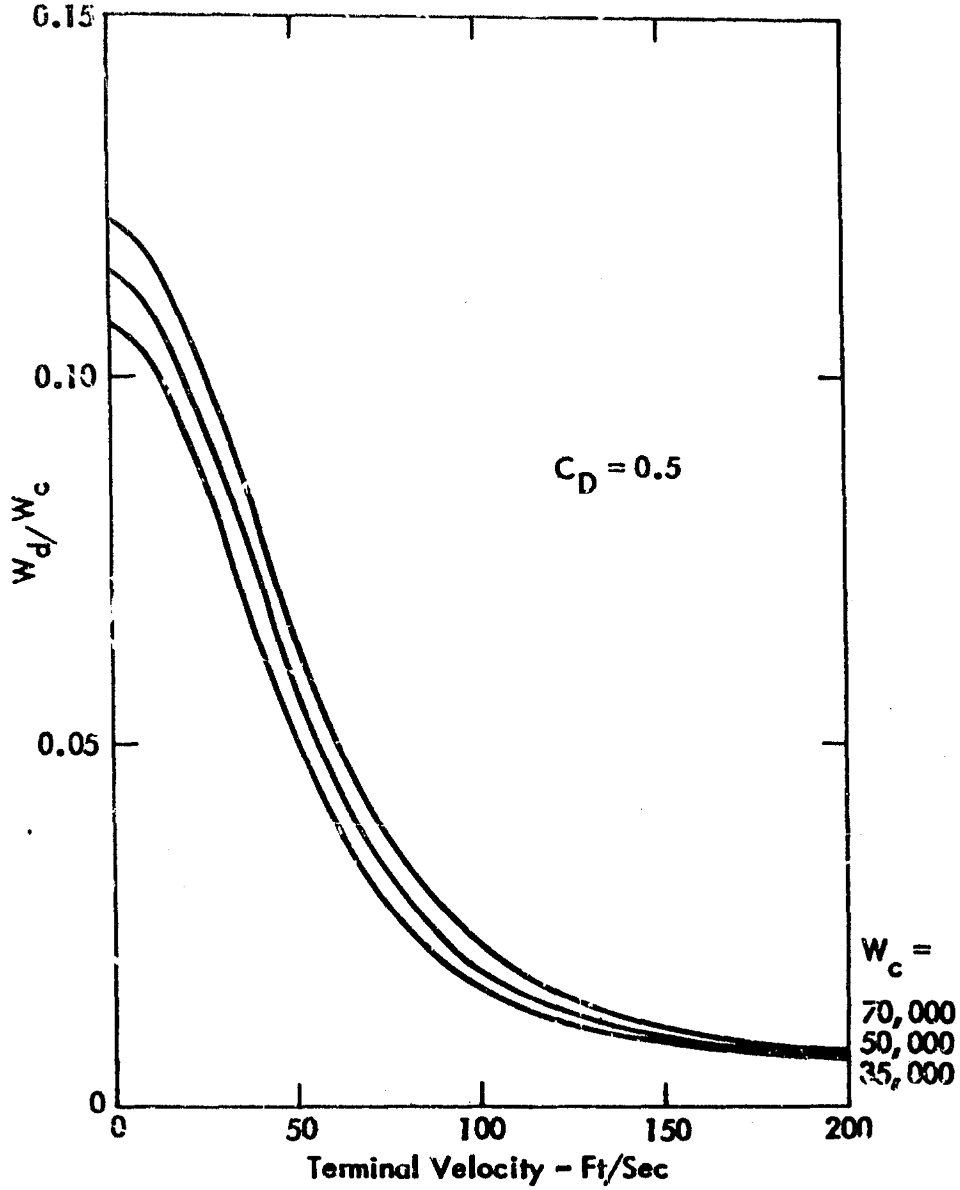


Figure 26 – System Weight Ratio – Paravulcoon

Results and Conclusions - Airbreathing engines demonstrate extremely high system weight ratios, even for deceleration of the cargo at a relatively low rate. For cargo deceleration at 0.25 g, the system weight ratio is greater than 0.5. Weight ratios in this range are not compatible with the requirements of aerial delivery operations.

Analysis - For the purposes of this analysis, only the weight of the jet engines and fuel was included in calculations of system weight. Weight of engine cluster structure, fuel tanks, and structure required for attaching engines to the cargo was neglected. System weight ratios are therefore somewhat lower than are attainable in a functional system, but are sufficiently accurate for comparison with other concepts.

The weight of jet engines and fuel required for a system of this type is given by

$$W_d = T\,(C_1 + SFC\ t_d) \tag{35}$$

where C_1 is the specific engine weight, SFC is the specific fuel consumption, and

$$t_d = \frac{v_d - v_t}{(n_o - 1)\,g} \tag{36}$$

$$T = n_o\,(W_c + W_d) \tag{37}$$

Therefore, it is possible to write the system weight as

$$W_d = \frac{n_o\,W_c\,(C_1 + SFC\ t_d)}{1 - n_o\,(C_1 + SFC\ t_d)} \tag{38}$$

This equation was solved for parametrically varied values of n and $(v_d - v_t)$ with the following values for specific engine weight and specific fuel consumption:

$C_1 = 0.19$ lb. installed engine weight/lb. thrust

$SFC = 0.64$ lb/hr/lb thrust

Data obtained from these calculations are presented in Figure 27, which describes system weight ratio for a terminal velocity of 25 feet/second as a function of initial velocity and initial thrust to weight ratio. This figure indicates that, even for deceleration at the extremely low rate of 0.25 g, the system weight ratio is greater than 0.5. Such a weight requirement, in addition to the large altitude loss attending recovery at low deceleration rates, is not compatible with aerial delivery operations. It is concluded that the use of airbreathing engines for the recovery of heavy payloads is not feasible.

Rocket

General - The rocket aerial delivery concept utilizes solid fuel rockets for deceleration of the cargo to an acceptable impact velocity. The configuration of such a system may take the form of a multi-nozzle propulsion unit attached directly to the cargo platform or suspended by a drogue parachute above the cargo. In the latter configuration, illustrated in Figure 28, individual nozzles are canted to avoid flame damage to the suspension line and cargo. Rocket ignition may be achieved by ground sensing probes or an altitude actuated device.

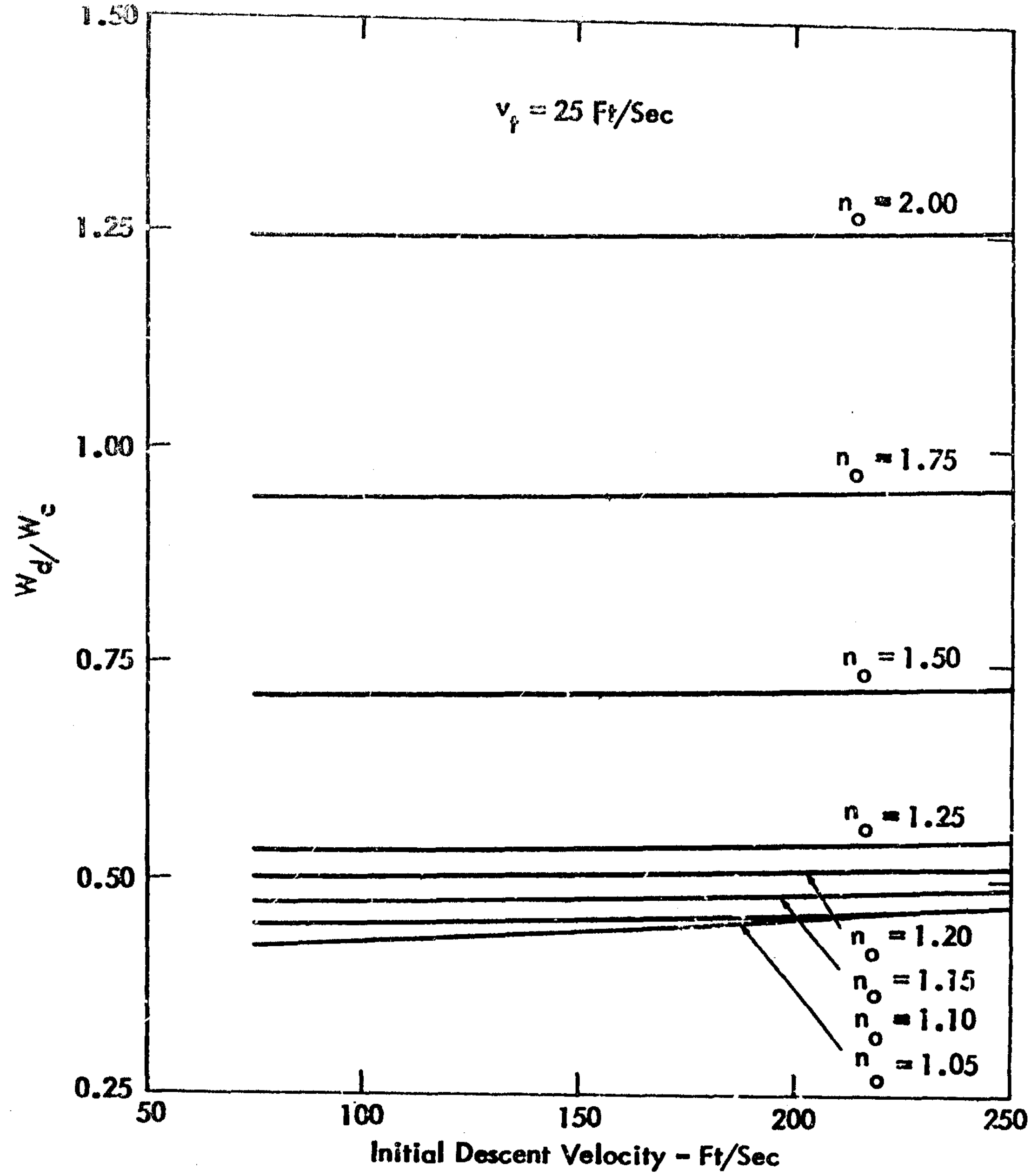


Figure 27 - System Weight Ratio - Airbreathing Engine

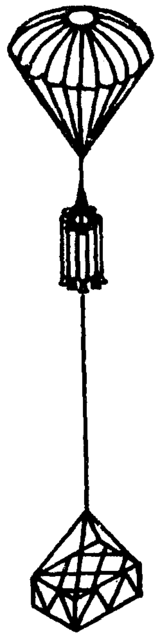


Figure 28 – Rocket Delivery Concept

Results and Conclusions – On a weight basis, rocket systems are somewhat less efficient than parachute systems for recovery from high initial velocities. However, the converse is true for recovery from initial velocities below 150 feet/second. Rocket deceleration systems are optimally employed in the recovery phase of aerial delivery, after the deployment of an aerodynamic decelerator during the descent phase to decrease cargo velocity to less than 150 feet/second.

Analysis – Weight correlating factors were calculated for a descent system concept utilizing solid propellant rockets as reaction force generators. The rocket casing structure weight was determined on the basis of the following assumptions:

o	Combustion chamber pressure	$p = 1000$ psi
o	Fiberglass casing tensile strength including 1.33 safety factor	$f_t = 42{,}500$ psi
o	Casing specific density	$\gamma_1 = 1.66$
o	Propellant specific density	$\gamma_2 = 1.60$

For a cylindrical casing capped by hemispherical ends, the volume of casing material is

$$V_1 = 2\pi r^3 \left[\frac{l}{r} - 1\right]\frac{p}{f_t} \tag{39}$$

$$V_2 = \pi r^3 \left[\frac{l}{r} - \frac{2}{3}\right] \quad \text{where } V_2 = \text{internal volume} \tag{40}$$

The casing/propellant weight ratio is

$$\frac{W_1}{W_2} = 2\,\frac{p}{f_t}\,\frac{\gamma_1}{\gamma_2}\left(\frac{l}{r} - 1\right)/\left(\frac{l}{r} - \frac{2}{3}\right) \tag{41}$$

The value of the weight ratio for various length/radius ratio values is

l/r	W_1/W_2
4	.0435
5	.0447
6	.0453

For solid propellant rockets, a good estimation of nozzle weight is afforded by Reference 14:

$$W_3 = 2.5 \times 10^4\ F \cdot t \tag{42}$$

where F is the thrust in pounds and t is burning time in seconds.

Utilizing the specific impulse relation, $F \cdot t = I_{sp} \cdot W_2$, with a typical value of 185 seconds for I_{sp},

$$W_3 = .0462\ W_2 \tag{43}$$

The decelerator unit is assumed to consist of individual motor units assembled in a cluster suspended between the descent control device and the drop cargo. The weight of structure required for clustering correlates best with the thrust force generated by the assembly. In lieu of an accurate calculation, a conservative assessment can be made by assuming that the weight of necessary structure, fittings and lugs is

$$W_4 = .1291\ W_2 \tag{44}$$

The system weight can then be written as

$$W_d = W_1 + W_2 + W_3 + W_4 \tag{45}$$

$$W_d = 1.22\ W_2 \tag{46}$$

Utilizing the ratio of initial to final thrust/weight ratio:

$$\frac{n_o}{n} = \frac{W_1 + 0.22\ W_2}{W_1 + 1.22\ W_2} \tag{47}$$

$$\frac{W_d}{W_1} = 1.22\ \frac{W_2}{W_1} = \frac{1.22\left(1 - \frac{n_o}{n}\right)}{1.22\frac{n_o}{n} - 0.22} \qquad (48)$$

These relations were explored by means of an automatic computing routine. Results of the investigation are shown in Figure 29 which presents the system weight ratio W_d/W_c as a function of initial descent velocity v_d with initial thrust/weight ratio, n_o, as a parameter. The system weight ratio improves with increasing values of n_o. However, as the value of n_o increases above the peak drag/weight ratio developed by the descent control device, these gains tend to be offset due to increasing needs for structural reinforcement of the cargo suspension system. For this reason, values of n_o greater than 3.5 - 4.0 do not appear to provide any particular advantage.

Comparison of weight ratios shown in Figure 29 with those for parachute systems from Figure 14 indicates that parachute systems are, in general, more efficient for recovery from high initial velocities. For recovery from a velocity of 200 feet/second, weight ratios corresponding to a 70,000-pound cargo are .047 for a parachute system and .057 for a rocket system with $n_o = 4.0$.

However, there does appear to be some advantage in the use of rocket decelerating systems in conjunction with parachute systems. If a parachute system is used to decelerate the cargo from 200 to 100 feet/second, the weight ratio is 0.01. The weight ratio for a rocket system capable of decelerating the cargo from 100 to 25 feet/second is 0.023. The combined ratio is 0.033, compared to 0.047 for a recovery system using parachutes alone. The difference between the systems amounts to about 1000 pounds of system weight for a 70,000-pound cargo.

A system utilizing parachutes during the descent phase and rockets for final recovery provides the most favorable weight figures of any concept investigated. In addition, it provides some attractive operational features, including a relatively fast descent and a short recovery distance.

Impact Phase

The impact phase of the aerial delivery process comprises all events which occur between initial ground contact of the cargo, or attachments to the cargo, and the time when the cargo velocity is reduced to zero. Since a definition of the impact phase specifies a requirement for contact with ground, concepts postulated for utilization in this phase are limited to those involving reactions with the ground. Practical physical systems capable of reducing cargo velocity under this limitation take the form of materials or mechanisms designed to absorb or dissipate the kinetic energy of the cargo.

General requirements of systems to be utilized during the impact phase are the following:

- Absorption or dissipation of the total cargo kinetic energy
- Deceleration of the cargo at a rate consistent with acceptable cargo loading

In this study, the kinetic energy which must be absorbed or dissipated during impact corresponds to weights between 35,000 and 70,000 pounds at velocities ranging up to 80 feet per second. These energies range from 2.17 x 10^5 foot pounds for a cargo weight of 35,000

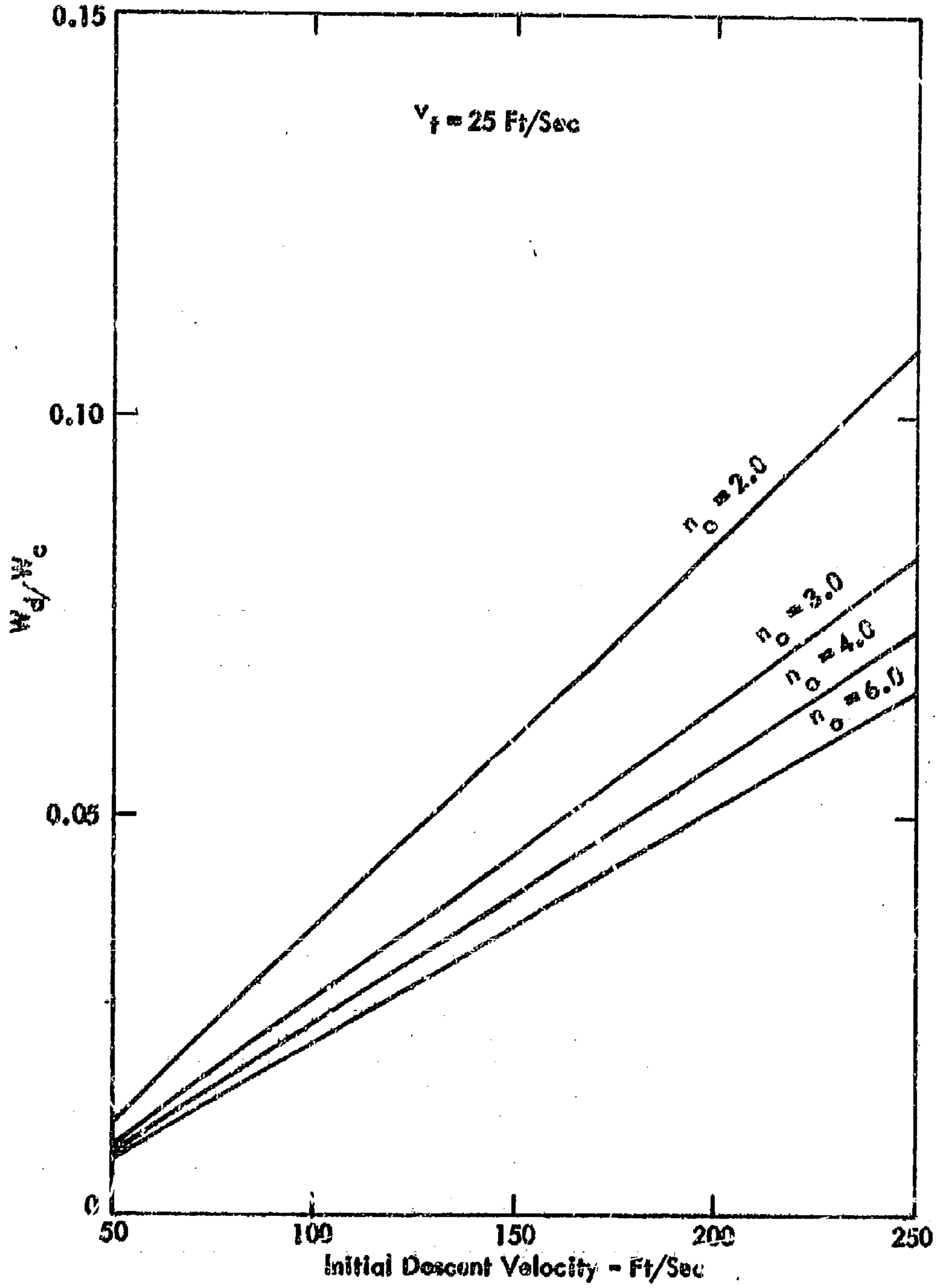


Figure 29 – System Weight Ratio – Rocket

pounds at a velocity of 20 feet per second to 6.96×10^6 foot pounds for a cargo weight of 70,000 pounds at a velocity of 80 feet per second. The maximum acceptable deceleration rate depends upon the fragility of the cargo and the method of packaging for delivery. For purposes of this study, cargo deceleration rates of 5, 10, 15 and 20 g are assumed.

In addition to the general requirements specified above, there are several operational characteristics which are desirable in impact cushioning systems. Desirable characteristics include minimization of the following quantities:

- Deceleration stroke
- System weight
- System volume
- Sensitivity to variations in vertical velocity
- Sensitivity to horizontal velocity
- Sensitivity to variation in impact attitude

In an optimum impact attenuation system, the stroke of the energy absorbing material or mechanism should be the minimum consistent with other system requirements. The length of the deceleration stroke influences the maximum cargo height for storage and extraction from the aircraft. The minimum stroke provides the lowest center of gravity upon ground impact, thus decreasing toppling tendencies of the load and sensitivity of the system to slight variations in platform attitude. Values of the ideal deceleration stroke are shown as function of impact velocity and deceleration rate in Figure 30.

The desirability of minimizing the weight and volume of impact attenuation systems results from aircraft payload and cargo volume limitations. In addition, a low impact system weight decreases the requirements placed on systems utilized in the extraction, descent, and recovery phases of aerial delivery.

The performance of descent and recovery systems varies over a finite range as a result of inherent system limitations and variations in the operational environment. Therefore, it is necessary that the impact attenuation system be capable of satisfactory operation when pertinent impact parameters deviate from nominal values. An acceptable impact system should possess some insensitivity to cargo horizontal velocity and small variations in cargo vertical velocity and cargo attitude.

In evaluating the feasibility of candidate impact attenuation concepts, primary consideration was given to the weight and volume of systems compatible with cushioning payloads in the 35,000 to 70,000-pound range. For concepts having acceptable weight and volume requirements, secondary factors were considered, including deceleration stroke and sensitivity to variations in impact parameters.

<u>Displacement Type Hydraulic Shock Absorber</u>

<u>General</u> - Energy absorption systems utilizing the metered flow of fluid through an orifice are capable of generating or sustaining large forces for short time periods, and thus appear to be compatible with the requirements attending the cushioning of heavy payloads.

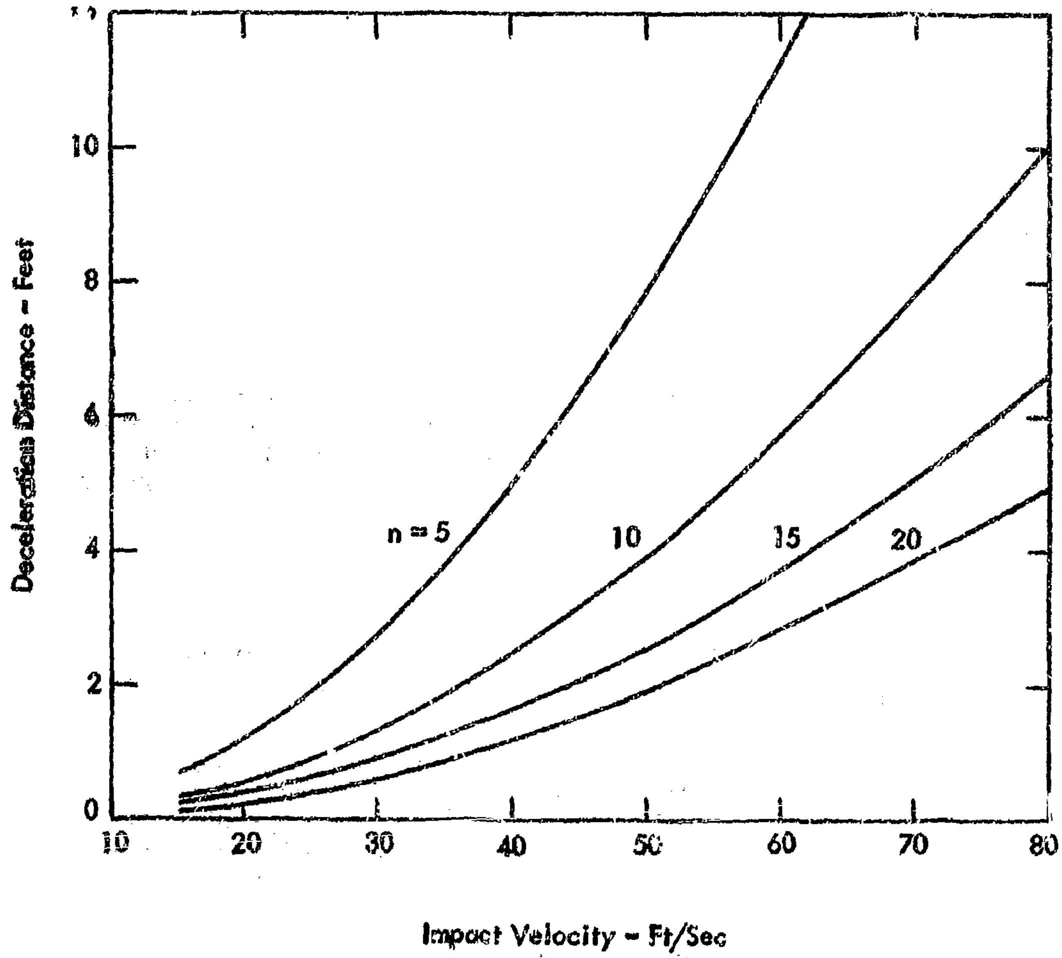


Figure 30 - Ideal Deceleration Stroke versus Impact Velocity

The basic components of a system of this type are one or more fluid-filled piston-cylinder devices rigidly attached to the cargo platform. The cylinders are attached to the platform such that an attachment to the piston extends below the platform. Thus, as the platform approaches the ground, the piston is driven into the cylinder, forcing fluid through an orifice near the top of the cylinder. Forces of the magnitude required in the impact phase of aerial delivery are obtainable through proper sizing of the piston, cylinder, and orifice.

Results and Conclusions - The weight of a hydraulic shock absorbing system capable of decelerating a 70,000-pound payload with an impact velocity of 25 feet/second at a constant rate of 20g is estimated to be between 2000 and 3000 pounds. This is from 6 to 9 times the weight of paper honeycomb required for similar impact conditions. Such a deceleration system requires extensive structural modification of the cargo platform and is highly sensitive to platform impact attitude. It is concluded that hydraulic shock absorbers are not optimally employed in the deceleration of heavy payloads in the impact phase of aerial delivery operations.

Analysis - As described in Reference 15, the force on the piston in a hydraulic shock absorber is given by:

$$F = \frac{\gamma}{2g} \frac{A_p^3}{c_c^2 A_o^2} v_p^2 \qquad (49)$$

where the subscripts p and o refer to the piston and orifice, respectively, and c_c is the efflux jet contraction coefficient. In the operation of such a system, the piston velocity v_p decreases from the impact velocity v_i to zero as the cargo platform is decelerated. Since the force on the piston varies as the square of the piston velocity, the decelerating force on the cargo decreases rapidly as the piston velocity decreases.

The net result of this variation is a deceleration distance much greater than that required for a constant decelerating force. Deceleration distances significantly greater than those obtained under constant deceleration are not desirable for aerial delivery operations.

It is possible to maintain a constant force on the piston by varying the orifice area during the piston stroke such that the ratio

$$\frac{v_p^2}{c_c^2 A_o^2}$$

remains constant.

Since $$v_p = (v_i^2 - 2ns)^{1/2} \qquad (50)$$

it is seen that the orifice area must be steadily decreased during the deceleration. A mechanical system capable of varying the orifice area in the precise manner required would be quite complex. However, it is possible to vary the effective orifice area by using several orifices spaced at appropriate distances along the length of the cylinder. Utilizing this technique, the orifice area is decreased by the piston progressing through the cylinder and sealing orifices in the cylinder walls.

For purposes of illustration, assume the use of four shock absorbing cylinders for the 20g deceleration of a 70,000-pound cargo with an impact velocity of 25 feet per second. If the efflux velocity from the orifices is limited to 200 feet per second, resulting in a fluid pressure of 270 pounds per square inch, each piston must have an area of 1296 square inches, or a diameter of 40.7 inches. For a constant 20g deceleration, the piston stroke is 4.85 inches.

Using the equations describing the structural characteristics of thick-walled cylinders, it is possible to estimate the weight of the shock absorbing system. If the piston and cylinder are made of medium carbon steel and water is used as the working fluid, the weight of each shock absorber is about 260 pounds. Thus, the total weight of the active components is 1040 pounds. This value does not include the weight of structural components required to transmit the impact velocity to the piston, secure the cylinders to the cargo platform, and distribute the forces over the platform area.

It is estimated that the total system weight would be greater than the weight of the active components by a factor between two and three. Thus the total system weight would be between 2000 and 3000 pounds, or from 6 to 9 times the weight of paper honeycomb required under these impact conditions.

Although it is possible to use hydraulic shock absorbers for impact attenuation in the aerial delivery of heavy payloads, such an application incurs a significant weight penalty as compared to cushioning techniques currently in use. In addition, such a system requires extensive structural modification of the cargo platform and demonstrates high sensitivity to variations in platform attitude at impact.

Displacement Type Pneumatic Shock Absorber (Airbag)

General - In current pneumatic cushioning systems, airbags are utilized in cylindrical or barrel-shaped configurations which collapse for storage under the cargo platform. Upon extraction of the cargo from the aircraft, the airbags are allowed to extend under the force of gravity. The airbags fill with air at atmospheric pressure as the extension occurs.

Upon contact with the ground, air is compressed and forced through orifices of suitable size as the airbag volume is decreased. The pressure of the air contained in the airbag generates the decelerating force applied to the cargo platform.

Results and Conclusions - On a weight basis, airbag decelerating systems compare favorably with systems utilizing the structural deformation of honeycomb materials. In addition, since the airbags collapse for storage, volume requirements of airbag decelerators are similar to those for honeycomb materials. Disadvantages inherent in the employment of airbag decelerators include an extremely long deceleration stroke and sensitivity to horizontal velocity and platform attitude. Utilization of airbag decelerators for the cushioning of payloads in the 35,000 to 70,000-pound range requires airbag pressures approximately twice as great as any previously used, with a corresponding increase in the weight of construction materials. An absolute determination of the operational characteristics of airbags designed for heavy payloads can be obtained only through experimental investigations. However, on the basis of current test results applicable to light payloads, airbag decelerators appear to be inferior to cushioning techniques utilizing deformable structures.

Analysis – Several series of tests (Reference 16) have been conducted to demonstrate the feasibility of pneumatic shock absorbers, with mixed results. Tests conducted previously utilized airbags designed for payload weights significantly below the 35,000 to 70,000-weight range of interest in this study, and therefore may be of questionable applicability. However, approximate operational characteristics of airbag decelerators may be obtained from these test results.

Major problems inherent in airbag decelerating systems are the long deceleration stroke, sensitivity to horizontal velocity and platform attitude, and the relatively high air pressure required for heavy payloads.

Due to the compressibility of air, a large fraction of the total airbag stroke is required to build up the necessary internal pressure to begin deceleration of the payload. Thus, the deceleration rate varies throughout the stroke. Consequently, the deceleration distance is much greater than the ideal value obtained from a constant deceleration rate. Test results indicate that deceleration strokes for airbags range from two to five times the ideal value, depending upon airbag design. The primary disadvantage of this characteristic is that it increases the height of the cargo center-of-gravity during the early portion of the deceleration, thus increasing the tendency of the cargo to topple.

Airbag performance is predictable only when compression forces are applied evenly in the direction of the bag axis. Airbags are therefore rather sensitive to cargo horizontal velocity and the attitude of the cargo platform upon ground contact. Airbags have been observed to shear or buckle under conditions attending moderate horizontal velocities and deviation of the platform from horizontal.

Utilization of airbags for deceleration of payloads in the 35,000 to 70,000-pound range requires air pressures appreciably higher than those currently employed. Assuming a 9 x 56-foot platform for a 70,000-pound cargo, it is possible to attach 54 airbags with 3-foot diameters to the platform. The total area over which force is applied is about 1520 square feet. For deceleration at the rate of 20g, an average pressure of 26.8 pounds/inch^2 is required in each bag. This is significantly greater than the average pressures of 6 to 15 pounds/inch^2 used in current airbag designs. It is anticipated that airbags capable of operating under pressures in the required range could be designed. However, their construction would require the use of heavier materials whose lack of flexibility would possibly preclude extension of the airbags by gravity. In such a case, bag extension could be accomplished by pre-pressurization utilizing compressed air or small explosive charges.

Airbag performance may be improved by incorporating changes designed to decrease the required deceleration stroke and sensitivity to horizontal velocity and platform attitude. Suggested changes include pre-pressurization of airbags, use of compartmented airbags, and use of variable diameter orifices. However, airbags utilizing such improvements have not yet been demonstrated.

Turbulent Drag Hydraulic Brake

General – A braking system based on turbulent drag effects utilizes the resistance of fluid media to the motion of high-drag configurations. Such a system designed for cargo deceleration during impact assumes the form of one or more multi-vaned rotor-stator combinations immersed in the working fluid. Appropriate mechanical linkages are required to translate the vertical motion of the cargo into motion of the rotors.

Results and Conclusions - A turbulent drag hydraulic braking system capable of decelerating a 70,000-pound cargo with an impact velocity of 25 feet/second at the rate of 20 g requires an active surface area of approximately 2400 square feet. The weight and volume of a system having an area of this size are obviously excessive for use in aerial delivery operations. The range of operating conditions for which systems utilizing fluid drag are efficient energy absorbers does not include those attending the impact phase of aerial delivery.

Analysis - For a generalized fluid drag braking system, the force on a surface of area A and velocity v, moving through a fluid of density ρ, is given by

$$F = C_D A\left(\frac{1}{2}\rho v^2\right) \tag{51}$$

Assuming a drag coefficient of 1, a velocity of 25 feet per second, and water as the working fluid, a drag area of 2400 square feet is required for a system capable of decelerating a 70,000-pound cargo at a rate of 20 g. A fluid drag braking system with moving surfaces of such an area capable of sustaining the forces inherent in the impact phase of aerial delivery would be unacceptable due to both volume and weight considerations.

Since, for a given surface area, the force resulting from fluid drag varies as the square of the velocity, area requirements decrease rapidly with increasing velocities. However, any decrease in system size and weight resulting from the use of a higher velocity would be largely eliminated by the size and weight of the mechanism required to generate a velocity in the braking system greater than the cargo impact velocity.

Viscous Drag Hydraulic Brake

General - An energy absorption system based on viscous drag effects utilizes the resistance to shearing exhibited by a fluid between two surfaces in relative motion. A braking system of this type may assume the form of concentric rotating drums or properly positioned plane surfaces immersed in the working fluid. Appropriate mechanical linkages are required to translate the vertical motion of the cargo into relative motion of the surfaces.

Results and Conclusions - A viscous drag braking system capable of decelerating a 70,000-pound payload with an initial velocity of 25 feet/second at the rate of 20 g requires a moving surface area of about 2.8×10^7 square feet. A mechanism with an area requirement of this magnitude is obviously impractical for use in aerial delivery operations.

Analysis - This analysis assumes a generalized viscous drag braking system comprised of two adjacent surfaces of undefined configuration with appropriate mechanical linkages for transforming the kinetic energy of the cargo into motion of one of the surfaces. If fluid movement between the surfaces is considered to be laminar, the viscous force opposing motion of the surface is given by

$$F = \eta \frac{Av}{x} \tag{52}$$

where x is the distance between the surfaces.

For a braking system with a surface separation of 10^{-2} feet utilizing water as a working fluid, a surface area of 2.8×10^7 square feet is required to decelerate a 70,000-pound cargo at 20 g. This calculation assumes a constant velocity of 25 feet per second for the moving surface.

It is obvious that a mechanism possessing such an area requirement is not compatible with the demands of aerial delivery operations. The required area can be reduced by utilizing a more viscous working fluid and increasing the velocity of the moving surface. However, based on reasonable values for these quantities, the area requirement cannot be reduced to an acceptable value.

Mechanical Friction Brake

General - Braking systems utilizing forces generated by mechanical friction between moving surfaces dissipate the cargo kinetic energy in the form of heat. The physical configuration of systems using this method of energy dissipation may take the form of disks, expanding drums, bands, or rails.

Results and Conclusions - A mechanical braking system capable of decelerating a 70,000-pound cargo with an impact velocity of 25 feet/second at the rate of 20 g requires a braking area of about 15 square feet. Forces exerted on the braking surfaces are on the order of 5×10^6 pounds, corresponding to a pressure of over 2.3×10^3 pounds per square inch. A mechanical system providing the necessary braking surface area, the required forces between braking surfaces, and the capability of rapidly adjusting such forces is considered to be impractical for application to aerial delivery systems.

Analysis - The feasibility of utilizing a system depending upon mechanical friction for dissipating the cargo kinetic energy during impact can be evaluated by assuming a generalized braking system. The specified operational requirements are independent of the physical configuration of the system. Therefore, the calculations and discussions, which follow are generally applicable to any system depending upon mechanical friction for energy dissipation.

The several problem areas inherent in this application of friction braking systems result from the following considerations:

- Limited duration of braking cycle
- Magnitude of forces required on braking surfaces
- V ariation of coefficients of friction with increasing temperature

In the design of any system for use during the impact phase of aerial delivery, a primary goal is the minimization of the vertical dimension of the decelerating mechanism. This requirement results from constraints imposed by the vertical height of the aircraft cargo compartment. Therefore, the deceleration distance and the attendant deceleration time should approach the minimum attainable value. Deceleration times corresponding to the ideal deceleration distances range from 0.031 seconds for deceleration from 20 feet/second to 20 g to 0.497 seconds for deceleration from 80 feet/second at 5 g. For a nominal deceleration from 25 feet/second at 20 g, the deceleration time is 0.039 seconds.

The brief duration of the braking cycle places extremely stringent requirements on a friction braking system. Any mechanical system exhibiting response times in this range is necessarily comprised of components manufactured to close tolerances. Such a system is inherently expensive and is not optimally employed under the conditions attending aerial delivery operations. Additionally, the dissipation of the total cargo kinetic energy in this time period requires a large braking surface. As a first approximation, the required braking surface area is given by

$$A = 3.86 \times 10^{-2} \frac{W_c v_i^{3/2}}{(T_2 - T_1)} \left(\frac{n}{\rho c_p K g}\right)^{1/2} \tag{53}$$

where ρ, c_p, and K refer to the material of which the heat conducting braking surface is made. Assume the use of carbon steel braking surfaces with an allowable temperature increase of 500°F. For deceleration at a rate of 20 g from an impact velocity of 25 feet/second, area requirements range from 7.5 square feet for a 35,000-pound cargo to 15 sq. feet for a 70,000-pound cargo.

This application of a friction braking system requires extremely large forces on the braking surfaces. The magnitude of this force is approximated by

$$F = \frac{n W_c}{\mu} \tag{54}$$

For a braking system utilizing an asbestos-fabric brake material against a steel surface, values of μ range from 0.30 at room temperature at 0.16 at 200°F, and decrease even further above that temperature. Assuming a total temperature increase of 500°F, a mean value of 0.15 for μ is not unreasonable. Based on this assumption, forces ranging from 1.17×10^6 lb to 9×10^6 lb are required for the range of parameters considered in this study. In order to maintain a constant deceleration rate, as required to minimize the initial vertical height of the system, the force applied to the braking surfaces must increase as the coefficient of friction decreases.

From these approximate calculations, it appears that a friction braking system compatible with the requirements attending the impact phase of aerial delivery is unacceptable on the basis of size, weight, and cost. A mechanical system providing the necessary braking surface area, the required forces between braking surfaces, and the capability of rapidly adjusting such forces, is a large, heavy, and expensive mechanism.

Controlled Structural Deformation

General - In impact attenuation systems utilizing this concept, the cargo kinetic energy is absorbed by the plastic deformation of suitable materials. Cushioning systems may use a wide variety of materials in diverse structural configurations. Commonly considered materials include felt, paper, foamed plastics, rubber, and metal. Such materials may be used in bulk form, as a honeycomb, or in a number of geometrical shapes.

Results and Conclusions - Several materials exhibit properties compatible with the requirements of cushioning heavy payloads for aerial delivery. Among these materials are paper honeycomb, corrugated paper, aluminum honeycomb, and foamed plastics. While both corrugated paper and aluminum honeycomb are more efficient energy absorbers on a weight basis, paper honeycomb exhibits more predictable stress-strain characteristics and is thus better suited to the cushioning of frangible payloads. The weight ratio for a UB-3 paper honeycomb impact attenuation system at an impact velocity of 25 feet/second is 0.005. Thus, only 350 pounds of honeycomb are required for the deceleration of a 70,000-pound payload.

Analysis - The suitability of deformable materials for use as energy absorbers can be determined if the stress-strain characteristics of the materials are known. The stress-strain curve includes the most fundamental items of information concerning the suitability of a material for use as an energy absorber and thus as a cushioning material. The stress-strain curve for UB-3 paper honeycomb is shown in Figure 31.

The stress-strain curve provides the following information:

- The maximum stress encountered over a given interval of strain,
- The shape of the stress-strain curve. The ideal curve is one in which the stress remains constant at all levels of strain.
- The maximum strain to which a material may be deformed without inducing excessively high stresses.
- The energy absorbed per unit volume of material. This quantity permits determination of the volume of cushioning required for a specific mass at a given impact velocity.
- The average stress encountered over a given interval of strain.
- The rebound energy. It is this elastic energy, stored in the material at the bottom of the cushioning stroke, which causes the dropped item to bounce. Energy storage characteristics may limit the usable stroke of cushioning materials.

In terms of these quantities, the weight of cushioning material required is

$$W_1 = \rho \cdot \frac{W_c \cdot v_1^2}{2E \cdot g} \tag{55}$$

and the initial vertical thickness of cushioning material is

$$s_o = \left(\frac{S_m}{\epsilon \bar{S}}\right) \frac{v_1^2}{2g(n+1)} \tag{56}$$

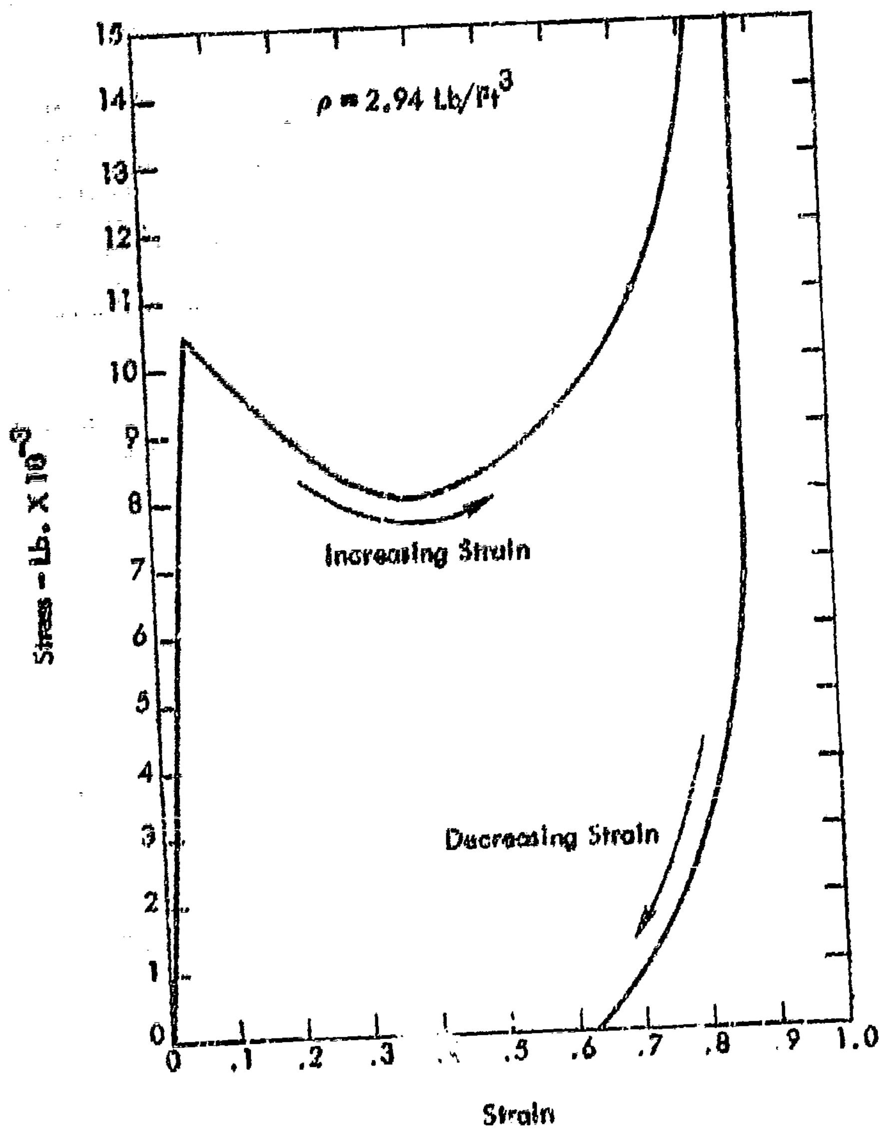


Figure 31 – Dynamic Stress – Strain Curve for UB-3 Paper Honeycomb

The ratio of initial vertical thickness to ideal deceleration stroke is given by

$$\frac{s_o}{s} = \left(\frac{S_m}{\epsilon \overline{S}}\right) \left(\frac{n}{n+1}\right) \qquad (57)$$

where

W_1 = Weight of Cushioning Material Lbs

W_c = Cargo Weight Lbs

v_i = Impact Velocity FPS

ρ = Density of Cushioning Material Lbs/Ft^3

E_1 = Energy Absorbing Capability of Cushioning Material FT LBS/FT^3

S_m = Maximum Compressive Stress of Cushioning Material Lbs/Ft^3

$\overline{S}$ = Average Compressive Stress Over Useable Stroke of Cushioning Material Lbs/Ft^2

ϵ = Useable Degree of Compression of Cushioning

Material = $\dfrac{\text{Compression Stroke}}{\text{Original Weight}}$

These relations indicate that, for given impact conditions, the weight of cushioning material required is decreased by using materials with large values of (E/ρ). Minimization of the ratio (s_o/s) requires the use of a material for which the quantity ($S_m/\epsilon S$) is small.

Table V, derived from data in Reference 17, shows characteristics of common bulk materials which absorb energy through structural deformation. This table indicates that corrugated paper, paper honeycomb, foamed plastics, and aluminum honeycomb exhibit properties desirable for impact attenuation.

As opposed to energy absorption through the deformation of bulk materials, it is also possible to employ various structural shapes for energy absorption. Representative shapes and corresponding energy absorption characteristi. taken from References 15 and 18, are illustrated in Table VI. Comparison of Tables V and VI indicates that, on the basis of energy absorbed per unit weight, the crumpling of metal cylinders is more efficient than the structural deformation of bulk materials.

In application, the theoretical energy efficiency of structural shapes is not realized. Since such shapes tend to concentrate decelerating forces at a few points on the cargo platform, additional structural members are required to strengthen the platform and distribute the loading. When bulk materials are utilized for impact cushioning, such modifications are not required. In addition, energy absorption characteristics of shaped absorbers are very sensitive to horizontal velocity and platform attitude.

Based on these considerations, bulk cushioning materials appear to be more adaptable to aerial delivery operations than shaped energy absorbers. Of the candidate bulk cushioning materials, paper honeycomb is most adaptable to the requirements of impact attenuation. While both corrugated paper and aluminum honeycomb are more efficient energy absorbers on a weight basis, paper honeycomb exhibits more predictable stress-strain characteristics and is thus better suited to the cushioning of frangible payloads.

TABLE V

CHARACTERISTICS OF BULK ENERGY ABSORBING MATERIALS

Material	ρ $\frac{Lb}{Ft^3}$	ϵ	S_m Lb/Ft^2	$\bar{S}$ Lb/Ft^2	E $\frac{Ft \cdot Lb}{Ft^3}$	$\frac{E}{\rho}$ $\frac{Ft \cdot Lb}{Lb}$	$\frac{S_m}{\epsilon \bar{S}}$
Black Packit "C"	5.5	.7	11,000	2,580	2,580	470	4.26
Celotex No. 2	18.7	.48	40,000	23,000	11,400	610	3.51
Corrugated Paper	4.65	.7	21,000	17,000	11,900	2,560	1.77
Kimpak	8.8	.7	2,500	1,500	1,050	119	2.38
NuWood	17.8	.6	200,000	100,000	60,000	3,360	3.36
UB-3 Paper Honeycomb	2.94	.7	10,500	8,500	5,960	2,030	1.76
Wood	38.0	.3	440,000	250,000	75,000	1,970	5.86
Felt	13.9	.7	38,000	9,300	6,500	468	5.85
Nukraft	2.5	.4	1,000	500	200	80	5.00
Rubatex Hardboard	4.5	.7	15,000	9,300	6,500	1,450	2.30
Shredded Foam Rubber	5.9	.7	3,000	1,000	700	119	4.29
Tulatex	1.7	.7	1,000	500	250	147	4.00
Armofoam	2.5	.7	3,000	1,000	700	280	4.29
Durafoam	2.5	.7	3,000	1,000	300	120	10.0
Dylite	3.0	.5	9,000	5,500	2,750	920	3.28
Ensolite	6.4	.5	2,500	1,000	500	78	5.00
Foam King	8.9	.3	1,000	500	150	17	6.66
H-R Foam	2.72	.6	7,500	3,340	2,000	735	3.75
Lockfoam	5.13	.7	7,000	2,140	1,500	292	4.66
Silicone Resin	4.59	.7	8,000	3,120	2,250	490	3.56
Stafoam	3.22	.7	7,000	4,300	3,000	932	2.33
Styrofoam Q-103-15	3.0	.7	22,000	14,250	9,980	3,330	2.20
Urefoam	2.48	.7	15,000	6,600	4,600	1,850	3.26
URF	2.5	.4	1,500	1,000	400	160	3.75
Fiberglass	9.9	.4	7,500	3,120	1,250	127	6.00
Lt. Wt. Concrete	15.1	.5	16,000	9,000	4,500	298	3.56
Aluminum Honeycomb	2.7	.7	18,000	14,000	9,800	3,630	1.84
Steel Honeycomb	6.73	.3	34,000	22,000	6,600	980	5.15

TABLE VI

CHARACTERISTICS OF SHAPED ENERGY ABSORBERS

Material	Configuration	Dimensions	Density Lb/Ft^3	Effective Density Lb/Ft^3	ϵ	S_m Lb/Ft^2	$\bar{S}$ Lb/Ft^2	E $\frac{Ft \cdot Lb}{Ft}$	$\frac{E}{\rho_{eff}}$ $\frac{Ft \cdot Lb}{Ft^3}$	$\frac{S_m}{\epsilon \bar{S}}$
Aluminum	Cylinder (crumpling)	1.5" O.D. .049" wall	173.0	22.5	.7	5,000	4,600	3,220	11,600	1.55
Steel	Cylinder (crumpling)	1.5" O.D. .035" wall	500.0	46.5	.7	19,100	9,000	6,300	11,000	3.04
Steel	Cylinder (roll-up)	2" O.D. .049" wall	500.0	12.2	.8	7,500	5,250	4,100	3,820	1.83

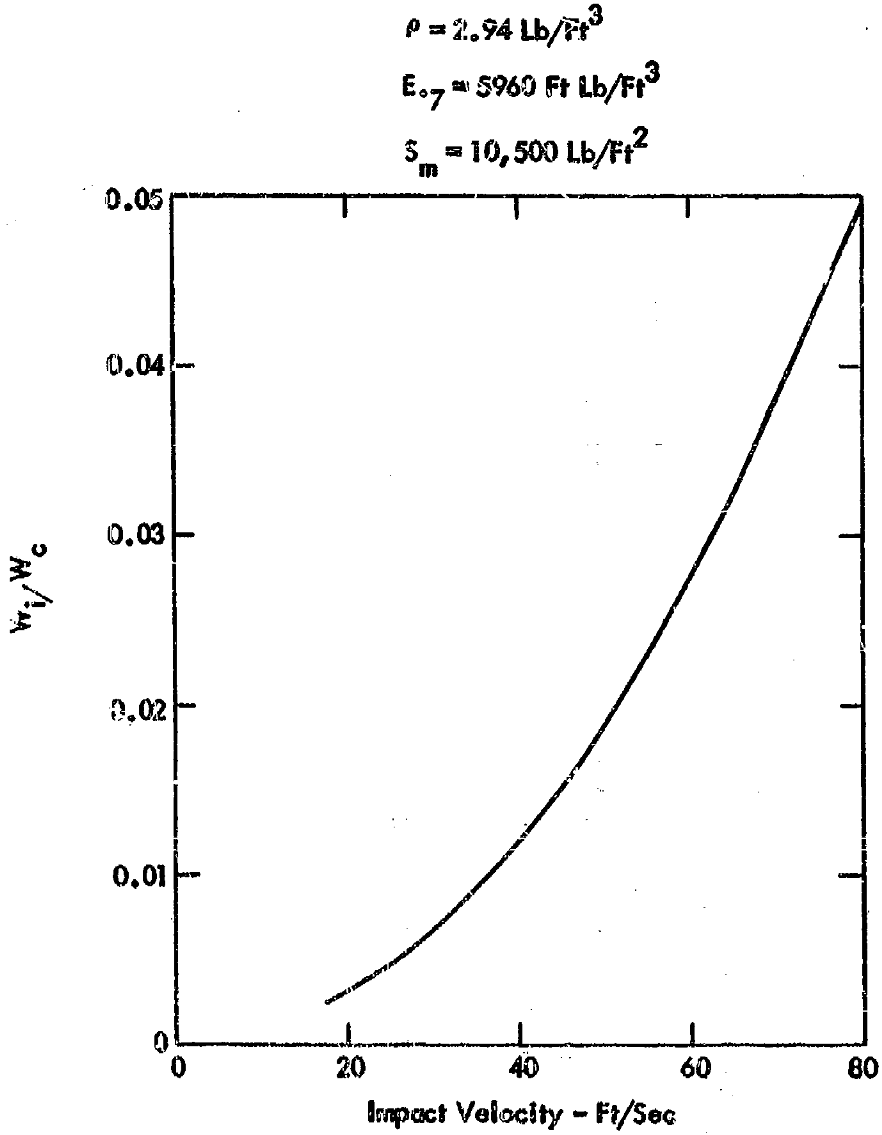


Figure 32 – System Weight Ratio – UB-3 Paper Honeycomb

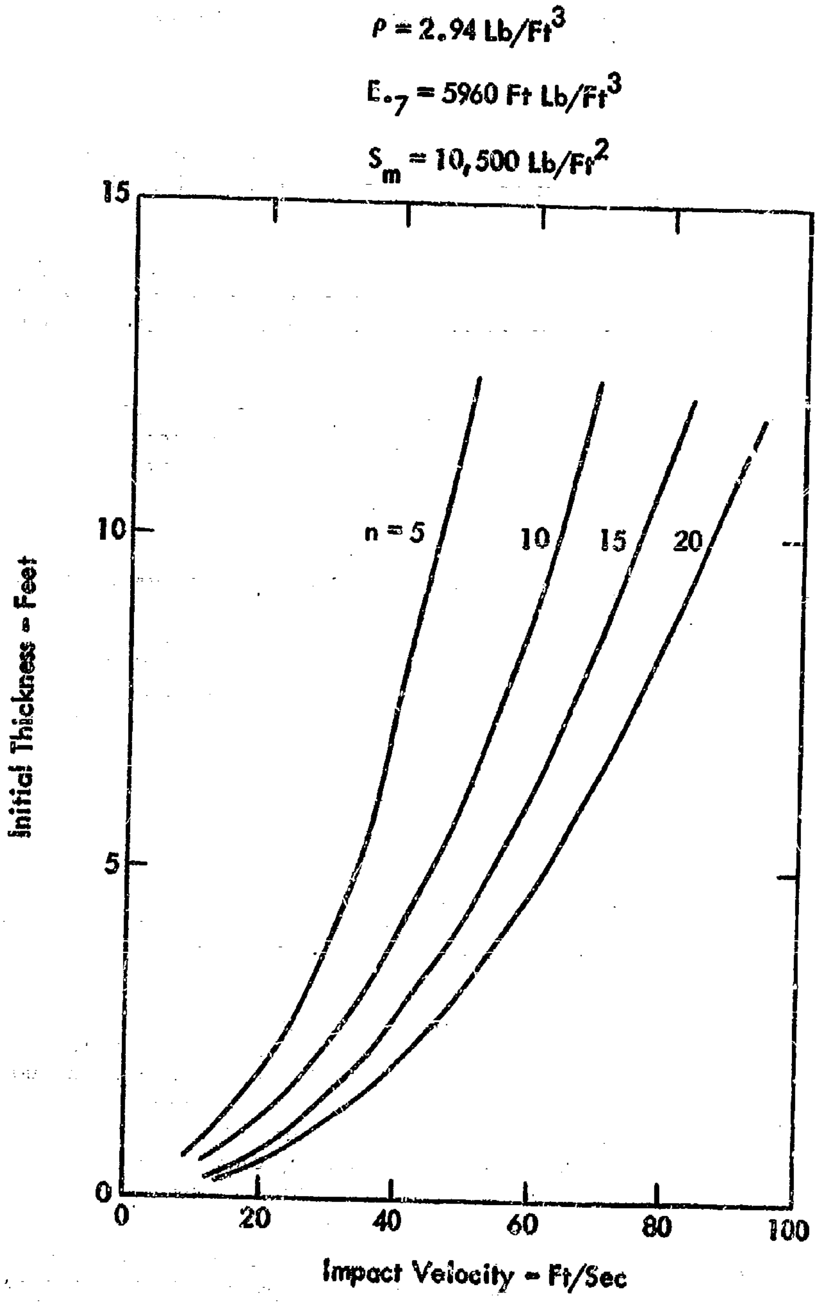


Figure 33 – Initial Thickness versus Impact Velocity – UB-3 Paper Honeycomb

Figures 32 and 33 describe impact system requirements when UB-3 paper honeycomb is used as a cushioning material. Figure 32 shows the system weight ratio as a function of impact velocity. In Figure 33, the initial cushion thickness is given as a function of cargo deceleration rate and impact velocity.

Soil Deformation

General - Dissipation of the cargo kinetic energy through deformation of soil by suitably shaped penetrating probes attached to the cargo platform was considered as possible means of impact attenuation.

Results and Conclusions - Soil properties, including the resistance of soils to penetration, vary widely as a function of location. It is not considered feasible to utilize soil deformation techniques for decelerating frangible payloads in diverse locations having unknown soil characteristics.

Analysis - Natural soils exist in tremendous variety and gradation of properties and, in natural soil profiles, can occur in a wide range of sequences. Data describing the resistance of various soils to penetration by foreign objects are extremely incomplete. It is known, however, that resistance to penetration varies by orders of magnitude among the various types of soil.

The cargo deceleration is directly proportional to the decelerating force which, in this case, is the resistance of the soil to penetration. Therefore, design of a system utilizing this mechanism must vary as a function of soil characteristics in order to decelerate the payload at a required rate. Due to the extreme variation of soil properties, even within localized regions, the performance of impact attenuation systems based on soil deformation is not likely to be sufficiently predictable for use in aerial delivery operations.

Selection of Systems

The feasibility analyses completed for candidate concepts in the several phases of aerial delivery provide a basis for the formulation of complete aerial delivery systems utilizing the optimum concept for each phase. In this section, concept characteristics are summarized and evaluated relative to the capabilities of other concepts in satisfying established requirements. Based on these evaluations, concepts are selected for each phase and combined to obtain complete aerial delivery systems.

Table VII presents a comparison of candidate concepts for employment in the extraction phase. In addition to a requirement for extensive modification of the aircraft, the catapult extraction concept is unacceptable due to excessive weight and power requirements. While the inclined plane and extraction aircraft concepts are usable in aircraft of the C-5A class, neither is capable of providing a load factor of the magnitude required for extraction from the C-141. Of the concepts considered, only the parachute extraction concept is capable of operation over the complete range of airspeed, altitude, and cargo weight in a manner consistent with established constraints.

Concepts considered for employment in the descent and recovery phases are compared in Table VIII. As a general result, it appears that passive systems utilizing high-drag-aerodynamic decelerators exhibit greater overall efficiency than other types of descent and recovery systems.

Concepts utilizing active components, such as windmilling rotors, powered rotors, and air-breathing engines, have extremely unfavorable weight ratios. In addition, such concepts exhibit high volume requirements and severe operational problems, particularly during deployment.

TABLE VII

CONCEPT EVALUATION – EXTRACTION PHASE

Concept	Concept Characteristics: Weight	Volume	Complexity	Aircraft Modifications	Evaluation	Remarks
Inclined Plane	Low	Low	Low	None	Poor	Usable for limited range of aircraft speeds
Catapult	High	High	High	Major	Poor	Heavy and complex – large power requirement
Parachute	Low	Low	Low	None	Good	Usable over full range of aircraft speeds and cargo weights
Extraction Aircraft	Medium	Medium	High	Major	Poor	Inadequate extraction load factors

TABLE VIII

CONCEPT EVALUATION - DESCENT AND RECOVERY PHASES

Concept	Concept Characteristics			Performance	Sensitivity	Operational Requirements			Evaluation		Remarks
	Weight	Volume	Complexity	Wind	Initial Velocity	Altitude	Clear Area	Aircraft Modifications	Descent Phase	Recovery Phase	
Parachute	Low	Low	Low	High	Low	Low	High	None	Good	Good	Usable over full range of aircraft speeds and cargo weights. Altitude losses during initial deployment and final inflation restricts application to drop altitudes 1200 feet
L/D Parachute	Medium	Medium	Medium	Medium	Low	Low	Medium	None	Fair	Fair	Cannot be clustered - extremely large canopy sizes for heavy payloads
Paracone	High	High	Medium	High	Low	High	High	None	Poor	Poor	Impractical sizes for cargo weights considered
Ballute	High	High	Low	Medium	Low	High	Medium	None	Fair	Fair	Not suitable for low velocity operation
Parawing	High	High	High	Medium	High	w	Medium	Major	Poor	Poor	Cannot be towed at required aircraft speeds
Glider	High	High	High	Medium	Medium	Low	High	Minor	Poor	Poor	Extremely heavy - large clear area required
Windmilling Rotor	High	High	High	High	Low	Medium	High	None	Poor	Poor	Impractical rotor sizes for cargo weights considered
Balloon	High	High	Medium	High	Low	High	High	Minor	Fair	Poor	Excessive system weight for low terminal velocity
Paravulcoon	Medium	Medium	Medium	High	Low	High	High	None	Fair	Fair	Limited to high altitude deployment - long descent times
Rocket	Low	Low	Medium	Low	High	Low	Low	None	Poor	Good	Satisfactory for recovery phase
Airbreathing Engine	High	High	High	Low	Medium	Medium	Medium	None	Poor	Poor	Extremely heavy and complex
Powered Rotor	High	High	High	High	Low	Medium	Medium	None	Poor	Poor	Heavy - large power requirement

Fixed wing aerodynamic devices also have high weight ratios and undesirable operational limitations. Fixed wing gliders have clear area requirements for both landing and retrievel similar to those of powered aircraft of the same cargo class. Parawing configurations within the current state-of-the-art cannot be towed in an unloaded condition at speeds greater than about 87 knots and are therefore unsuitable for delivery systems utilizing modern cargo aircraft.

Concepts utilizing both buoyancy and aerodynamic forces for cargo deceleration are less efficient on a weight basis than simple aerodynamic devices. Included in this class of concepts are balloon and paravulcoon decelerators. The system weight necessary to generate the buoyant characteristics exhibited by such devices is excessive for the resulting increase in system performance.

Concepts utilizing aerodynamic drag forces for cargo deceleration include ballutes, paracones, L/D parachutes, and conventional parachutes. Ballutes are designed for operation at high velocities and exhibit inferior drag characteristics at velocities of interest in this study. Drag characteristics of paracones are also inferior to those of conventional parachutes. Since they cannot be clustered, the size of paracones for the delivery of heavy payloads at low terminal velocities presents severe operational problems. Similar problems are inherent in the use of L/D parachutes. Due to aerodynamic considerations and control problems, L/D parachutes cannot be clustered for the delivery of heavy payloads. Therefore, the size of individual parachutes is extremely large for heavy cargo weights.

The rocket delivery concept is not suitable for long-duration application as required in the descent phase, but may be advantageously employed in conjunction with a descent decelerator for rapid cargo deceleration during the recovery phase.

Conventional parachute systems demonstrate favorable weight ratios, volume requirements, and operational characteristics over the complete range of aircraft speeds and cargo weights under consideration. Some form of parachute system may be employed for delivery altitudes ranging from 800 to 30,000 feet. At altitudes above 1200 feet, parachutes may be used for both the descent and recovery phases, or as a descent decelerator in conjunction with a rocket recovery system. Below 1200 feet, parachutes require rocket augmentation in order to achieve acceptable impact velocities.

Table IX summarizes the characteristics of concepts applicable to the impact phase of aerial delivery. As indicated by this table, novel approaches to the problem of cushioning payloads for aerial delivery show little merit. In general, it is found that systems employing active components are not well suited for the deceleration of heavy payloads. Mechanical systems capable of absorbing large quantities of energy while varying applied forces with sufficiently short response times are inherently rather massive, complex, and expensive. Systems included in this category are those based on mechanical friction and hydraulic shock absorption.

Systems dependent upon the relative velocity of moving components are extremely inefficient for impact cushioning. Velocity dependent systems, such as those utilizing turbulent drag or viscous drag, are efficient energy absorbers under steady state conditions characterized by relatively high velocities. They are not ideal for use under the transient, short-duration conditions attending the impact phase of aerial delivery.

On the basis of weight and volume requirements, airbag decelerators compare favorably with systems utilizing structural deformation. However, there are a number of disadvantages in the use of airbags for cushioning heavy payloads. Major problems are the long deceleration stroke, sensitivity to horizontal velocity and platform attitude, and the relatively high air pressure required for heavy payloads.

TABLE IX

CONCEPT EVALUATION - IMPACT PHASE

Concept	Concept Characteristics: Weight	Concept Characteristics: Volume	Concept Characteristics: Complexity	Performance Sensitivity: Impact Velocity	Performance Sensitivity: Horizontal Velocity	Performance Sensitivity: Platform Attitude	Deceleration Stroke	Platform Modifications	Evaluation	Remarks
Hydraulic Shock Absorber	High	High	High	High	High	High	Short	Major	Poor	High system weight - sensitive to impact conditions
Pneumatic Shock Absorber	Low	Low	Medium	High	High	High	Long	Minor	Fair	Long deceleration stroke - sensitive to impact conditions
Turbulent Drag Hydraulic Brake	High	High	High	High	High	High	Short	Major	Infeasible	Excessive size, weight, and complexity
Viscous Drag Hydraulic Brake	High	High	High	High	High	High	Short	Major	Infeasible	Excessive size, weight, and complexity
Mechanical Friction Brake	High	High	High	High	High	High	Short	Major	Infeasible	Excessive size, weight, and complexity
Controlled Structural Deformation	Low	Low	Low	Medium	Medium	Medium	Short	None	Good	Satisfactory for impact velocities below 50 ft/sec.
Soil Deformation	Medium	Medium	Medium	High	High	High	Medium	Major	Infeasible	Not sufficiently predictable for satisfactory operation

Based on operational characteristics of candidate impact attenuation systems, a passive system utilizing structural deformation of paper honeycomb appears to be most readily adapted to the requirements of aerial delivery operations. Advantages attending the use of this type of impact attenuation system include low system weight, moderate sensitivity to variations in impact velocity and platform attitude, and a short deceleration stroke.

Paper honeycomb cushioning systems also exhibit a lower sensitivity to the horizontal component of the impact velocity than other systems considered. Honeycomb is normally mounted between the cargo platform and the load and is thus less influenced by surface motion than systems requiring extensions below the platform.

The aerial delivery systems described in Table X are the result of optimum combinations of concepts selected on the basis of evaluations presented in Tables VII, VIII, and IX. The two selected systems permit delivery at altitudes ranging from 800 to 30,000 feet. Delivery from altitudes as low as 800 feet is possible when the Para-Rocket Delivery System is employed. Conventional Parachute Delivery Systems are compatible with delivery from altitudes greater than 1200 feet.

Design criteria, performance analyses, and an evaluation of these systems will be presented in the following section of this report.

TABLE X

SELECTED AERIAL DELIVERY SYSTEMS

Operational Phase	Para-Rocket System	Conventional Parachute System
Extraction	Parachute	Parachute
Descent	Parachute	Parachute
Recovery	Rocket	Parachute
Impact	Paper Honeycomb	Paper Honeycomb

PERFORMANCE OF SELECTED SYSTEMS

This section presents results from the performance analysis for the selected delivery system concepts. The approach taken in this analysis follows closely the method described in Appendix B, Evaluation Methodology. For the C-141 airplane, critical performance requirements for the extraction phase sub-systems were established. For the C-5A airplane, the limitations are not as restrictive as those for the C-141. The investigations leading to these performance requirements are reported in Appendix A, from which specific design data were selected for use in this section. Other system design data used in this section were taken from appropriate parts of the concept feasibility analysis section. The section is divided into the following parts:

- *System Description*
- *Selection of Design Points*
- *System Design Data*
- *Scope of Performance Evaluation*
- *Results of Performance Evaluation*

System Description

Para-rocket System

The selected para-rocket system, shown in Figure 34, consists of the following components:

- Combined extraction and descent control parachute
- Recovery rocket assembly
- Rocket ignition and extinction sensing elements attached to the drop load platform
- Shock absorber material for impact shock alleviation

The extraction/descent control parachute should be a low opening shock parachute capable of extracting the load from the airplane with an initial peak extraction load factor in the range 1.4 - 2.0 g. If lower values for the extraction load factor are required for operational reasons peculiar to the airplane, a separate descent control chute may be deployed after extraction. This chute should be sized to permit the load to descend at the rate of 150-175 feet/second.

The recovery rocket assembly consists of a cluster of an even number of rocket units arranged symmetrically around a "back-bone" structure, with nozzles canted 30 degrees down and out from the back-bone axis. The upper end of the back-bone is attached to the apex of the parachute riser lines. The lower end of the back-bone contains a fitting to which is attached either the apex of the drop cargo suspension lines, or a riser attached to the suspension line apex. The distance between the rocket nozzle plane and the drop cargo should be on the order 100-120 feet. The rocket cluster must possess electrically initiated igniters and extinction devices. The latter may consist of electrically fired blow-ports for relieving the chamber pressure.

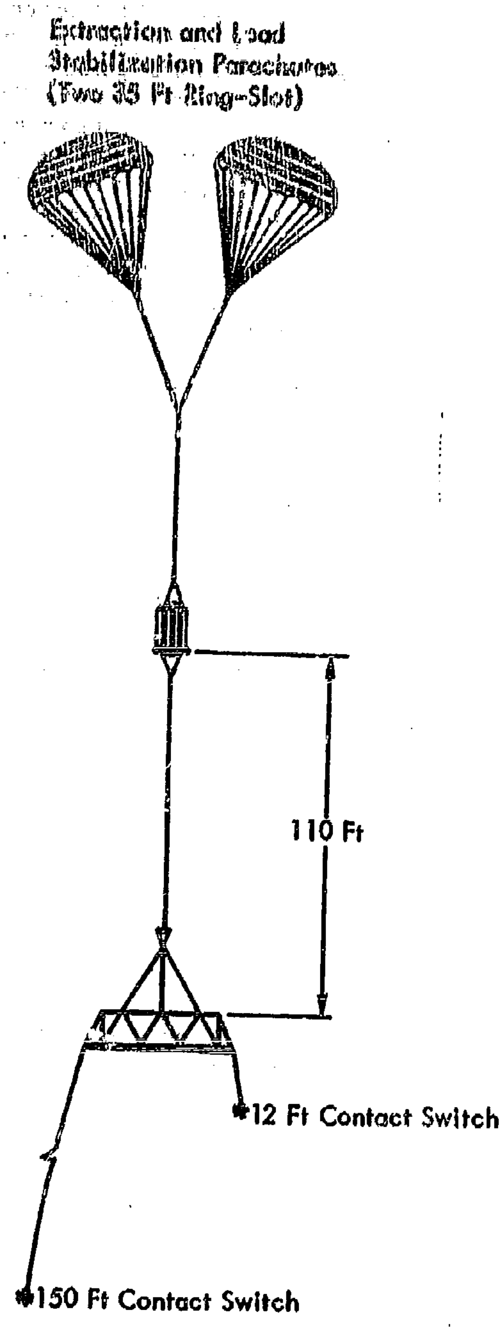


Figure 34 - Para-rocket Aerial Delivery System

The sensing elements of the rocket ignition and extinction control system may consist of sounding lines with plumb bobs which are deployed from the cargo platform upon completed extraction or deployment of the descent control parachute. The deployment actions for the sensing devices also serve to arm the ignition and extinction circuits. A possible arrangement involves three sensing elements with different sounding line lengths. The longest line activates the rocket ignition upon ground contact of the plumb bob. Ground contact of the next longest line activates the extinction circuits for half of the rocket units, the extinguished units being arranged symmetrically about the back-bone axis. Finally, ground contact of the third sensor activates the extinction circuits for the remaining still active rocket units immediately prior to platform impact. The deployed lengths of the three feeler lines are adjusted to achieve the correct deceleration program for the cargo weight, rocket size and parachute equilibrium speed combination.

The platform impact shock absorbing material may be of conventional paper honeycomb.

Parachute System

The parachute system might be adapted for operation in two modes:

- Conventional mode
- High speed descent and low level recovery mode

For operation in the conventional mode, the system consists of the following components:

- Extraction parachute
- Main descent parachute cluster
- Drop cargo platform with impact shock alleviating material

For operation in the high speed descent mode the system, as shown in Figure 35, consists of components as follows:

- Combined extraction and descent control parachute
- Altitude sensor or timing device for controlled release of descent control parachute along with deployment of main recovery parachute cluster
- Main recovery parachute cluster
- Cargo platform with impact shock alleviating material

Alternatively, the high speed descent mode can also be achieved by suitably reefed deployment of the main parachute cluster immediately following cargo extraction, with chute disreefing being triggered by signals from a time or altitude sensor.

The extraction parachute should be a low opening shock parachute capable of extracting the cargo from the airplane with an initial peak load factor of 1.4 - 2.0 g.

For operation in the conventional mode, and for recovery, the main parachute battery may consist of a cluster of preferably not more than eight parachutes sized to afford a sea-level equilibirum descent velocity of 25 feet/second.

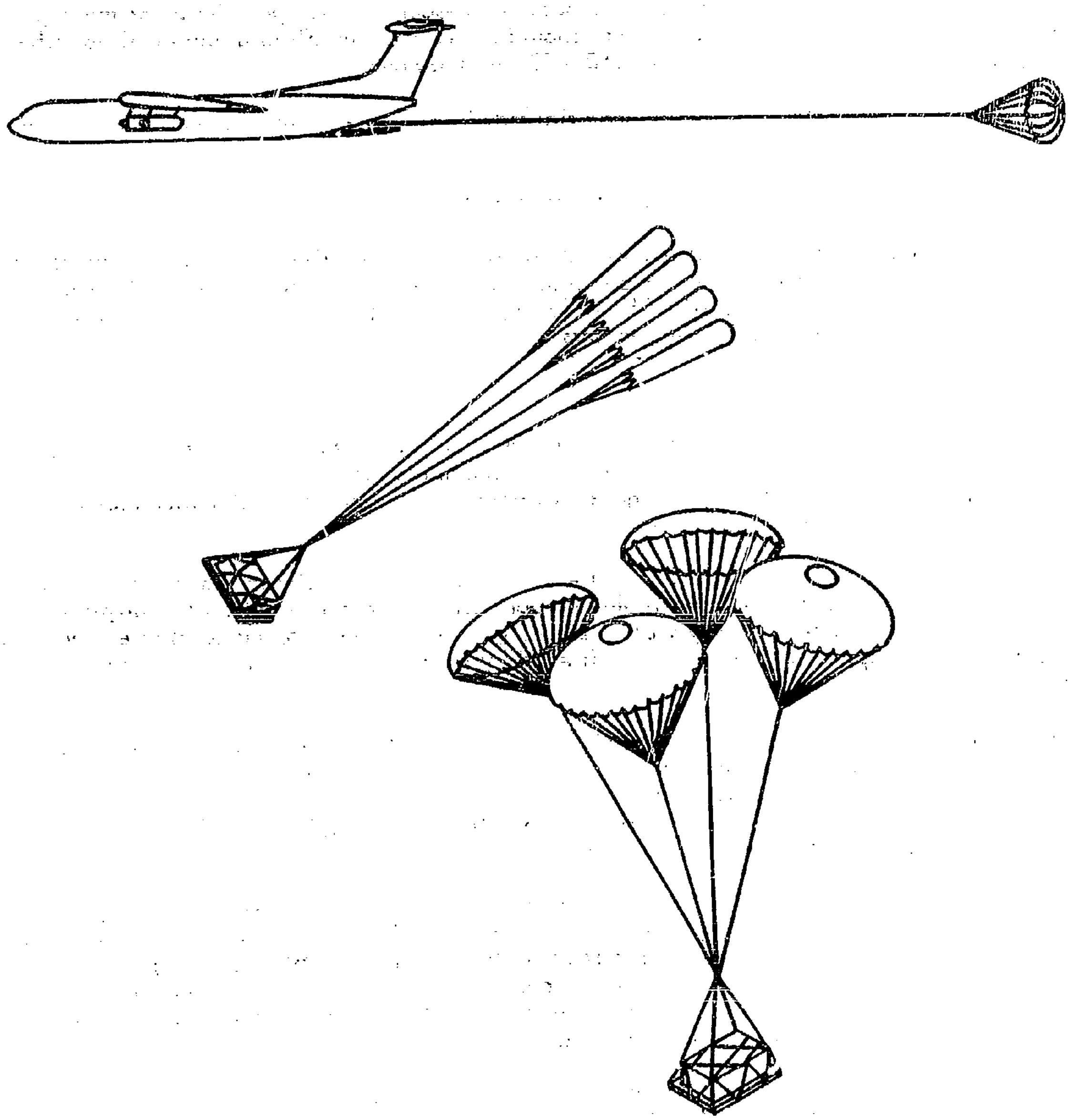


Figure 35 – Parachute Aerial Delivery System

For operation in the high speed descent mode, the descent control parachute, or the degree of reefing of the main parachute cluster, should be adjusted to afford a sea-level equilibrium descent velocity in the range of 150 - 175 feet/second.

The platform impact shock absorbing material may be the same as for the para-rocket system.

Design Point Selection

Selection of system design points is partly predicated on capability limitations for the specefic airplane to which the system is applied, and partly predicated on capability limitations inherent in the system itself. The following is a discussion of the design point selection with reference to these limiting factors.

Aircraft Limitations

Figure 7 shows the average extraction load factor required for the C-141 airplane in order that the airplane pitch angle excursion due to cargo motion should not cause the airplane design loads to be exceeded. The required average extraction load factor increases with cargo weight and aircraft flight speed.

Previous experience with the C-130 and the C-141 airplanes has shown that excessive extraction load factors, although desirable and permissible from the standpoint of airplane flight safety, lead to undesirably violent pitching motion of the drop cargo after extraction. A reasonable compromise appears to be afforded by an average extraction load factor of about 1.5.

Using this value, a cross-plot is presented in Figure 36, which shows the relation between permissible cargo weight and airplane flight speed at extraction, along with the cargo weight and airplane flight speed ranges specified for the study. For the C-5A airplane, the maximum drop cargo weight is limited by specification to 50,000 pounds, with no weight or speed limitations within this range.

As is illustrated in Figure 36, the permissible speed range for the C-141 is extremely narrow for the highest drop cargo weight, but widens as the cargo weight decreases. Any delivery system designed for multi-aircraft compatibility must necessarily satisfy requirements imposed by the "critical" aircraft. In addition, since system performance rather tends to a slight degradation with increase in aircraft speed, the following design points have been selected for the purpose of system performance analysis:

Cargo Gross Weight Range - Pounds	Airplane Speed at Extraction - Knots
35,000 - 50,000	150
50,000 - 70,000	130

Design average extraction load factor $\bar{n}_e = 1.5$

System Limitations

The only limitation imposed on the design point selection by system features is concerned with specification of the minimum drop altitude; i.e., the minimum flight altitude for cargo extraction.

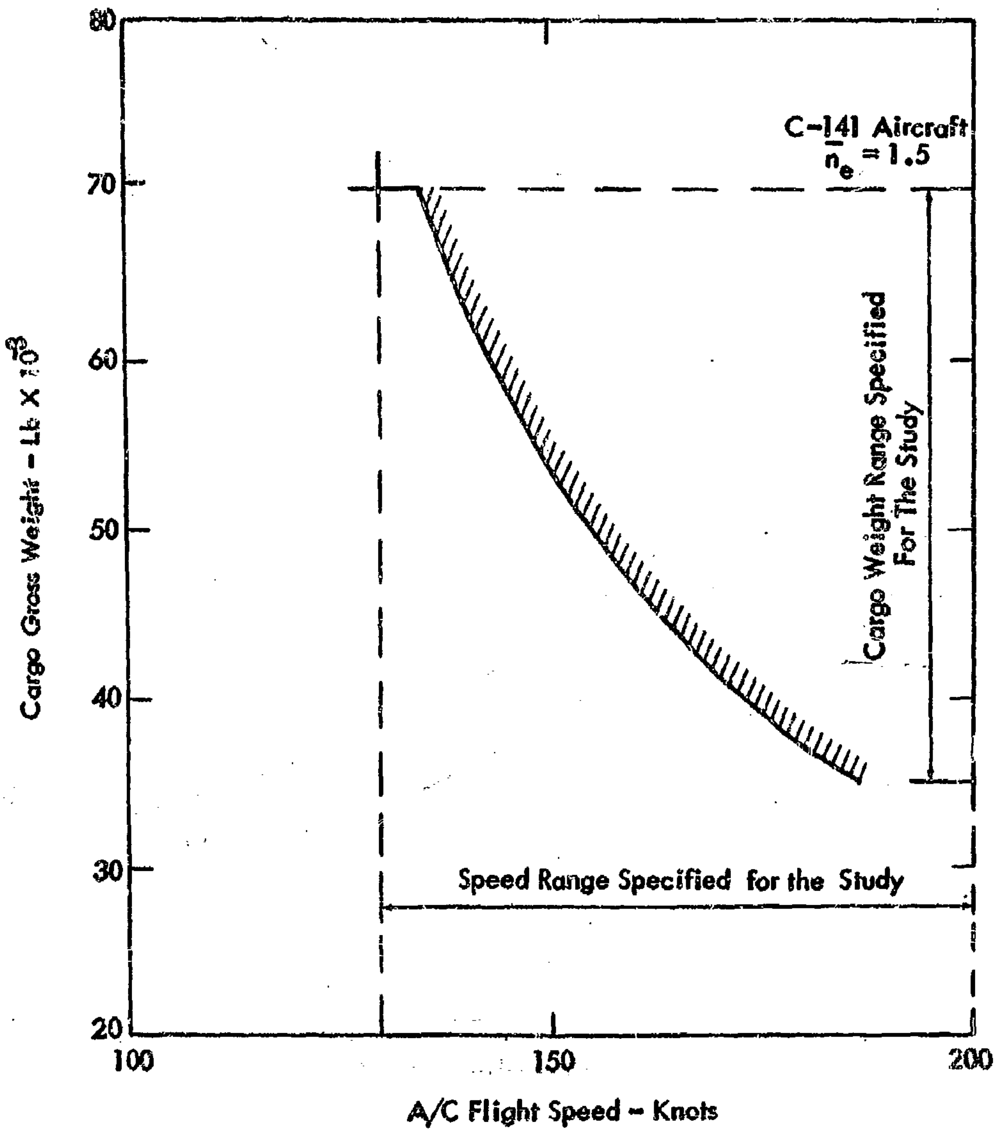


Figure 36 - Limiting Combinations of Cargo Weight and Aircraft Flight Speed at Extraction

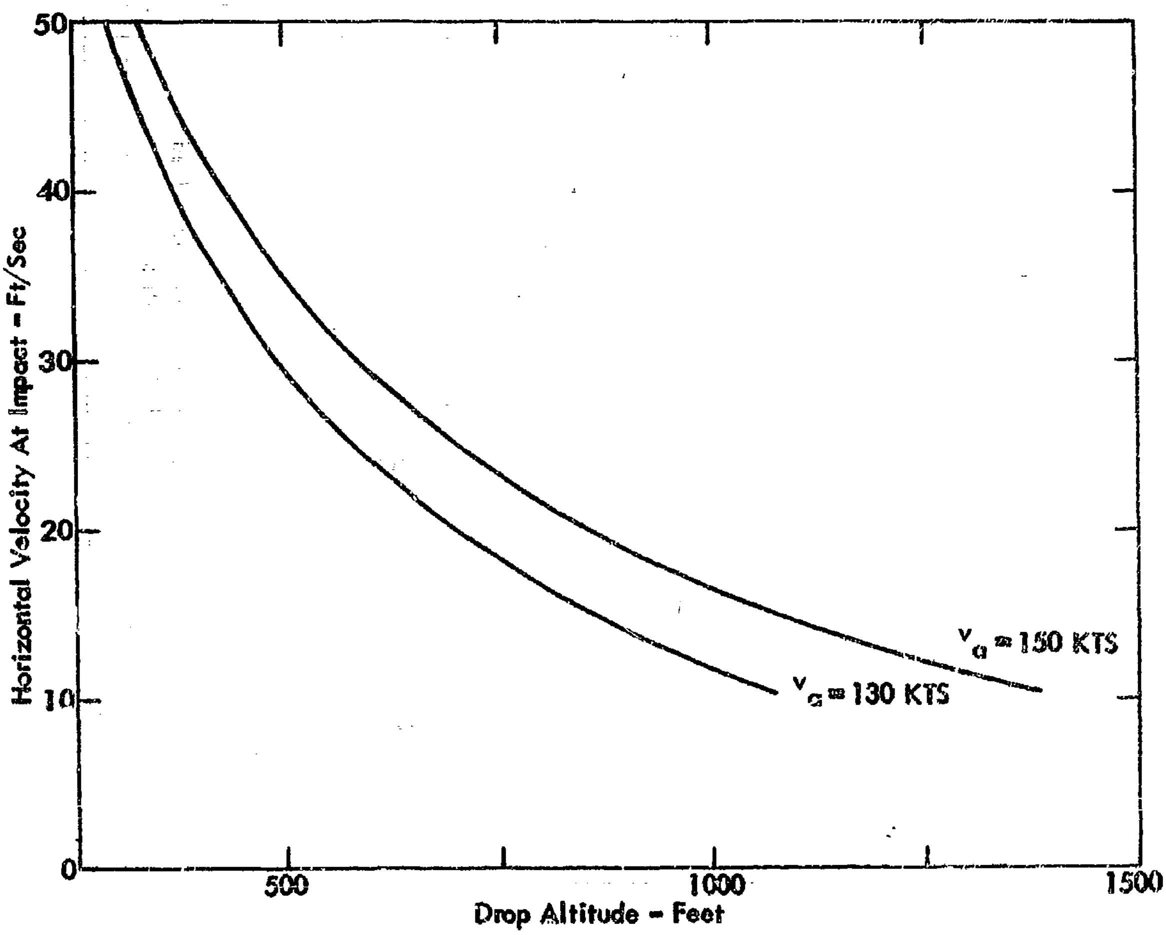


Figure 37 - Horizontal Impact Velocity Component versus Drop Altitude - Para-rocket Delivery System

For the para-rocket system, this altitude depends on the acceptable magnitude of the horizontal impact velocity component, as is shown in Figure 37. Assuming that a value of 15 feet/second can be tolerated, the minimum drop altitude is as follows:

Cargo Weight Range - Pounds	Minimum Drop Altitude - Feet
35,000 - 50,000	1100
50,000 - 70,000	900

For the parachute system, the minimum drop altitude must be equal to or greater than the cargo drop distance during the main parachute cluster deployment and inflation period.

Figure 38 shows these quantities as evaluated by means of a computer program developed from the equations given in Reference 4.

The reason for the apparent incongruities in the altitude loss components shown in Figure 38 lies in the particular combinations of aircraft speed at extraction and extraction load factor used in the evaluation. These combination, shown in Table X, were on one hand predicated on the requirements for minimum average extraction load factor mentioned earlier, and on the other hand on the requirement for standardized components in a simulated operational system. The most unfavorable combination yields a total deployment and inflation altitude loss of 1040 feet. This assessment has a certain built-in element of optimism. The main canopy was assumed to be inflated in a vertical descent condition, while the actual trajectory tanget was closer to a 50° angle to the horizon. This would lead to a somewhat longer inflation time and a larger altitude loss during inflation. For this reason a minimum drop altitude of 1200 feet was judged to be a more realistic assessment of the system capability.

System Design Data

The following paragraphs outline the design data for the selected systems to the level of detail required for input to the performance evaluation model. The essential features of this model are:

- o The drop cargo is represented as a point mass with no aerodynamic drag.
- o The extraction system is represented as a standard unit of a $(\text{speed})^2$ - proportional drag device which may be deployed singly or paired, in conjunction with a specified extraction floor length.
- o The descent control system is represented as a standard unit of a $(\text{speed})^2$ - proportional drag device. For the para-rocket concept, the extraction system also functions as the descent control system, while the parachute system achieves descent control by means of reefed main parachutes. The descent control system is deployed immediately following extraction. It is deployed in clusters of units not exceeding eight in number.
- o For the para-rocket system concept, the recovery system is represented by a rocket cluster suspended between the descent control system and the cargo. The system is characterized by propellant specific impulse, thrust, total burning time, and inert mass ratio.

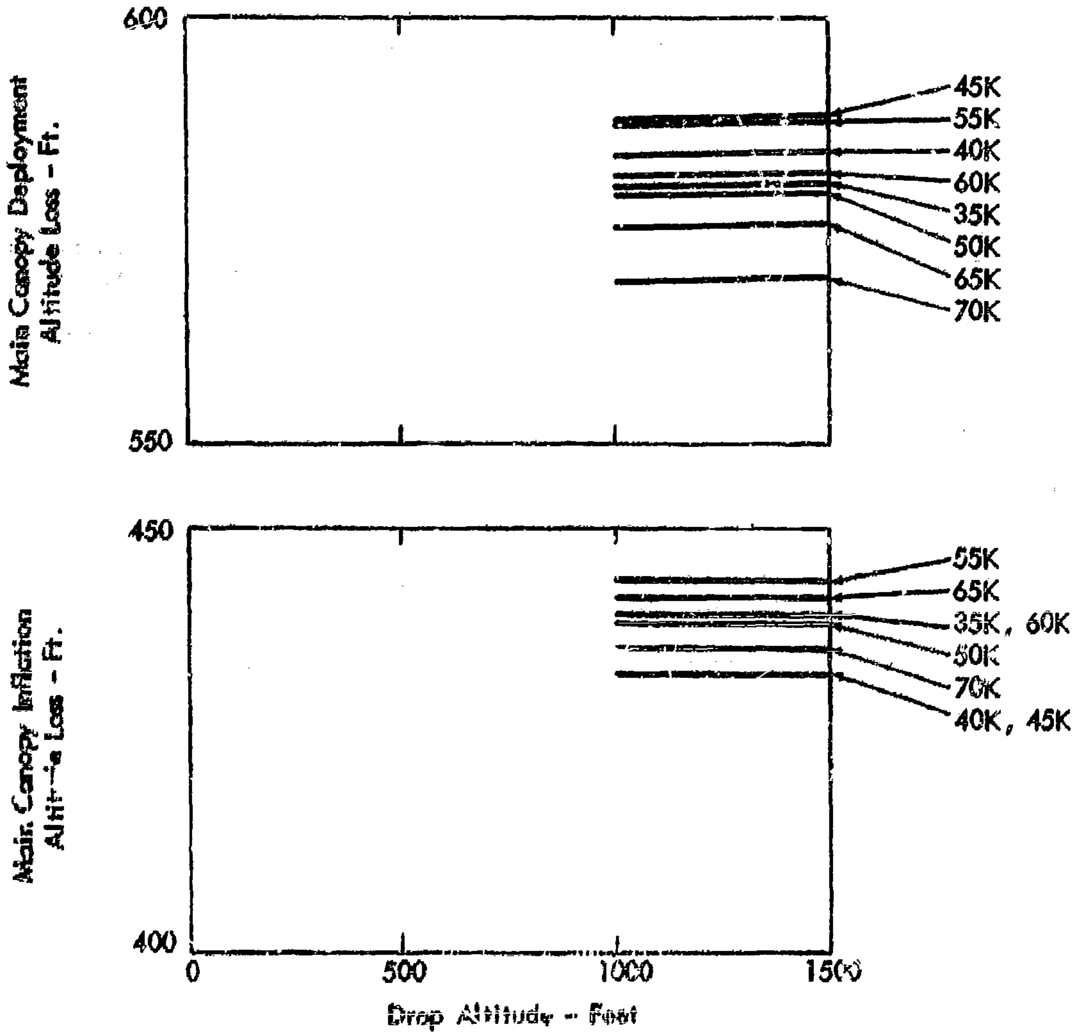


Figure 38 - Compc.ients of Altitude Loss During Main Canopy Deplc ment and Inflation

For the parachute system concept, the recovery system consists of a cluster of not more than eight units of the standard (speed)^2 – proportional drag device.

- o The impact shock alleviating system consists of an energy absorbing device possessing constant, stroke-independent force characteristics.

Para-rocket System

Extraction – The extraction system design was based on the concept of one single size of extraction parachute accommodating the complete range of cargo loads. This parachute, a 47.8-foot diameter ring-slot type, will be used as shown in Table XI.

TABLE XI

EXTRACTION SYSTEM DATA

Cargo Weight Pounds	Number of Extraction Parachutes	Extraction Load Factor g	Aircraft Speed Knots
35,000	1	1.5	131.5
40,000	1	1.5	140.5
45,000	1	1.518	150.0
50,000	1	1.366 (>1.277)*	150.0
55,000	2	1.680	130.0
60,000	2	1.540	130.0
65,000	2	1.422	130.0
70,000	2	1.32 (>1.18)*	130.0

*Minimum required average extraction load factor for cargo weight and speed combination – C-141 aircraft.

The weight of a single parachute with suspension lines is 150 pounds (Reference 4).

Descent – It is assumed that the descent control will be accomplished by the extraction system. The performance in this mode is illustrated by the values in Table XII.

TABLE XII

DESCENT CONTROL PERFORMANCE CHARACTERISTICS

Cargo Weight Pounds	Number Of Parachutes	Sea Level Descent Equilibrium Speed Feet/Second
35,000	1	179.25
40,000	1	193.0
45,000	1	205.7
50,000	1	216.8
55,000	2	169.8
60,000	2	176.75
65,000	2	184.70
70,000	2	191.0

Recovery – The recovery system consists of a cluster of rockets, with nozzles canted outward about 30 degrees, suspended from the apex point of the descent control parachute cluster. From the lower end of the rocket cluster assembly, a load suspension line is attached which connects with the cargo platform suspension arrangement. The length of the cargo suspension line is about 100 feet. The recovery system weight, W_r, can be expressed as

$$W_r = C_1 W_P + C_2 (n_r + 1) W_c \tag{58}$$

where

$$C_1 = \frac{\text{Rocket Gross Weight}}{\text{Net Rocket Propellant Weight}}$$

W_p = Net rocket propellant weight

C_2 = Weight/strength coefficient for load suspension, in pounds of weight per pound of load

n_r = Rocket thrust load factor, $T/(W_c + W_r)$

The rocket propellant weight, W_p, can be expressed as

$$W_P = T \frac{t_b}{I_{sp}} = n_r (W_c + W_r) \frac{t_b}{I_{sp}} \tag{59}$$

where

t_b = Rocket burning time in seconds

I_{sp} = Effective specific impulse for propellant, allowing for nozzle cant angle

The rocket burning time is

$$t_b = \frac{\Delta v}{g (n_r - 1)} \tag{60}$$

where

Δv = Velocity increment absorbed in recovery

Consolidating these equations, the following expression is obtained for the recovery system weight ratio

$$W_r/W_c = \frac{C_1 \dfrac{n_r}{n_r - 1} \dfrac{\Delta v}{g\, I_{sp}} + C_2 (n_r + 1)}{1 - C_1 \dfrac{n_r}{n_r - 1} \dfrac{\Delta v}{g\, I_{sp}}} \tag{61}$$

Typical state-of-the-art values for the constants are

$C_1 = 1.15$

$C_2 = 1.413 \times 10^{-3}$ (100-foot nylon webbing)

$I_{sp} = 160$ (30-degree nozzle cant angle)

Figure 39 shows values for the system weight ratio W_r/W_c for varying values of recovery velocity increment Δv and recovery load factor n_r.

The data shown in Figure 39 indicate that high values of the recovery load factor would be advantageous from a system weight ratio standpoint. In order to determine reasonable design parameter values however, several factors must be considered. Principal of these are:

- o Altitude change during recovery
- o Sensitivity of final recovery velocity to errors in recovery altitude assessment.

Figure 40 shows the variation of altitude loss during recovery as a function of recovery velocity increment Δv and recovery load factor n_r. The recovery altitude loss decreases with increasing n_r, although the rate of recovery altitude reduction also decreases with increasing n_r.

Since the action of the recovery system is triggered by a ground proximity signal which is preset for a specific recovery altitude, the sensitivity of the final recovery velocity to errors in recovery altitude setting is important. A low sensitivity is desirable. Figure 41 shows the variation of the sensitivity coefficient $dv_f/d(\Delta h)$ with variations in recovery velocity increment Δv and recovery load factor, n_r. The sensitivity is lowest for low values of n_r and increases with increasing values of n_r. Within the velocity range of principal interest, the sensitivity is about 50 percent greater for $n_r = 4.0$ than for $n_r = 3.0$. For this reason, and because the recovery altitude range for $n_r = 3.0$ is considered acceptable, a value of $n_r = 3.0$ has been selected as basis for the performance evaluation.

In order to present a realistic picture of the system performance, a modular concept was assumed. The characteristics of this unit are:

Thrust, T	= 27,000 pounds
Burning time, t_b	= 2.157 seconds
Total Impulse, I	= 61,750 pound · seconds

The cluster assembly characteristics for the various drop cargo weights are as shown in Table XIII. The last two columns are based on the cargo weight and equilibrium descent velocities shown in Table XII.

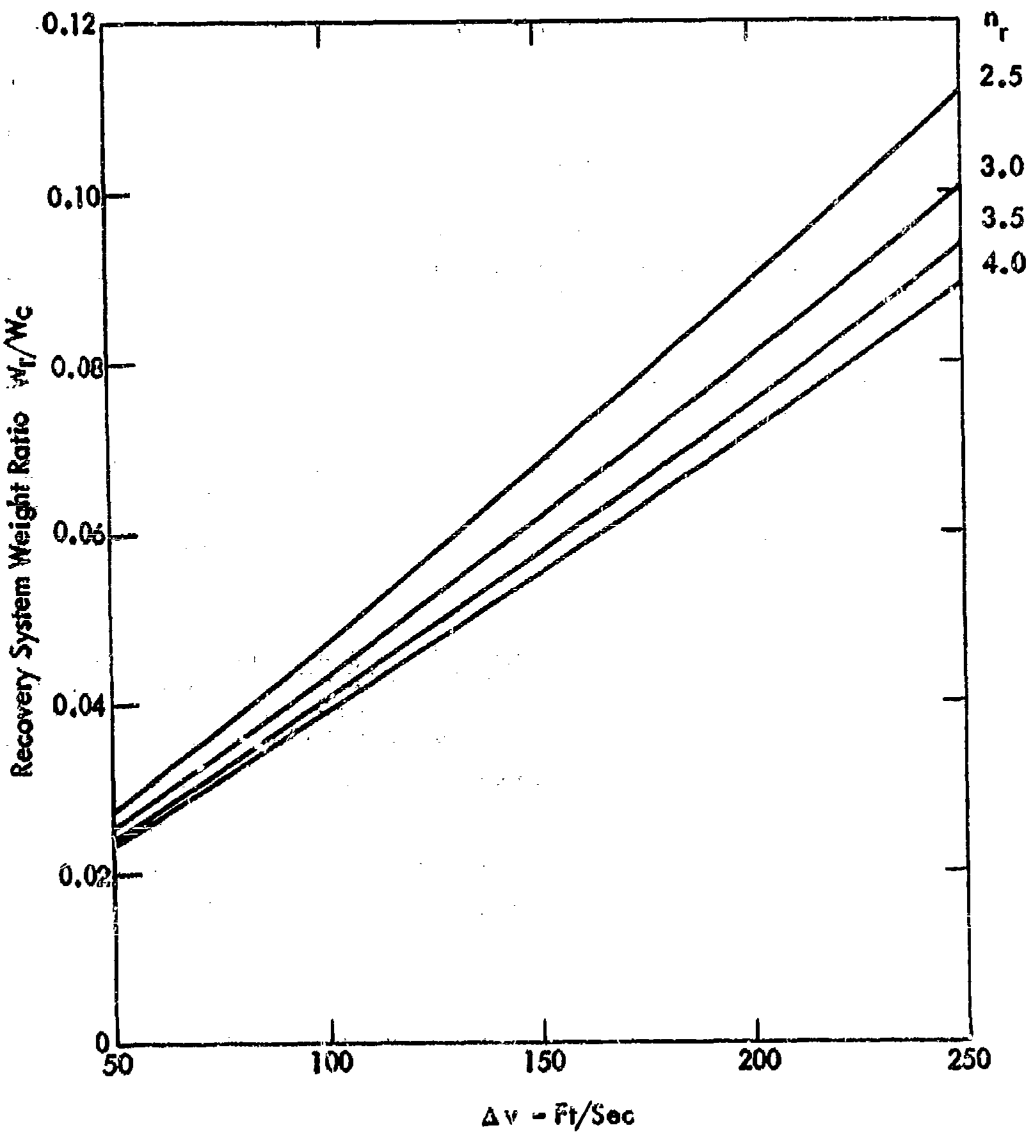


Figure 39 - Variation of System Weight Ratio with Recovery Velocity Increment and Recovery Load Factor - Para-rocket Recovery System

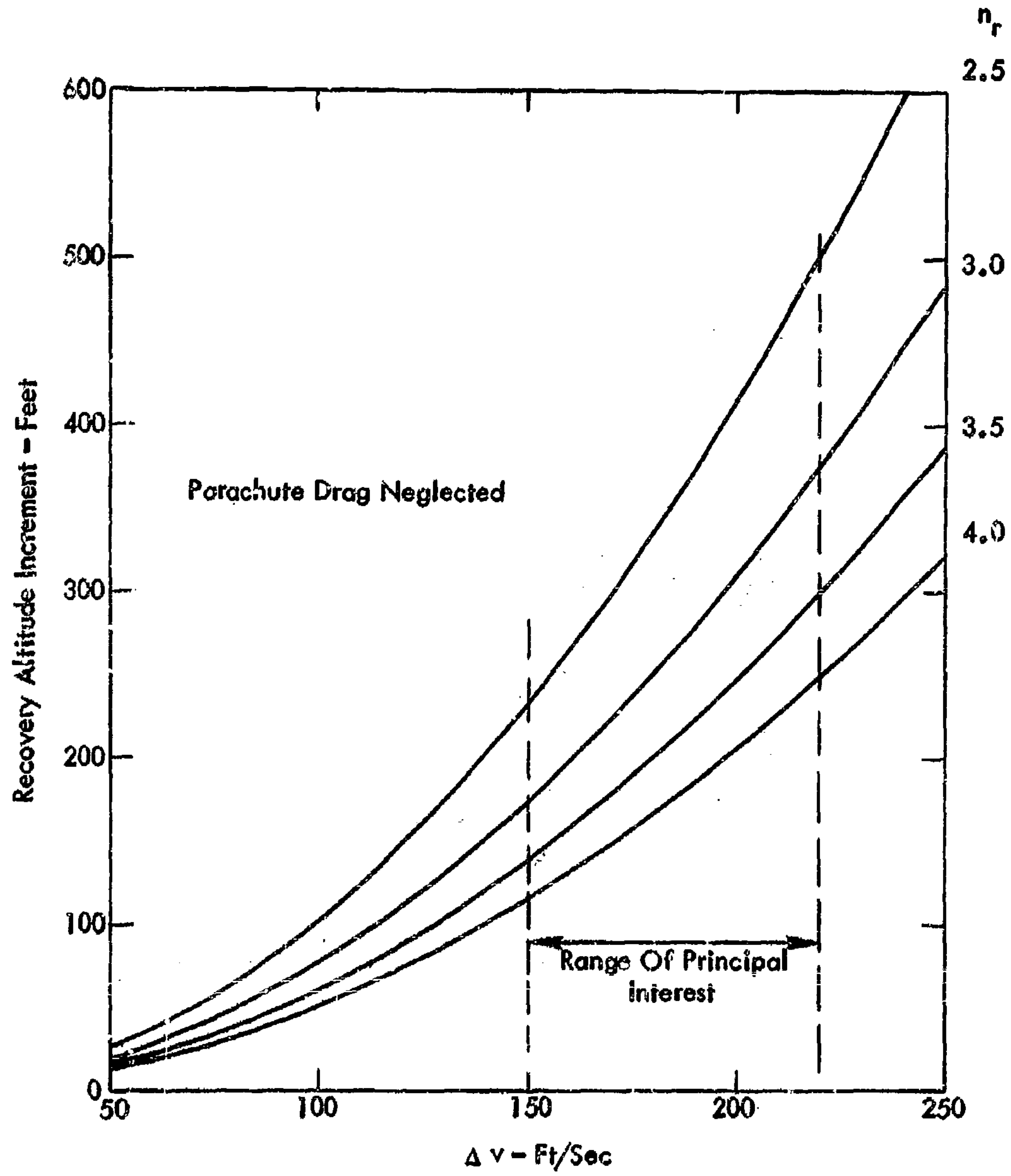


Figure 40 - Variation of Recovery Altitude Increment with Recovery Velocity Increment and Recovery Load Factor - Para-rocket Recovery System

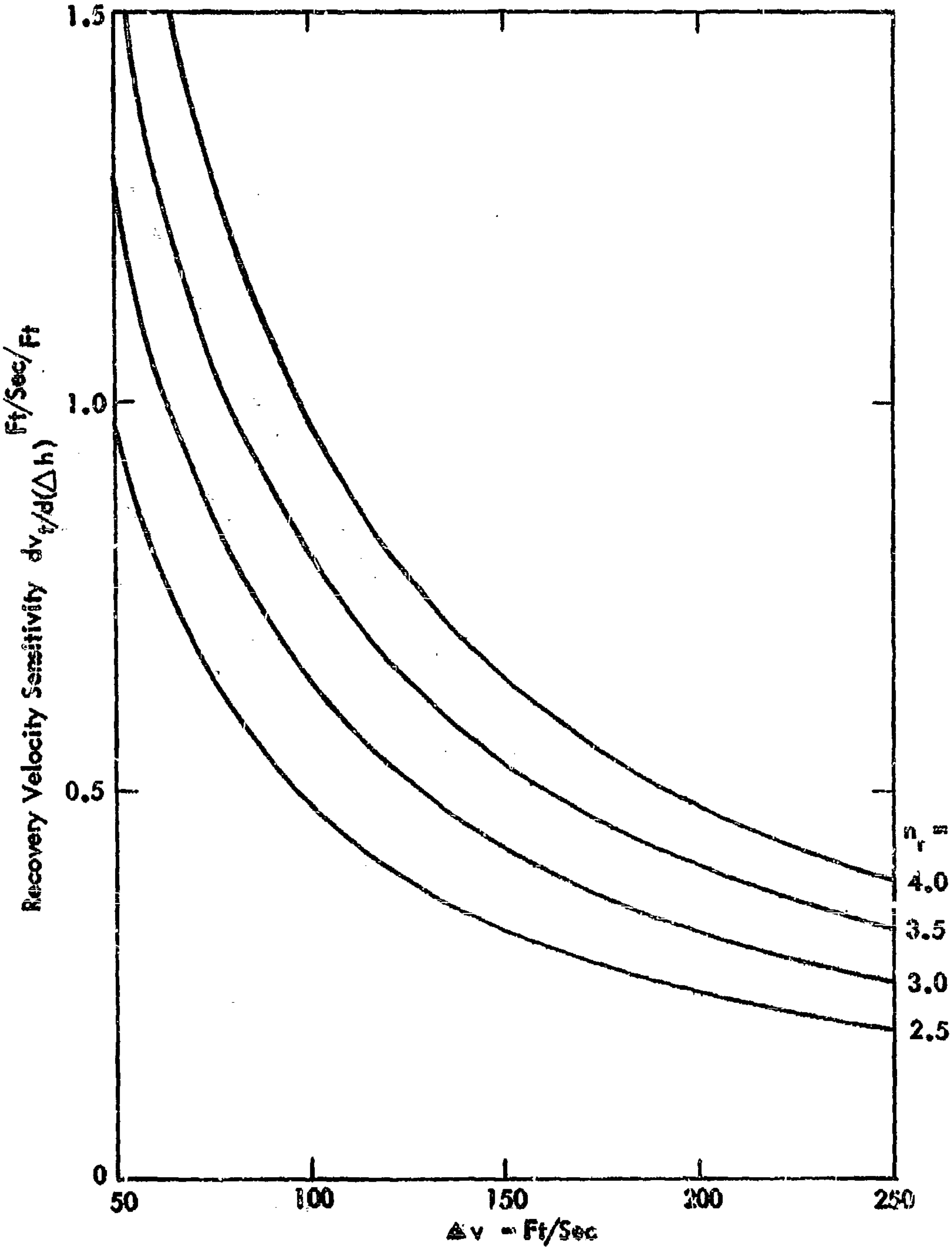


Figure 41 – Sensitivity of Final Recovery Velocity to Recovery Altitude Error for Various Velocity Increments and Load Factor – Para-rocket Recovery System

TABLE XIII

ROCKET CLUSTER CHARACTERISTICS

Cargo Weight, Pounds	Number of Modules	Rocket Load Factor	Cluster Impulse, Pound · Seconds	Cargo Impulse Range Pound · Seconds 0 FPS	25 FPS
35,000	4	3.087	247,000	258,000	220,300
40,000	5	3.376	308,700	314,000	270,750
45,000	6	3.600	370,300	373,600	325,000
50,000	7	3.78	432,000	436,000	382,100
55,000	6	2.947	370,300	380,700	320,700
60,000	7	3.149	430,000	433,000	367,400
65,000	8	3.327	430,000	486,400	416,000
70,000	8	3.087	494,000	542,200	466,300

These values were used for the performance evaluation.

Impact – The impact attenuation system is assumed to consist of paper honeycomb padding on the cargo platform in an amount designed to accommodate a 25 foot/second vertical impact velocity at an impact load factor or $n = 20.0$. This corresponds to a required thickness for the honeycomb padding of about 6 inches.

Parachute System

The parachute system was based on a modular concept in order to accommodate the wide range in cargo weights with a minimum number of different components required in inventory.

Extraction – Since the performance requirements for this system are determined by aircraft limitations, the same extraction system will be used as was described for the para-rocket system, above.

Descent and Recovery – This system is based on a 141.5-foot flat canopy reefable parachute as the standard building block. In the descent control mode, this parachute is deployed reefed in clusters of from four to eight parachutes depending on the weight of the cargo. The degree of reefing is adjusted to achieve a sea level terminal velocity of about 175 feet/second.

The number of parachutes is shown in Table XIV.

Weights for the parachute system are as follows:

Extraction	W_e = 150 pounds (per chute)
Descent and Recovery (Including riser lines)	W_r = 561 pounds (per chute)

Impact – The impact attenuation system is assumed to be identical to that used for the para-rocket system.

TABLE XIV

PARACHUTE CLUSTER CHARACTERISTICS

Cargo Weight Pounds	Number of Parachutes in Cluster	Sea-Level Equilibrium Velocity Feet/Second
35,000	4	25.0
40,000	5	23.9
45,000	6	23.13
50,000	6	24.40
55,000	7	23.66
60,000	7	24.72
65,000	8	24.10
70,000	8	25.0

Scope of Performance Evaluation

The extraction, descent and recovery phase characteristics for the two systems were explored by means of cargo drop simulations performed on automatic digital computing equipment. The drop conditions were set up for altitudes from 1000 feet to 30,000 feet, for cargo weights varying in 5000-pound increments within the range from 35,000 pounds to 70,000 pounds, and with aircraft flight speeds and peak extraction load factors assigned to be compatible with the aircraft limitations described in the section on Design Point Selection. The scope of the performance analyses is shown in Table XV.

In addition, the expected values for the drop precision in terms of root-mean-square miss distances were determined for all cargo weights for drops from 1500, 15,000, and 30,000 feet.

Results of Performance Evaluation

Extraction System Performance

The extraction system performance is characterized by:

- o Duration of extraction period
- o Cargo exit velocity from the airplane
- o Cargo airspeed after extraction
- o Cargo ground travel during extraction

The variation in cargo extraction time with flight altitude from zero to 30,000 feet is shown in Figure 42 for all cargo weights within the specified range. There is a general tendency for the extraction time to decrease with increasing flight altitude. The reason for this tendency is that the relative reduction of extraction parachute true airspeed during the extraction period is less at high altitude than at lower altitudes (true airspeed = indicated airspeed x $\sigma^{-1/2}$).

TABLE XV

SCOPE OF PERFORMANCE EVALUATION

Drop Cargo Weight, Pounds	A/C Flight Speed KIAS	Drop Alt. Feet	Extraction System Ring-Slot Chute: No. of Chutes	Extraction System Ring-Slot Chute: Extrac. Load Factor	Descent Control, Ring-Slot Chute: Computed Performance Data	Descent Control, Reefed Main Chute: No. of Chutes	Descent Control, Reefed Main Chute: Computed Performance Data	Recovery System, Rocket: Computed Data	Recovery System, Disreefing: Computed Data
35,000	131.5		1	1.500		4			
40,000	140.5		1	1.500	Extraction	5	Descent Time	Recovery	Recovery
		1,000,			Time			Distance	Distance
45,000	150.0		1	1.518		6	Horizontal		
		10,000			Exit Velocity		Travel	Recovery Load Factor	Recovery Load Factor
50,000	150.0		1	1.366	Cargo Exit True Air-speed	6			
		15,000			Descent Time		Terminal		
55,000	130.0		2	1.680		7	Velocity	Impact Velocity	Impact Velocity
		20,000			Horizontal			System Wt. Ratio	System Wt. Ratio
60,000	130.0		2	1.540	Travel	7			
		30,000							
65,000	130.0		2	1.422	Terminal Velocity	8			
70,000	130.0		2	1.320		8			

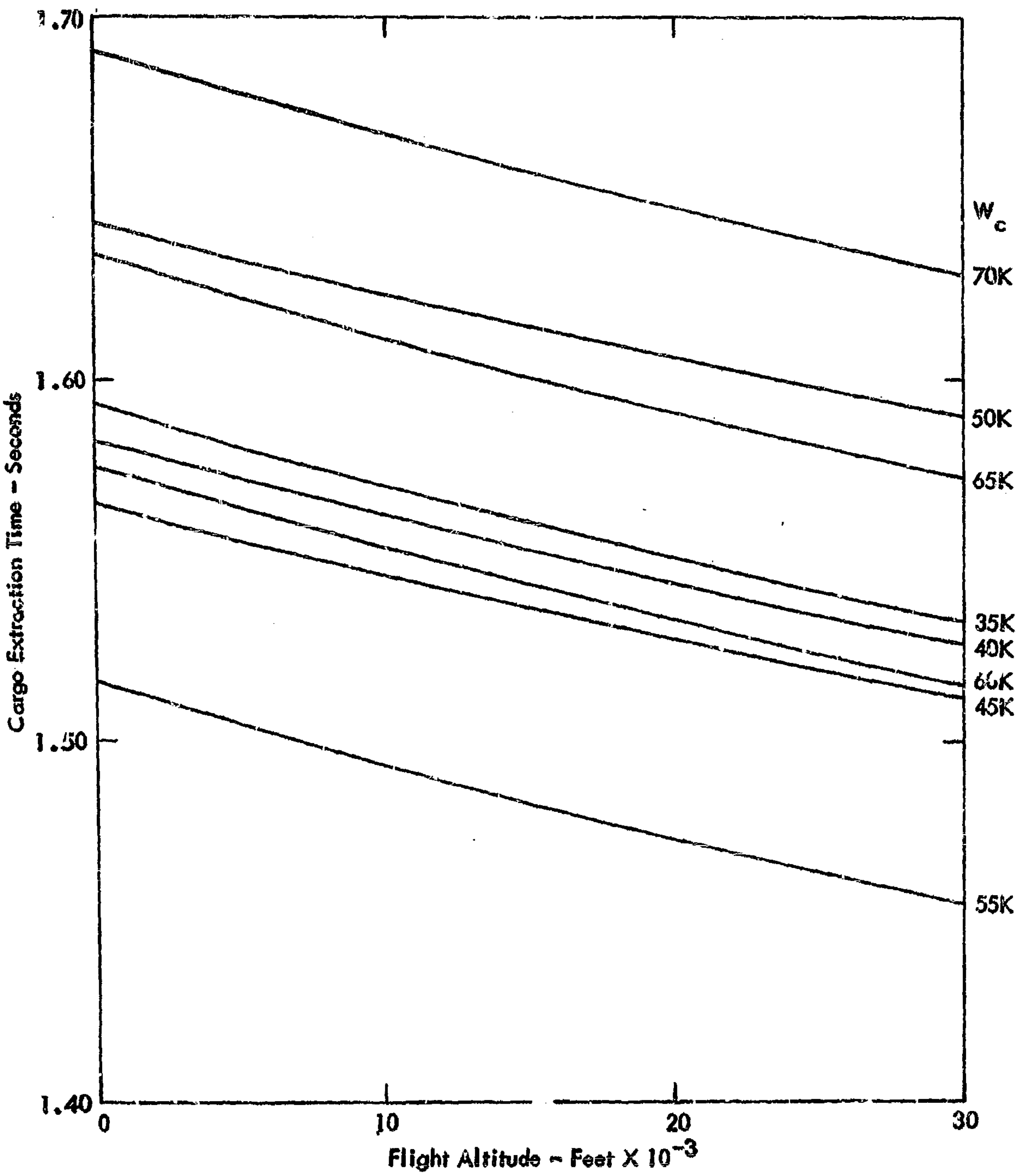


Figure 42 - Cargo Extraction Time versus Flight Altitude

For equal initial values of extraction load factor (corresponding to equal indicated airspeeds), the decay of extraction parachute drag during the extraction period will consequently be less at high than at lower altitudes, leading to a higher average extraction load factor and shorter extraction times (for equal extraction floor lengths). The data assume an extraction floor length of 50 feet.

The particular pattern of cargo extraction times for the various, cargo weights shown in Figure 42 reflects the influence of the combinations of cargo weights, initial extraction load factors and flight speeds at extraction shown in Table XI.

Figure 43 shows the variations of cargo exit velocity and post-extraction true airspeed for the cargo for all altitudes and specified cargo weights.

Figure 44 shows the variation of cargo horizontal travel from the extraction initiation point during the extraction period. This is the most significant performance parameter for the extraction system, due to its direct relation to the total horizontal travel distance of the cargo from initiation of the extraction to ground impact. The magnitude of the extraction horizontal travel distance is influenced by:

- o Variations in indicated airspeed at extraction
- o Gusts occurring at extraction
- o Variations in cargo weight from the nominal value.

The magnitudes of these influences will be demonstrated in the sensitivity analysis.

The performance characteristics presented above were achieved with extraction system weight ratios as shown in Table XVI.

TABLE XVI

EXTRACTION SYSTEM WEIGHT RATIOS

Cargo Weight Pounds	Number of Extraction Chutes	Extraction System Weight Ratio
35,000	1	.00429
40,000	1	.003753
45,000	1	.003335
50,000	1	.00300
55,000	2	.00546
60,000	2	.0050
65,000	2	.00462
70,000	2	.00428

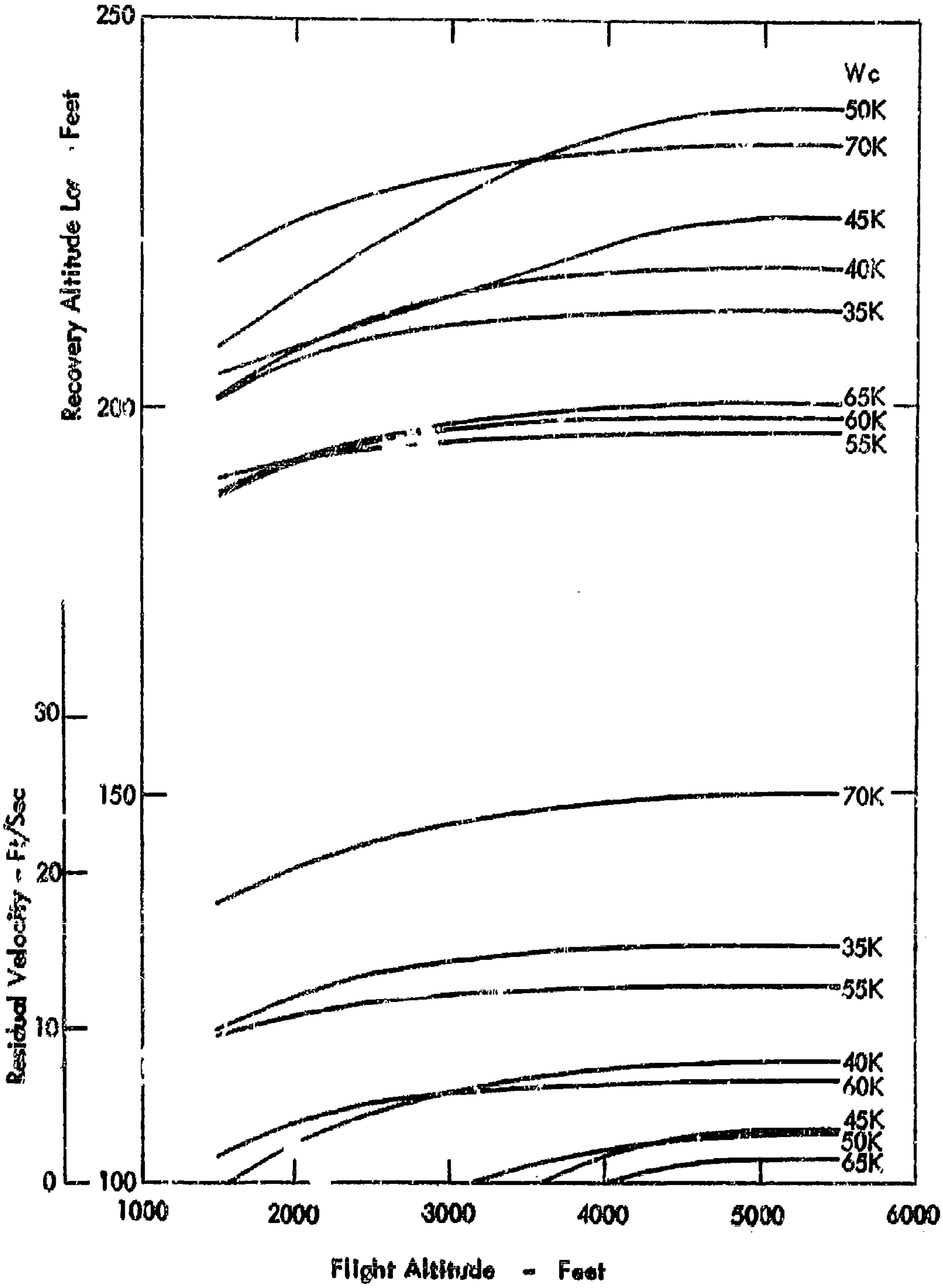


Figure 51 - Recovery Altitude Loss and Residual Velocity - Para-rocket Recovery System

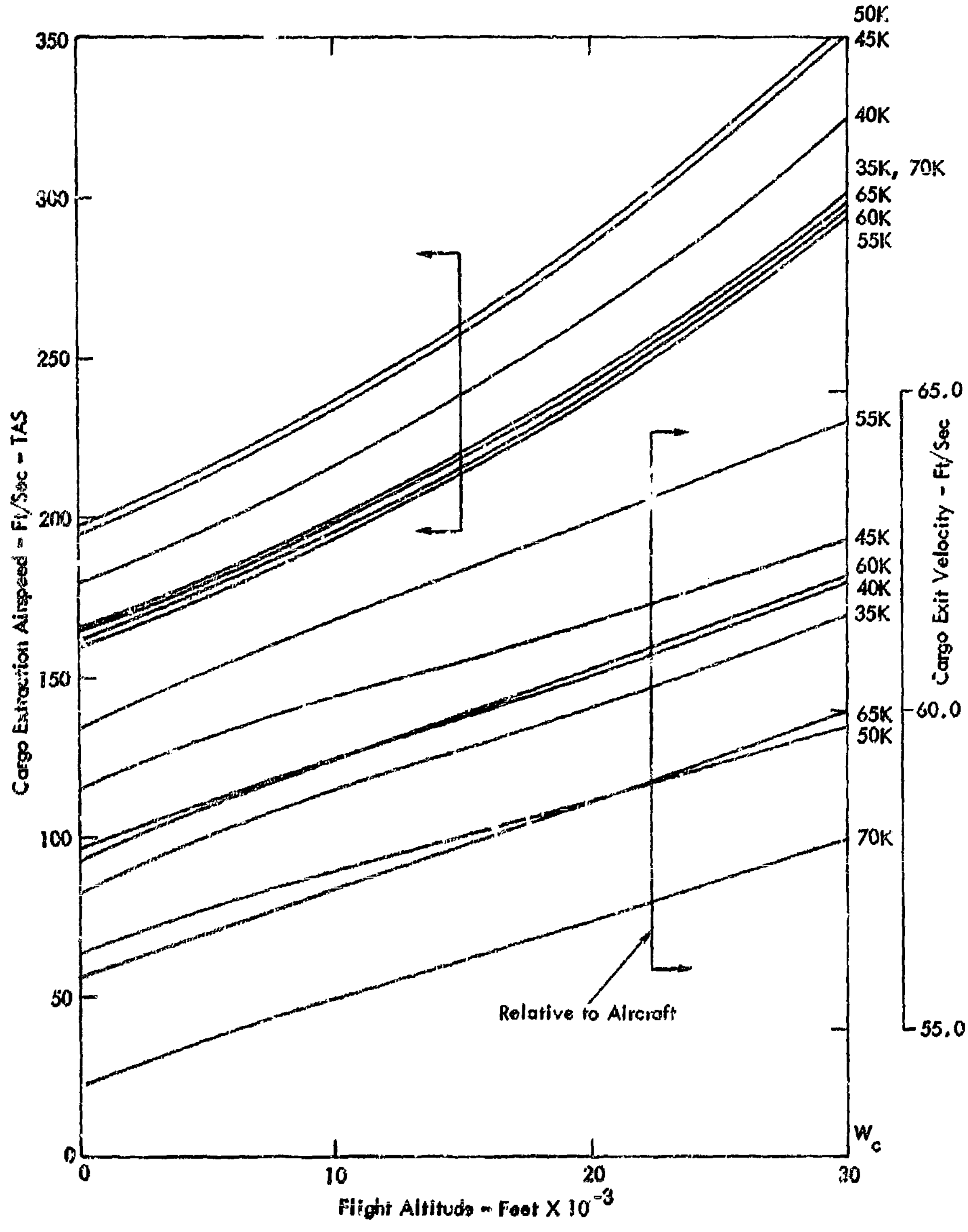


Figure 43 - Cargo Exit Velocity and True Airspeed after Extraction

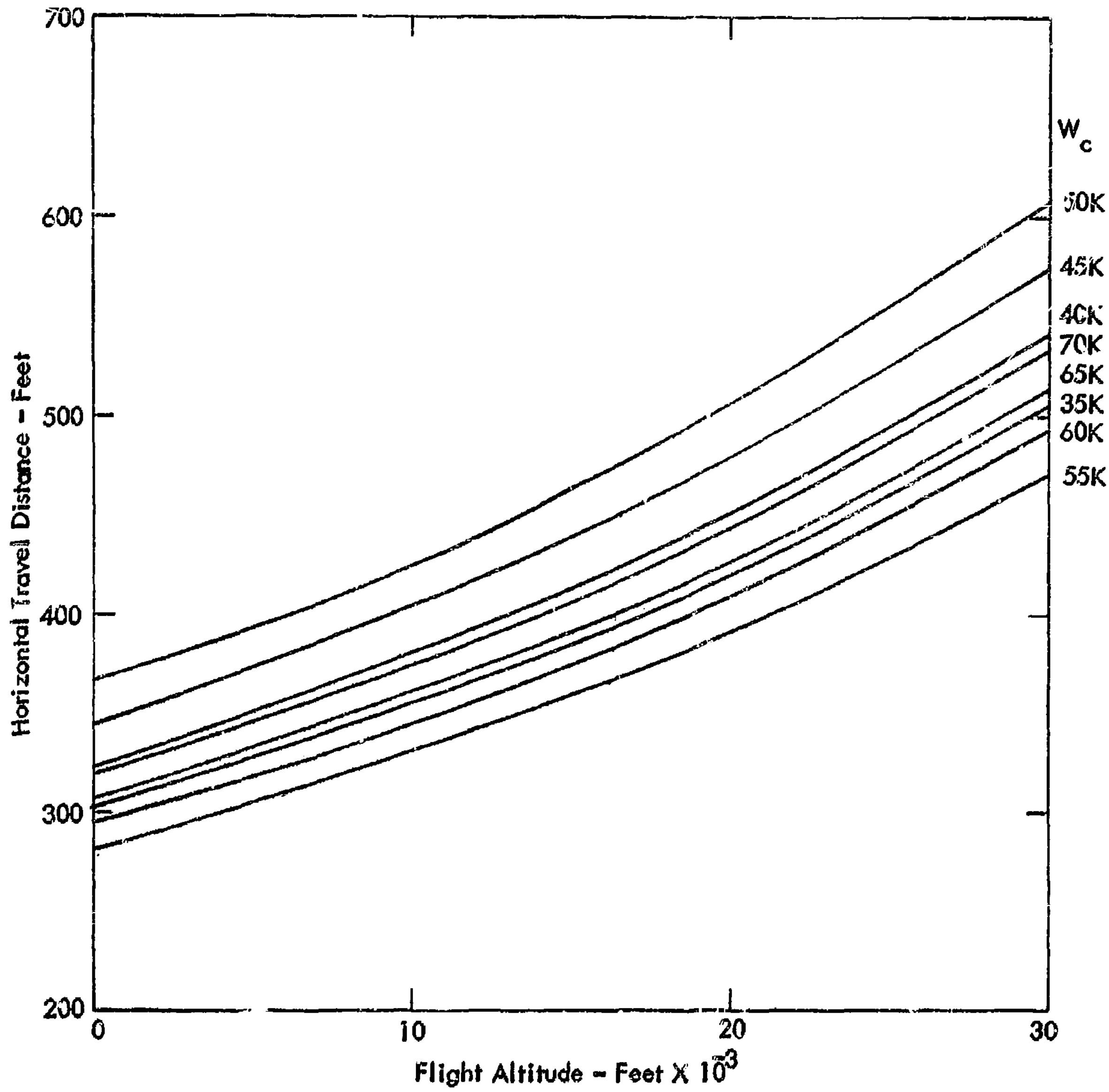


Figure 44 - Cargo Horizontal Travel During Extraction

Descent System Performance

The performance of the descent control system is essentially described by:

- o The trajectory descent time
- o The ground travel distance of the drop cargo
- o The equilibrium or terminal descent velocity

The trajectory descent time is important from the standpoint of measuring the exposure of the drop cargo to outside influences such as wind drift and hostile activity.

The horizontal travel distance data yield information necessary for correct selection of drop aiming point by the flight crew. The equilibrium or terminal descent velocity serves to specify the requirements for recovery system performance in terms of requirements for recovery impulse, recovery altitude, and recovery system weight.

Para-rocket System - The para-rocket system utilizes the extraction parachutes for descent control. The recovery performance of this system is shown in Figures 45 through 47.

The trajectory descent time data, shown in Figure 45 is important inputs to the evaluation of drop precision which will be presented later.

The horizontal travel distance, shown in Figure 46 exhibits two features of interest. One is the considerable spread in horizontal travel distance for drops from equal altitudes with the different cargo weights. This spread is due to the unavoidable differences in terminal velocity resulting from the combinations of extraction chute drag area, cargo weight, and aircraft speed at extraction.

The other interesting feature is the fairly rapid change in horizontal travel distance in the altitude range between 1000 and 2500 feet. This indicates that this altitude range is the most critical with respect to altitude error influence on cargo drop precision.

The drop cargo terminal velocities, shown in Figure 47 illustrate three features of interest.

One is the spread in terminal velocities which results for the same reasons as the spread in ground travel distance. The second is the insensitivity of terminal velocity to flight altitude for altitudes greater than 5000-7500 feet. The third is the rather large, but varying reductions in terminal velocity for the different cargo weights within the altitude range from 0 - 5000 feet. This feature indicates that, since the recovery system obviously must be sized to accommodate the cargo impulse requirements associated with drops from altitudes greater than 5000 feet, it must also possess features permitting the recovery action to be controlled to suit the lesser impulse requirements for drops from altitudes below 5000 feet.

Parachute System - Corresponding data for the reefed main parachute descent control system performance are shown in Figures 48 through 50. Except for two features, these data are qualitatively similar to those shown for the extraction chute descent control discussed above. The first of these features is the much smaller spread between the different cargo weights. This reduction in data spread is caused by the better match between drop cargo weight and descent control device drag area which is achieved by a four-step incrementing of the number of parachutes, along with the seven step incrementing of the cargo weight.

The second feature is the apparently anomalistic behavior of the terminal velocity within the drop altitude range from 1000 - 2500 feet. This behavior is caused by the wide range in cargo airspeeds after extraction, as shown in Figure 43. The post-extraction cargo airspeeds

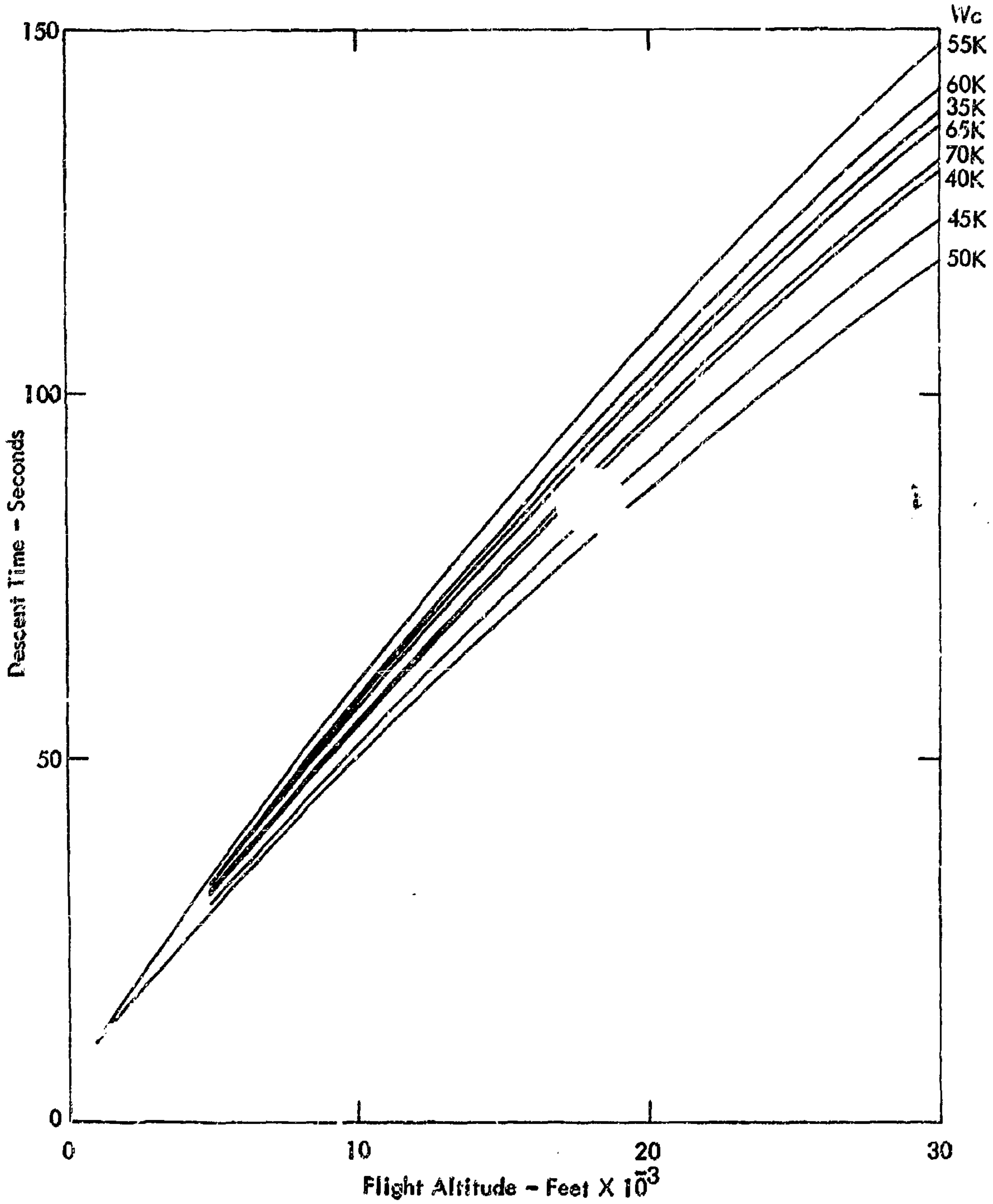


Figure 45 - Cargo Descent Time versus Flight Altitude for Descent with Extraction Chute

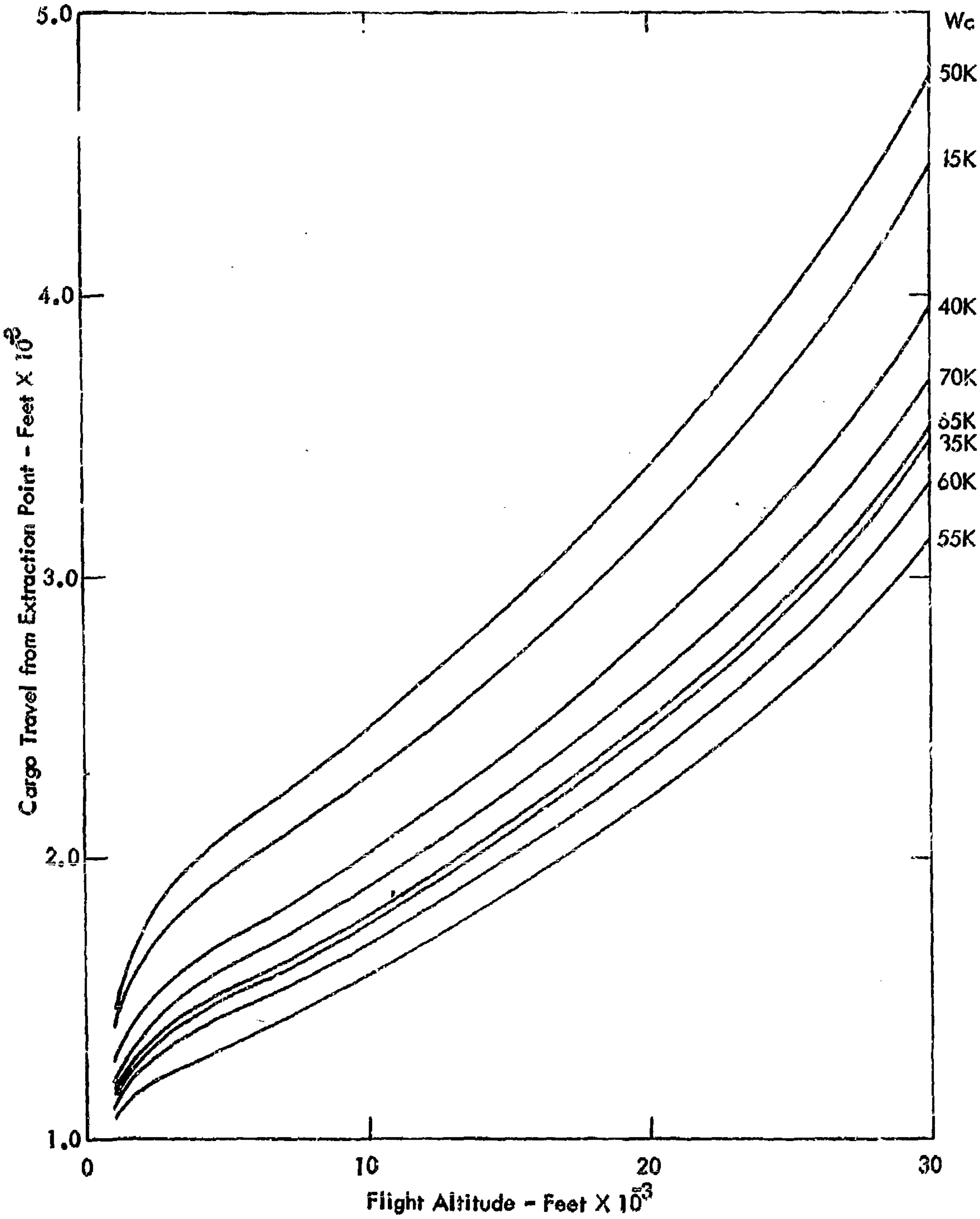


Figure 46 - Cargo Horizontal Travel Distance versus Flight Altitude for Descent with Extraction Chute

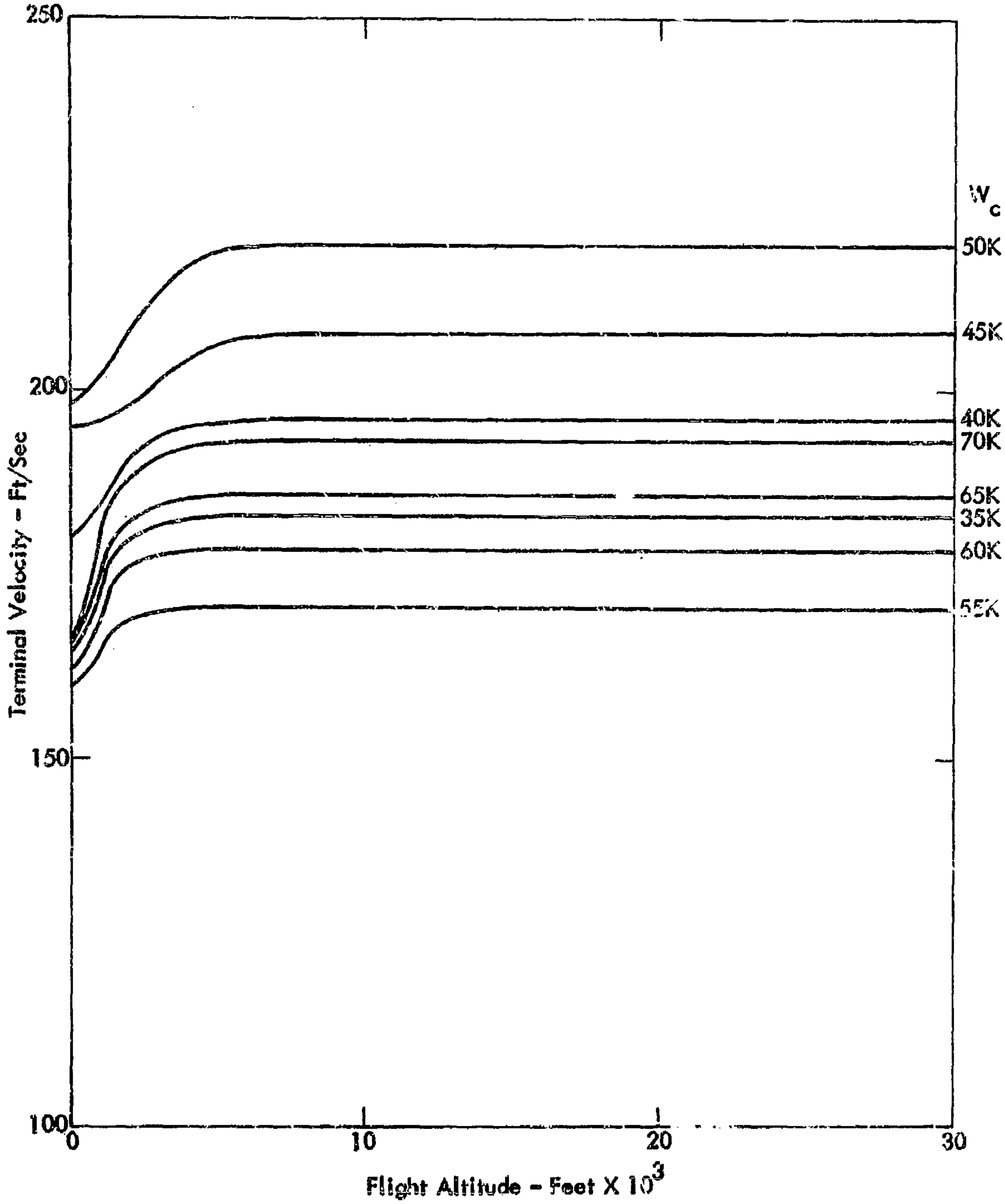


Figure 47 - Cargo Terminal Velocity versus Flight Altitude for Descent with Extraction Chute

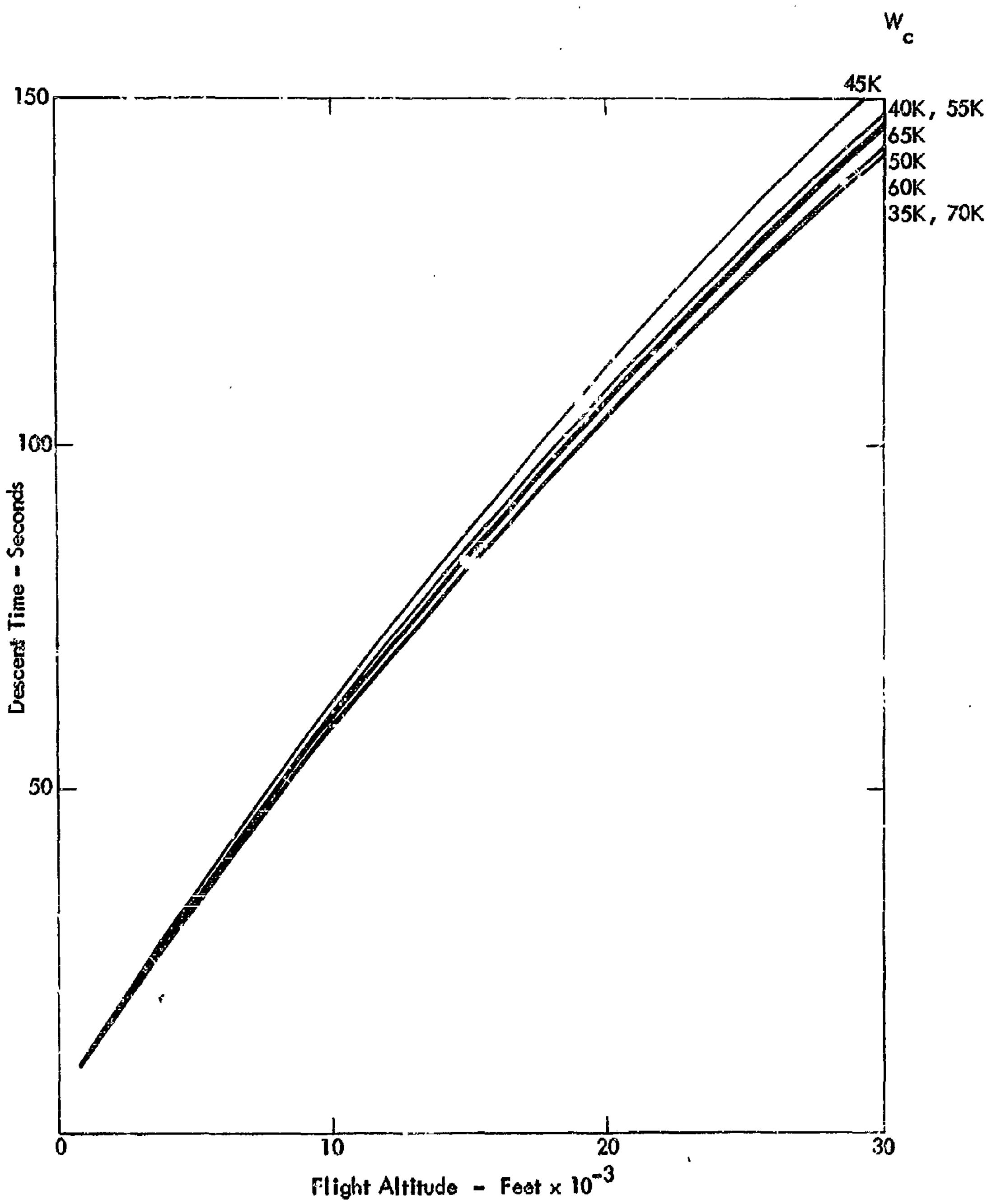


Figure 48 - Cargo Descent Time versus Flight Altitude for Descent with Reefed Main Chute

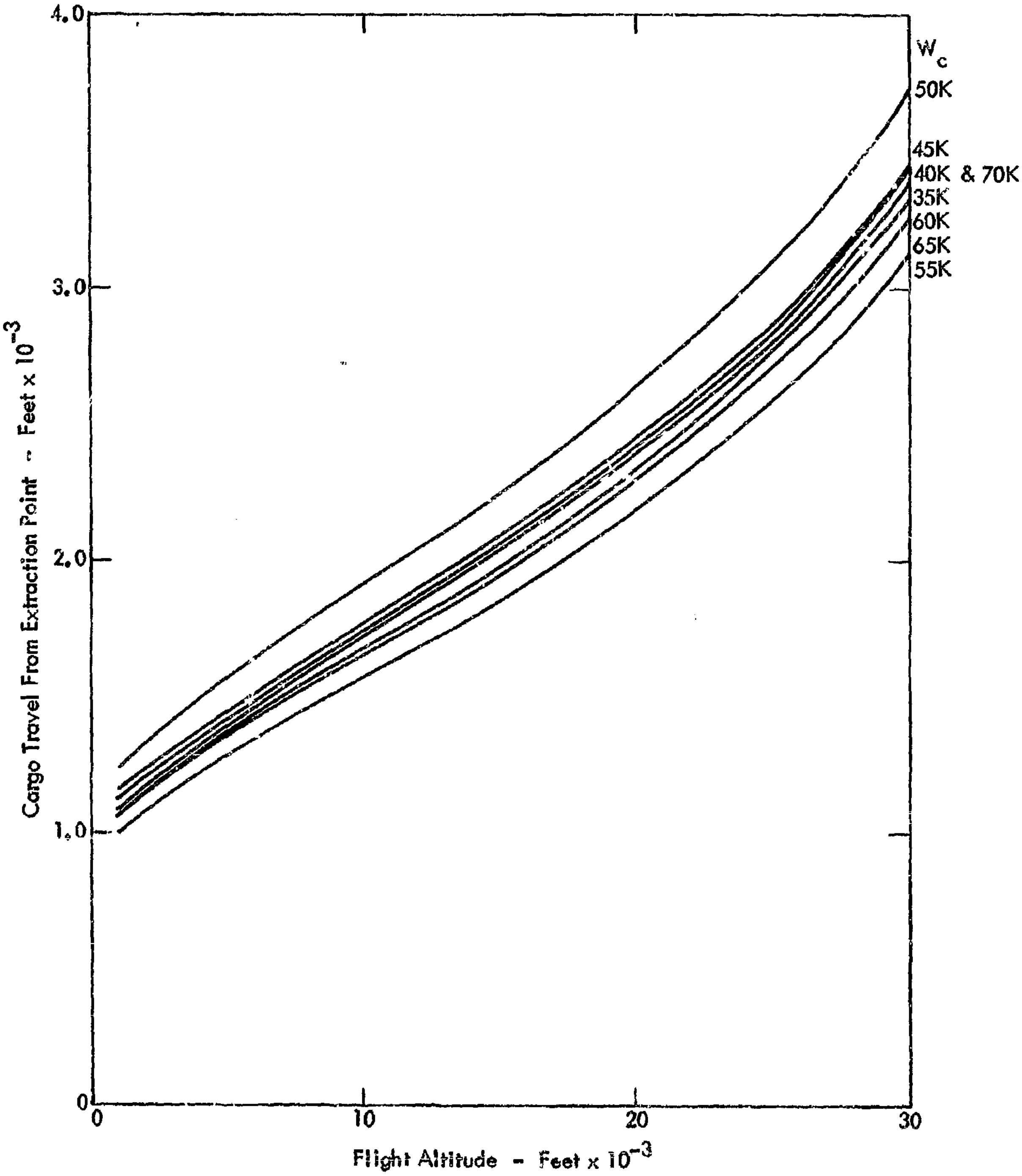


Figure 49 - Cargo Horizontal Travel Distance versus Flight Altitude for Descent with Reefed Main Chutes

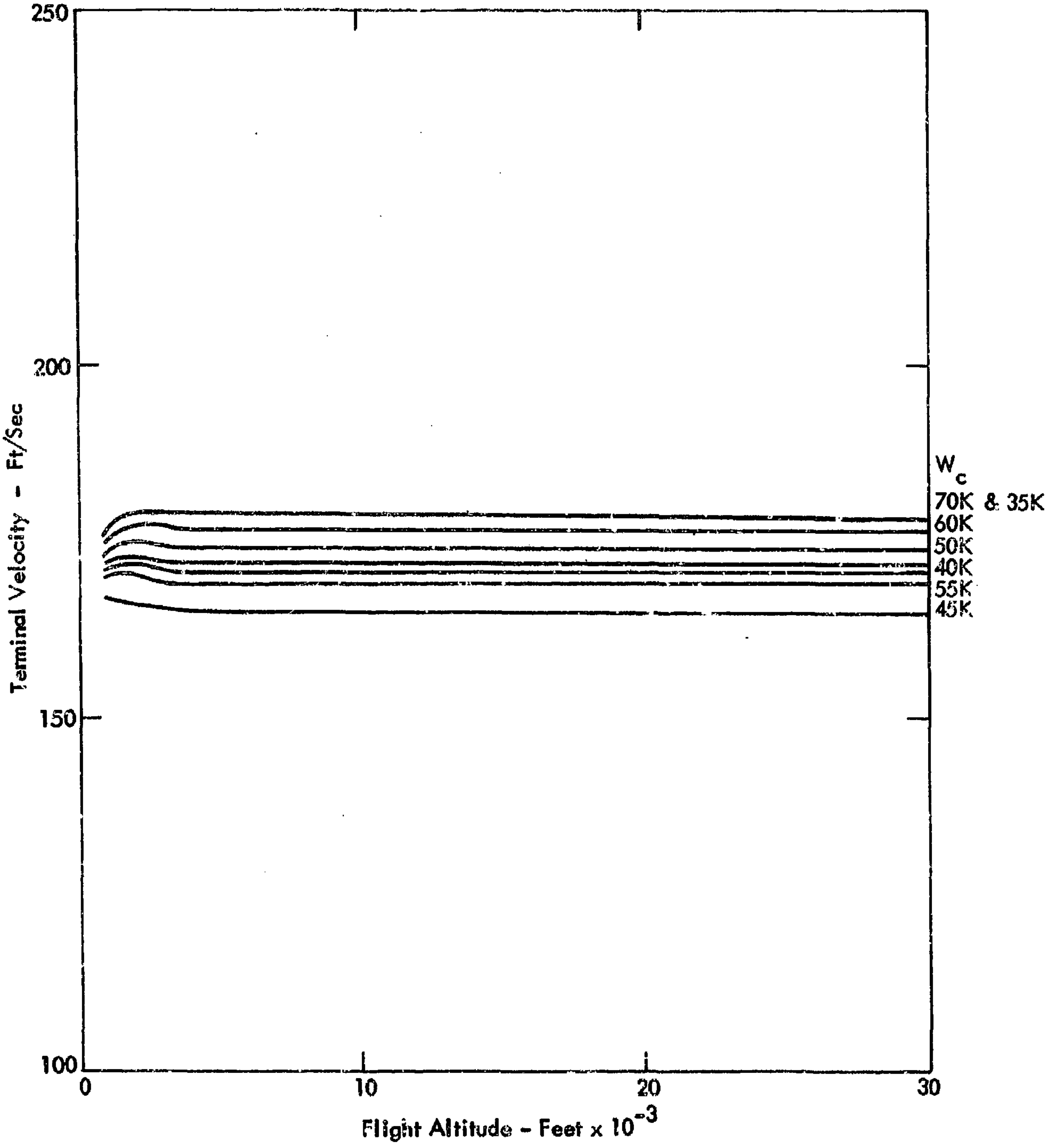


Figure 50 - Cargo Terminal Velocity versus Flight Altitude for Descent with Reefed Main Chute

for certain cargo weights are less than, and for other cargo weights are greater than the equilibrium airspeed for the descent control system.

Recovery System Performance

The recovery system performance is expressed in terms of:

- o Minimum recovery distance
- o Residual cargo velocity after recovery
- o Recovery system weight ratio

Para-rocket Recovery System -- The recovery altitude loss, or the minimum recovery distance, and the residual cargo velocity are shown as functions of flight altitude at extraction in Figure 51. The altitude range covered by this figure is 1500 - 5000 feet. The recovery performance data remain constant for drop altitudes above 5000 feet. The recovery altitudes indicated in Figure 51 are those at which rocket ignition must be triggered by signal from some ground proximity-sensing device in order to obtain the residual velocity values shown in the figure. Deviations from these values will cause the impact velocities to increase above the values indicated.

The weight ratio data for the para-rocket recovery system are shown in Table XVII. These data are independent of drop altitude, since the rocket units must be sized to accommodate the largest impulse requirements, which always are associated with high altitude drops.

TABLE XVII

RECOVERY SYSTEM DATA

Cargo Weight Pounds	Number of Rockets In Cluster	Total Rocket Weight Pounds	Weight of Riser Lines Pounds	System Weight Pounds	System Weight Ratio
35,000	4	1669	202	1871	.05342
40,000	5	2088	248	2336	.0584
45,000	6	2505	293	2798	.0622
50,000	7	2923	338	3261	.06525
55,000	6	2505	307	2812	.05115
60,000	7	2923	352	3275	.0546
65,000	8	3340	398	3738	.0575
70,000	8	3340	403	3743	.0535

Parachute Recovery System - The performance of the parachute recovery system is affected significantly by the following operational circumstances:

- o Whether recovery is accomplished immediately following shedding of the extraction system and deployment of the main parachute system
- o Whether recovery is accomplished in termination of a descent phase controlled by reefed main parachutes

The first of these circumstances defines essentially a minimum drop altitude situation, while the second one pertains to all situations involving delayed recovery.

The reason for this significance is that parachutes exhibit significantly longer inflation times when inflated in a horizontal streaming attitude, than when inflated in a near vertical attitude. This behavior was demonstrated by computer runs with a program developed from the inflation time calculation method given in Reference 4. The lowest flight altitudes compatible with safe recovery are accordingly obtained by delaying the deployment of the main parachutes until the extraction parachute drag, along with gravitational action, has aligned the cargo-parachute system in a steep attitude angle. For the purpose of analysis, it was assumed that a cargo-parachute system inclination to the vertical of 35-40 degrees is sufficient. This condition is always satisfied by main parachute deployment delays of 8 seconds from initiation of the drop sequence. The altitude loss during this delay period was investigated on a drop simulation program. The results of this investigation are shown on Figure 52 along with the vertical velocity at the end of the delay period.

The altitude loss during the delay period is always less than 600 feet, while the maximum vertical velocity is always less than 134 feet per second. Allowing an estimated two-second period for uncovering the main parachutes leads to a total altitude loss of 870 feet before start of main canopy inflation.

The canopy inflation times and the altitude loss during canopy inflation were computed for the combinations of cargo weights and numbers of parachutes established in the section describing system design data. These calculations were based on the method presented in Reference 4.

These calculations show a remarkable constancy of the principal recovery parachutes, as illustrated in Table XVIII.

TABLE XVIII

PARACHUTE RECOVERY SYSTEM CHARACTERISTICS

Cargo Weight Pounds	Number of Chutes	Initial Speed Feet/Second	Filling Time Seconds	Recovery Distance Feet	Terminal Velocity Feet/Second	Peak Load Factor
35,000	4	166.5	7.8	440.0	24.3	3.182
40,000	5	162.9	8.3	443.0	23.1	3.137
45,000	6	160.5	8.6	443.0	22.4	3.119
50,000	6	165.0	8.0	439.0	23.7	3.178
55,000	7	162.4	8.4	444.0	22.9	3.134
60,000	7	165.6	7.9	440.0	24.0	3.174
65,000	8	163.4	8.2	442.0	23.3	3.145
70,000	8	162.0	7.8	436.0	24.3	3.081

It is concluded therefore, that a minimum safe drop altitude for "direct" main canopy deployment drop would be

$$h_{min} = 870 + 450 = 1320 \text{ Feet}$$

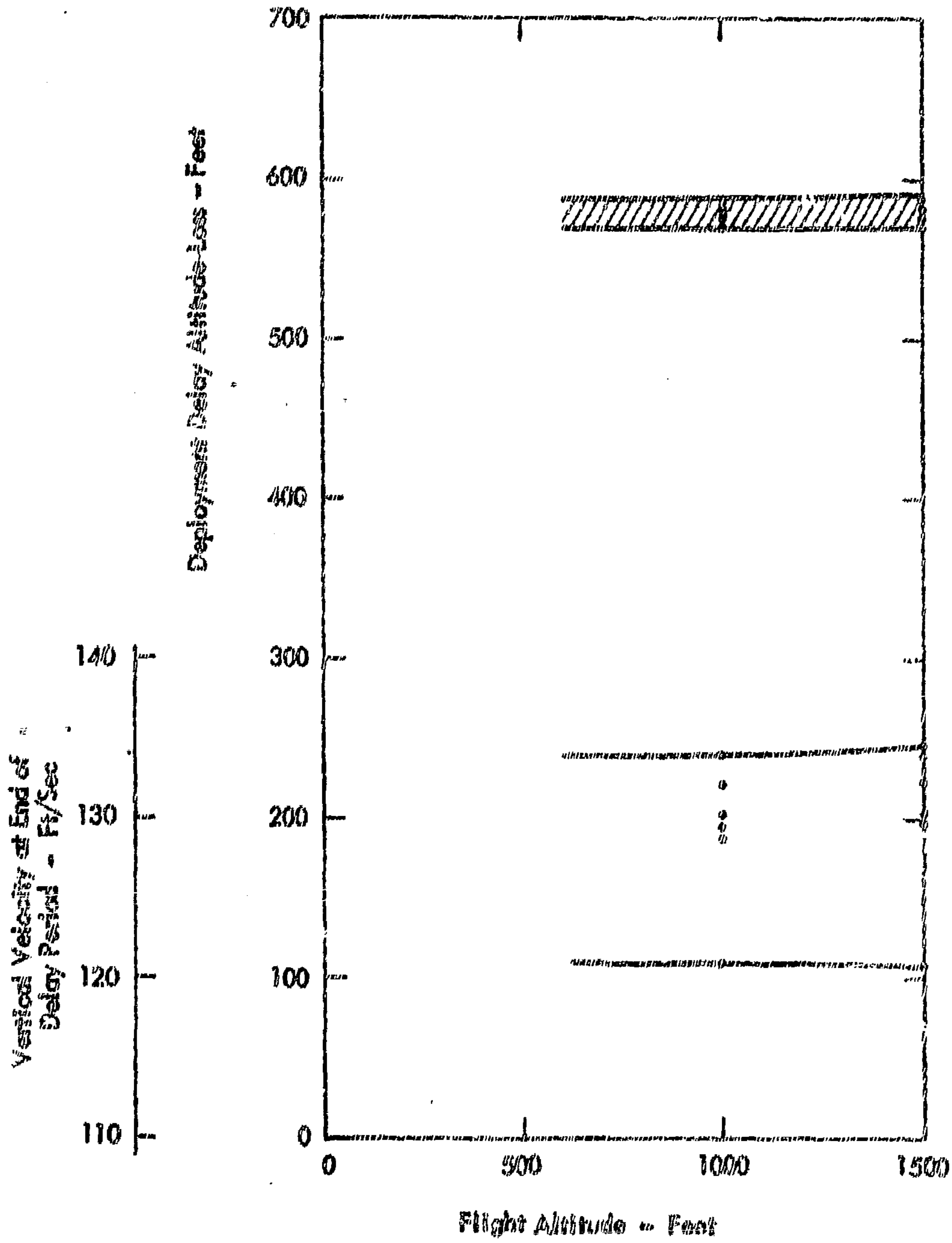


Figure 52 - Determination of Minimum Drop Altitude for Parachute System

For recovery from high altitude, reefed main canopy descents, similar calculations of canopy inflation times and recovery distances were made. The results of these calculations are shown in Table XIX.

Impact System Performance

The impact attenuation system performance is measured by the nominal required thickness or stroke of the shock absorbing material. For a nominal permissible impact shock level of 20 g, using maximum values for the residual recovery velocities, the data shown in Table XX illustrates the impact control system performance for both the para-rocket system and for the parachute system.

TABLE XIX

RECOVERY PERFORMANCE FROM DESCENT WITH MAIN CANOPIES REEFED TO 2 PERCENT DRAG AREA

Cargo Weight Pounds	Number of Chutes	Initial Speed Feet/ Second	Terminal Speed Feet/ Second	Peak Load Factor	Inflation Time Seconds	Recovery Distance Feet	Weight Ratio	Packed Volume $Feet^3$
35,000	4	179.8	24.5	4.610	7.6	423.0	.08175	81.8
40,000	5	173.0	23.1	4.496	8.3	428.0	.08940	102.2
45,000	6	167.5	22.4	4.404	8.6	425.0	.0954	122.6
50,000	6	176.5	23.8	4.582	7.8	420.0	.0858	122.6
55,000	7	172.3	23.1	4.493	8.2	423.0	.0910	143.0
60,000	7	178.7	24.2	4.602	7.7	422.0	.0834	143.0
65,000	8	175.0	23.4	4.537	8.1	426.0	.0880	163.5
70,000	8	180.7	24.5	4.634	7.6	424.0	.08175	163.5

TABLE XX

IMPACT SYSTEM PERFORMANCE

	Impact Velocity - Feet/Second (Nominal Maximum)		Required Shock Absorber Stroke - Feet	
Cargo Weight Pounds	Para-Rocket System	Parachute System	Para-Rocket System	Parachute System
35,000	15.5	25.0	.197	.51
40,000	7.9	25.0	.051	.51
45,000	3.2	25.0	.0087	.51
50,000	3.4	25.0	.0095	.51
55,000	12.8	25.0	.134	.51
60,000	6.5	25.0	.035	.51
65,000	1.5	25.0	.0037	.51
70,000	25.3	25.0	.560	.51

Drop Precision Performance

The drop precision performance is measured in terms of the standard deviation, or the root-mean-square value, of the miss distance. The miss distance is the distance between the actually achieved point of impact and the location of the target center or aiming point. Since the length of the actual miss distance varies from one drop to another, it is a random variable, and can only be evaluated in statistical terms, such as the value of its standard deviation.

The miss distance is the sum of the following components:

- o Deviation in ground travel distance during extraction
- o Deviations in ground travel distance during descent
- o Deviations in ground travel distance during recovery

These deviations are caused partly by deviations from controllable nominal values of:

- o Cargo weight,
- o Aircraft flight speed at cargo extraction,
- o Aircraft flight altitude at cargo extraction,

and partly by random influences such as:

- o Gust velocity during extraction
- o Wind speed and directional changes during descent and recovery.

The magnitudes of the miss distance components are related to the magnitudes of the various causative factors by sensitivity coefficients. In the following analysis, miss distance contributions due to aircrew reaction time lags are not taken into account, basically because this contribution would be of the same order for the two systems which are to be composed, and thus would not improve on the discrimination in the comparison. The derivation of sensitivity coefficients and perturbation factors is shown in Appendix D.

The XXI shows the value of the sensitivity coefficients as determined from computer-simulated drops with the two systems along with the numerical values of the perturbation factors.

Table XXII shows the results of the drop precision calculations in terms of RMS miss distance in feet for the various nominal drop weights and altitudes of 1500, 15,000 and 30,000 feet. Along with these data are also shown values for the drop load densities, computed as $W_c/\pi\bar{x}^2$. The drop load densities are shown as gross and as net values. The gross values are the nominal cargo weights divided by the probable hit area. The net values were obtained by subtracting the appropriate subsystem weights from the nominal cargo weights. This difference approximates that part of the load carried by the aircraft which has operational utility for the recipient, and represents therefore a realistic figure of merit for the system.

TABLE XXI

BASIC DATA FOR DROP PRECISION EVALUATION SENSITIVITY
COEFFICIENTS AND PERTURBATION FACTORS

Drop Altitude Feet	W_c Lbs	$\partial x_e / \partial v_a$	$\partial x_e / \partial W_c$	$\partial x_e / \partial u$	$\partial x_d / \partial v_a$	$\partial x_d / \partial W_c$ P-rocket	$\partial x_d / \partial W_c$ P-chute	$\partial x_d / \partial h$ P-rocket	$\partial x_d / \partial h$ P-chute	$\partial x_d / \partial v_w$ P-rocket	$\partial x_d / \partial v_w$ P-chute	Perturbation Factors (RMS) $\overline{\Delta h}$ Feet	$\overline{\Delta W}$ Pounds	$\overline{\Delta u}$ Fps	$\overline{\Delta v_w}$ Kts
	35K	0	004505	1.465	0	.03575	.03236	.1375	.0825	15.9	21.4	65	1021	10	3
	40K	0	.004220	1.466	0	.03495	.02910	.1630	.0775	15.6	21.6	65	1021	10	3
	45K	0	.00416	1.457	0	.03587	.02777	.2260	.0725	15.4	21.7	65	1021	10	3
1,500	50K	0	.00378	1.540	0	.03260	.02587	.2630	.0870	15.3	21.6	65	1021	10	3
	55K	0	.002654	1.381	0	.02087	.018825	.1050	.0775	16.1	21.5	65	1021	10	3
	60K	0	.002547	1.445	0	.02520	.01838	.1310	.0820	16.0	21.4	65	1021	10	3
	65K	0	.002448	1.507	0	.01948	.01683	.1450	.0800	15.9	21.5	65	1021	10	3
	70K	0	.002360	1.557	0	.02170	.01650	.1625	.0775	15.8	21.5	65	1021	10	3
	35K	0	.00574	1.865	0	.05955	.05780	.0680	.0650	82.19	89.99	200	1021	10	3
	40K	0	.005395	1.875	0	.05950	.05115	.0775	.0610	77.8	93.2	200	1021	10	3
	45K	0	.005367	1.880	0	.06235	.04827	.0870	.0610	76.2	95.7	200	1021	10	3
15,000	50K	0	.004927	2.010	0	.05785	.04490	.0925	.0720	71.2	91.9	200	1021	10	3
	55K	0	.00432	1.738	0	.03498	.03353	.0630	.0600	87.0	93.7	200	1021	10	3
	60K	0	.00327	1.860	0	.03300	.03290	.0670	.0630	83.9	90.6	200	1021	10	3
	65K	0	.003222	1.980	0	.03252	.02989	.0700	.0625	81.2	92.6	200	1021	10	3
	70K	0	.003070	1.995	0	.03185	.02931	.0730	.0610	78.8	89.99	200	1021	10	3
	35K	0	.007345	2.390	0	.09970	.09695	.1480	.1470	140.8	150.1	350	1021	10	3
	40K	0	.00688	2.390	0	.09850	.08540	.1720	.1475	132.7	155.8	350	1021	10	3
	45K	0	.006767	2.372	0	.1040	.08020	.1800	.1475	126.0	160.5	350	1021	10	3
30,000	50K	0	.00615	2.504	0	.09620	.07440	.2025	.1530	126.4	153.4	350	1021	10	3
	55K	0	.004343	2.225	0	.05738	.05680	.1325	.1275	149.7	156.8	350	1021	10	3
	60K	0	.004153	2.360	0	.05592	.05525	.1440	.1275	143.9	151.1	350	1021	10	3
	65K	0	.00430	2.460	0	.05442	.05000	.1501	.1225	138.9	154.7	350	1021	10	3
	70K	0	.00385	2.555	0	.05325	.04899	.1503	.1475	134.4	149.9	350	1021	10	3

TABLE XXII

MISS DISTANCE AND DROP LOAD DENSITIES

Drop Alt. Feet	Cargo Weight 1000 Lbs	Para-Rocket System: Miss Distance Ft (RMS)	Para-Rocket System: Drop Load Density Lbs/Ft^2 Gross	Para-Rocket System: Drop Load Density Lbs/Ft^2 Net	Parachute System: Miss Distance Ft (RMS)	Parachute System: Dropload Density Lbs/Ft^2 Gross	Parachute System: Dropload Density Lbs/Ft^2 Net
	35	81.9	1.560	1.560	86.8	1.4770	1.3735
	40	80.4	1.970	1.843	86.6	1.7000	1.5670
	45	80.6	2.208	2.058	86.5	1.9170	1.7575
1,500	50	79.4	2.529	2.347	85.6	2.1710	2.0075
	55	76.8	2.970	2.793	82.9	2.5500	2.3410
	60	78.4	3.143	2.948	82.5	2.8090	2.6000
	65	76.0	3.582	3.350	82.7	3.0270	2.7900
	70	76.4	3.819	3.587	82.7	3.2600	3.0180
	35	411.5	.0658	.0618	422.0	.0626	.05818
	40	390.0	.0838	.0784	437.0	.0667	.06142
	45	372.5	.1033	.0962	449.3	.0710	.06515
15,000	50	427.5	.1252	.1161	430.0	.0861	.07955
	55	427.5	.0936	.0880	438.0	.0914	.08395
	60	417.3	.1097	.1028	417.0	.1072	.09920
	65	403.3	.1273	.1190	432.0	.1109	.10220
	70	391.3	.1456	.1368	418.3	.1274	.11800
	35	713.0	.0219	.02058	730.0	.0209	.01943
	40	673.0	.0281	.02627	756.5	.0222	.02047
	45	640.0	.0349	.03252	779.5	.0236	.02167
30,000	50	612.5	.0424	.03936	743.5	.0288	.02610
	55	752.0	.0309	.02904	758.5	.0304	.02790
	60	723.0	.0365	.03456	730.0	.0358	.03314
	65	698.0	.0424	.03965	757.5	.0370	.03410
	70	675.5	.0488	.04584	723.5	.0426	.03945

EVALUATION OF SELECTED SYSTEMS

This section presents an evaluation of the two selected systems on the basis of the following:

- o Specific productivity
- o Sensitivity to operational factors

Specific Productivity

The specific productivity is expressed in terms of the delivery density rate in pounds per square foot per hour which is obtained by dividing the drop cycle time, t_c, into the net drop density values presented in the section on system performance.

The drop cycle time is defined as the time interval required to perform the following functions:

- o Removal of harness and other drop gear from the cargo along with other on-site actions preparatory to transportation of cargo away from the drop site.
- o Collection and preparation of drop gear for transportation away from the drop site
- o Transportation of cargo and drop gear a specified distance away from the drop area aiming point.

Under operational conditions, one would expect the two first-mentioned activities to be performed concurrently. The time required depends both on the effort involved and on the size of the available drop area crew.

With respect to cargo preparation, no discernible difference in effort appears likely between the two systems, since the operation of both systems involves nearly identical cargo loads and accelerator experiences for the drop cargo. Consequently, the forms and amounts of webbing and strap-down provisions are also very similar. The type of cargo would, however, exert a dominant influence on the preparation effort involved. Bulk cargo would tend to require extensive preparation efforts, particularly if the shipment is broken down into package units of convenient weight for man-handling. The current evaluation is based on an estimated preparation rate for the drop cargo of .0057 hours/1000 pounds, which is believed to be representative for the preparation effort required for cargo consisting of heavy equipment items.

A major difference between the two systems can be expected with regard to the effort involved in clearing the impact area of residual and salvageable drop gear. An impression of this difference is afforded by Table XXIII, which shows the weight and characteristic size of residual, salvageable drop gear corresponding to nominal cargo weights for both systems.

In order to provide estimates of the effort and time elements involved in this aspect of the operation, the following basic data were assumed:

50 foot diameter ring-slot parachute and riser; 150 pounds
  Straighten and roll-up: 1 man 2-3 minutes
140 foot diameter flat canopy parachute and riser, 561 pounds
  Straighten and roll-up: 4 men 15-20 minutes
Loading on transporter: 1 minute/500 pounds
Handling capability for one man: 150-200 pounds
Size of gear salvage and drop area clearing crews:
  Para-rocket system:
    35,000-50,000 pound cargo - 1 man
    55,000-70,000 pound cargo - 2 men
  Parachute System: 4 teams @ 4 each = 16 men

TABLE XXIII

WEIGHT AND SIZE OF RESIDUAL DROP GEAR

Nominal Cargo Weight Pounds	Para-Rocket System		Parachute System	
	Weight Pounds	Dimension Feet^2	Weight Pounds	Typical Dimension Feet^2
35000	360	1870	2143	63000
40000	490	1870	2805	78700
45000	560	1870	3366	94400
50000	630	1870	3366	94400
55000	710	3740	3927	110000
60000	780	3740	3927	110000
65000	850	3740	4490	126000
70000	850	3740	4490	126000

It is realized that the rates assumed reflect near ideal conditions with a minimum of drop gear tangling in vegetation.

Finally the time required for removal of cargo and salvaged drop gear from the impact area has been assessed on the basis of an average transportation rate of 5 ton miles/hour and a required transportation distance equal to three times the root-mean-square miss distance for each drop altitude and nominal cargo weight.

Results of the estimation are shown in Table XXIV for the cargo preparation and drop gear salvaging activities.

Table XXV presents the results of the transportation time calculations, along with the values of the drop cycle times. The drop cycle time is the sum of the transportation time and the largest of the cargo preparation time and the drop gear collecting time.

The results of the drop cycle time estimations were used to evaluate the specific productivities for each system. As shown in Table XXVI, this evaluation has been carried out for all nominal cargo weights and for drop altitudes of 1500, 15000, and 30000 feet. It is based on the net drop densities shown in Table XXII.

The clear superiority of the Para-Rocket system is due to the slightly better drop precision attainable with this system and the shorter drop cycle time.

Sensitivity to Operational Factors

The principal operational factor to which the two systems exhibit marked difference in sensitivity is surface wind at the impact area. With an equilibrium descent speed of 25 feet per second, the Parachute system is sensitive to surface winds to the extent that a 10-15 knot wind might overturn the drop cargo after impact. A reliably operating, ground sensing quick release system for the main parachutes would afford relief from this sensitivity.

The Para-Rocket system is fundamentally insensitive to ground wind conditions due to the relatively small size of the extraction/descent control parachutes.

TABLE XXIV

ESTIMATED TIME ELEMENTS FOR PREPARATION OF CARGO AND COLLECTING OF RESIDUAL DROP GEAR (CONCURRENT ACTIVITIES)

Nominal Cargo Weight Pounds	Cargo Preparation Time Hours	Collecting Time for Residual Drop Gear - Hours	
		Para-Rocket	Parachute
35000	.33	.067	.32
40000	.38	.067	.59
45000	.43	.069	.612
50000	.48	.071	.612
55000	.52	.124	.631
60000	.57	.126	.631
65000	.62	.128	.650
70000	.67	.128	.650

TABLE XXV

ESTIMATION OF DROP CYCLE TIME

Drop Altitude Feet	Nominal Drop Cargo Weight Pounds	Drop Cargo Transportation Distance - Miles		Drop Cargo Transportation Time - Hours		Drop Cycle Time = Drop Cargo. Trans. Time + Largest of Cargo Prep'n Time or Drop Gear Collecting Time - Hours	
		Para-Rocket	Parachute	Para-Rocket	Parachute	Para-Rocket	Parachute
	35000	.0465	.0493	.1626	.1725	.4926	.5045
	40000	.04565	.04915	.1827	.1967	.5627	.7867
	45000	.04575	.04910	.2060	.2210	.6360	.8330
1500	50000	.04510	.04860	.2256	.2430	.7056	.8550
	55000	.04360	.04707	.2398	.2587	.7592	.8897
	60000	.04500	.04683	.2700	.2810	.8400	.9120
	65000	.04313	.04695	.2802	.3050	.9002	.9550
	70000	.04340	.04695	.3040	.3288	.9740	1.9788
	35000	.2336	.2396	.317	.838	1.147	1.168
	40000	.2212	.2480	.8855	.9925	1.266	1.583
	45000	.2110	.2550	.9500	1.148	1.380	1.760
15000	50000	.2020	.2440	1.0200	1.220	1.500	1.832
	55000	.2423	.2485	1.3320	1.3660	1.852	1.997
	60000	.2370	.2368	1.4220	1.4200	1.992	2.051
	65000	.2290	.2452	1.4870	1.5930	2.107	2.243
	70000	.2220	.2375	1.5550	1.6620	2.225	2.312
	35000	[illegible]	.4145	1.4170	1.4500	1.747	1.780
	40000	.3820	.4290	1.5300	1.7160	1.910	2.3060
	45000	.3635	.4425	1.6370	1.9920	2.067	2.6040
30000	50000	.3476	.4220	1.7370	2.1100	2.217	2.7220
	55000	.4270	.4306	2.3480	2.3680	2.868	2.9990
	60000	.4105	.4145	2.4620	2.4870	3.032	3.1180
	65000	.3962	.4300	2.5740	2.7930	3.194	3.4430
	70000	.3830	.4108	2.6820	2.8770	3.352	3.5270

TABLE XXVI

COMPARISON OF SPECIFIC PRODUCTIVITY

FOR SELECTED SYSTEMS

Drop Altitude Feet	Nominal Cargo Weight Pounds	Special Productivity $Lb/Ft^2/Hr$ Para-Rocket System	Special Productivity $Lb/Ft^2/Hr$ Parachute System
	35000	3.167	2.740
	40000	3.500	1.994
	45000	3.236	2.110
1500	50000	3.328	2.348
	55000	3.677	2.640
	60000	3.510	2.851
	65000	3.720	2.925
	70000	3.680	3.060
	35000	.0539	.04975
	40000	.0619	.04882
	45000	.0697	.03700
15000	50000	.0775	.04342
	55000	.0475	.04200
	60000	.0516	.04835
	65000	.0565	.04556
	70000	.0615	.05105
	35000	.01178	.01092
	40000	.01375	.00888
	45000	.01574	.00832
30000	50000	.01776	.00959
	55000	.01014	.00933
	60000	.01134	.01063
	65000	.01240	.00990
	70000	.01366	.01118

III - AERIAL RETRIEVAL SYSTEMS

CRITERIA FOR CONCEPT CLASSIFICATION

The development of criteria for the classification of aerial retrieval concepts generally parallels the procedure utilized for aerial delivery concepts. Logical criteria are established for concept classification, basic terms are defined, and the rationale by which combinations of these terms are accepted or rejected is outlined.

Operational Phases

In terms of fundamental physical processes, the basic function performed by an aerial retrieval system is the application of a sequence of metered and timed impulses to the payload such that the payload velocity is changed from zero to the aircraft flight speed in a manner compatible with aircraft and payload limitations. The total impulse requirement is equal to the sum of the individual impulses in the sequence and is a function of payload weight, aircraft flight speed and altitude, and the type of trajectory followed by the retrieved payload.

For the purposes of analyzing the requirements of aerial retrieval operations, it is convenient to consider the complete retrieval procedure as the combination of seven distinct phases. The individual phases are different for the two operational concepts under consideration.

The first operational concept includes retrieval of the payload, towing the payload to a new deployment area, and subsequent aerial delivery of the payload. The seven phases characterizing this operation are as follows:

1. Preparation
2. Engagement and Ascent
3. Towing
4a. Release
5a. Descent
6a. Recovery
7a. Impact

The second operational concept involves retrieval of the payload and subsequent boarding of the payload into the cargo compartment of the retrieval aircraft. The seven phases describing this operation follows

1. Preparation
2. Engagement and Ascent
3. Towing
4b. Closure
5b. Attachment
6b. Boarding
7b. Stowage

It is observed that the first three phases are identical for the two operational procedures. Thus, any acceptable aerial retrieval concept must be capable of satisfying the requirements of phases 1 through 3 in addition to those inherent in either phases 4a through 7a or 7b. Inspection of these phases with regard to operational requirements leads to the conclusion that characteristics of Phase 2 have an overriding influence on the characteristics of the remaining six. For this reason Phase 2 will be utilized exclusively for the classification of retrieval concepts. The remaining six phases are identified primarily for the purpose of future application in the comparative evaluation of concepts.

Concept Classification Criteria

The engagement and ascent phase comprises all events which occur from the moment of first physical contact between the ground station retrieval gear and airborne retrieval gear until equilibrium conditions between the cargo and retrieval aircraft have been achieved. The desired kinematic effects on the cargo during this phase may be achieved through reaction of a force by any one or combination of the following reaction modes:

- Reaction with the retrieval aircraft
- Reaction with the air
- Reaction with impulse propellant
- Reaction with the ground

The first reaction mode, "reaction with the retrieval aircraft," is self-explanatory. All retrieval concepts ultimately utilize this reaction mode.

The second, "reaction with the air," includes all methods in which the reaction of the impulse-generating force acting on the payload is ultimately transmitted to the surrounding air.

"Reaction with impulse propellant" comprises all methods relying on the reaction of jet or rocket devices for generation of the impulse increment.

The final reaction mode, "reaction with the ground," includes all methods in which the impulse increment is generated by forces whose reactions are ultimately transferred to the ground.

Consistent with the procedure followed in the development of classification criteria for aerial delivery concepts, the four reaction modes are assigned the code number shown below.

Reaction Mode Description	Code No.
Reaction with the Airplane	(1)
Reaction with the Air	(2)
Reaction with Impulse Propellant	(3)
Reaction with the Ground	(4)

If it is assumed that each of these four impulse increment reaction locations can be utilized singly or in combination with one, two, or all three of the remaining methods in the engagement and ascent phase of the retrieval operation, all possible groups of retrieval system concepts are established. The possible concept groups formed through application of this procedure are as follows:

Different Reaction Mode Combination				
	(1) (2) (3) (4)	(1,2) (1,3) (1,4) (2,3) (2,4) (3,4)	(1,2,3) (1,2,4) (1,3,4) (2,3,4)	(1,2,3,4)
No. of Combinations	4	6	4	1

Thus, there are a total of 15 possible concept groups. These groups can be considered as the trunks of concept family trees. The limbs and branches for each tree emerge from consideration of specific energy storage, release, and transformation methods for realizing each impulse force reaction mode.

A number of the concept groups imply physical configurations which are not readily applied to the engagement and ascent phase of aerial delivery. These groups are illustrated in the chart below. The concept groups rejected in this figure either involve reaction with the ground or do not involve reaction with the retrieval aircraft.

Concept groups based on reaction with the ground require configurations which are not compatible with the requirements of aerial retrieval operations. Examples of such configurations are inclined ramps for converting gravitational to kinetic energy, and inclined launching catapults for converting latent energy to kinetic and gravitational energy.

IMPULSE REACTION MODE COMBINATION FILTER (AERIAL RETRIEVAL)

Impulse Reaction Mode Combination Code No.	Reason for Rejection
(4) (1,4) (2,4) (3,4) (1,2,4) (1,3,4) (2,3,4) (1,2,3,4)	Physical realization of mechanism beyond state-of-the-art
(2) (3) (2,3)	Implies precise matching of aircraft flight path and velocity - capability not within state-of-the-art.

Several difficult problems are inherent in the implementation of such devices. Included are:

- o Timing of launch with aircraft arrival
- o Matching of cargo trajectory with aircraft flight path
- o Lack of directional control capability immediately following launch
- o Lack of mobility due to large launching installations for low acceleration systems or, conversely, heavy launching platforms for high acceleration systems

As a result of these inherent limitations, concept groups which rely upon the ground reaction mode are eliminated from further consideration with respect to the development of sub-group derivatives.

As stated previously, all retrieval system concepts ultimately involve a reaction with the retrieval aircraft. Therefore, all concept groups which do not include this reaction mode can reasonably be eliminated from further consideration. The technical requirements of concepts which do not include reaction with the retrieval aircraft are sufficiently stringent as to be considered beyond the current state-of-the-art. These requirements include:

- o Timing of launch with aircraft arrival
- o Matching of cargo trajectory with aircraft flight path
- o Matching of cargo velocity with aircraft velocity

A mechanism capable of satisfying such requirements while demonstrating the flexibility necessary for aerial retrieval operations has a level of complexity similar to that of manned systems, such as helicopters and aircraft.

After elimination of the concept groups involving unrealistic physical requirements, the number of permissible concept groups is reduced to four. These concept groups are illustrated in Figure 53. For convenience, the permissible concept groups from Figure 53 are reorganized and assigned group numbers as shown in Figure 54.

The sub-groups related to each basic concept group are derived by considering the applicable physical principles for generating the reaction forces. Using the general analysis concerning energy transformation developed for classification of aerial delivery concepts, a summary of the available energy conversion principles and their applicable reaction modes is shown in Figure 55. The number of possible reaction force generating modes which are available for each impulse reaction mode is also indicated. Methods by which the kinetic energy of the cargo relative to the aircraft can be transformed into mechanical work are shown in the first major column, together with available means by which the resultant force may be reacted. The terms "aerodynamic action," friction action," and "mechanical deformation" comprise in themselves a large number of energy transformation methods. "Mechanical deformation," for example, includes both elastic and inelastic deformations, and "aerodynamic action" includes gliders, helicopters, and parawings.

The total number of retrieval concept sub-groups is obtained by forming the product of permissible reaction mode combinations, shown in Figure 54, and the corresponding reaction force generating modes, shown in Figure 55, which total 18 are illustrated in Figure 56. The procedure used for identification of retrieval systems sub-groups corresponds to that employed for aerial delivery systems.

Operational Phase	Cargo Impulse Reaction Mode														
	(1)	(2)	(3)	(4)	(1,2)	(2,3)	(3,4)	(1,3)	(1,4)	(2,4)	(1,2,3)	(2,3,4)	(1,2,4)	(1,3,4)	(1,2,3,4)
Engagement & Ascent Control		X	X	X		X	X		X	X		X	X	X	X

Code for Impulse Reaction Modes:

(1) Reaction with Aircraft
(2) Reaction with Air
(3) Reaction with Impulse Propellant
(4) Reaction with Ground
(1,2), (2,3,4) etc. Denote Combined Modes

Number of Permissible Concept Groups = 4

Figure 53 – Generating Matrix for Groups of Retrieval System Concepts

Operational Phase	Retrieval System Concept Group (Reaction Mode Combinations)			
Group No.	01	02	03	04
Engagement and Ascent Control	(1)	(1, 2)	(1, 3)	(1, 2, 3)

Code for Reaction Modes:

(1) Reaction with Airplane
(2) Reaction with Air
(3) Reaction with Impulse Medium

(1, 2), (1, 2, 3) etc. Denote Mixed Modes

Figure 54 – Reaction Mode Structure for Ranked Aerial Retrieval System Concept Groups

Impulse Reaction Mode \ Energy Form/Conversion Mode	Basic Energy Form						
	Kinetic			Gravitational		Latent	
	Aerodynamic Action (A)	Friction Action (B)	Mechanical Deformation Action (C)	Buoyancy Action (D)	Direct Action (E)	Impulse Action (F)	Direct Action (G)
Reaction with Aircraft (1)	✓	✓	✓				
Reaction with Air (2)	✓			✓			
Reaction with Impulse Medium (3)						✓	
Reaction with Ground (4)					✓		✓

Possible Combinations

Impulse Reaction Mode	Reaction Force Generation Mode Combinations	Number
(1)	(A), (B), (C)	3
(2)	(A), (A + D)	2
(3)	(F)	1
(4)	(E), (G)	2

Figure 55 - Compatibility of Energy Conversion - Reaction Force Generating Modes with Reaction Modes (Aerial Retrieval)

Group No.	01		
Sub-Group No.	01.01	01.02	01.03
Engagement And Ascent	1(A)	1(B)	1(C)

Group No	02					
Sub-Group No.	02.01	02.02	02.03	02.04	02.05	02.06
Engagement And Ascent	1(A), 2(A)	1(B), 2(A)	1(C), 2(A)	1(A), 2(A + D)	1(B), 2(A + D)	1 (C), 2(A + D)

Group No.	03		
Sub-Group No.	03.01	03.02	03.03
Engagement and Ascent	1(A), 3(F)	1 (B), 3(F)	1 (C), 3(F)

Group No.	04					
Sub-Group No.	04.01	04.02	04.03	04.04	04.05	04.06
Engagement And Ascent	1(A), 2(A), 3(F)	1(B), 2(A), 3(F)	1 (C), 2 (A), 3(F)	1(A),2 (A + D), 3(F)	1 (B),2 (A + D), 3 (F)	1 (C), 2 (A +D), 3(F)

Figure 56 — Aerial Retrieval System Concept Classification

The generation of specific retrieval system concepts must proceed directly from the sub-groups outlined in Figure 56. Each of these sub-groups is characterized by energy transformation methods and reaction modes which determine retrieval aircraft responses during retrieval, and total system weight relative to cargo weight retrieved. Subsequent efforts related to retrieval system concept selection will be concentrated on evaluating these aspects of the sub-groups in order to assist in selection of the concept or concepts most suited to retrieval of cargo in the 3,000 to 10,000 pound weight range.

FORMULATION OF CONCEPTS

The concept classification system presented in the previous section constitutes a useful guide in the formulation of techniques for performing the engagement and ascent phase of the aerial retrieval operation. While the concept classification system does not function as a concept generator, it does provide a comprehensive description of available mechanisms for energy transformation. This tends to preclude the omission of complete classes of concepts from consideration.

For convenience in conducting feasibility analyses in subsequent sections, aerial retrieval concepts are separated into two distinct groups characterized by either aircraft fly-by or circling aircraft techniques. Concepts based on aircraft fly-by techniques are listed in Table XXVII. Retrieval concepts utilizing circling aircraft techniques are shown in Table XXVIII.

Since there is only one phase in the aerial retrieval procedure during which an impulse is imparted to the payload, the concepts tabulated in Tables XXVII and XXVIII represent complete aerial retrieval systems. Consequently, the combinations of reaction modes and reaction force generating modes corresponding to these systems are presented. The classification sub-groups which describe each system are listed in the last column of both tables.

TABLE XXVII

FORMULATION OF AERIAL RETRIEVAL CONCEPTS - AIRCRAFT FLY-BY TECHNIQUE

Operational Phase	Reaction Mode/ Reaction Force Generating Mode Combinations	Concept Description	Classification Sub-groups
Engagement and Ascent	1(B)	Winch Brake	01.02
	1(B), 3(F)	Winch Brake/Rocket Boost	03.02
	1(A), 2(A)	Magnus Rotor	02.01
	1(A), 2(A+D)	Balloon Ascension	02.04
	1(A), 3(F)	Rocket Ascension	03.01
	1(A), 2(A)	Lifting Line (Low)	02.01
	1(A), 1(A)	Rigid Glider	02.01
	1(A), 2(A)	Parawing	02.01
	1(A), 2(A)	Trailing Airborne Lift Device	02.01
	1(A), 2(A)	Lifting Line (High)	02.01
	1(A), 2(A+D)	Balloon Line	02.04
	1(A), 3(F)	Balloon Line/Rocket Boost	03.01
	1(A), 2(A)	Rotary Lift Device	02.01
	1(A), 3(F)	Rocket Line	03.01

TABLE XXVIII

FORMULATION OF AERIAL RETRIEVAL CONCEPTS - CIRCLING AIRCRAFT TECHNIQUES

Operational Phase	Reaction Mode/ Reaction Force Generating Mode Combinations	Concept Description	Classification Sub-groups
Engagement	1(B), 2(A)	Half Moon	02.02
and	1(B), 2(A)	Derrick	02.02
Ascent	1(B)	Single Line	01.02
	1(B), 2(A+D)	Single Line/Balloon	02.05
	1(B), 3(F)	Single Line/Rocket	03.02
	1(B), 2(A+D)	Single Light Line/Balloon	02.05

ANALYSIS OF CONCEPT FEASIBILITY

The previous section compiled a number of retrieval concepts. The more attractive techniques are listed in Tables XXVII and XXVIII of the previous section.

A first order analysis was conducted on each of the concepts listed to determine its merit and to single out the techniques deserving more detailed analysis and investigation.

There are four characteristics of primary technical interest which serve as "measuring sticks" when evaluating aerial retrieval concepts:

(1) Accelerations and loads experienced by the aircraft during the pick-up operation.

(2) Size of the clear ground area required to effect the retrieval operation.

(3) Complexity of the system and accompanying reliability level and operational problems.

(4) Power demands on the aircraft.

With regard to the fourth characteristic, aircraft power demands, it was determined in analysis of the various concepts that aircraft power is not a limiting factor in any of the systems considered since, in all cases, the aircraft can sustain the impact loads as the payload is engaged and accelerated. The horsepower drain on the aircraft is simply a function of the kinetic energy lost during the period of time covering payload hook-up and acceleration to aircraft speed. Therefore, the relative merit of the retrieval concepts considered in this study can be assessed on the basis of the interplay and combined effect of items (1), (2), and (3) above: accelerations and loads, clear ground area, and system complexity.

The interplay of the remaining three factors can be illustrated by considering the simplest, most direct aerial retrieval technique, a direct ground snatch. In this technique, the aircraft makes a low-level approach trailing a hook on a boom, snags the payload by hooking a target line held aloft, and hauls the payload up and out of the area. This technique has been employed with very light loads, such as mail bags, but is not practical for heavier loads. In the cases where the payload weighs thousands of pounds, the accelerations and forces felt on the aircraft and on the payload are in the thousands of "g's".

In addition to the problem of forces on the A/C and payload, considerable ground clearance area is required before the payload can be hauled to sufficient altitude to clear surrounding trees and terrain. The system, however, is extremely simple and is reliable when used with light weight payloads. Its success depends only upon the pilot's ability to engage the payload line. It cannot, however, be used for heavy payloads because of high forces and the clear area requirements.

For each retrieval technique considered, the following paragraphs present a sketch and general discussion of the system operation, the pertinent portion of the analysis performed on the system, and the results and conclusions drawn from the analysis. In every case, the deficiencies of the system can be classified in accordance with the three most pertinent characteristics listed previously. Following the discussions of the various concepts, the "Selection of Systems" Section presents the key points of consideration with regard to each system and discusses the relative merits of all techniques investigated.

The most severe case in each of the techniques presented is for the 10,000 lb retrieval payload. Examples given in detail are for the 10,000 lb case. Where appropriate, evaluation factors are presented as a function of retrieval payload weight.

Aircraft Fly-by Concepts

This category covers retrieval techniques in which the aircraft trails a length of line along a stabilizing boom with a pick-up hook attached to the end of the line. The trailing line represents only a small portion of the total available line wound on a winch brake device located in the cargo compartment of the aircraft.

As the aircraft flies over a target line attached to the payload, the trailing hook engages the target line, thus forming a single line from the payload to the winch. In order to limit peak acceleration levels, it is necessary for the winch to pay-out line, thus reducing the rate at which energy is imparted to the payload, and thereby reducing peak impact loads by spreading them over a greater time span. The winch is braked to impart maximum allowable accelerations to the payload without overloading the hook-up line.

In general, the impact loads on the aircraft function inversely with the line length between the hook-up point and the payload. The major sub-categories in this section are based on the coupling line length between the hook-up point and the payload.

Short Coupled - Low Aircraft Approach

The concepts discussed in this section utilize a short line length from the hook-up point to the payload. The target line is assumed to be held above the payload on 50-foot stanchions, thus enabling the aircraft to effect hook-up without participating in preliminary descent and flare maneuvers.

Three systems are considered in this section. These are:

1. Winch-Brake
2. Winch-Brake/Rocket Boost
3. Magnus Effect Rotor

Winch-Brake

General - This concept utilizes a winch-brake arrangement which functions as previously described.

In this technique, the aircraft makes a low-level pass 50 feet above the payload and snatches the payload off the ground by engaging a trailing steel line and hook onto a nylon line held on stanchions above the payload. The procedure is illustrated in Figure 57.

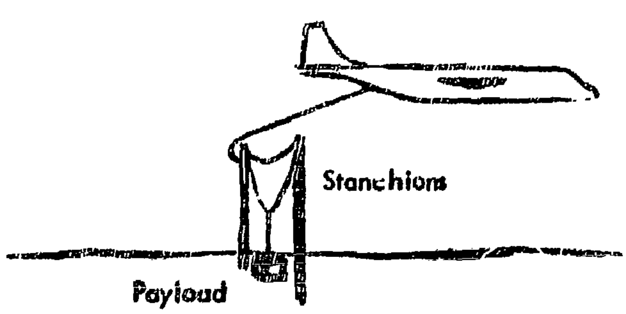


Figure 57 - Winch Brake Retrieval Concept

During the phase immediately after engagement is completed, after the line becomes taut, the aircraft maintains level flight while paying out line and accelerating the payload to aircraft speed. Nylon line elongation during this phase supplements cable pay-out.

When the payload speed is the same as the aircraft speed, the aircraft assumes and maintains a specified climb rate and climbs out towing the payload.

Results and Conclusions -- Even if it is assumed that the 60,000-pound impact phase loading (for 10,000 lb. payload) could be managed by the winch and aircraft, significant problems are present in this system. A very elaborate winch design would be required, since winch control, timing, and operation are key factors.

The trajectory of the payload over the ground indicates that too large a clear area is required for this system. For a 10,000 lb. payload, some 1700 feet of area, having obstacles no higher than 9 feet, is required to allow the payload to reach a 50-foot altitude. This trajectory assumes an initial payload acceleration of 6 g's. Lower accelerations will result in the payload striking the ground.

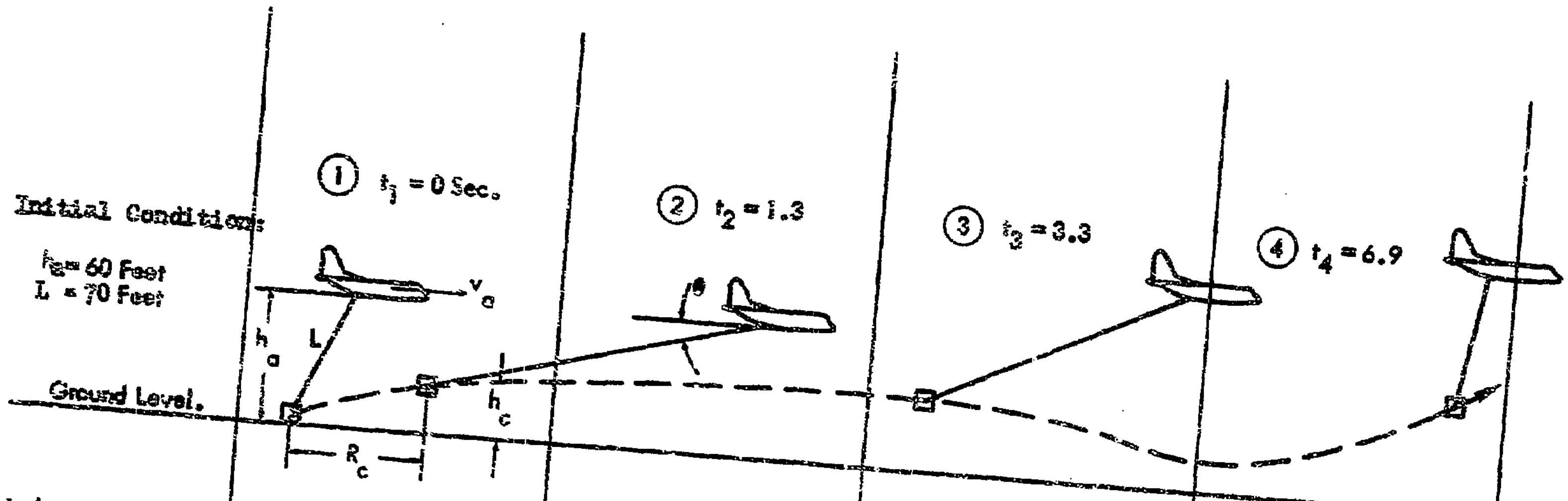
Analysis -- Figure 58 depicts the winch-brake ground snatch technique. The values given, as in Figure 59 and 60, are for a 10,000 pound payload. The four key points of interest are shown with accompanying conditions.

At point (1) the tow line is hooked up and taut, the aircraft is at some speed higher than 250 feet/second, to allow for deceleration to this speed at the end of phase (1)-(2), and the payload is at rest.

During phase (1)-(2), the payload is accelerated to aircraft speed while leaving the ground and traveling essentially in the direction of the tow line. The aircraft winch pays out line and the line elongates such that a maximum of 60,000 pounds is felt in the line (6 g's on the payload). While the aircraft decelerates to 250 feet/second and maintains altitude, the payload velocity vector approaches horizontal as θ approaches 0 degrees. Also during phase (1)-(2) the pilot rotates the aircraft such that a climb rate of 2000 fpm can commence at point (2), the beginning of phase (2)-(3). The aircraft holds the 2000 fpm for the remainder of phase (2)-(3) and phase (3)-(4). In order for the C-130 to meet the 2000 fpm climb rate requirement, 8000 pounds of JATO thrust augmentation are required for phase (2)-(3) and (3)-(4).

At point (2) payload acceleration is completed, the tow line length has extended to 216 feet, including a 10% stretch of the nylon portion, and the payload is at an altitude of 26 feet moving horizontally at 250 feet/second. The aircraft winch, which has stopped, is now reversed to retrieve the tow line into the aircraft.

In order to simplify the analysis and to allow determination of the payload trajectory farther downrange, it was assumed that an aircraft-mounted winch could be designed to meet the very difficult requirements of phase (1)-(2) above. The analysis presented is optimistic in this respect, since any depreciation in winch performance will result in an increase in clear ground area required. Computer data generated for the retrieval concept discussed later in this report indicates that an ordinary winch operated with a constant braking force will not meet the requirements of this low aircraft approach winch - brake technique. A winch with variable, preprogrammed braking will be required.



Airplane:	①	②	③	④
v_a Ground Speed.	250 Ft/Sec	250	250	250
h_a Altitude	60 Feet	60	126.8	247
L Tow Line Length	70 Feet	216	210.8	192.8
θ Tow Line Angle With Horizontal	59°	9.1°	24.2°	87°
Payload: 10,000 lb				
h_c Payload Altitude	0 Feet	25.8	35.5	51.6
R_c Payload Range	0 Feet	161	683.7	1764

Figure 58 -- Winch Brake Retrieval Concept Performance

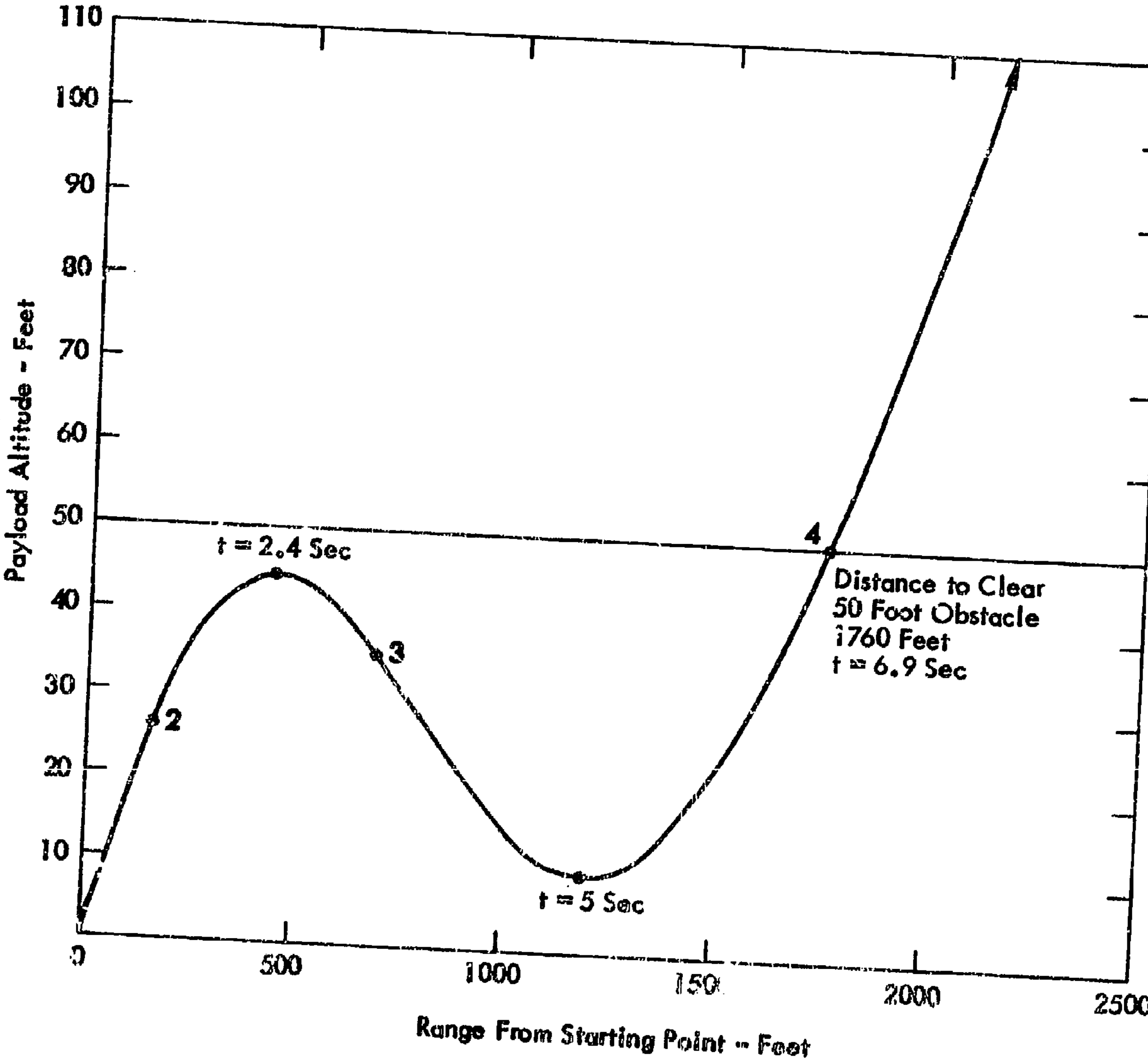


Figure 59 - Payload Trajectory - Winch Brake Retrieval Concept

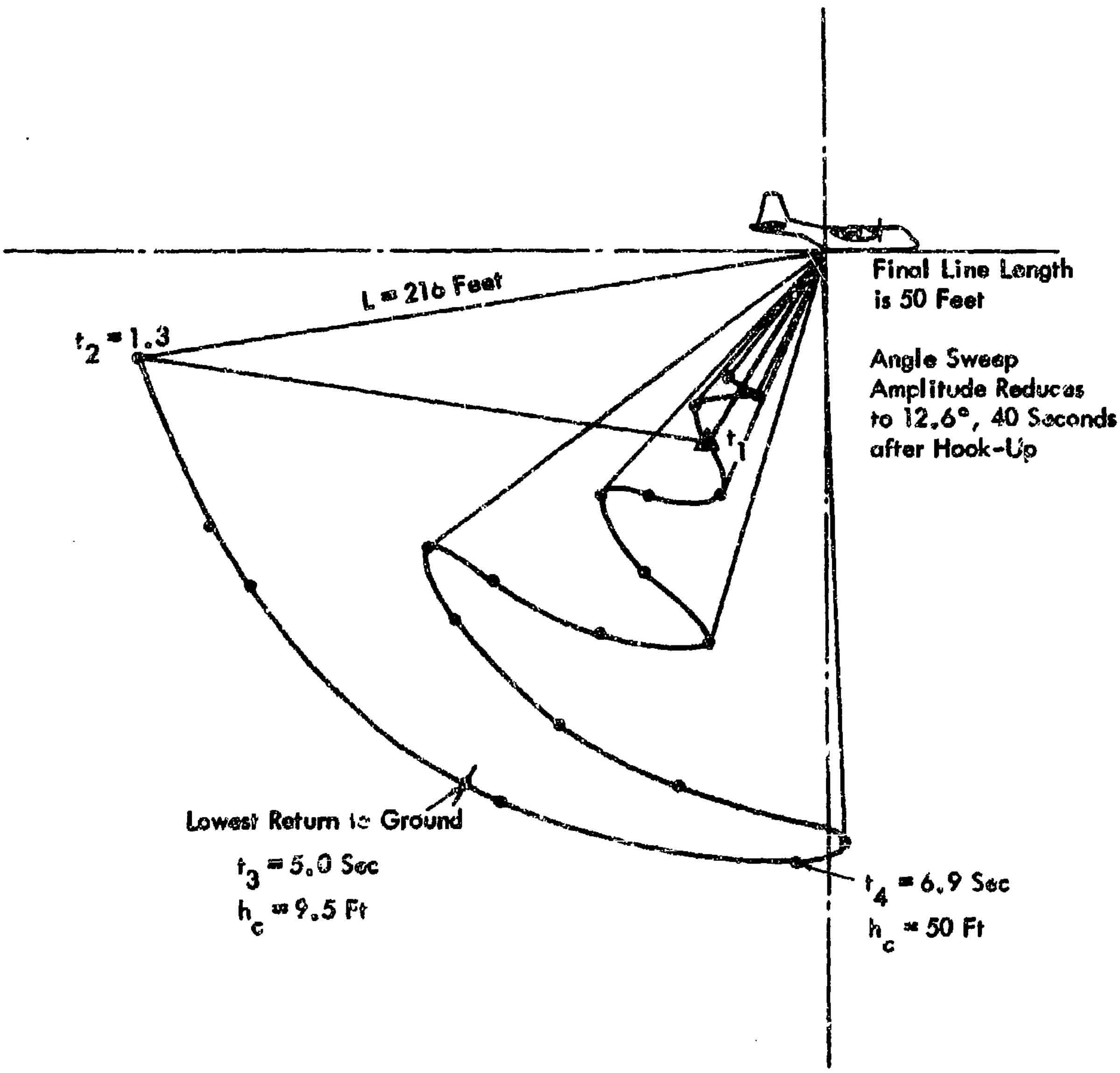


Figure 60 - Motion of Payload Relative to Aircraft - Winch Brake Retrieval Concept

During phase (2)-(3), the aircraft climbs at 2000 fpm and the winch rpm increases from 0 at point (2) to a speed equivalent to a line reel-in rate of 5 feet/second at point (3). The winch maintains a line reel-in rate of 5 fps until the payload is at final aircraft tow position. A 100-horsepower winch is sufficient to meet the reel in requirements of this analysis.

During phases (2)-(3) and (3)-(4) the payload is acted upon by drag forces, gravity, and line tension. In addition to the motion of the payload resulting from these forces, the aircraft is climbing at 33.4 fps (2000 feet/minute) and the line is reeling in at 0-5 feet/second.

A computer program was developed which takes the above factors into account and describes the motion of the payload during phases (2)-(3) and (3)-(4).

The significant results of the program for the 10,000 lb. payload case are tabulated in Figures 58, 59, and 60. Figure 59 is a plot of the payload altitude versus range with signifcant points in time noted. Figure 60 depicts the motion of the payload relative to the aircraft. A change in aircraft rate of climb was taken into account beginning at t = 11.3 seconds. In this analysis, in order to show the technique in the best light, JATO was used for 10 seconds, from t = 1.3 to t = 11.3. After 11.3 seconds an aircraft rate of climb of 500 feet/minute was used.

Data were calculated up to the time when the payload had been retrieved to within a distance of 50 feet from the aircraft and assumed a stable tow position for the 250-feet/second (150-knot) flight speed.

Figure 59 shows the track of the payload up to the time when it has attained an altitude of over 100 feet. Payload Altitude after 100 feet is of little interest.

Figures 61 and 62 present data on the key trajectory points for payloads ranging from 3000 to 10,000 pounds. Figure 61 shows the relation between the retrieval payload weight and the position of the payloads lowest return to the ground and the time at which it occurs.

Figure 62 relates the total ground clearance required to the weight of the retrieval payload. Ground clearance is measured from engagement point to the point where the payload has achieved an altitude of 50 feet.

The remaining discussion applies to retrieval payloads from 3000 to 10,000 pounds.

Examination of the data presented here shows one very significant point. The ground track or range required for the payload to achieve and maintain an altitude of at least 50 feet is over 1650 feet. This amount of clear area severely limits the flexibility of such a retrieval system. Proposed models of the C-130 can operate in and out of a 1500-foot field (Reference 19) with payloads greater than 10,000 pounds.

From an operational standpoint, the technique appears to be feasible but places severe demands upon the aircraft commander and crew and requires the use of a very sophisticated winch-brake mechanism. During a 7-second time span, the aircraft has (1) hooked the payload and (2) rotated to the required climb altitude while (3) firing the JATO bottles at the precise second required. The winch in the aircraft has (1) payed out some 160 feet of line in approximately 1.3 seconds, (2) braked to stop, (3) reversed direction, and (4) achieved full reel-in rpm.

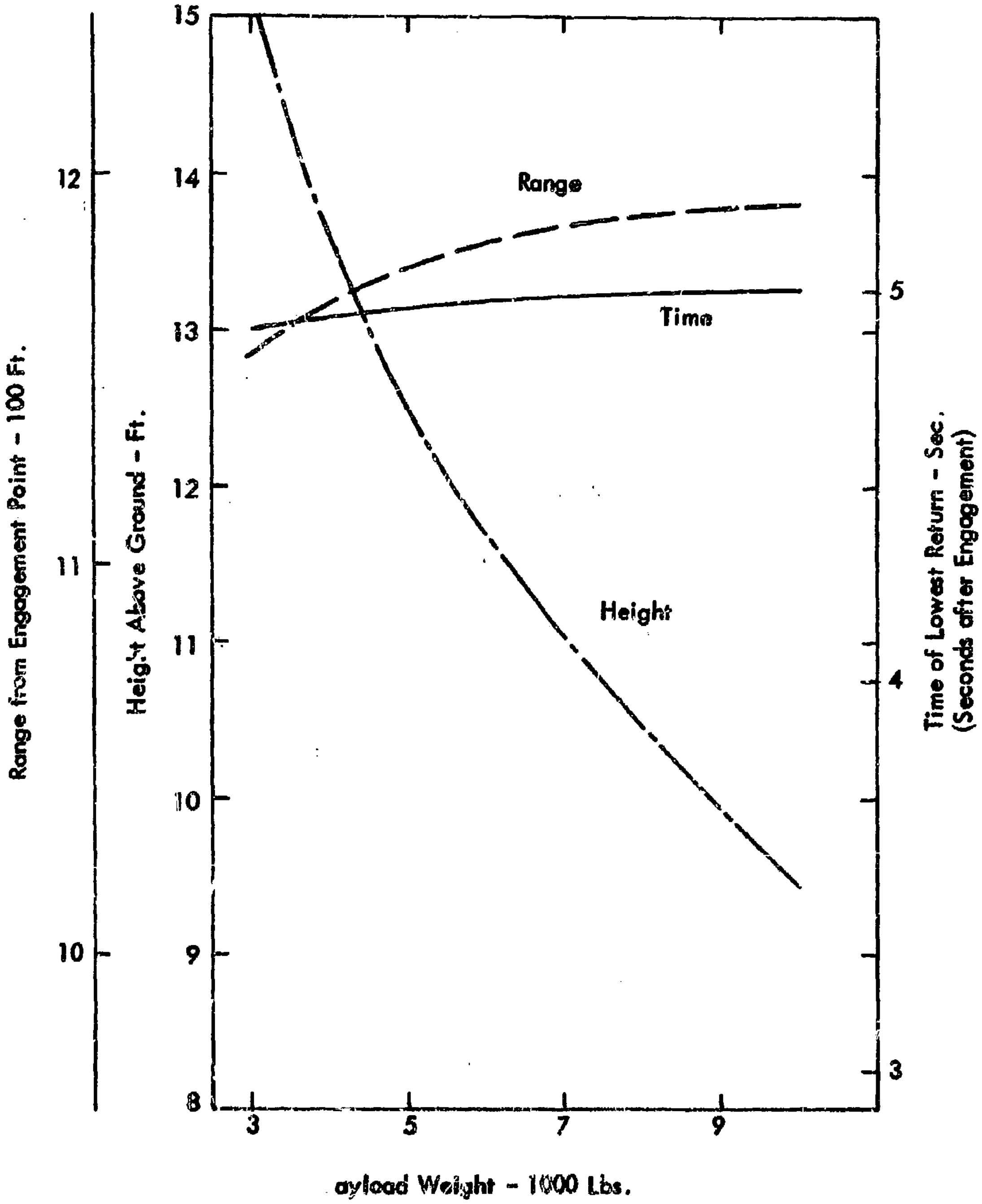


Figure 61 - Winch Brake Concept Payload Trajectory Parameters

The JATO firing and winch operation could be designed for automatic control, taking signals from the line loading; however, the demands on the pilot and crew remain.

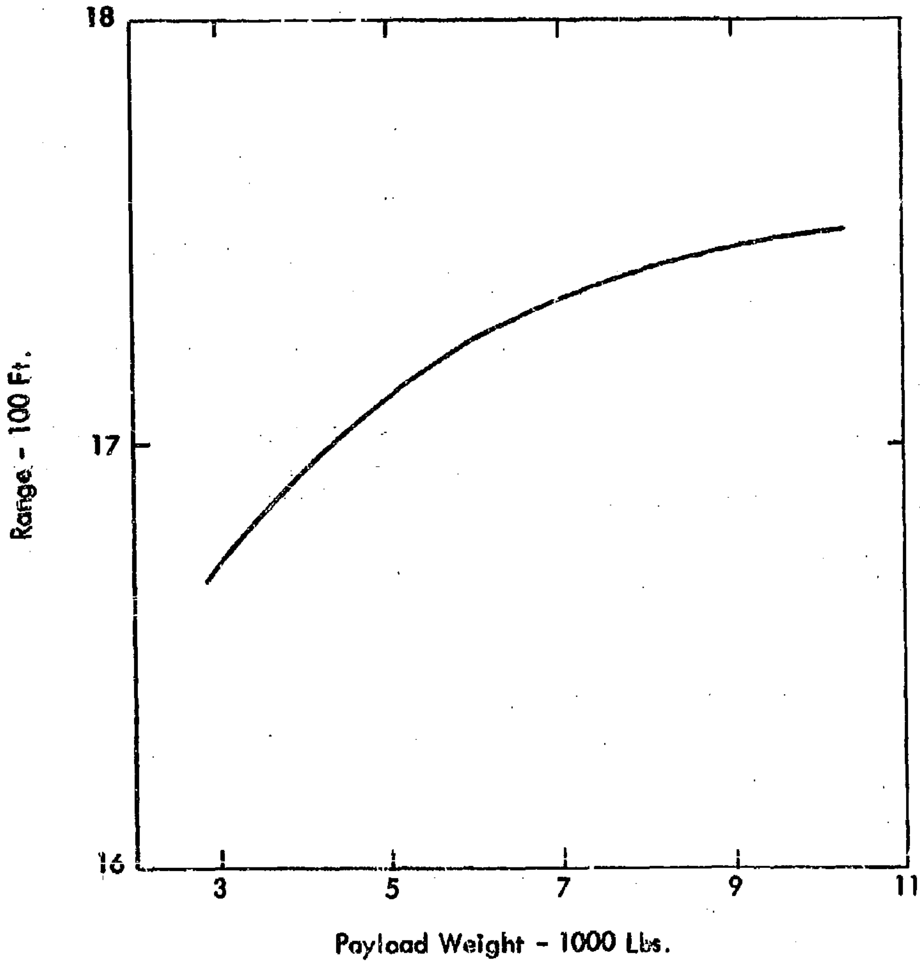


Figure 62 – Winch Brake Concept Range Required for Payload to Clear 50 Feet

Significant engineering problems must be solved in order to cause a system of the type described here to function properly. The design of a fairly advanced winch is the primary item.

It should be noted that the analysis here assumes the winch to be capable of holding a constant line tension during the impact phase. In the analysis of the selected "Balloon-Line" retrieval system a winch with a simpler "Constant-brakeforce" capability is employed. The computer program used for the balloon line analysis was applied to the "winch-brake" technique using a constant brake-force technique. Retrieval was unsuccessful in every case. Also, the winch must be attached to the aircraft in a way that will distribute the high loading during the hook-up phase into the fuselage structure.

Winch-Brake/Rocket Boost

General - This concept is essentially the same as the previous winch-brake concept with one primary exception. Solid rockets are used in the initial impact and acceleration phase both to accelerate the payload to aircraft speed and to lift it rapidly to an altitude above 50 feet.

The rockets are dropped with the initial kit and are mounted to the payload in a manner similar to that described in the section on Payload Ascension Concepts. Figure 63 depicts the Rocket Boost System attached to the payload prior to retrieval.

On engagement, the rockets ignite and accelerate the payload along a planned path so that an altitude of 50 feet is obtained after a minimal lateral travel, and the payload is accelerated without placing high loads on the aircraft and winch.

After burn-out of the rockets, the aircraft continues to climb and tow the payload up and out of the area.

Results and Conclusions - This system is considered impractical for operation in a field type environment. The handling and mounting requirements of solid rockets, particularly of the size required in this system, are not compatible with field operations.

Analysis - This technique requires a complex system of components which must be handled under field conditions. A breakdown of the major hardware items required for this concept is as follows:

A/C Winch & Cable

50 Ft. Knockdown or Telescoping Stanchions

Frame or Structure for Attaching Solid Rockets to Payload

Solid Rocket Motors

Nylon Target Hook-Up Line

The above components must initially be dropped in a kit from the aircraft and assembled by ground crew personnel. The following is an estimate of the size and weight of solid rocket motors required to satisfy the requirements of this system.

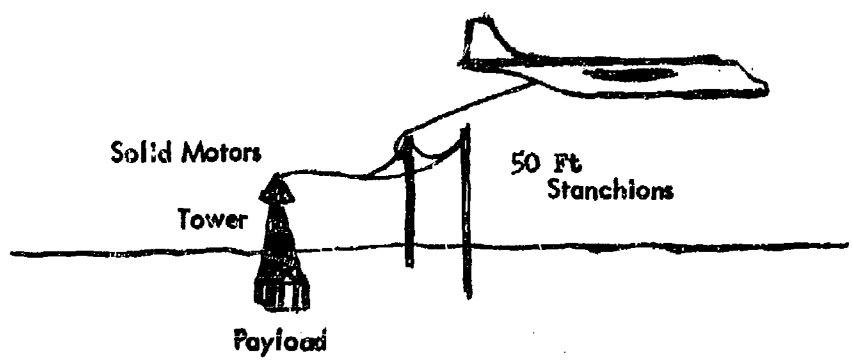


Figure 63 - Winch Brake/Rocket Boost Retrieval Concept

Assume a change of velocity, Δv of 300 fps is required and that the I_{sp} for the solid propellant is 180. Then:

$$e^{\frac{\Delta v}{(I_{sp}).(g)}} = \frac{W_I + W_p + W_c}{W_I + W_c} = e^{\frac{300}{180 \times 32.2}} = 1.053 \qquad (62)$$

where:

W_c = Payload weight of 10,500 lb. (including 500 lb. for rocket support structure)

W_p = Propellant

W_I = Rocket inert weight

$W_I + W_p$ = Rocket gross weight

$W_I + W_p + W_c = W_G$ = System gross weight

Since:

$$\frac{W_I + W_p + W_c}{W_I + W_c} = 1.053 = \frac{W_I + W_c}{W_I + W_c} + \frac{W_p}{W_I + W_c} \qquad (63)$$

then:

$$\frac{W_p}{W_I + W_c} = .053$$

$$W_p = .053\ (W_I + W_c)$$

$$1 = .053\left(\frac{W_I}{W_p} + \frac{W_c}{W_p}\right) \qquad (64)$$

Let $W_p/(W_p + W_l) = 0.8$ (65)

$$W_p = .8W_p + .8W_l$$

$$W_p = \frac{.8}{.2} W_l = 4\,W_l, \quad \frac{W_l}{W_p} = \frac{1}{4} = 0.25 \tag{66}$$

from (64):

$$1 = .053 \quad (.25 + \frac{10,500}{W_p})$$

$$W_p \doteq \frac{10,500}{18.64} = 563 \text{ lb.}$$

from (66):

$$W_l = \frac{W_p}{4} = \frac{563}{4} = 141 \text{ lb.}$$

$$W_{rocket} = W_p + W_l = 704 \text{ lb.}$$

From the conditions given in the previous section on the winch brake technique:

$$t_b = \text{burn time} = 1.3 \text{ seconds}$$

$$\frac{W_p}{t_b} = \frac{563}{1.3} = 433 \text{ lb/sec} = \dot{W}_p \tag{67}$$

Thrust, $T = I_{sp} \times \dot{W}_p = 180 \times 433 = 78,000$ lb. (68)

The lift-off thrust-to-weight is then:

$$\frac{T}{W_G} = \frac{78,000}{10,500 + 704} = 6.97 \tag{69}$$

A solid rocket system of this size will be difficult to manage in the field. The ground personnel will be required to assemble the unit and mount it on the payload so that the thrust vector of the rocket package is in the correct direction. If the unit is misaligned, the retrieval attempt will be seriously jeopardized, possibly resulting in the loss or damage of the P. L.

The total rocket weight of 704 lb. will be broken down into at least 3 units mounted so that the rocket blast will not damage the payload. This requires that the mounting structure extend considerably above the payload (see Figure 63) so that the ground crew will need lifting aids such as a block and tackle or portable crane to assembly the system.

Additional complications could arise as a result of air dropping the rocket system kit. The shock loads sustained by the components when dropped by the aircraft may cause them to malfunction. This is a system reliability factor which is not assessed in detail herein, but is considered in the system complexity rating discussed in a later section.

Also, the peak thrust of a solid rocket and the burn time are functions of the soak temperature of the propellant. Figure 64 depicts a typical plot of solid rocket thrust versus time.

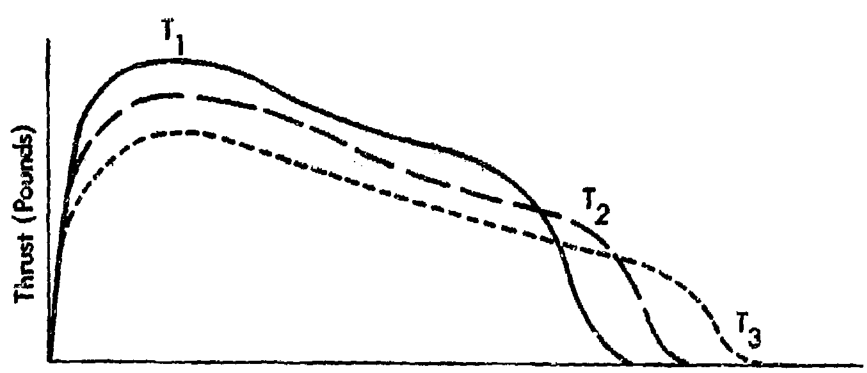


Figure 64 – Solid Rocket Thrust versus Time

In the above figure, T_1, T_2, and T_3 represent propellant soak temperatures. During the pick-up operation the rockets may be exposed to a variety of environmental temperatures so that thrust and burn time could vary considerably during firing.

The complicated nature of this system plus the critical winch design required eliminates this concept from serious consideration.

Magnus Effect Rotor

General – In this concept, the magnus effect rotor is dropped from the aircraft as a kit, assembled and affixed to the payload on the ground. The aircraft flies by and hooks a line attached to the rotor-payload. The hook-up line is wound at the rotor in such a way that an aircraft engagement of the tow line spins up the rotor, thus providing lift while also accelerating the rotor-payload horizontally. The rotor-payload unit continues to climb with the aircraft and accelerates to the aircraft speed. The rotor-payload then reaches a steady state tow condition in trail behind the aircraft. Figure 65 depicts the magnus rotor in tow behind the aircraft.

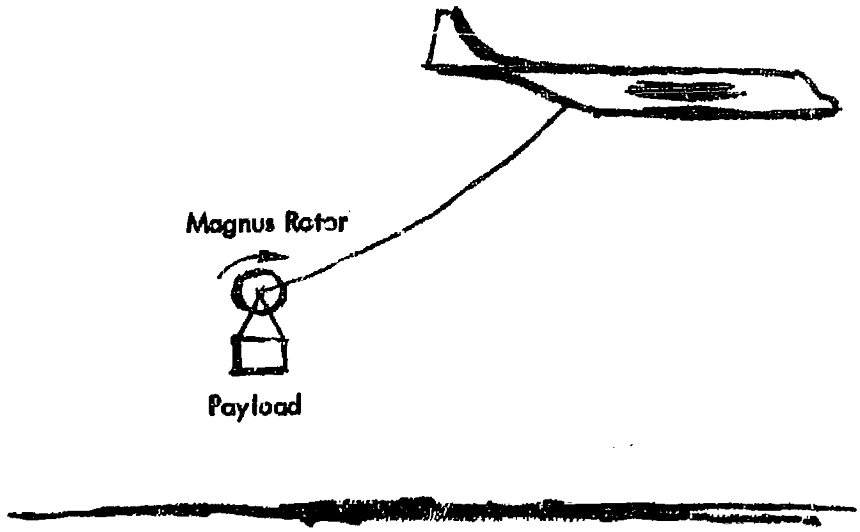


Figure 65 - Magnus Effect Rotor Retrieval Concept

Results and Conclusions - Since a magnus rotor will require complicated devices to provide stability and control and variable lift capability it has been dropped from further consideration.

Analysis - Mathematical analyses indicate that the magnus rotor can be utilized in a system designed to retrieve payloads on the order of 10,000 pounds.

In comparison with using a glider in a similar system the magnus rotor:

1. Provides very short takeoffs.
2. Has a much lower L/D than a glider producing the same lift at the same airspeed.
3. Presents a more complicated overall system than the glider, which contributes to lower reliability.

Presentation of detailed analysis on this system is not considered pertinent since one primary factor eliminates the magnus rotor from serious consideration: the rotor is capable only of producing lift. It has no inherent stability in either the roll, pitch or yaw planes, and simply produces lift as a function of the speed at which it is being pushed or pulled through the air. In order to achieve control on the rotor additional aerodynamic surfaces must be appendaged to the rotor and then controlled remotely.

Since the speed at which the rotor-payload is being towed will vary (during the pick-up phase primarily) and since initial lift required is higher than steady state lift, a simply designed magnus rotor will not suffice. The rotor to be used in this application will require variable lift capability.

The excessively complex control system associated with this retrieval technique places it in an advanced state-of-the-art category and eliminates it from further consideration.

Short Coupled - High Aircraft Approach

The concepts discussed in this section utilize a short line length from the hook-up point to the payload. The payload is lifted to several hundred feet by either a balloon or solid rockets and the airplane flies over, hooking a target line above the payload.

Two systems are considered in this section:

- Balloon Payload Ascension
- Rocket Payload Ascension

Balloon Payload Ascension

General - This payload ascension technique operates in the following manner. The aircraft makes a low-level pass and drops a kit containing the ascension balloon, bottled helium, associated lines and attachment hardware. Ground personnel attach the balloon to the payload and inflate it using the bottled helium. The balloon ascends carrying the payload to a specified altitude and is guyed to the ground to prevent further ascension.

The aircraft then makes its pass, snagging the balloon cable as depicted in Figure 66. The balloon is designed to rip and deflate on pick-up and a sensing device releases the guy line from the payload. The payload is then in tow behind the aircraft.

Results and Conclusions - The balloon ascension system described above is considered impractical for the following reasons:

(1) The large size of the balloon leads to several problems. Among these are erection difficulties under field conditions, the associated time required and also drift during the pick-up run.

(2) The possibility exists that the balloon will be destroyed in a pick-up attempt without effecting a successful hook-up. This leads to additional complication in that a large recovery parachute is needed to save the payload should the pick-up attempt fail.

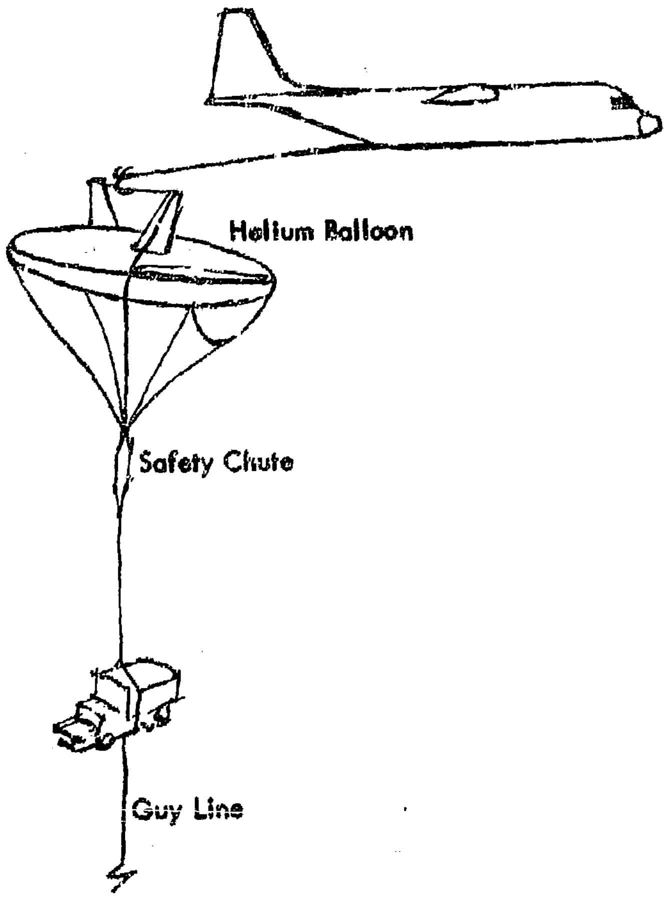


Figure 66 - Balloon Payload Ascension Retrieval Concept

Analysis - Figure 67 diagrams the forces on the balloon system. The equation of vertical forces on the balloon is:

$$F_v = 0 = F_B - W_T - ma$$

where F_B = byouant force on balloon

$$W_T = W_B + W_c + W_p + W_R$$

W_B = weight of balloon

W_c = weight of safety chute

W_p = weight of payload

W_R = weight of harness, lines etc. at the payload

m = total mass of system = $\frac{W_T}{g}$

a = vertical acceleration

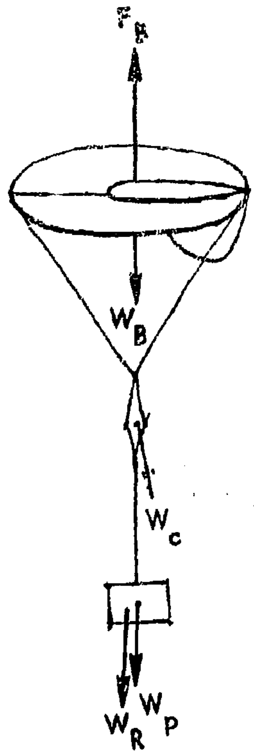


Figure 67 - Force Diagram for Helium Balloon

Weight estimates

W_B = 750 lbs.

W_c = 1000

W_p = 10,000

W_R = 1000

W_T = 12,750 lbs.

Assume $a = 1/2\ \text{ft/sec}^2$

Then:

$$F_B = W_T + ma = 12{,}750\ \text{lbs.} + \frac{12{,}750}{32.2} \cdot 1/2$$

$$F_B = 12{,}948\ \text{lbs.}$$

The buoyant force generated by the displacement of air with helium is given by:

$$F_B = \rho_A V_B - \rho_H V_B = V_B(\rho_A - \rho_H) \tag{72}$$

where:

ρ_A = density of air in lbs/ft^3

V_B = volume of air in ft^3

ρ_H = density of helium in lbs/ft^3

To determine the balloon volume required then

$$V_B = \frac{F_B}{(\rho_A - \rho_H)} = \frac{12,948}{.0765 - .0111} = \frac{12,948}{.0654}$$

$$V_B = 198,000 \ ft^3$$

Assuming the balloon is ellipsoidal, the volume is given by

$$V_B = \frac{4}{3}\pi abc$$

where a, b, c are the lengths of the semi-axes. (See Figure 68).

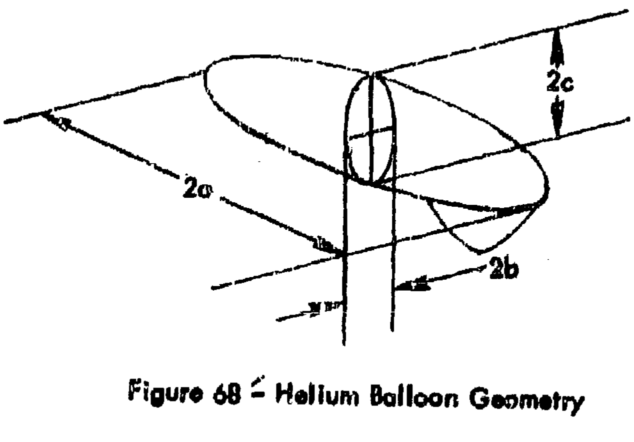


Figure 68 – Helium Balloon Geometry

Letting $c = b$ and $a = 3c$ the volume in terms of "a", the length, is

$$V_B = \frac{4}{3}\pi\, a\, \frac{a}{3}\, \frac{a}{3} = \frac{4}{27}\pi a^3 \tag{73}$$

then

$$a = \left(\frac{27 V_B}{4\pi}\right)^{1/3} = \left(\frac{27 \times 198,000}{4\pi}\right)^{1/3} = (426,000)^{1/3}$$

$$a = 75.\ \text{ft.}$$

$$2a = \text{length} = 150\ \text{ft.}$$

$$2c = \text{diameter} = \frac{2a}{3} = 50\ \text{ft.}$$

Figure 69 presents the helium balloon size required for payloads from 3000 to 10,000 lbs. The large size of these balloons suggests serious problems with ground handling and inflation, involving an appreciable assembly and erection time. Gusting surface winds could make it impossible to erect the balloon.

The problem of releasing the balloon after aircraft engagement is made is also significant. The balloon must be rapidly deflated rather than simply released, since it must be securely affixed to the payload prior to pick-up. Unless the balloon is destroyed rapidly it will create unmanageable drag for the aircraft. Additionally, a safety parachute is required to get the payload back down safely in event the balloon is destroyed.

After engagement, in order to keep impact forces as low as possible, it is necessary for the winch to pay out several hundred feet of tow line. Consequently, the payload then swings down in an arc toward the ground. Therefore, in order for the system to operate properly, a pick-up altitude of 800-1000 feet is required.

At 1000 feet in a 30 knot wind a tethered balloon of 198,000 ft^3 volume undergoes a maximum excursion of approximately 250 feet, making it a somewhat difficult target.

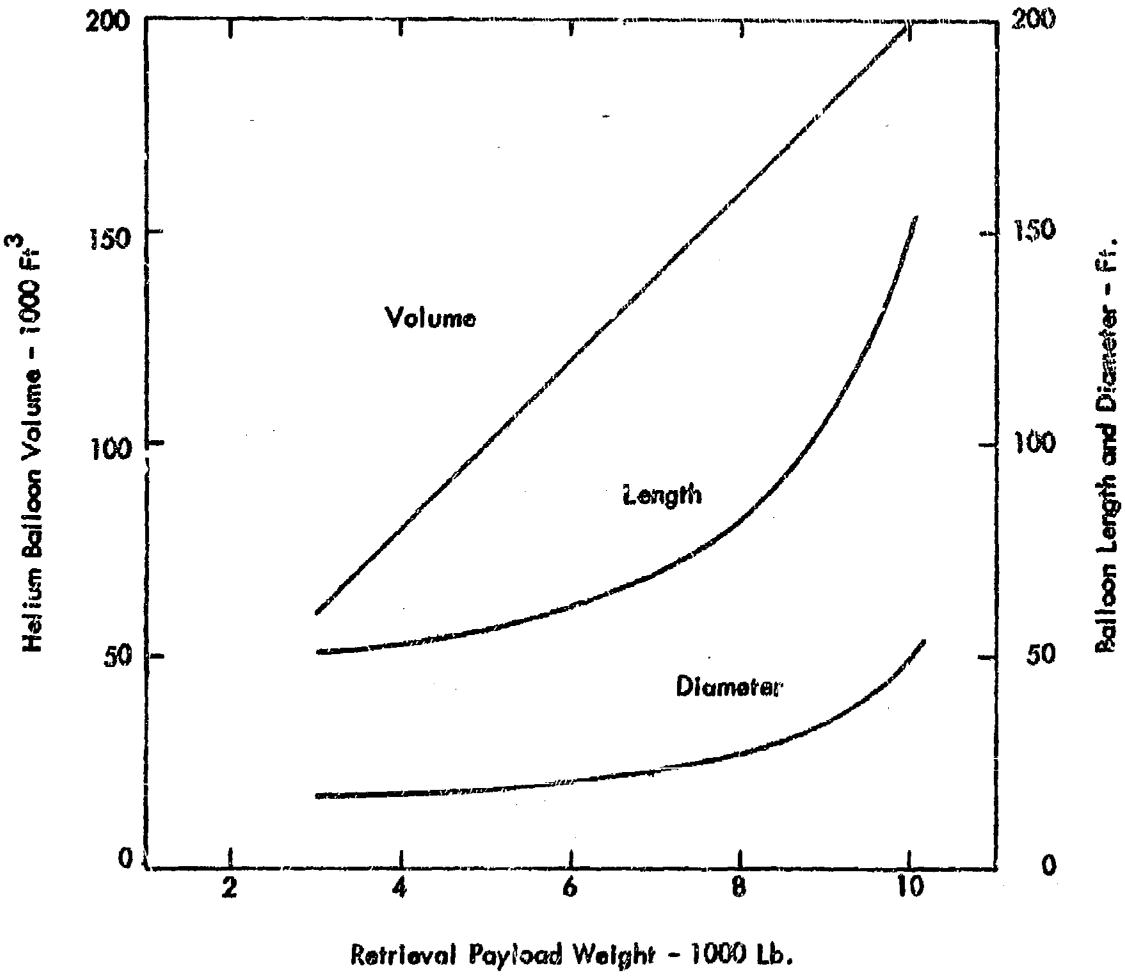


Figure 69 - Balloon Payload Ascension, Balloon Size versus Retrieval Payload Weight

Rocket Ascension/Parachute Retrieval Concept

General - In this concept, the retrieval aircraft first makes a pass and drops a kit containing a solid rocket ascension system and parachute.

A ground crew assembles the rocket ascension system and mounts it to the payload. At a time controlled by the pilot of the aircraft, the rockets are fired, lifting the system to a predetermined altitude. The parachute opens and allows the payload and spent rocket unit to begin a slow descent. The aircraft then passes and engages the parachute - payload by snagging a line suspended on "ears" above the parachute.

Figure 70 depicts the operation of this concept.

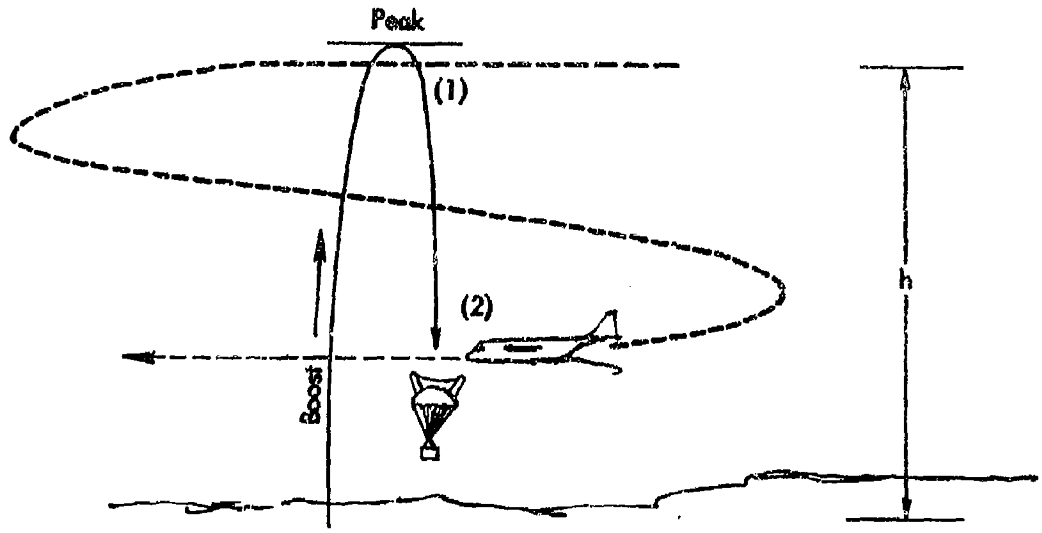


Figure 70 - Rocket Ascension/Parachute Retrieval Concept

Results and Conclusions - There are many factors which make this system impractical for payload retrieval operations. The primary factors are:

(1) The high accelerations and loads on the payload and aircraft at engagement,

(2) The limited time available to engage the payload during the descent of the system, and

(3) The difficulties which will be experienced by the ground crews in assembling the ascension system for proper operation.

Analysis - Since the payload and parachute are descending and have essentially no horizontal speed, the engagement phase impact loads are higher than if the payload were located on the ground. The section on ground snatch techniques in this report discusses the elaborate winch system which is required to handle a ground snatch of the payload. A winch of the same type would be required for the rocket ascension technique, and must be designed to handle even higher loads.

The payload must also be lofted to a substantial altitude to allow a reasonable period of time for engagement by the aircraft. The required altitude can be estimated as follows.

- Time for plane to circle: Radius of turn is 4000 feet at speed of 250 fps.

$$t = \frac{\text{distance}}{\text{speed}} = \frac{2\pi \times 4000}{250} = 100 \text{ seconds}$$

- Assume parachute allows cargo to drop at a speed of 25 feet/second.
- Allow 100 feet drop from peak for chute to open. Assume that last pass must be made at a minimum altitude of 500 feet.

For each phase of the pick-up sequence, the payload-chute descent is estimated as follows:

	Payload/Chute Descent Distances
chute opening	100 ft.
during first pass	50 ft.
a/c circling	2500 ft.
margin above ground	600 ft.
Total Altitude	3250 ft.

Allowing an additional margin of 250 feet, the total minimum altitude required for just two passes at the payload-chute target is 3500 feet. For each additional pass, an additional 2500 feet of altitude is needed.

A system of this nature requires perfect timing in order to be successful. The initial position of the aircraft relative to the payload and chute must be fairly exact in order to provide a good chance of success on the first pass and allow sufficient time for a second pass. Engagement must be made with a moving target which makes the task even more difficult.

Another significant disadvantage to this system is the delivery, ground handling, and assembly of the rocket-chute ascension system.

A similar solid rocket ascension system is discussed in the section on ground snatch techniques. The discussion of the system in that section applies to the payload ascension system being considered here. However, in this case, the rocket system is even heavier since a chute is included and the total package must be given a larger Δv to attain the 3500 feet of altitude required.

Long Coupled - Low Aircraft Approach

A long line is employed in this concept to connect the aircraft with the payload. In the Lifting Line concept, the line is extended up-range toward the approaching aircraft. In the Glider and Parawing concepts, the line is extended downrange.

In all cases, stanchions are used to hold the nylon target line aloft for engagement by a trailing aircraft hook.

Four concepts are discussed in this section:

Lifting Line	Glider	Parawing	Trailing Airborne Lift Device

Lifting Line

General - This system consists of a line equipped with a number of aerodynamic vanes spaced at various points along the line. The vanes serve a dual purpose: They shape the line to damp the build-up of forces in the system and also provide small increments of lift.

The line can either be laid out along the ground in the direction of aircraft approach and the hook-up portion held aloft on stanchions, or the entire lifting line length can be held aloft by a balloon. The latter technique should actually be classified as a "Long Coupled - High Aircraft Concept," but due to the similarities of the two techniques they are discussed together in this section.

In the former concept, the vanes are positioned along the ground in the direction from which the aircraft is to approach. The hook-up end of the line is held aloft by 50-foot stanchions to allow the aircraft to make a pass at no lower than a 60-foot altitude. Theoretically, the line begins to "fly" off the ground after engagement, shaping itself as shown in Figure 71, so that the payload lifts off in a near vertical trajectory.

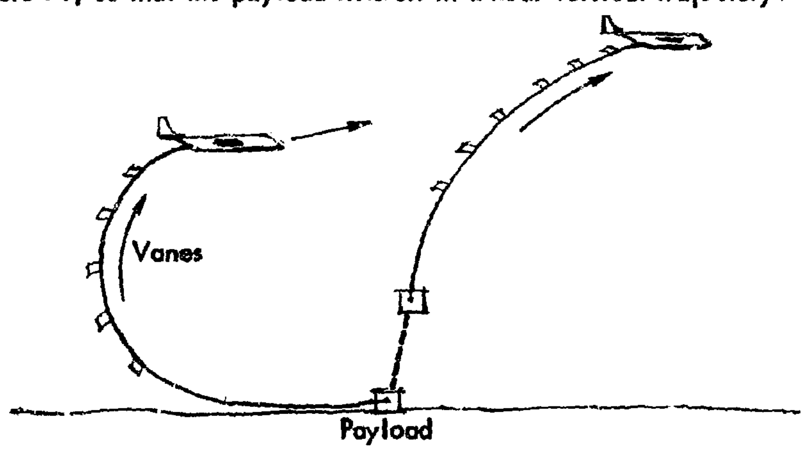


Figure 71 - Lifting Line Retrieval Concept

The latter concept, in which the lifting-line equipped with vanes is held aloft by a balloon, operates similarly to the suspended balloon-line. The primary function of the vanes is the same as when the line is initially on the ground. The vanes curve the line, reduce impact loads, and give the payload a near vertical trajectory.

Results and Conclusions - This system is considered to be impractical for a number of reasons. The primary difficulties stem from the operation and handling of such a system. In order to retrieve a 10,000-pound payload, for example, it is necessary to drop an equipment kit weighing at least 7500 pounds. Figure 72 depicts the relation between total kit weight and retrieval payload weight for payloads from 3000 to 10,000 pounds.

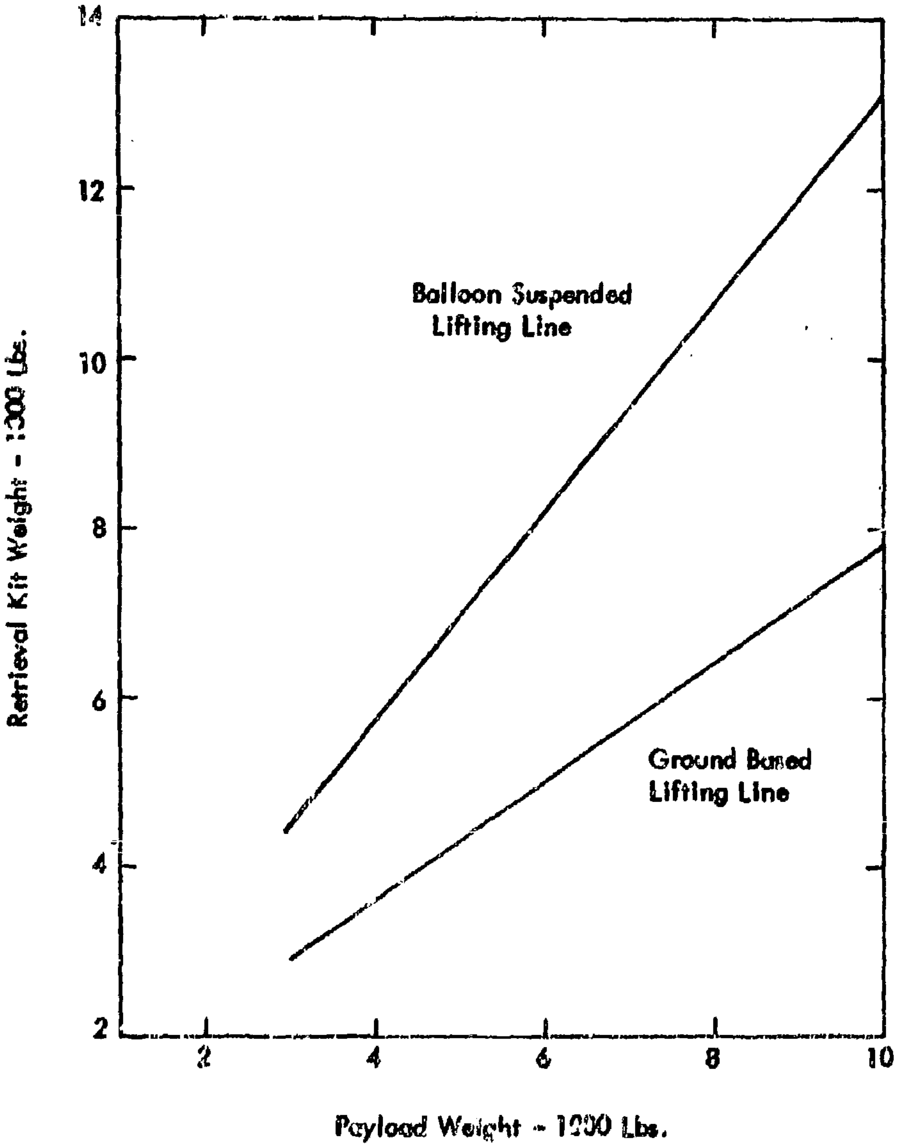


Figure 72 - Lifting Line Technique Retrieval Kit Weight versus Retrieval Payload Weight

A third reason is that the complexity of such a system makes successful operation in the field unlikely.

<u>Analysis</u> - Initial consideration was given to constructing a computer program to simulate the lifting line technique.

The mathematical simulation of the lifting line concept involves the determination of line shape as a function of time. The line shape is defined by the aerodynamic forces and the tension due to the accelerating payload. The aerodynamic force at each point on the line is a function of local velocity, and this velocity distribution is constrained by the continuity of the line. The result is a very complex variational problem. The calculus of the variations problem is further complicated because of different end conditions before and after the payload has lifted off the ground. All of the parameters involved are functions of time. In addition, since aerodynamic characteristics are locally discontinuous when vanes are stalled, this problem is not amenable to an exact analytic solution. In view of these factors, a numerical computer solution would involve a major expenditure of effort. Such a program was considered to be beyond the scope of this study.

In lieu of a computer program analysis, a simpler approach was taken for a cursory evaluation of the lifting line concept.

The most significant feature of the lifting line concept is, of course, the aerodynamic vanes spaced at intervals along the line. A primary consideration is the size and weight of these vanes. Three simplified techniques were used to estimate the vane size required for this system. The results of the estimates were similar, and the calculations indicate that an excessive amount of total lifting surface is required.

Figure 73 illustrates one of the three techniques used for estimating the vane size. Assume

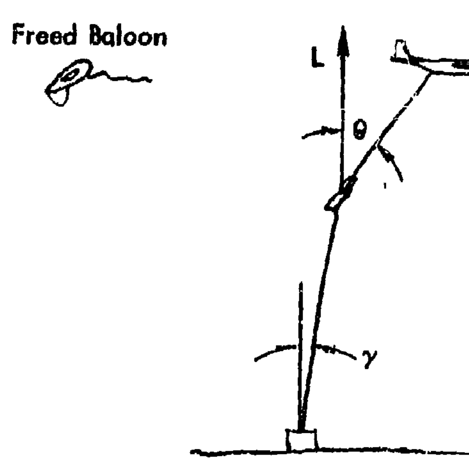


Figure 73 - Lifting Line Geometry

initially that there is only one vane, as shown in Figure 73, and that the vane is designed to lift the payload near vertically at a 3g acceleration. Further simplifying assumptions are that an instantaneous steady-state condition is being observed, thus eliminating accelerations, and that vertical speed is negligible compared to horizontal speed.

The forces on the single vane are shown in Figure 74.

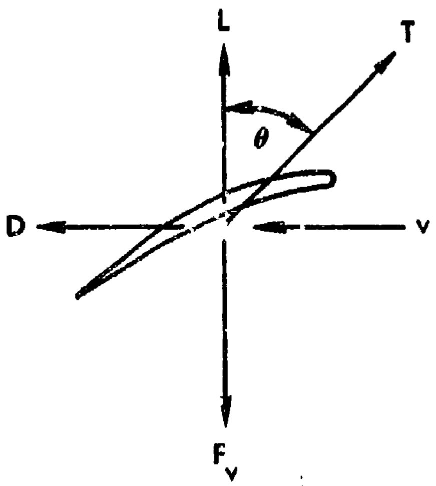


Figure 74 - Force Diagram for Lifting Surface

Therefore:

$$\sum F_V = 0 = L + T \cos\theta - F_V \qquad (73)$$

$$\sum F_H = 0 = T \sin\theta - D \qquad (74)$$

where:

L = Lift on vane

T = Line tension

D = Drag on vane

F_V = Vertical force on payload

θ = Angle of tow line to vertical

Assume that the vane operates at an L/D of 5, then:

$$L/D = 5; \; L = 5D \qquad (75)$$

Solving the above equations yields:

$$L = \frac{F_V}{\left(1 + \frac{\cot\ \theta}{5}\right)}$$

let: $F_V = 3\ mg$

$\theta = 30^\circ$

$\cot\theta = 1.732$

then using a 10,000 pound sample payload:

$$L = \frac{3\ mg}{\left(1 + \frac{\cot \theta}{5}\right)} = \frac{3 \times 10{,}000/32.2 \times 32.2}{1 + \frac{1.732}{5}}$$

$$L = 22{,}300 \text{ pounds}$$

The vanes are operating at a wide range of angles of attack. Assuming a C_L maximum of 1.0 for each vane, and a linear C_L versus α curve, an average C_L is taken as 0.5 for the single vane.

If the aircraft has a horizontal speed of 250 feet/second and the payload has a horizontal speed of essentially zero, the speed of the single vane can be estimated at no more than 2/3 of the aircraft speed, or 167 feet/second.

The total lifting surface area can be estimated by:

$$S_T = \frac{L}{\bar{C}_L \ \bar{q}} \tag{76}$$

where

$$L = 22{,}300$$

$$\bar{C}_L = 0.5 \text{ (average } C_L \text{ for all operating vanes)}$$

$$\bar{q} = 1/2 \ \rho \ V^2 = 1/2 \times .00238 \times 167^2 = 33.2$$

$$S_T = \frac{22{,}300}{0.5 \times 33.2}$$

$$S_T = 1350 \text{ feet}^2$$

Assume that a total of 30 vanes are distributed along the more efficient portion of the line. Each vane must then be capable of withstanding loads associated with the maximum C_L of 1.0 and the maximum q of 75 psf (v = 250 feet/second).

The maximum lift each vane must be capable of withstanding then, is:

$$L_V = C_L \ S_V \ q \tag{77}$$

where

$$S_V = \frac{1350}{30} = 45 \text{ feet}^2$$

$$L_V = 1.0 \times 45 \times 75$$

$$L_V = 3370 \text{ pounds}$$

and the drag:

$$D_V = \frac{3370}{5} = 675 \text{ pounds}$$

A vane design can then be suggested as shown in Figure 75.

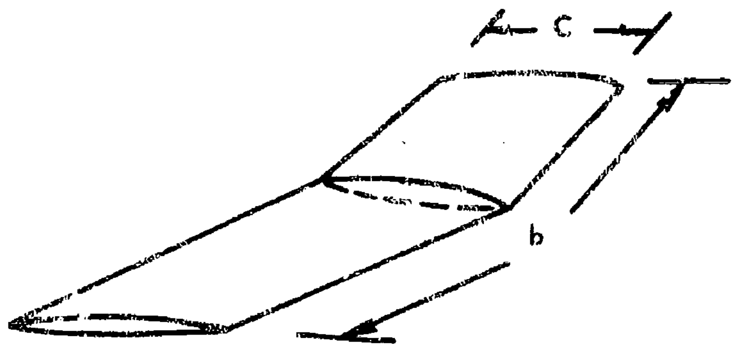


Figure 75 – Representative Lifting Surface Configuration

$$S_V = b \times c = 45 \text{ feet}^2 \tag{78}$$

let:

$b = 9$

$c = 5$

Assuming an optimistic weight for the lifting surface of 5 pounds/feet^2, the weight of each vane is then:

$$W_V = 45 \times 5 = 225 \text{ pounds} \tag{79}$$

The total weight of 30 vanes is then:

$$W_T = 30\, W_V = 6750 \text{ pounds} \tag{80}$$

First considering the concept in which a helium balloon is used to support the lifting-line, it can be seen that the balloon size required is excessive. The total weight to be supported by the balloon will include some 6750 pounds of vanes plus at least 250 pounds of nylon line.

In order to support the total of 7000 pounds, a balloon of 114,000 feet^3 volume, some 126 feet long and 42 feet across is required.

The weight breakdown of the initial drop kit is approximated by:

Balloon	520 pounds
Helium bottles	5,000 pounds
Nylon line	250 pounds
Lifting vanes	6,750 pounds
Payload harness	500 pounds
Total	13,020 pounds

This in order to retrieve 10,000 pounds, roughly 13,000 pounds must be delivered.

For the concept wherein the lifting line is laid out on the ground and stanchions are used, the system weighs at least 7500-8000 pounds, (See Figure 71). The likelyhood that lifting line will function in practice as predicted in theory is unknown. Unless the line "flies" off the ground perfectly, the retrieval attempt may fail, damaging or destroying a sizeable portion of the retrieval gear as well as the payload.

Fixed-Wing Glider

General - The system depicted in Figure 76 is composed of a fixed-wing glider mounted to the payload on the ground, a nylon line attached to the glider/payload, and stanchions to support the nylon line for engagement.

The purpose of the long nylon line is twofold: (1) the stretch in the nylon (up to 20 percent of original length) reduces peak impact loads, and (2) the line coming into the payload in the horizontal plane allows acceleration of the glider/payload in the correct direction. If a short line is used, as discussed for other systems, the vertical glider/payload acceleration would be too great as compared to the horizontal acceleration.

The components are dropped in kit form from the aircraft, assembled by ground personnel, and attached to the payload.

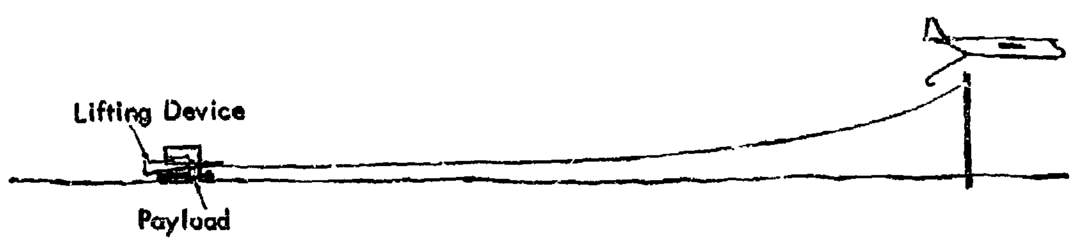


Figure 76 - Fixed-Wing Glider Retrieval Concept

The aircraft approaches the target, engages the line and pulls the glider/payload along the ground until it reaches flying speed. The device then flies off the ground in tow by the aircraft.

Results and Conclusions - The fixed-wing glider is not acceptable for use in the system described for three reasons:

1. Glider size and weight: A glider capable of retrieving 10,000 pounds weighs at least 10,000 pounds and requires a wing span of 35 to 40 feet.
2. Ground roll required: Holding a maximum line tension of 25,000 pounds (controlled by winch payout) the ground roll required for the glider to clear a 50-foot obstacle was computed to be 1200 feet.
3. Field operation: It is impossible to have a glider function properly in this application without either a crew on board or an elaborate remote flight control system.

Analysis - Assuming a lift coefficient, C_L, of 1.2 a sea level density, and a steady state tow speed of 150 knots (250 feet/second), the wing area for such a glider can be determined.

$$S = \frac{L}{C_L\ q} \tag{81}$$

where

L = total lift required of glider = payload weight + glider weight = 20,000 pounds (based on WWII gliders, where gross weight is about twice payload weight)

C_L = 1.2

q = 75 psf (@ 250 fps)

then

$$S = \frac{20,000}{1.2\ (75)} = 220 \text{ feet}^2$$

An example of a wing this size is one with a 6-foot chord and roughly a 37-foot span.

A computer program was developed to determine the take-off distance required for the glider/payload to clear a 50-foot obstacle.

The program was designed to take into account:

1. Line elongation during early engagement and ground roll.
2. Line reel-out, when line tension reaches a preset maximum.
3. Change in angle of attack of the glider/payload.

The program neglects:

1. Ground roll friction
2. Ground effects
3. Crosswind gust effects

Several glider/payload weights were analyzed at tow line tensions of 25,000, 35,000, and 45,000 pounds. Results of the initial runs were examined for effect on the aircraft performance.

The deceleration of the aircraft during the pickup of the glider/payload was determined through the following relation:

$$\sum F_x = 0 = T - D - F_L \cos\theta - ma \qquad (82)$$

where

T = Aircraft thrust available

D = Drag of aircraft

F_L = Line tension

θ = Line angle with horizontal

m = Mass of aircraft

a = Deceleration of aircraft

Referring to the aircraft limitations section of this report it can be determined that the excess thrust available for the C-130 at the flight condition of this analysis is roughly 18,700 pounds. Therefore, in the above equation:

$T - D = 18{,}700$ pounds

Assuming that θ is small and $\cos\theta = 1.0$, then:

$$a = \frac{18{,}700 - F_L}{m}$$

substituting $F_L = 25{,}000$ pounds, and

$$m = \frac{120{,}000}{g}$$

$$a = \frac{-6{,}300 \times 32.2}{120{,}000} = -1.69 \text{ ft/sec}^2$$

The deceleration time was determined from the computer run to be 8.3 seconds. Therefore the loss in airspeed for the aircraft is:

$$V = a\ t \qquad (83)$$

$V = -1.69 \times 8.3 = 14$ ft/sec $= 8.3$ knots

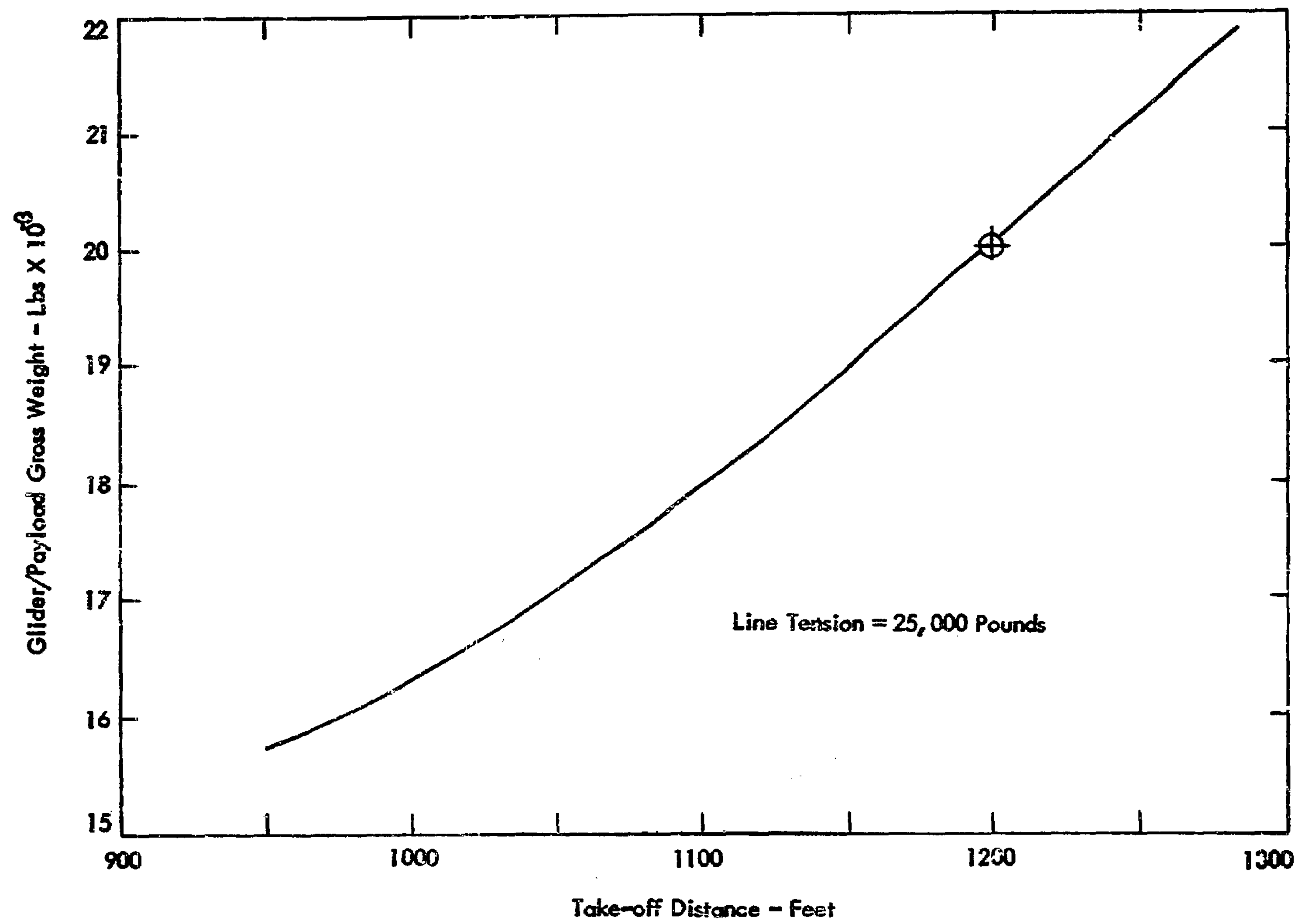


Figure 77 – Gross Weight versus Take-off Distance – Fixed Wing Glider

A similar analysis for a line tension of 35,000 pounds was performed yielding an aircraft deceleration of 15.8 knots.

Since the aircraft is at a very low altitude and low air speed, its deceleration should be kept to a minimum. The remainder of the analysis, therefore, was restricted to use of a 25,000-pound tow line tension.

Figure 77 presents the pertinent results of the analysis.

Note that for a glider/payload weight of 20,000 pounds the distance required to clear a 50-foot obstacle was computed to be 1200 feet. This value represents the largest ground clearance required of the retrieval techniques considered, with the exception of the "winch-brake" system which requires 1700 feet.

Parawing

General - This system functions as the glider system previously described. The parawing is stored in the aircraft and delivered in similar fashion to the glider.

Results and Conclusions - Since the parawing cannot be towed at speeds higher than 86 knots as shown in the section on circling line concepts of this report, further analysis of this retrieval system was not required.

Trailing Lift Device

General - A system was considered in which a lifting device is towed over the pickup point on a low approach, as shown in 78. A system of lines connect the aircraft with the lift device such that the engagement hook is located at a point between the aircraft and the lift devices.

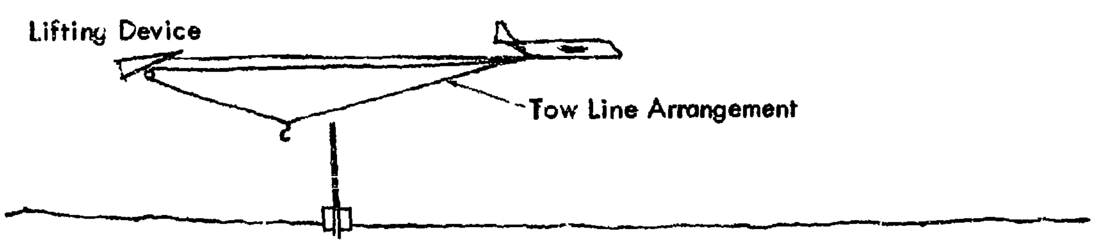


Figure 78 - Trailing Lift Device Retrieval Concept

When hookup is effected, the payload moves up and aft relative to the aircraft in a somewhat elliptical path. As the payload reaches aircraft and lift device speed it is retained in a position near the lift device and both units are towed by the aircraft.

The primary purpose of the rather elaborate system of cables or lines is to allow transfer of momentum to the payload at a slow rate, thus reducing impact loads.

Results and Conclusions - This system is considered impractical because of limitations associated with candidate lift devices and the operational problems associated with the use of such a system in the field.

Analysis - Successful operation of this system requires exact component positioning prior to and after engagement. Under field condition, gusts, crosswinds, and thermals make it extremely difficult to fly the system in the manner required.

Two candidate lift-devices for this system are the glider and the parawing.

Analysis of these two devices in other sections of this report indicate that (1) the parawing cannot be used due to speed limitations, and (2) the glider has serious deficiencies in retrieval applications. A glider suitable for use in this application must weigh at least as much as the retrieval payload pounds and have either a crew on board or an elaborate remote control flight system.

Long Coupled - High Aircraft Approach

The techniques and systems considered in this category utilize a long nylon coupling line between the aircraft and the payload to be retrieved. The target line is lofted to a specified altitude as dictated by the requirements of each system. The aircraft passes over the target line, engages a trailing hook onto the line, and lifts the payload in a near vertical trajectory. After engagement loads have subsided, the aircraft begins to climb and reel-in line as the payload oscillates and finally rests in a steady-state tow position.

Five concepts are classified in this category. These are:

- Lifting Line - High
- Balloon Line
- Balloon Line/Rocket Boost
- Line Rotary Lift Device
- Rocket Line

Lifting Line - High

This concept was previously discussed under the heading of "Lifting Line."

Balloon Line

General - This system uses a helium balloon to lift the payload retrieval line aloft, while the payload remains on the ground. This concept is illustrated in Figure 79.

On an initial pass, the aircraft drops a kit containing the balloon, retrieval line, and harness. A ground crew attaches the kit to the payload, inflates the balloon, and restrains the payload line as the balloon ascends to the planned altitude. The aircraft returns and engages the cross line above the balloon, destroying or freeing the balloon and lifting the payload off the ground.

The aircraft winch allows line pay-out and holds the maximum acceleration on the payload to 3g's. As soon as possible, the winch stops pay-out and begins to reel the payload into a position near the aircraft. The payload is then towed to base.

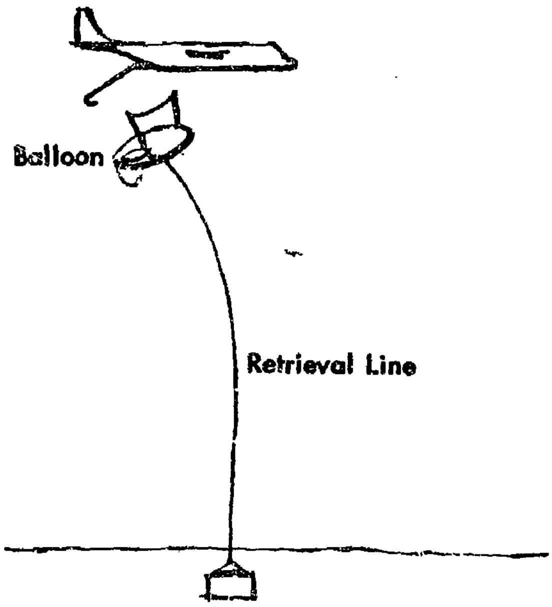


Figure 79 - Balloon Line Retrieval Concept

Results and Conclusions - This technique offers several advantages over the other concepts analyzed in the study:

1. Lower aircraft and payload accelerations and loading during engagement
2. Less winch pay-out required
3. More vertical payload trajectory off the ground and a correspondingly smaller required clear area

It has been concluded that this retrieval system is perhaps the most promising of those considered.

A later section of this report presents a detailed analysis of the balloon line concept and the predicted performance of the system.

Analysis - Several improvements over the basic ground snatch technique discussed previously are afforded by the balloon line system of retrieval.

By extending the nylon line to an altitude of 500 feet or more, several advantages are realized. The drag, elongation, and inertia of the line cause it to form a curved shape from the aircraft to the payload after engagement. This causes the payload to follow a near vertical trajectory and clear the ground area after a minimal lateral excursion.

A second advantage of the balloon system also results from the properties of the long nylon line. The line elongates and curves over behind the aircraft thus requiring less winch-cable pay-out than a lower altitude engagement technique. This results in lower loads on the aircraft and a less complicated winch design. A detailed discussion of the balloon altitude is presented in the section on Performance of Selected System.

The equipment required is essentially the same as that presently used in the Fulton pickup system currently undergoing tests by the Air Force (Reference 20). The only significant differences in equipment required are in size and weight of the suspension balloon and the nylon line, and a different engagement mechanism on the aircraft.

In the Fulton system, the nose of the aircraft strikes the suspended line and holds it as the lightweight payload is pulled off the ground. In the balloon-line retrieval technique, due to the heavy payloads involved, the aircraft must trail the hook from a stronger load point than the aircraft nose. The target line must be suspended above the balloon and therefore accessible to a trailing hook on the aircraft.

On impact, the balloon will either separate from the system, or rip and deflate allowing the aircraft to tow only the line and the payload.

Balloon Line - Rocket Booster

General - In this retrieval technique, the system operates essentially the same as the balloon line system previously discussed. Rockets are mounted on the payload to reduce load levels and cause the payload to rise more quickly.

Results and Conclusions - The section on Winch-Brake - Rocket Boost in this report discusses the complexity and operational problems involved with a rocket boost unit mounted to a retrieval payload.

The relatively simple balloon-line concept has been shown to be an attractive system from the standpoint of aircraft and payload loading, trajectory, and system simplicity. The addition of boost rockets to the payload is considered to be an unnecessary complication of the system.

Analysis - None required.

Line Rotary Lift Device

General - In this system, a powered rotary lift device is attached to a rope attached to the payload. The rotor device ascends trailing the rope to the payload on the ground. The rotor device is then jettisoned to descend independently from the rope, and a parachute opens allowing the rope to descend to a rate of approximately 25 feet/second.

As the parachute and rope descend slowly the aircraft passes and engages a target line held above the parachute on "ears".

The payload is lifted from the ground by the aircraft, reeled in to a point near the aircraft, and towed to base.

Results and Conclusions - This system is undesirable. The limited time available for engagement by the aircraft reduces the reliability of such a system. Unless the line is lifted to an altitude of 4000 feet there is time for only one pass at the chute.

As the parachute descends and before aircraft engagement, slack line accumulates on the ground around the payload. On aircraft engagement, this slack line tightens almost instantaneously causing an excessive "g" loading on the line and on the aircraft.

The rotor craft returns to the ground and is lost unless it is restrained by a line so that it can be pulled in to the ground base where the payload originated. If other payloads remain at the same location, the rotor craft can be used again, otherwise it must be considered an expendable unit.

Rocket Line

General - This system operates in essentially the same manner as the Line Rotary Lift Device except that the line is carried aloft by a solid rocket in this system.

Results and Conclusions - This system is undesirable for the same reasons given for the Line Rotary Lift Device.

Aircraft Circling Concepts

This category includes techniques wherein the cargo aircraft circles above the payload on the ground and is connected to the payload by the retrieval line. The concepts discussed in this section employ various means of effecting initial engagement between the aircraft and the payload and of retrieving the payload after engagement is accomplished. In all of the techniques presented in this section, the engagement tow line is fed from an aircraft mounted winch and eventually reeled back in by the winch until the payload is in a convenient towing position behind the aircraft.

In contrast to the retrieval techniques in the preceding section, the retrieval line hanging aft of the aircraft is of considerable length and does not have a stabilizing boom. The following comments discuss in general the dynamic behavior of long towed cables, both with and without a body attached to the end of the cable.

The required length of the line is determined primarily by the ratio of its weight to the aerodynamic loads ($W/C_N S$) and the minimum turn radius which the aircraft can maintain. Once over the payload to be retrieved, a circling pattern is established by the aircraft so that each point on the line follows a circular path in its own horizontal plane. For uniformly distributed line weight, and cables of characteristically high weight to normal force ratios, the trailing line tends to align itself closer to the streamwise direction as the distance from the aircraft increases. Adding a pure drag force at the end of the line causes an increase in line tension and a decrease in line sag, and the end of the line rides higher. If a weight is added to the end of a trailing line, line curvature reverses so that the cable angle of attack is greatest at the point where the load is attached, and the end of the cable rides at a lower altitude.

In the case of the unloaded cable of uniform weight, the line in the vicinity of the aircraft departs from a directly aft trailing configuration and begins to move across the circle which the aircraft flies. Thus the relative wind direction on the cable changes and an outward directed aerodynamic force develops. This force combined with centrifugal forces eventually balance the inwardly directed line tension forces. Thus, successive points behind the aircraft along the cable tend to follow paths of decreasing radii.

A different situation develops as an aircraft departs from straight flight to a turning maneuver. The decreasing radii for each point along the cable away from the aircraft results in a decreasing cable velocity to the relative wind. As the aircraft turns, the cable sag tends to increase along the line to the point where the increased angles of attack compensate the reduced relative velocity.

A few years ago, Lockheed conducted an analytical study of a "Yo-Yo" retrieval concept, (Reference 21).

In the Yo-Yo concept, illustrated in Figure 80, a powered cab weighing approximately 2500 pounds is towed behind a cargo aircraft. As the aircraft goes into a circular flight pattern, the cab is lowered to the ground through the spiralling action of the cable. The aircraft then achieves a constant radius circular flight path and the powered cab reaches a fixed position under the center of the aircraft flight circle near the ground.

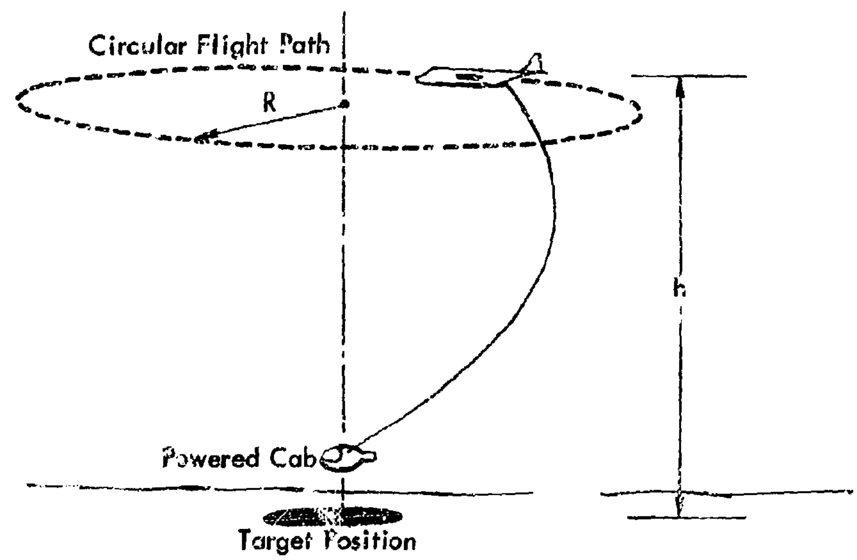


Figure 80 - "Yo-Yo" Retrieval Concept

The powered cab maintains position over the point on the ground while the aircraft circles. Figure 81 presents computed data relative to the "Yo-Yo" concept. The figure presents a flight envelope for the C-130 flying with full flaps and maintaining a turning load factor of n = 1.4, corresponding to approximately a 45° bank, at 110,000 pounds aircraft gross weight. This results in a turn radius of 1500 feet.

A minimum airspeed boundary of 1.2 V_s is shown for the C-130 in a 45° bank. Note that the data indicate that at a speed of 137 knots and an altitude of 2800 feet, the full 2100 pound side thrust capability is required of the powered cab to maintain position over the ground. Any decrease in altitude or increase in flight speed requires more side thrust on the cab.

The amount of side thrust required of the cab decreases with increasing altitude.

Flight tests were conducted in support of the "Yo-Yo" study. The purpose was to determine the capability of the C-130 aircraft to maintain a constant altitude, small radius, circular flight path, as would be required in the "Yo-Yo" concept. For the flight tests, the C-130 was flown at 137 knots IAS at altitude of about 2800 feet. The radius of turn was approximately 1600 feet.

One important fact discovered in the flight tests which applies to all circling line techniques, was the degree of difficulty the entire C-130 crew had in maintaining the prescribed flight pattern. With the copilot manipulating power levers and the flight engineer constantly reading off bank angle, the pilot was barely able to fly the intended path. The procedure was reported to be very difficult and fatiguing. Although the use of the auto-pilot eased the difficulties of the crew somewhat, the flight path was still difficult to maintain since the pilot was required to assist the auto-pilot to allow for wind.

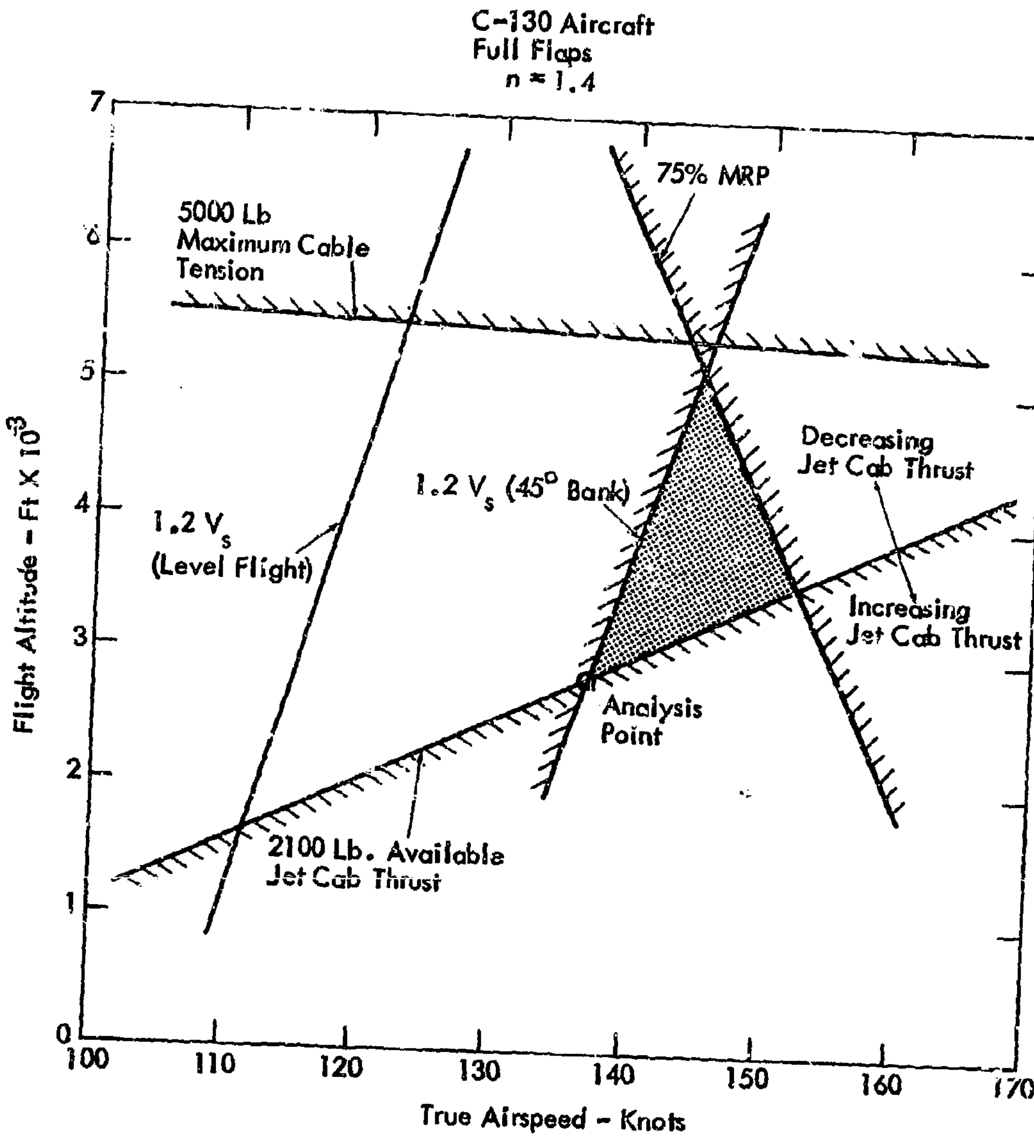


Figure 81 - "Yo-Yo" Retrieval Concept Flight Regime

An additional difficulty lay in the inability of the pilot to see the fixed reference point on the ground.

The conclusion drawn from the flight tests is that flight path control problems are serious. It appears to be very difficult for even a very experienced pilot to maintain a constant altitude, constant radius flight path about a fixed point on the ground in an aircraft of this size. During the 20-25 seconds required to traverse one-half the flight circle, it is possible for the aircraft to drift as much as 500 feet in a 15-knot wind.

The above difficulties are amplified when requirements are added for changing altitude to make a ground pick-up, towing a lift drag device, or operating with a second aircraft.

The following sections discuss six specific circling line concepts. These are:

1. Half-Moon
2. Derrick
3. Single Line
4. Single Line Balloon
5. Single Line Booster
6. Single Light Line - Balloon

Half Moon

General This concept configuration, depicted in Figure 82, consists of an aircraft towing a trailing lifting line. At the end of the trailing line is attached a lift-drag or pure drag body. As the aircraft flies a circular path, the towed body is at a point on the flight path 180° from the aircraft. The aircraft and trailing lift-drag body are connected by a second "crossover" line with a vertical load line attached at its center. The attach point of the vertical lift line and the cross-over cable falls on or near an imaginary vertical line passing through both the payload to be retrieved and the center of the aircraft flight path circle.

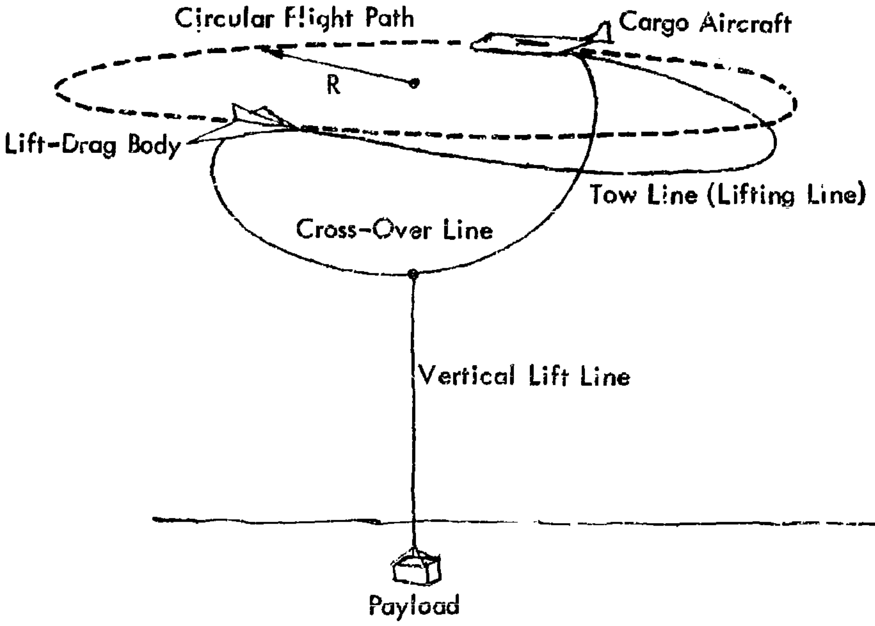


Figure 82 - Half-Moon Retrieval Concept

Under these conditions, the vertical load line remains relatively stationary above the payload and should theoretically be easily attached to the payload.

Results and Conclusions - This concept is limited to light loads and small aircraft capable of turning in a radius of 150 to 200 feet. The system is not practical for larger payloads and aircraft primarily due to the size and complexity of the lift/drag device required and the maximum allowable towing speed of such a device.

Assuming a lift/drag device could be developed which meets the requirements of this system, the concept is still undesirable from an operational standpoint. The system is extremely vulnerable to ground fire and as discussed in the previous section it is very difficult for a pilot to maintain circular flight about the payload on the ground, particularly in a moderate crosswind.

Analysis - The significant point which eliminates this concept from consideration is the maximum speed at which a parawing or rogallo wing can be towed.

Based upon the current state-of-the-art, the maximum wing loading ($\frac{L}{S_w}$) which can be considered for a parawing type lift device is 15. Below an angle of attack of 20^o a parawing is subject to buffet and flutter and resulting instability. The corresponding lift coefficient, C_L, of a parawing at 20^o angle of attack is 0.6.

Considering the following relations,

$$L = C_L S_w q = (C_L S_w \rho \, 1/2) \cdot (v)^2 \tag{84}$$

or

$$v = \sqrt{\frac{2L}{C_L S_w \rho}} = \sqrt{\frac{2}{C_L \rho}} \left(\frac{L}{S_w}\right) \tag{85}$$

Where: $\frac{L}{S_w}$ = 15 lb/ft^2

C_L = 0.6

ρ = .00238 slugs/ft^3 (sea level density)

The maximum parawing flight speed can be determined as:

$$v_{max} = \sqrt{\frac{2 \quad (15)}{0.6 \quad (.00238)}} = \sqrt{21,000}$$

$$v_{max} = 145 \text{ ft/sec} \cong 86 \text{ knots}$$

This speed is well below the stall speeds of the aircraft considered in this study.

If a parawing device is developed which can be towed at reasonable speeds for the aircraft under consideration, the device will require a pitch attitude control capability. In addition, since a large component of the total load is applied inward toward the center of the circle, a roll capability is necessary. The parawing must be capable of rolling into a bank and changing pitch so that both vertical and lateral load requirements are satisfied. Without this roll and pitch capability in the trailing wing, the payload will move laterally along the ground instead of rising vertically.

Another factor is that it is extremely difficult for the aircraft pilot to control both the aircraft position and the parawing position so that the vertical lift line stays in fixed position relative to the ground.

Derrick

General - This retrieval system, shown in Figure 83, employs two aircraft flying 180° apart in a circular flight path approximately 3000 feet in diameter. The aircraft are connected by a cross-over cable with a vertical lift line attached at the center. The attachment point of the vertical lift line and the cross-over cable falls on, or very near an imaginary vertical line passing through both the payload to be retrieved and the center of the aircraft flight path circle.

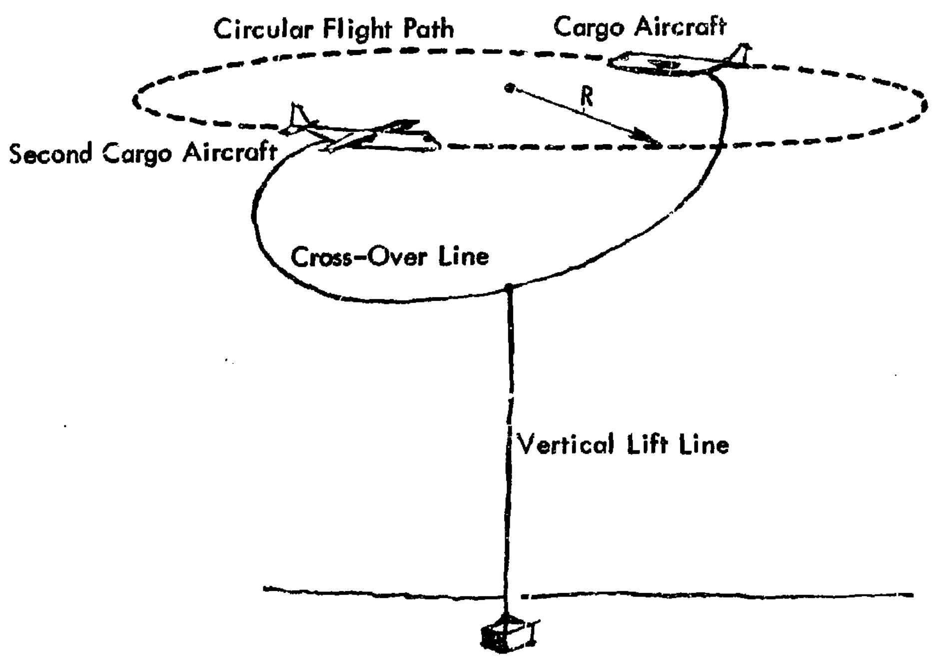


Figure 83 - Derrick Retrieval Concept

Under these conditions, the vertical load line should remain stationary above the payload and should theoretically be easily attached to the payload.

Results and Conclusions - This system has been shown to be undesirable from an operational standpoint. Difficulties in attaching the cross-over cable between the two aircraft, flying a perfectly circular flight path so that the vertical lift line stays directly above the payload, and effecting the retrieval and transfer to one of the aircraft, make this system impractical. In addition, two aircraft are required, which is an expensive way to pick up a 5 ton payload.

The two aircraft are extremely vulnerable while circling.

Analysis - The initial difficulty of this system is that of effecting a connection of the cross-over cable between the two aircraft. This would probably be accomplished by using a refueling type technique with the lead aircraft trailing the cross-over cable. The trailing aircraft would acquire the cable by an engagement device located on the aircraft nose. Since the nose of the trailing aircraft would not have sufficient strength to participate in the ground payload retrieval operation, the cross-over cable would be attached to a suitable load point on the trailing aircraft. This could be accomplished by the use of another cable connected to the nose of the aircraft and to the load point on the aircraft, as shown in Figure 84.

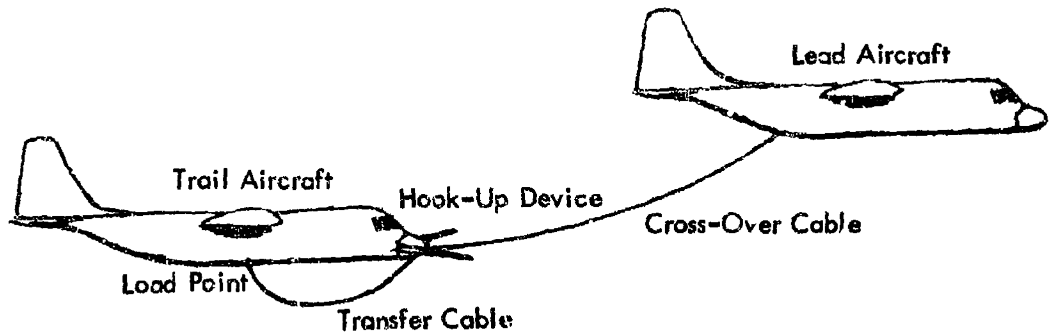


Figure 84 - Cable Transfer Technique - Derrick Retrieval Concept

A remotely controlled connection between the cross-over cable and the transfer cable must be effected, followed by a release of the cable from the nose of the trailing aircraft.

Having connected the two aircraft with the cross-over cable the distance is increased between the two aircraft until the situation depicted in Figure 83 is achieved. The vertical load line has been pre-connected to the cross-over cable and fed out of the lead aircraft with the cross-over cable.

The process of achieving the above arrangement will be tedious and time consuming, with both aircraft very vulnerable to ground fire.

Assuming that the circular flight path can be achieved initially by the two aircraft, it will be practically impossible for the two pilots to maintain the flight circle about a fixed point on the ground due to reasons discussed previously in paragraph on circling line techniques.

Finally, the procedure of transferring the payload to one aircraft after accomplishing pick-up will be tedious. The aircraft must now position themselves so that minimum "g's" are felt on the cable and aircraft when the payload is released from the other aircraft.

Single Line

General - In the basic circling line technique, a single line is fed from the aircraft as the plane circles about the payload on the ground. With the correct weight and length of line, and the correct altitude, the line theoretically spirals in to a nodal point at the payload.

The line is then affixed to the payload and the aircraft begins a circling climb, causing the payload to rise nearly vertically from the retrieval point.

Results and Conclusions - This concept is considered to be impractical for several reasons.

It was concluded that for a rope of the size required to retrieve 10,000 pounds in this manner, a circling altitude of approximately 5000 feet is required to achieve a nodal point at the payload on the ground. This represents a line length of over 6000 feet, which is considered excessive.

Further, as the aircraft begins to climb, the payload weight at the end of the spiral line, causes an unbalance in the system. The changed system requires even more aircraft altitude and line length in order to maintain the payload at a nodal point.

Additionally, the flight path control problem is more severe for this concept than the others considered since the aircraft altitude is greater.

Analysis - Figure 81 at the beginning of this section is reproduced from Lockheed Engineering Report 3406 and represents the minimum C-130 turn radius condition investigated in the Lockheed "Yo-Yo" concept study.

At a circling TAS of 135 knots and an altitude of 2600 feet, Figure 81 indicates that 2100 pounds of thrust are required of a powered cab weighing 2500 pounds to counteract lateral line loads and maintain position over a fixed point on the ground.

It can be concluded that, without the 2100 pounds of side thrust available at the end of the line, a much higher altitude is required to achieve a nodal point at the payload. This conclusion is further corroborated in a recent report by Grumman (Reference 22).

Grumman Project 306 reported that for a payload of 10,000 pounds, and an airplane altitude of 4845 feet, a total cable length of 6500 feet is required to achieve a nodal point at the payload.

Further insight into the problems and difficulties of the circling line retrieval technique is afforded by examination of Reference 23.

This document reports on a flight test program undertaken by the Air Material Command to evaluate the "Circular Flying Pickup" or simple circling line retrieval technique. The program utilized a C-47 aircraft equipped with a power driven winch and 6400 feet of 3/16 inch flexible steel cable. The objective of the test was to place the end of the trailing line onto a 12-foot x 12-foot tarpaulin placed on the ground.

This was to be accomplished by paying out line and circling above the target until the end of the line, with a red marker attached, was placed on the tarpaulin.

The test was unsuccessful and a portion of the results of the report are presented here for information:

"8. After 40 minutes of precision flying the tests were discontinued for the following reasons:

a. At the altitude being flown and with the amount of cable being payed out, the pilot was unable to get the weighted end of the cable down to the ground.

b. Due to the proximity of the hangars and other buildings, flying at lower altitudes or increasing the length of suspended cable was too hazardous."

Examination of the results of Grumman Project 306 and of the Air Material Commands, flight test lead to an interesting conclusion. Since a 3/16" diameter steel cable is roughly that which will be required to lift 3000 pounds (with a 1.5 safety factor), it can be concluded that for the range of payloads from 3000 to 10,000 pounds, over 6000 feet of cable will be required to achieve a nodal point.

Another significant point can be realized through analysis of Figure 81 with regard to the single line concept. Assuming a nodal point is attained and hook-up to the payload is accomplished, a side load on the payload will develop as the airplane begins to climb and lift the payload, since the end of the line is no longer at a nodal point. This side load is inevitable unless the airplane climbs to an even higher altitude corresponding to a nodal point for the end of the line with payload attached. This conclusion is corroborated in a report by All American Engineering Company.

All American conducted circling line flight tests with a C-119 at Edwards AFB in January 1961. The objective of the test was to demonstrate that a floating discoverer capsule can be retrieved using the circling line technique. The above tests successfully demonstrated this technique; however, the report on the tests, Reference 24, draws a conclusion which substantiates Lockheed's findings in this study.

All American states that:

> "When the Discoverer capsule broke water, it did not remain in the center of the circle. It described a small circle of its own, moving at a low rate of speed. Its motion was slow enough to prevent any damage to the capsule when it was placed back in the water. Similarly, it does not appear that a man would have been injured or distressed if he re-entered the water momentarily at that speed. However, it appears that if greater loads were picked up, the larger the load, the larger the circle it would develop, and the faster it would move."

In addition to the problem of payload tracking after lift-off, the engagement operation for this system would be difficult and hazardous to the ground personnel who would have to secure the "nodal point" end of the line to the payload. Any gusting wind moves the "nodal point" causing the end of the line to whip around. The slightest whipping action of the line makes it extremely difficult to hold the line to secure it to the payload.

Recently, All American Engineering began, under ARPA funding, a flight test program for the purpose of evaluating a single circling line retrieval technique similar to the concept discussed herein. The basic difference between the technique discussed in this report and the technique now being tested by All American is in the manner in which initial hook-up to the payload is accomplished.

The following paragraphs discuss this technique in light of other information concerning circling line techniques presented in this report.

The concept being flight tested by All American operates as follows:

The line that reels out the winch in the aircraft is attached to a suitable weight. The aircraft makes a low pass over the payload, drops the weight with cable attached in the vicinity of the payload, and begins a climbing turn while paying out line. After the aircraft has established a circular pattern at a specified altitude, ground personnel unhook the line from the weight and attach it to the payload to be retrieved, or to an "anchor" point fixed in the ground. In the case where the line is attached to the payload, retrieval is effected as in the basic circling line concept.

In the case where the ground "anchor" is used, a trolley is run down the line attaching the circling aircraft to the ground by using a second winch and line. The trolley is lowered to the ground, and personnel and/or equipment are taken off or placed on the trolley and it is winched back up to the aircraft. This latter system forms an "elevator" to the aircraft on which light payloads or personnel may be transported up or down.

These two techniques are interesting and appear to offer advantages over the basic circling line technique. However, there are problem areas in both concepts which should be considered.

When large aircraft are to be used, the turn radius is large and the aircraft must circle at several thousand feet to minimize side loads on the ground end of the hook-up line. This means that the weight which is dropped initially must be fairly large in order to hold the line end as the aircraft climbs and circles. The handling and dropping of this weight from a cargo aircraft can present problems.

A large clear area is required since the aircraft must make a low approach in order to accurately place the weight on the ground. The subsequent climb and turn while cable reel-out takes place may permit cable entanglement in ground obstacles unless sufficient clear space is available. In the case of large aircraft and long lines, the side loads on the ground end of the cable can amount to several thousand pounds as illustrated by Figure 81. This may present a problem for the ground crew as they attempt to detach it from the weight and attach it to the payload or to an anchor point.

In the case where the line is connected to a payload on the ground and then retrieved, the analysis of the single circling line applies to this technique.

In the case where the line is attached to an anchor point to utilize an elevator technique, side loading on the end of the line is the most important consideration. It was shown previously that side loads which are experienced at the ground end of the line can be fairly high. These loads increase with larger payloads and the anchor point must be capable of withstanding this without pulling out of the ground. This suggests a heavy field installation requiring special equipment.

The technique is not considered to be suitable for retrieval of the cargo weights considered in this study.

Single Line-Balloon

General - As depicted in Figure 85, the aircraft circles the balloon on an elliptical path, reorienting the major axis of the ellipse until the trailing line drags along the near vertical line which connects the balloon to the payload. The aircraft circling radius is gradually increased until a hook at the end of the trailing line engages the balloon line. As the aircraft returns to a fixed flight heading, the hook moves up to meet a retaining latch near the balloon attachment point. The action of the hook engaging the latch actuates a release to free the balloon from the system.

The aircraft begins to climb out, lifting the payload along a near vertical trajectory, and turns to the desired heading while reeling in the payload.

Results and Conclusions - The single line balloon concept is considered undesirable for the same reasons as those for the single line concept.

Analysis - In this system, it is not necessary for the pilot to cause the trailing end of the line to reach a nodal point before engagement. During the hook engagement procedure, a low altitude can be flown trailing a relatively short line.

However, after engagement, the plane must climb to an altitude corresponding to a nodal point for the end of the line with the payload attached. The remainder of the retrieval procedure is identical to the single line technique discussed previously.

The procedure of hooking the balloon line, as depicted in Figure 85, requires considerable piloting skill although not as much as the engagement procedure in the trailing line concept.

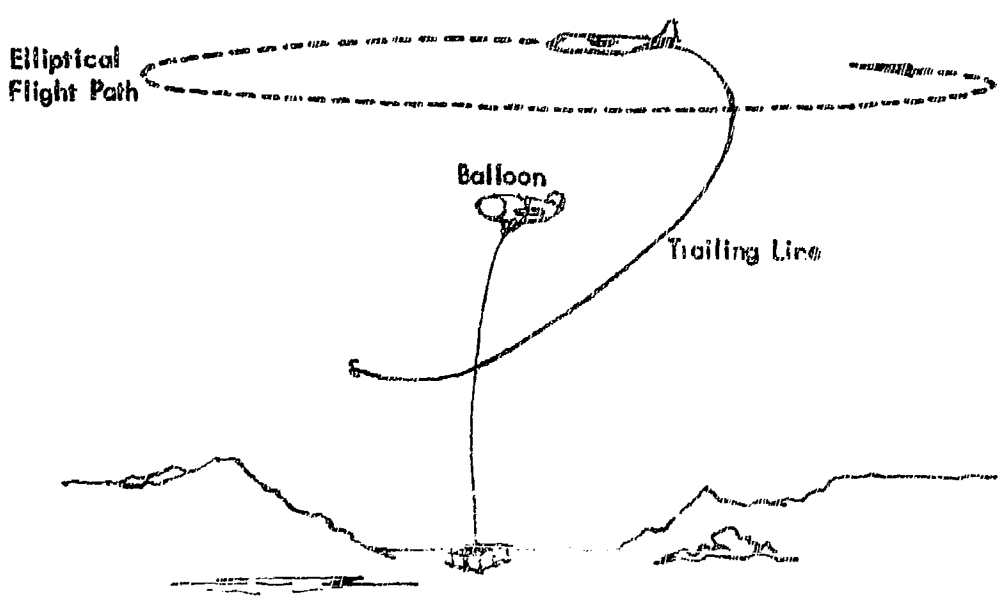


Figure 85 - Single Line - Balloon Retrieval Concept

The analysis given for the single line applies almost totally to the single line-balloon concept. The latter technique is considered undesirable for the same reasons as the former.

Single Line - Booster

General - This concept functions essentially the same as the Single Line system with the exception that a rocket booster is attached to the payload. The booster fires at lift-off of the payload, thus reducing the loads in the trailing line and on the aircraft.

Results and Conclusions - This concept is rejected for the same reasons as the Single Line Concept.

Analysis - The primary disadvantages of the basic Single Line circling line system are not related to excessive loads in the retrieval line. The accelerations are relatively low. Therefore, there is no real need for boost assist on this concept.

Single Light Line - Balloon

General - This system operates essentially the same as the Single Line - Balloon. The exception is that a light nylon line is used for balloon suspension and is attached to the heavier line on the ground. After the aircraft achieves engagement with the balloon, the light line is drawn into the aircraft. When the primary load line is drawn up and into the aircraft, a climbing turn is begun to lift the payload.

Results and Conclusions - This concept offers little advantage over the Single Line - Balloon system and is rejected for the same reasons.

Analysis - The only advantage of this system over the Single Line - Balloon system is that a lighter, smaller balloon is required.

It has a significant disadvantage in the additional line length required to do the job. Essentially twice the line length is needed for this system as in the Single Line - Balloon system.

This system is the most time consuming of all the circling line concepts. It is estimated that from 30 to 40 minutes are required from the time the aircraft arrives in the vicinity of the payload until the time pick-up is completed and the payload is in tow.

Selection of Systems

Table XXIX presents a summary of the retrieval systems discussed in the previous section. Opposite each concept are comments related to the deficiencies or advantages of the technique, and a numerical "merit rating" for the concept. The lower rating numbers indicate better system characteristics. The procedure used to arrive at the merit rating for each retrieval concept is discussed in the following paragraphs.

The merit of each retrieval concept was assessed by evaluating the concept from the standpoint of the three characteristics of primary technical interest. These characteristics are repeated here for reference:

(1) The complexity of the system and accompanying reliability level and operational problems

(2) The size of the clear ground area required to effect the retrieval

(3) The accelerations and loads experienced by the aircraft during the retrieval

A fourth item, power demands on the aircraft, was shown to be inconsequential since the aircraft used in the study were not powered limited in any of the techniques analyzed.

The determination of characteristics (2) and (3) above, in most cases, is purely analytical. In some cases, however, the analyses did not lend themselves to clean mathematical solutions, and, therefore, loads and clear ground area characteristics were estimated using the best available data.

TABLE XXIX

SUMMARY OF RETRIEVAL TECHNIQUES

Concept	Comments	Complexity Rating: Small Balloon	Large Balloon	Rockets	Lifting Device	Winch	Stanchions	Parachute	Flight Control	Long Line	Two Aircraft	Complex Rating Total	Clear Ground Area Rating	Aircraft Retrieval Forces Rating	Relative Merit
Short Coupled/Low A/C Approach															
(1) Winch Brake	Bad - High Forces & Large Clear Area Req.					3	1					4	10	3	17
(2) Winch Brake/ Rocket Boost	Poor - System Too Complex			4		2	1					7	1	1	9
(3) Magnus Rotor	Bad - High Loads & Complex System				5	2	1		2			10	1	2	13
Short Coupled - High A/C Approach															
(4) Balloon P/L Ascension	Bad - High Forces & Complex System		5			2		1				8	1	3	12
(5) Rocket P/L Ascension	Bad -			4		2		1				7	1	3	11
Long-Coupled-Low A/C Approach															
(6) Lifting Line (Low)	Bad - System Too Complex; Large Clear Area				3	2	1	1				7	5	1	13
(7) Glider	Bad -				3	2	1					8	8	1	17
(8) Parawing*	Bad -				3	2	1		2			8	8	1	17
(9) Trailing Air-Borne Lift Device	Bad - System Too Complex				3	2	1		2	4		12	1	1	14
Long Coupled High A/C Approach															
(10) Lifting Line (High)	Bad - System Too Complex		5		3	2			2			12	1	1	14
(11) Balloon Line	Good - System Attractive in All Respects	1				2						3	1	1	5
(12) Balloon Line Booster	Poor - System Too Complex	1		4		2						7	1	1	9
(13) Line Rotary Lift Device	Poor - System Too Complex, High Forces				4	2		1				7	1	2	10
(14) Rocket Line	Poor -				4	2		1				7	1	2	10
A/C Circling (15) Half Moon	Bad - Too Complex Operationally and/or Mechanically				3	2			2	4		11	1	1	13
(16) Derrick	Bad -					2				4	3	9	1	1	11
(17) Single Line	Bad -					2				4		6	5	1	12
(18) Single Line - Balloon	Bad -					2				4		7	5	1	13
(19) Single Line Booster	Bad -			4		2				4		10	1	1	12
(20) Single Light-Line Balloon	Bad -	1		4		2				4		7	5	1	13

*Inclusion of this concept assumes an advancement in parawing design, since present devices are limited to speeds below study average stall speeds.

The determination of the first characteristic, system complexity, was more difficult since it involves judgment rather than numbers. In order to assess the complexity of each retrieval system, a complexity rating system was devised. The rating system takes into account not only component complexity, but also difficulties associated with the operation of each component.

Factors considered in component complexity include:

(1) The actual physical complexity of the mechanical and structural sub-systems associated with a component

(2) The operational difficulties which are encountered by the air crew in utilizing each component. Items in this category include difficulties associated with winch operation, handling of the tow line(s), and deployment of the kits to be used by ground crew and flight path control of the aircraft

(3) The operational difficulties which are encountered by the ground crew in utilizing each component. Items in this category include the assembly and erection of the components and the attachment of components to the payload

The list of components used in the various retrieval systems along with their "complexity rating" and a brief discussion of the rating is presented in Table XXX. The problems associated with the hook-up mechanisms exist for all techniques. These problems were considered comparable and therefore inconsequential in a comparative rating system such as used here. For these reasons, hook-up gear is not assigned a rating.

The complexity rating of each concept or total system is determined by simply adding the ratings of all the components used in a given system.

In order to arrive at a total relating merit rating for each of the concepts considered it was necessary to assign numerical ratings to the second and third characteristics of primary technical interest: (2) clear ground area required around the payload, and (3) aircraft accelerations and loads.

A series of judgments were necessary in order to do this. First, the relative importance of the three characteristics was considered. It was judged that component complexity should carry the most weight in the total relative merit rating. Since the computed complexity ratings range from 3 to 12, a starting point was provided. It was judged then that the characteristic of secondary importance is clear ground area. A concept which requires less than 50 feet of clear ground area is certainly much more attractive than one which requires 1500 feet of clear area. A concept that requires 1500 feet or more of flat area is hardly worthy of consideration since advanced C-130 models will operate in and out of flat clear areas of approximately 1500 feet. Using this logic, a set of numerical ratings for clear area required was established:

Maximum Distance from Payload (Ft)	Rating
0 - 50	1
50 - 500	5
500 - 1500	8
Over 1500	10

The minimum rating of 1 above compares to the minimum complexity rating of 3 and the maximum rating of 10 above compares to the maximum complexity rating of 12.

TABLE XXX

COMPONENT COMPLEXITY RATINGS

Component	Discussion	Rating
Small Balloon	Balloon used to lift a target line to altitude sufficient for high level aircraft approach. Involves delivery kit including balloon, lines, harnesses, and helium bottles.	(1)
Large Balloon	Balloon used to lift either the entire retrieval payload or a very heavy system above the payload. Involves essentially the same items as the light balloon but is much larger. Assembly and erection problems for ground crews are serious especially under wind conditions. Considerable time consumed for retrieval.	(5)
Rockets	Solid rocket package used either to loft a target line or loft the entire payload to altitude. Delivery kit must include rock motors, structural harness or tower for mounting motors to payload, parachute, lines, and aiming device or aid. Ground crew problems considerable in erecting and operating this unit properly. Considerable time consumed for retrieval.	(4)
Lifting Device	An aerodynamic lifting device used to lift either the target line or the entire payload. The basic rating of 3 is assigned to gliders and parawings, while the rating for a powered lifting rotor is 4. Due to its complexity, the magnus rotor is assigned a rating of 5.	(3, 4, 5)
Winch	Cable winch-brake system located in the aircraft cargo compartment. The design and operation of this component is essentially the same for all retrieval concepts with the exception of the low approach winch-brake. In this concept, the low approach winch brake is given a (3) rating due to increased complexity.	(2), (3)
Stanchions	Telescoping or tape-roll type rods used to hold a target line some 50 feet above the ground. These must be delivered in kit form and assembled and erected by ground crew.	(1)
Parachute	Used either to: (1) allow a slow descent of the target line or payload, or (2) as a safety device for the balloon payload ascension concept.	(1)
Flight Control	A remote flight control system used in conjunction with a lifting device as described above. The rating given applies also if an air crew is required instead of a control system.	(2)
Long Line	All concepts use target and tow lines; however, the use of a very long line creates particular problems. These include all the problems discussed previously in the circling line	(4)

TABLE XXX (Continued)

Component	Discussion	Rating
	concepts, plus the extended time required to deploy and reel in the long line, as well as the larger winch required to store and handle the line. For these reasons the long line is given a complexity rating of 4.	
Two Aircraft	The necessity of using an additional aircraft complicates the system.	(3)

Another judgment was required to assign appropriate rating to the remaining characteristic: the accelerations and loads experienced by the aircraft.

In all systems considered, it is felt that the aircraft can be modified to accommodate the loads anticipated. Certainly, if this is not true of a particular concept, then the concept is not worthy of discussion. With this in mind, the only reason for making the loads characteristic one of primary technical interest is the degree of aircraft modification required. In some of the concepts considered, as much as 10 g may be experienced by the winch and aircraft over a very short span of time. In such a case the winch must be securely attached to the aircraft structure to properly dissipate the high loads. Where extensive modification to the aircraft is required, the performance of its normal mission may be impaired.

A set of numerical ratings were assigned to this characteristic:

Impact g Loading on Aircraft	Rating
0 - 3	1
3 - 6	2
6 - 10	3
Over 10	Excessive

Figure 86 presents a bar graph depicting the relative merit of the retrieval concepts considered in this study. On the chart, the amount of clear ground area required is represented by the clear portion of the bar. System complexity with respect to both hardware and operational difficulty is represented by the shaded portion of the bar. The reaction loads experienced by the aircraft are represented by the black portion of the bar. The lengths of each portion of the bar and the total bar length is scaled from left to right based on the merit ratings given in Table XXIX.

The best system is listed at the top, with the others listed in order of decreasing suitability. A near perfect system would have a rating of 3, one point each for complexity, clear area, and loads.

Note that this study confirms the obvious fact that a near perfect system for aerial retrieval does not exist. The most attractive system is the Balloon Line System, which appears at the top of the list.

Even with the Balloon-Line System, the aircraft incurs substantial loads, and the system components are far from simple. In operation, the pilot must make a very accurate approach to the target line in order to effect a successful engagement. The aircraft winch must be operated in a fairly precise manner to keep the accelerations and loads at a tolerable level. Considerable design and engineering effort would be required to develop this concept into an operational reality.

The following section discusses the performance and operational characteristics of the Balloon Line System in detail.

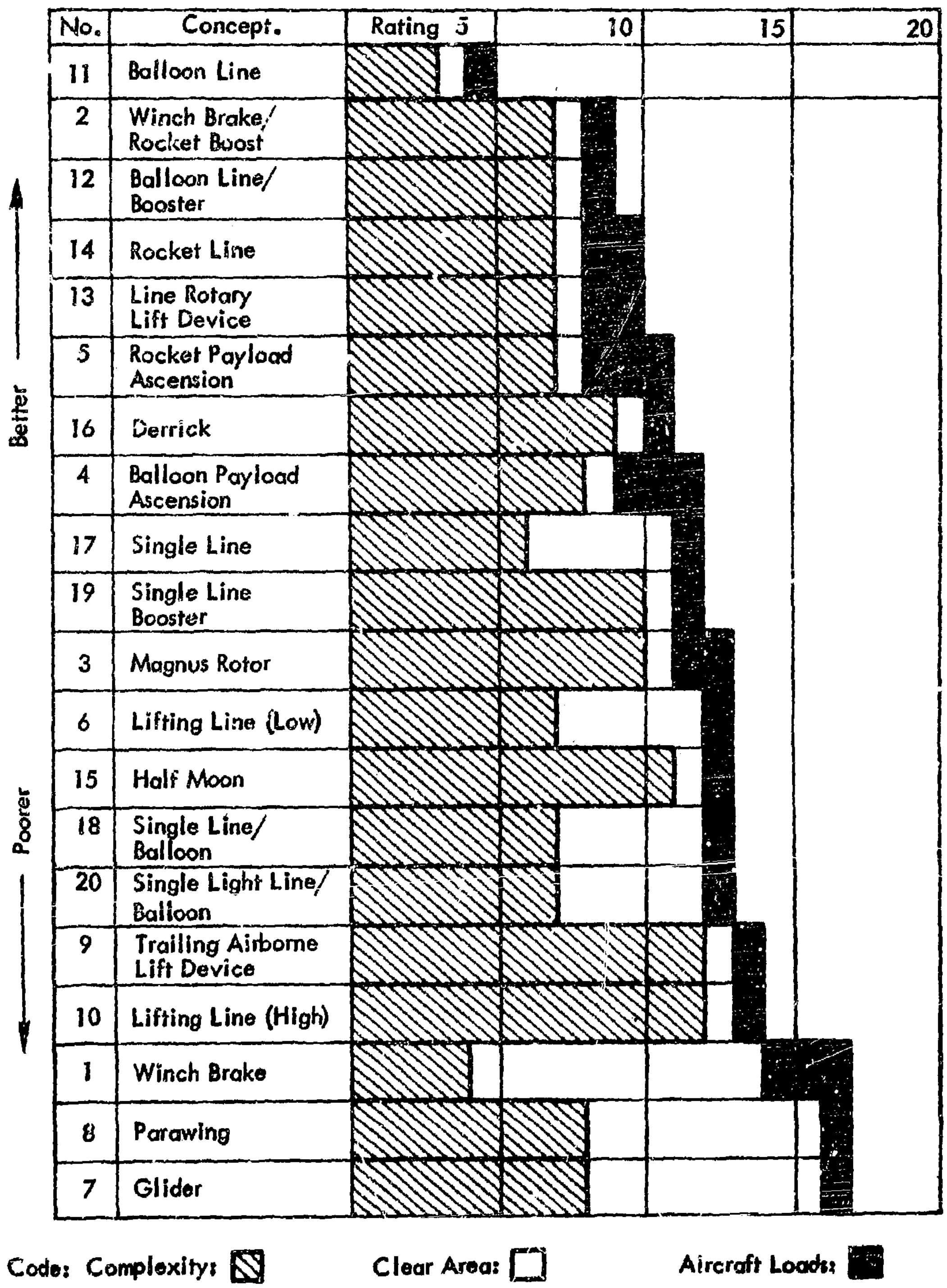


Figure 86 – Relative Merit of Aerial Retrieval Concepts

PERFORMANCE OF SELECTED SYSTEM

On the basis of studies conducted to determine the feasibility of a general range of retrieval system concepts, as reported in the previous section, it was determined that the most promising systems were those which are based on a cargo connected line suspension technique. In particular, it was determined that the simplest method, and also the method which resulted in the least system weight, was one which makes use of a helium filled balloon to support the cargo retrieval line. This concept is referred to as the Balloon Line Retrieval System. As discussed under the heading "Selection of Systems" in the preceding section, the Balloon Line Retrieval System is considered to be the only promising technique suitable for application to the retrieval of the moderately heavy payloads of interest in this study.

The purpose of this section is to report the results of an investigation undertaken to establish the performance of this cargo retrieval technique. The following text will present a general description of the system, a discussion of the system design point selection with respect to aircraft and system limitations, system design data, and scope and results of the performance evaluation.

System Description

The Balloon Line Aerial Retrieval System is shown in Figure 87. A description of the major components and subsystems and overall system operation is presented in the following text.

Major Subsystem and Component Description

The following list of components associated with the balloon line retrieval technique are functionally described in this section. Quantitative data on size and weight are given in a later section entitled "System Design Data". The numbering system associated with the components list below may be used with Figure 87 and Figure 88 as an aid in identification.

1. Boom, hook support
2. Hook and automatic latch assembly
3. Cable, winch
4. Winch
5. Aircraft mounted pulleys and pulley brackets
6. Aircraft mounted JATO thrust augmentation units*
7. Balloon, helium
8. Nylon line, cargo retrieval
9. Cargo package
10. Paper honeycomb
11. Recovery parachute
12. Load/Line Disconnect Assembly
13. Radio frequency transmitter, aircraft mounted
14. Radio frequency receiver, cargo mounted
15. Power pack and switch circuit
16. Pendant loop cable
17. Pendant loop support pole (foamed plastic filled aluminum tube)

* For 6000 through 10,000 pound payloads only, as required.

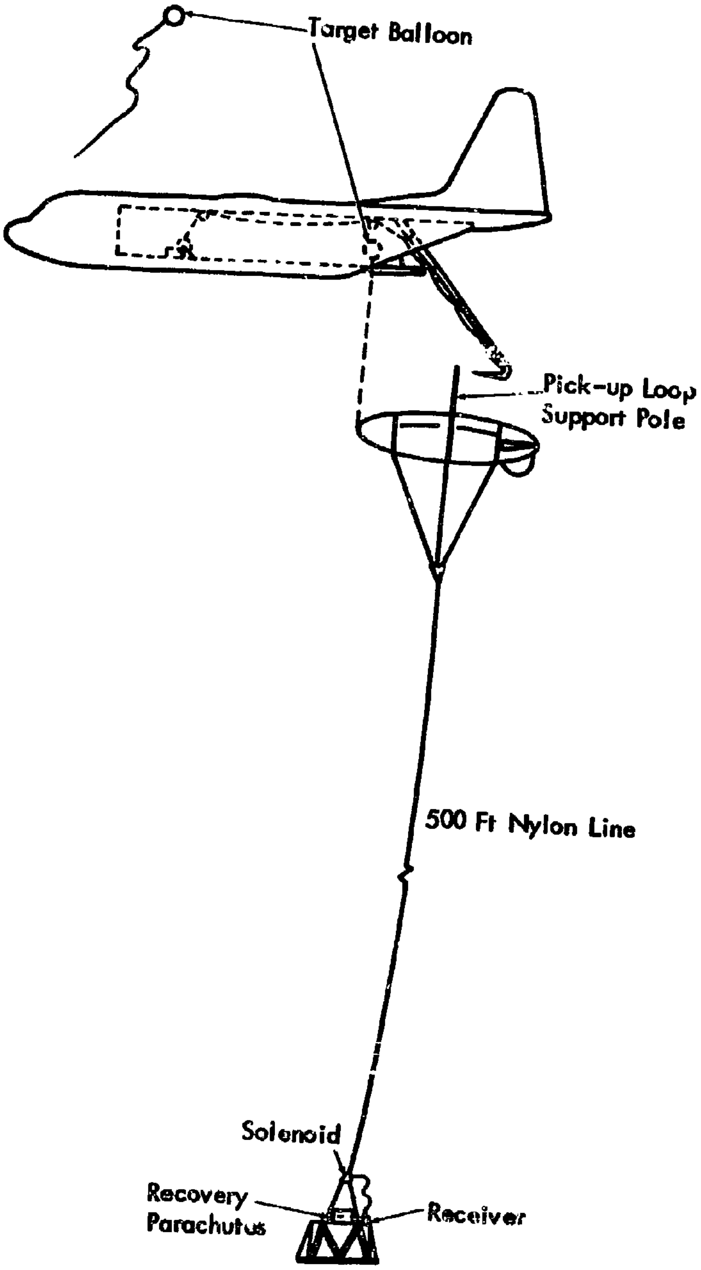


Figure 87 – Balloon Line Aerial Retrieval System

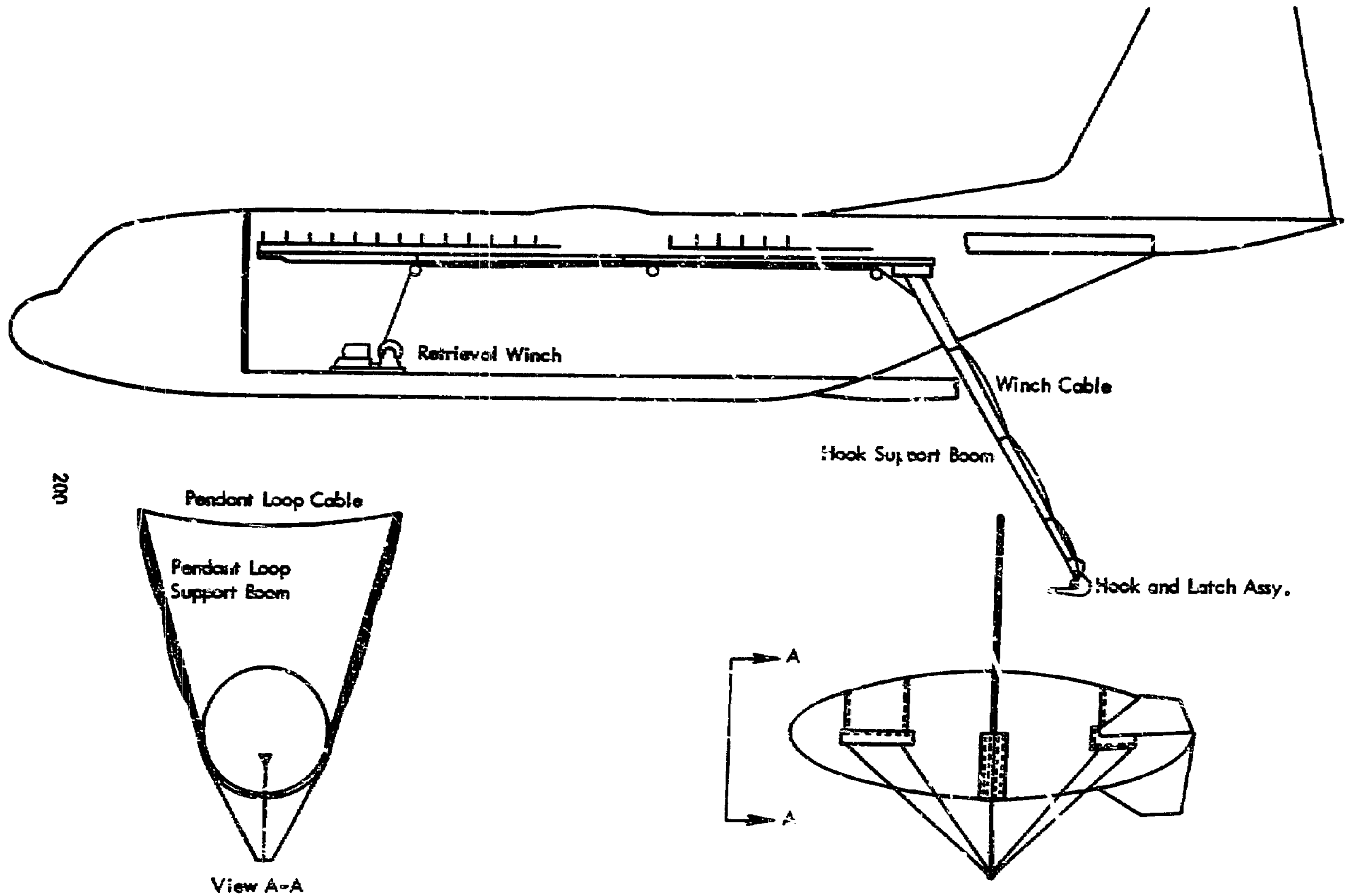


Figure 88 - Balloon Line Aerial Retrieval System - Component Details

The aircraft mounted hook support boom shown in Figure 88, should be of sufficient length to assure that the balloon is outside the aircraft flow field until after hook engagement. It should also be mounted on an overhead track to provide capability for rapid boom extension and retraction. The hook assembly, which engages and retains the pendant cable, must be designed to release from the boom and withdraw cable from the winch drum only after the pendant loop is securely held by the hook latch. The hook latch should thus be designed to close by action of the pendant cable on a tripper located in the hook apex. Latch motion should also function to release the hook from its retaining lugs on the support boom. The winch is considered to be of the constant brake-force type, designed to apply a braking action after a set number of drum revolutions. The JATO thrust units are required only for the heavier payloads, and are primarily for the purpose of assuring that the aircraft can maintain a steady climb rate for a short period of time following hook engagement with the cargo pendant loop.

The balloon is configured to provide aerodynamic as well as aerostatic lift. Its approximate shape is that of a prolate spheriod. Inflated vertical and vee-tail stabilizers serve to orient the balloon with the wind, act as damping surfaces to pitch and yaw motions, and minimize the inclination angle of the balloon during wind conditions. The pendant loop support pole is of thinwalled aluminum tube, filled with a foamed plastic material to increase rigidity. It supports the pendant loop, which should be a steel cable constructed to have energy absorbing characteristics. The ability of this cable to absorb energy serves to reduce cable rebound as contact is made with the hook support pole. Nylon was chosen for the cargo lift line, both for its unusually high strength to weight ratio and its energy storing characteristics. This nylon line is connected to the cable loop by a suitable fitting on the underside of the helium balloon.

A recovery parachute is attached to the cargo package and connected to the cargo lift line by a parachute deployment line. The lift line, in turn, is fastened to cargo suspension lines by an electrically actuated mechanical disconnect. This disconnect is solenoid operated and receives power from a battery pack which accompanies the cargo to be retrieved. The power pack also operates a radio frequency receiver, the output of which is connected across an electro-magnet. When the proper radio signal is received from the towing aircraft, the magnet is activated to close a switch and complete the circuit between the load disconnect solenoid and the power pack. In this manner, the retrieved cargo can be released at any desired new location, using the recovery parachute and paper honeycomb to obtain moderate descent rates and impact loads.

Description of System Operation

A retrieval/redeployment package, which includes the balloon, recovery parachute, lift line and cable loop, and load disconnect circuitry, is air dropped at the cargo retrieval site. Preliminary operations required to prepare the cargo for retrieval and redeployment , including placement of paper honeycomb and securing rigging and load attachment lines, should already be accomplished when the retrieval package is received. The lift line is attached to the cargo, power pack strapped in place and activated, pendant loop support pole assembled, and both target balloon and main balloon inflated. The balloon is then released and allowed to ascend, extending the cargo lift line to its full length.

A target balloon attached to the nose of the main balloon offers a target for the retrieval aircraft to properly position the engagement hook with the lift line pendant loop. The nose of the aircraft strikes the target balloon, the aircraft passes over the main balloon, and the retrieval hook passes within the pendant loop above the main balloon. The loop then moves downward along the hook support boom, striking the retrieval hook. As the line moves into the apex of the hook, it actuates a tripper to trip the cable locking latch and to release the hook from the boom. The nylon line begins to stretch as line tension increases, until line tension exceeds the cargo weight. At this point the cargo begins to accelerate, and continues to accelerate as line tension builds up to a pre-set winch brake force. This brake force essentially sets the value of the maximum cargo acceleration, since cable reel-out occurs as the line tension exceeds the restraining force on the winch. When the cargo is moving at aircraft flight speed, the loadmaster can operate the winch to bring the cargo into the vicinity of the aircraft and just outside the aircraft wake.

Only cursory examination was given to boarding the retrieved cargo, since this requires a detailed knowledge of the cargo configuration as well as the aircraft flow field. However, based on past Lockheed studies of personnel retrieval at the aft end of the aircraft, it appears that an "A" frame rig is required to position and stabilize the load as it comes over the ramp lip. Any attempt to move cargo over the ramp without such a rig would almost certainly cause damage to the cargo being retrieved, and possible damage to the aircraft as well. An alternative to the "A" frame is an overhead supported cantilevered rig which moves out over the load and lifts it vertically above the ramp lip and then longitudinally into the aircraft. In either case, once boarded, the load must be re-rigged on an aerial delivery platform with an extraction parachute prior to redeployment at a new site. As stated in Reference 1, the retrieved load must be redeployed at a new site by means of aerial delivery. For this reason, and due to the extensive aircraft modification required to board heavy loads, release of a towed load and descent by recovery parachute was considered to be more practical than boarding the load for subsequent extraction and descent by recovery parachute.

Design Point Selection

Determination of the system design point is based upon consideration of both aircraft and cargo limitations. Aircraft limitations are concerned primarily with the capability of the aircraft to accept pitching moments during acceleration of the cargo to aircraft flight speed and the capability of the aircraft to compensate pitching moments and drag loads during the steady state tow condition. Only two system limitations need be considered in system design. These are the acceleration loads which the payload can withstand and the trajectory which the payload must follow in order to avoid ground obstructions. However, since the payload trajectory shape is determined to a major extent by the line forces during cargo acceleration, the governing consideration in system design point selection was one of determining the minimum line forces which would produce an acceptable cargo trajectory. This approach is realistic, particularly in view of the wide range of payload types which may be of interest for ground-to-air retrieval, and the possible variation of their acceptable acceleration load limits. The following text discusses the overall system design point selection with respect to aircraft and system limitations.

Aircraft Limitations

In order to establish the relative capability of the C-130, C-141A, and C-5A aircraft for a fly-by ground-to-air retrieval of cargo loads weighing from 3000 to 10,000 pounds, a parametric investigation of aircraft loads was undertaken. At the time this study was undertaken, no retrieval technique had been selected. Therefore, in order to evaluate relative aircraft capability, the minimum impulse required to accelerate a load from standstill to 150 knots at 500 feet altitude was determined. This minimum impulse, which is 10.3 pound-seconds per pound of cargo weight, was applied to the aircraft at the least favorable condition with respect to gust encounter. It has been shown that this condition occurs at the point where the aircraft is one quarter wave length into a (1-cos) gust. The parameters varied were payload weight and gust amplitude. Results are shown in Figure 89. Although both the C-141A and C-5A appear to have satisfactory load histories throughout the range of gust conditions, the C-130 load limit was exceeded for all gust velocities during retrieval of a 10,000 pound load. These high load factors encountered by the C-130 aircraft were not unexpected since the analog program used to compute these values assumed no elevator deflection to counteract aircraft pitch motion. Since the C-130 was shown to be the critical aircraft with respect to pitch response during cargo retrieval, subsequent investigations with respect to aircraft stability and loads were centered around this aircraft.

Upon selection of the balloon line retrieval technique as the most promising for the cargo weights considered in this study, it was possible to evaluate, as a function of time, the line loads and load application angles during the cargo retrieval phase. For reasons which are under "System Limitations," immediately following this section, an aircraft maximum flight speed of 150 knots, an aircraft flight altitude of 500 feet, and a brake setting of 4.5 times the cargo weight were chosen as design point conditions. The time variation of line loads and line angles at the aircraft were then determined for the maximum payload weight of 10,000 pounds. The results are shown in Figure 90. As can be seen, the maximum line tension exceeds the 45,000 pound brake force by approximately 15,000 pounds. These are relatively short duration loads on the aircraft, but are of high intensity and will cause an aircraft pitch-up motion unless compensated by a positive (downward) deflection of the elevator. An investigation was made to determine the required elevator deflection to compensate the pitching moments imposed by retrieval of this 10,000 pound load. The method used is presented in Appendix A and the results shown in Figure 91. Data are shown for zero flaps and a resultant elevator trim position of 0.75 degrees. With the aircraft in this configuration, the maximum incremental elevator deflection available is 14.25 degrees. This is sufficient to counteract all aircraft pitch motion except the small pitch impulse represented by the cross-hatched area. Incremental aircraft pitch angle due to this uncompensated pitching moment was computed to be 0.43 degrees, equivalent to an incremental aircraft load factor of 0.07. Figure 92 shows this load factor added to the load factor induced by wind gust. From this it can be seen that, with respect to stability and loads, the C-130 aircraft can retrieve loads up to 10,000 pounds using a 500 foot elevated balloon station and a 150 knot fly-by-technique. However, elevator deflection at the time of hook engagement is required. Aircraft pitching moment is not significantly affected by balloon station height, but primarily by aircraft speed and payload weight retrieved. The above discussion relates, therefore, to all balloon station altitudes of interest, i.e., between 100 and 1000 feet, corresponding to constant equivalent airspeeds.

As shown by Figure 143 of Appendix A, at an aircraft speed of 150 knots and a gross weight of 110,000 pounds, available excess thrust horsepower is approximately 9300. This is equivalent to approximately 20,000 pounds of excess thrust, or 200,000 pound-seconds of impulse during the cargo acceleration phase. The retarding impulse on the aircraft, due to the horizontal component of line force, must be less than the total impulse on the aircraft, shown by the area under the line tension curve of Figure 90. Since the area under this curve represents a total impulse of approximately 192,000 pound-seconds, it is concluded that loss of aircraft speed during cargo acceleration can be prevented by the application of available excess thrust at the time of hook engagement.

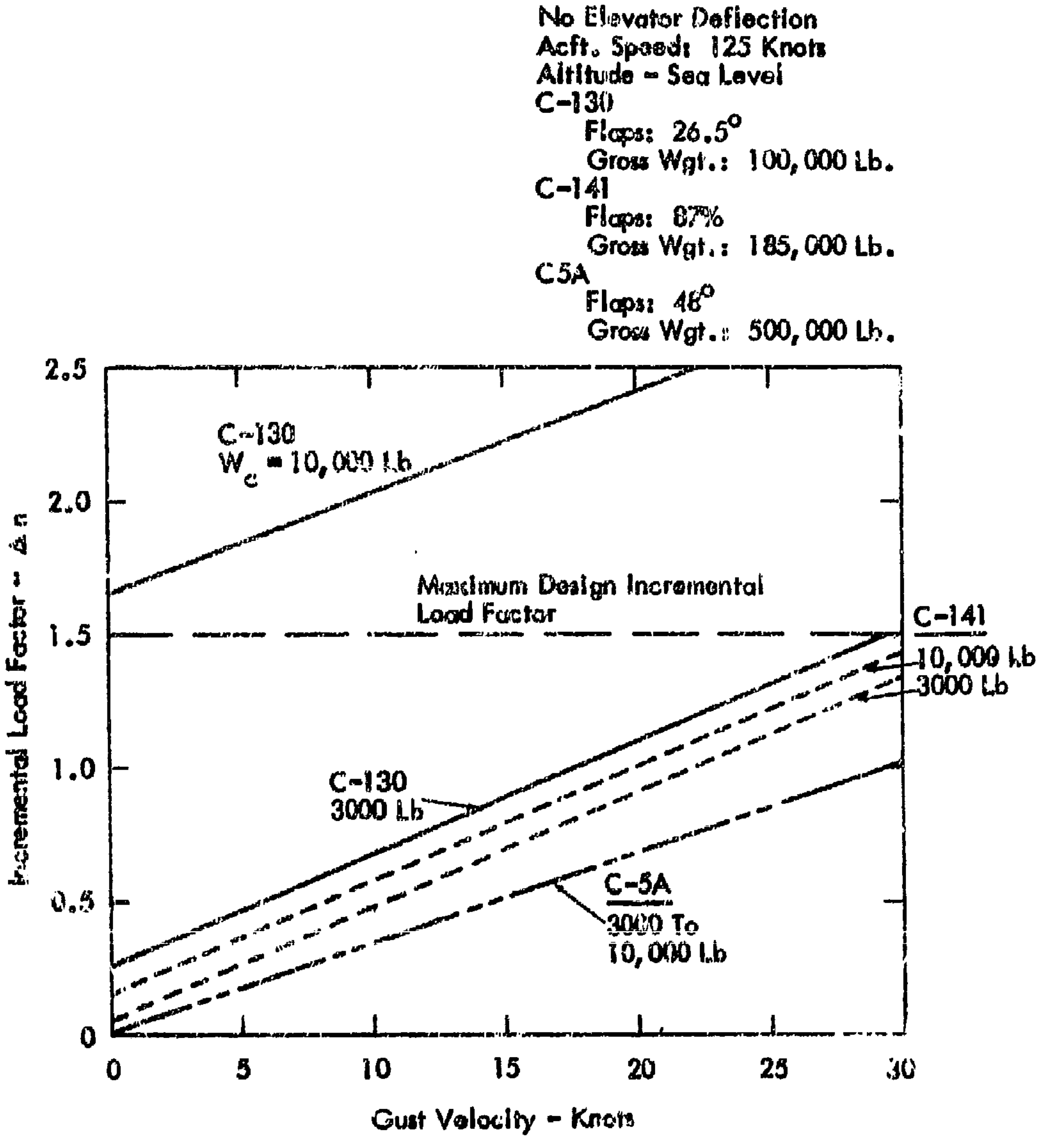


Figure 89 - Comparison of Relative Aircraft Load Factors during Retrieval

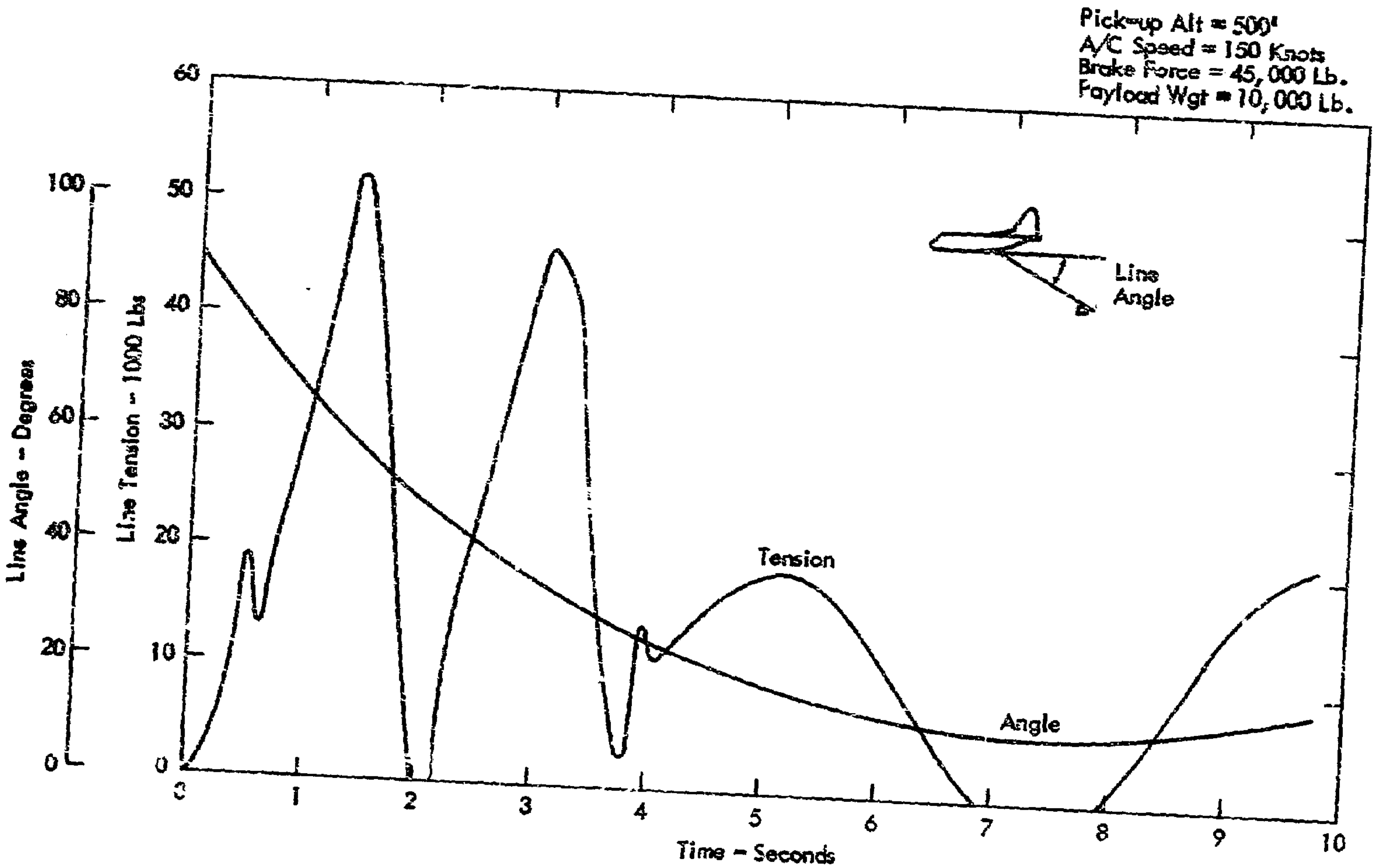


Figure 90 - Time History of Line Tension and Angle

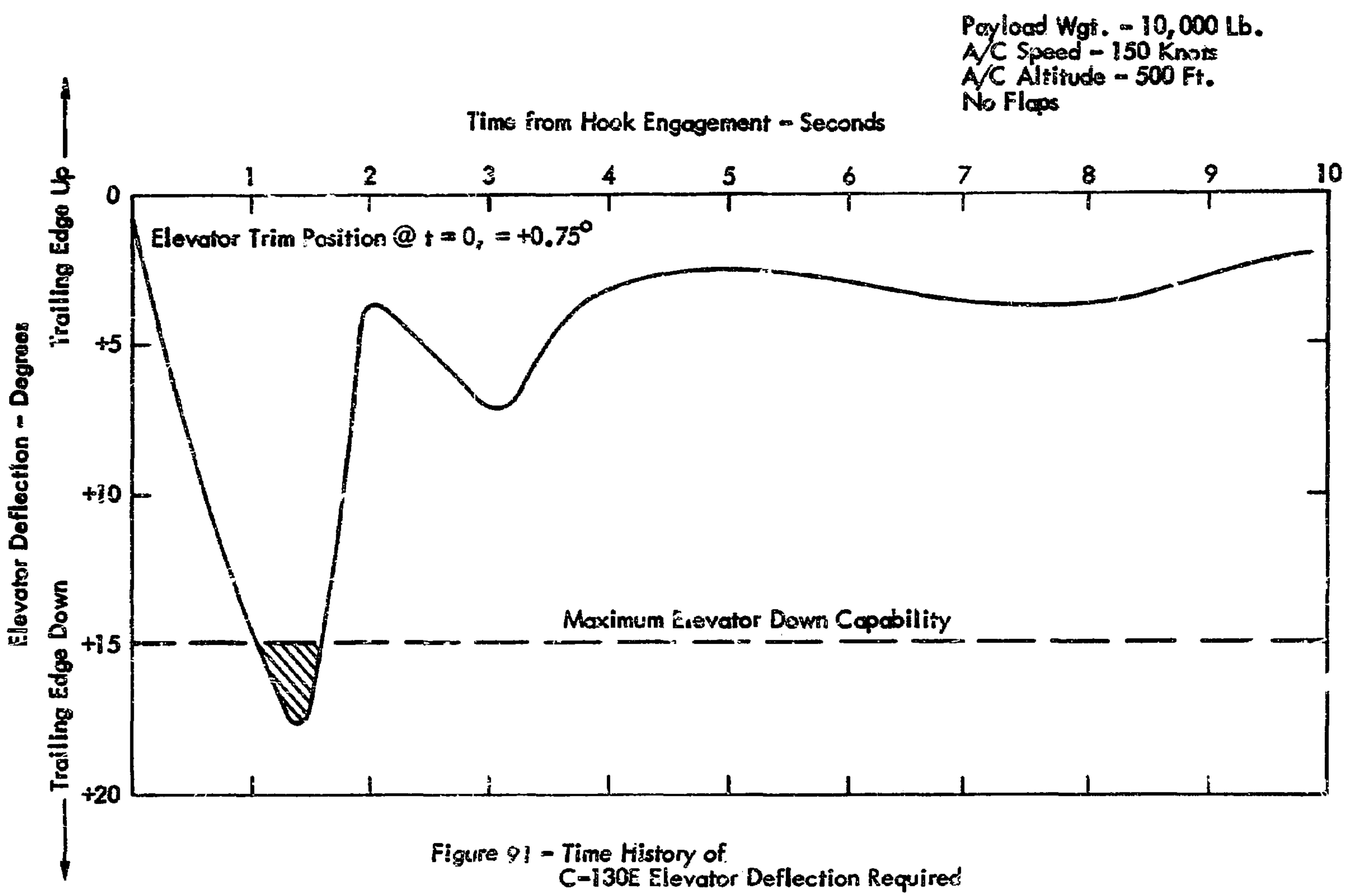


Figure 91 - Time History of C-130E Elevator Deflection Required

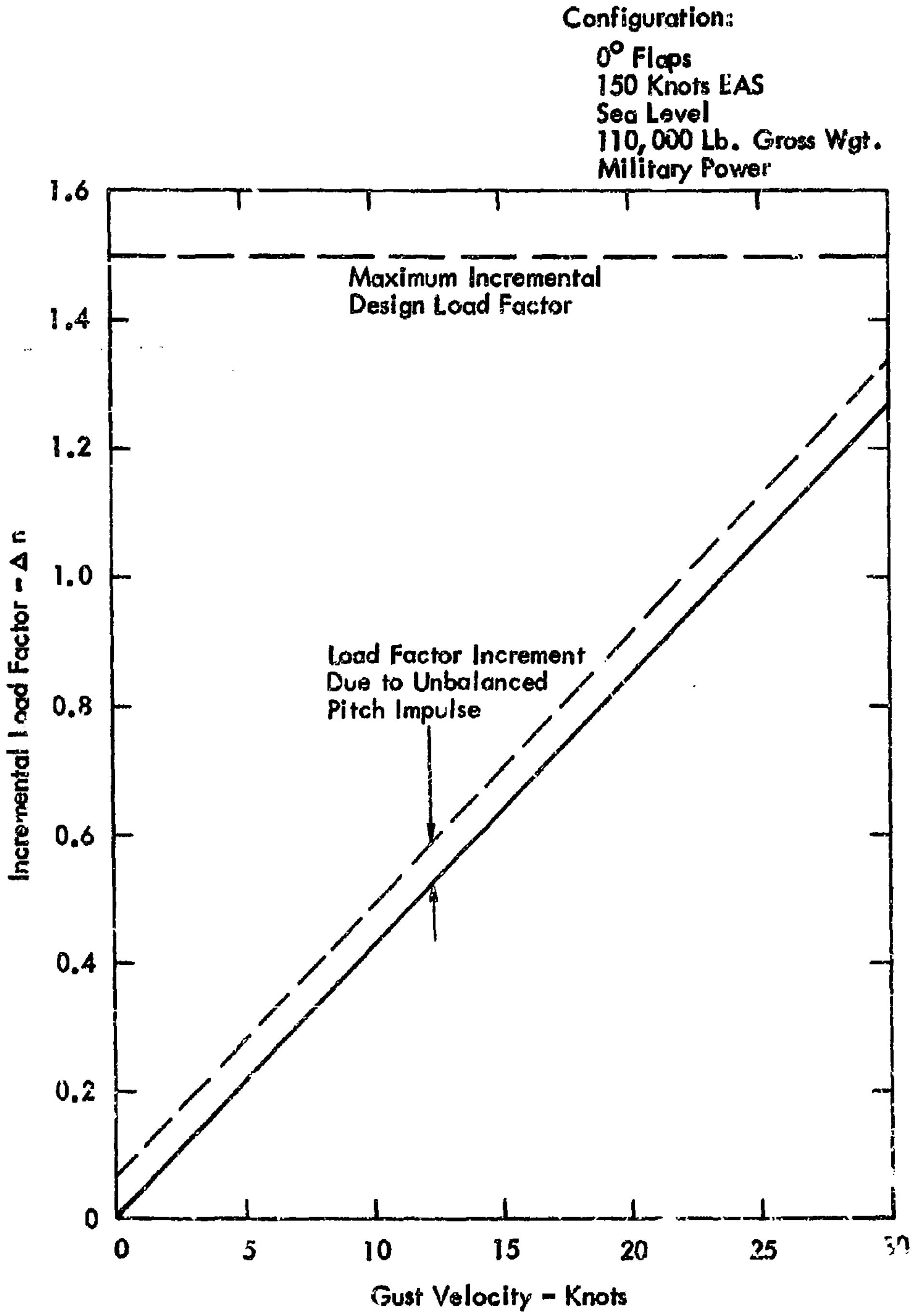


Figure 92 - C-130E Load Factor versus Gust Velocity

During equilibrium tow of the payload it is necessary that sufficient thrust is available to overcome aircraft, cable, and payload drag, and that adequate elevator control is available to compensate pitching moments. An existing Lockheed digital computer program was used to compute the shape and tension in a tow line for a range of aircraft speeds and payload weights. These data, shown in Figures 135 through 142 of Appendix A, were used to compute pitching moments and drag loads on the aircraft during the steady-state tow condition. The most critical case, that of an aircraft towing a 10,000 pound payload, is presented in Figures 93 and 94. Required elevator deflections, with the load separated from the aircraft by distances varying from 200 feet to 1000 feet, vary from a maximum of 3.6 degrees to 2.6 degrees down elevator for the range of flight speeds shown. Minimum elevator deflections are required at the longer line lengths. The procedure used to calculate these required elevator deflections is given in Appendix A. Available and required thrust, considering payload, aircraft and line drag is shown in Figure 94. Cable drag is shown to have a significant effect at the longer line lengths. At the upper range of flight speeds investigated, the available excess thrust becomes marginal. However, at 150 knots flight speed adequate thrust is available with power settings less than normal power.

System Limitations

Fly-by cargo retrieval techniques, for the 130 to 200-knot speed range considered by this study, require that acceleration levels which the cargo experiences be limited to acceptable values through incorporation of a shock absorbing system in the cargo/aircraft linkage. Woven nylon line is characterized by a number of highly desirable characteristics which make it an ideal material for use in this regard. Primary among these are its extremely high strength to density ratio, its relatively linear stress/strain characteristics, and relatively high elongation to ultimate strength. These combine to produce a light weight system which applies energy to the cargo at an initially low onset rate so that the cargo is gradually accelerated to aircraft speed. The magnitude of this acceleration, for a given cargo weight and aircraft speed, is governed by the length of nylon line connecting the aircraft and cargo. Since the length of this line directly affects the size of the balloon required to support it, it becomes advantageous to keep this line length as short as possible.

For this reason, a supplementary method for absorbing shock during cargo acceleration is employed. This method consists of a winch, winch drum and brake, and a length of flexible, non-rotating steel cable. The brake acts to limit maximum line tension by allowing cable to pay out as line tension exceeds the brake force. The effect of cable reel-out, however, is to cause a dip in the cargo trajectory after it has reached its maximum altitude. A primary constraint on the system design point selection is the minimum height above the ground which the cargo experiences before achieving a steady state tow condition.

As discussed in the previous section, the system design point must be selected based on considerations of aircraft engagement speed, aircraft engagement altitude, and winch brake force setting. The primary constraint mentioned in the previous paragraph, that of trajectory height above the ground at the cargo dip point, is a function of these three considerations. Figures 95, 96 and 97 present the results of a parametric study undertaken to allow selection of the system design point. Design point data were evaluated for payload weights of 3000, 6500, and 10,000 pounds. The minimum height of

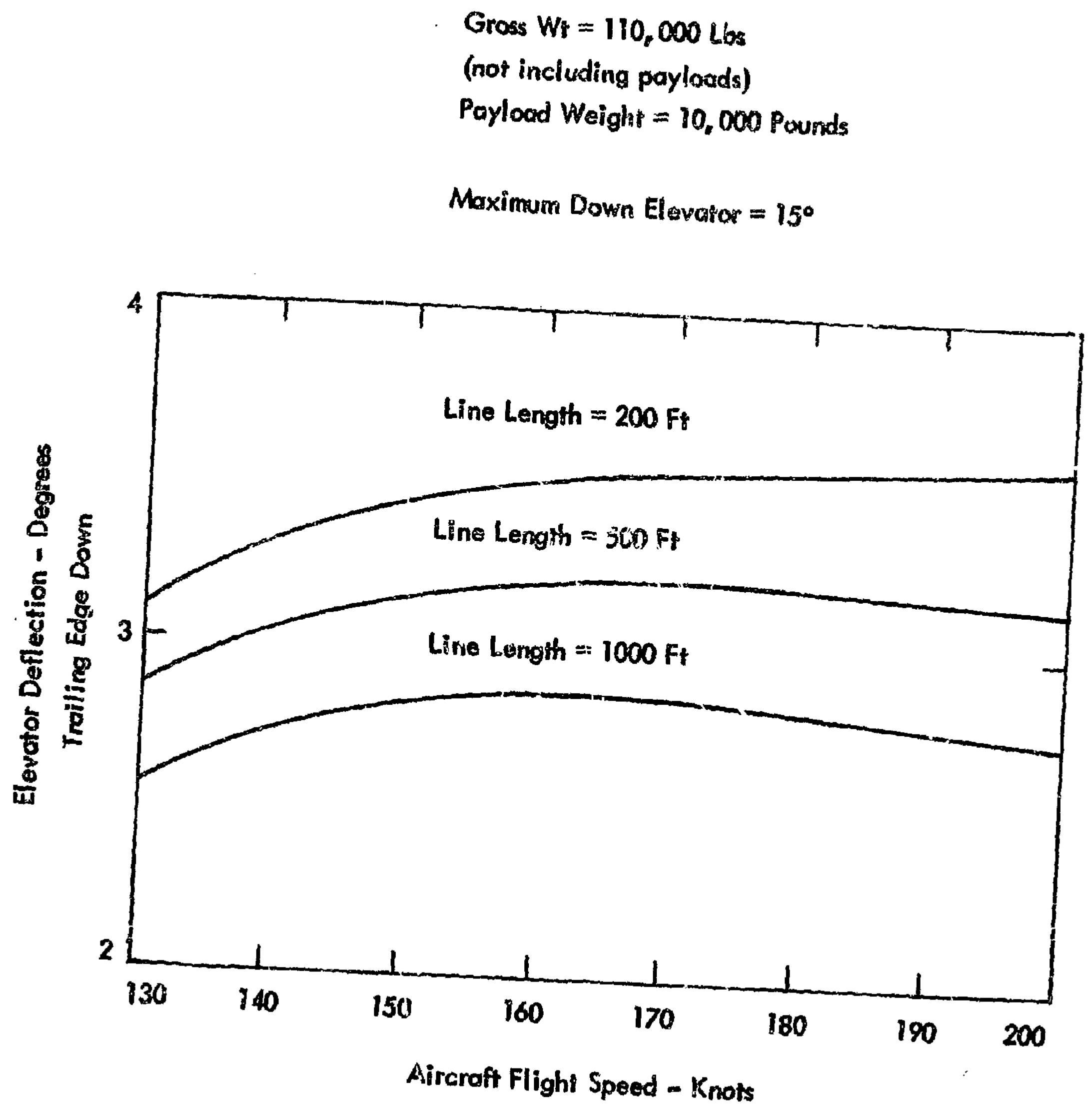


Figure 93 - C-130E Elevator Deflection versus Aircraft Flight Speed

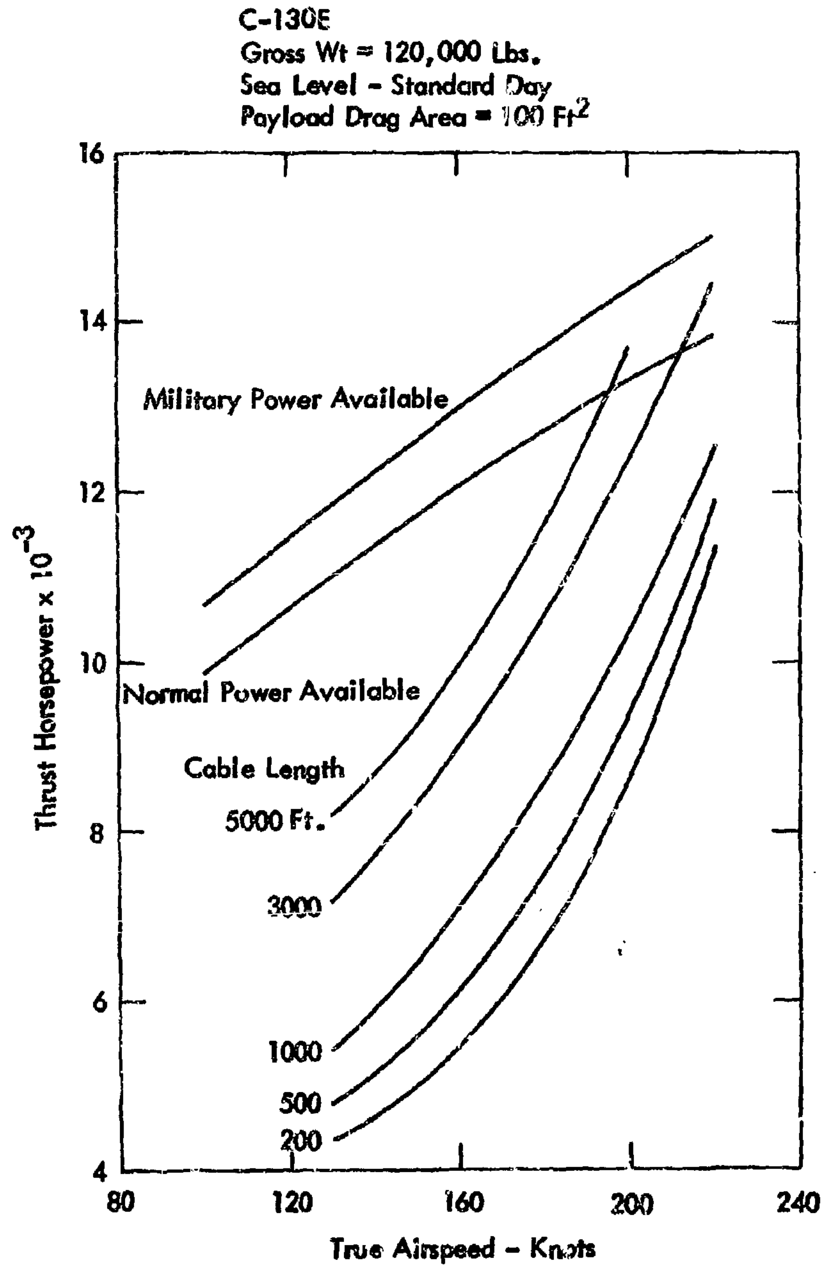


Figure 94 - Power Required and Available Towing 10,000 Pound Load

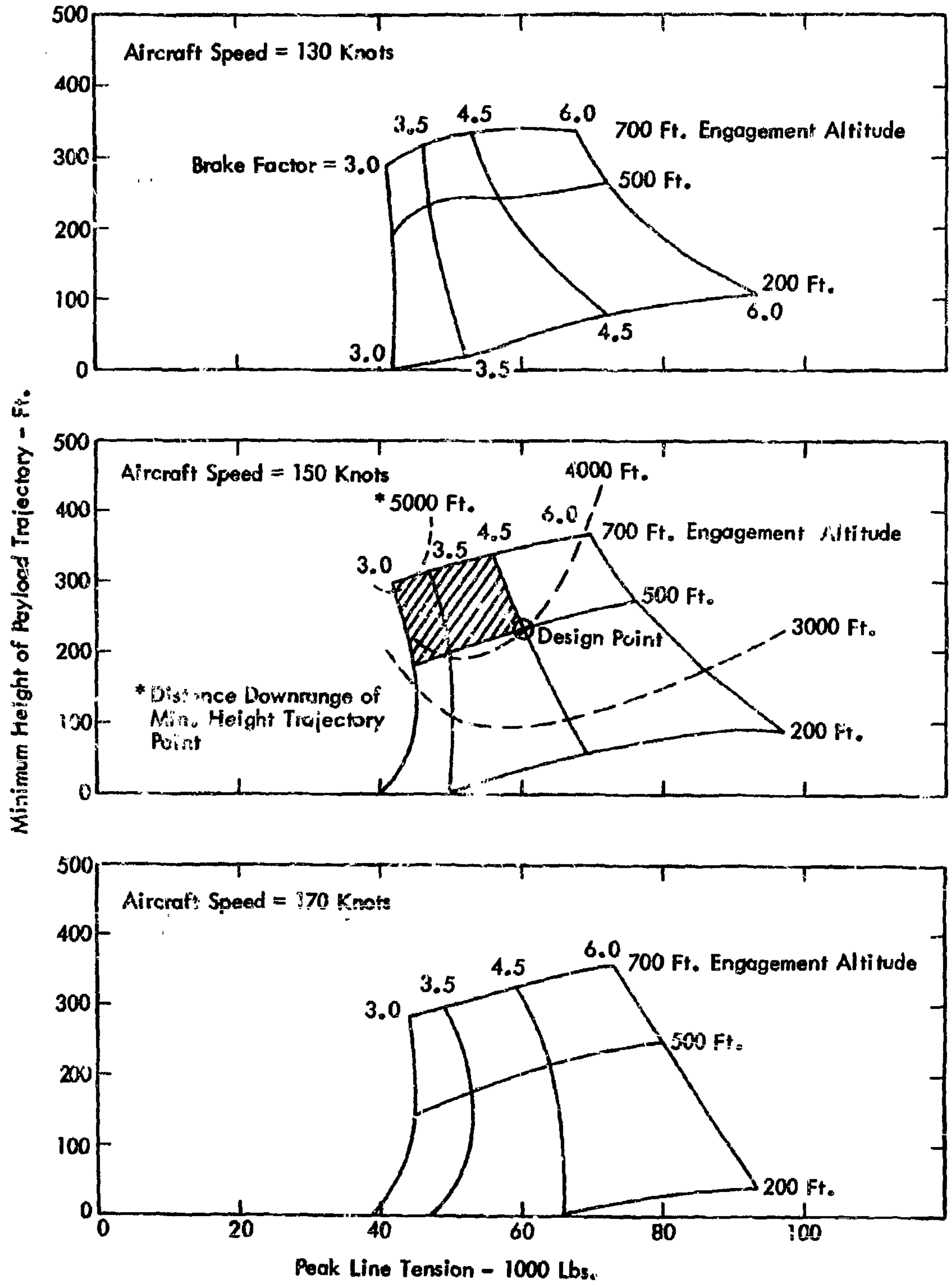


Figure 95 - Balloon Line Retrieval Spectrum of Parameters, Payload Weight -10000 Pounds

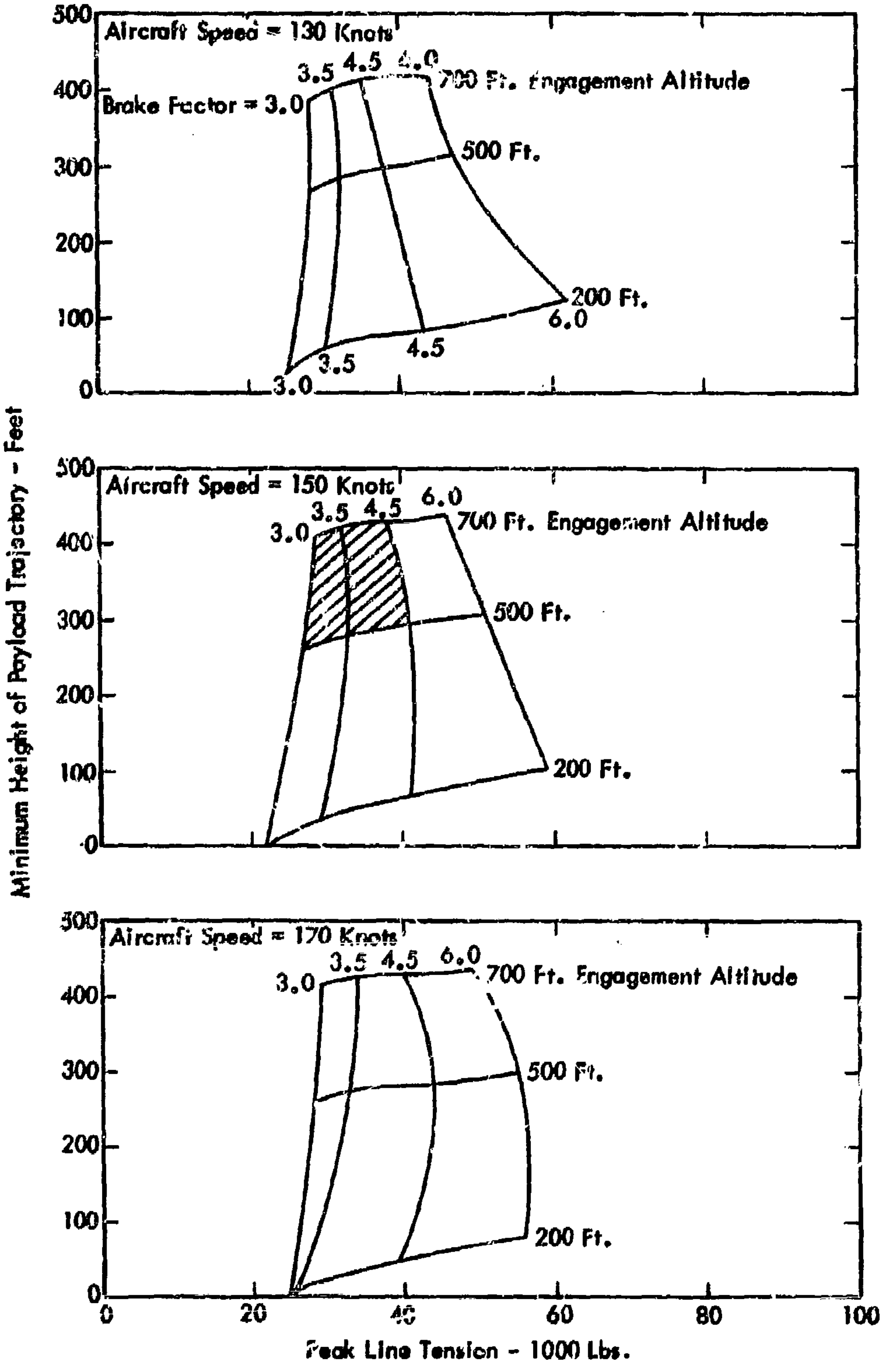


Figure 96 - Balloon -Line Retrieval Spectrum of Parameters. Payload Weight - 6500 Pounds

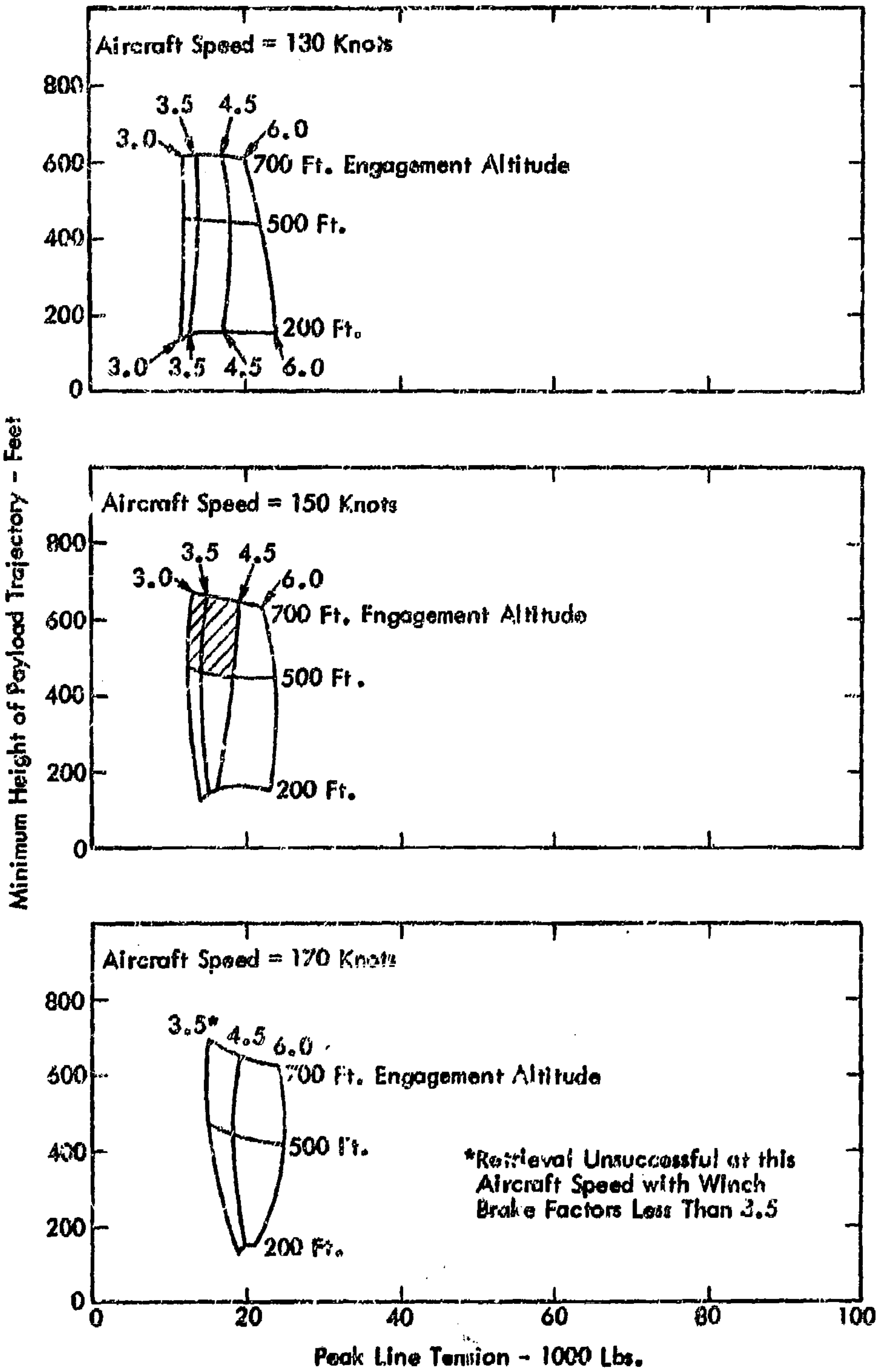


Figure 97 - Balloon - Line Retrieval Spectrum of Parameters. Payload Weight - 3000 Pounds

payload trajectory is shown as a function of the peak tow line tensions experienced. The "minimum height of the payload trajectory" refers to the lowest return of the payload to the ground after initial engagement. The "peak tow line tension" refers to the highest tow line force experienced during the course of each retrieval, from initial engagement to achievement of steady state tow conditions.

Examination of the data presented in Figures 95, 96, and 97 leads to the following discussion and selection of a system design point.

At first assessment, the most attractive retrieval speed appears to be 130 knots, since the minimum payload trajectory points are higher and line tensions are lower than the other two speeds considered. However, an aircraft engagement speed of 130 knots is slightly above stall speed in the case of the C-130 and even closer to the stall speed of larger aircraft. Since the peak line tensions are fairly high in some of the cases examined, a speed of 130 knots does not seem advisable from a flight safety stand point. Figure 91 depicts the elevator deflection requirements for a retrieval case, with an engagement speed of 150 knots. Note that for this case more elevator is required to produce equilibrium than is available. The elevator capability however is exceeded for only a short span of time leading to a small upset in aircraft attitude which can be quickly overcome as elevator deflection requirements decrease. At slower speeds, the elevator is less effective, thus leading to a greater disturbance of aircraft attitude which is certainly undesirable. For these reasons, the engagement speed of 130 knots can be considered less desirable than higher speeds.

The information on Figures 95, 96, and 97 depict two important trends when comparing a 150 knot engagement speed with a 170 knot speed. At 170 knots the peak line tensions are higher for most cases and the trajectory minimum heights are lower. In some cases for 200 feet engagement altitudes at 170 knots, retrievals are unsuccessful since the payload returns to strike the ground. Also for a specific brake setting at a given altitude, line tensions are higher when using a 170 knot engagement speed than when 150 knots is used.

Thus it appears that the better engagement speed of the three considered is 150 knots.

Continuing the rational, the engagement altitude of 200 feet appears undesirable since both the higher line tension and lowest payload trajectory minimum heights are experienced along this line.

Also a brake load factor of 6.0 compared to the other brake load factors considered appears to offer little payload altitude advantage in exchange for a severe penalty in peak line tension.

In addition to those factors discussed above, one other item is of interest when considering the spectrum of retrieval conditions. Each payload trajectory considered resulted in the minimum height occurring at a different distance downrange from the payload origin point. Figure 95 presents in dashed lines for the 10,000 pound payload 150 knot engagement speed case, the interrelation of the downrange location of the minimum height point of each trajectory with the other parameters involved.

The significant point, here, is that large ground clearance areas are required for all the cases taken. The minimum distance from origin to trajectory low point on the curve shown in Figure 95 is roughly 2000 feet.

Since such a large ground clearance area is required then the important consideration is again the height of the trajectory at its low point, rather than the distance downrange.

The conclusion, then, is that the optimum retrieval conditions, of those considered, are found in the shaded areas of the curves presented in Figures 95, 96, and 97.

Retrieval with engagement altitudes of 500 to 700 feet and brake factors of 3.0 to 4.5 appear to offer reasonable values of minimum height of payload trajectory (175 to 630 feet) and peak line tension (12,000 to 60,000 pounds) at an aircraft speed of 150 knots, over the range of payload weights from 3000 to 10,000 pounds.

In order to achieve as high a retrieval trajectory as possible and in order to minimize the required balloon size, the shaded area can be narrowed to one select point, the lower right corner defined by a brake factor of 4.5 and an engagement altitude of 500 feet.

The system design point is then determined:

- o Aircraft Hook engagement speed - 150 knots
- o Brake force - 4.5 times cargo weight
- o Balloon station height - 500 feet.

Additional data which further substantiates the design point selection are presented in Figures 98 through 106. Tow line length refers to line length between cargo and aircraft, prior reel-in, it includes the nylon retrieval line plus all cable. Figures 98, 99 and 100 show the variation of tow line length with increasing aircraft speed with winch brake force to cargo weight ratio as a parameter. These data are based on a balloon height of 500 feet and payload weights of 10,000, 6500, and 3000 pounds. The tow line length is observed to vary directly as the square of the aircraft speed and inversely as the square of the brake force load factor. Therefore, from the standpoint of minimizing line reel-out, it is advantageous to use high brake forces and low aircraft retrieval speeds.

As would be expected, a decrease in aircraft altitude at hook-engagement results in shorter tow line lengths. This effect is shown in Figures 101, 102, and 103 for three retreival speeds, a brake force of 45,000 pounds, and payloads of 10,000, 6500, and 3000 pounds. However, while lower altitudes are advantageous with respect to the amount of nylon line which must be supported by the balloon station, these low retrieval altitudes result in the requirement for additional winch cable pay-out, since the shorter nylon line has less capacity for elongation. The magnitude of this effect is shown in Figures 104, 105, and 106, with aircraft retrieval speed as a parameter. Another advantageous aspect of higher retrieval altitudes is the increased probability of proper aircraft piloting techniques immediately following hook engagement. As the retrieved cargo is being accelerated, a pitch-up moment is applied to the aircraft. This must be counteracted by forward control stick motion to obtain downward elevator deflection. Pilot tendency to delay application of down elevator until actual pitch motion has begun results in higher normal load factors on the aircraft as retrieval altitude is decreased.

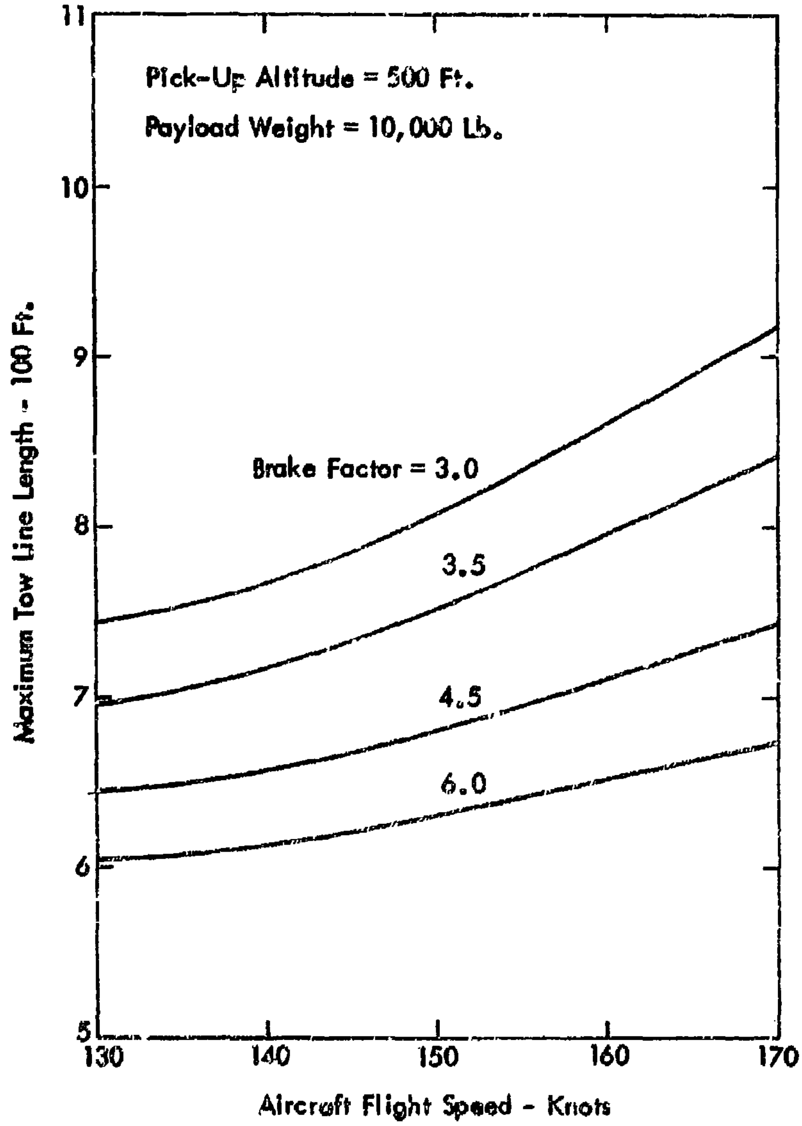


Figure 98 - Line Length versus Aircraft Flight Speed - 10,000 Lb. Load

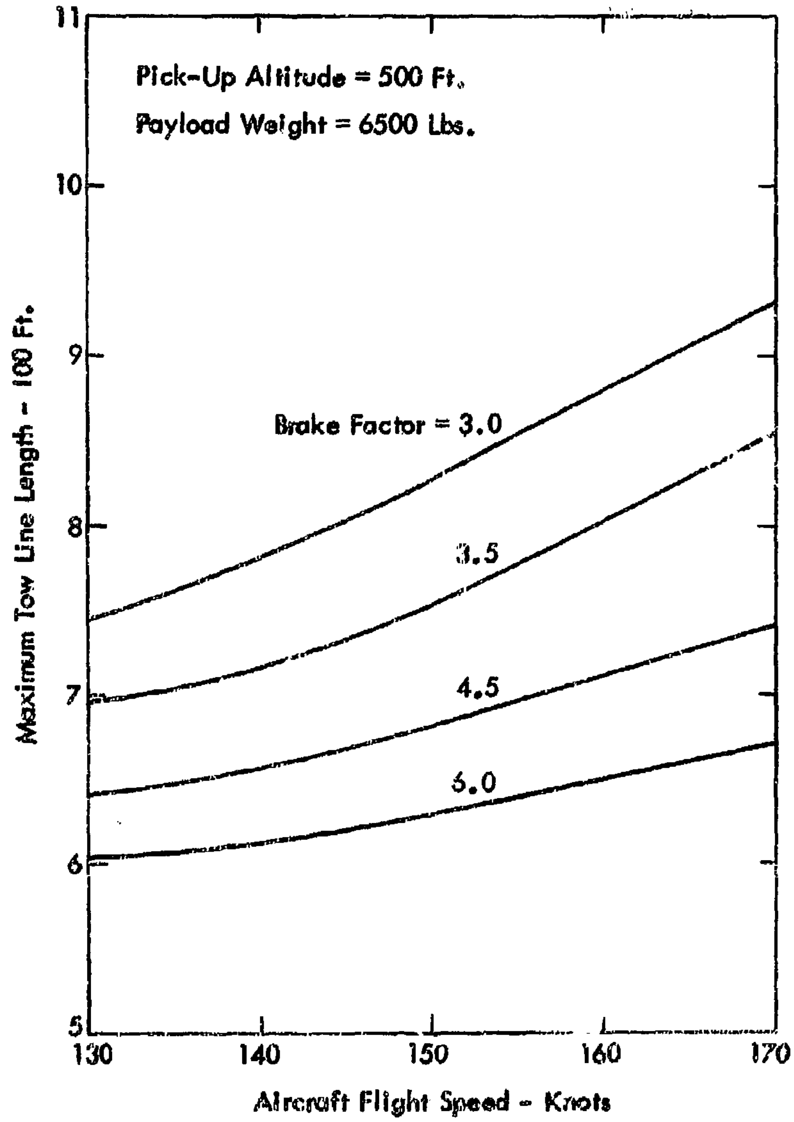


Figure 99 - Line Length versus Aircraft Flight Speed - 6500 Lb. Load

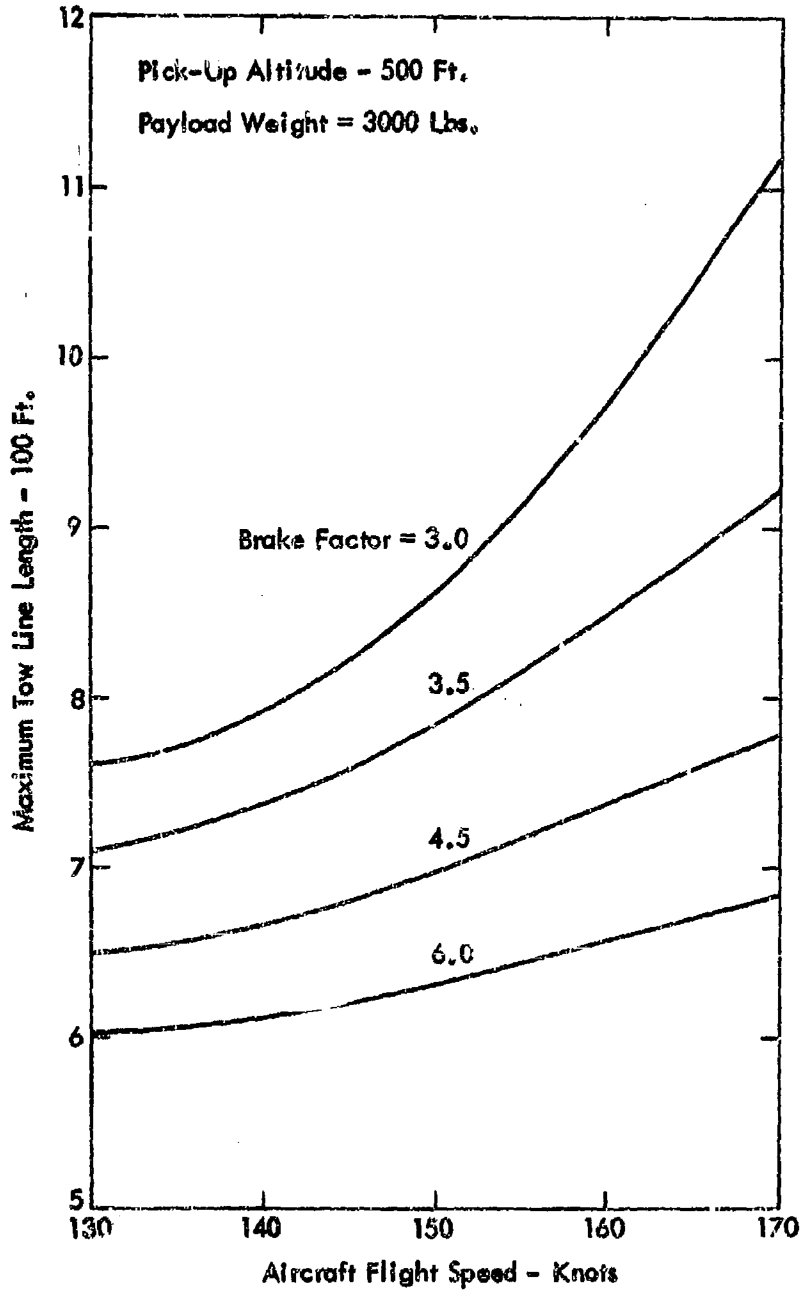


Figure 100 - Line Length versus Aircraft Flight Speed - 3000 Lb. Load

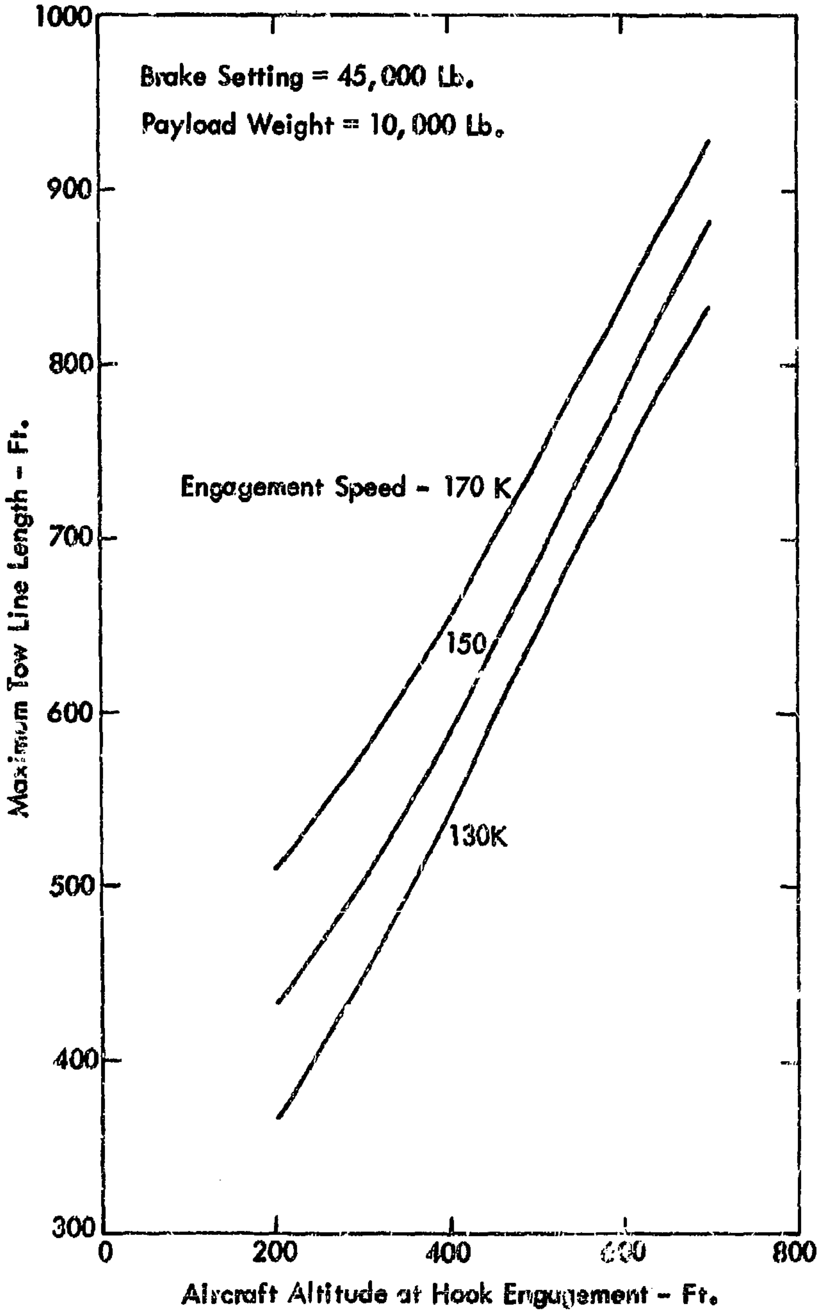


Figure 101 - Line Length versus Aircraft Altitude - 10,000 Lb. Load

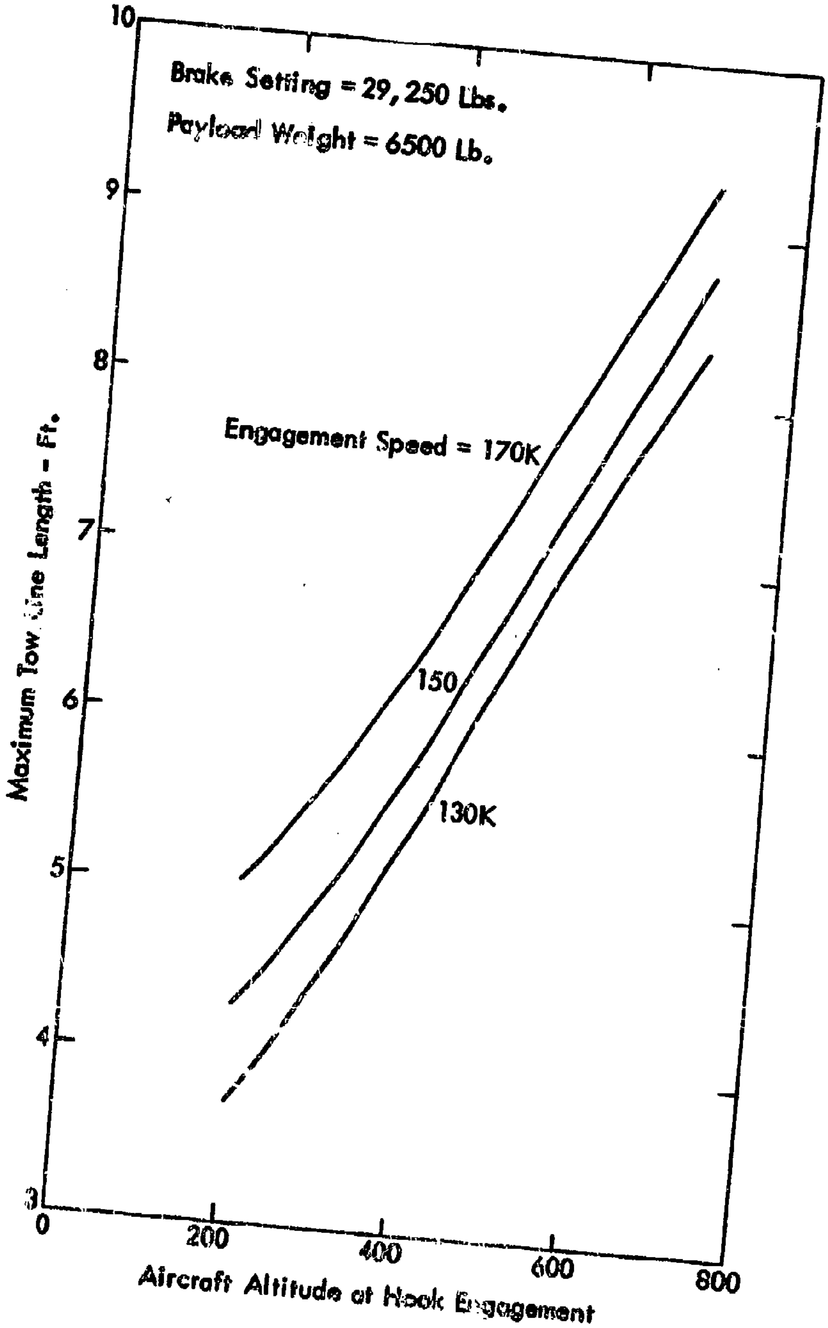


Figure 102 - Line Length versus Aircraft Altitude - 6500 Lb. Load

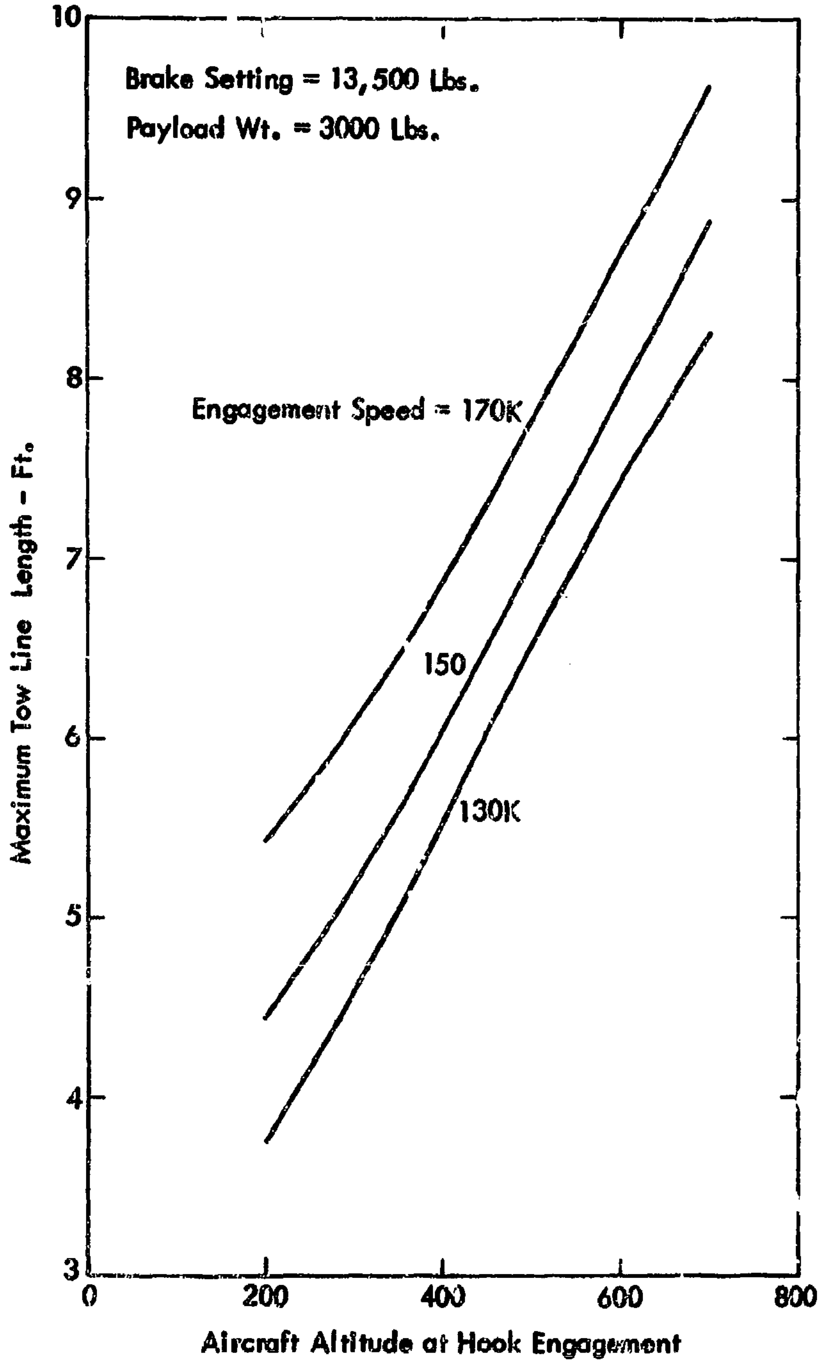


Figure 103 - Line Length versus Aircraft Altitude - 3000 Lb. Load

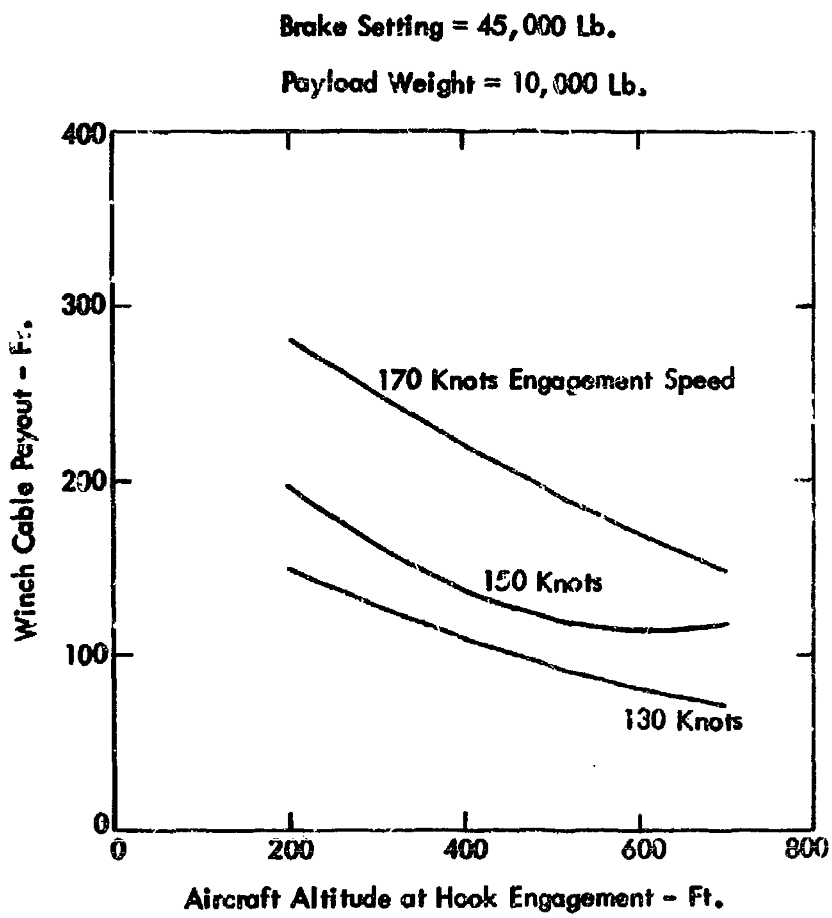


Figure 104 – Winch Cable Payout versus Retrieval Altitude

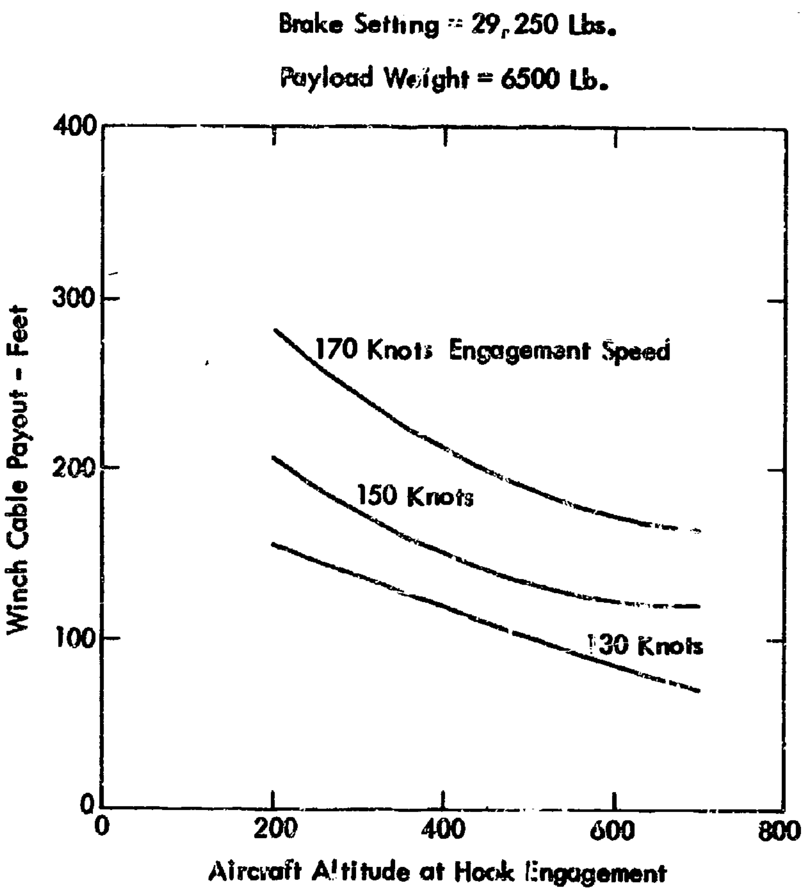


Figure 105 - Winch Cable Payout versus Retrieval Altitude

Brake Setting = 13,500 Lbs.

Payload Weight = 3000 Lbs.

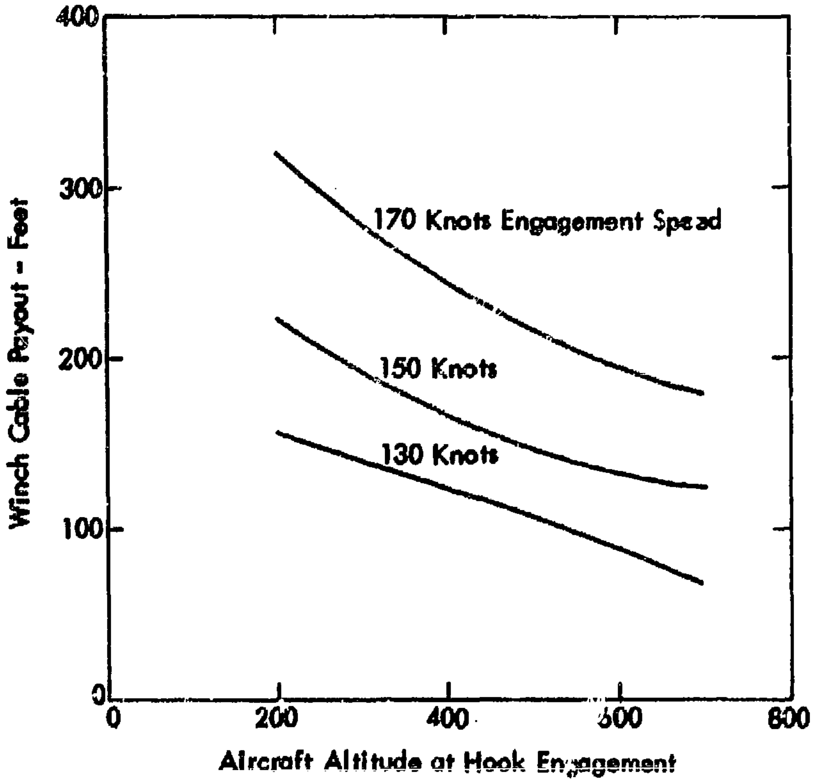


Figure 106 - Winch Cable Payout versus Retrieval Altitude

As illustrated in Figures 98, 99, and 100, required brake retardation force shows only a moderate increase for any fixed value of maximum tow linelength as aircraft speed is increased from 130 knots to 150 knots. At a 500 foot balloon station height, this represents an incremental climb requirement of approximately 325 feet, or approximately 14 seconds of climb time at 1500 fpm climb rate. As shown in Figures 135 through 137, Appendix A, equilibrium tow positions for cargo in the weight range from 3000 to 10,000 pounds is on the order of 23 to 55 degrees below the horizontal at 150 knots flight speed and 800 feet tow line lengths. The cargo reaches this equilibrium position, with very little overswing, approximately 20 seconds after hook engagement. The flexibility afforded in aircraft operational procedures when performing cargo retrieval at a balloon height of 500 feet and a hook engagement speed of 150 knots makes this combination highly desirable with respect to system design point selection. Adequate margin above aircraft stall speed is available, line tension to cargo weight ratios are moderate, open ramp door capability exists with the C-130, C-141, and C-5A aircraft, and sufficient altitude is available to permit proper pilot technique following hook engagement.

Figure 107 presents for the design point, the possible combination of brake factors and payload weights along with the corresponding minimum height point of the payload trajectory and the maximum length of tow line required. Note that for the selected 4.5 brake factor, the length of tow line required is practically constant for all payload weights while the minimum height point increases as the payload weight decreases.

Selection of a constant brake force load factor was made in the interests of operational simplicity as well as to provide a margin of safety in ground clearance distance in the lower range of payload weights. The following section discusses the results of the system design point selection in regard to its effect on balloon and lift line design requirements.

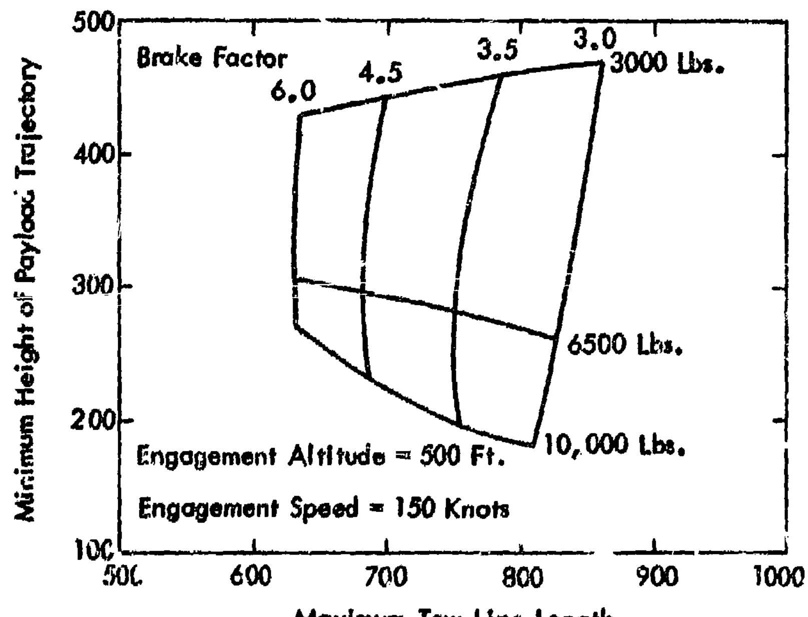


Figure 107 - Minimum Payload Trajectory Height versus Maximum Tow Line Length

System Design Data

Ground-to-air retrieval utilizing an elevated balloon station imposes stringent requirements on the choice of materials and components in order to obtain a minimum system weight. Particularly in regard to the balloon supported retrieval line and the balloon material, the employment of materials having high strength to density characteristics is mandatory if balloon size and helium requirements are to be kept within reason. Recent developments in balloon material by the E.I. DuPont Company have been incorporated in the Fulton Aerial Retrieval System. This material consists of mylar sheet covered with a light weight nylon cloth. It results in a strong balloon material with excellent resistance to abrasion under field conditions. Weight of this material plus bridle and attachments is approximately 0.035 pounds/feet^2 based on balloon surface area. Figure 108 shows balloon envelope weight as a function of balloon volume, assuming a prolate spheroid balloon configuration with a length to diameter ratio of 3.5. Figure 109 shows the theoretical maximum lift of helium as a function of balloon volume together with actual net lift in consideration of balloon envelope weight. These data are based on a 90 degree Fahrenheit temperature and an altitude of 500 feet.

The nylon lift line which must be supported by the balloon should have a high strength to density ratio in order to minimize line weight and thus minimize balloon size. A nylon woven textile webbing material is chosen, equivalent to MIL-W-4088B. Figure 110 presents the relationship between the ultimate line strength and the line weight per foot of length when using this material. Using a figure of four times the cargo weight as the design strength requirement for the lift line, and a safety factor of 1.5 on the design load, ultimate strength requirements were determined as a function of payload weight. These results were used with Figures 109 and 110 to determine balloon size for payload weights from 3000 to 10,000 pounds. Figure 111 shows these results. Over the weight range of interest in this study, balloon volume requirements vary from 1300 to 3700 feet^3. Corresponding balloon diameters and lengths range from 9 to 13 feet and 31.5 to 44.5 feet respectively. Assuming a drag coefficient of 0.20 if the balloon is allowed to weathercock during inflation, and 0.40 if held broadside to the wind, the maximum drag force in a 30 knot wind will vary from 40 to 550 pounds for the 10,000 pound payload balloon.

Table XXXI presents a compilation of balloon and retrieval line design requirements for 1000 pound increments of cargo weight from 3000 to 10,000 pounds. These data are based on the previously selected 500 foot nylon retrieval line. Balloon volume and sizes given include a 20 percent excess lift force over stated line weights. This excess lift, which is in conformance with current design practice incorporated in the Fulton Aerial Retrieval System, provides a relatively high degree of balloon stability in wind and gust conditions as high as 30 knots. Balloon angular displacement for a range of wind velocities is given in next section. Engagement reliability of the balloon station, including the effects of 30 knot wind gusts, is discussed in a subsequent section.

Helium storage bottle requirements were based on the previously determined quantities of helium gas necessary to support the cargo retrieval line. These bottles were assumed to be six feet long, glass filament wound, with a length-to-diameter ratio of 12. Physical properties of the helium bottles are based on data given in Reference 25. Material density is 0.07 pounds/cubic inches and has a working stress of 200,000 psi. Storage bottle wall thickness is based on a safety factor of 2.0. The bottle volume of 1.145 cubic feet provides for storage of 350 cubic feet of helium at 4500 psi. Table XXXII presents a listing of the gas storage bottle requirements for each incremental cargo weight. The second column in the table gives the actual quantity of helium required for the indicated cargo weight. The number of bottles shown in the third column provides a minimum twenty percent additional quantity of helium to provide a 3 psi pressure differential for

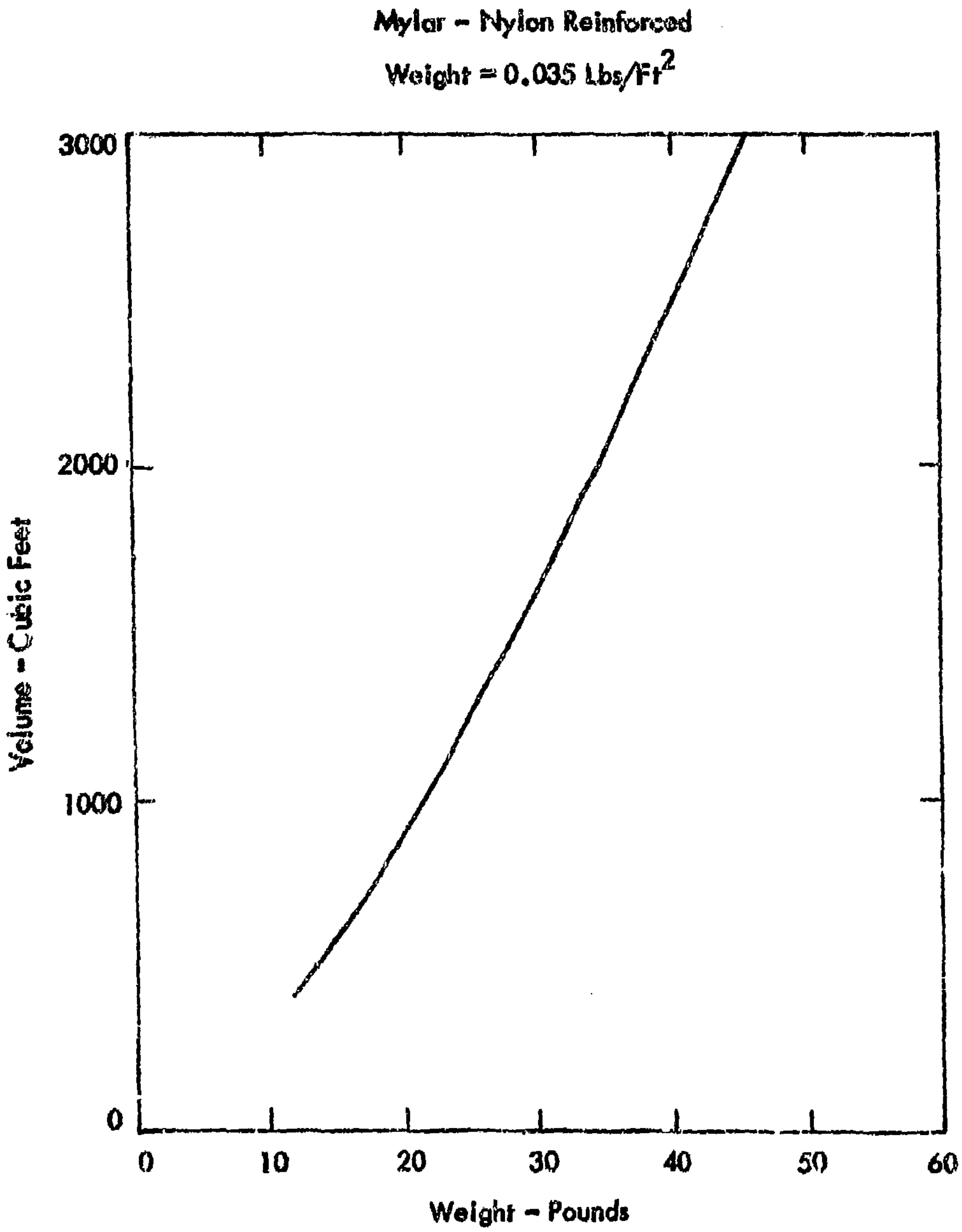


Figure 106 - Balloon Envelope Weight

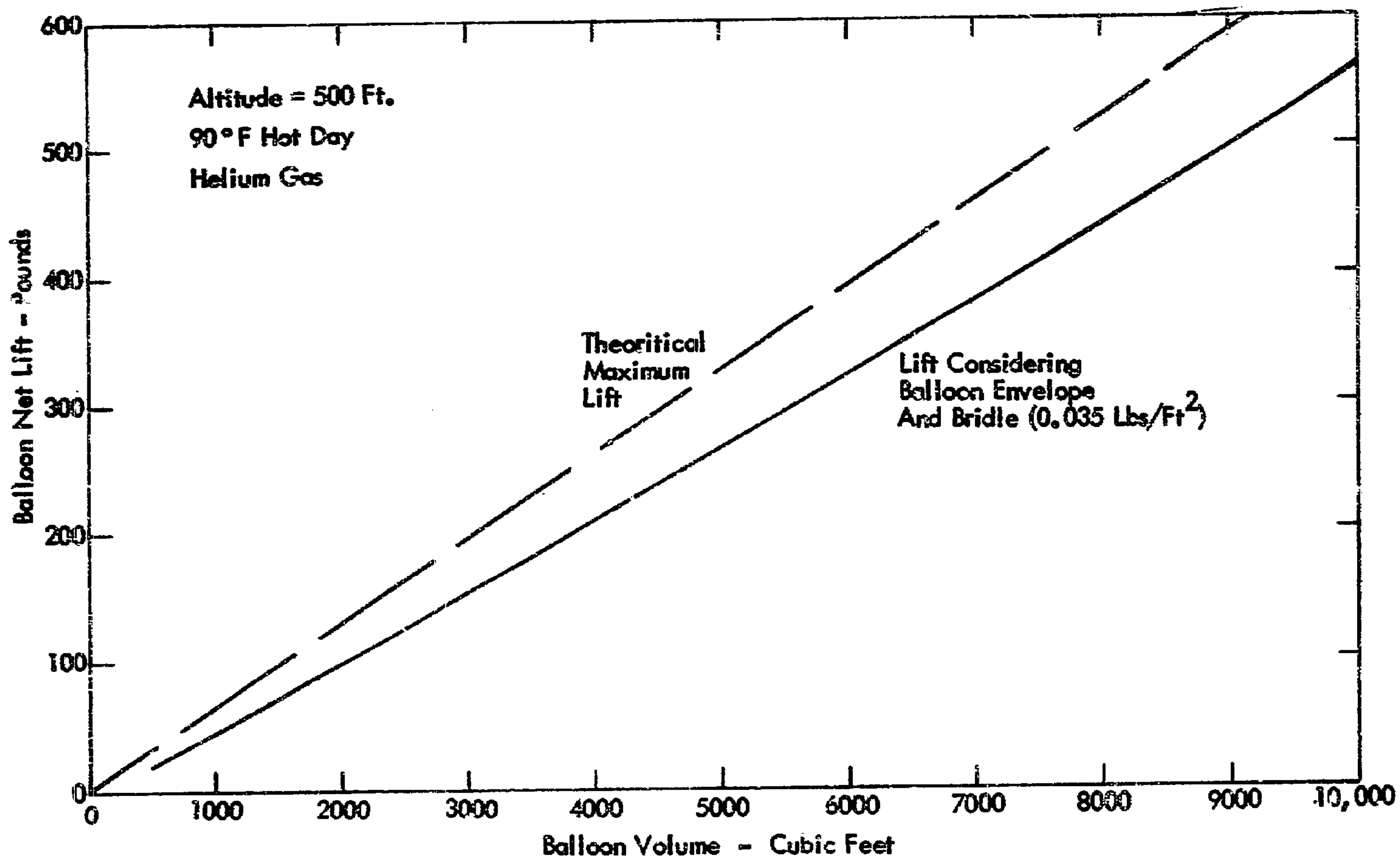


Figure 109 - Line Suspension Balloon Requirements

Tensile Strength - 42,650 Lbs/In^2
Density - 0.02285 Lbs/In.^{3}
Based On Nylon Woven Textile Webbing - Mil-W-4088B

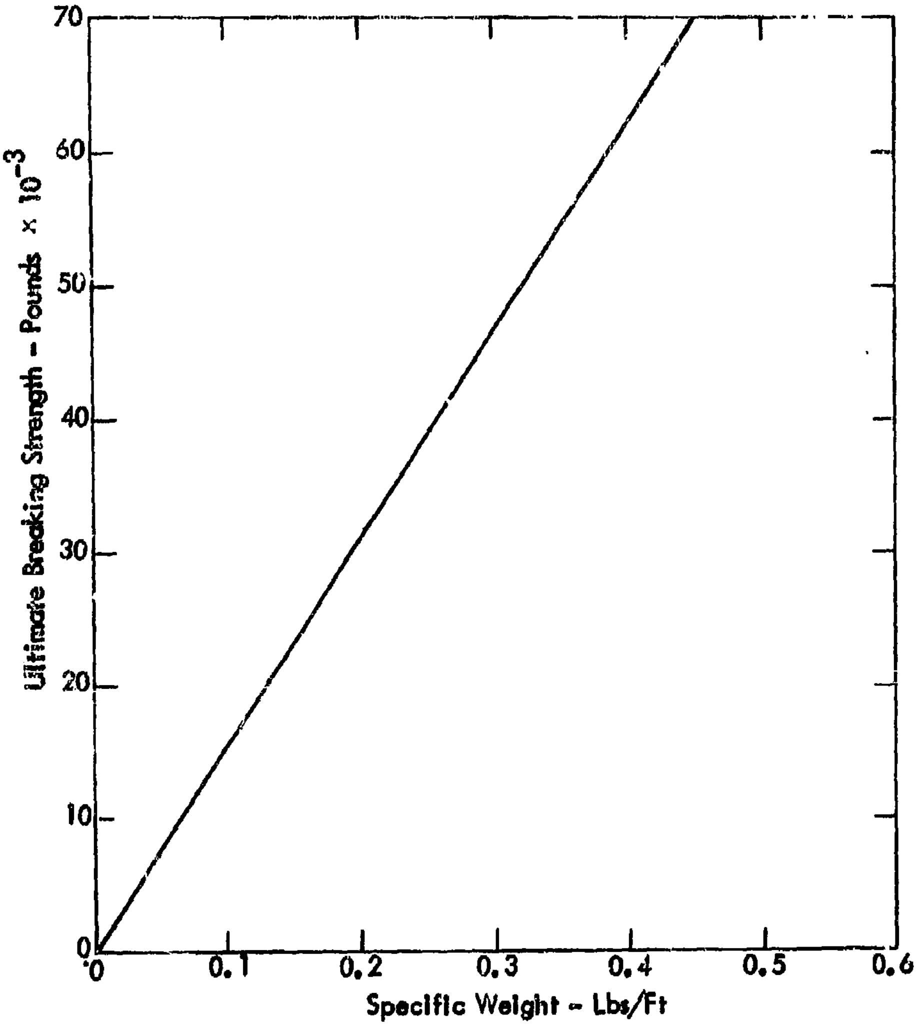


Figure 11C - Nylon Rope Characteristics

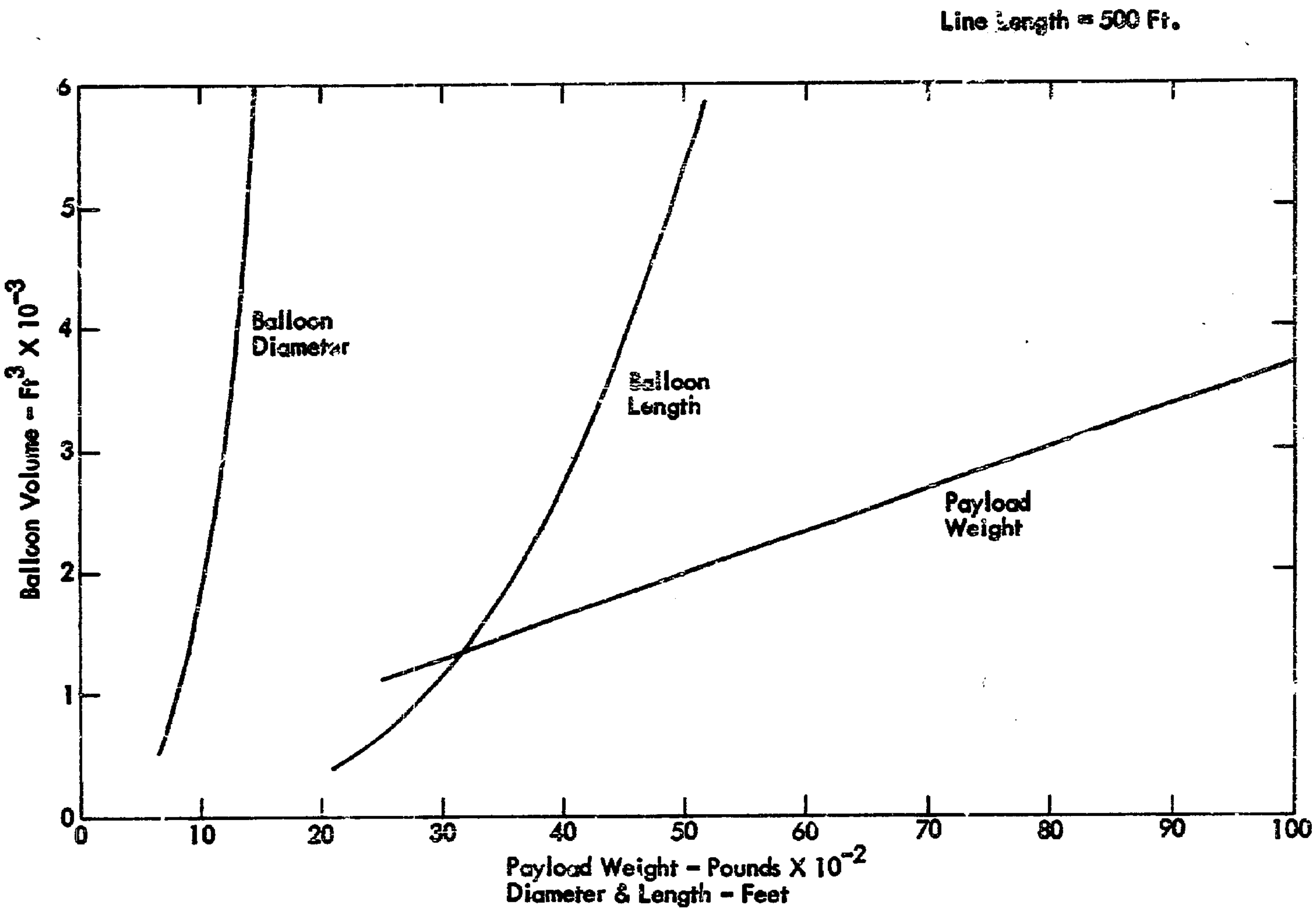


Figure 111 - Helium Volume Requirements versus Payload Weight

TABLE XXXI

BALLOON AND LIFT LINE CHARACTERISTICS

Gross Payload Weight	Lift Line Design Load	Lift Line Ultimate Load	Line Weight	Balloon Volume	Balloon Weight	Balloon Diameter	Balloon Length
Pounds	Pounds	Pounds	Pounds	$Ft.^3$	Pounds	Feet	Feet
3,000	12,000	18,000	58.0	1,275	25.50	8.75	31.2
4,000	16,000	24,000	77.5	1,640	30.25	9.60	33.8
5,000	20,000	30,000	97.0	1,975	34.25	10.30	36.0
6,000	24,000	36,000	116.0	2,325	38.20	11.00	38.0
7,000	28,000	42,000	135.5	2,670	42.10	11.60	39.9
8,000	32,000	48,000	155.0	3,025	46.00	12.10	41.5
9,000	36,000	54,000	174.0	3,370	49.75	12.50	43.0
10,000	40,000	60,000	194.0	3,720	53.50	12.90	44.5

TABLE XXXII

HELIUM BOTTLE SIZE, WEIGHT AND PACKAGING REQUIREMENTS

Gross Payload Weight	Helium Volume At 4500 PSI (Required)	Number of Helium Bottles Required	Total Wgt. of Helium And Helium Bottles	Total Volume of Packaged Bottles
Pounds	FT^3	Unit	Pounds	FT^3
3,000	4.17	4	60	17.67
4,000	5.36	5	75	20.8
5,000	6.45	6	90	25.0
6,000	7.60	7	105	29.1
7,000	8.72	8	120	33.3
8,000	9.88	9	135	37.4
9,000	11.00	10	150	41.6
10,000	12.15	11	165	45.8

the inflated balloon. The last column presents storage volume requirements for the indicated number of bottles, assuming a package size of 10 x 10 x 72 inches.

Table XXXIII shows recovery parachute type, weight and volume requirements to provide aerial delivery redeployment capability for the indicated cargo weight. This data is based upon information provided in Reference 26.

The following section presents the balloon line system performance results based upon design data developed in this and the previous section.

Results of Performance Evaluation

Aerodynamic lift and drag characteristics of the recommened balloon station design are taken from Reference 27. Rigging angles were selected to provide a relatively constant lift to drag ratio for wind speeds from zero to 30 knots. Corresponding angles of attack vary from 6 to 20 degrees. Figure 112 shows the angular displacement of the balloon as a function of wind velocity. Maximum excursion is approximately 16 degrees from a vertical at the ground tether point. In a 30 knot wind the aerodynamic lift is approximately 50 percent greater than the aerostatic lift. Corresponding drag is approximately 144 pounds, or 25 percent of the total lift in a 30 knot wind. An aerodynamically shaped helium balloon is shown to have adequate position stability characteristics with respect to employment as a balloon station for support of the cargo lift line. Stability of the configuration in gust conditions is discussed with respect to hook engagement reliability in the next section.

The kinetics of the cargo trajectory were investigated by writing equations of motion in consideration of line forces resulting from cargo weight, aerodynamic drag, and relative motion between the aircraft and the cargo. Winch drum moment of inertia was described as a function of drum weight and diameter plus the cable weight remaining on the drum core. The balloon station was assumed to be directly above the cargo at the moment of aircraft hook contact. Line aerodynamic and inertial forces were neglected. Both assumptions were made in order to simplify the problem sufficiently to allow computer simulation. In effect, both assumptions lead to conservative results with respect to trajectory characteristics; i.e., actual free flight demonstration would indicate a more vertical lift-off trajectory and less dip in the trajectory following initial ascent. These differences are due to aerodynamic and inertia forces on the line which cause the cargo to follow the initial line direction more closely than the computer simulation predicts. In practice it is desirable to approach the balloon in a direction opposite to the wind direction to take advantage of this line/cargo aerodynamic interaction.

Figure 113 presents cargo trajectory characteristics for cargo weights of 3,000, 6,500 and 10,000 pounds. Aircraft speed is 150 knots and an initial climb rate of 1,500 feet per minute on military power is assumed. Figure 113 shows that cargo minimum ground clearance decreases with increasing cargo weight, for a constant initial balloon station height. Maximum line tension for these trajectories is approximately four times the cargo weight. As cargo weight increases, aircraft rate of climb decreases due to the higher forces occurring in the retrieval line. Figure 114 shows the effect of adding eight JATO units to the C-130 aircraft for retrieval of a 10,000 pound cargo. JATO thrust augmentation is a nominal 8,000 pounds for 15 seconds. The trajectory with JATO shows an improvement in trajectory minimum altitude of 250 feet over the non-JATO case. In all cases the trajectories shown are satisfactory with respect to initial climb angle and minimum ground clearance. Initial climb angles on the order of 30 degrees indicate the requirement for a retrieval site clear area approximately 300 feet in diameter to provide clearance of a 70 foot obstacle. A typical cargo line tension and velocity

TABLE XXXIII

RECOVERY PARACHUTE CHARACTERISTICS

Gross Payload Weight	Type	Number	Weight Each	Volume Each	Total Weight	Total Volume
Pounds	Desig.		Pounds	Ft^3	Pounds	Ft^3
3,000	G-11	1	240	11	240	11
4,000	G-12	2	120	5	240	10
5,000	G-12	2	120	5	240	10
6,000	G-12	3	120	5	360	15
7,000	G-11	2	240	11	480	22
8,000	G-12	4	120	5	480	20
9,000	G-12	4	120	5	480	20
10,000	G-11	3	240	11	720	33

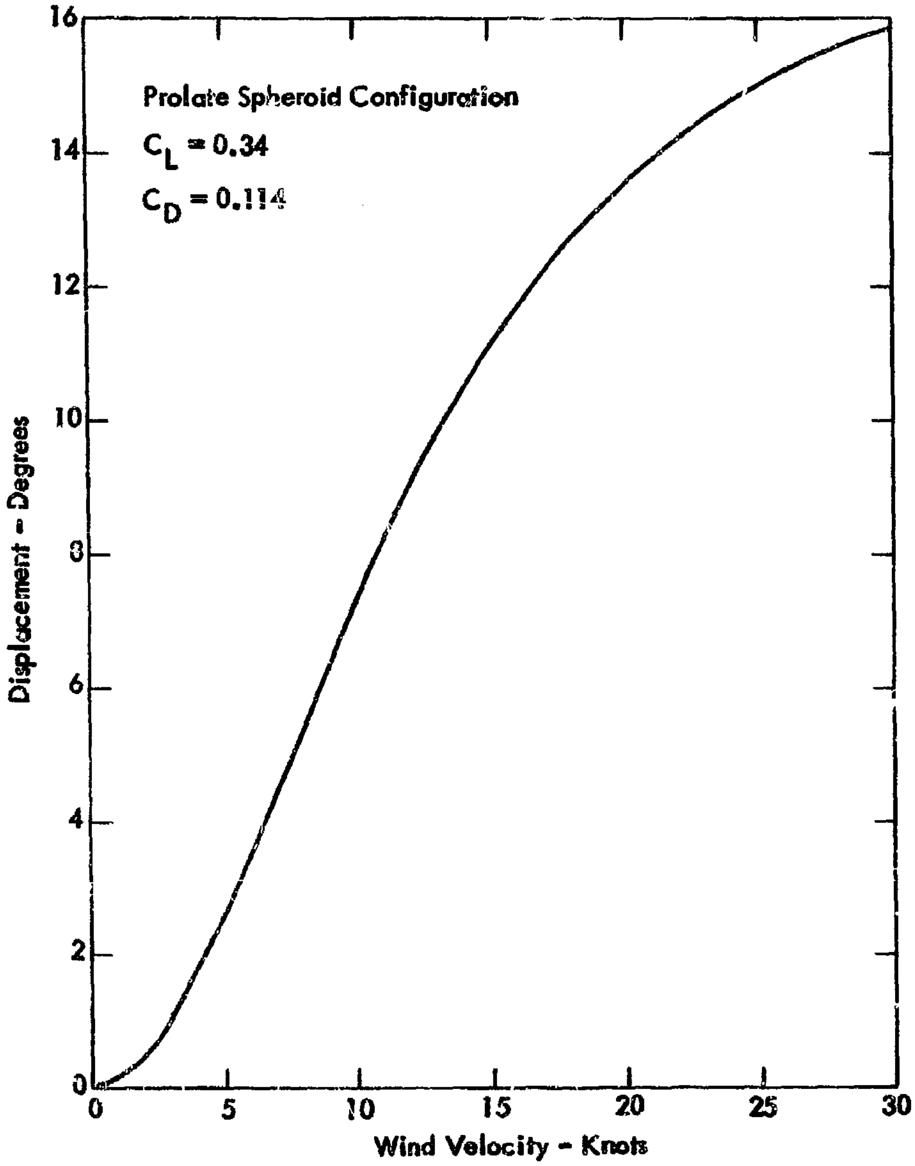


Figure 112 - Angular Displacement of Aerostatic/Aerodynamic Lift Balloon

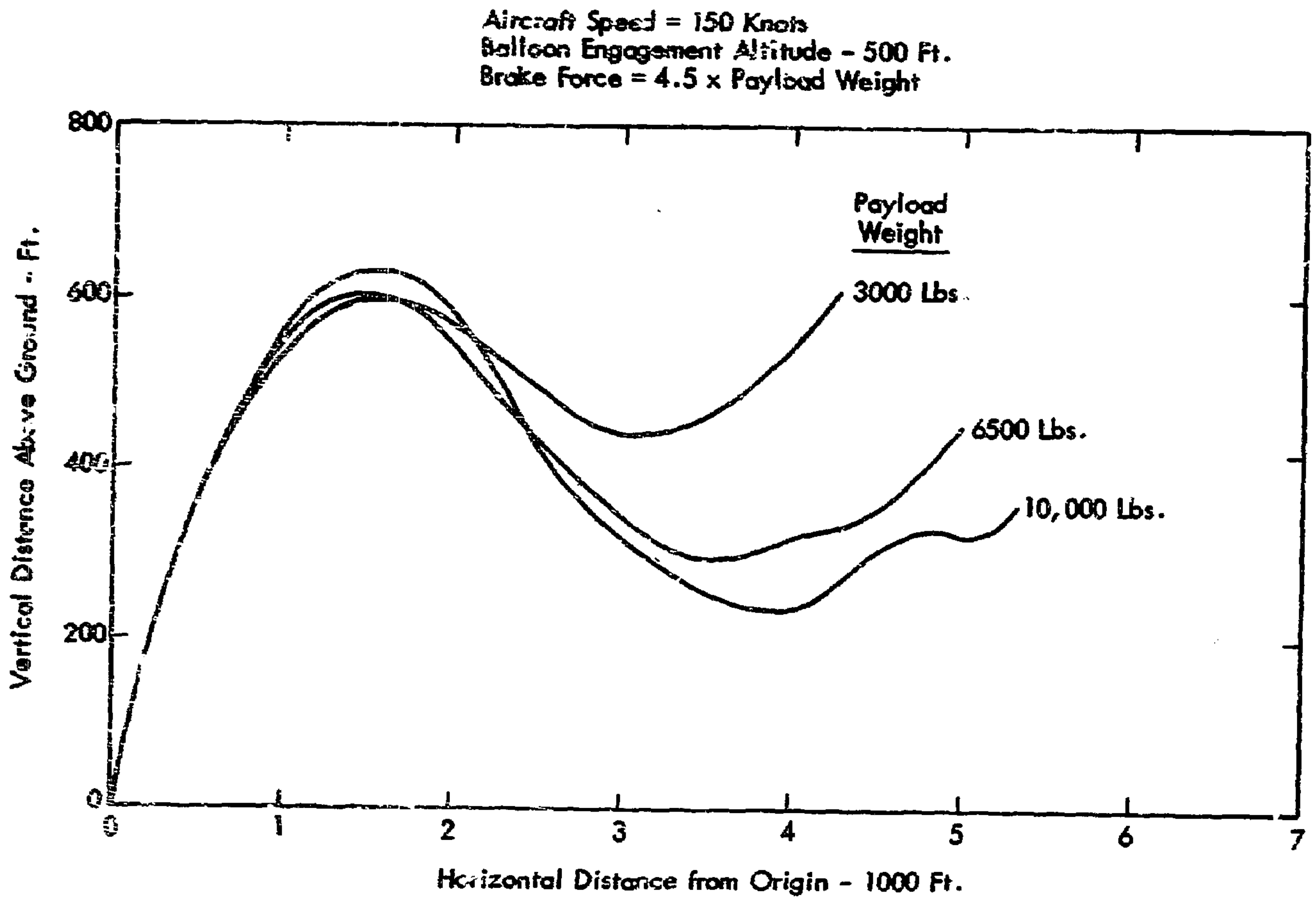


Figure 113 - Payload Trajectory Characteristics

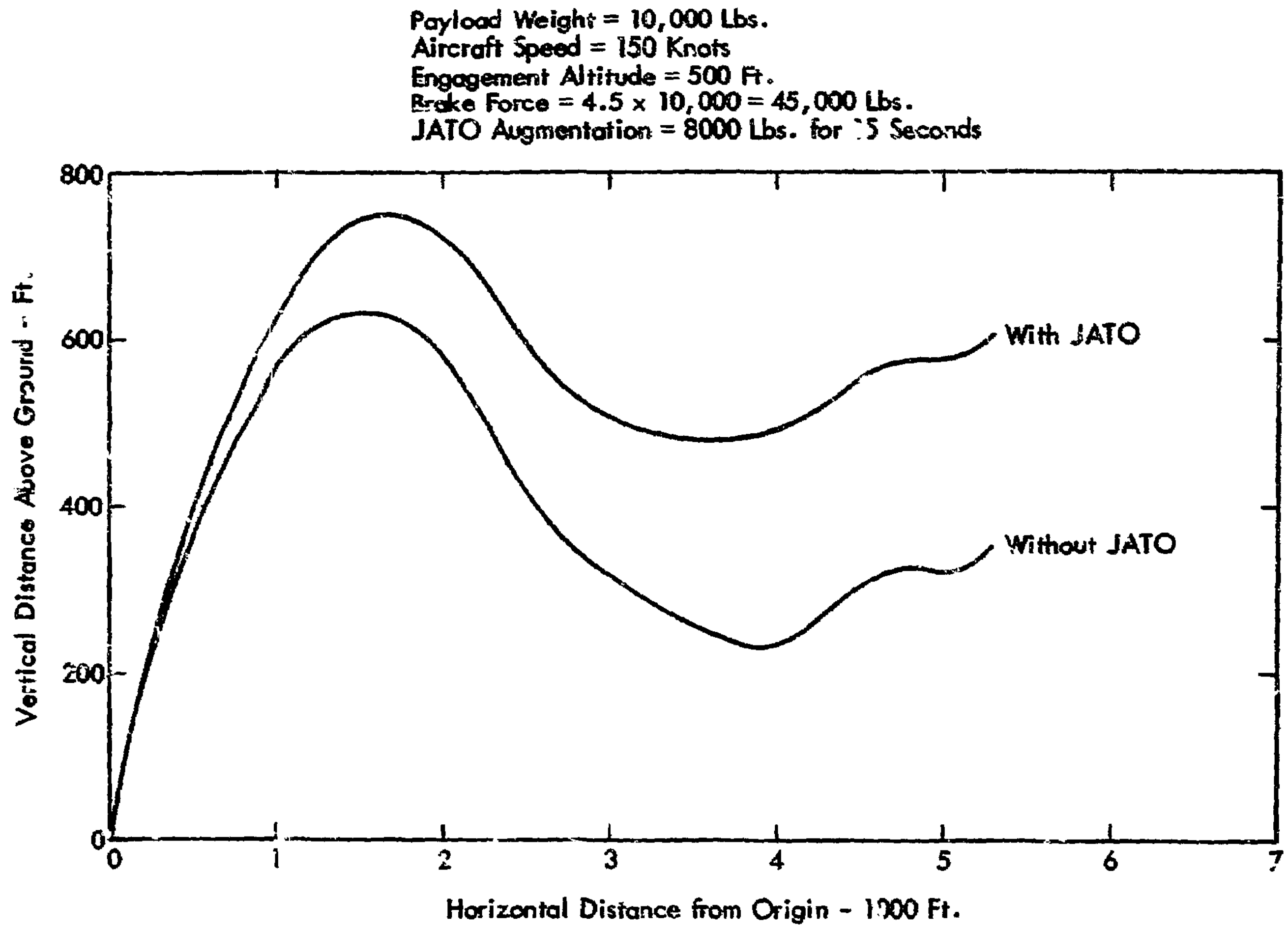


Figure 114 - Effect of JATO Augmentation on Payload Trajectory Characteristics

time history is shown in Figure 115. These data are plotted for a 10,000 pound payload with a brake force setting equal to 4.5 times the cargo weight. Vertical velocity is decreasing, following an initial peak, as the cargo approaches the initial peak of the lift-off trajectory. Maximum line force is on the order of six times the cargo weight.

A summary of system physical characteristics is shown in Table XXXIV. Due to the modular approach taken in recovery parachute selection and helium storage bottle design, system weight efficiencies are seen to fluctuate over the range of gross cargo weights from 3,000 to 10,000 pounds. System weight efficiency is defined as the ratio of net cargo weight to gross cargo weight. The gross cargo is the sum of the net cargo weight, shown in column four, and the total system weight shown in column two. The values shown in the last column, derived by taking the ratio of total system weight to net cargo weight, indicate that ground-to-air retrieval and redeployment of cargo by the recommended balloon/line technique required an additional weight equal to approximately 12 percent of the cargo weight.

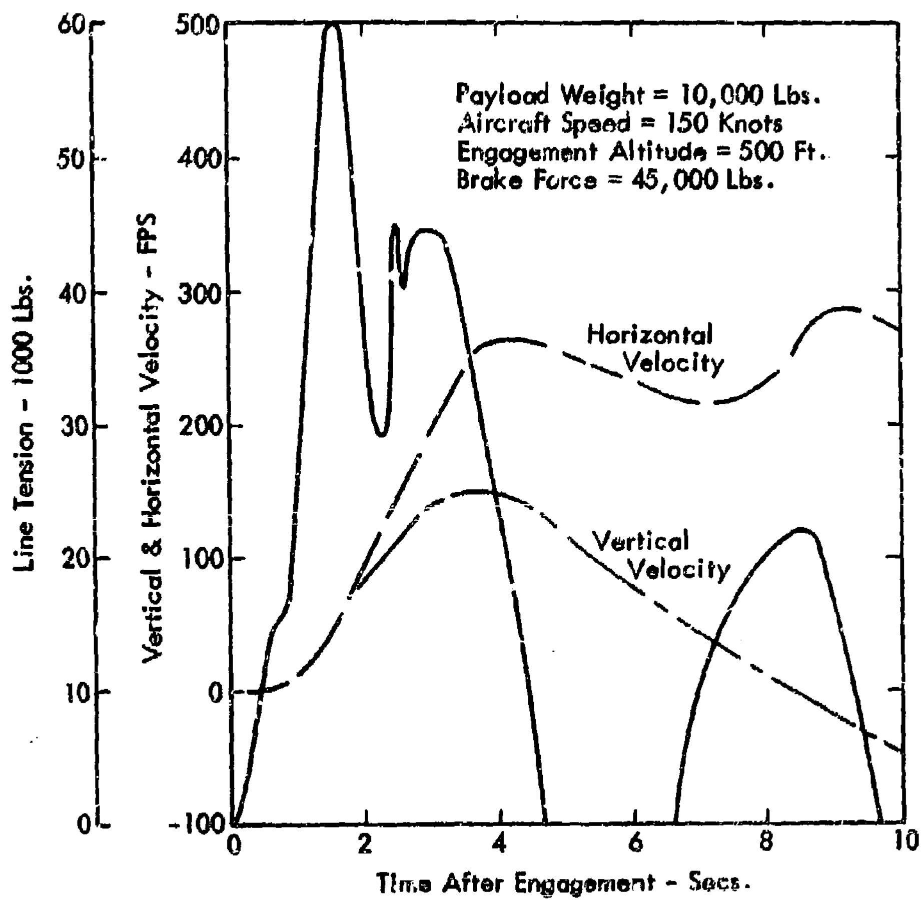


Figure 115 - Typical Time History of Payload Velocity and Line Tension

TABLE XXXIV

BALLOON LINE RETRIEVAL

SYSTEM-WEIGHT AND VOLUME SUMMARY

Gross Payload Weight	Total System Weight	Total System Volume	Net Cargo Weight	System Weight Efficiency	System To Cargo Weight Ratio
Pounds	Pounds	Ft^3	Pounds		
3,000	384	27.7	2,616	.872	.147
4,000	423	30.8	3,577	.894	.118
5,000	462	35.0	4,538	.907	.102
6,000	620	44.1	5,380	.987	.115
7,000	778	55.3	6,222	.889	.125
8,000	8.6	57.4	7,184	.898	.114
9,000	854	61.6	8,146	.905	.105
10,000	1,133	78.8	8,867	.887	.128

EVALUATION OF SELECTED SYSTEM

This section presents results of the evaluation of the selected retrieval system concept.

The method used in the evaluation follows closely the approach outlined in Appendix B, which is centered on the determination of a concept ranking number

$$CPN_{R_i} = P_e \frac{W_c}{\pi \bar{r}_m^2 (T_c + T_r)} \cdot \frac{W_c}{W_s + W_c} \qquad (86)$$

with

P_e = Retrieval engagement probability

W_c = Net cargo weight

W_s = Retrieval and delivery system weight

$\bar{r}_m$ = Root-mean-square delivery dispersal

T_c = Delivery cycle time

T_r = Retrieval preparation time

In the case of a retrieval-delivery operation, a slightly different interpretation must be allotted to the concept of "delivery cycle time" as compared with that used in delivery system evaluation.

In the latter case, the operational situation used for concept evaluation essentially constitutes a pipeline type of supply flow, where events occur regularly separated by repetitive time intervals; hence the expression, "cycle time."

Retrieval-delivery operations, however, are more likely to appear as a series of unrelated single events, and the concept of drop cycle time loses meaning.

A meaningful interpretation of T_c can, however, be retained in the context of retrieval-delivery operations by redefining T_c as the time required for stripping the drop cargo of retrieval and delivery gear and for clearing the impact area of delivery equipment debris or salvageable delivery equipment.

Pick-Up Engagement Probability

The pick-up engagement probability is assumed to be identical with the contact probability. It is evaluated as follows:

The situation immediately prior to a pick-up engagement is shown in Figure 87. The essential elements are the following:

- o A pole, carrying one or more engagement hooks, extended below the retrieval airplane

- A part of a loop on the cargo lift line suspended horizontally over the balloon and normal to the flight path of the retrieval airplane

For the purpose of analysis, an engagement is considered to be achieved whenever the flight path is such that any part of the pole intercepts any part of the suspended length of the lift line loop. Conversely, failure to achieve contact is registered as an engagement failure.

From an analytical standpoint, it is convenient to restate the conditions as follows:

A retrieval engagement is achieved whenever the flight path of the airplane is controlled so as to intercept a target area attached to the balloon whose width equals the projection of the suspended lift line loop on a plane normal to the flight path, and whose height equals the projection of the pole on the same plane.

Failure to achieve pick-up engagement can be traced to two basic sources:

- Inept control of the airplane flight path by the pilot
- Random, unanticipated motion of the target which is beyond the compensative powers of the pilot/airplane combination

Only the last item will be considered in this analysis.

A tethered balloon exhibits some degree of oscillatory motion when exposed to wind. There are two basic causes for this motion. One is the periodic shedding of Von Karman vortices which may cause yaw angle oscillations and induce oscillatory lateral displacements. This type of motion will not be considered because design features can be incorporated to suppress this phenomenon. The other, which is the subject for this analysis, is random motion caused by gustiness of the wind.

Dynamic Properties of the Balloon

A tethered balloon can be conceived as an inverted pendulum with small mass, small restoring forces, and very large damping constants.

It corresponds dynamically to a first-order system, possessing a transfer function which is flat at near unit value over the lower and middle parts of the frequency range and which drops down to near zero at higher frequencies. This means essentially that the balloon excursion responses are proportional to and in phase with the exciting gust velocity increments.

Gust Description

This analysis is based on a power spectral density description of the gust characteristics. Actual data used were taken from Reference 28.

The following data were used:

Spectral shape:	Woodlands, 400-600 feet altitude
Scale length:	$L' = 400$ feet, 400-600 feet altitude
Turbulence parameter:	$(\overline{\Delta u/v_w})^2 = .10$ at 500 feet altitude

While these data specifically pertain to vertical gusts, the concept of isotropic turbulence is generally applied as a working hypothesis in gust studies. It is also adopted here.

Balloon Motion

In steady wind conditions, the aerodynamic drag of the balloon and the tether line causes the balloon to drift downwind until a force equilibrium between aerostatic lift, aerodynamic lift, aerodynamic drag and tether line tension is achieved. The equilibrium is characterized by a drift angle θ, measured from the vertical through the ground tether point. Values for θ as a function of wind speed are shown in Figure 112.

Changes in wind speed cause variations in θ along with variations in longitudinal and vertical displacement of the balloon. Due to the dynamic properties of the balloon described above, the readjustment to the new equilibrium position is practically instantaneous. Only the vertical displacement component is important from the standpoint of engagement probability. Changes in wind direction have the following effects. First, since the balloon has weathercock stability, it aligns itself with the new wind direction with a negligibly short time lag. Second, it drifts laterally until the projection of the tether line on the horizontal plane is also aligned with the new wind direction. Again, the response to a gradually changing wind direction is practically lag free, while for an extremely abrupt change, some time lag in the response can be expected. The lateral displacement of the balloon is very important from the standpoint of engagement probability.

The magnitudes of the displacement vector components for the balloon are:

Vertical displacement

$$\overline{\Delta z} = h \sin\theta \frac{d\theta}{d_w} \cdot \overline{\Delta u} \tag{87}$$

Lateral displacement

$$\overline{\Delta y} = h \sin\theta \left(\frac{\overline{\Delta u}}{v_w}\right)_y \tag{88}$$

where

$$\left(\frac{\overline{\Delta u}}{v_w}\right)_y = .707 \cdot \left(\frac{\overline{\Delta u}}{v_w}\right)$$

$$\theta = \tan^{-1}\left(\frac{D_A}{L_S + L_A}\right) \tag{89}$$

$$\frac{d\theta}{dv_w} = \frac{1 + L_A/L_S}{\left[1 + L_A/L_S\right]^2 + (D_A/L_S)^2} \cdot \frac{2\,C_D}{v_w} \tag{90}$$

where

- h = Length of balloon lift line, feet
- $\overline{\Delta u}$ = Root-mean-square gust velocity, fps (Ref. 28)
- v_w = Steady wind component, fps
- θ = Inclination from the vertical of radius vector from the ground tether point to balloon
- L_A = Aerodynamic lift of balloon
- D_A = Aerodynamic drag of balloon

L_S = Excess balloon buoyancy lbs

C_L = Balloon lift coefficient

C_D = Balloon drag coefficient

S_B = Reference area = $V_B^{2/3}$ (Ref. 29)

V_B = Balloon volume, ft^3

Displacement calculations were made using the following numerical data:

h	= 500 ft	(Design data)
$(\overline{\Delta u/v_w})^2$	= .10, .20	(Ref. 28)
V_B	= 6000 ft^3	(Design data)
C_L	= .34	(Ref. 29)
C_D	= .114	(Ref. 29)
L_S	= 60 lbs	(Design data)

Engagement Probability Degradation

Reduction of the engagement probability is caused by the random vertical and horizontal displacement of the balloon under gust conditions which cannot be anticipated by the pilot controlling the flight path of the retrieval airplane.

If the balloon motion is slow, it can be noticed at sufficiently large distance that appropriate flight path corrections can be made; if, however, it is abrupt and happens only a short time before anticipated contact, the engagement opportunity may be missed. The important factor is the characteristic response time constant for the pilot/airplane combination. An absolute lower bound for this response time is afforded by the duration of the short-period longitudinal oscillation of the airplane. A typical value is of the order 1.0 - 1.5 seconds. For corrections involving lateral motion of the airplane as well, a considerably longer period may result, probably of the order 3 - 5 seconds. This corresponds to a characteristic wave-length for the airplane response of from 750 - 1250 feet, representing the lower limit for the distance between balloon and airplane within which a balloon displacement perturbation can be accommodated by control of the flight path.

Gust Encounter Probability

The gust frequency, or the number of gusts per second is given by

$$n_g = \frac{v_w}{L'} \tag{91}$$

where

v_w = Wind speed

L' = Characteristic gust wavelength

The probable number of gust occurrences during the critical approach period for the airplane is

$$N_{gp} = t_R \cdot n_g \tag{92}$$

where

t_R = Response time constant for pilot/airplane combination.

Interpreting gust occurrences as discrete events, the probability of gust encounters can be written as

$$P_{(gust)} = 1 - e^{-N_{gp}} \tag{93}$$

Engagement Target Location

The size of the engagement target area is

$$A_t = a \cdot b \tag{94}$$

where

a = length of pick-up pole projection on a plane normal to the flight path

b = length of projection of lift line engagement loop on a plane normal to the flight path

The probable size of the area within which the target is located is

$$A_p = A_t + \overline{\Delta y} \cdot b + \overline{\Delta z} \cdot a + \pi \cdot \overline{\Delta y} \cdot \overline{\Delta z} \tag{95}$$

where

$\overline{\Delta z}$ = root-mean-square value of vertical displacement due to gust

$\overline{\Delta y}$ = root-mean-square value of lateral displacement due to gust

The event that the target is displaced from its center location is contingent upon the event that a gust has occurred within the critical time period t_R = 4 seconds. This probability is $P_{(gust)}$ as shown above.

The probability of the event that a miss is registered upon an encounter with a displaced target is

$$P_{(Miss)} = (1 - \frac{A_t}{A_p}) = (1 - \frac{a \cdot b}{(ab + \overline{\Delta y} \cdot b + \overline{\Delta z} a + \pi \cdot \overline{\Delta y} \cdot \overline{\Delta z})}) \tag{96}$$

The resulting probability of target engagement is consequently

$$P_{Hit} = 1 - P_{(gust)} \cdot P_{Miss} \tag{97}$$

Results

Figure 116 presents the results of the analysis, shown as a plot engagement probability versus wind speed for gust variance values of .10 and .20. The results indicate a quite serious degradation in engagement probability for wind speeds exceeding 20 knots.

The results are, however, not so sensitive to gust variance. Experimental data on which these results are based, indicate a spread in gust variance between the limits shown in the figure. It is concluded that the engagement probability values shown in Figure 116 represent a realistic assessment of expected performance for any system using this type of engagement.

Time Element Estimation

The retrieval preparation time t_r depends basically on the crew size available for preparation, but is also a function of the weight and configuration of the retrieval cargo. In lieu of specified data for these characteristics, it has been assumed for the purpose of evaluation that the preparation time is a linear function of retrieval cargo weight varying from 1 hour for 3000 lbs cargo weight to 3.0 hours for 10,000 lbs. It is believed that these values would approximate realistic averages for field conditions.

The impact area time t_c is also a function of the crew size available. In consideration of the cargo weights involved, it has been assumed that the crew size has been sized to make the cargo preparation time essentially a function of cargo weight.

The derigging time factors have been assessed as 3000 lbs - 10 minutes; 10,000 lbs - 30 minutes, with linear variations for intermediate weights. In addition to the derigging operations, the task of clearing the impact area of drop gear debris and salvageable drop gear components was also assessed. Table XXXIII gives the particulars for the delivery systems involved. The following factors have been used in the estimation:

Parachute Type	Task	Time, Min's	Crew Size
G-11	Straighten & Roll-up	10.0	2
G-12	Straighten & Roll-up	5.0	1
Both	Stow on Transporter	1 min/100 lbs	

A fixed clear-up crew size of two men has been assumed for this table.

Table XXXV gives the results of the time estimation for the retrieval-delivery operations. The total ground time is taken as the sum of the cargo rigging time and the pacing item of cargo derigging time or drop gear salvage and clear-up time, under the assumption that the last two tasks are carried out concurrently.

The delivery dispersal measure $\bar{r}_m$ is assumed as 80 feet, corresponding to a delivery drop altitude of 1500 feet as shown in the section presented in the delivery system evaluation data.

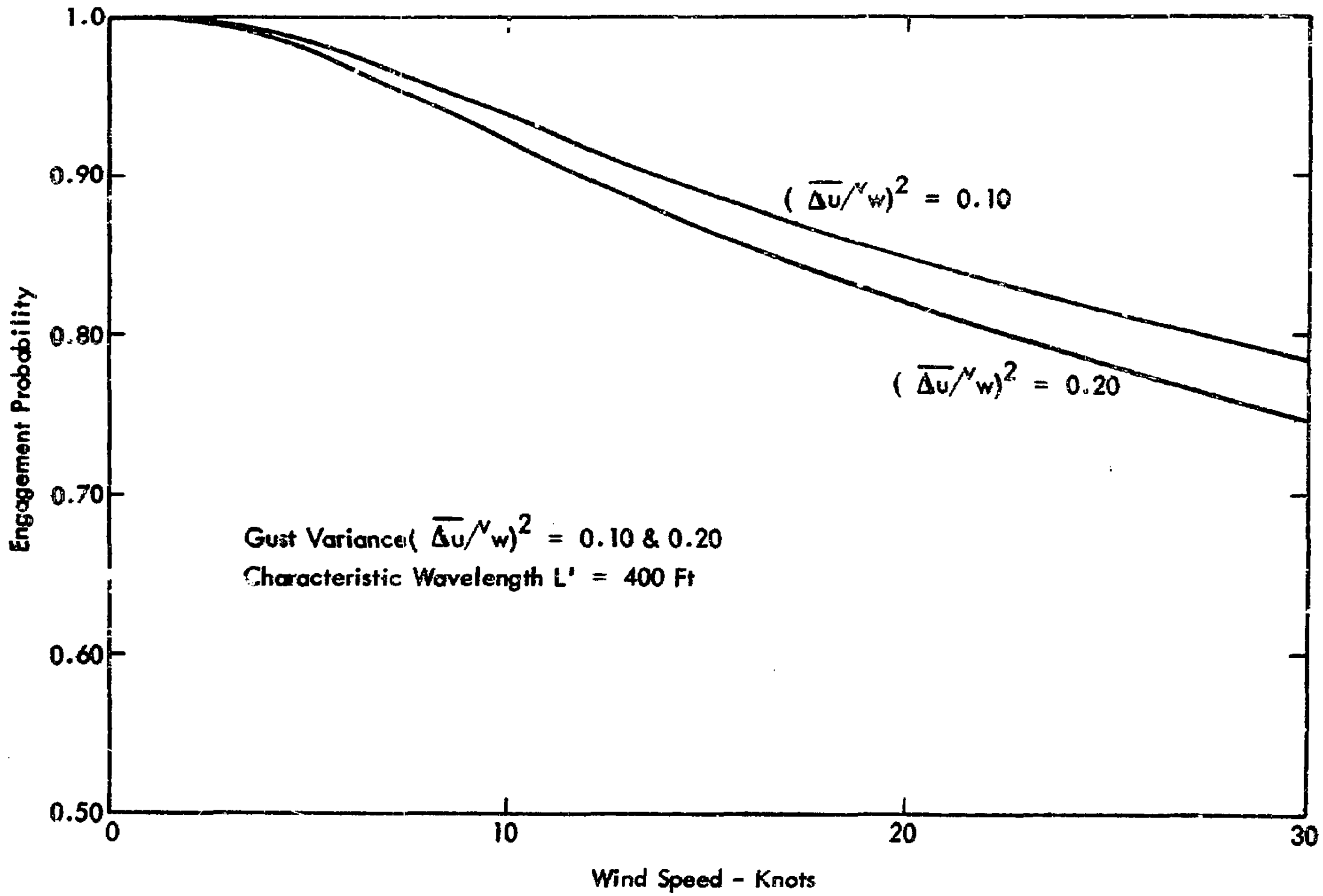


Figure 116 - Retrieval Engagement Probability for Balloon Line Retrieval System

TABLE XXXV

ESTIMATION OF TIME FACTORS IN RETRIEVAL-DELIVERY OPERATIONS

Nominal Cargo Weight Pounds	Parachute Type	No. of Parachutes	Cargo Rigging Time t_r Hours	Cargo Derigging Time, t_{c_1} Minutes	Drop Gear Salvage & Clear-Up Time t_{c_2} Minutes	Total Ground Op's Time = t_r + Pacing Element of t_{c_1} or t_{c_2} Hours
3,000	G-11	1	1.0	10	12*	1.20
4,000	G-12	2	1.286	13	13	1.5028
5,000	G-12	2	1.572	16	16	1.8390
6,000	G-12	3	1.857	19	19	2.1740
7,000	G-11	2	2.114	21	21	2.4640
8,000	G-12	4	2.143	24	24	2.5430
9,000	G-12	4	2.172	27	27	2.6215
10,000	G-11	3	3.000	30	36*	3.6000

*Pacing Elements

Values for the weight efficiencies $\frac{W_c}{W_c + W_s}$ are taken from Table XXXIV.

Pick-up engagement probability values P_e are taken from Figure 116 for wind speed of 0, 10, 20, and 30 knots.

Results

Values for the concept performance number computed for each nominal retrieval cargo weight are shown in Table XXXVI.

It should be noted that the concept performance numbers shown in Table XXXVI represent estimates of performance for average operating conditions. Two principal areas of sensitivity should be mentioned.

The data given are quite sensitive to variations in the ground operations time values shown in Table XXXV. Although the values quoted there represent estimates of average conditions, values characterizing particular operational situations may depart considerably from the averages, depending on terrain, soil, available manpower, etc.

The second principal area of sensitivity pertains to the assessment of engagement probability. Under similar operating conditions, a certain system scale effect may be present due to variations in the length of the engagement loop on the lift line. This effect is however bound to be minor.

A source of greater variation can be traced to differences in prevailing wind velocity. This is an environmental parameter which is subject to considerable fluctuations between different localities. The same comment applies to the gust variance.

TABLE XXXVI

VARIATION OF SYSTEM PERFORMANCE WITH PAYLOAD WEIGHT & WIND SPEED

Nominal Payload Weight Pounds	System Performance Number Lbs/sqft/hr			
	$v_W = 0$	$v_W = 10$ Kts	$v_W = 20$ Kts	$v_W = 30$ Kts
3,000	.109	.1022	.0927	.0856
4,000	.119	.1116	.1011	.0934
5,000	.1233	.1156	.1048	.0968
6,000	.1238	.1161	.1053	.0972
7,000	.1264	.1185	.1075	.0992
8,000	.1413	.1325	.1202	.1109
9,000	.1554	.1458	.1313	.1220
10,000	.1232	.1156	.1048	.0968

CTOL/VTOL EFFECTIVENESS EVALUATION

A cursory analysis was made of the cost effectiveness of the candidate retrieval system relative to transport by VTOL aircraft and helicopters. The presumed purpose of such a study is to provide sufficient information concerning the relative value of such systems so as to permit assessment of the merit of continued research and development of retrieval systems. The cursory nature of the analysis is based upon the impracticality of applying a spectrum of missions to a varied environment of operations in different types of war as considered in the light of postulated enemy strategy — all within the scope of the desired study. However, despite the simplified approach, the study used techniques which provide comparisons of the cost, productivity, vulnerability, and reliability of the system of retrieval by airplane as contrasted with transport of payloads by VTOL and helicopters.

It is emphasized that the comparisons of cost and effectiveness must, therefore, be considered relative in nature. The scope of the program as a whole, and this study in particular, did not permit a sophisticated and detailed collection of pertinent cost data. Neither could the performance of the various aircraft include detailed calculations of the various segments of the mission profiles. Nevertheless, inasmuch as the assumptions and techniques were equally applied to each aircraft system, the results are considered valid and indicative of the best aircraft system or technique.

The analysis used the following procedure and operations:

- o Selection of aircraft for comparison
- o Establishment of scenarios — with a basic mission task
- o Determination of relative effectiveness using a Retrieval Index
- o Determination of relative cost using a Cost Index
- o Analysis of relative cost effectiveness

Selection of Aircraft

The following aircraft systems were selected for analysis in order to provide a representative capability based upon existing or projected aircraft:

- o CTOL: C-130, C-141, and C-5A (as required)

Based on continuing Lockheed-Georgia Company studies, the following were utilized:

- o VTOL: (1) A tilt-wing design with a low cruise speed of M = .65 capable of payloads of 20,000 pounds at 500 nautical miles radius, and 35,000 pounds at 200 nautical miles radius.

  (2) A Direct-Lift design representative of swept wing designs capable of achieving a cruise speed of M = .85 and payloads identical with VTOL (1).

The following helicopters were selected from, and pertinent data based upon, those existing in the military inventory:

- Helicopters: (A) Conventional single rotor helicopter with payload carried internally and loaded through aft-loading fuselage doors.

  (B) Conventional twin rotor helicopter with loading similar to helicopter (A).

  (C) A single rotor helicopter with load carried externally. This helicopter features high payload capacity for short radii.

Parametric Aircraft Data

In order to perform the cost effectiveness analysis, pertinent performance, configurations, and cost data were collected and are presented in Table XXXVII. Data for Lockheed airplanes were taken from appropriate SAC charts, Reference 29, and the C-5A proposal. Comparable data for the VTOL aircraft were derived from past Lockheed studies concerning VTOL cargo transports. Data for the helicopters were derived from material presented in References 30 and 31.

Retrieval System

The retrieval system used with CTOL airplanes for this analysis consisted of a nylon line, a helium-filled balloon, a winch, and miscellaneous pickup equipment in the airplane. In operation, one end of the nylon line was fastened to the payload with the line itself held aloft by the balloon. Retrieval is effected by the airplane snagging the line at the balloon.

Basic Assumptions

Application of the selected aircraft to cost effectiveness analysis required establishment of certain pertinent basic assumptions which are:

1. Existing, or known projected, aircraft are used as a basis for analysis. This results in application of retrieval systems to airplanes which are not tailored specifically to retrieve or transport 10,000 pounds only. Otherwise stated, the airplanes required for analysis retrieve payloads considerably less than design maximum payload, and, as such, operate at varying degrees of efficiency. This assumptive selection also accounts for the fact that the VTOL aircraft and helicopters have payload capabilities in excess of the 10,000 pounds proposed for retrieval by airplane.

2. The specific equipment to be retrieved and transported is not identified and is appropriately prepared for retrieval or transport by ground personnel.

3. All aircraft are assumed to have the ability to retrieve and redeliver people. This is assumed in order to fit the systems into the proposed scenarios.

4. VTOL aircraft and helicopters are assumed to be on the ground for retrieval operations. Loading and unloading times are assumed to be 0.2 hour each.

5. The full load capability of the VTOL and helicopter types are used because of Assumption 4. The payload to be airlifted is varied as a function of the radius flown.

6. The full range and radius capability of the aircraft will be utilized to make as many unrefueled round trips as possible.

TABLE XXXVII

COST EFFECTIVENESS PARAMETERS

Parameter	Aircraft							
	C-130	C-141	C-5	A	B	C	Tilt Wing VTOL	Direct Lift VTOL
V-Cruise, Kts.	290	440	440	145	140	95	485	635
Range (loaded), N.Mi.	1900	3800	2700	615	215	220	1000	1000
Cruise Alt., Ft.	25,000	30,000	30,000	5000	5000	5000	20,000	30,000
Crew Size (Officers)	4	4	4	2	2	3	4	4
Crew Size (Airmen)	1	1	2	1	0	0	1	1
No. & Type Eng.	4-prop	4-jet	4-jet	2-rotor	2-rotor	2-rotor	4-prop 2-jet	20-jet
T.O. ESHP	4050@			1300@	2650@	4050@	14,300@	
T.O. Thrust, Lb.		21,000@	41,000@				7000@	(4-15,800@) (12-11,700@) (4-10,000@)
Prop. Wt., Lb.	7200	17,960	28,040	590	1150	1740	36,000	32,000
Emp. Wt., Lb.	73,000	135,800	318,300	11,933	17,878	17,240	94,000	86,000
Prop. Cost, Million $	.352	1.2	2.56	.09	.190	.28	1.65	3.75
Plane Cost, Million $	1.8	5.5	12.0	.83	1.66	2.0	5.57	7.87
Fuel Cap. Gals.	9680	23,080	49,000	1544	617	880	3000	6000
Avg. Fuel Cons., Lb/Hr	3450	9700	19,550	1160	2300	3460	10,900	22,000
Mean TBO, Hr.	4800	2500	2500	2500	2500	2500	2500	2500
Reliability, %	96	94	98	78	78	78	90	90
Availability, %	75	75	75	65	65	65	75	75
Vulnerability	1	2.08	3.45	11.88	22.00	29.7	25.1	30.0
V-Retrieval, Kts.	120	120	120	0	0	0	0	0

TABLE XXXVII (Cont'd)

COST EFFECTIVENESS PARAMETERS

Parameter	Aircraft							
	C-130	C-141	C-5	A	B	C	Tilt Wing VTOL	Tilt Lift VTOL
Retrieval Alt., Ft.	500	500	500	0	0	0	0	0
Retrieval Wt., Lb.	10,000	10,000	10,000	A 50M - 8200 100M - 7100 200M - 5000	B 12,500 10,600 6,600	C 50M - 15,000 100M - 15,000 150M - 15,000	35,000 20,000	35,000 -≤200M 20,000 --500M

7. All aircraft are based 50 nautical miles from the point of retrieval. Aircraft requiring refueling return to this base in order to preclude transport of fuel to the retrieval point.

8. The initial supply of helium for the retrieval system is available to the ground support troops. Additional helium is airdropped as required.

9. Refueling time for VTOL aircraft is assumed to be 0.2 hour, while that for helicopters is assumed to be 0.1 hour.

10. Retrieval and outbound flight speed for the C-130 is 150 knots, the maximum speed with the cargo doors open. For the C-141 and C-5A, the comparable speed is assumed at 200 knots. The speed for return is that block speed appropriate for the doors in a closed position for the radius flown and derived from Reference 29.

11. The outbound speed of helicopter (C) considers the drag of the external cargo, and the return speed is adjusted accordingly.

Other assumptions of a minor nature are set forth as necessary during the development of the method.

Scenarios

Prior to establishment of the scenarios, it became apparent that certain tactical situations were likely to exist which would mitigate against one type of aircraft or another. Specifically, some aircraft have high payload to gross weight capability for short range operations, but have very little payload capability for longer ranges. Some, such as the helicopter, are extremely limited in total range when compared with the basic range capability of, say, C-130 or C-141 airplanes regardless of payload capacity. Consequently, it became apparent that two scenarios were necessary to adequately measure the operational effectiveness of VTOL aircraft versus retrieval by CTOL systems. Hence, one sconairo has a mission task which is within helicopter range capability and the other a task beyond helicopter range capability.

Short Range – Scenario A

Tactical Situation – Pathet Lao forces have advanced down the eastern banks of the Mekong in Laos through the mountain passes and are attempting to drive to the South China Sea. The apparent route in Viet Nam is the main highway from Dak To to An Nhon on the coast via Kontrum. The objective is to split U.S. and Viet Nam forces into two groups: one concentrated in the north at Da Nang and another around Saigon. Once split, the northern group can be conquered by pressure from the Viet Cong in the north and from the Pathet Lao forces in the south.

U.S. Operation – In a counter move, U.S. Forces based in eastern Thailand in the region just southwest of Savannakhet, Laos, will jump on a counter thrust. The objective will be to drive across Laos into Viet Nam and link with U.S. Forces at Quang Tri. This move would effectively bottle up Pathet Lao forces and place them in the position in which they are hoping to place U.S. Forces. To achieve the element of surprise, and to circumvent the necessity for bridging the Mekong, troops and equipment will be airlifted across the river into the relatively flat area around Muong Pha Lane. Again, in the interests of speed and surprise, equipment will be retrieved and transported from a "where it is" location and will be subsequently airdropped near Muong Pha Lane. For operations in this scenario, the maximum transport distance is the maximum range of the helicopters which is assumed to be 200 N.M.

Long Range - Scenario B

Tactical Situation - The situation in Viet Nam has deteriorated to the point where a complete evacuation of U.S. Forces is mandatory. In this "Dunkirk" style situation, it is assumed that sealift cannot completely handle the task due to insufficient time to assemble the necessary ships and a general lack of dock facilities. It is further assumed that available airfields are crowded with fighter and attack-type airplanes.

U.S. Operation - In order to salvage as much equipment as possible, it has been decided to use retrieval techniques to airlift equipment to a point near Bangkok, Thailand, which is 400 nautical miles from the retrieval point within the Saigon perimeter. Total radius from base is, therefore, 500 nautical miles. Upon arrival at Bangkok, the equipment will be classified and stored for later transhipment by sealift using the port facilities at Bangkok and sailing down the Gulf of Siam.

This scenario is beyond the range of helicopters and analysis will be confined to CTOL and VTOL aircraft.

Retrieval Effectiveness

In order to measure the effectiveness of the various systems for relocating material in the type of missions suggested by the scenarios, the total payload retrieved or transported was determined. To accomplish this, it was considered that the total payload so moved should consider the number of aircraft involved, their survivability under combat situations, their productivity or rate of delivery, and their dependability as a function of reliability of the total system. The total quantity moved (R) can therefore be expressed by the following relationship:

$$R = \text{Number A/C} \times \text{Survivability} \times \text{Productivity} \times \text{Dependability}$$

where

Number A/C = number of aircraft procurable by 100 million production dollars

$$\text{Survivability Index} = \frac{1}{\text{vulnerability}}$$

Productivity = Tons of payload transportable by each aircraft in a day consisting of 10 hours operation

Dependability = Reliability and availability as a function of maintainability of aircraft plus retrieval system

Each of these terms is discussed in detail in the following paragraphs except the number of aircraft, which is discussed in the section entitled "Costs."

Productivity

The productivity is measured by the tons-per-day moved by each aircraft and associated retrieval system in a military operation lasting 10 hours per day. As such, it is this measure that accounts for the effects of speed. In Scenario A, range is a variable, but in

Scenario B, range is a constant. In both scenarios, appropriate time for ground loading and unloading, as well as refueling, is accounted for.

Basic procedure consisted of takeoff from the aircraft base and flight to the point of retrieval which is 50 nautical miles distant. At this point, the CTOL airplanes retrieved the 10,000 pounds "on the fly," while the VTOL aircraft and helicopters landed for loading aboard. The payload was airlifted to the point of delivery where the CTOL airplanes airdropped the payload, with VTOL and helicopters landing for discharge of cargo. The return flight was made to the point of retrieval where the process was repeated. The fuel capacity of the airplanes was such that continuous round trips could be made in the 10 hour period without refueling. However, it was necessary to refuel the VTOL and helicopters at the end of each trip, thus requiring a return to the original base.

The unit productivity of each type of aircraft was computed from the number of trips flown in the assumed 10 hour day. Fractional trips were included inasmuch as these data are applied to a fleet concept. The unit productivity is shown in Figure 117.

These data indicate that the VTOL aircraft are the best, followed by CTOL and the helicopters in that order. Included in these calculations are the results of calculations to show the deterioration of productivity of the C-130 if it should be required to return to base to reload JATO, as would be necessary if the retrieval system selected required such additional thrust.

One of the penalties incurred by the helicopters is the time required to load and unload the cargo. Accordingly, the unit productivity was computed for loading times larger and smaller than that originally assumed. The resulting effect is presented in Figure 118.

The total fleet productivity is presented by Figure 119. These data are simply the product of unit productivity times the number of aircraft procured by $100,000,000. No account is made on this graph of availability, dependability, or survivability.

Vulnerability

The vulnerability analysis described herein is necessarily based on greatly simplified models. Although it is believed that the comparisons indicate relative differences between aerial-retrieval and ground-loading operations, it is emphasized that no significance should be attached per se to the magnitudes.

All of the selected aircraft are investigated except VTOL (2), the direct lift configuration, which is omitted as being obviously the most vulnerable due to its multiplicity of engines. Each of the airplanes is assumed to perform the retrieval at an altitude of 500 feet.

The helicopters are assumed to begin gradual descent from 500 feet altitude as they approach within 3000 feet of the loading base. A similar pattern is followed at takeoff. The average velocity during ascent and descent is assumed to be 50 knots. The flight profile of the VTOL aircraft is assumed to be the same as for the helicopters. However, the average velocity during ascent and descent is assumed to be 100 knots.

The factors which are assumed to have an influence on loading vulnerability are:

- o Average velocity during the encounter
- o Average slant range
- o Exposure time on the ground
- o Inherent vulnerability (vulnerable area)

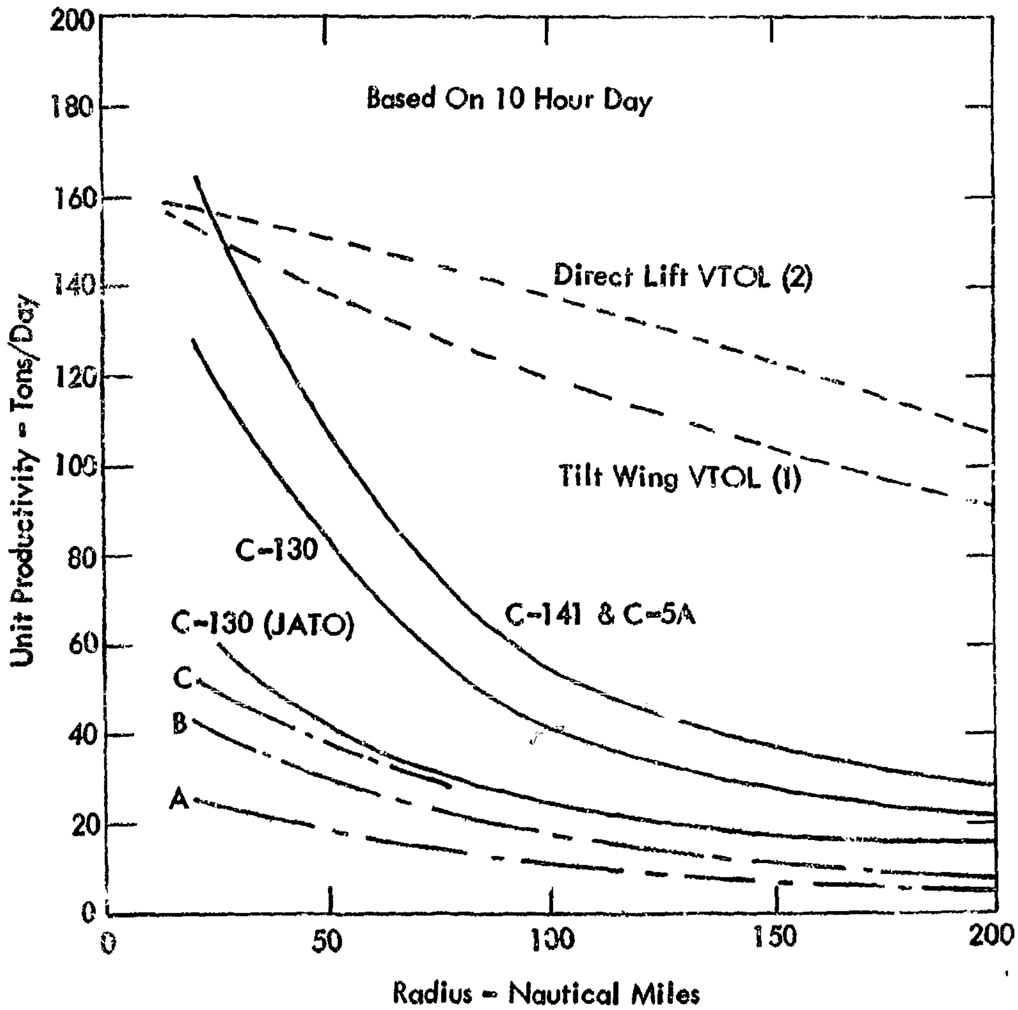


Figure 117 - Unit Productivity Per Aircraft

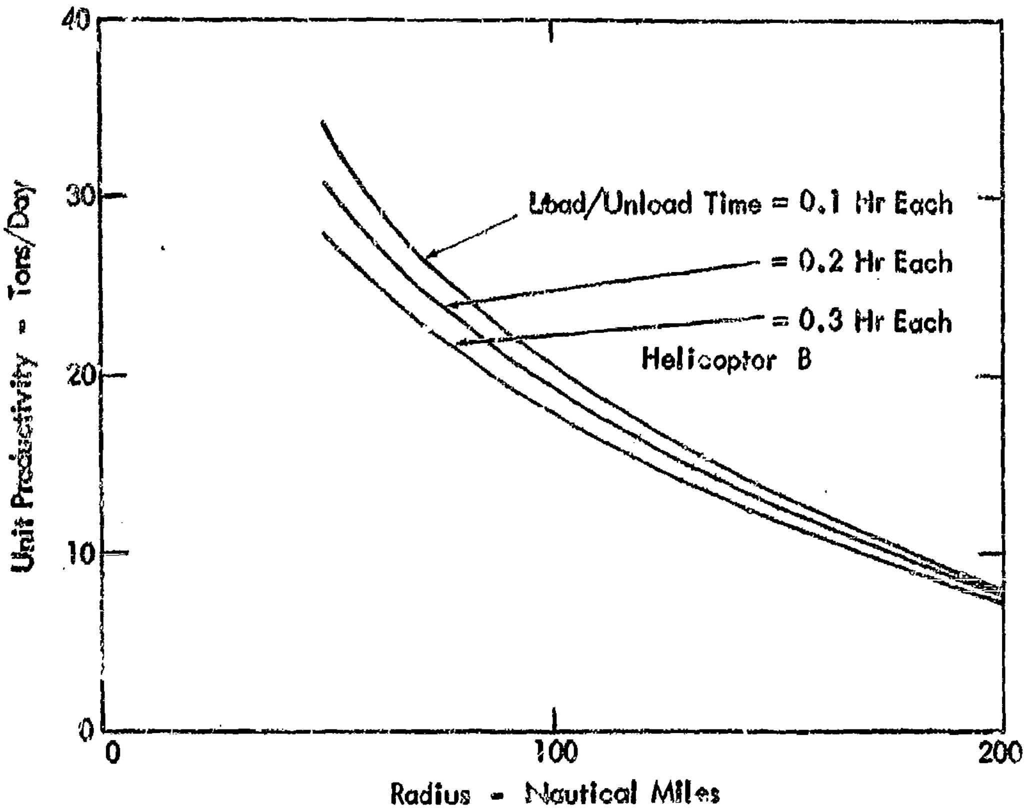


Figure 118 - Effect of Loading/Unloading Time on Unit Productivity

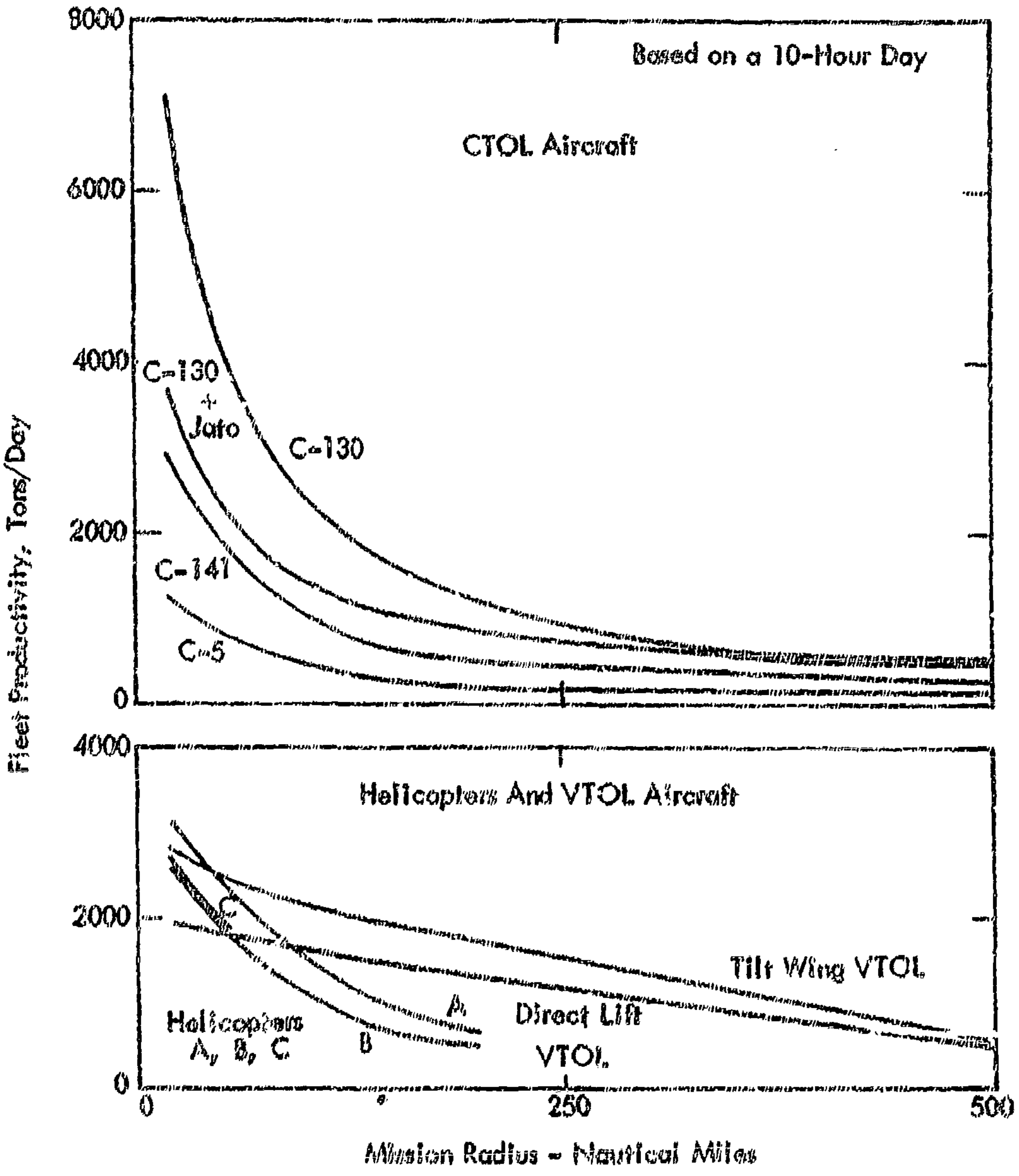


Figure 119 - Daily Fleet Productivity

The combined effects of these factors is used to determine relative vulnerability ratings between the various aircraft.

For overflying airplanes, the assumed threat consists of a .50 cal. machine gun site located directly under the flight path with maximum effective slant range of approximately 2000 feet. The average slant range in the firing zone is assumed to be 1000 feet. The vulnerability of the balloon used in the retrieval systems is assumed negligible in terms of damage due to small arms fire. This is based upon the low inflation pressures used and on the wartime experience of non-rigid airships which have been holed by weapons of considerably larger caliber without undue loss.

For helicopters and VTOL aircraft, the threat consists of a .50 cal. machine gun site located directly under the approach or take-off path at a distance of 1500 feet from the landing base. The enemy also has mortars and recoilless rifles of several thousand yard range which are used to attack the aircraft on the ground during the assumed .2 hour loading time. The average slant range in the firing zone is assumed to be somewhat less than for the overflying aircraft, or about 700 feet.

Velocity - An approximation to the expected kill probability during an encounter is given by

$$P_K = \frac{nA_v}{2\pi\sigma^2} \tag{98}$$

A_v = vulnerable area of the aircraft (ft^2)

n = number of projectiles fired during the encounter

σ = standard deviation of the miss distance (ft)

For small arms fire, σ^2 is proportional to v^2 and n is inversely proportional to v. Hence,

$$P_K = \frac{k}{v^3} \tag{99}$$

The results of the computation of the vulnerability indices for velocity is shown in Table XXXVIII.

Slant Range - For a given weapon angular dispersion, σ, the average standard deviations of the weapon miss distances for the overflying aircraft are related to those for the landing aircraft by the equation

$$R_0/R_L = \sigma_0/\sigma_L \tag{100}$$

where

R_0 = average slant range from weapon to overflying aircraft (ft)

R_L = average slant range from weapon to landing aircraft (ft)

σ_0 = standard deviation of weapon miss distance for overflying aircraft (ft)

σ_L = standard deviation of weapon miss distance for landing aircraft (ft)

hence

$$\sigma_L = \sigma_0 (R_L/R_0)$$

It is assumed that R_L = 700 feet and R_0 = 1000 feet. Hence

$$\sigma_L = 0.7\ \sigma_0$$

$$\text{but } P_K = \frac{nA_V}{2\pi\sigma_L^2} \text{ for the landing aircraft.} \qquad (101)$$

Therefore

$$P_K = \frac{nA_V}{\pi\sigma_0^2} \text{ for the landing aircraft.} \qquad (102)$$

TABLE XXXVIII

VELOCITY VULNERABILITY INDICES

Aircraft	Assumed Ave. Velocity during Encounter (Kts)	V^3	$\frac{1}{V^3}$	Relative Vulner. Indices for Velocity
C-130	150	3.38×10^6	0.296×10^{-6}	1*
C-141	150	3.38×10^6	0.296×10^{-6}	1
C-5	150	3.38×10^6	0.296×10^{-6}	1
Helicopter (A)	50	0.125×10^6	8×10^{-6}	27
Helicopter (B)	50	0.125×10^6	8×10^{-6}	27
Helicopter (C)	50	0.125×10^6	8×10^{-6}	27
VTOL (1)	100	1×10^6	1×10^{-6}	3.38

*The C-130 is used as the baseline for vulnerability throughout this analysis.

Thus, the relative vulnerability index of the landing aircraft must be doubled to account for the decreased average slant range during flight through the firing zone as shown in Table XXXIX.

TABLE XXXIX

SLANT RANGE VULNERABILITY INDICES

Aircraft	Relative Vulnerability Indices for Average Slant Range
C-130	1
C-141	1
C-5	1
Helicopter (A)	2
Helicopter (B)	2
Helicopter (C)	2
VTOL (1)	2

Ground Exposure Time - The helicopters and the VTOL aircraft are considered extremely vulnerable to mortar fire during the 0.2 hour period of loading operations. It is difficult, however, to measure this vulnerability quantitatively, since it depends strongly on the enemy's skill and reconnaissance capabilities as well as on weapon effectiveness factors. In order to be conservative, it is assumed that friendly troops surrounding the base limit the increased vulnerability during loading to 10 percent. The results are shown in Table XL.

TABLE XL

GROUND EXPOSURE VULNERABILITY INDICES

Aircraft	Relative Vulnerability Indices for Ground Exposure
C-130	1
C-141	1
C-5	1
Helicopter (A)	1.1
Helicopter (B)	1.1
Helicopter (C)	1.1
VTOL (1)	1.1

Vulnerable Areas - The major vulnerable components of any aircraft are the crew, the fuel system, the flight control system, and the propulsion system. Several simplifying assumptions are made for this analysis in order to reduce the calculation of vulnerable areas to a manageable level. The assumptions are:

- Crew armor kits are provided for all aircraft in order to essentially ensure the survivability of a minimum crew.

- Self-sealing blankets and explosion suppression devices are installed in the fuel tanks of each aircraft. This effectively reduces the vulnerability of the fuel systems to a negligible level.

- The vulnerability of flight control subsystems can be neglected for small arms fire because of designed redundancy for safety and reliability.

- The average presented vulnerable area of an engine depends on the horsepower of that engine. If the horsepower varies by a factor of F, the average presented vulnerable area varies by a factor of $F^{0.4}$. Each engine of each aircraft is assumed to be entirely independent of any other engine on that aircraft. Thus, damage to a vulnerable engine component cannot result in the loss of more than one engine.

- The average presented area of each of the engines of Helicopter A is 30 ft^2.

- A total of 10 shots is fired at each aircraft during an encounter.

- The standard deviation of the miss distance of the small arms fire is 69.1 feet for any aircraft.

The last three assumptions are necessary in order to calculate quantitative kill probabilities that can be adjusted for effects of engine multiplicity. The actual values selected have little, if any, bearing on the final comparative ratings.

The encounter kill probabilities for each aircraft engine are found using the equation

$$P_K = \frac{nA_v}{2\pi\sigma^2} \tag{103}$$

The calculations are shown in Table XLI.

The kill probability of the entire propulsion system of an aircraft, P_T, is given by the first $(r - s + 1)$ terms of the binomial expansion.

$$P_T = \left[P_K + (1 - P_K)\right]^r \tag{104}$$

where

r = number of engines

s = number of engines out for aircraft loss

In the case of aircraft having 4 engines, the kill probability of the entire propulsion system of each type is given by the kill probability for the left engines plus that for the right engines, both as determined by the above expansion. In the case of the VTOL aircraft, the kill probability of the entire propulsion system is given by the kill probability for the left main engines plus that for the right main engines plus that for the control engines.

The calculations are presented in Table XLII.

Total Vulnerability - The relative vulnerability factors are multiplied together to obtain the final vulnerability index for each aircraft. The results are summarized in Table XLIII.

It is seen that the C-130 is by far the least vulnerable of any of the aircraft considered. The C-141 and the C-5 are about 2 and 3.5 times, respectively, more vulnerable than the C-130 because of their larger engines. Note that the engine multiplicity calculations magnify the differences that exist in the average presented vulnerable areas of the engines. Helicopter (A) is about 12 times more vulnerable than the C-130, and Helicopter (B) 22 times more vulnerable. Helicopter (C) is somewhat more vulnerable than the other helicopters - about 30 times more vulnerable than the C-130. The VTOL aircraft has high vulnerability—almost 25 times as great as the C-130. In addition, it is obvious that the relative vulnerability of VTOL (2), the Direct Lift VTOL, would be considerably higher because of its 20-engined configuration.

TABLE XLI

ENCOUNTER KILL PROBABILITIES

Aircraft	Engines	Horsepower of each Engine	Average Presented Vulnerable Area of each Engine (ft^2)	Adjustment Factor Relative to Hel. (A)	A_V = Relative Average Presented Vulnerable Area (ft^2) of each Engine	Approximate Encounter Kill Probability of each Engine
C-130	4	4,050	-	1.575	47.3	0.0157
C-141	4	9,650	-	2.23	67.8	0.0226
C-5	4	18,800	-	2.91	87.3	0.0291
Helicopter (A)	2	1,300	30	1.00	30.0	0.0100
Helicopter (B)	2	2,650	-	1.33	40.0	0.0133
Helicopter (C)	2	4,050	-	1.575	47.3	0.0157
VTOL(I)	4 (main)	14,300	-	2.60	78.0	0.0260
	2 (control)	2,150	-	1.22	36.6	0.0122

TABLE XLII

PROPULSION SYSTEM VULNERABILITY

Aircraft	Number of Engines, r	Number of Engines Out for Aircraft Loss, s	r - s + 1	P_K	P_T	Relative Vulnerability Rating for Propulsion System
C-130	2(left)	2	1	0.0157	0.00049	1.00
	2(right)	2	1	0.0157		
C-141	2(left)	2	1	0.0226	0.00102	2.08
	2(right)	2	1	0.0226		
C-5	2(left)	2	1	0.0291	0.00169	3.45
	2(right)	2	1	0.0291		
Helicopter (A)	2	2	1	0.0100	0.00010	0.20
Helicipter (B)	2	2	1	0.0133	0.00018	0.37
Helicopter (C)	2	2	1	0.0157	0.000246	0.50
VTOL (1)	2(left) 2(main)	2	1	0.026		
	2(right) 2(main)	2	1	0.026	0.00165	3.37
	2(control)	2	1	0.0122		

TABLE XLIII

TOTAL NORMALIZED VULNERABILITY INDICES

Aircraft	Velocity Index	Slant Range Index	Ground Exposure Index	Vulnerable Area Index (Propulsion)	Product Index	Vulnerability Index Normalized Relative to C-130
C-130	1.0	1.0	1.0	1.0	1.0	1.0
C-141	1.0	1.0	1.0	2.08	2.08	2.08
C-5	1.0	1.0	1.0	3.45	3.45	3.45
Helicopter (A)	27.0	2.0	1.1	0.20	11.88	11.88
Helicopter (B)	27.0	2.0	1.1	0.37	22.00	22.00
Helicopter (C)	27.0	2.0	1.1	0.50	29.7	29.7
VTOL	3.38	2.0	1.1	3.37	25.1	25.1

Dependability

Analysis involving fleets of aircraft and associated systems must include some measure of the availability of the aircraft and the reliability of both the aircraft and associated systems. These have been combined into one term-dependability. As used herein, reliability refers to the percentage of times used during a ten hour day's operation that a piece of equipment, whether aircraft or retrieval system, successfully completed its mission. Aircraft availability is the percentage of aircraft that were ready for use at any time, and as such reflects maintainability.

The reliability and availability factors are based upon actual values determined by service operation. When such data were not available, estimates were made based upon design specifications and requirements extant for such types of aircraft.

Lockheed experience with the Fulton retrieval system has shown a reliability of 97% which includes missed passes and balloon breakage. The Fulton system is man-rated whereas the system selected for analysis is for cargo only. Accordingly, the reliability of the recommended system has been estimated to be 0.875. It is emphasized that the total system dependability for CTOL aircraft incorporating retrieval systems is obtained from the product of airplane dependability times retrieval system reliability.

Cost

Analysis of the cost aspects of the systems comparison required a consideration of those costs which occurred as a result of the mission. The following costs were considered:

- o Procurement
- o Operation
- o Maintenance

It was necessary to determine the numbers of each type of aircraft involved, and hence the need for analysis of procurement costs. The operating costs are those which directly result from performance of the mission. The maintenance costs are those which accrue as a result of operation of the aircraft. The results of the cost analysis are tabulated in Table XLIV and a detailed discussion of these costs follows.

Procurement

Inasmuch as the evaluation of the retrieval concepts is a relative one, an arbitrary sum of $100,000,000 was allocated for procurement of each type of airplane. The total price, less amortized RDT&E retrieval system costs, was divided by the unit production cost of each particular aircraft. The unit prices for Lockheed airplanes are based upon the predicted price for construction of one airplane estimated to be in effect after completion of present contractual commitments. The unit production prices for the helicopters are based upon data tabulated in Reference 31. Prices for VTOL aircraft were derived from recent VTOL design studies by Lockheed.

The concept of retrieval by CTOL aircraft "on the fly" requires development and procurement of equipment in addition to the aircraft. In order to impartially amortize RDT&E costs of this additional equipment, the costs were divided among the three types of CTOL aircraft in proportion to the numbers of a particular CTOL aircraft to the total number of CTOL aircraft procured. The number of aircraft procured for $100 million, including the additional equipment RDT&E costs amortized for the CTOL aircraft, is listed in Table

TABLE XLIV

COST RESULTS

		C-130	C-141	C-5	Tilt Wing VTOL	Direct Lift VTOL	A	B	C
Airframe Labor Cost/Hr./A/C		42.55	60.30	129.85	39.85	38.30	21.75	23.55	23.55
Airframe Material Cost/Hr./A/C		17.78	58.58	98.08	42.58	44.58	10.61	17.95	20.48
Engine Labor Cost/Hr./A/C		6.08	14.20	20.52	18.80	69.64	4.02	4.38	4.76
Engine Material Cost/Hr./A/C		20.92	94.08	202.20	21.61	29.06	3.12	7.13	10.73
Total Maintenance Cost/Hr./A/C		87.33	227.16	450.65	122.84	181.58	39.50	53.01	59.32
Fuel Cost/Hr./A/C		51.80	145.50	293.25	98.20	163.11	9.69	29.05	48.95
Crew Cost/Hr./A/C		20.30	20.30	22.00	20.30	20.30	11.00	9.25	13.90
Operational Cost/Hr./A/C		159.53	392.96	765.90	241.34	384.99	60.19	91.31	122.17
No. Planes for $\$100 \times 10^6$		54	18	8	18	12	120	60	50
Fleet A/C Oper. Cost/Hr.		8609.22	7073.28	6127.20	4344.12	4619.88	7222.80	5478.60	6108.50
Fleet Helium Cost/Hr.		4317.11	1913.90	854.81					
Fleet JATO Cost/Hr.		64,501							
System Fleet Operating Cost/Day	(with JATO)	774,273.30							
	(without JATO)	129,263.30	89,871.80	69,820.10	43,441.20	46,198.80	72,228.00	54,781.00	61,085.00

XLIV. The retrieval system reusable equipment cost was considered to be negligible in comparison with the aircraft costs and was not included.

Operating Costs

Operating costs consist of crew costs and fuel costs. These costs are the operating costs required to meet the situations as described in the scenarios. To accomplish the prescribed missions, the aircraft utilization is assumed to be ten hours per day with maintenance deferred until completion of the mission.

Crew Costs - The crew costs are dependent on the crew complement for the different aircraft under consideration. The annual crew cost is obtained by adding the annual salary of all officers and the annual salary of all crewmen on an airplane and multiplying this by the number of crews assigned to an airplane. For an annual average officer's salary of \$11,100 and an average annual crewman's salary of \$4200, the annual cost per airplane is \$11,100 n_o + 4200 n_a, where n_o is the number of officers and n_a is the number of crewmen in one crew. The number of flying hours per day for the crew is taken as the same as the number of flying hours for the aircraft, e.g. 10 hours per day. For an average of 1.5 crews per airplane, the hourly crew cost in dollars is as follows:

$$C_{CH} = 1.5\ (11,100\ n_o + 4200\ n_a)/(10)(30)(12) = (55.5\ n_o + 21\ n_a)/12 \qquad (105)$$

Fuel Costs - Fuel cost estimates are dependent on the type of mission flown. It is assumed that the use of the airplane is equally divided between the two types of missions outlined in the scenario. Thus, one-half of the usage is in short range missions of 50-mile radius and one-half in missions of 500-mile radius. These are taken as the typical use of the airplane, with the exception of helicopters, which are used for short range missions only. For these missions, the fuel consumption per mission and the operating time of the engines per mission is determined so that the fuel consumption per engine as a function of operating time is known. The fraction of the operating time of the engines for the total mission time is determined from a time analysis of the aircraft and the missions. The cost of fuel is taken as \$0.015 per pound. Therefore, fuel cost in dollars per hour for CTOL and VTOL aircraft is as follows:

$$C_{FH} = 0.015\ F_1\ (T_{ml})/(2\ t_{ml}) + F_s\ (T_{ms})/(2\ t_{ms}) \qquad (106)$$

where

F_s = Pounds of fuel used in short-range mission

t_{ms} = Time for short-range mission

T_{ms} = Engine operating time per mission time for short-range mission

F_1 = Pounds of fuel used in long-range mission

t_{ml} = Time for long-range mission

T_{ml} = Engine operating time per mission time for long-range mission

The fuel cost in dollars per hour for helicopters is

$$C_{FH} = 0.015\ F_s\ (T_{ms})/t_{ms} \qquad (107)$$

Retrieval System Costs - Operation of the retrieval system itself generated some costs which are included in the total operating cost for CTOL systems. The first cost is the expense of the helium from the broken balloon. The second is the expense of JATO bottles which could possibly be used in conjunction with the system when the C-130 is the CTOL airplane utilized. The total system operating cost as a function of mission radius is graphically presented in Figure 120.

Helium Cost - To determine the helium cost per balloon, the balloon size had to be calculated.

In a 10,000-pound payload the pickup line was assumed to be capable of a 3 g loading. Using a safety factor of two, a line capability of 60,000 pounds is required. The appropriate nylon line weighed 0.5 pounds/foot. Thus for a 400-foot line, the balloon is required to support 200 pounds of line weight. To reduce gust effects, the lift of the balloon was increased by 25 percent to 250 pounds.

The balloon volume in terms of its lifting force is given in Reference 27 by the equation:

$$F = 0.066\,V - 0.219\,V^{2/3} \tag{108}$$

where V = balloon volume, ft^3
F = lifting force, lbs

For a volume of 4750 ft^3, a helium density of 0.0114 lb/ft^3 and a cost of \$2.50/lb, the cost of helium per balloon is calculated to be \$132.50.

JATO Cost - The C-130 was designed so that it could use 8 JATO Boosters of 1000 pounds thrust (15 sec.) each. The cost of a JATO Booster and its igniter is given as \$395 by the Lockheed Purchasing Department.

Maintenance Costs - Maintenance costs are divided into airframe maintenance and engine maintenance. Each of these is further divided into labor and material. For purposes of cost comparison, the maintenance costs are based on Reference 32 by the Air Transport Association (ATA).

To obtain the airframe labor cost per flight hour, theairframe labor hours per flight hour as given by an ATA formula are multiplied by the labor rate which is taken as \$3.00 per hour. A burden factor of 87 percent is also included in the ATA estimates. The airframe labor cost is given by :

$$C_{LA} = (1.03)(1.87)(3.00)(3.0 + 0.067\,W_a/1000) \tag{109}$$

where

W_a = empty weight of airplane less engines
(1.03) labor non-revenue factor.

To obtain the total airframe material cost per flight hour, a material burden factor of 23.3 percent is included in the estimate of airframe material cost per flight hour given by the ATA formula:

$$C_{MA} = (1.03)(1.233)\,2.5 + 7.9\,C_{spa}/10^6) \tag{110}$$

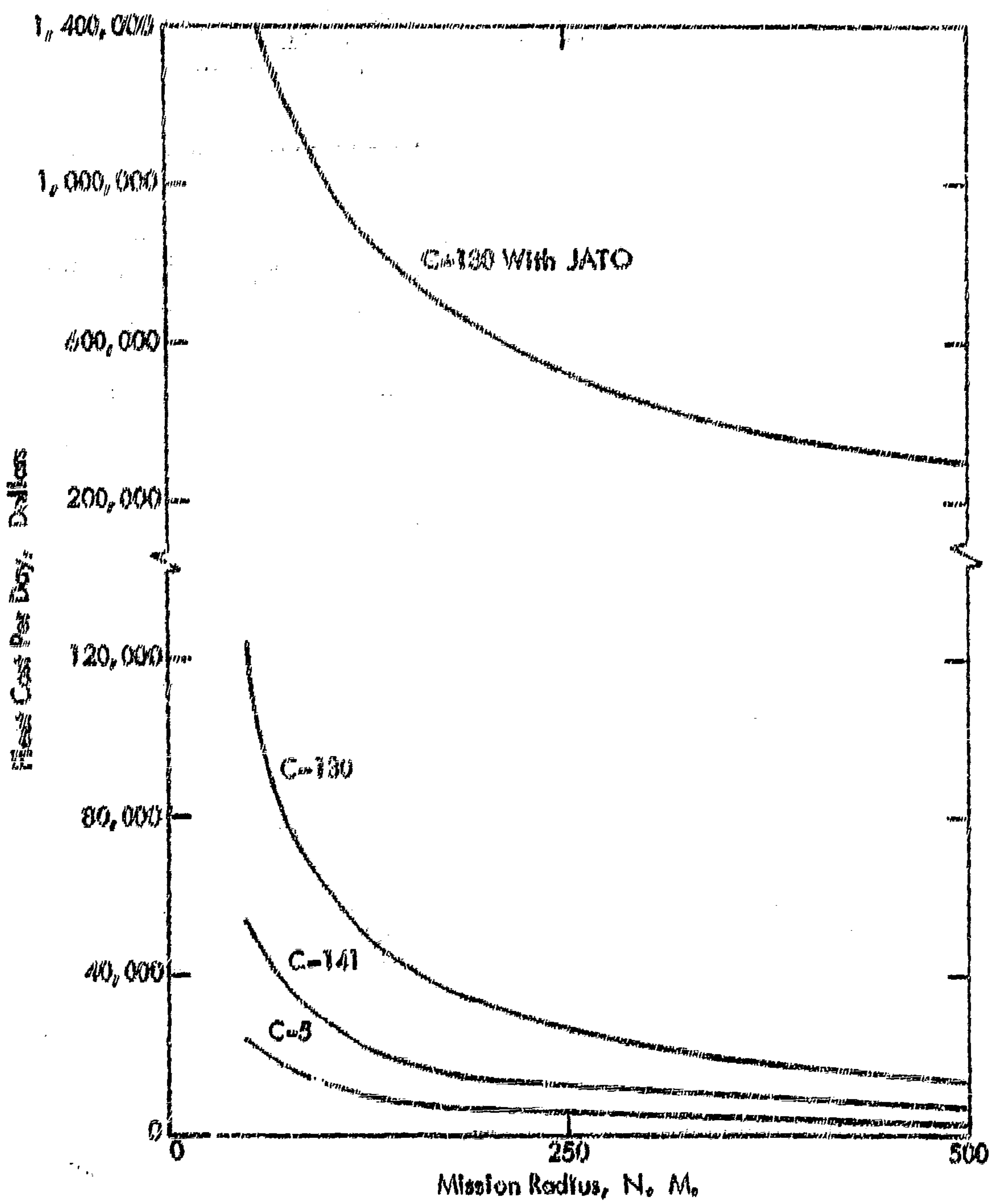


Figure 120 - Retrieval System Operating Cost-Helium and JATO Expense

where

C_{spa} = Cost of airplane less engines

(1.03) = Material non-revenue factor.

Engine labor costs depend on the type of engine. To obtain the engine labor cost per engine per operating hour, the engine labor hours per engine per operating hour are multiplied by the labor rate, burden factor, and labor non-revenue factor.

For a turbojet or turbofan, the labor cost per engine per operating hour equation as given by the ATA is as follows:

$$C_{LE} = (1.03)(1.87)(3.00) \left[(0.718 + 0.0317\ T/1000)(1100/H_{eo}) + 0.10\right] \quad (111)$$

where

T = Engine thrust at sea level, standard day, uninstalled
H = Mean time between overhauls.

For turboprop engines, the engine labor cost per engine per operating hour is given by the ATA formula:

$$C_{LE} = (1.03)(1.87)(3.00) \left[(0.4956 + 0.0532\ ESHP/1000)(1100/H_{eo}) + 0.10\right] \quad (112)$$

where

ESHP = Takeoff equivalent shaft horsepower.

In the ATA formula for the total engine material cost per engine per operating hour, the material burden factor of 23.3 percent and the material non-revenue factor of 1.03 are included.

Therefore, the engine material cost is given by:

$$C_{ME} = (1.03)(1.233)(81.45\ C_E/10^6 - 0.47)/(0.021\ H_{eo}/100 + 0.769) \quad (113)$$

where

C_E = Cost of engine.

When using CTOL aircraft or helicopters, the engine maintenance costs are obtained simply by multiplying C_{LE} and C_{ME} times the number of each type of engine. When using VTOL aircraft, the time of use of each type of engine is also taken into account. The total hourly maintenance cost for a fleet of N aircraft is:

$$C_M = N \left[C_{LA} + C_{MA} + \sum_i n_i\, p_i\, (C_{ME} + C_{LE})\right] \quad (114)$$

where

n_i = Number of engines of the i^{th} type per aircraft

P_i = Percentage of time that i^{th} type engine is used.

By combining the crew cost, fuel cost, and total maintenance cost, the hourly operational cost for a fleet of N aircraft is obtained.

Cost Effectiveness

The results of the Retrieval Effectiveness and Cost Analyses have been combined to provide a measure of cost effectiveness. The ratio of Retrieval Effectiveness to Cost as a function of Mission Radius is presented in Figure 121. This is, in effect, a plot of tonnage retrieved or delivered per unit cost as a function of distance transported.

These data indicate that the C-130 airplane using a retrieval system is op :mum when operated in the manner suggested by the postulated scenarios. The C-130 system is capable of retrieving 9 times the tonnage per unit cost of the best helicopter, and twenty-eight times the tonnage of the second best helicopter.

The C-130 system had the added advantage of being able to perform longer range retrieval missions than the helicopters.

The C-141 and C-5 systems did not perform well in comparison to the C-130 system and the helicopter. This was expected because of the severe penalty imposed by limiting the retrieval load to 10,000 pounds which is considerably below their capabilities. The low productivity of the VTOL aircraft was due to the high initial and operating expenses of the aircraft and the high vulnerability.

While the results of this analysis are indicative of the desirability of additional research and development of a retrieval system, it should be noted that several prime factors have been neglected due to the scope of the analysis. This analysis has assumed the availability on the site of the necessary retrieval systems and its components, and no account has been made of the cost of transport of such a system to the theater of conflict. Problems associated with storage have also been neglected.

The analysis presumed air superiority in the areas of retrieval and delivery as well as in the corridor of flight. The relative vulnerability, if such were not the case, would have a significant effect on the results Indeed, it seems logical that the tactical situation of Scenario B would be a result of a lack of air superiority.

No account has been made of the types and sizes of payload to be retrieved. Nor has any consideration been made of priorities which might be assigned if the analysis had included transport of specific items of equipment associated with a specific Army unit.

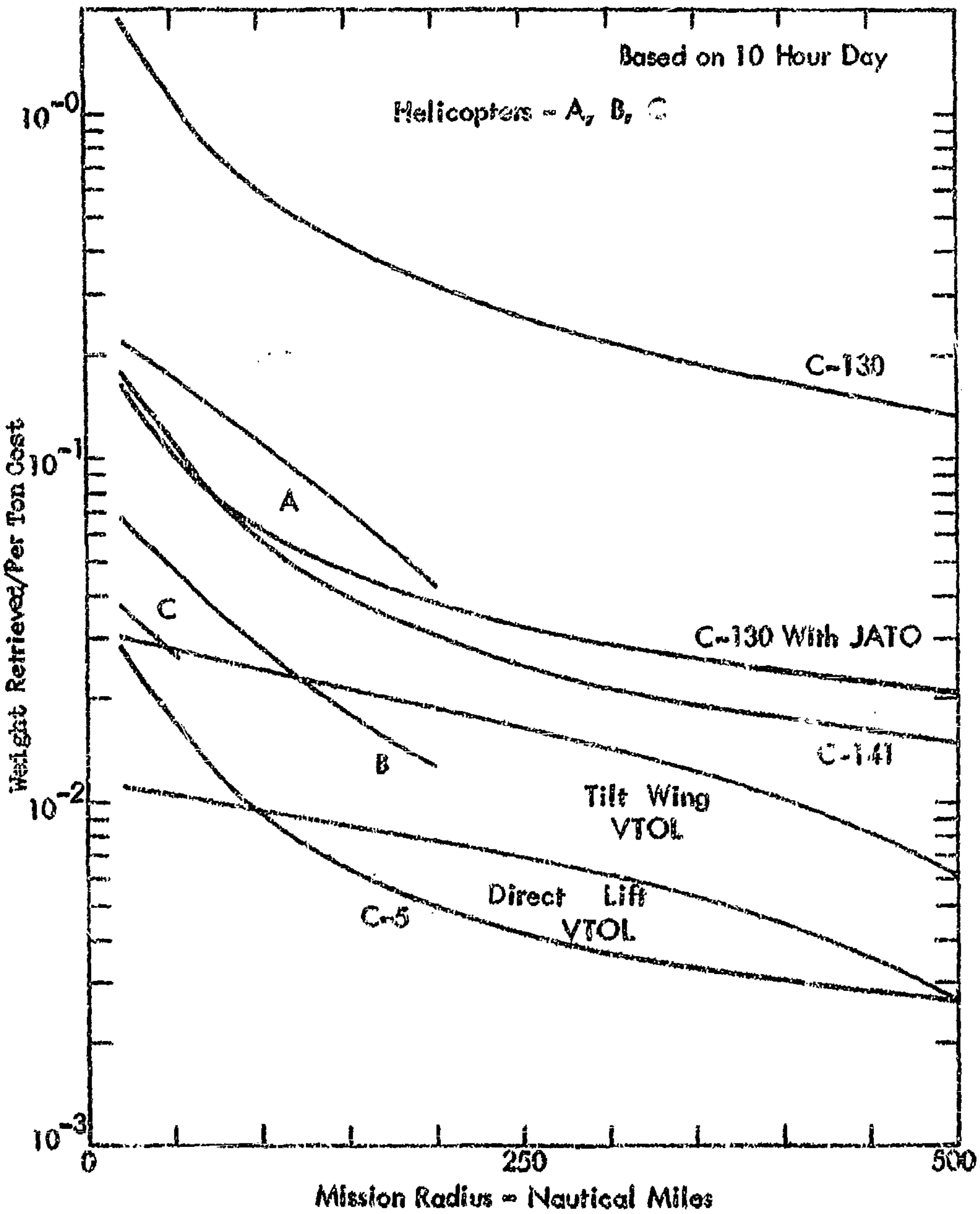


Figure 121 – Retrieval Cost Effectiveness

IV. CONCLUSIONS

AERIAL DELIVERY

Unless otherwise noted, the following study conclusions pertain to unit loads of equipment weighing from 35,000 to 70,000 pounds, and to both the C-141 and C-5A aircraft.

Conclusions

1. Based upon preliminary stability and control studies, including consideration of aircraft flight and ramp loads, the aerial delivery of these heavier payloads from either aircraft is feasible.

2. The most promising aerial delivery systems for these heavier loads employ conventional extraction parachute techniques to extract the cargo from the aircraft in-flight.

3. The most promising aerial delivery systems were determined in this study to be those which used either the extraction parachutes or reefed main parachutes to achieve a high payload descent velocity.

4. Recovery of the payload from descent velocity to ground impact velocity is best accomplished with a modular rocket motor package from an altitude of approximately 200 feet, or by dis-reefing main parachutes at an altitude of approximately 450 feet.

5. The plastic deformation of paper honeycomb is found to be optimum for impact energy absorption with the heavier loads of this study. This conclusion is based upon recommended delivery altitudes for the study aircraft as well as properties of the impact velocity dissipation system, including its weight, sensitivity to system performance variations, load impact attitude, cost, and height of stroke.

6. Minimum load extraction altitude for an aerial delivery system employing extraction parachutes for descent and rocket motors for deceleration in the recovery phase is approximately 700 feet.

7. Cargo landing point scatter is reduced with an extraction parachute descent/rocket recovery technique in comparison with a conventional airdrop technique, for all load extraction altitudes from 1,500 to 30,000 feet.

8. Minimum load extraction altitude for an aerial delivery system employing main cargo parachutes for load deceleration in the recovery phase is approximately 1200 feet.

9. Cargo landing point scatter is reduced with a reefed main parachute descent/low altitude dis-reef technique in comparison with a conventional air drop technique, for all load extraction altitudes from 1,500 to 30,000 feet.

10. An extraction parachute descent/rocket recovery technique has a reduced landing point scatter in comparison with a reefed main parachute descent/low altitude dis-reef technique for all load extraction altitudes above 1200 feet.

11. In high wind conditions, load tumbling following cargo impact is less frequent with the extraction parachute descent/rocket recovery system than with the system employing main cargo parachutes to recover the load.

12. The feasibility of performing aerial delivery of these heavier loads by ground proximity parachute extraction depends upon the behavior of large 48-foot single and paired extraction parachutes during deployment, inflation, and tow, while in ground effect. Detailed theoretical and wind tunnel model testing is required to establish the validity of this technique for heavier loads.

13. Based upon the requirement for clusters of from four to eight main cargo parachutes to effect the recovery of these heavier loads, and in consideration of extraction parachute entanglement and uneven loading with extraction parachute clusters larger than two, the technique of cargo extraction by reefed main recovery parachutes does not show feasibility in this study.

14. The capability for aerial delivery of heavier loads from rear loading cargo aircraft is enhanced by delivery systems which offer the maximum of simplicity and a minimum of weight and volume requirements. These system characteristics are generally exhibited by systems which have simple and direct load paths for the action forces, along with rapid and automatic deployment of retardation devices.

GROUND-TO-AIR RETRIEVAL

Unless otherwise noted, the following study conclusions pertain to unit loads of equipment weighing from 3,000 to 10,000 pounds, and to the C-130, C-141, and C-5A aircraft.

Conclusions

1. Based upon preliminary stability and control studies, including consideration of aircraft flight loads and available excess aircraft thrust, the ground-to-air retrieval of these heavier loads by all three aircraft using the recommended system is feasible.

2. The most promising ground-to-air retrieval system for these heavier loads employs a 500 foot high, helium filled balloon station to support the load retrieval line, which is engaged by an aircraft-installed hook and cable system.

3. These heavier loads should be towed behind rather than taken aboard the retrieval aircraft.

4. The most promising technique for re-deployment of these heavier loads is one which allows the load to be released by radio frequency signals and provides for load recovery by main descent parachutes.

APPENDIX A. AIRCRAFT LIMITATIONS

General

The capability of the cargo aircraft to meet demands imposed in delivery and retrieval of large cargo payloads is an important consideration in this study. The moments, loads, and accelerations applied to the aircraft must be examined in terms of their effect on aircraft stability and control, load factor limitations and thrust horsepower required and available. Other considerations are those of aircraft cargo compartment dimensions, and ramp loads.

More specifically, aircraft stability and control must be considered due to large changes in externally applied forces and moments. It is necessary to determine the adequacy of the aircraft control system with regard to minimizing the peak normal acceleration so that the aircraft limit load factor is not exceeded. In emergency jettison using a gravity technique, sufficient pitch control must be available to offset the pitching moment due to the extreme aft drop cargo position.

An adequate opening must be available as the payload tips over the ramp lip during extraction to avoid physical interference of the payload with the aircraft, and the ramp must be capable of withstanding the applied loads.

During retrieval operations, the excess thrust available must exceed the drag of the trailing cargo, and sufficient elevator control must be available to offset pitching moments generated by the retrieved cargo.

Candidate aircraft were examined with regard to the above factors and in all cases lighter aircraft proved to be more critical than heavier aircraft.

The following paragraphs present the critical analyses performed for aerial delivery and aerial retrieval operations, along with basic aircraft performance data used in the analyses.

Aerial Delivery

The C-5A and the C-141 were examined with respect to the extraction phase of aerial delivery. Results indicated that the C-5A, due to its size, showed very little reaction to the extraction of a 70,000 pound cargo. The C-141, however, was shown to be more critical. Therefore, analyses of the remaining phases of aerial delivery, emergency jettison and ramp cargo tip-off, were restricted to the C-141 aircraft.

The following paragraphs present a discussion of the analyses conducted and the pertinent results.

Extraction - C-141 and C-5

For aircraft using aft end cargo extraction, the criteria and performance requirements for the extraction system are established from consideration of the aircraft stability and control characteristics. The limiting factor is the magnitude of the flight load factor experienced by the aircraft during extraction of the cargo. As the cargo moves rearward, the aircraft is disturbed in the pitch mode. The increase in angle of attack results in an increased load factor. For a specific aircraft and cargo, the cargo extraction speed and total extraction time must be such that the pitching moment impulse created does not result in an excessive load factor. Since the cargo extraction speed and extraction time are direct results of the extraction force applied to the drop cargo, the ratio of the extraction force to the cargo weight, the extraction load factor, becomes the critical design factor.

When higher extraction load factors are used, the cargo moves rearward and out faster, the aircraft is less disturbed in pitch and the peak aircraft load factors are lower. The converse is true of lower extraction load factors.

Another important factor in the extraction of large cargo loads is the force exerted by the cargo on the ramp as it leaves the aircraft.

Longitudinal equations of motion in three degrees of freedom were developed to describe the physics of the extraction operation. The equations were programmed for use with the analog computer. Figure 122 depicts the reference axes, forces, moments, and dimensions used in equations to follow.

The equations used in the computer analyses are as follows:

$$\sum F_x = m_a \dot{U} = T\cos\alpha_{frl} - W_a \sin\gamma - D, f(\alpha_{frl}) + F_p \sin\alpha_{frl} - T_1 \cos\phi \qquad (115)$$

$$\sum F_z = -m_a U\dot{\gamma} = -T\sin\alpha_{frl} + W_a\cos\gamma - L, f(\alpha_{frl}, \delta_e, i_T) + F_p\cos\alpha_{frl} + T_1\sin\phi \qquad (116)$$

$$\sum M_{cg} = I_y\ddot{\theta} = M_{a.c.}, f(\alpha_{frl}) + M_{\dot{\theta}}\dot{\theta} + M_{\dot{\alpha}}\dot{\alpha} + M, f(\delta_e, i_T) + F_p x_c + x_c(T_1\sin\phi) - a(T_1\cos\phi) \qquad (117)$$

$$F_p = W_c\cos\theta + m_c U\dot{\gamma}\cos\alpha_{frl} - m_c\dot{\theta}\dot{x}_c - m_c\dot{x}_c\dot{\theta} \qquad (118)$$

These equations were also used to determine the aircraft reaction due to a vertical gust. Vertical gusts cause changes in the angle of attach such that:

$$\alpha_{tot} = \alpha_{frl} + \alpha_{gust} \qquad (119)$$

Where

$$\alpha_{gust} = \frac{\alpha_{g\,max}}{2}\left(1 - \cos\frac{2\pi d}{25\bar{c}}\right) \qquad (120)$$

$\dot{U}$ = Forward acceleration of A/C

T = Power Plant Thrust

T_1 = Line Tension or Extraction Force

ϕ = Angle of T_1 with horizontal (down positive)

i_T = horizontal tail incidence angle

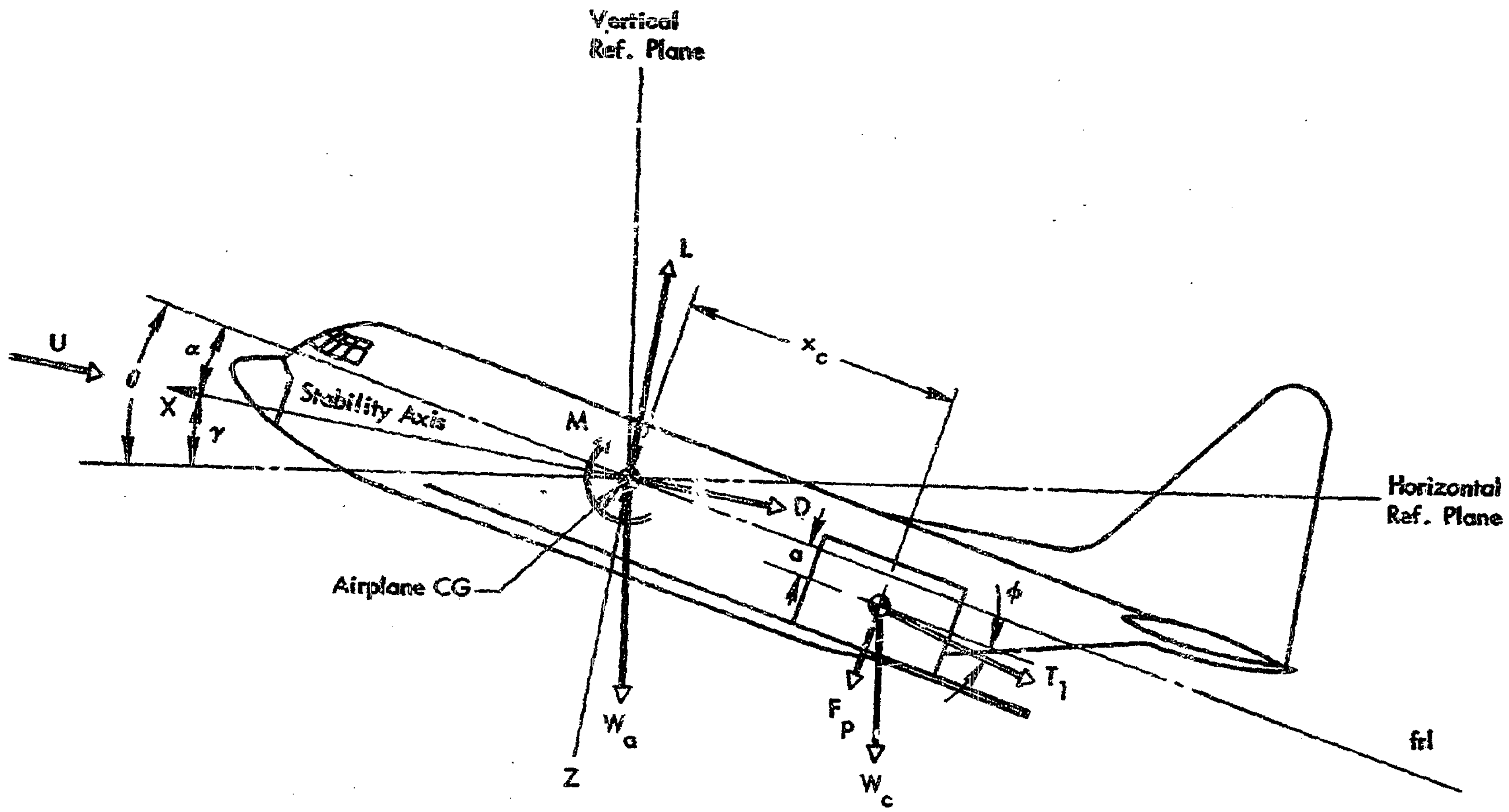


Figure 122 - Cargo Extraction Force Diagram

Data computed on aircraft load factors experienced for various flight conditions and extraction load factors are presented in Figures 123 through 126. With regard to each figure, the abscissa is calibrated in terms of drop cargo weight and the ordinate in terms of flight load factor. Solid lines representing specific extraction load factors show the variation in aircraft load factor with cargo weight. The dashed line represents the aircraft limit load factor of 2.5 g. Data are presented for 0, 10, and 30 fps gust conditions at airspeeds of 130 and 150 knots.

Note that the C-5 experienced no load factor approaching the limit throughout the range of variables investigated.

With an airspeed of 130 knots the C-141 reached the limit load factor of 2.5 at the 10 fps gust condition with a 0.5 extraction load factor and a drop load of 48,000 pounds. With an airspeed of 150 knots, the limit load factor was experienced for a drop load of 35,000 pounds with the same extraction load factor and gust velocity. The 30 fps gust condition caused the limit load factor to be exceeded for all investigated combinations of drop cargo weight and extraction load factors.

The analog data presented in Figures 123 through 126 are for only two aircraft speeds. It is desirable to extrapolate this data to determine the extraction load factors applicable to the full range of aircraft speeds of interest.

The following procedure affords a reliable and conservative method for extrapolation of the data. The list of symbols used in the following analyses are defined for reference:

Notation

n_F	=	Flight load factor
$n_{F_{max}}$	=	Flight load factor; design limit
Δn_F	=	Flight load factor increment
Δn_{F_U}	=	Flight load factor increment due to gust
Δn_{F_e}	=	Flight load factor increment due to extraction pitch impulse
n_e	=	Extraction load factor
W_A	=	Airplane gross weight
W	=	Drop cargo weight
ℓ_e	=	Extraction floor length
V	=	Airplane flight speed
U	=	Gust velocity
S	=	Wing area
$\bar{c}$	=	Moment reference chord length
C_{L_α}	=	Lift curve slope
C_{M_α}	=	Moment curve slope
I_{yy}	=	Moment of inertia about pitch axis
α	=	Angle of attack

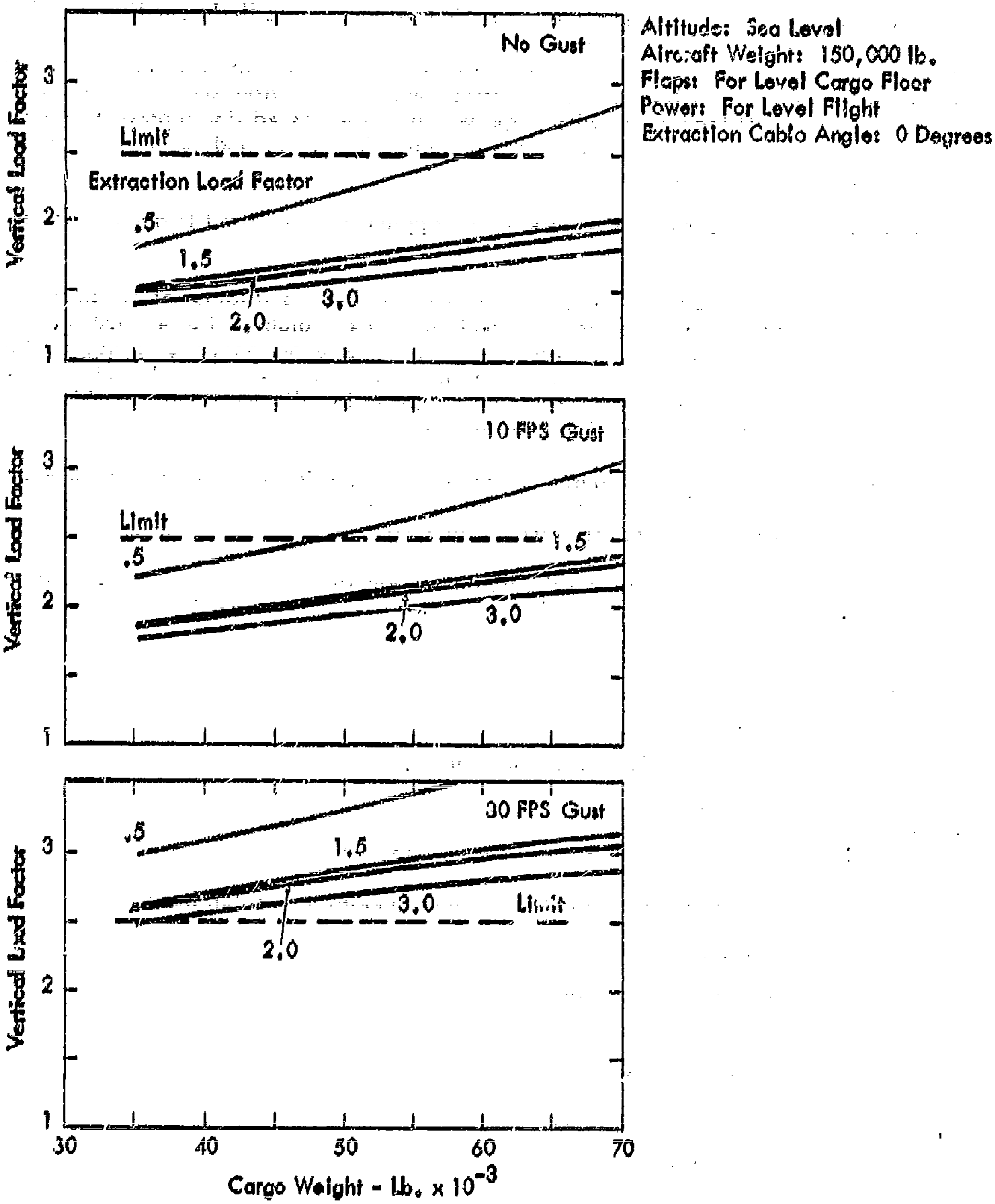


Figure 123 - C-141 Vertical Load Factor for Aerial Delivery - Equivalent Airspeed = 130 Knots

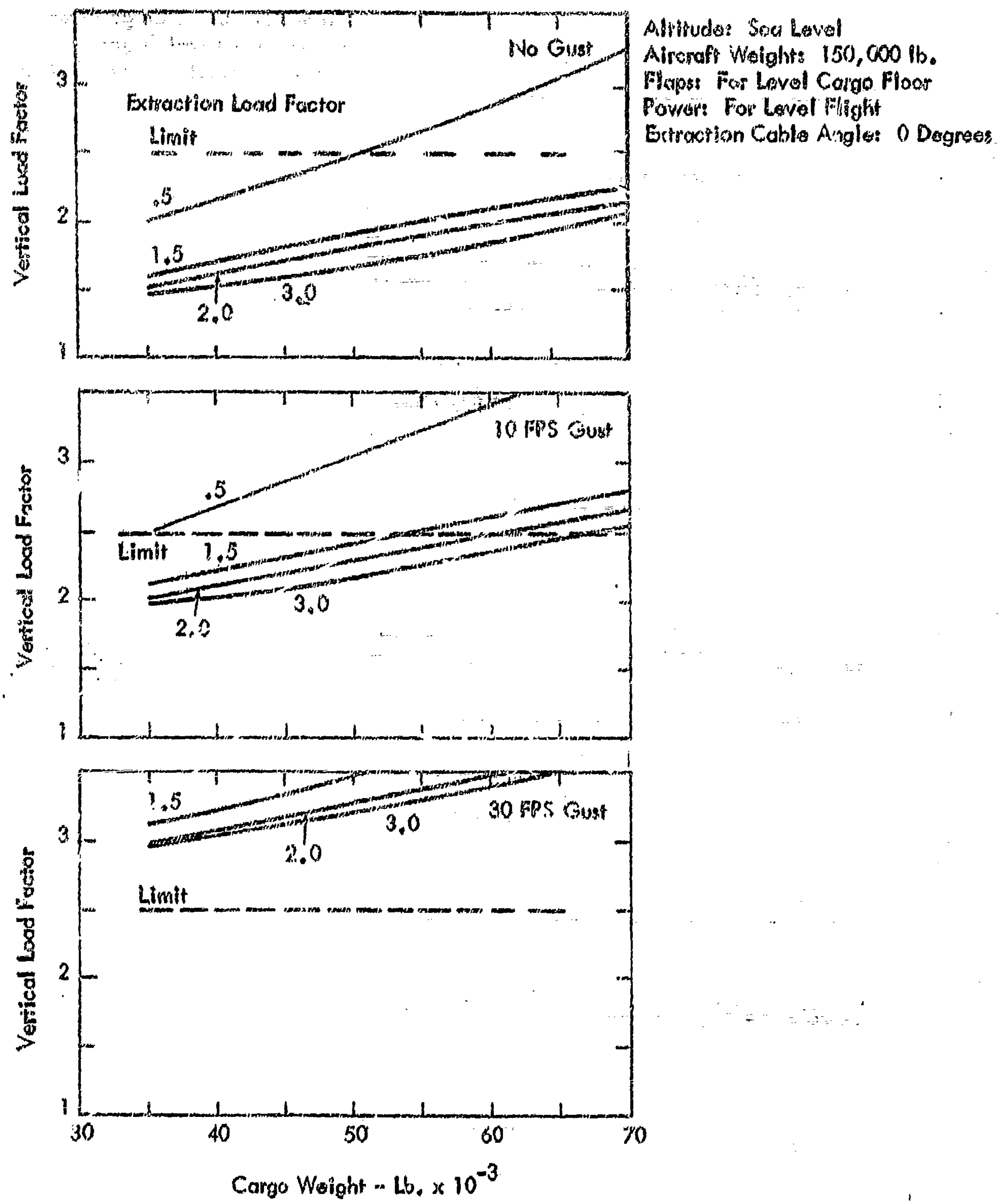
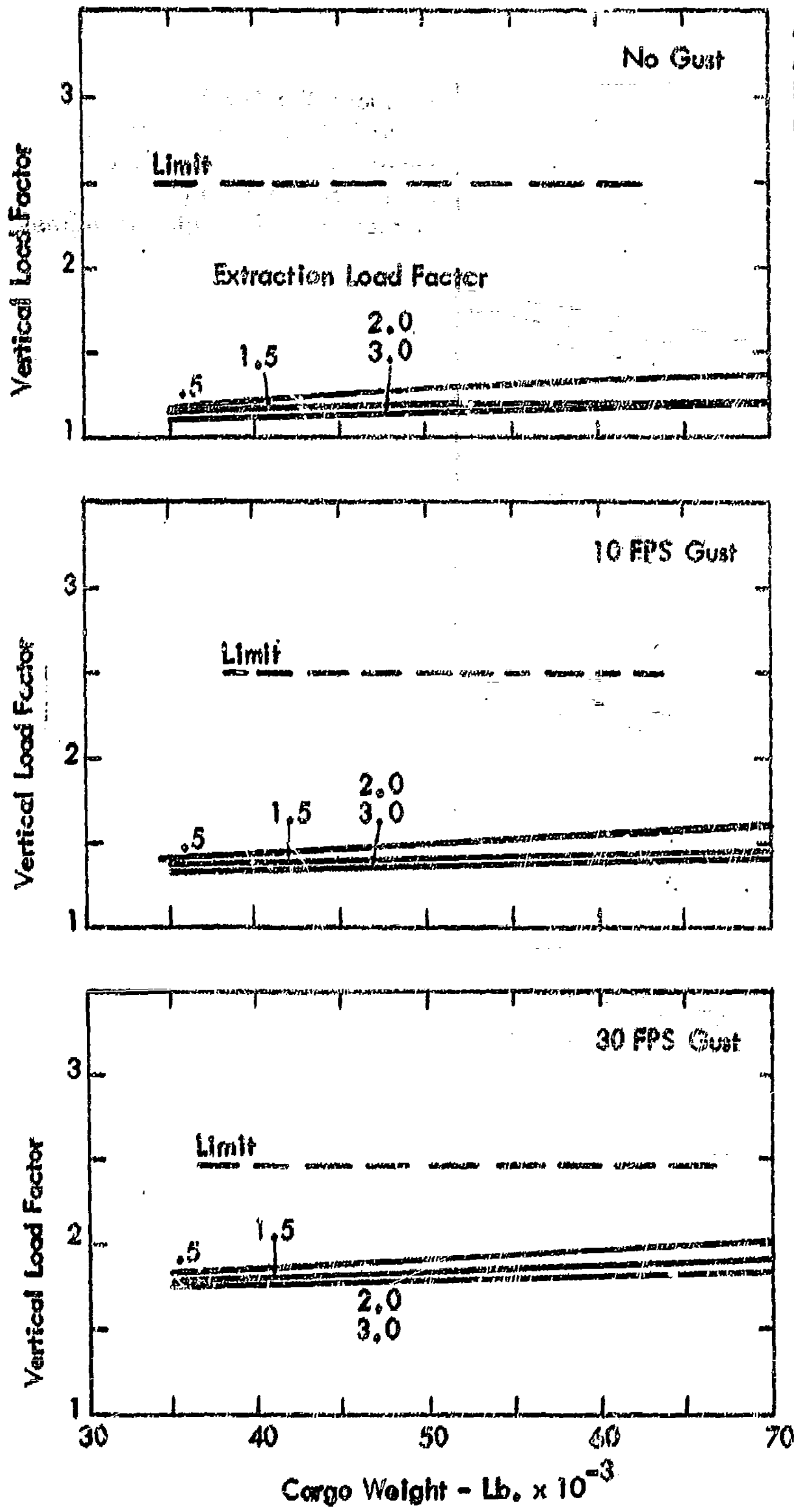
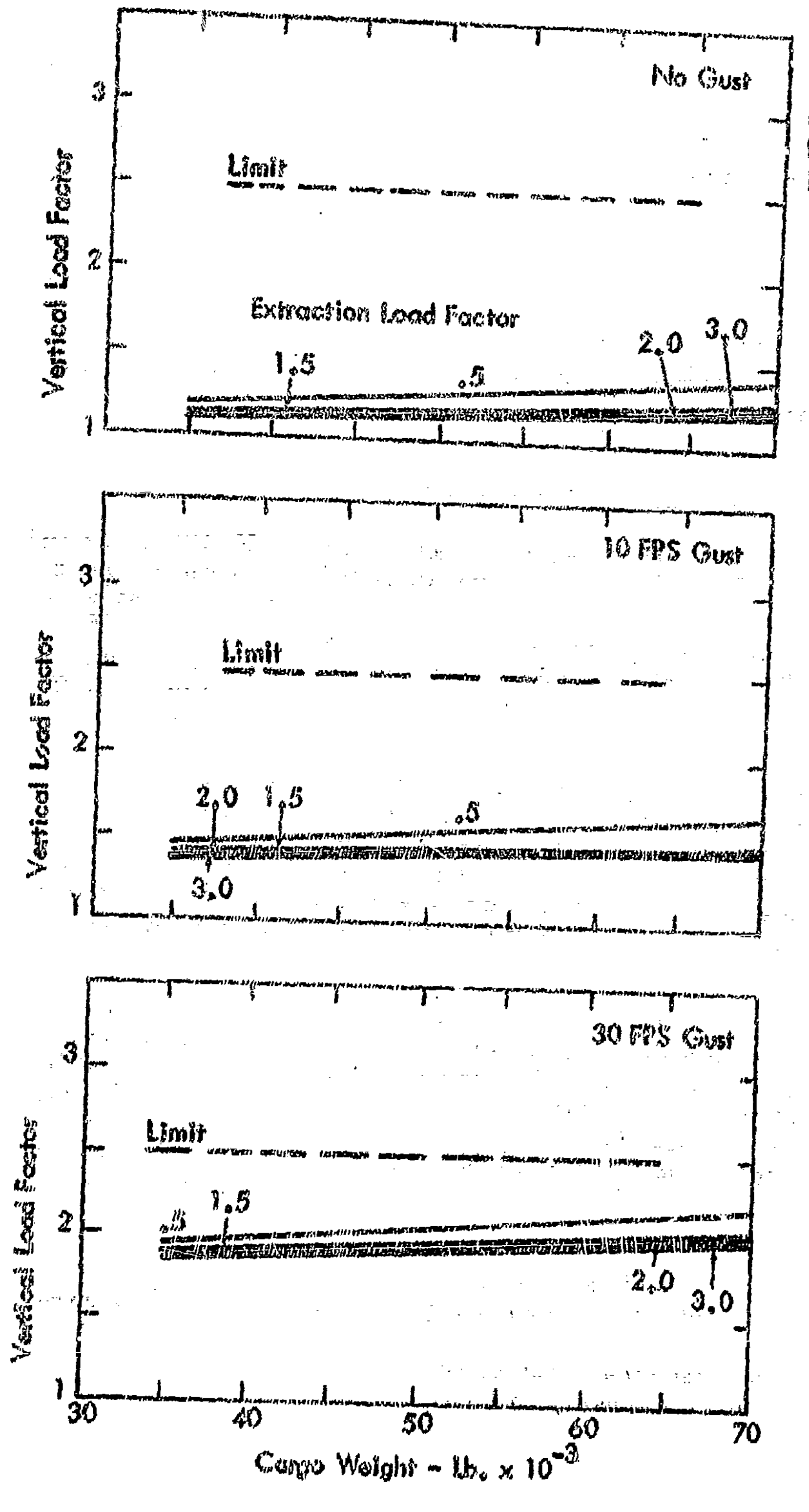


Figure 124 - C-141 Vertical Load Factor for Aerial Delivery - Equivalent Airspeed = 150 Knots



Altitude: Sea Level
Aircraft Weight: 500,000 lb.
Flaps: For Level Cargo Floor
Power: For Level Flight
Extraction Cable Angle: 0 Degrees

Figure 125 - C-5A Vertical Load Factor for Aerial Delivery - Equivalent Airspeed = 130 Knots



Altitude: Sea Level
Aircraft Weight: 500,000 lb.
Flaps: For Level Cargo Floor
Power: For Level Flight
Extraction Cable Angle: 0 Degrees

Figure 126 - C-5A Vertical Load Factor for Aerial Delivery - Equivalent Airspeed = 150 Knots

I_y = A/C moment of inertia

$\ddot{\theta}$ = pitching acceleration

$M_{a.c.}$ = aerodynamic pitching moment

$M_{\dot{\theta}}$ = Pitch damping moment

$\dot{\theta}$ = pitching velocity

$M_{\dot{\alpha}}$ = angle-of-attack damping moment

$M, f(\delta_e, i_T)$ = pitching moment as function of elevator deflection and horizontal tail incidence angle.

x_c = horizontal distance from cargo c.g. to A/C c.g.

a = vertical dist. from cargo c.g. to a/c stability axis

Analyses were performed for a C-141 aircraft weight without cargo of 150,000 pounds and for a C-5 weight without cargo of 500,000 pounds. Both aircraft were assumed to have a center of gravity at 25 percent mean aerodynamic chord, assuming standard day, sea level conditions. The cargo densities used are 1250 pounds/feet for a 35,000 pound load, 1525 pounds/feet for a 55,000 pound load, and 1750 pounds/feet for a 70,000 pound load. Considered are extraction load factors of .5, 1.5, 2.0, and 3.0, aircraft speeds of 130 and 150 knots, and maximum vertical gust speeds of 0, 10, and 30 feet per second.

The aircraft pitching moment was assumed to decrease linearly from the time the cargo center of gravity passes the ramp door lip until the end of the cargo clears the aircraft. Included in the equations is the aircraft response to vertical gusts having a 1-cos wave form. This wave form is programmed so that the most adverse conditions exist during the drop. Recent parametric studies have shown this to occur when the aircraft is one-fourth the way through the gust wave length at the time the cargo center of gravity reaches the ramp door lip.

The aircraft flap and power settings were assumed to be such that level flight was obtained with the cargo floor level. The following 16 parameters were recorded for each computer run: pitching acceleration; pitching velocity; pitch angle; angle of attack; lift coefficient; rate of change of flight path angle; flight path angle; elevator deflection; forward acceleration; forward velocity; altitude change; normal acceleration change; rate of change in angle of attack; cargo platform force; pitching moment caused by aft movement of cargo; and the (1-cos) gust. Cargo weight, extraction load factor, maximum gust speed, and aircraft speed were varied.

The program was run for both stick fixed flight and for flight conditions when the pilot uses elevator control to attempt to offset the unbalancing pitch moment. Results showed that the highest aircraft load factors are experienced during stick-fixed flight and the highest ramp platform loads are experienced when elevator control is used. Only the most critical data is presented in the following material.

$\Delta\alpha$ = Angle of attack increment

g = Acceleration of gravity

Δt_e = Duration of extraction period

ΔP = Increment of pitch impulse

q = Flight dynamic pressure $= \frac{\rho}{2} V^2$

Subscripts 1, 2 refer to different flight conditions

Permissible flight load factor increment due to extraction pitch impulse is

$$\Delta n_{F_e} = n_{F_{max}} - \Delta n_{F_u}$$

$$\Delta n_{F_{u_2}} = \Delta n_{F_{u_1}} \left(\frac{V_1}{V_2} \right)$$

$$\Delta n_{F_{e_2}} = n_{F_{max}} - \Delta n_{F_{u_1}} \left(\frac{V_1}{V_2} \right) \tag{121}$$

Pitching moment impulse during cargo extraction

$$\Delta P = \int_0^{\Delta t_e} W \cdot x(t)\, dt$$

$$x(t) = \frac{1}{2} n_e g t^2$$

$$\therefore \Delta P = W \cdot g \cdot n_e \int_0^{\Delta t_e} \frac{1}{2} t^2\, dt = \frac{1}{6} W g n_e \Delta t_e^{\,3} \tag{122}$$

Extraction floor length

$$L_e = \frac{1}{2} g n_e \Delta t_e^{\,2}$$

$$\therefore \Delta t_e = \left[\frac{2 L_e}{g n_e} \right]^{1/2}$$

$$\Delta P = \frac{1}{6} W g n_e \left[\frac{2L_e}{g n_e}\right]^{3/2} = \frac{1}{6} W \left[\frac{g^{2/3} n_e^{2/3} 2L_e}{g n_e}\right]^{3/2}$$

$$\therefore \quad \Delta P = \frac{1}{3} W \left[\frac{2L_e^3}{g n_e}\right]^{1/2} \tag{123}$$

A pitching moment impulse applied to a system possessing rotational inertia and a linearly restoring moment is equivalent to an increment of angular momentum given by

$$\Delta P = I_{yy} \cdot \dot{\alpha} \tag{124}$$

where $\dot{\alpha}$ = angular velocity

For the same system, conservation of energy requires that

$$C \cdot \Delta\alpha^2 = I_{yy} \cdot \dot{\alpha}^2 \tag{125}$$

where

C represents the rate of restoring moment with angular displacement for a stable aerodynamic system

$$C = C_{M_\alpha} \cdot S \cdot \bar{c} \cdot q \tag{126}$$

$$\therefore \quad C_{M_\alpha} \cdot S \cdot \bar{c} \cdot q \cdot \Delta\alpha^2 = I_{yy} \dot{\alpha}^2$$

$$\dot{\alpha}^2 = \left(\frac{\Delta P}{I_{yy}}\right)^2$$

$$C_{M_\alpha} \cdot S \cdot \bar{c} \cdot q \cdot \Delta\alpha_e^2 = \frac{\Delta P^2}{I_{yy}}$$

$$\therefore \quad \Delta\alpha_e = \Delta P \left[\frac{1}{C_{M_\alpha} \cdot S \cdot \bar{c} \cdot q \cdot I_{yy}}\right]^{1/2} \tag{127}$$

The pitch angle excursion due to pitch impulse is related to the flight load factor increment by:

$$\Delta n_{F_{e_2}} = \Delta n_{F_{e_1}} \left(\frac{\Delta\alpha_{e_2}}{\Delta\alpha_{e_1}}\right) \tag{128}$$

$\therefore$

$$\frac{\Delta n_{F_{e_2}}}{\Delta n_{F_{e_1}}} = \frac{\Delta P_2}{\Delta P_1}\left[\frac{\dfrac{1}{C_{M_\alpha} \cdot S \cdot \bar{c} \cdot I_{yy} \cdot q_2}}{\dfrac{1}{C_{M_\alpha} \cdot S \cdot \bar{c} \cdot I_{yy} \cdot q_1}}\right]^{1/2}$$

$$\frac{\Delta n_{F_{e_2}}}{\Delta n_{F_{e_1}}} = \frac{\Delta P_2}{\Delta P_1}\left[\frac{q_1}{q_2}\right]^{1/2}$$

$\therefore$

$$\frac{\Delta n_{F_{e_2}}}{\Delta n_{F_{e_1}}} = \frac{W_2}{W_1}\left[\frac{q_1}{q_2}\right]^{1/2}\left[\frac{L_{e_2}^3 \; n_{e_1}}{L_{e_1}^3 \; n_{e_2}}\right]^{1/2} \tag{129}$$

Substituting from Equation 121

$$n_{F_{max}} - \Delta n_{F_{v_2}}\left(\frac{q_1}{q_2}\right)^{1/2} =$$

$$\Delta n_{F_{e_1}} \frac{W_2}{W_1}\left(\frac{q_1}{q_2}\right)^{1/2} \cdot \left(\frac{L_{e_2}}{L_{e_1}}\right)^{3/2}\left(\frac{n_{e_1}}{n_{e_2}}\right)^{1/2}$$

Solving for the extraction load factor n_e:

$n_{e_2} =$

$$n_{e_1}\left\{\frac{\Delta n_{F_{e_1}}}{n_{F_{max}} - \Delta n_{F_{v_1}}\left(\dfrac{q_1}{q_2}\right)^{1/2}}\right\}^2\left(\frac{W_2}{W_1}\right)^2 \cdot \left(\frac{q_1}{q_2}\right) \cdot \left(\frac{L_{e_2}}{L_{e_1}}\right)^3 \tag{130}$$

or

$$n_{e_2} = n_{e_1} \left\{ \frac{\Delta n_{F_{e_1}}}{n_{F_{max}} - \Delta n_{F_{u_1}} \left(\frac{V_1}{V_2} \right)} \right\}^2 \left(\frac{W_2 V_1}{W_1 V_2} \right)^2 \left(\frac{L_{e_2}}{L_{e_1}} \right)^3 \qquad (131)$$

This expression correlates the required extraction load factor with changes in flight speed V, drop cargo weight W and extraction floor L_e, for constant gust velocity U.

Figure 127 depicts the data computed using Equation (131) above. The data presented were computed using the limit load factor of 2.5 for the C-141 and considering a 10 fps gust condition. The moderate gust velocity of 10 fps was selected for two reasons: firstly the probability of occurrence of a 10 fps gust is fairly high and secondly, the short duration of the cargo extraction period (1 - 3 secs.) makes the encounter with a higher gust velocity during the critical period less likely.

Within the above constraints, the data presented represent the full range of extraction load factors for the cargo weights and aircraft speeds considered.

Figures 128 through 131 present the ramp loading experienced by the C-5 and C-141 during the extraction operation.

Note that the C-5 limit ramp load is not exceeded in any of the conditions investigated.

The C-141 ramp platform limit load is exceeded for both the 10 fps and 30 fps gust conditions, at an airspeed of 150 knots and an extraction load factor of $n = 0.5$.

It is concluded then that for the extraction phase of aerial delivery the only limiting conditions occur for the C-141 aircraft in high gust conditions when low extraction load factors are used.

Gravity Emergency Cargo Jettison

A study was conducted to determine the emergency cargo jettison capability of the C-141 aircraft using gravity to provide the extraction forces. This capability is desirable in certain emergency situations such as engine out, insufficient fuel, airframe damage, or in the case of extraction system failure or malfunction.

In this technique, the aircraft pitches up allowing gravitational acceleration to pull the cargo out. The amount of pitch-up allowed for the technique is dependent on the airspeed, since the ratio of the change in aircraft flight load factor with change in angle of attack increases with airspeed. Using 2.5 as a maximum load factor, an analysis was performed to determine the maximum increase in angle of attack, $\Delta \alpha$, which could be allowed for each airspeed and the resulting upsetting pitching moment on the aircraft in terms of a pitching moment coefficient ΔC_m. The analysis was performed for three cargo weights 30,000 pounds, 50,000 pounds, and 70,000 pounds.

Each combination of cargo weight and airspeed produced a specific extraction force and corresponding extraction load factor, n_e.

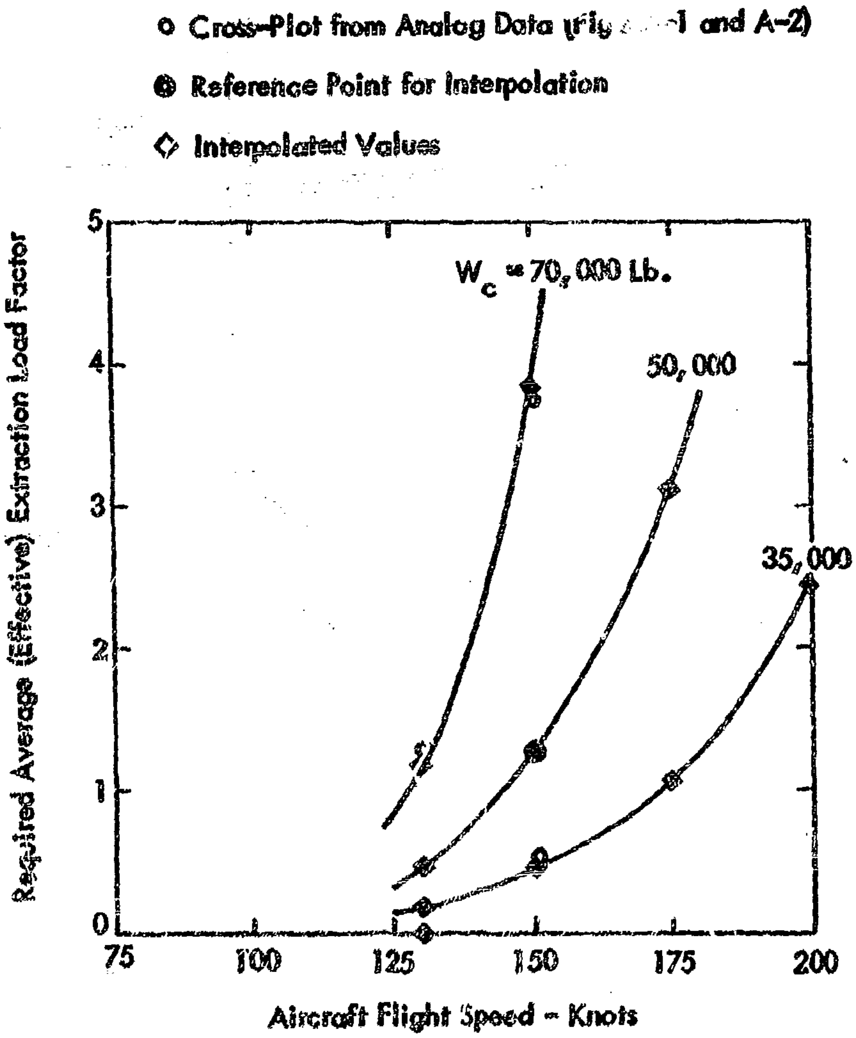


Figure 127 - C-141 Extraction Load Factors Required for Limitation of Pitch Impulse Response

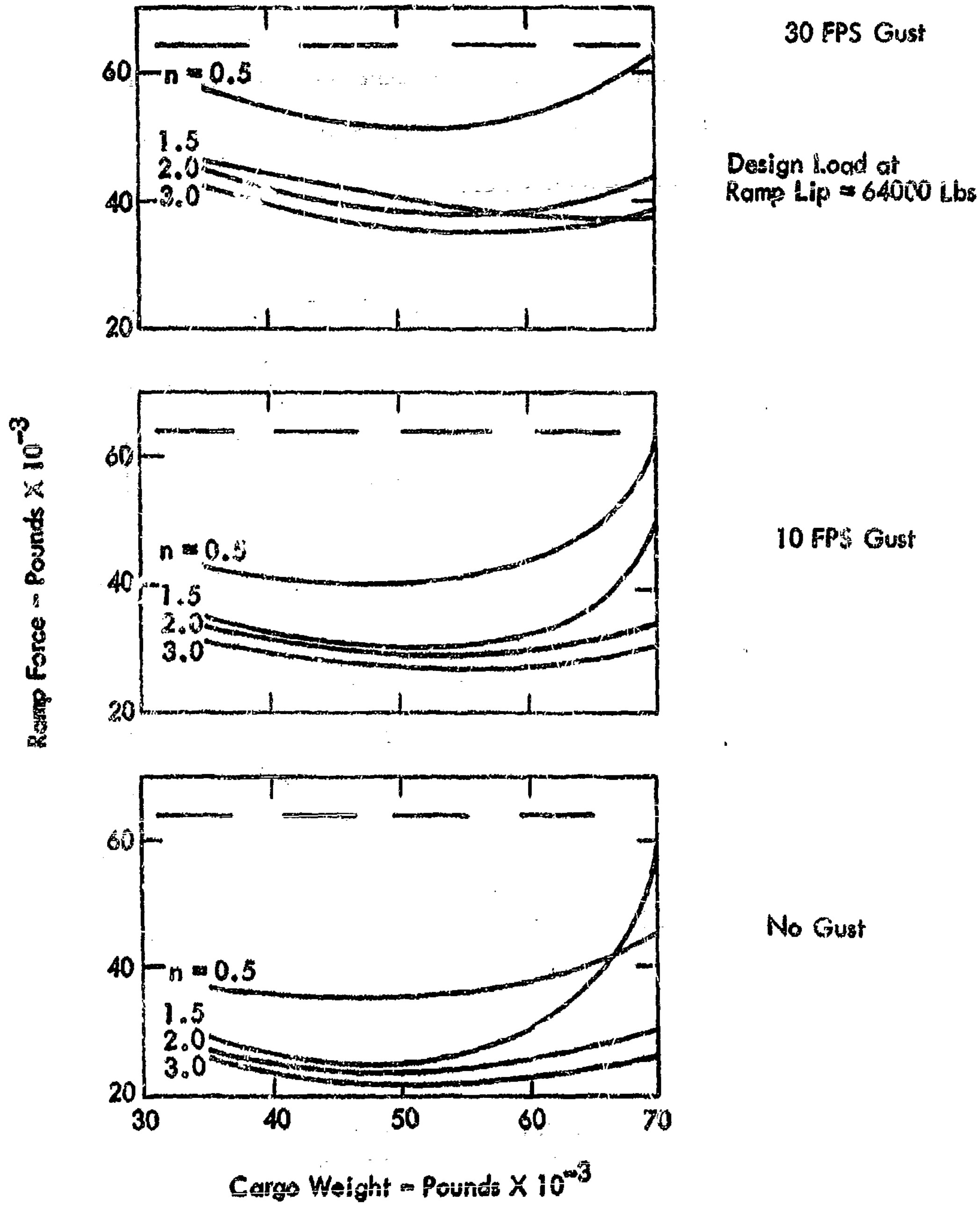


Figure 128 - Force at Ramp Lip of C-141 Aircraft - Equivalent Airspeed = 130 Knots

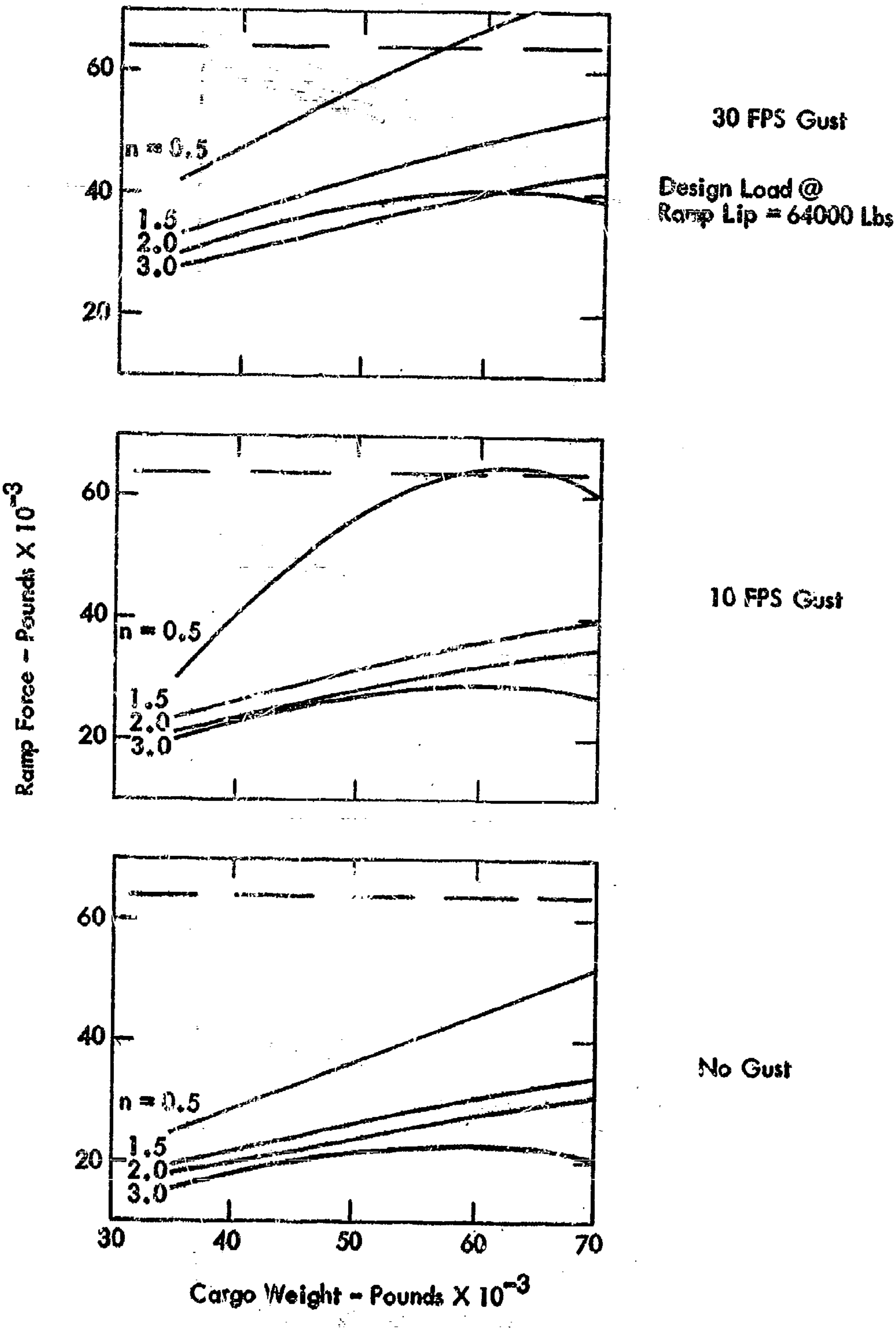


Figure 129 – Force at Ramp Lip of C-141
Aircraft – Equivalent Airspeed = 150 Knots

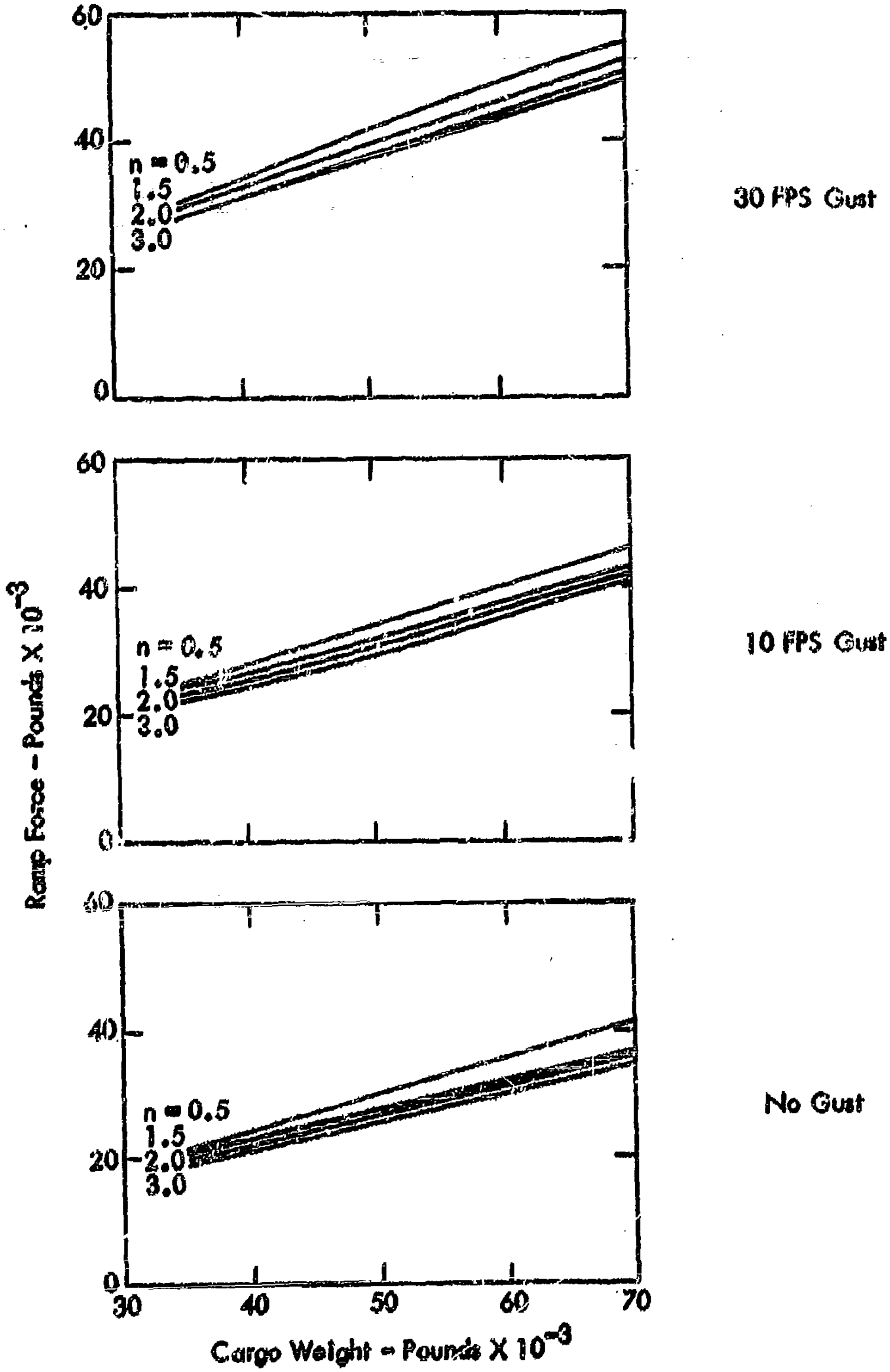


Figure 130 - Force at Ramp Lip of C-5A Aircraft - Equivalent Airspeed = 130 Knots

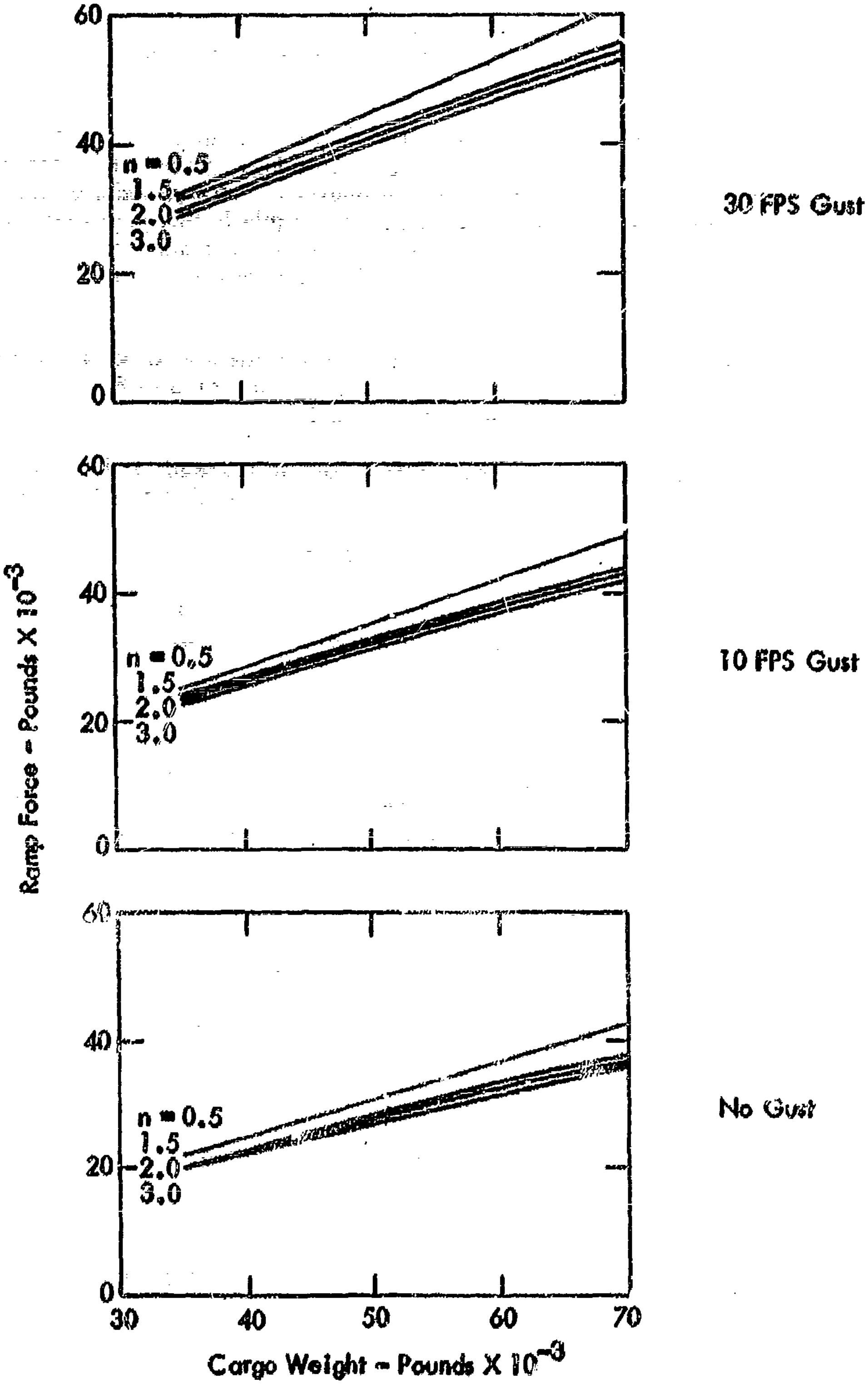


Figure 131 - Force at Ramp Lip of C-5A Aircraft - Equivalent Airspeed = 150 Knots

Figure 132 presents the results of the analyses. Note that as airspeed is increased the upsetting moment coefficient ΔC_m on the aircraft decreases and that ΔC_m is lower for the lower cargo weights.

The near horizontal dashed line represents the elevator power available to counteract the ΔC_m caused by the gravity extracted cargo. This elevator power is presented also as a ΔC_m to the aircraft. For the elevator analysis, the trimmed elevator for each flight condition was determined and the ΔC_m available is that resulting from movement of the elevator from the trimmed position to the position of maximum deflection. For the range of variables considered, the ΔC_m available from the elevator is a fairly constant value of ~ 0.52.

The significant result of the analysis is that gravity emergency cargo jettison is possible for only a limited range of variables. The solid lines presented in Figure 132 represent conditions under which gravity jettison may be used.

A 35,000 pound cargo can be jettisoned in this manner at speeds of from 166 knots to 200 knots. A 50,000 pound cargo may be jettisoned at speeds from 191 knots to 200 knots. The applicable extraction load factors for the above conditions are presented also in Figure 132 represented by the lower solid lines.

It is concluded, therefore, that gravity emergency cargo jettison can be considered for lower weight cargo loads but is marginal for higher weight drop cargo.

Ramp Cargo Tip-Off Analysis

A mathematical analysis was made of cargo dynamics during a parachute extraction operation. By assuming a uniform cargo density, the equations of motion were made independent of cargo weight. It was assumed that the cargo motion would be translational and rotational in a vertical x - z plane. Figure 133 diagrams the forces applicable in this analysis.

The governing equations are as follows:

Summing translational forces in the horizontal (x) direction gave:

$$\sum F_x = n_e \cdot W - F_F \cos\phi + F_R \sin\phi - \frac{W}{g}\ddot{x} = 0 \qquad (132)$$

Similarly for the z direction:

$$\sum F_z = W - F_F \sin\phi - F_R \cos\phi - \frac{W}{g}\ddot{z} = 0 \qquad (133)$$

Summing the moments about the center of gravity of the cargo gave the rotational equation as:

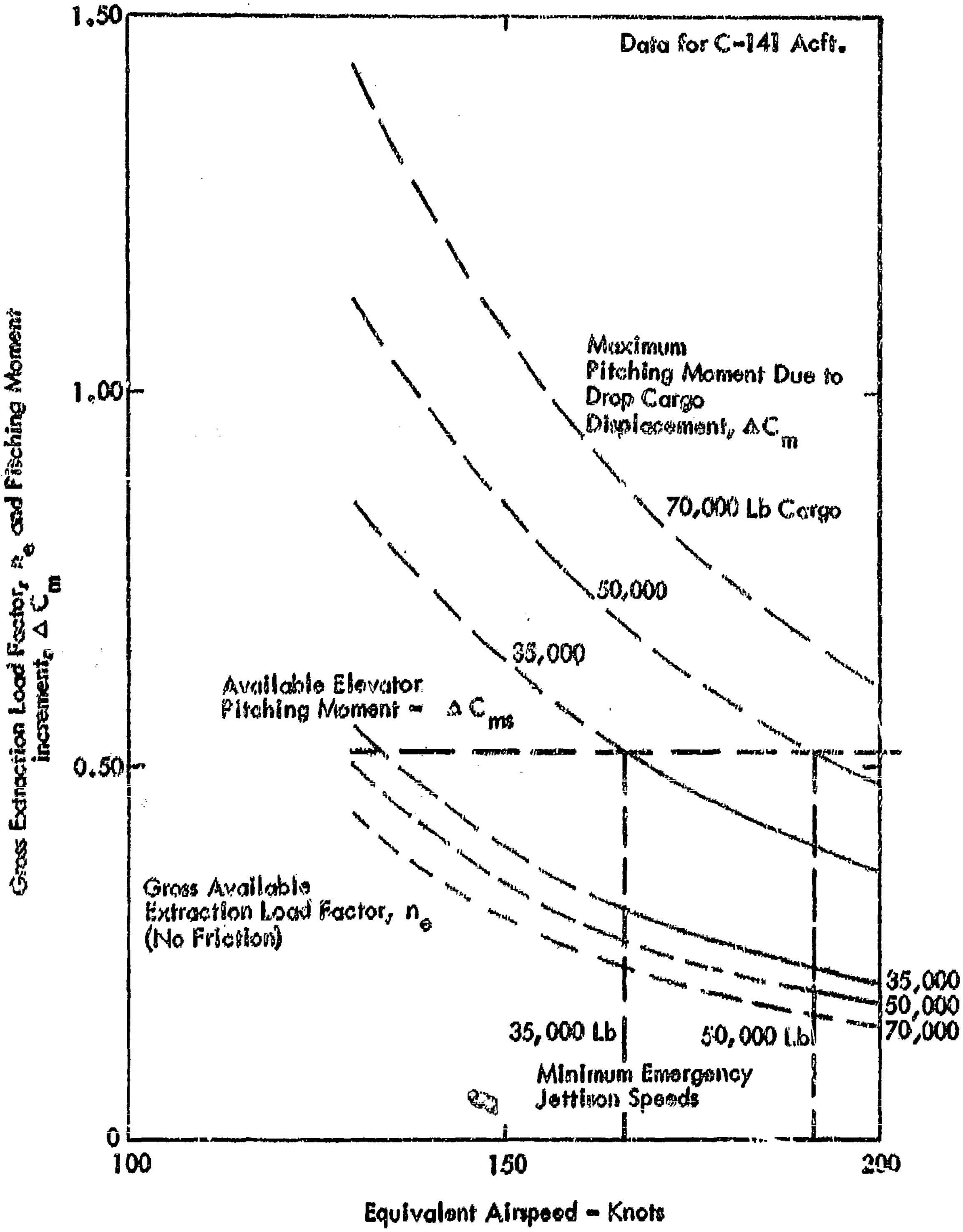


Figure 132 - Performance Characteristics for Gravity Emergency Cargo Jettison

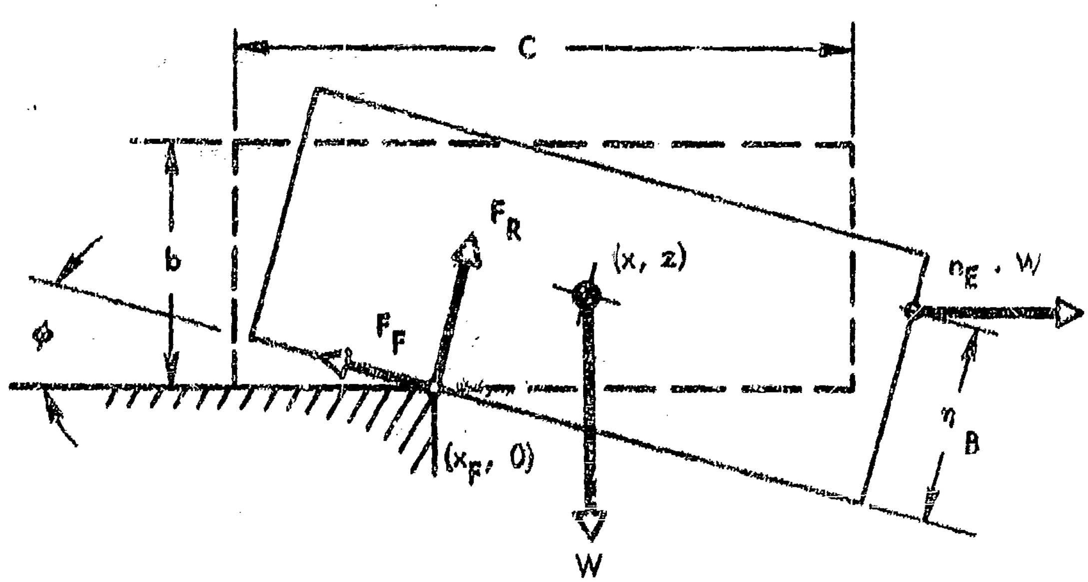


Figure 133 - Ramp Cargo Tip-Off Analysis Force Diagram

$$\sum M_y = F_R\left(\frac{x-x_F}{\cos\phi} - \frac{b}{2}\tan\phi\right) + \mu F_R \frac{b}{2} - n_e W\left[\left(\frac{x-x_F}{\cos\phi} - \frac{b}{2}\tan\phi + \frac{c}{2}\right)\sin\phi - \eta_B \cdot b \cdot \cos\phi - z\right] - \frac{W}{g} k^2 \ddot{\phi} = 0 \tag{134}$$

The force exerted by the ramp on the cargo was assumed proportional to the weight of the cargo remaining in the aircraft.

Thus

$$F_R \cos\phi = W\left[1 - \frac{x-x_F}{g}\ddot{\phi}\right] \tag{135}$$

Combining (134) and (135) produced

$$-\frac{1}{g}\left\{(x-x_F)\left[\frac{x-x_F}{\cos\phi} + \frac{b}{2}(\mu - \tan\phi)\right] + k^2\right\}\ddot{\phi} + \left[\frac{x-x_F}{\cos\phi} + \frac{b}{2}(\mu - \tan\phi)\right]$$

$$- n_e\left[\left(\frac{x-x_F}{\cos\phi} + \frac{1}{2}(c - b\tan\phi)\right)\sin\phi - \eta_B \cdot b\cos\phi - z\right] = 0 \tag{136}$$

Solving (132) and (133) for the accelerations resulted in:

$$\ddot{x} = n_e \cdot g + \frac{F_R}{W} g \left(\sin\phi - \mu\cos\phi\right) \tag{137}$$

$$\ddot{z} = g - \frac{F_R}{W} g\left(\cos\phi - \mu\sin\phi\right) \tag{138}$$

Multiplying (137) by $(\cos\phi - \mu\sin\phi)$ and (138) by $(\sin\phi - \mu\cos\phi)$ and then combining gave:

$$-\left(n_e - \frac{\ddot{x}}{g}\right) = \left(1 - \frac{\ddot{z}}{g}\right)\frac{\sin\phi - \mu\cos\phi}{\cos\phi - \mu\sin\phi} \tag{139}$$

Substituting the above into (136) resulted in

$$\ddot{\phi} = g\left(1 - \frac{\ddot{z}}{g}\right)\left\{(x-x_F) + z\,\frac{\sin\phi - \mu\cos\phi}{\cos\phi - \mu\sin\phi}\right\} \Big/ \left[k^2 + z^2 + (x-x_F)^2\right] \tag{140}$$

Substituting (140) into (137) and (138) yielded

$$\ddot{x} = g \left\{ n_e + \left(1 - \frac{x - x_F}{g} \ddot{\phi}\right)(\tan\phi - \mu) \right\} \tag{141}$$

$$\ddot{z} = g \left\{ 1 - \left(1 - \frac{x - x_F}{g} \ddot{\phi}\right)(1 + \mu \tan\phi) \right\} \tag{142}$$

The effects on the translational and rotational motion were determined for various extraction load factors, initial conditions, and attachment locations for the extraction line through the use of a digital computer. Various cargo sizes (from 7 to 9 feet in height; from 20 to 48 feet in length) were considered for extraction load factors up to 1.0 and for extraction attachment points over the height range.

The angular velocity was observed to increase with an increasing extraction application location point as shown in Figure 134. This indicates a need to consider the point of location of the extraction line on the cargo if the resulting angular velocity is a matter of concern.

The maximum rise of the upper edge of the cargo was less than two inches.

Thus, it is concluded that cargo tipping does not present a problem in aerial delivery operations.

The following symbols were used in the tip off analysis.

Fx	-	forces in X-direction
n_e	-	extraction factor = $\dfrac{\text{extracting force}}{\text{payload weight}}$
W	-	payload weight
F_F	-	friction force
F_R	-	normal force of ramp on cargo
g	-	acceleration of gravity
ϕ	-	angle of rotation
$\ddot{x}$	-	Acceleration in the x-direction
F_z	-	forces in z-direction
$\ddot{z}$	-	acceleration in the Z-direction
M_y	-	moments about the y-axis
x_F	-	reaction point
μ	-	coefficient of friction
b	-	cargo height
c	-	cargo length
k	-	radius of gyration
$\ddot{\phi}$	-	angular acceleration
η_B	-	percentage of height used for attachment

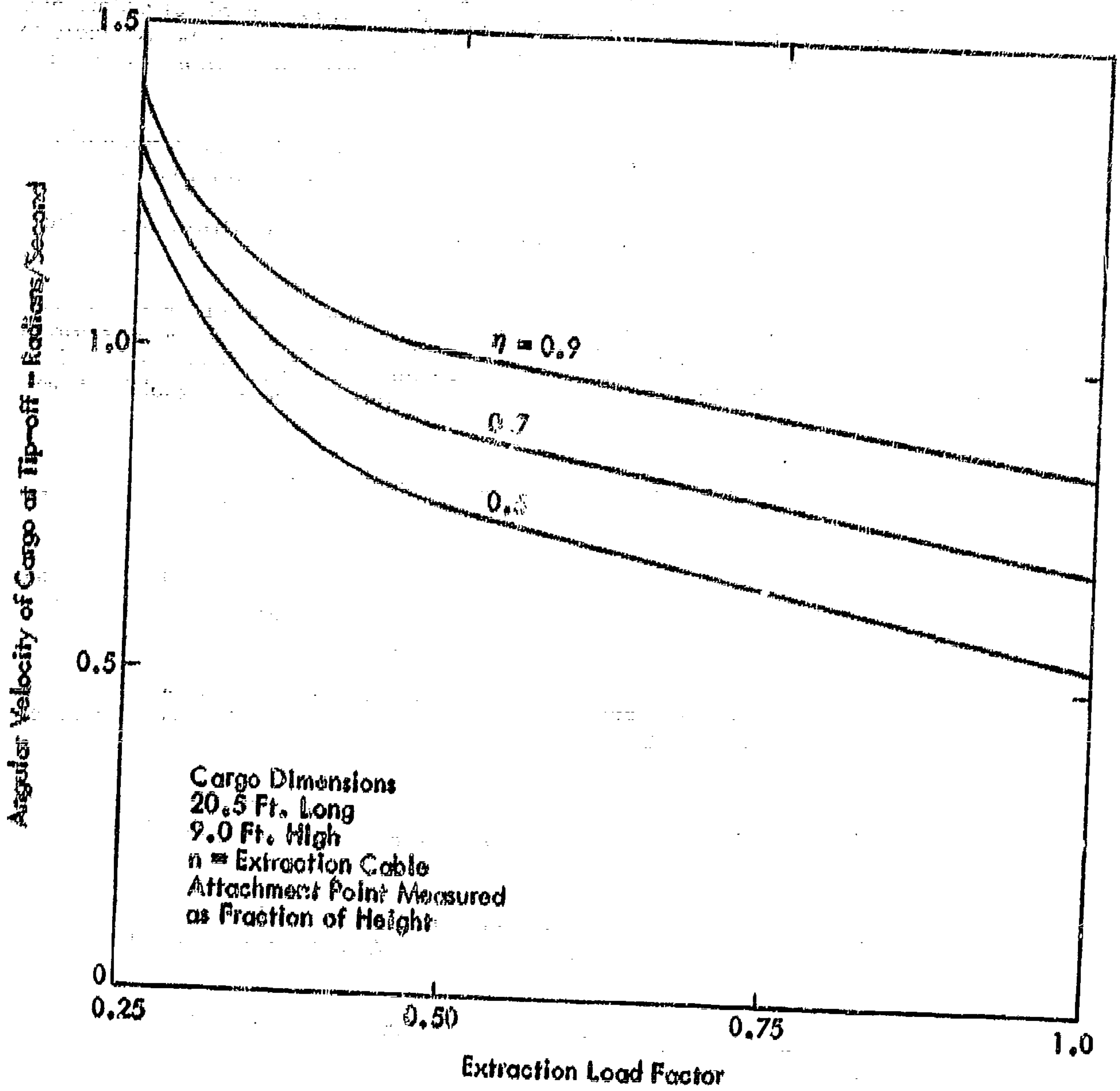


Figure 134 - Rotation Rate at Tip-off

Aerial Retrieval

The primary considerations during the aerial retrieval operations are again stability and control, load factors encountered, and thrust horsepower required and available.

More specifically, the aircraft elevator must be capable of counteracting upsetting pitching moments during the impact phase of retrieval and also must be capable of maintaining level flight during cargo tow situations. Sufficient elevator control must be available to prevent the aircraft from pitching to high angles of attack which result in excessive load factors.

The aircraft must have adequate excess thrust to overcome the load encountered during the impact phase of retrieval and the drag of payloads during steady tow conditions.

Analyses were performed on the C-130 aircraft to determine its capabilities and limitations with regard to the above factors.

The procedure followed was to determine the range of tow line angles and tow line tensions which would be experienced by the aircraft. Secondly, an exercise was performed to develop the elevator deflections required to offset the disturbing moments created by the application of tow line forces. Finally, the aircraft load factors resulting from the disturbing pitching moments were determined.

In the case of the impact phase of retrieval, tow line angles and tensions were taken from data computed for the Balloon Line retrieval concept discussed previously in this report.

Tow line angles and forces for steady - state tow conditions were computed for selected tow line lengths and payload weights using an in-house C-130 computer program. The steady tow data are presented in Figures 135 through 142.

Using the tow line data, elevator deflection requirements of the C-130 were determined both for the impact phase of the balloon-line retrieval concept and for steady state tow conditions with various tow line lengths.

The balloon-line impact phase analysis was accomplished using a 500 foot line length and a 10,000 pound payload. Results of this analysis are presented in Figure 91 on page 206 of this report.

The steady state tow analysis was performed with the aircraft towing a 10,000 pound payload at tow line lengths of 200 feet, 500 feet, and 1000 feet. Results of this analysis are presented in Figure 93 on page 209 of this report.

In both analyses, the aircraft gross weight was 110,000 pounds not including the applied loads of the payload and tow line.

The method of analysis was to determine the total moment of the aircraft about its center of gravity for the specified conditions and then determine the elevator deflection required to overcome the calculated moment. In order to simplify the analysis it is assumed that the aircraft c g is at the 1/4 point of the mean aerodynamic chord (m.a.c.).

The total upsetting moment about the airplane c.g. then is

$$M_p = T\,(d \sin \theta - h \cos \theta) \qquad (143)$$

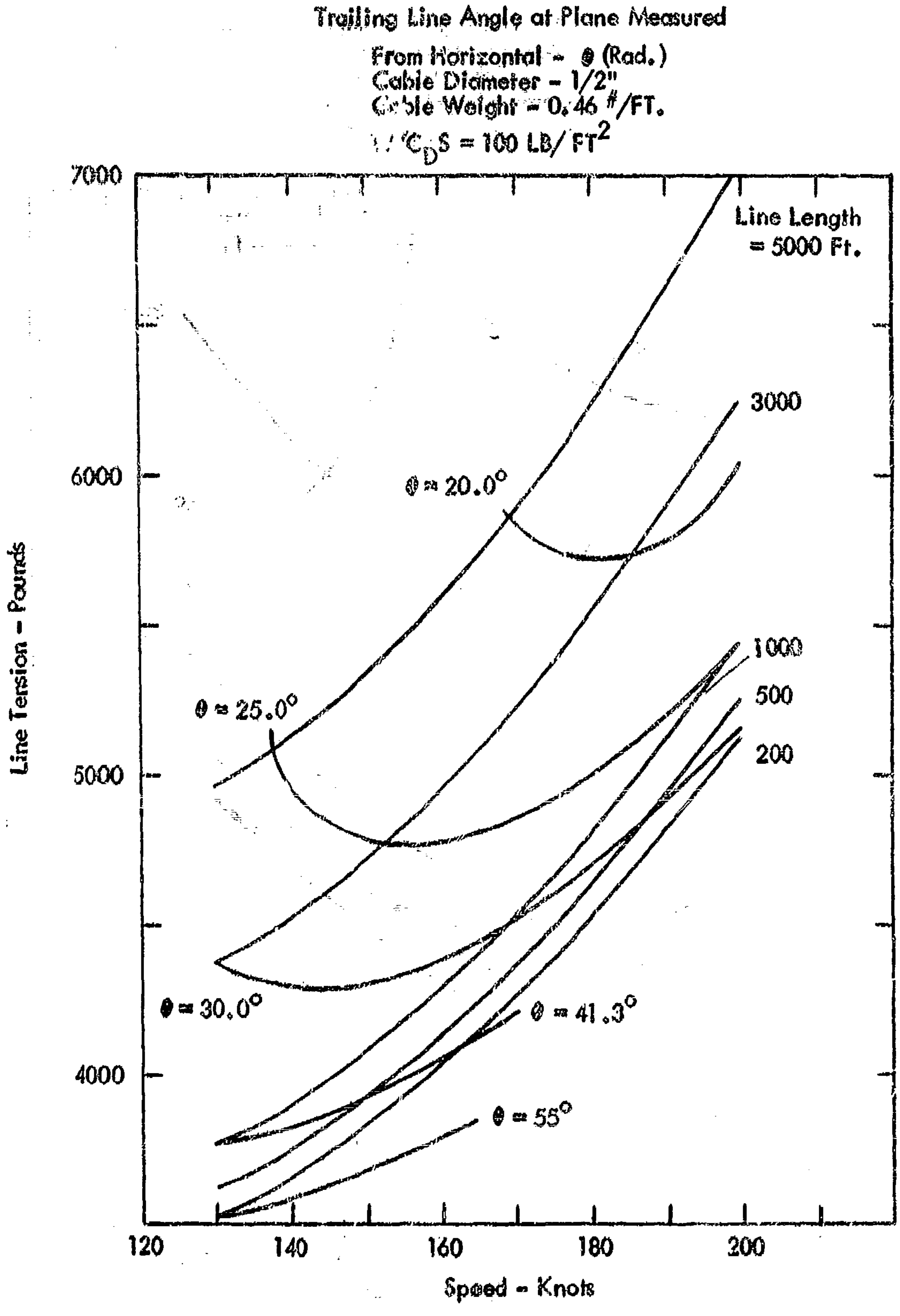


Figure 135 - Payload Cable Characteristics - 3000 Pound Payload

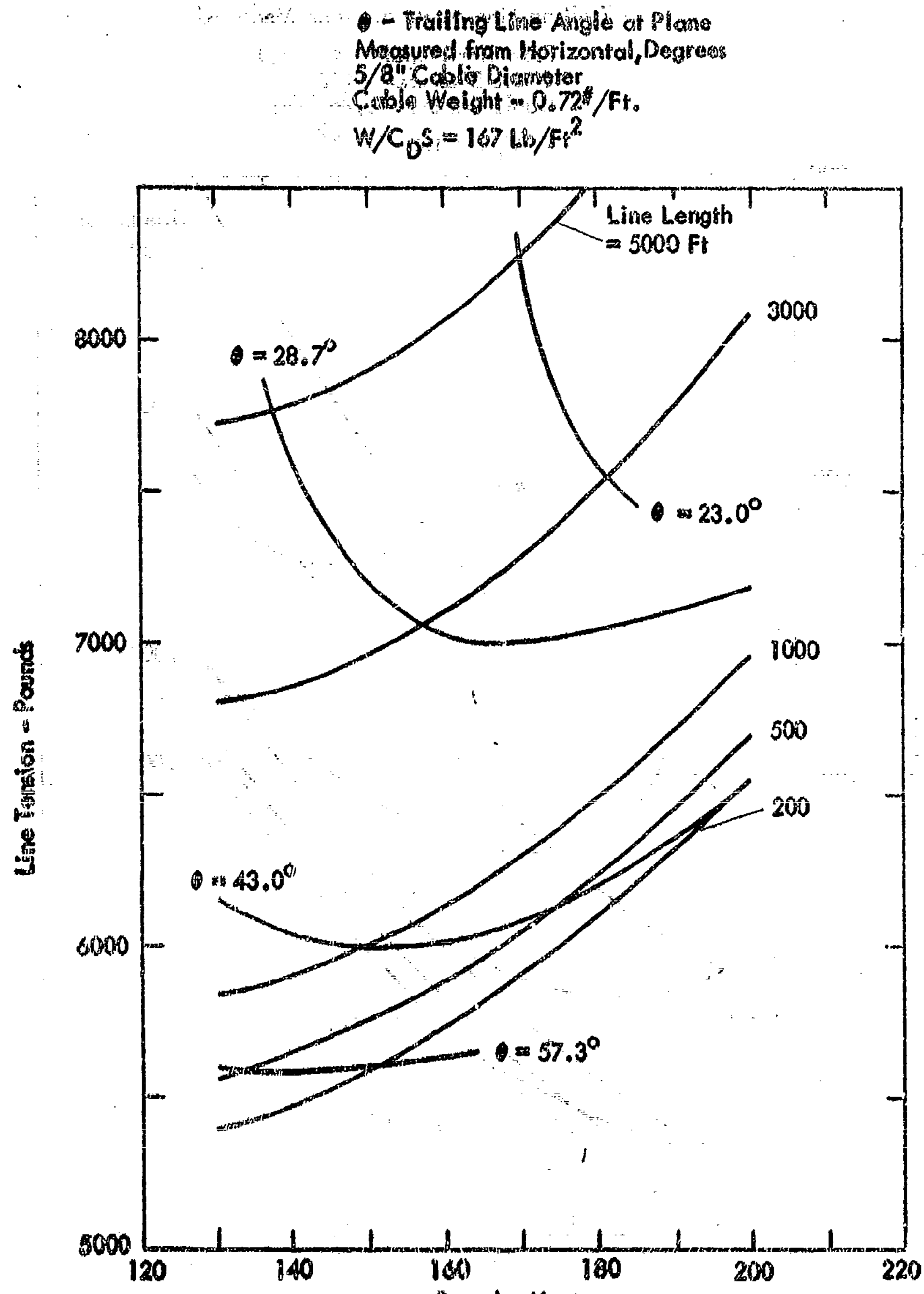


Figure 136 – Payload Cable Characteristics – 5000 Pound Payload

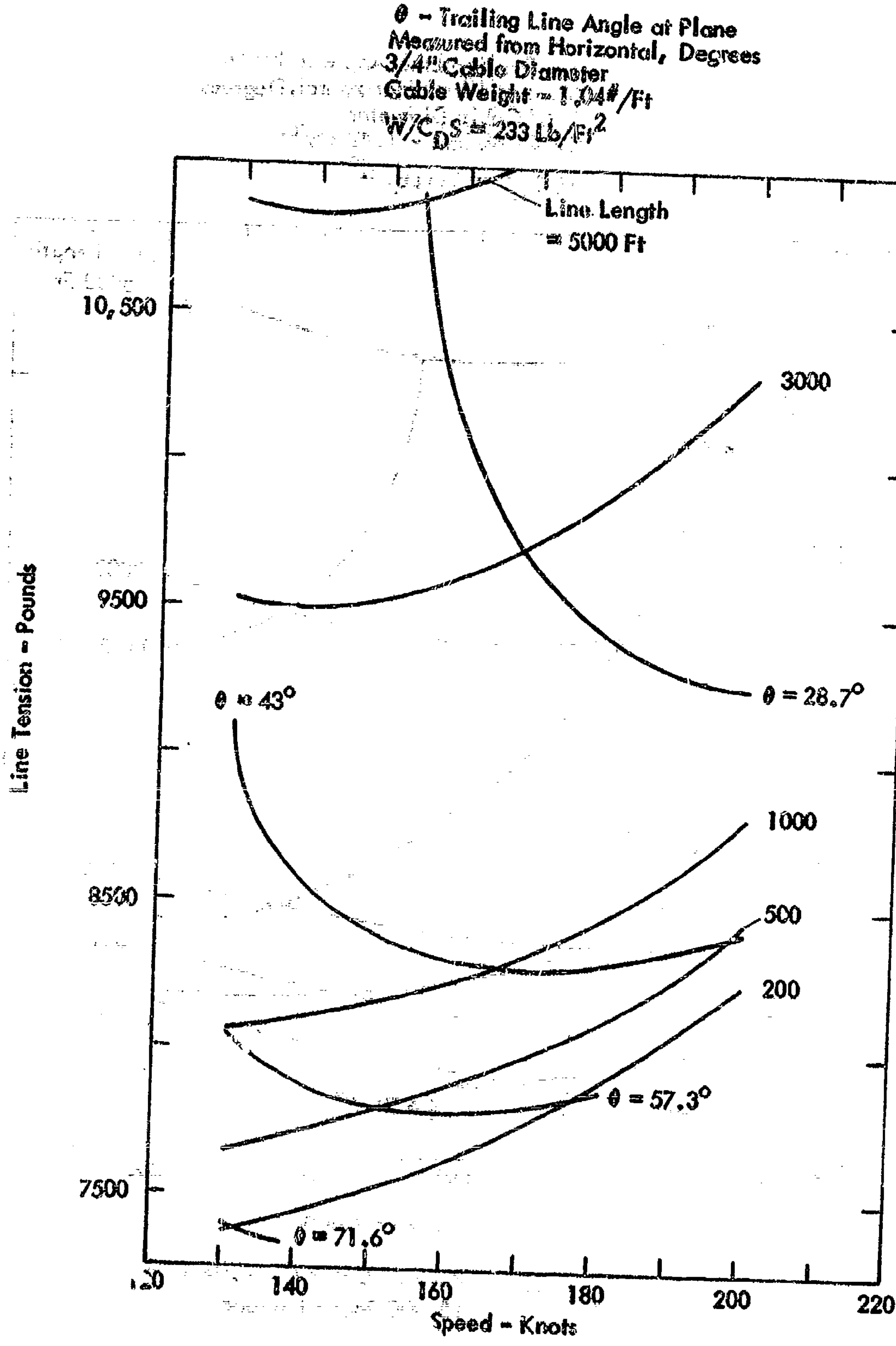


Figure 137 – Payload Cable Characteristics – 7000 Pound Payload

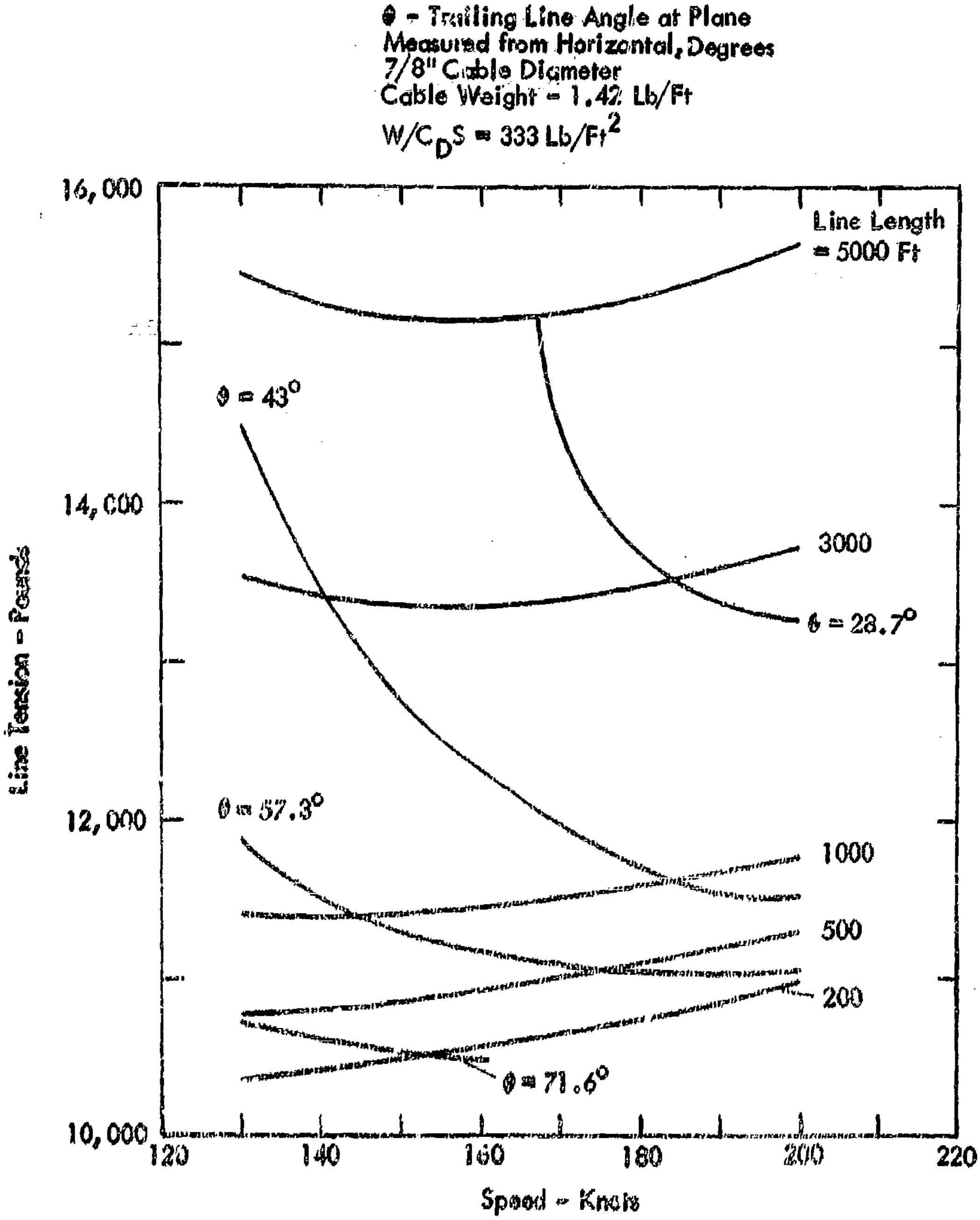


Figure 138 - Payload Cable Characteristics - 10,000 Pound Payload

1/2" Cable Diameter
Cable Weight - 0.46#/Ft.
W/C_DS = 100 Lb/Ft^2

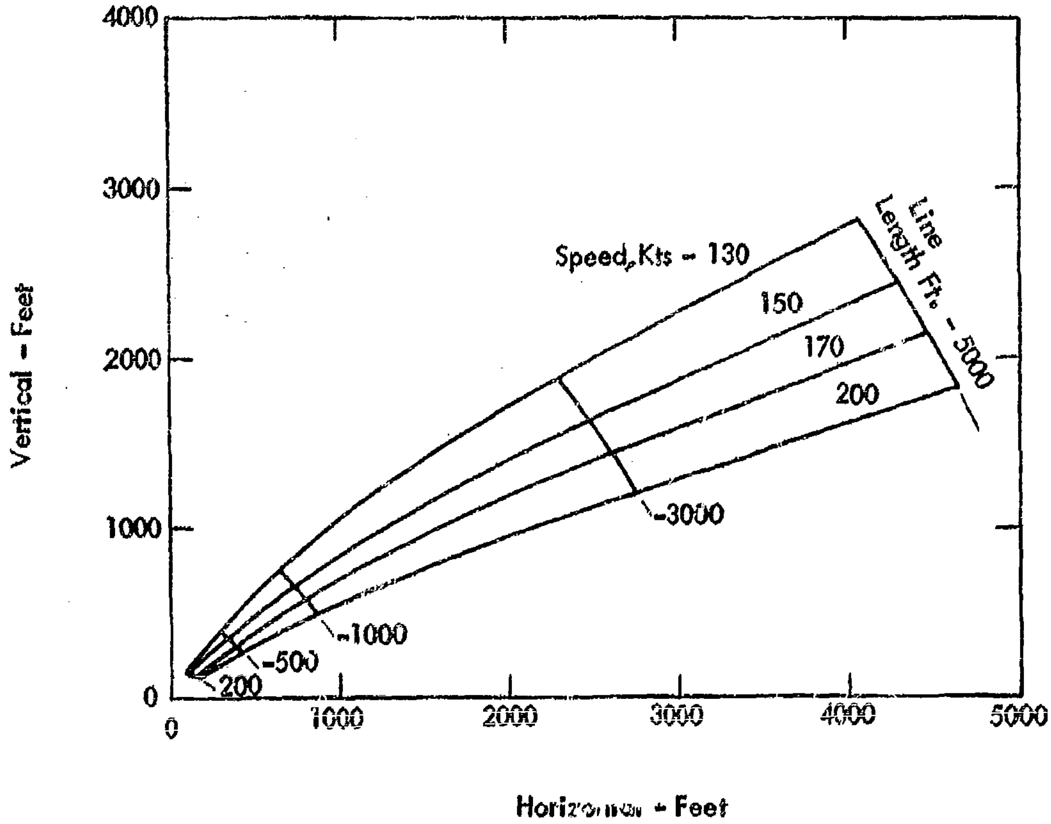


Figure 139 - Payload Position Relative to Tow Plane - 3000 Pound Payload

5/8" Cable Diameter
Cable Weight - 0.72#/Ft
$W/C_DS = 167$ Lb/Ft^2

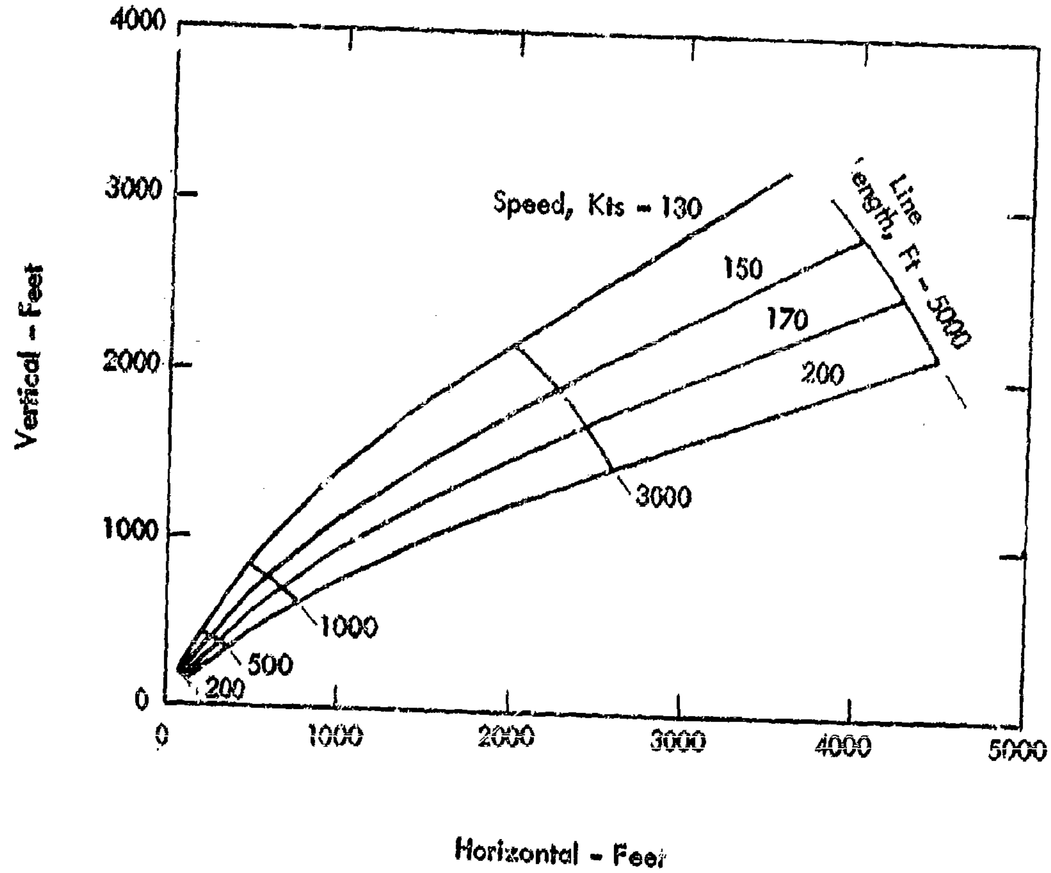


Figure 140 - Payload Position Relative To Tow Plane - 5000 Pound Payload

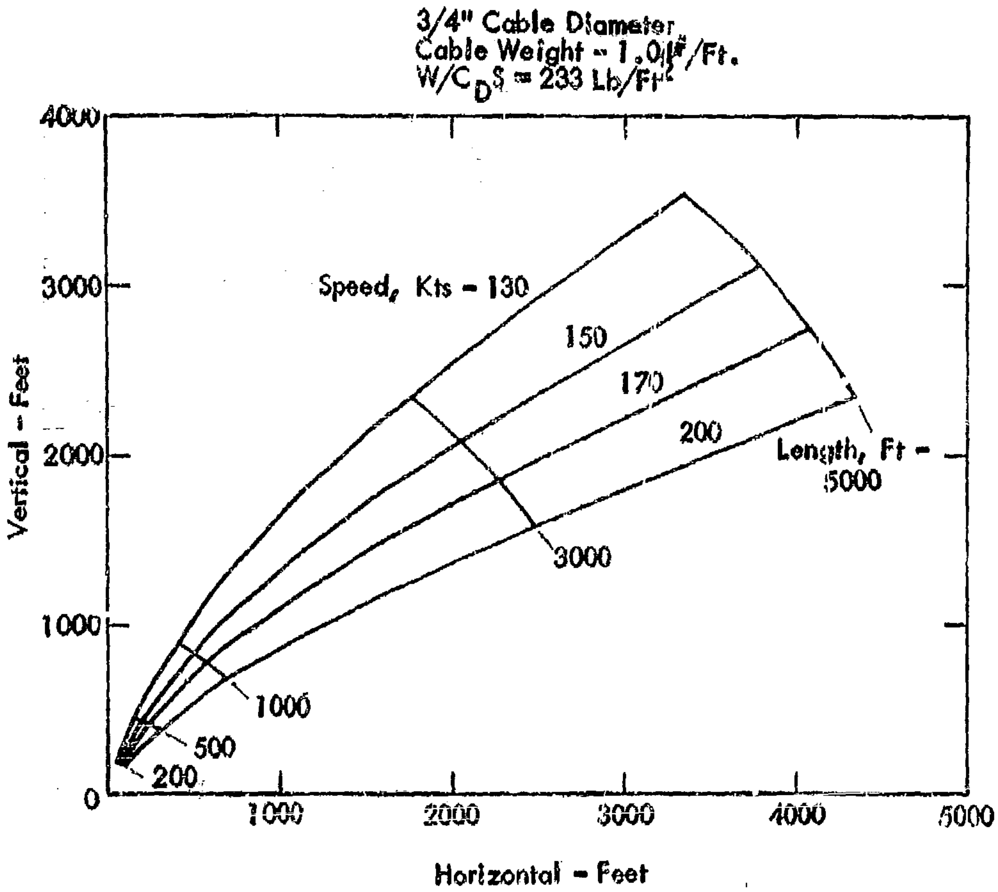


Figure 141 - Payload Position Relative to Tow Plane - 7000 Pound Payload

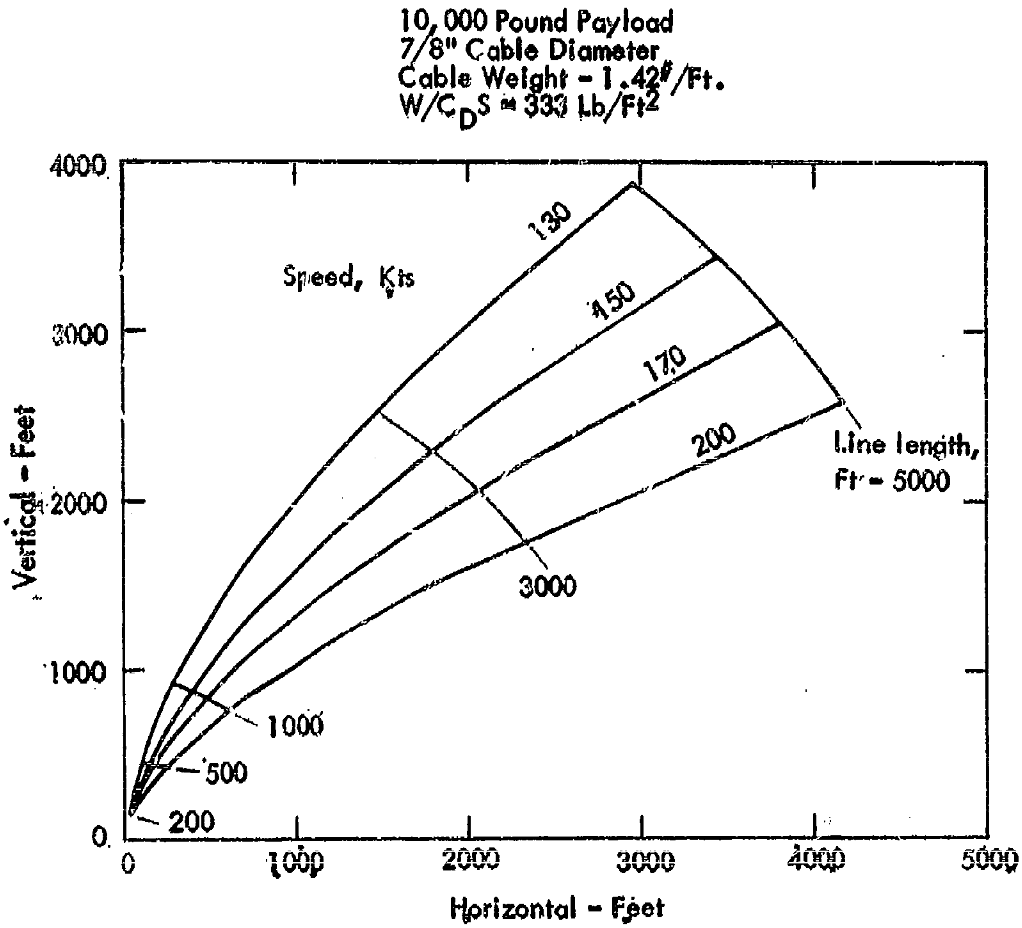


Figure 142 – Payload Position Relative to Tow Plane – 10,000 lb. Payload

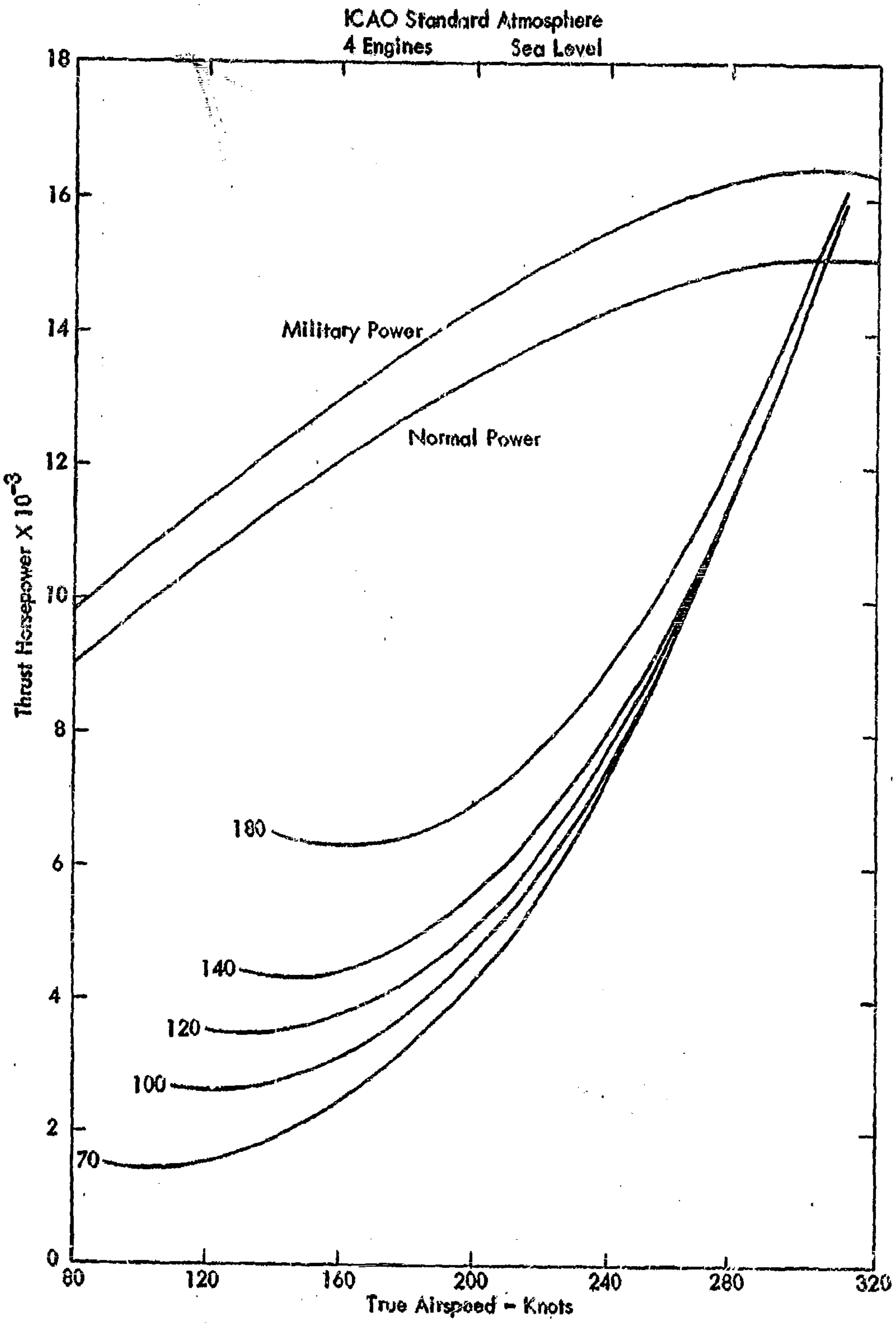


Figure 143 – C-130E Thrust Required and Available – Flaps and Gear up

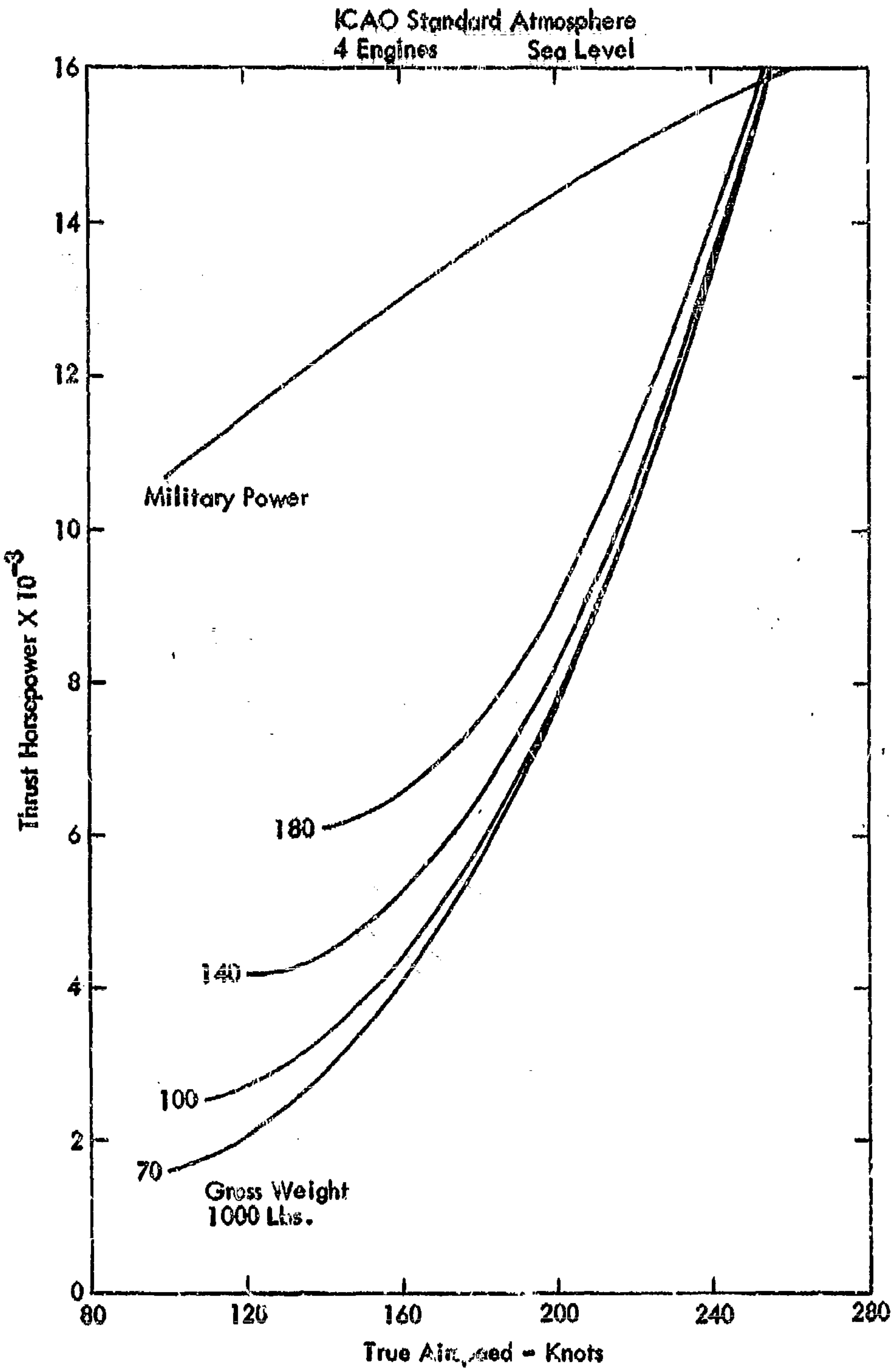


Figure 144 - C-130E Thrust Required and Available - 50 Percent Flaps, Gear Up

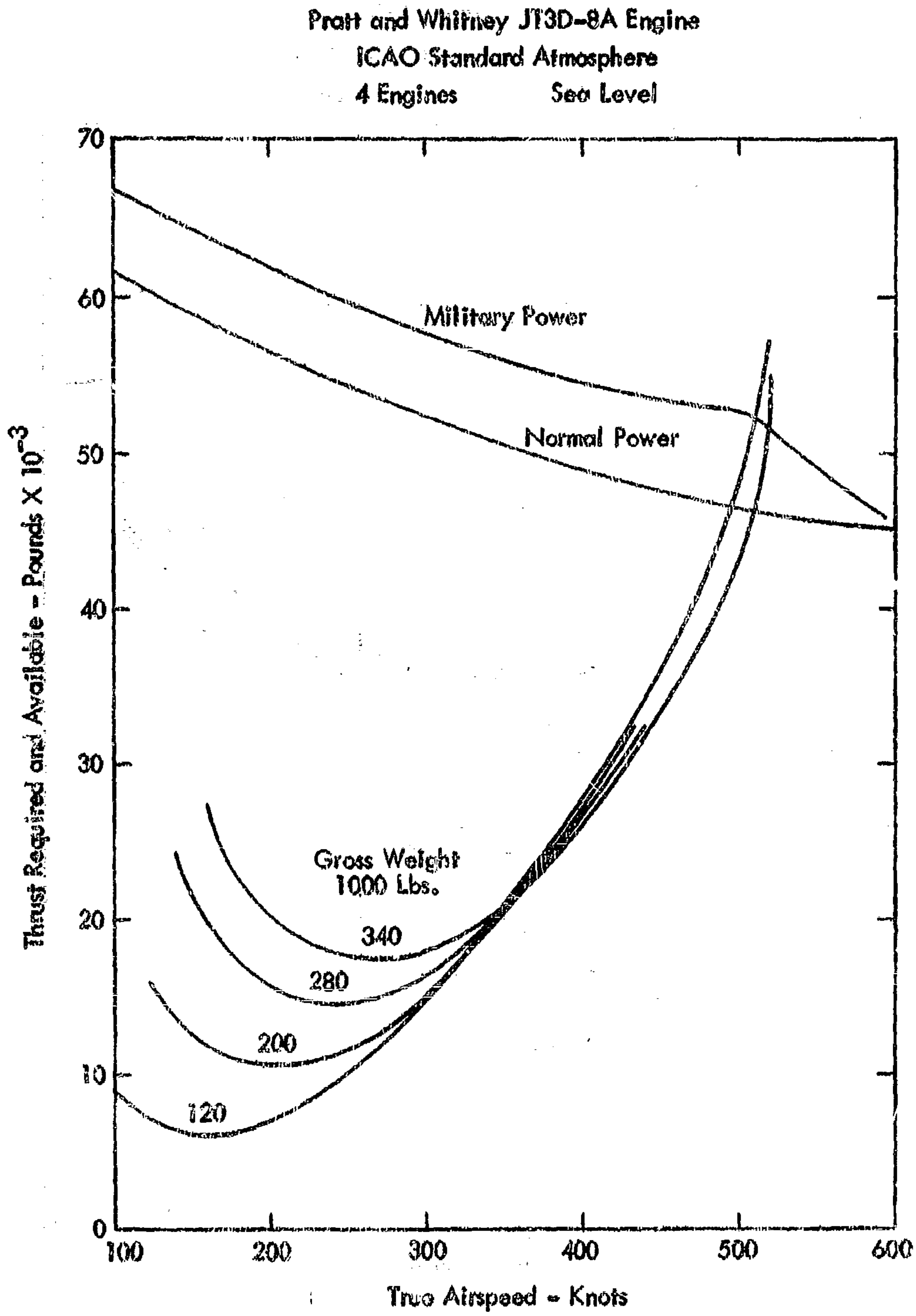


Figure 146 - C-141 Thrust Required and Available - Flaps and Gear Up

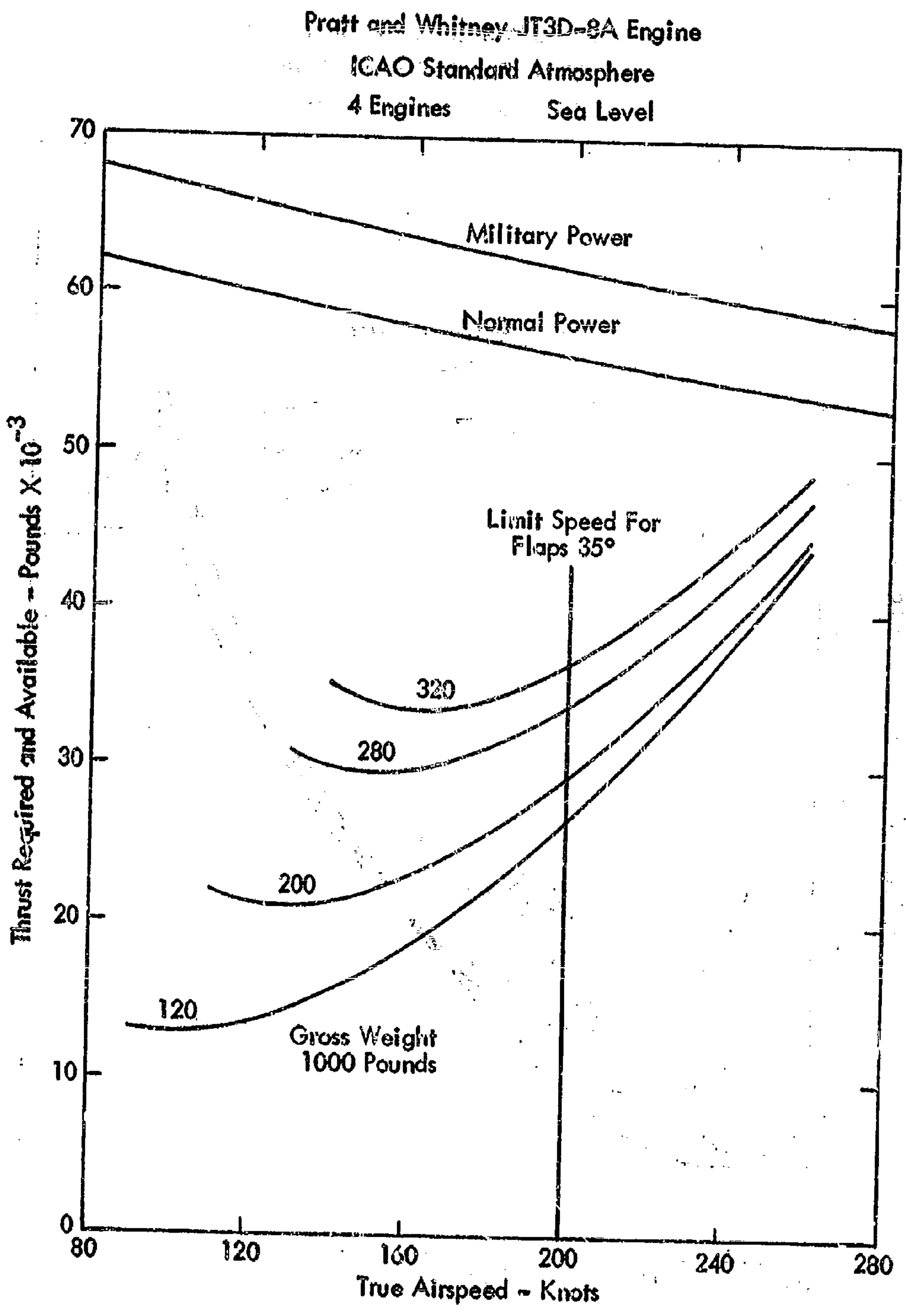


Figure 146 - C-141 Thrust Required and Available - 35 Percent Flaps, Gear Up

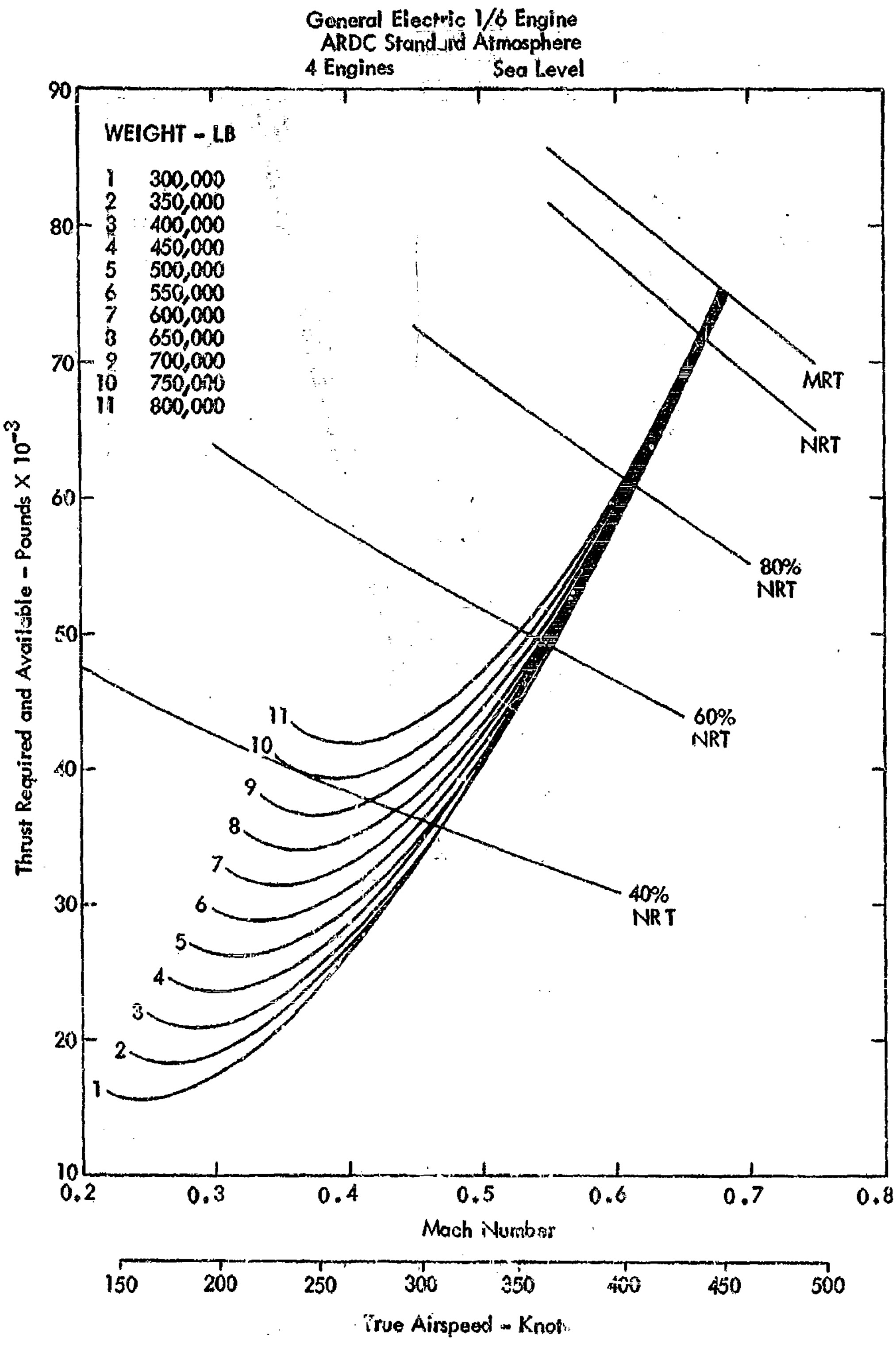


Figure 147 C-5A Thrust Required and Available - Flaps and Gear Up

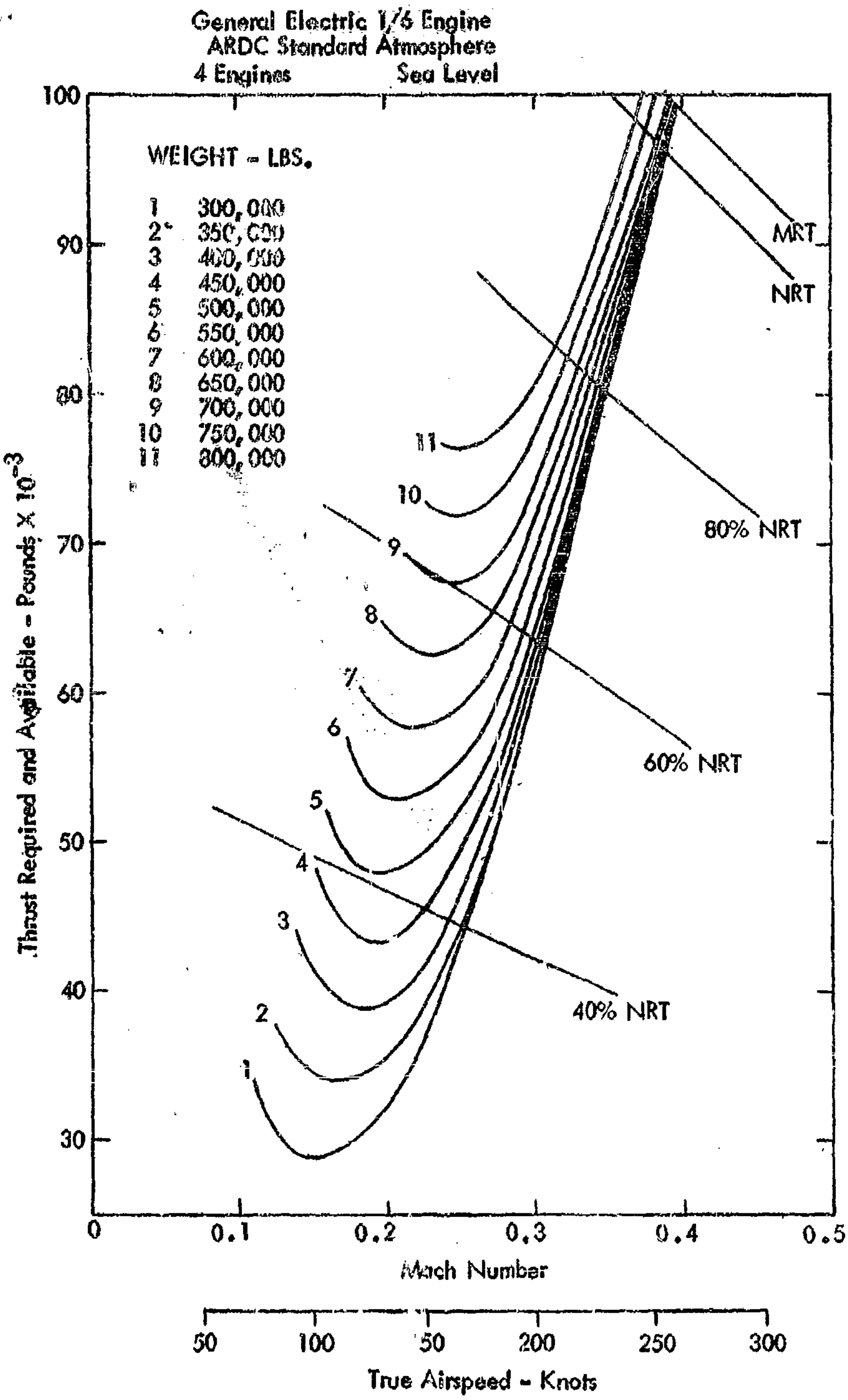


Figure 148 C-5A Thrust Required and Available - 30 Degree Flaps, Gear Up

where:

T = Line tension

d = horizontal distance to cg

h = vertical distance to cg

θ = line angle with horizontal

The applied moment is then reduced to coefficient form:

$$C_{m_{a_p}} = \frac{Mp}{Sq\bar{c}} \tag{144}$$

where:

S = C-130 wing area - feet^2

q = dynamic pressure - pounds/feet^2

$\bar{c}$ = length of mean aerodynamic chord - feet

The total moment coefficient of the aircraft is then made up of the C_{m_a} of the aircraft alone plus the $C_{m_{a_p}}$ applied by the tow line:

$$C_{m_{a_t}} = C_{m_a} + C_{m_{a_p}} \tag{145}$$

Two basic equations of aircraft longitudinal stability are used to determine the elevator deflection:

The sum of moments about the cg must = 0; hence:

$$0 = C_{m_{a_t}} + C_{m_{\delta_e}} \cdot \delta_e + C_{m_{\delta_t}} \cdot \delta_t \tag{146}$$

where:

$C_{m_{\delta_e}}$ = Change in moment coefficient per degree of elevator deflection

δ_e = elevator deflection in degrees.

$C_{m_{\delta_t}}$ = change in moment coefficient per degree of elevator tab deflection

δ_t = elevator tab deflection, degrees.

The second equation is derived from the fact that sum of elevator hinge moments must be zero for a trimmed elevator.

Hence:

$$0 = C_{h_{\alpha_t}} \cdot \alpha_t + C_{h_{\delta_e}} \cdot \delta_e + C_{h_{\delta_t}} \cdot \delta_t + C_{h_o} \tag{147}$$

where:

$C_{h_{\alpha_t}}$ = change in elevator hinge moment per degree os horizontal tail angle of attack

α_t = angle of attack of horizontal tail

$C_{h_{\delta_e}}$ = change in elevator hinge moment per degree of elevator deflection.

δ_e = elevator deflection in degrees

$C_{h_{\delta_t}}$ = change in elevator hinge moment per degree of tab deflection

δ_t = elevator tab deflection

C_{h_o} = hinge moment coefficient due to fuselage angle of attack.

The values of the above stability coefficients and derivatives may be determined from C-130 stability data. Since $C_{m_{\alpha_t}}$ can be determined as shown previously, equations 146 and 147 above may be solved simultaneously for the values of δ_e and δ_t for any given flight condition.

In the case of the balloon-line hook-up, line tension and tow line angle varied with time throughout the engagement phase. The data presented in Figure 91, page 206 resulted from solution of stability equations (146) and (147) for each condition of tow line angle and tension.

For the steady state tow conditions, the equations were solved for each flight condition. The elevator deflections required to hold level flight for each of the tow conditions are described in Figure 93, page 209.

In the elevator analysis for the impact phase of retrieval, the maximum aircraft angles of attack and the corresponding aircraft load factors were determined. The data generated on aircraft load factors are included in Figure 92, page 207, of this report.

Figures 143 through 148 present the thrust and thrust horsepower available and required for the C-130, C-141, and C-5 for a standard day, sea level, four-engine operation.

APPENDIX B

EVALUATION METHODOLOGY

Introduction

As part of the investigations connected with the conceptual development of aerial delivery and retrieval systems for heavier payloads, the Lockheed-Georgia Company has developed a methodology for evaluating the performance of these concepts. The evaluation methodology is used during the Phase III portion of the study in order that the most promising systems, in consideration of design, operational, and performance parameters, may be identified.

The evaluation methodology developed for this study is discussed in some detail in the introductory remarks in the next section, which presents and account of the evolution of the methodology used along with numerical data for use in application of the method. Results obtained with this methodology give a valid estimate of the relative ranking of the several concepts. Also, since the performance measures used to evaluate the concepts express actual relationships of operational interest, an absolute measure of the performance of each concept results from the evaluation technique described in this report.

Methodology

Several methods for concept evaluation have been examined. Upon closer analysis, it appears that the various methods can be classified into one of two broad categories:

- o Ranking methods based on a weighted scoring of concept design, operational, and performance parameters
- o Ranking methods based on concept performance evaluated in terms of a single, operationally meaningful performance parameter.

As the study progressed, it became apparent that the first approach mentioned above possessed serious shortcomings which might lead to erroneous results. Specifically, the assignment of weighting factors to design, operational, and performance parameters can be a valid step in determining overall system worth only if these weighting factors reflect the proportion of missions where each parameter dominates. In those cases where missions are well defined, the method of weighted scoring is relatively simple and thus to be preferred to the method of relative performance based on operational variants.

For the current evaluation, which covers concepts whose operational use will extend over the next decade, attempts at mission analyses of sufficient depth and scope to yield significant relative frequencies of occurrence of requirements for specific performance aspects would be both prohibitive in terms of effort and uncertain in results. Of necessity, they would have to be based on subjective ideas relative to future theaters of operation and scenarios. The decision was made, therefore, to base the comparative evaluation on a ranking of system performance expressed in terms of a singly derived, operationally meaningful performance parameter.

A flow chart illustrating the application of the selected method is shown in Figure 149. As shown in the figure, the evaluation process begins with a functional description of the concept to be analyzed. This description consists of the two following principal parts:

- o Definition of operational phases
- o Selection of parameter values for design point definition

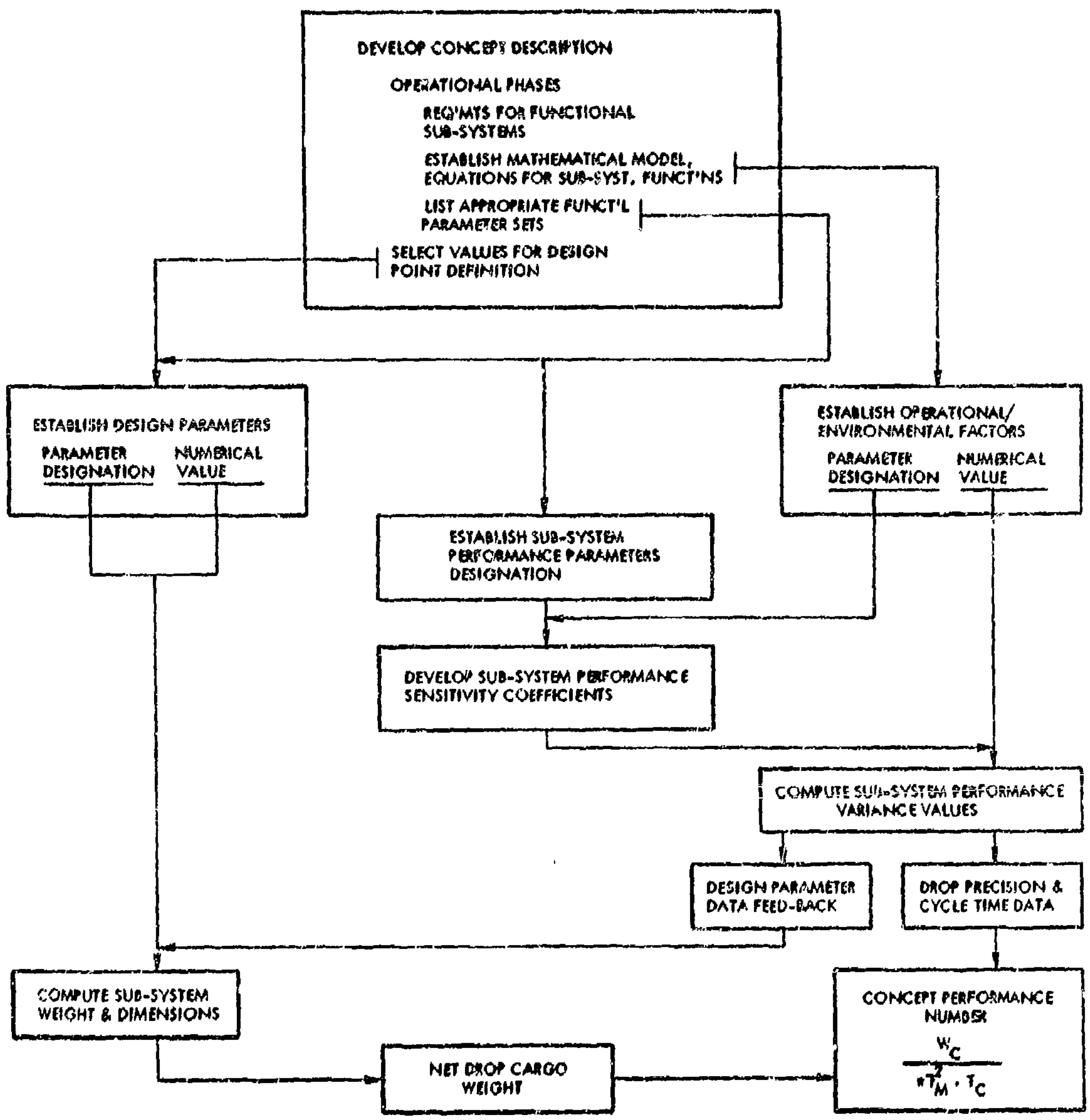


Figure 149 - General Method For Concept Evaluation

The definition of operational phases, is used as follows:

- o To define requirements for functional subsystems
- o To establish mathematical models for subsystem functions
- o To list the appropriate sets of functional parameters

The mathematical modeling serves to identify the set of operational/environmental parameters which exert influence on the functions and performance of the different subsystems. Associated with this task is the establishment of a list of designated subsystem performance parameters. Selection of items for this list is based on an examination of whether a particular parameter tends to exert a significant influence on the functions performed in a later operational phase.

The next step in the procedure is to develop sensitivity coefficiencts for the several subsystem performance parameters with respect to the appropriate operational/environmental factors. Combining numerical values for the sensitivity coefficients with numerical values for variations and scatter in operational/environmental factors yields data for subsystem performance variances. Certain of these data may tend to amplify or extend the set of design parameter values and are consequently fed back in' design process for determination of system component weights and dimensions. Th nder of the process follows a logical sequence to produce the final measures of concept performance as given in Figure 149.

Aerial Delivery

A major problem of existing aerial delivery systems, which sets them apart from surface modes of delivery, is their inability to achieve consistent point-to-predetermined-point delivery accuracy. Paradrop systems, for example, demonstrate this problem in current operations.

In view of this situation, some means must be found to measure both delivery precision and other concept features accurately if a fair evaluation of the various concepts is to be realized.

There are several ways in which a merit ranking of different concepts with regard to overall performance can be achieved. Perhaps the most obvious one is to form the ratios (r_i) of parameter values which express different aspects of the concept performance with corresponding values that could be established for an "ideally" performing concept, and, to accept, as a measure of "total" or overall concept performance, the following sum:

$$\text{Concept Ranking Number (CRN)} = \sum_{i=1}^{i=M} K_i \cdot r_i \qquad (148)$$

where

$$r_i = \frac{\text{Concept performance capability for aspect (i)}}{\text{"Ideal" performance for aspect (i)}}$$

K_i = relative weighting factor

M = Number of performance aspects upon which the evaluation is based.

There are two basic objections to this approach:

The first objection is that the CRN established in the manner outlined above does not present the concept performance capability in terms which intuitively and immediately can be applied to operational situations where a need for aerial delivery capability exists.

The second objection concerns the value of weighting factors to be applied to the several terms of Equation 148. It arises from the fact that the operational and environmental factors which exert influence on the system performance will vary from one operational situation to another, and also that operational considerations will shift emphasis on the various performance aspects, i.e., change the numerical values of the K_i's from one situation to another. In order to obtain representative values for the K_i's, a very comprehensive survey of all missions requiring the application of airdrop capability would be needed so that statistical data for the distribution of K_i-values could be derived. From these distributions, the median values could be taken as representing the most fair and unbiased evaluation basis.

A second approach to the problem of establishing a method for concept capability ranking consists of functionally combining the several parameters expressing different aspects of the concept performance to obtain an operationally meaningful single performance parameter value. For airdrop concepts, a Concept Performance Number (CPN) can be established from operational considerations. In forming the expression for the CPN, the following factors will be used, each of which expresses operational significant performance aspects:

- o Net weight of delivered cargo, W_c
- o Probable miss distance for the delivery, $\bar{r}_m$
- o Minimum time interval between any two successive deliveries, T_c

The concept performance number can then be defined as a cargo delivery density rate,

$$CPN = \frac{W_c}{\pi \bar{r}_m^2 \ T_c} \quad \text{Tons/Square foot/Hour} \tag{149}$$

Expressed in this form, the concept performance capability can be applied immediately to operational situations characteristics by requirements for specific delivery rates in tons/hour at drop zones of given areas.

In the following paragraphs, an outline of the methods for deriving individual performance measures are presented.

Analysis of Specific Functional Phases

The nucleus of the method is an operational analysis, at the conceptual level, of the several functionally distinct phases of the airdrop operation. This is done in order to identify parameters which exert influence on the basic performance factors outlined above. The functional phases considered in this analysis follow:

- Initial cargo preparation and loading
- Drop cargo extraction/ejection
- Cargo descent control/recovery
- Impact deceleration control
- Cargo drop zone disposition

In addition, possible impact on concept performance of requirements for emergency cargo jettison capability will be examined.

Initial Cargo Preparation and Loading - Functions in this phase which specifically pertain to cargo drop operations are:

- Weight of cargo being prepared
- Weight and/or volume of gear involved
- Effort and time required for the operation

Influence on the basic performance factors can be traced principally to the weight and volume of required gear. If the total drop load weight is limited, then this weight increment reduces the available weight of useful cargo. The amount of required shock-proofing and harnessing material and equipment, however, is not sensitive to any operational or environmental factors appearing in this phase but is determined by design conditions developed from consideration of operational and environment factors which belong to other phases of the drop operation. The time required for initial preparation of cargo could conceivably be considered as a parameter of some significance. Its importance, however, will tend to be masked by the variation in flight time between loading and drop zones. In addition, since most of the cargo preparation effort will have to be un-done as part of the functions performed in the cargo drop zone disposition phase, significant differences between concepts in this regard will be properly evaluated for this phase.

Cargo Extraction/Ejection - This phase comprises the following activities:

- Readying of extraction gear
- Disconnection of tie-down gear
- Activation and operation of extraction system

Parameters required for an exhaustive functional description of activities in this phase are

- Drop cargo package weight (includes weight of attached drop gear) W_{dc}
- Manpower requirement
  - Crew size N_e
  - Crew effort active time t_{cre}
- Aircraft flight speed V
- Cargo floor sliding distance X_s
- Cargo extraction load factor n
- Cargo extraction impulse I_{ce}
- Cargo tip-off pitch impulse I_{pe}
- Cargo extraction time interval t_e
- Aircraft extraction drag impulse I_{de}
- Aircraft pitch impulse I_p

For identification of parameters which qualify as measures of the performance of any subsystem, the deciding test is whether the parameter in question exerts a significant influence on any subsequent course of events.

With these considerations in mind, the following list of performance parameters for the extraction/ejection subsystem can be established:

- Drop cargo package weight W_{dc}
- Cargo exit velocity V_e
- Cargo extraction time interval t_e
- Location of the airplane relative to intended impact point at cargo exit X_e
- Cargo tip-off pitch impulse I_{pe}

Operational and environmental factors which exert significant influence on these performance parameters follow:

- Variations in drop cargo weight $\overline{\Delta W}_{c(RMS)}$
- Variations in flight speed $\overline{\Delta V}(RMS)$
- Gust velocity $\overline{\Delta U}(RMS)$

The degree of influence on extraction/ejection system performance of the operational and environmental factors can be traced by sensitivity coefficients. These sensitivity coefficients can be expressed mathematically as partial derivatives with respect to each one of the operational and environmental factors. For the cargo extraction/ejection phase, the following set of sensitivity coefficients is obtained:

$$\partial V_e/\partial W_c,\ \partial V_e/\partial V,\ \partial V_e/\partial U$$
$$\partial t_e/\partial W_c,\ \partial t_e/\partial V,\ \partial te/\partial U$$
$$\partial X_e/\partial W_c,\ \partial X_e/\partial V,\ \partial X_e/\partial U$$
$$\partial I_{pe}/\partial W_c,\ \partial I_{pe}/\partial V,\ \partial I_{pe}/\partial U$$

Performance parameter deviations (RMS) for the cargo extraction/ejection phase are next determined by the following relations:

Exit velocity,

$$\overline{\Delta V}_e = \left\{\left[(\partial V_e/\partial W_c)\ \overline{\Delta W}_c\right]^2 + \left[(\partial V_e/\partial V)\ \overline{\Delta V}\right]^2 + \left[(\partial V_e/\partial U)\ \overline{\Delta U}\right]^2\right\}^{1/2} \tag{150}$$

Extraction time,

$$\overline{\Delta t}_e = \left\{\left[(\partial t_e/\partial W_c)\ \overline{\Delta W}_c\right]^2 + \left[(\partial t_e/\partial V)\ \overline{\Delta V}\right]^2 + \left[(\partial V_e/\partial U)\ \overline{\Delta U}\right]^2\right\}^{1/2} \tag{151}$$

Cargo exit point location,

$$\overline{\Delta X}_e = \left\{\left[(\partial X_e/\partial W_c)\ \overline{\Delta W}_c\right]^2 + \left[(\partial X_e/\partial V)\ \overline{\Delta V}\right]^2 + \left[(\partial X_e/\partial U)\ \overline{\Delta U}\right]^2\right\}^{1/2} \tag{152}$$

Cargo pitch impulse,

$$\overline{\Delta I}_{pe} = \left\{\left[(\partial I_{pe}/\partial W_c)\ \overline{\Delta W}_c\right]^2 + \left[(\partial I_{pe}/\partial V)\ \overline{\Delta V}\right]^2 + \left[(\partial I_{pe}/\partial U)\ \overline{\Delta U}\right]^2\right\}^{1/2} \tag{153}$$

Of the four performance parameters listed above, the cargo exit pitch impulse, I_{pe}, is excluded from further consideration in the elevation scheme for the following reasons:

- Its magnitude depends strongly on independent control which can be exercised by proper arrangement of extraction bridle attachment adjusted to fit the particular extraction load configurations.
- The multitude of possible extraction load configurations that would need investigation.
- The relatively weak influence of residual pitching motion of the drop cargo on the amount (but not the arrangement) of impact shock absorbing material.

Cargo Descent Control/Recovery – This phase covers the activities and events following exit of the drop cargo from the airplane ramp and terminates upon ground contact of the cargo pallet or impact shock absorber.

The system functions and activities occurring in this phase are specifically directed toward the operational objective of depositing the drop cargo in a predetermined location with a terminal rate of approach at that location less than, or equal to, a specified design value.

Parameters required for a complete description of functional activities and events in this phase follow:

o Drop cargo weight	W_c
o Aircraft flight speed	V
o Drop altitude	H
o Drop cargo exit velocity	V_e
o Wind speed	V_w
o Gust velocity	U
o Drop cargo load factor (Magnitude and direction)	n
o Drop cargo exit point	X_e

Parameters which describe the system performance during this phase follow:

o Drop cargo weight	W_e
o Impact point coordinate deviations	X_t, Y_t
o Cargo impact velocity (x, y, z, denote component values along respective axes.)	$V_{t(x,y,z)}$

Operational and environmental factors which exert a significant influence on these performance parameters follow:

o Cargo weight variations	$\Delta\bar{W}_c$
o Flight speed variations	$\Delta\bar{V}$
o Cargo exit speed variations	$\Delta\bar{V}_e$

- Wind speed variations $\Delta\bar{V}_w$
- Gust velocity variation $\Delta\bar{U}$
- Altitude variations $\Delta\bar{H}$

The degree of influence is expressed by the sensitivity coefficients :

$$\partial X_t/\partial W_c,\ \partial X_t/\partial V,\ \partial X_t/\partial V_e,\ \partial X_t/\partial V_w,\ \partial X_t/\partial U,\ \partial X_t/\partial H$$

$$\partial Y_t/\partial W_c m\ \partial Y_t/\partial V,\ \partial Y_t/\partial V_e,\ \partial Y_t/\partial V_w,\ \partial Y_t/\partial U,\ \partial Y_t/\partial H$$

$$\partial V_{t(x,y,z)}/\partial W_c,\ \partial V_{t(x,y,z)}/\partial V,\ \partial V_{t(x,y,z)}/\partial V_e,$$
$$\partial V_{t(x,y,z)}/\partial V_w,\ \partial V_{t(x,y,z)}/\partial U,\ \partial V_{t(x,y,z)}/\partial H$$

Performance parameter deviations (RMS) for the descent control/recovery phase follow, accordingly:

$$\bar{X}_t = \Big\{\left[(\partial X_t/\partial W_c)\Delta\bar{W}_c\right]^2 + \left[(\partial X_t/\partial V)\Delta\bar{V}\right]^2 + \left[(\partial X_t/\partial V_e)\Delta\bar{V}_e\right]^2 + \left[(\partial X_t/\partial U)\Delta\bar{U}\right]^2 + \left[(\partial X_t/\partial H)\ \Delta\bar{H}\right]^2\Big\}^{1/2} \quad (154)$$

$$\bar{Y}_t = \Big\{\left[(\partial Y_t/\partial W_c)\Delta\bar{W}_c\right]^2 + \left[(\partial Y_t/\partial V)\Delta\bar{V}\right]^2 + \left[(\partial Y_t/\partial V_e)\Delta\bar{V}_e\right]^2 + \left[(\partial Y_t/\partial U)\Delta\bar{U}\right]^2 + \left[(\partial Y_t/\partial H)\Delta\bar{H}\right]^2\Big\}^{1/2} \quad (155)$$

$$\bar{V}_{t(x,y,z)} = \Big\{\left[(\partial V_{t(x,y,z)}/\partial W_c)\overline{\Delta W}_c\right]^2 + \left[(\partial V_{t(x,y,z)}/\partial V)\overline{\Delta V}\right]^2 + \left[(\partial V_{t(x,y,z)}/\partial V_e)\overline{\Delta V}_e\right]^2 + \left[(\partial V_{t(x,y,z)}/\partial U)\ \overline{\Delta V}\right]^2 + \left[(\partial V_{t(x,y,z)}/\partial H)\ \overline{\Delta H}\right]^2\Big\}^{1/2} \quad (156)$$

(x, y, z denote component values.)

Impact Deceleration Control – This phase covers the activities and events following initial ground contact of the drop cargo pallet and terminates when the cargo is at rest on the ground. The functional activities for this phase are directed toward the objective of absorbing the kinetic and potential energy possessed by the cargo at the instant of ground contact under the constraint of a tolerable acceleration exposure for the drop cargo.

Parameters required for a complete description of functional activities and events in this phase follow:

Geometric configuration of drop cargo
Inertia properties of drop cargo

- o Weight W_v
- o Moments of Inertia I_x, I_y, I_z
- o Impact velocity components V_{ix}, V_{iy}, V_{iz}
- o Rotational velocity components $\omega_x, \omega_y, \omega_z$
- o Cargo attitude angles $\gamma_x, \gamma_y, \gamma_z$
- o Soil shock absorbing capability
- o Soil sliding friction coefficient μ_s
- o Shock absorber travel distance ΔH_s
- o Shock absorber load-compression characteristics

The rotational state parameters ($I_x, I_y, I_z, \omega_x, \omega_y, \omega_z$ and γ_xm γ_y, γ_z) are not considered in this analysis, for the reasons given earlier in the analysis of the cargo extraction/ejection phase. Further, inorder to simplify the analysis, a constant value of the soil sliding friction coefficient μ_s is assumed without introducing a bias in the concept evaluation. Similarly, soil shock absorbing properties are neglected for all concepts. Finally, a stroke-independent shock absorber force characteristic is assumed. This assumption can be made without prejudice to any concept since the phase considered only covers the shock-absorbing qualities required for the drop cargo pallet or platform.

With these assumptions, the list of parameters required for a functional description of activities and events in the impact deceleration control phase reduces to the following:

- o Drop cargo weight, W_{cd}
- o Impact velocity components, V_{ix}, V_{iy}, V_{iz}
- o Soil sliding friction coefficient, μ_s
- o Limiting impact load factor, n_i

For the purpose of analysis it is convenient to express the cargo weight as a sum of two terms:

$$W_{cd} = W_c + \Delta W_{pl} \tag{157}$$

where

$\overline{W}_c$ = the design value for the condition considered, and

ΔW_{pl} = a random element of variation

Similarly, the impact velocity components can also be expressed as two-term sums:

$$V_{i(x,y,z)} = \overline{V}_{i(x,y,z)} + \Delta V_{i(x,y,z)} \tag{158}$$

where

$\bar{V}_{i(x,y,z)}$ = design value for the component considered, and

$\Delta V_{i(x,y,z)}$ = randomly varying increments

The soil sliding friction coefficient, μ_s, and the limiting value for the tolerable impact load factor, n_i, are both assumed to be constant for all concepts.

Parameters which describe the system performance for this phase follow:

- o Cargo weight, W_{cd}
- o Shock absorber compression, ΔH_s
- o Cargo ground sliding distance, $\Delta \bar{r}_s = \left[\Delta \bar{X}_s^2 + \Delta \bar{Y}_s^2\right]^{1/2}$ (159)

The numerical values for these performance parameters are functions of the phase input variables W_c and $V_{i(x,y,z)}$, with sensitivity coefficients

$$\partial X_s / \partial W_c, \; \partial X_s / \partial V_{ix}$$

$$\partial Y_s / \partial W_c, \; \partial Y_s / \partial V_{iy}$$

and standard deviations

$$\overline{\Delta X}_s = \left\{\left[(\partial X_s / \partial W_c)\, \overline{\Delta W}_{pl}\right]^2 + \left[(\partial X_s / \partial V_{ix})\, \overline{\Delta V}_{ix}\right]^2\right\}^{1/2} \quad (160)$$

$$\overline{\Delta Y}_s = \left\{\left[(\partial Y_s / \partial W_c)\, \overline{\Delta W}_{pl}\right]^2 + \left[(\partial Y_s / \partial V_{iy})\, \overline{\Delta V}_{iy}\right]^2\right\}^{1/2} \quad (161)$$

The measure for the total drop cargo dispersion, r_m, can be determined from the sum of cargo displacement variances from the extraction/ejection phase through the impact phase. This sum, for each component, follows:

$$\Delta \bar{X}_m^2 = \Delta \bar{X}_e^2 + \Delta \bar{X}_t^2 + \Delta \bar{X}_s^2 \quad (162)$$

$$\Delta \bar{Y}_m^2 = \Delta \bar{Y}_t^2 + \Delta \bar{Y}_s^2 \quad (163)$$

$$\bar{r}_m = \left[\Delta \bar{X}_m^2 + \Delta \bar{Y}_m^2\right]^{1/2} \quad (164)$$

The required shock absorber stroke, ΔH_s, is a function of the weight of the cargo, W_c, the vertical impact velocity component V_{iz} and the limit value for the impact load factor, n_i. This relation can be expressed as follows:

The pre-impact kinetic energy is

$$KE_i = 1/2 \, \frac{W_{cd}}{g} \, V_{iz}^2 \, . \quad (165)$$

Potential energy absorption required for the impact is $PE_i = W_{cd} H_s$. (166)

Total impact energy absorption required follows:

$$E_i = n_i W_{cd} \Delta H_s = 1/2 \ \frac{W_{cd}}{g} \ V^2 + W_{cd} \Delta H_s \tag{167}$$

$$H_s = \frac{V_{iz}^2}{2g(n_i - 1)} \tag{168}$$

Equation (168) expresses the required shock absorber travel as a function of V_{iz} and n_i. However, in order to apply this equation, it is necessary to consider the ranges of variation in both cargo weight and impact velocity as expressed in Equations (157) and (158).

Since a constant shock absorber load/stroke characteristic is assumed, it follows that the lightest load experiences the highest impact load factor, regardless of actual amount of shock absorber compressions. The maximum shock absorber travel, however, is required for the combination of the largest drop cargo weight and the largest impact velocity. This impact energy absorption must consequently occur at an impact load factor n_i' which is less than the specified limit value n_i. The following expression accounts in an approximate manner for both the extremely small probability of encountering a large negative deviation in drop cargo weight and for the probability of the combined event of very large, positive-weight and impact-velocity deviations:

$$n_i' = n_i \ \frac{\bar{W}_{cd} - 3 \ \Delta\bar{W}_{pl}}{\bar{W}_{cd} + \Delta\bar{W}_{pl}} \tag{169}$$

where

$\Delta\bar{W}_{pl}$ = the standard deviation at drop cargo weight variation within the weight range considered.

The required shock absorber travel, H_s, is a design feature of the concept which serves to measure the requirements for volume and weight of the impact shock absorbing component of the system. Evaluation of H_s must, therefore, be based on a design criterion which logically accounts for the fact that a limiting condition is considered. This is accomplished by determining the required shock absorber travel as

$$\Delta H_s = \frac{(\bar{V}_{iz} + 3 \cdot \Delta\bar{V}_{iz})^2}{2g \ (n_i - 1)} \tag{170}$$

where

$\bar{V}_{iz}$ = the nominal or design vertical impact velocity component for the system under consideration, and

$\Delta\bar{V}_{iz}$ = the standard deviation of vertical impact velocity component, evaluated as shown in the analysis of the descent control/recovery phase.

Cargo Drop Zone Disposition – Activities in this phase consist of the following:

- o Removal of drop gear, harnessing and shock absorber material from the drop cargo
- o Preparation of cargo for removal from the immediate drop area
- o Transport of cargo
- o Clearing the drop area of obstructions and debris associated with the last drop

The single parameter expressing system performance for this phase is the drop cycle time, T_c, which measures the time interval which must be allowed between any two successive deliveries.

The drop cycle time can be conceived as the sum of the following time increments:

$$T_c = t_{cg} + t_{ct} \tag{171}$$

where

t_{cg} = time to remove harness and other drop gear from the drop load along w[illegible]-site actions preparatory to transportation of the cargo away f[illegible] [illegible]mmediate drop area, and

t_{ct} = time re[illegible]uired to transport the drop cargo and drop gear debris and components a specified distance away from the drop area aiming point.

For t_{cg}, the weight and bulk of material and gear which must be disassembled, along with the size of available crew, must be considered. It appears reasonable to expect that on the average, t_{cg} can be expressed as a direct function of the weight of material to be handled.

$$t_{cg} = C_1 \; (W_c + W_{si}) \tag{172}$$

where

C_1 = an empirical constant, hours/ton.

For t_{ct}, the weight and bulk of material to be handled along with the transportation production rate for available transportation facilities, and the length of transportation distance required is given by:

$$t_{ct} = \frac{W_c + W_{si}}{TPR} \cdot D \tag{173}$$

where

TPR = transportation production rate, ton miles/hour

D = required transportation distance.

The transportation distance, D, is related to the anticipated scatter in repeated drops and can with reasonable confidence be set equal to

$$D = 3 \cdot \bar{r}_m \tag{174}$$

Using these relationships, the drop cycle time becomes

$$T_c = C_1 (W_c + W_{si}) + 3 \cdot \frac{W_c + W_{si}}{TPR} \cdot \bar{r}_m \tag{175}$$

$$T_c = (W_c + W_{si}) \left\{ C_1 + \frac{3\bar{r}_m}{TPR} \right\}$$

Determination of Concept Performance Number

In order to compute the va. .s of CPN_d as giv by Equation (149), the numerator is determined in the manner described in the following:

Weight nomenclature,

W_{pl}	=	aircraft payload weight
W_c	=	net cargo weight
W_{sa}	=	weight of delivery system components carried permanently in the airplane
W_{st}	=	weight of extraction and trajectory control components
W_{si}	=	weight of impact shock-proofing and harnessing components remaining with cargo through impact

then

$$W_c = W_{pl} - (W_{ca} + W_{st} + W_{si}) \tag{176}$$

and drop cargo weight

$$W_{cd} = W_c + W_{si} \tag{177}$$

In Equation (176), W_{pl} represents the independent variable which is assigned the values shown in Figure 150, Column 7.

The value of W_{sa} depends on specific features of the concept under investigation and on the extent to which these features are sensitive to the various design parameters outlined in Figure 150, particularly the extraction load factor n_e. The value of W_{st} is again strongly influenced by conceptual features and design parameters as outlined in Figure 150, in this case with particular reference to the load factor n.

PARAMETER	SYMBOL	CLASSIFICATION: DESIGN	CLASSIFICATION: OPERATIONAL/ ENVIRONMENTAL	CLASSIFICATION: PERFORMANCE	APPLIED IN STUDY TO: DETERMINE A FIXED DESIGN CONSTANT (ALL CONCEPTS)	APPLIED IN STUDY TO: DEFINE SELECTED DESIGN POINT	APPLIED IN STUDY TO: PERTURB PERFORMANCE MEASURE FOR SENSITIVITY EVALUATION	APPLIED IN STUDY TO: EXPRESS RESULTS FROM PERFORMANCE EVALUATION
FLIGHT SPEED	V	•	•			130, 131.5, 140.5, 150	$\Delta\bar{V}$ = 3 KTS RMS	
DROP ALTITUDE	H	•	•			1500, 15,000, 30,000 Ft.	$\Delta\bar{H}$ (RMS) = 1 H 0<H<300 .11 H 300<H<500 .01 H + 50 H>500	
WIND SPEED	V_W	•	•			30 KTS	$\Delta\bar{V}_W$ = 3 KTS (RMS)	
GUST SPEED	U	•	•			30 FPS	$\Delta\bar{U}$ = 10 FPS (RMS)	
PAYLOAD WEIGHT	W_{PL}	•	•			35,000, 40,000, 45,000 50,000, 55,000, 60,000 65,000, 70,000 LB.	$\Delta\bar{W}_{PL}$ - 1021 LBS (RMS)	
NET CARGO WEIGHT	W_C							•
CARGO EXTRACTION LOAD FACTOR	n_e	•						
DESCENT CONTROL/ RECOVERY LOAD FACTOR	n	•						
IMPACT LOAD FACTOR	n_i	•			20 "g" (VERTICAL)			
IMPACT VELOCITY	V_i	•			≤ 25 FPS			
IMPACT POINT LOCATION DISPERSAL	$\bar{r}_M$			•				•
CARGO DROP CYCLE TIME	$\bar{t}_C$			•				•
COEFFICIENT OF SLIDING FRICTION	μ_s		•		0.35			
IMPACT SHOCK ABSORBER WEIGHT CONSTANT	C_s				0.035			
DROP CARGO PREPARATION TIME RATE	C_1				NUMERICAL VALUE TO BE DETERMINED			
CARGO TRANSPORTATION RATE	TR				35,000 LBS: 87.5 70,000 LBS: 105			
CARGO DROP DENSITY RATE	CPN_D							•

Figure 150 - Delivery System Concept Evaluation - Basic Parameters

The value of W_{si} is principally influenced by the required amount of shock absorber travel as computed from Equation (170), along with the appropriate cargo drop weight, as computed from Equation (177). Since for each concept to be evaluated one would presume application of the most efficient method for impact shock absorption, the weight of shock absorbing material can be determined on the assumption of equal efficiency for all concepts. Under this assumption, the weight of shock-absorbing material can be expressed as follows:

$$W_{si} = W_c \cdot C_s \cdot \Delta H_s \tag{178}$$

and

$$W_c = W_{pl} - (W_{sa} + W_{st}) - W_c \cdot C_s \cdot H_s$$

$$W_c = \frac{W_{pl} - (W_{sa} + W_{st})}{1 + C_s \cdot \Delta H_s} \tag{179}$$

With these data, the concept performance number can be evaluated as

$$CPN_d = \frac{W_{pl} - (W_{sa} + W_{st})}{\pi \bar{r}_m^{\,2} \quad W_c \; (1 + C_s \cdot \Delta H_s) \left\{ C_1 + \frac{3\bar{r}_m}{TPR} \right\}} \tag{180}$$

Discussion of Weighting Factors/Performance Perturbation Constants

A list of the basic parameters that characterize the operation and performance of aerial delivery systems is shown in Figure 150. The parameters are called out by name and symbol, and are classified in the three overlapping categories of design, operational/environmental and performance. In a further set of four columns, the areas of application of each parameter are indicated.

The first of these columns indicates parameter-values which are necessary for the concept evaluation method outlined previously but which cannot be assumed to differ from one concept to another.

The entries in this column are:

- Impact load factor, n_I
- Coefficient of ground sliding fraction μ_s
- Impact shock absorber weight constant (pound/pound/foot)
- Drop cargo preparation time rate (hour/ton)
- Transportation production rate (ton mile/hour)

The magnitude of the impact load factor is basically determined by the acceleration tolerance of the drop cargo which will vary over a wide range. The value of 20 g vertical has been selected as reflecting current practice and requirements. Application of a fixed value for n_I tends to rank the various concepts with respect to magnitude and consistency of the impact velocity. Concepts exhibiting consistently high and/or large scatter in impact velocity are penalized in performance due to the larger amounts of weight and volume of shock absorbing material required for these concepts in order to hold the actually experienced impact load factor at or below the prescribed limit.

The coefficient of ground sliding friction, μ_s serves basically to generate data for the displacement of the cargo from the initial impact point if the impact velocity possesses any horizontal component. These displacement distances are part of the impact point scatter around the drop aiming point. Actual magnitudes for ground-sliding coefficients of friction vary widely with ground conditions such as soil type, vegetation, and moisture, and with the type of surface presented by the drop cargo. The value of $\mu_s = 0.35$ appears to represent a good average.

The impact shock absorber weight constant C_s is applied with a fixed value in the evaluation of all concepts. The reason is that regardless of the theoretical advantages of particular recovery devices, impacts with finite impact velocities are bound to occur under operational conditions, and a fair allowance for this eventuality should give each concept the benefit of equal shock-absorbing efficiency for the impact condition.

The drop cargo preparation time rate, C_1, is a factor which appears related both to the type of cargo and to particular concept features. Mathematically, C_1 expresses the time rate in hours/ton required for stripping the cargo of drop harness gear and for preparing it for transportation away from the immediate drop impact area, along with clearing the impact area of debris.

The transportation production rate (TPR), in ton miles/hour, is applied to measure the length of the time element required to clear the drop impact area for the next drop. The numberical value for this constant depends on the type of cargo, on available transportation facilities, and on topographical and climatological features. It is also completely independent of conceptual drop system features. It can therefore be applied as a constant without prejudice for any particular concept.

The second column of Figure 150 presents parameter values which are used to define specific design points common to all concepts. Wind speeds and aircraft flight speeds and altitudes are representative values and include the extreme ranges specified in Exhibit A of the contract (Reference 1). A 30-foot-per-second maximum gust velocity was selected as being consistent with currently accepted aircraft design practice. Payload weight design points are shown in compliance with requirements spelled out in Exhibit A of the contract (Reference 1).

The third column shows parameter values which are used to generate data for the performance sensitivities of the various concepts. They are construed as weighting factors to be applied to numbers expressing the sensitivities of a concept in regard to particular performance aspects. The product of these weighting factors and the corresponding sensitivity coefficients yield values for performance decrements which are used in the final evaluation of concept performance capability.

The weighting factors all have in common that they are derived from parameters that are subject to only limited degrees of operational control. In fact, they are intended to describe as nearly as possible the exact degree to which these particular parameters are beyond operational control. This is achieved by expressing the weighting factors in terms of standard deviations (or RMS), also called standard errors.

The flight speed standard deviation, $\Delta\bar{V}$ = 3 knots, was selected from consideration of the presentation afforded by the standard air speed indicator dial, assuming that the target air speed may fall at any point between dial index markings.

The altitude standard deviation, $\Delta\bar{H}$, is conceived as consisting of two components: one represents the probable error committed by the pilot in attempting to hold a specified flight altitude with reference to altimeter indications, and the second represents fluctuations in ground elevation contour along the flight track.

For deliveries at very low altitudes in the range from zero to 300 feet, it is assumed that the delivery site must be sufficiently level that the ground roughness component can be neglected. For this altitude band the altitude deviation is assessed as 10 percent of the target altitude.

For the altitude band 300 feet $< H <$ 500 feet, the piloting component of the altitude deviation is assumed to remain at 10 percent of the nominal altitude, while an elevation profile component of 0.01 H becomes noticeable. This value was assessed from unpublished data from an earlier investigation of ground elevation fluctuations along typical flight tracks and represents RMS values for ground distances equal to the flight altitude. For the altitude band above 500 feet, the piloting component of the deviation was assessed at a constant 50 feet, based on data from Journal of Aircraft, May-June 1965, "Recent Developments in Pressure Altimetry," by William Gracey. The ground elevation fluctuation component was assessed at 0.01 H.

The wind speed standard deviation $\Delta\bar{V}_W$ was assessed at 10 percent of the design wind speed of 30 knots. It is interpreted as a probable error of actual wind speed estimation.

The gust standard deviation, $\Delta\bar{U}$, was assessed as 10 feet per second, in line with the philosophy that the design value should amount to three or more times the standard deviation in order to make its probability of occurrence sufficiently small. The standard deviation for drop cargo weight, ΔW_{pl}, was assessed assuming a triangular distribution of possible cargo weights over each 5000-pound range, centered on the nominal values. This assumption leads to the value ΔW_p = 1021 pounds.

Summary of Aerial Delivery Methodology

The proposed method for evaluating aerial delivery concepts is based on a quantitative derivation of system performance. The performance measure, expressed as net weight of cargo delivered per unit area per unit time, is evaluated for each concept and used to establish the concept relative ranking. Net cargo weight is established as aircraft payload weight less weight of the delivery system. The referenced area measures the drop precision capability of the system and is expressed in terms of the probable miss distance. The time is defined as the time interval between any two successive drops, allowing for clearing the drop zone of the previous delivery.

The entire delivery operation, from initial preparation of cargo to final cargo disposition at the drop zone, is considered in six phases of functional activity. These functional activity phases are most easily defined by the characteristic type of operations conducted on the cargo from start to end of the phase. These operations conducted on the cargo can be expressed by mathematical relationships which contain terms expressing both performance parameters and operational/environmental parameters. The sensitivity of the concept performance, as expressed by the impact velocity and miss distance from the nominal impact point, to variations in operational/environmental parameters is obtained with the aid of these mathematical relationships programmed on digital and analog computers. The resulting sensitivity coefficients are combined with the standard deviations expressing the expected variation of values of operational/environmental parameters shown in Figure 150, to produce measures of impact velocity and miss distance. Impact velocity, converted to shock absorption system weight, increases the total delivery system weight and thus detracts from net delivered cargo weight. Miss distance is used to compute the size of the probable impact area. The drop cycle time, or time between two successive drops, is computed allowing for the amount of cargo, amount of shock absorbing material, and the cargo transport distance. Cargo transport distance is computed as the distance from the center to the impact area perimeter. Finally, concepts are examined for compatibility with emergency cargo jettison capability. Concepts possessing this capability will be given preference in the comparative evaluation, providing that the differences in performance ranking numbers are small.

Aerial Retrieval

The preceding text has developed the methodology used for the comparative evaluation of aerial delivery systems. The methodology used for the evaluation of aerial retrieval systems is essentially the same, i.e., a sensitivity analysis of characteristic concept performance parameters is conducted in order to determine the overall system performance. This sensitivity analysis is based on realistic operational and environmental factors and established design limits. There is, however, a basic difference in the derivation of the concept performance number. In aerial delivery operations, one of the major problem areas is associated with improving the delivery precision, i.e., reducing the impact point scatter about the aiming point.

In aerial retrieval operations, on the other hand, a major problem area is associated with achieving a positive engagement with the retrieval load. The degree of success in this aspect of the operation, as expressed in terms of engagement probability, is a direct measure of the capability of the system. Moreover, the engagement probability depends strongly on both inherent features of the concept and the operational/environmental circumstances surrounding each retrieval attempt, as is described in greater detail below.

Since the weight of the retrieval load is limited to 10,000 pounds and since a part of this weight must be allotted to such pick-up system components as are attached to cargo during the retrieval operation, an additional factor influencing the effectiveness of the concept can be expressed as the ratio of useful load to total retrieved load, including system components.

Various retrieval system concepts differ considerably in regard to the effort and time required to prepare for the actual retrieval, T_r.

Finally, certain retrieval concepts are compatible with boarding of the pick-up cargo, while others do not possess this capability, thus necessitating a mode of aerial delivery for cargo re-deployment. In the latter case, selection of possible delivery modes is more restricted than for retrieval concepts which are compatible with boarding of the load.

In view of these considerations, it appears necessary to establish separate concept ranking numbers for retrieval concepts according to whether the retrieval concept is limited to a subsequent aerial delivery.

For concepts that require subsequent aerial delivery, a concept ranking number is established as follows:

$$CPN_{R1} = P_e \cdot \frac{W_c}{\pi r_m^2 (T_c + T_r)} \cdot \frac{W_c}{W_s + W_c} \tag{181}$$

where

P_e = Retrieval engagement probability

W_c = Net cargo weight

W_s = Weight of complete system

r_m = Root mean square delivery dispersal*

T_c = Delivery cycle time*

* Discussed earlier in this section under "Aerial Delivery"

The retrieval preparation time, T_r, is given by

$$T_r = C_r \cdot W_{cr} \tag{182}$$

where

C_r = A predetermined constant for each concept (hours/ton), and

W_{cr} = The total weight to be retrieved including cargo, harnessing, lift system and tow lines.

For concepts which are compatible with cargo boarding, the retrieval concept ranking number is as follows:

$$CPN_{R2} = P_e \frac{W_c}{T_r} \cdot \frac{W_c}{W_c + W_s} \tag{183}$$

where the different terms are as defined above.

Analysis of Specific Functional Phases

As with aerial delivery systems, aerial retrieval systems can be ranked according to their capability for fulfilling the inherent requirements associated with the several functional phases characteristic of the overall system operation. Three of these functional activity phases are considered with respect to the evaluation of aerial retrieval concepts. These are:

- o Preparation for retrieval
- o Payload retrieval
  - Engagement
  - Towing and/or boarding
- o Payload redeployment

Preparation for Retrieval - This phase is considered to begin with the assembly of lifting and towing gear on the cargo to be retrieved. It includes deployment of retrieval lines, if any, and attachment of harness gear and tie downs, and cargo relocation of movement as required to obtain the necessary conditions for cargo retrieval. According to the performance measures for retrieval concept comparison discussed above, this phase relates only to the time required for cargo preparation for retrieval. This time is affected primarily by variations between concepts, but it is also a function of cargo weight, W_{cr}. As cargo weight increases, the time required for harnessing, tie-down, retrieval line deployment, and lift system attachment also increases for any one aerial retrieval concept.

The cargo preparation time, T_r, is evaluated from Equation (182) with the value of the constant, C_r, being determined from detailed analyses of specific concept features.

Payload Retrieval - This phase covers the activities and events from the initial alignment of the retrieval aircraft with the target indicator until stable tow conditions or boarding of the retrieved cargo has been accomplished. It subdivides naturally into two sequential chains of events, namely, those leading up to and concluding with the achievement of a firm engagement, and those associated with the subsequent lift-off, acceleration, and control of cargo motion relative to the ground and the airplane. The two event-chains are hereafter referred to as the "engagement sequence" and the "trajectory sequence", respectively.

Engagement - From the functional analysis standpoint, the objective of the engagement sequence is to achieve a spatial and temporal coincidence of the two mating parts of the pick-up engagement gear.

The problem is analogous to that of hitting a target of specified dimensions with a device which can be aimed and controlled with limited degrees of precision. In application of this notion, it is convenient to introduce the following definitions.

A_t = Target exposure area normal to flight path, or cross-sectional area of the engagement corridor.

A_p = Area containing all possible flight path intercepts with the target exposure plane.

The area, A_p, is contained within the envelope contour generated by displacing the area, A_t, from its centroid by a displacement vector whose magnitude depends on the following:

- The sensitivity of target center location with respect to operational/environmental factors
- The magnitudes of variations in operational/environmental factors
- The degree of precision which can be achieved for the aimed engagement component flight path control

The target area location can be expressed in terms of the target area centroid coordinates normal to the flight path, y_t, z_t.

Specific operational/environmental factors which might influence these coordinates depend on particular conceptual features, but one would expect gustiness of the air to have a major effect in most cases. The sensitivity of centroid location can be expressed as the partial derivatives, $\partial Y_t / \partial U$, $\partial Z_t / \partial U$.

The target displacement vector components then become

$$\Delta Y_t = (\partial Y_t / \partial_U) \cdot \Delta U \tag{182}$$

$$\Delta Z_t = (\partial Z_t / \partial_U) \cdot \Delta U \tag{183}$$

where ΔU is the magnitude of the gust velocity causing the target displacement. The gust velocity inself is a random variable in magnitude as well as in direction. It can be expressed in terms of its root-mean-square volume denoted ΔU, and a characteristic frequency of occurrence, n_g gusts/sec.

The aiming accuracy for the pickup engagement device is a very complicated function of the dynamic properties of the pilot-airplane combination. If target location shifts occur as a slow enough rate, it is possible for the pilot to compensate by re-direction of the flight path, while if the shifts are violent and rapid, the task of compensating becomes increasingly more difficult and finally exceeds the capability of the pilot-airplane combination.

The capability limit can be expressed in terms of a characteristic response time lag, T_r. Target location shifts which have been completed with a lead time on anticipated contact which is greater than T_r can in general be compensated, while location shifts with lead times on anticipated contact that are less than T_r stand a progressively lesser chance of compensation, as the lead time decreases.

Utilizing the notions developed above, the probability of missing the target can be evaluated as follows:

The event of a miss is contingent upon the occurrence of two separate events, viz:

- One or more gusts are encountered within the critical time period T_r before anticipated contact, and
- The magnitude of at least one gust is sufficient to displace the target completely out of the "engagement corridor".

Since the gusts range widely in magnitude, these two events can be considered as independent. The probability of encountering one or more gusts within the critical time period T_r preceding anticipated contact is a function of the average number of expected gusts during that time interval which can be written

$$P_{(gust)} = 1 - e^{-n_g \cdot T_r} \tag{184}$$

The probability that at least one gust is sufficiently powerful to displace the target out of the engagement corridor depends on the area ratio A_t/A_p and can be written

$$P_{(o)} = 1 - \frac{A_t}{A_p} \tag{185}$$

The probability of missing an engagement is consequently

$$P_{(miss)} = P_{(gust)} \cdot P_{(o)} \tag{186}$$

and the probability of achieving an engagement is

$$P_e = 1 - P_{(miss)} = 1 - (1 - e^{-n_g \cdot T_r})(1 - A_t/A_p) \tag{187}$$

The size of the flight path intercept area A_p depends both on the magnitudes of the target displacement vector components ΔY_t and ΔZ_t and on the configuration of the target exposure area A_t. For a rectangular target of width (a) and height (b), the expected size of the intercept area is

$$A_p = \pi \cdot \overline{\Delta Y}_t \cdot \overline{\Delta Z}_t + a \cdot \overline{\Delta Z}_t + b \cdot \overline{\Delta Y}_t + a \cdot b \tag{188}$$

where $\overline{\Delta Y}_t$ and $\overline{\Delta Z}_t$ are displacement components associated with the root-mean-square value for the gust velocity, $\overline{\Delta U}$.

<u>Towing or Boarding</u> – The activities and events in this phase are concerned with the motion of the cargo subsequent to a successful engagement.

The basic parameter which characterizes events in this phase is the cargo load factor, n, and its variation with time. The cargo load factor depends on the following operational/environmental parameters:

- Pick-up aircraft power reserve
- Pick-up aircraft flight speed, V
- Pick-up altitude, H
- Wind speed, V_w
- Gust velocity, U

These factors, along with specific features peculiar to individual concepts serve to establish design criteria which are used to evaluate weight and volume requirements for the various components of the system. In contrast to the corresponding phase in the delivery system evaluation, there is no need to consider any random perturbation of parameters in this phase. Design criteria in terms of cargo load factor time histories can be obtained by feeding limiting data for operational/environmental parameters into computer representations of the system functions. Output of this analysis is strength-weight and volumetric requirements for the following:

- Lift systems
  - Lift lines
  - Lift generator
  - Cargo harness
- Winch systems
  - Power requirements
- Boarding systems

Payload Redeployment - The performance of the cargo ground-to-air retrieval concept is also evaluated for cargo redeployment. The functional activities to be considered in this phase depend on whether the retrieved cargo is being towed or has been brought aboard the aircraft. In either event, the methods used for determining the concept redeployment performance number are identical to those described for earlier aerial delivery systems under the heading "Analysis of Specific Functional Phases", with the following exceptions:

- An additional increment of time, T_p, is added to account for the difference between concepts in time required to prepare the cargo for pick-up.
- The resultant performance number is modified by the probability of cargo pick-up in order to reflect the overall lower system reliability in relation to a system which must perform aerial delivery only.
- The penalty which the aircraft experiences due to the weight of the pick-up system aboard the aircraft is expressed in a cargo-to-system weight ratio reduction factor.

Determination of Concept Performance Number

Values for the concept performance numbers are determined in accordance with Equation (191) for combined retrieval/redeployment concepts and in accordance with Equation (193) for concepts assuming retrieval only. In both these equations, the net cargo weight, W_c, appears in the numerator.

System weight, W_s, includes the weight of all components required for operation of the system whether they are carried in the airplane or not. Since the total retrieved weight, W_{cr}, is held at constant values, the net cargo weight, W_c, is evaluated as follows:

$$W_c = W_{cr} - W_{sl} \qquad (189)$$

where

W_{sl} = Weight of cargo harness, lift system and tow lines.

Discussion of Weighting Factors/Performance Perturbation Constants

A list of the basic parameters that characterize the operation and performance of aerial retrieval systems is shown in Figure 151. The parameters are classified in the three overlapping descriptive categories of design, operational/environmental, and performance. In the next four columns, the areas of application of each parameter are indicated. The first of these columns indicates parameter values which are necessary for the concept evaluation method, outlined previously, but which cannot be assumed to differ from one concept to another. The only entries in this column applicable to retrieval concepts have to do with subsequent cargo redeployment and, as such, are shown in Figure 150 and are discussed earlier in the report.

The second column presents parameter values which are used to define specific design points common to all concepts. The flight speeds, wind speeds, and altitudes are representative values selected on the basis of ranges indicated in Exhibit A of the RFQ and from current feasibility investigations of aerial retrieval systems. A 30 foot-per-second maximum gust velocity was selected as conforming to currently accepted aircraft design practice. Concept performance is evaluated for the design payload weights of 3000 to 10,000 pounds in 1000-pound increments as shown.

The third column shows parameter values which are used to generate data for the performance sensitivities of the various concepts. They can be construed as weighting factors to be applied to numbers expressing the sensitivities of a concept in regard to particular performance factors. The product of these weighting factors and the corresponding sensitivity coefficients yield performance decrements which are used in the final evaluation of concept performance capability.

All weighting factors are consistent in that they are derived from parameters that are subject to only limited degrees of operational control. They are, in fact, intended to describe as nearly as possible the degree to which these parameters are beyond operational control. This description is achieved by expressing them in terms of standard deviations, or (RMS) values.

The flight speed standard deviation, $\triangle V = 3$ kts, has been selected from consideration of the resolution afforded by marking of standard air speed indicators, assuming desired pick-up airspeed equally as likely to fall between markings as on a marking.

The altitude standard deviation is taken as having two components, one of which represents the probable error committed by the pilot in attempting to hold a specified altitude by altimeter referencing. The second represents fluctuations in ground elevation along the ground track.

The wind speed standard deviation has been taken to be 10 percent of the design wind speed of 30 knots. This is assumed to be normal error in wind speed estimation. Gust deviation is given a one sigma value of 10-feet-per-second or one-third of the design value.

PARAMETER	SYMBOL	CLASSIFICATION			APPLIED IN STUDY TO:			
		DESIGN	OPERATIONAL/ ENVIRONMENTAL	PERFORMANCE	DETERMINE A FIXED DESIGN CONSTANT (ALL CONCEPTS)	DEFINE SELECTED DESIGN POINT	PERTURB PERFORMANCE MEASURE FOR SENSITIVITY EVALUATION	EXPRESS RESULTS FROM PERFORMANCE EVALUATION
FLIGHT SPEED	V	●	●			200, 165, 120 KTS	ΔV = 3 KTS RMS	
RETRIEVAL ALTITUDE	H_R	●	●			10, 50, 150, 300, 500 FT.	ΔH(RMS) = .1 H H < 300 = .11 H H = 300 = .01 H + 50 H = 500	
WIND SPEED	V_W	●	●			30 KTS	ΔV_W = 3 KTS (RMS)	
GUST SPEED	U	●	●			20 FPS	ΔU = 10 FPS (RMS)	
PAYLOAD WEIGHT	W_{PL}	●	●			3000, 4000, 5000, 6000, 7000, 8000, 9000, 10,000 LBS.	ΔW_{PL} = 300 LBS. (RMS)	
NET CARGO WEIGHT	W_C			●				●
CARGO RETRIEVAL LOAD FACTOR	n_r	●						
EQUIVALENT RETRIEVAL POINT LOCATION DISPERSAL	$\bar{r}_R$			●				●
CARGO RETRIEVAL CYCLE TIME	$\bar{t}_R$			●				●
CARGO RETRIEVAL PERFORMANCE NUMBER	CPN_R							●

Figure 151 - Retrieval System Concept Evaluation - Basic Parameters

Finally, the standard deviation of gross cargo weight to be retrieved has been calculated assuming a uniform distribution of possible cargo weights over each 1000 pound range. The value, ΔW_{pl} = 300 pounds has been rounded off to simplify application.

Summary of Aerial Retrieval Methodology

The method for evaluating aerial retrieval concepts is based on a quantitative derivation of system performance. Retrieval concepts are divided into two classes; one comprising concepts necessitating cargo towing and subsequent deployment by means of aerial delivery, and the other possessing capability for in-flight boarding of the retrieved cargo.

The performance measure for the cargo towing class of concepts is the product of its delivery performance number (discussed in the previous section entitled "Aerial Delivery"), the engagement probability, a weight efficiency factor, and a cycle time ratio. The weight efficiency factor is the ratio of net cargo weight to the sum of net cargo weight and delivery plus retrieval system weights. The cycle time ratio is the ratio of delivery system cycle time to the sum of delivery system cycle time and cargo retrieval preparation time.

The performance measure for the cargo boarding class of concepts is the product of engagement probability, net weight of retrieved cargo, and weight efficiency factor, divided by the time required to prepare the cargo for retrieval. The weight efficiency factor is the ratio of net cargo weight to the sum of net cargo and retrieval system weight.

For both classes of concepts, the engagement probability will be calculated as the ratio of two areas. The area in the numerator is the target area presented for hook engagement. The area in the denominator is the area swept by the actual target area moving under the influence of randomly varying operational/environmental factors. This is called a target dispersal area.

The entire retrieval operation, from initial preparation of the cargo to establishment of stabilized towing conditions or boarding, is considered at three phases of functional activity. As discussed in the Aerial Delivery Summary Section, mathematical relationships are derived which contain terms expressing performance and operational/environmental parameters. The sensitivity of the concept performance, as expressed by the engagement probability and the retrieval load factor, to variations in operational/environmental parameters is obtained with the aid of these mathematical relationships. The resulting sensitivity coefficients are combined with standard deviations expressing the expected values of variation in operational/environmental parameters, shown in Figure 151, to produce measures of the target dispersal area and retrieval load factor. The target dispersal area yields values for engagement probability. The retrieval load factor constitutes a design criterion for the system, influences the weight of the retrieval system and thus the net cargo weight and cargo weight efficiency factor for the concept. These performance measures are combined to produce the concept ranking number.

APPENDIX C

CTOL/VTOL EFFECTIVENESS METHODOLOGY

Introduction

A cursory analysis of cost effectiveness of the formulated retrieval system has been undertaken. The analysis was held to a cursory level because of the impracticability of applying a spectrum of missions to a varied environment of operations in different types of war as considered in the light of postulated enemy strategy, all within the scope of the desired study. Accordingly, a simplified approach to an investigation of the operational aspects of retrieval by conventional airplane (CTOL) versus VTOL aircraft and helicopters is proposed herein. Included in this simplified approach are comparisons of the validity, vulnerability, safety, and reliability of the systems and techniques. The method uses cost effectiveness techniques, which include the aforementioned qualities, as the most significant measure. Results provide a relative comparison of the validity of retrieval by CTOL aircraft contrasted with VTOL aircraft or helicopters.

In order to assess the cost effectiveness of the various retrieval systems as applied to aircraft systems, the simplified proposed approach utilizes the following procedure and operations:

- o Establish a scenario with a basic mission task to be performed
- o Determine relative effectiveness by use of a Retrieval Index
- o Determine cost by use of a Cost Index
- o Estimate Cost versus Effectiveness, graphically where possible

The above questions are applied to the following aircraft:

- o CTOL: C-130, C-141, and C-5A
- o VTOL: Low-speed, 20,000-pound payload type, with cruise speed of the C-130
  High-speed, 20,000-pound payload type, with cruise speed of Mach 0.85
- o Helicopter: CH-47, Chinook, and CH-54 Skycrane

The entire method and the specific operations mentioned above are discussed in detail in the following paragraphs.

Basic Assumptions

In order to establish the method of approach to cost effectiveness, certain basic assumptions are established as follows:

1. Existing, or known projected, aircraft are used. This use of existing aircraft results in application of retrieval systems to airplanes which are not tailored specifically to retrieve 10,000 pounds only. Otherwise stated, the airplanes previously enumerated retrieve payloads considerably less than design maximum payload, and, therefore operate at varying degrees of efficiency. This assumption also accounts for the fact that the projected VTOL airplanes and existing helicopters have payload capabilities in excess of the 10,000 poun[illegible] proposed for retrieval by airplane.

2. The specific equipment to be retrieved and transported is not identified.

3. All aircraft are assumed to have the ability to retrieve and redeliver people. This is assumed in order to fit the systems into the proposed scenarios.

4. VTOL aircraft and helicopters are assumed to be on the ground for retrieval operations.

5. The full load capability of the VTOL and helicopter types are used because of Assumption 4.

Other assumptions of a minor nature are set forth as necessary during the development of the method.

Scenarios

Prior to establishment of the scenarios, it became apparent that certain tactical situations were likely to exist which would mitigate against one type of aircraft or another. Specifically, some aircraft have high payload to gross weight capability for short range operations, but have very little payload capability for increasingly longer ranges. Some, such as the helicopter, are extremely limited in total range when compared with the basic range capability of C-130 or C-141 airplanes at any payload capacity. Consequently, it became apparent that two scenarios were necessary to adequately measure the operational effectiveness of VTOL aircraft versus retrieval by CTOL systems.

Hence, one scenario has a mission task which is within helicopter range capability and the other a task beyond helicopter range capability.

Short Range - Scenario A

Tactical Situation - Pathet Lao forces have advanced down the eastern banks of the Mekong in Laos through the mountain passes and are attempting to drive to the South China Sea. The apparent route in Viet Nam is the main highway from Dak To to An Nhon on the coast via Kontum. The objective is to split U. S. and Viet Nam forces into two groups: one concentrated in the north at Da Nang and another around Saigon. Once split, the northern group can be conquered by pressure from the Viet Cong in the north and from the Pathet Lao forces in the south.

U. S. Operation - In a counter move, U. S. Forces based in eastern Thailand in the region just southwest of Savannakhet, Laos, will jump on a counter thrust. The objective will be to drive across Laos into Viet Nam and link with U. S. Forces at Quang Tri. This move would effectively bottle up Pathet Lao forces and place them in the position in which they are hoping to place U. S. Forces. To achieve the element of surprise, and to circumvent the necessity for bridging the Mekong, troops and equipment will be airlifted across the river into the relatively flat area around Muong Pha Lane. Again, in the interests of speed and surprise, equipment will be retrieved and transported from a "where it is" location and will be subsequently airdropped near Muong Pha Lane. For operations in this scenario, it is assumed that the maximum transport distance is the maximum range of the helicopters.

Long Range - Scenario B

Tactical Situation - The situation in Viet Nam has deteriorated to the point where a complete evacuation of U. S. Forces is mandatory. In this "Dunkirk" style situation, it is assummed that sealift cannot completely handle the task due to insufficient time to assemble the necessary ships and a general lack of dock facilities. It is further assumed that available airfields are crowded with fighter and attack-type airplanes.

U. S. Operation - In order to salvage as much equipment as possible, it has been decided to use retrieval techniques to airlift equipment to Bangkok, Thailand, which is 460 nautical miles from the Saigon perimeter. Upon arrival at Bangkok, the equipment will be classified and stored for later transshipment by sealift using the port facilities at Bangkok and sailing down the Gulf of Siam.

This scenario is beyond the range of helicopters. It is assumed that the full-range capability of the CTOL and VTOL aircraft will be utilized to make as many unrefueled trips as possible. VTOL design range is assumed at 500 nautical miles for a payload of 20,000 pounds.

Retrieval Index

Effectiveness

In order to measure the effectiveness of the various aircraft with the operations outlined in the scenarios, a simplified measure is used. A Retrieval Index is employed which is defined as follows:

R = Number of aircraft x Survivability Index x Productivity x System Reliability

where

Number of Aircraft = number of aircraft procurable by 100 million production dollars

Survivability Index = 1 - vulnerability

Productivity = Tons of payload transportable by each aircraft in a day consisting of 10 hours operation

Reliability = Reliability and Maintainability of aircraft plus retrieval system

Number of Aircraft - Inasmuch as the evaluation of retrieval concepts is a relative one, the number of aircraft could have been picked at any value without negating the results of the effectiveness study. However, in order to determine the cost procurable by 100 million production dollars, some assumption must be made of the point on the learning curve at which the dollars are to be applied. These specific points and assumptions are discussed under the paragraph entitled "Costs".

Productivity - The productivity is measured by the tons-per-day moved by each aircraft and associated retrieval system in a military operation lasting 10 hours per day. As such, it is this measure that will account for the effects of speed. In Scenario A, range is a variable, but in Scenario B, range is a constant. In both scenarios, appropriate time for retrieval or ground loading, as well as refueling is accounted for. Inasmuch as the airplanes are all Lockheed airplanes, refueling rates are as specified for each basic design. The VTOL and helicopter refuel rates are assumed to be identical to those for the C-130. The time required for ground loading of cargo into VTOL aircraft is based upon C-130 experience. Retrieval is limited to 10,000 pounds for airplanes; loading of VTOL is 20,000 pounds, and the helicopter payloads are varied as a function of range.

Survivability Index - A simplified analysis was made of the vulnerability of fixed wing aircraft versus VTOL aircraft performing aerial retrieval and ground cargo loading operations, respectively, under an assumed level of enemy small arms fire.

The major factors causing differences in aircraft vulnerability are velocity, exposure time, slant range-to-weapon, and inherent vulnerability (vulnerable area). Each of these factors was analyzed to determine its effect on aircraft survivability and a simple model constructed to evaluate relative survivability for each mode of cargo handling, using realistic values for velocities, vulnerable areas, and exposure times as inputs. A graphical representation of the model is shown in Figure 152.

Reliability/Maintainability

This factor, which has a value approximating 0.8 to 0.95, is based upon actual values determined by service operation. Where such data are not available, estimates are based upon design specifications and requirements extant for such types of aircraft.

Cost Index

The total cost of the systems will include:

- o RDTE of the retrieval systems (for CTOL only)
- o Procurement ($100 million)
- o Operating costs
- o Maintenance costs

The specific means of determination of these costs are discussed in the following paragraphs.

RDTE

Inasmuch as known or projected aircraft are used, aircraft RDTE costs are considered as "sunk" costs and are not included in the cost comparisons of the different retrieval systems under consideration. However, the RDTE for special retrieval systems to be used with CTOL aircraft are estimated and included in the total system cost.

Procurement

The number of aircraft which can be procured for $100 million is dependent on the number of airplanes which have been produced, or are planned for the total inventory, before the retrieval system is procured. Letting this number be N_1, the total procurement cost is given by the following:

$$C_p = C_1 \quad (N_1 + N)^{1 + \log P/\log 2} - (N_1)^{1 + \log P/\log 2} \qquad (190)$$

where

C_1 = First unit cost, obtained from historical or projected data
N = Number of aircraft which can be purchased at a cost C_p
P = Learning curve slope

N_1, which essentially is the point on the learning curve or the number of aircraft produced, is assumed as follows for this analysis:

C-130 - Number produced as of 1 January 1966
C-141 - Number produced as of 1 January 1966
C-5A - 58
VTOL - 200 for both aircraft
Helicopters - 200 or actual production units, whichever is higher

Solving for N in Equation (190);

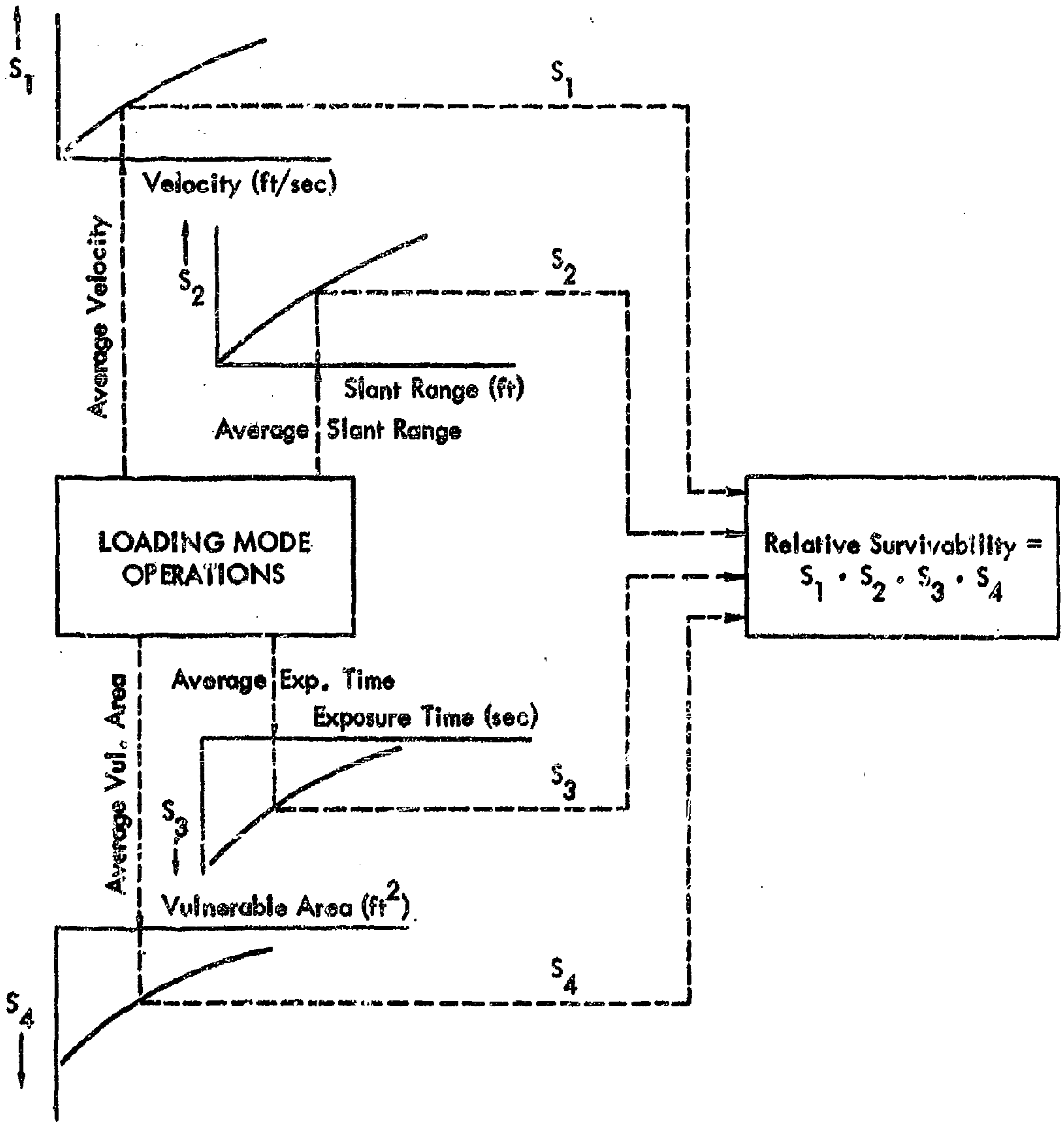


Figure 152 - Graphic Representation of Survivability Model

$$N = (N_1)^{\,1 + \log P/\log Z} + C_P/C_1^{\,1/(1 + \log P/\log 2)} - N_1 \qquad (191)$$

A historical value of learning curve slope for a complete aircraft, including airframe, engines, avionics and GFAE, is 85 percent. Therefore, the number of aircraft that can be procured for $100 million follows:

$$N = (N_1)^{0.76554} + C_P/C_1^{\,1.30627} - N_1 \qquad (192)$$

Operating Costs

Operating costs consist of crew costs and fuel costs. These costs are the peacetime operating costs required to maintain a wartime capability. The utilization in peacetime is considerably less than that which is attained in wartime. A reasonable value, based on C-130 experience, is 3.5 hours per day. Using this value, the total annual flying hours for a fleet size N is (3.5) (30) (12) N = 1260 N.

The crew costs are dependent on the crew complement for the different aircraft under construction. The annual crew cost ... ained by adding the annual salary of all officers and the annual salary of all crewmen on an airplane, and multiplying this by the number of aircraft in the fleet and the number of crews assigned to an airplane. For an annual average officer's salary of $11,100 and an average annual crewman's salary of $4,200, the annual cost per airplane is $11,100 n_o + 4200 n_a, where n_o is the number of officers and n_a is the number of crewmen in one crew. The number of flying hours per day for the crew is taken as the same as the number of flying hours for the aircraft, e.g., 3.5 hours per day. For an average of 1.5 crews per airplane, the hourly crew cost, in dollars, follows:

$$C_{CH} = 1.5\ (11{,}100\ n_o + 4200\ n_a)/(3.5)(30)(12) = 15/63\ (55\ n_o + 21\ n_a) \qquad (193)$$

Fuel cost estimates are dependent on the type of mission flown. It is assumed that the peacetime use of the airplane is equally divided between the two types of missions outlined in the scenario. Thus, one-half of the peacetime usage is in short range missions of 50-mile radius and one-half missions of 500 mile radius. These are taken as the typical use of the airplane, with the exception of helicopters, which are used only for short range missions. For these missions, the fuel consumption and mission time can be determined to establish the fuel consumption per flight hour. The cost of fuel is taken as $0.015 per pound. Therefore, fuel cost in dollars per hour for CTOL and VTOL aircraft is as follows:

$$C_{FH} = 0.015\ (1/2\ F_\ell/t_{ml} + 1/2\ F_S/t_{ms}) \qquad (194)$$

where

F_s = Pounds of fuel used in short range mission

t_{ms} = Block time for short-range mission

F_e = Pounds of fuel used in long-range mission

t_{ml} = Block time for long-range mission

The fuel cost in dollars per hour for helicopters is

$$C_{FH} = 0.015\ F_s/t_{ms} \qquad (195)$$

Annual operating costs for a fleet of N aircraft is

$$C_o = 1260\ N\ (C_{CH} + C_{FH}). \tag{196}$$

Maintenance Costs

Maintenance costs are divided into airframe maintenance and engine maintenance. Each of these is further divided into labor and material. For purposes of cost comparison, the maintenance costs are based on the Air Transport Association (ATA) Standard Method of Estimating Comparative Direct Operating Costs of Transport Airplanes June 1960.

Airframe labor hours per flight hour are given by the ATA formula:

$$K_{LA} = 3.0 + 0.067\ W_a/1000 \tag{197}$$

where

W_a = empty weight of airplane less engines

To obtain cost per flight hour, K_{LA} must be multiplied by the labor rate which is taken as $3.00 per hour. A burden factor of 87 percent has also been included in the ATA estimates. The airframe labor cost is therefore

$$C_{LA} = (1.03)(1.87)(3.00)(3.0 + 0.067\ W_a/\ 1000) \tag{198}$$

where (1.03) is the labor non-revenue factor.

Airframe material cost per flight hour is given by the ATA formula:

$$K_{MA} = 2.5 + 7.9\ C_{spa}/10^6 \tag{199}$$

where

C_{spa} = Cost of airplane less engines.

To obtain total material cost per flight hour, a material burden factor of 23.3 percent is included in the ATA estimate. The airframe material cost is therefore

$$C_{MA}\ 1/\ (1.03)\ (1.233)\ 2.5 + 7.9\ C_{spa}/10^6 \tag{200}$$

where (1.03) is the material non-revenue factor.

Engine labor costs depend on the type of engine. For a turbojet or turbofan, the engine labor hours per engine operating hour are given by the ATA formula:

$$K_{LE} = (0.718 + 0.0317\ T/1000)\ (1100/H_{eo}) + 0.10 \tag{201}$$

where

T = Engine thrust at sea level, standard day, uninstalled
H_{eo} = Mean time between overhauls

For turboprop engines, the engine labor hours per engine operating hour are given by the ATA formula:

$$K_{LE} = (0.4956 + 0.0532\ ESHP/1000)(1100/H_{eo}) + 0.10 \tag{202}$$

where

$ESHP$ = Takeoff equivalent shaft horsepower.

To obtain cost per operating hour, K_{LE} must be multiplied by the labor rate, burden factor, and labor non-revenue factor. The labor cost per engine operating hour is therefore as follows:

For turbojet or turbofan:

$$C_{LE} = (1.03)(1.87)(3.00)(0.718 + 0.0317\ T/1000)(1100/H_{eo}) + 0.10 \tag{203}$$

For turboprop:

$$C_{LE} = (1.03)(1.87)(3.00)(0.4956 + 0.0532\ ESHP/1000)(1100/H_{eo}) + 0.10 \tag{204}$$

Engine material cost per engine operating hour is given by the ATA formula:

$$K_{ME} = (81.45\ C_E/10^6 - 0.47)/(0.021\ H_{eo}/100 + 0.769) \tag{205}$$

where

C_E = Cost of engine

To obtain total engine cost per operating hour, the material burden factor of 23.3 percent and the material non-revenue factor of 1.03 must be included. Therefore, the engine material cost is

$$C_{ME} = (1.03)(1.233)(81.45\ C_E/10^6 - 0.47)(0.021\ H_{eo}/100 + 0.769) \tag{206}$$

When using CTOL aircraft or helicopters, the engine maintenance costs are obtained simply by multiplying C_{LE} and C_{ME} times the number of each type of engine. When using VTOL aircraft, the time of use of each type of engine must also be taken into account. A general formula for engine maintenance which is applicable to any aircraft is

$$C_{EM} = 1.03 \sum_i n_i P_i \Big\{ (1.87)(3.00) \Big\{ k_{1i} \Big[(0.718 + 0.0317\ T_i/1000) \cdot (1100/H_{eo}) + 0.10 \Big] + K_{2i} \Big[(0.4956 + 0.0532\ (ESHP)_i/1000)(1100/H_{eoi}) + 0.10 \Big] \Big\} + (1.233)(81.45\ C_{Ei}/10^6 - 0.47)/(0.021\ H_{eoi}/100 + 0.769) \Big\} \tag{207}$$

where

n_i = Number of engines of the i^{th} type per aircraft

P_i = Percentage of time that i^{th} type engine is used

k_{1i} = 1 for turbojet or turbofan
 = 0 for turboprop

k_{2i} = 1 for turboprop
 = 0 for turbojet or turbofan

The total annual maintenance cost for a fleet of N aircraft is

$$C_M = 1260\ N\ (C_{LA} + C_{MA} + C_{EM}) \tag{208}$$

Solution to these equations is obtained from computer analysis utilizing existing computer programs. Costs are added and the sum divided by an appropriate factor in order to obtain an index (C). This index has a magnitude on the order of 1.0 in order to be compatible with the Retrieval Index of comparable magnitude.

Cost Effectiveness

The overall validity of the various methods of retrieving payload are determined by the relative ranking of the indices. For Scenario A, the Cost Index, C, divided by the Retrieval Index, R, can be plotted against range as an abscissa as conceptually described by Figure 153. The plot would cover the range up to the maximum range of the helicopters. Presentation of the operational aspects of retrieval systems in such a form show whether such systems are valid in comparison with other systems usable to accomplish required missions.

For Scenario B the C/R ratio can be plotted against cumulative payload transported. Presentation in this form is indicative of the relative significance of the amount of tonnage to be moved in terms of type of retrieval system. A conceptual form of such a plot is given by Figure 154.

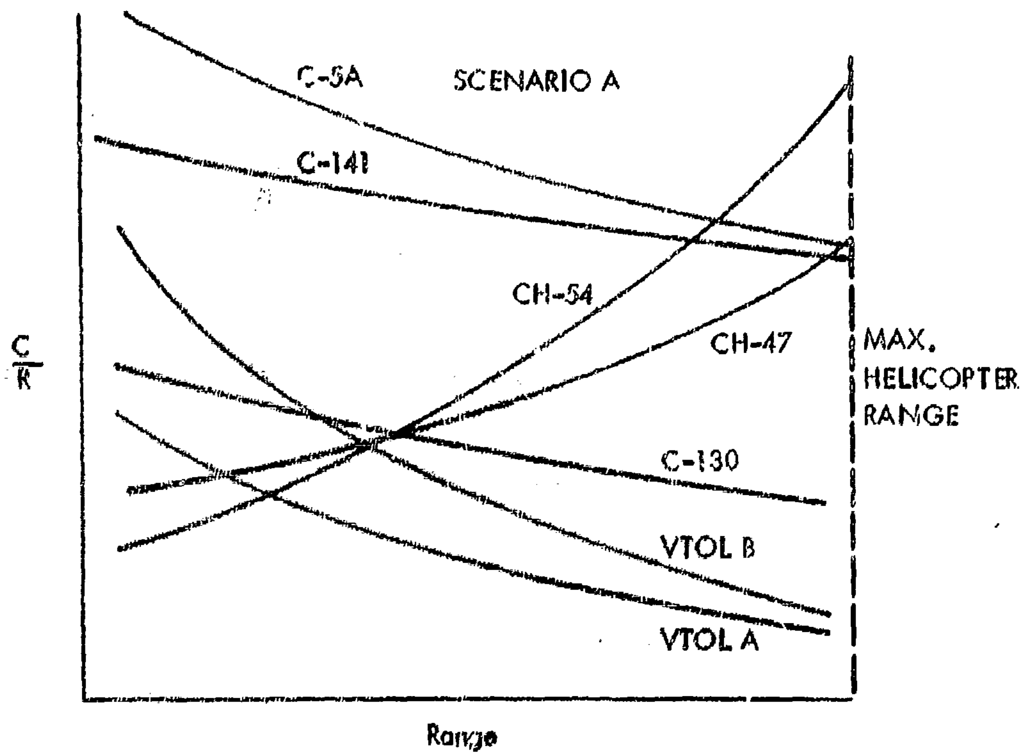


Figure 153 - Relative Effectiveness - CTOL versus VTOL Short Range

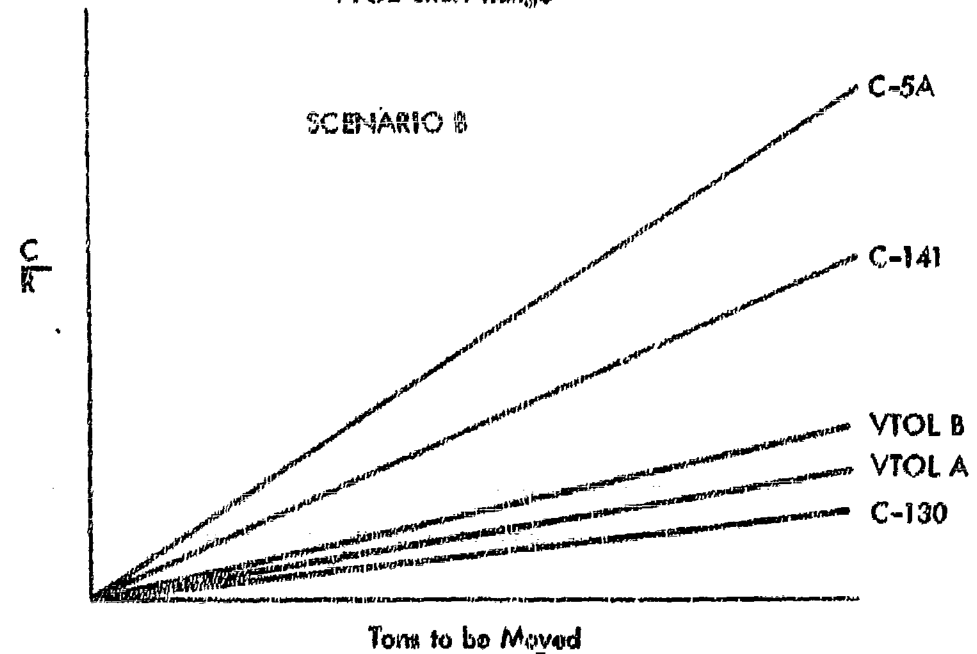


Figure 154 - Relative Effectiveness - CTOL versus VTOL Long Range

APPENDIX D

SENSITIVITY ANALYSIS - INFLUENCE COEFFICIENTS AND PERTURBATION FACTORS

General

The following paragraphs present the derivation of sensitivity coefficients used for evaluation of the delivery system drop precision data. Numerical data for the appropriate perturbation factors are also presented.

Influence Coefficients

Extraction Phase Ground Travel

1) Aircraft speed influence coefficient:

   Ground travel during extraction

$$x_e = v_a \cdot t_e - 1/2\, g\bar{n}_e t_e^2 \tag{209}$$

Cargo exit velocity

$$v_e = (2\, g\bar{n}_e \cdot l_c)^{1/2} \tag{210}$$

$$t_e = \frac{v_e}{g\bar{n}_e} = \left(\frac{2\, l_c}{g\bar{n}_e}\right)^{1/2} \tag{211}$$

$$x_e = v_a \left(\frac{2\, l_c}{g\bar{n}_e}\right)^{1/2} - 1/2\; g\bar{n}_e\, \frac{2\, l_c}{g\bar{n}_e} = v_a \left(\frac{2\, l_c}{g\bar{n}_e}\right)^{1/2} - l_c \tag{212}$$

With change in aircraft speed from a nominal value v_{a_o} to v_a, the average extraction load factor will also change from its nominal value $\bar{n}_{e_o}$ to the value $\bar{n}_e$ given approximately by

$$\bar{n}_e \cong \bar{n}_{e_o} \left(\frac{v_a}{v_{a_o}}\right)^2 \tag{213}$$

$\therefore$

$$x_e = v_a \left(\frac{2\, l_c}{g\bar{n}_{e_o} \left(\frac{v_a}{v_{a_o}}\right)^2} \right)^{1/2} - l_c = v_{a_o} \left(\frac{2\, l_c}{g\bar{n}_{e_o}} \right)^{1/2} - l_c$$

$$\therefore \quad \frac{\partial x_e}{\partial v_a} = 0 \tag{214}$$

The influence of variations in aircraft speed on extraction ground travel distance for the cargo is negligible.

2) Cargo weight influence coefficient:

With changes in cargo weight from the nominal value W_{c_o}, the average extraction load factor will also change in the ratio

$$\bar{n}_e = \bar{n}_{e_o} \left(\frac{W_{c_o}}{W_c} \right) \tag{215}$$

With

$$x_e = v_a \left(\frac{2\, l_c}{g\bar{n}_{e_o} \left(\frac{W_{c_o}}{W_c}\right)} \right)^{1/2} - l_e = v_a \left(\frac{W_c}{W_{c_o}} \; \frac{2\, l_c}{g\bar{n}_{e_o}} \right)^{1/2} - l_c \tag{216}$$

then $$\partial x_e / \partial \left(\frac{W_c}{W_{c_o}} \right) = 1/2\, v_a \left(\frac{2\, l_c}{g\bar{n}_{e_o}} \right)^{1/2} \left(\frac{W_c}{W_{c_o}} \right)^{-1/2} \tag{217}$$

$$\frac{\partial x_e}{\partial W_c} = 1/2\, \frac{v_a}{W_{c_o}} \left[\left(\frac{W_{c_o}}{W_c} \right) \frac{2\, l_c}{g\bar{n}_{e_o}} \right]^{1/2} \tag{218}$$

3) Gust influence coefficient:

Variation of extraction load factor with gust velocity:

$$\bar{n}_{e_u} = \bar{n}_{e_o} \left(\frac{v_a + u}{v_a} \right)^2 = \bar{n}_{e_o} \left(1 + \frac{u}{v_a} \right)^2 \tag{219}$$

$$x_e = v_a \left(\frac{2\, l_c}{g\bar{n}_{e_o} (1 + \frac{u}{v_a})^2} \right)^{1/2} - l_c \tag{220}$$

$$x_e = \frac{v_a}{1 + \frac{u}{v_a}} \left(\frac{2\, l_c}{g\bar{n}_{e_o}} \right)^{1/2} - l_c$$

$$x_e \left(1 + \frac{u}{v_a}\right) = v_a \left(\frac{2\, l_c}{g\bar{n}_{e_o}} \right)^{1/2} - l_c \left(1 + \frac{u}{v_a}\right)$$

$$dx_e \left(1 + \frac{u}{v_a}\right) + x_e \cdot \frac{du}{v_a} = - l_c \frac{du}{v_a} \tag{221}$$

$\therefore$

$$\frac{\partial x_e}{\partial u} \cong - \frac{1}{v_a} (x_e + l_c) \tag{222}$$

<u>Descent Phase Ground Travel</u>

1) Aircraft speed influence coefficient:

Expressing the descent phase ground travel distance in terms of an average horizontal acceleration factor $\bar{n}_{x_d}$, then

$$v_a = (2\, g\bar{n}_{x_d} x_d)^{1/2} \tag{223}$$

$$x_d = \frac{v_a^2}{2\, g\bar{n}_{x_d}}$$

Assuming proportionality between the average acceleration factor $\bar{n}_d$ and the descent control device drag load factor n_o at nominal speed v_o,

then

$$\bar{n}_{x_d} = K\, n_o \left(\frac{v_a}{v_o}\right) \tag{224}$$

$$x_d = \frac{v_a^2}{2\, gKn_o \left(\frac{v_a}{v_o}\right)^2} = \frac{v_o^2}{2\, gKn_o} \tag{225}$$

$$\frac{\partial x_d}{\partial v_a} = 0 \quad \text{(for all drop altitudes with vertical termination of the descent phase)} \tag{226}$$

2) Cargo weight influence coefficient

$$\bar{n}_{x_d} = \frac{W_{c_o}}{W_c} \cdot Kn_o \tag{227}$$

$$\frac{\partial x_d}{\partial W_c} = \frac{x_{d_o}}{W_{c_o}} \tag{228}$$

3) Wind error influence coefficient:

The contribution to miss distance due to error in wind estimate is proportional to the length of time that the cargo is exposed to the wind

$$\frac{\partial x_d}{\partial v_W} = t_d \tag{229}$$

4) Flight altitude error influence coefficient:

$\frac{\partial x_d}{\partial h}$ = Can be read as slope of ground travel distance versus flight altitude graph at each altitude and cargo weight.

Perturbation Factors

Cargo Weight Variations

For the purpose of analysis, a symmetric, triangular distribution centered on the nominal value and extending to the half-interval on either side will be assumed.

This assumption yields the probability density distribution function:

$$\begin{aligned} f(x) &= 4(x - 1/2) \qquad -1/2 \leqslant x < 0 \\ f(x) &= 2 - 4x \qquad 0 \leqslant x < +1/2 \end{aligned} \tag{230}$$

Distribution variance

$$Var(x) = \int_{1/2}^{0} (4x - 2)\, x^2\, dx + \int_{0}^{+1/2} (2 - 4x)\, x^2\, dx \tag{231}$$

$$\mathrm{Var}\ (x) = \left| x^4 - 2/3\ x^3 \right|_{-1/2}^{0} + \left| 2/3\ x^3 - x^4 \right|_{0}^{+1/2} = .04166 \tag{232}$$

Cargo weight standard deviation

$$\sigma W_c = (\text{Cargo weight increment}) \cdot (\mathrm{Var}\ (x))^{1/2} \tag{233}$$

$$\therefore \sigma W_c = (5000)\ (.204) = 1021\ \text{lbs.}$$

Gust Velocity

σu = 10 ft/sec EAS = 5.925 Kts EAS

Wind Velocity (estimation error)

σv_W = 5.065 ft/sec EAS = 3.0 KTS EAS

Altitude Error

$\sigma h = .01h + 50 \quad (h > 500\ \text{ft})$

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13. ABSTRACT

Analytical studies were conducted for the purpose of defining optimum systems for the aerial delivery of payloads in the 35,000 to 70,000-pound range and the aerial retrieval of payloads in the 3,000 to 10.000-pound range. A generalized approach was utilized in the analysis and evaluation of candidate systems for both functions. Included in the study was a definition of requirements for each operational phase, the development of criteria for concept classification and selection, feasibility analyses of candidate concepts, and a comparison of operational characteristics of delivery and retrieval concepts. Selected concepts were employed in the formulation of complete systems, for which detailed performance analyses and evaluations were conducted. Conclusions formed on the basis of the analytical study are presented.

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