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CONCEPTUAL STUDIES OF AERODYNAMIC GLIDER-DECELERATOR COMBINATIONS FOR HEAVY LOADS

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FOREWORD

This report was prepared in the Department of Aerospace Engineering and Mechanics of the University of Minnesota in compliance with U. S. Air Force Contract No. F33615-68-C-1227, "Theoretical Deployable Aerodynamic Decelerator Investigations," Task 606503, "Parachute Aerodynamics and Structures," Project 6065, "Performance and Design of Deployable Aerodynamic Decelerators." The analysis presented in this report was performed between 2 February 1970 and 30 November 1971.

The study was sponsored jointly by U. S. Army Natick Laboratories, Department of the Army, and Air Force Systems Command, Department of the Air Force, and administered under the direction of the Recovery and Crew Station Branch, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, with Mr. James H. DeWeese, AFFDL/FER, as Project Engineer.

The study was accomplished in cooperation with Mr. Robert A. Noreen and several students of Aerospace Engineering at the University of Minnesota. Mr. Edward J. Giebutowski, U. S. Army Natick Laboratories, participated in this study by providing valuable guidance, identification of principal performance requirements and supplying information in regard to existing delivery systems.

This report was submitted by the authors in December 1971.

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.

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ABSTRACT

Several systems for aerial delivery of large payloads with a gliding capability are composed and analyzed. For the gliding and landing phases these systems incorporate gliding parachutes, wings, lifting bodies, rotors, and retro-rockets. The feasibility of the systems is discussed and recommendations are made based on the results of the investigations.

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ILLUSTRATIONS

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SYMBOLS

C_D	drag coefficient, general
C_L	lift coefficient, general
C_T	tangent coefficient, general
D	diameter, drag force
d	reefing line diameter
F	system force
G	gravitational term corrected for apparent mass effect = $\frac{1}{\frac{m_a}{W_s} + \frac{1}{g}}$
h	altitude
I	retrorocket impulse
K	opening shock factor
L	lift force
L_s	suspension line length
m_a	apparent mass
S	area
T	retrorocket thrust
t	time
t_1	time of retrorocket action
t_c	coasting time of reefed parachute
t_f	filling time
V	velocity
V_v	rate of descent
V_1	final velocity after retrorocket action
V_e	equilibrium velocity
W_s	suspended weight

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x	distance, horizontal
α	angle of attack, trajectory angle
Δh	altitude loss over which retrorockets act
ρ	air density

Subscripts:

(eff)	effective
load	referring to payload
o	nominal, indicates initial when used with velocity V
p	projected
T	trim, stable
I	referring to 1st opening phase
II	referring to 2nd opening phase
III	referring to 3rd opening phase

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I. INTRODUCTION

Various systems for aerial delivery of heavy loads have been developed since large capacity cargo airplanes became available. An extension of these known delivery systems is the addition of a gliding capability, and the purpose of this study is to investigate the feasibility of developing such systems incorporating different devices which would provide the desired glide path.

Systems were analyzed which incoporate gliding parachutes, wings, lifting bodies, rotors, and other devices, such as balloons. Also, for terminal deceleration, combinations of parachutes and retro-rockets were considered to meet the requirements concerning the impact velocities.

Of all the systems analyzed, the most promising one consists of extraction and stabilization of the load by a cluster of ringslot parachutes, a large gliding parachute with a nominal diameter of 135 ft, and a retro-rocket system to reduce the vertical and horizontal velocities shortly before impact. This system meets the requirements of the statement of work for the recovery system and appears to be feasible under consideration of the state of the art.

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II. OBJECTIVES

Certain requirements and objectives to be met by a gliding aerial delivery system were proposed by the United States Army Natick Laboratories and can be summarized as follows.

The main recovery unit should function as an integral part in its deployment, development, and descent stages, although no launch altitude restriction was imposed. The release speed should be in the range of 130 kts to 150 kts. The minimum lift to drag ratio should be 0.8. The maximum opening shock should not exceed 3 g and the impact velocities should not be greater than 25 ft/sec vertical and 20 ft/sec horizontal.

The weights to be covered range from 30,000 lb to 70,000 lb, having dimensions up to 8 ft in height, 9 ft in width, and 28 ft in length. A practical limit for the size of the recovery package is indicated as 8 ft x 8 ft x 15 ft. Modular assembly is acceptable. The decelerator should not weigh more than 10% to 15% of the payload.

These criteria were used for examining the systems and determining their feasibility.

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III. CONFIGURATION 1 - GLIDING PARACHUTE SYSTEM

This configuration encompasses the phases of extraction and stabilization and uses for the gliding phase a large gliding parachute with a nominal diameter of 135 ft. The parachute could be of the ParaSail type, a solid flat circular type with an added porosity distribution, or another type of parachute capable of performing the required gliding characteristics. For the phase immediately preceding the landing a retro-rocket package is utilized to reduce the system's velocity to an acceptable value. Figure 1 shows schematically the functioning of this system.

A. Extraction and Stabilization

Due to the large size and weight of the payload a combined extraction-stabilization technique is envisioned. A cluster of four ringslot parachutes would extract the load. A transfer of the load to a bridle system, as seen in Fig 1, would occur with the ringslot parachutes remaining attached to the load as stabilizing parachutes.

A cluster of four ringslot parachutes has a drag coefficient of $C_{D_o} = 0.41$ (Ref 1). Thus four parachutes with diameters of $D_o = 32$ ft would provide a drag area of $C_{D_o} S_o = 1312$ ft^2. Assuming that the load is decelerated along a horizontal straight line until it clears the airplane, these extraction parachutes would reduce the velocity of a load of 30,000 lb or 70,000 lb from the release velocity of 150 kts or 253.5 ft/sec to velocities of 180 ft/sec or 200 ft/sec, respectively.

Before deploying the main gliding parachute, it appears to be advisable to stabilize the load and to let it assume a flight path favorable for the deployment of the main parachute. Therefore, trajectory calculations with the trajectory angle being the independent variable (Ref 2) were performed. The initial conditions for these calculations were the final velocities of the extraction phase and a trajectory angle of zero degrees (0°). The drag area used for this analysis includes values of 265 ft^2 and 126 ft^2, representing the payload and recovery package, respectively. The layout assumes that the extraction parachutes can be used to stabilize the load-parachute system.

The trajectory analysis will provide the time intervals at which the various parachutes should be actuated. In particular, the calculations showed that trajectory angles of -20° to -40° were obtained within 2 to 3 seconds after

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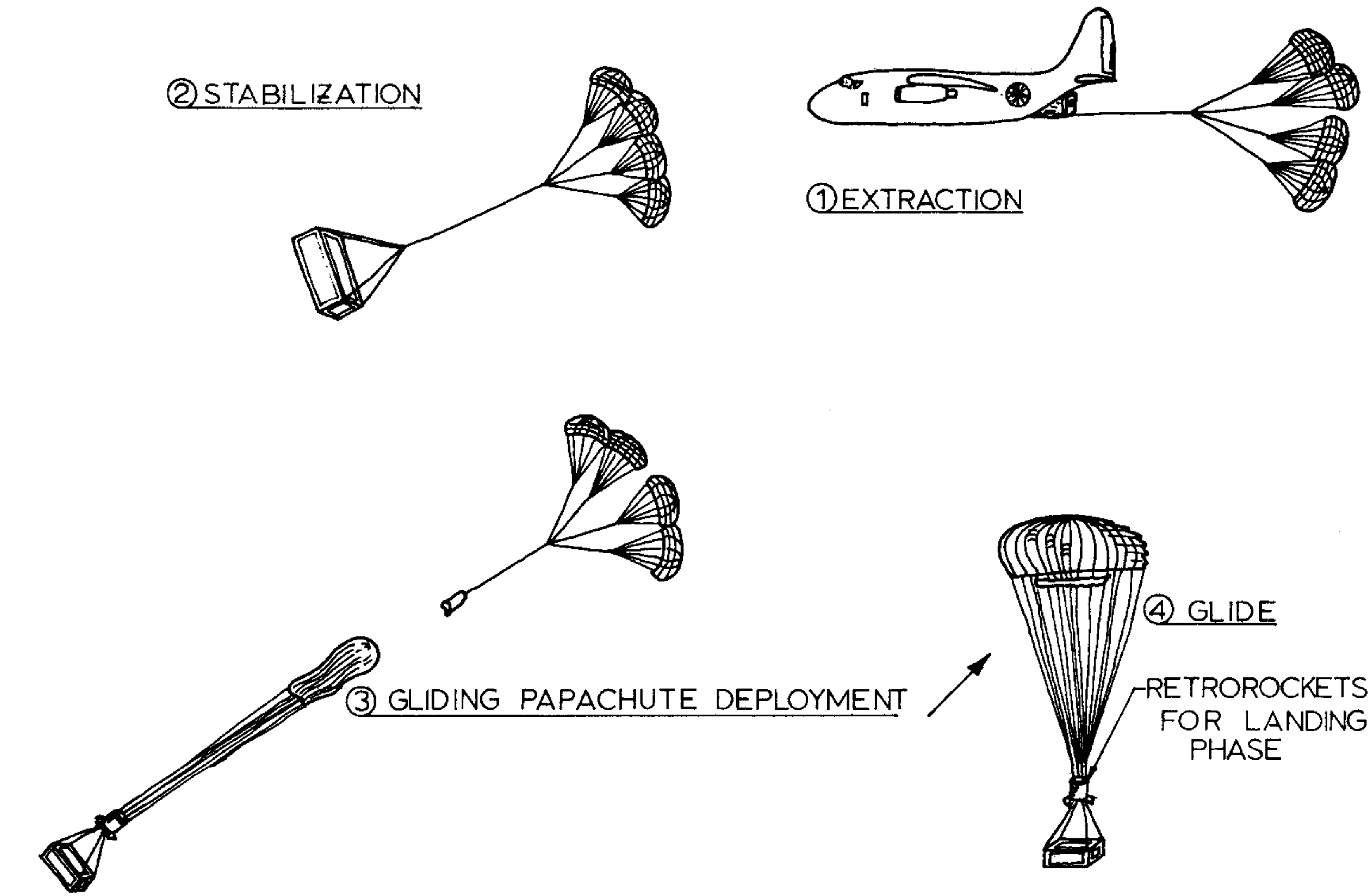

Fig 1 Delivery Sequence of an Aerial Delivery System Incorporating a Gliding Parachute

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completion of the extraction phase. The velocity at this instant is at or near its minimum and amounts to 110-118 ft/sec and 155-162 ft/sec for the 30,000 and 70,000 lb loads, respectively. These and other results are shown in Figs 5 and 8, and it appears that in view of the velocity minimum a stabilization period of 2 seconds provides favorable deployment conditions for the main parachute.

B. Gliding Phase

Based on the experience with large gliding parachutes which have already been developed to a certain degree of maturity, notably the ParaSail (Refs 3,4,5,6,7), parachute performance characteristics were assumed which are considered to be realistic under consideration of the surface loading and parachute size.

For a 135-ft parachute and suspended loads of 30,000 and 70,000 lb, the surface loading ranges from 2.1 lb/ft^2 to 4.9 lb/ft^2, and after consultation with the authors of Refs 3 and 4, the following performance characteristics were assumed: $C_{D_{o(eff)}} = 1.0$, $\alpha_T = 45^o$, $(L/D = 1)$, for the fully inflated parachute. In standard aerodynamic coefficients and for the trim angle $\alpha_T = 45^o$, these characteristics can be expressed as

$$C_{T_o} = C_{D_{o(eff)}} \cdot \cos^2 \alpha_T = 0.5$$

$$C_{D_o} = C_{T_o} \cdot \cos \alpha_T = 0.354$$

$$C_{L_o} = C_{T_o} \cdot \sin \alpha_T = 0.354.$$

For the 135-ft parachute under consideration the related area of these coefficients amounts to $S_o = 14,300\ ft^2$.

In the project layout a two-stage reefing sequence, as used on previous gliding parachutes, was assumed. For the trajectory and opening shock calculation, one also needs terms for the drag area of the parachute at the various stages. If the inflated but reefed parachute assumes the idealized shape of a truncated cone with a hemispherical cap, as shown in Fig 2, the projected diameter can be determined and the corresponding drag coefficient taken from Fig 3. In this manner the drag areas of the reefed parachute were calculated. The drag coefficient of the fully inflated gliding parachute assumed in this study is lower than the one shown for the ParaSail in Ref 6, because the data in Ref 6 refer to a very low surface loading, whereas the 135-ft parachute has a relatively

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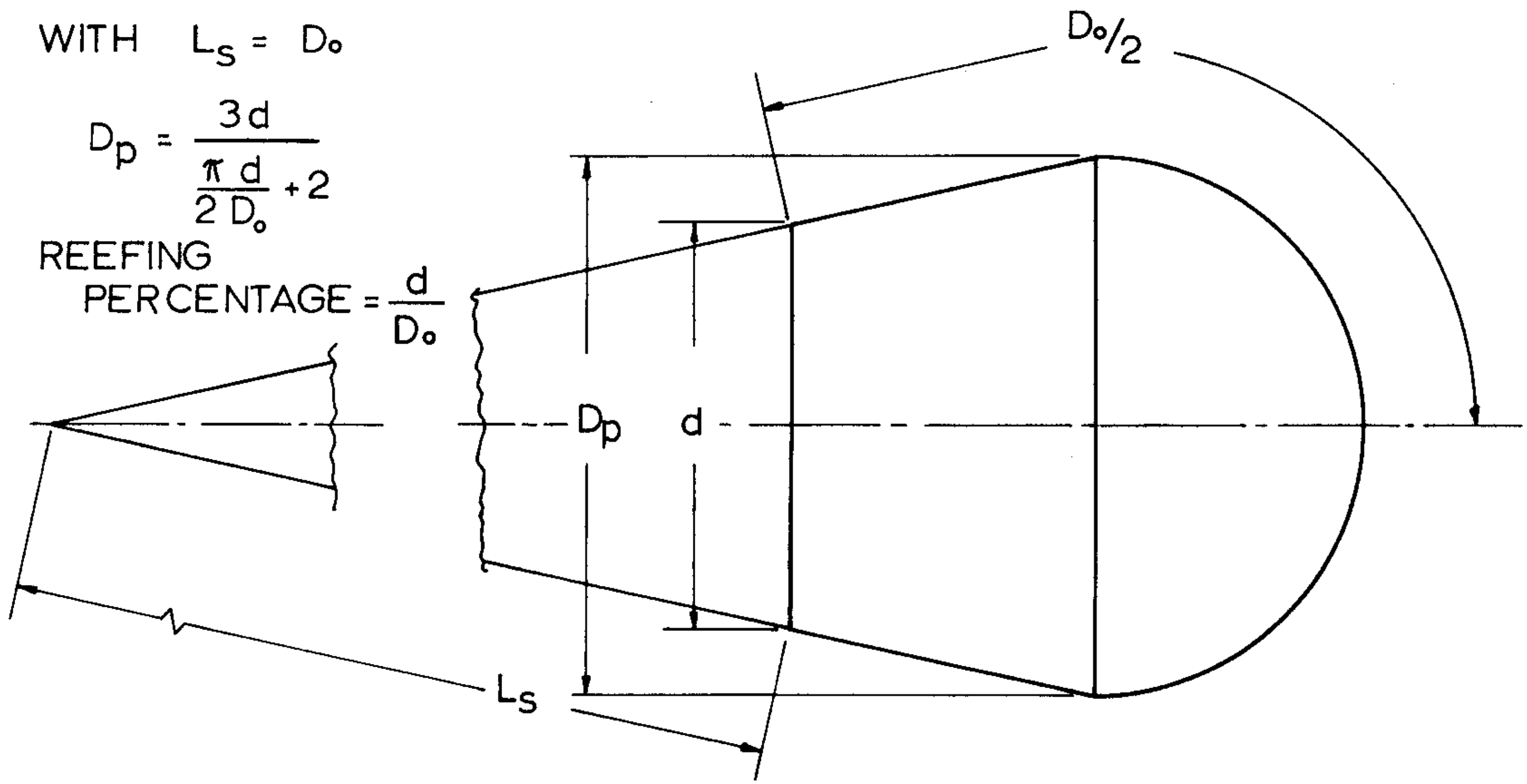

Fig 2 Idealized Profile of an Inflated but Reefed Parachute

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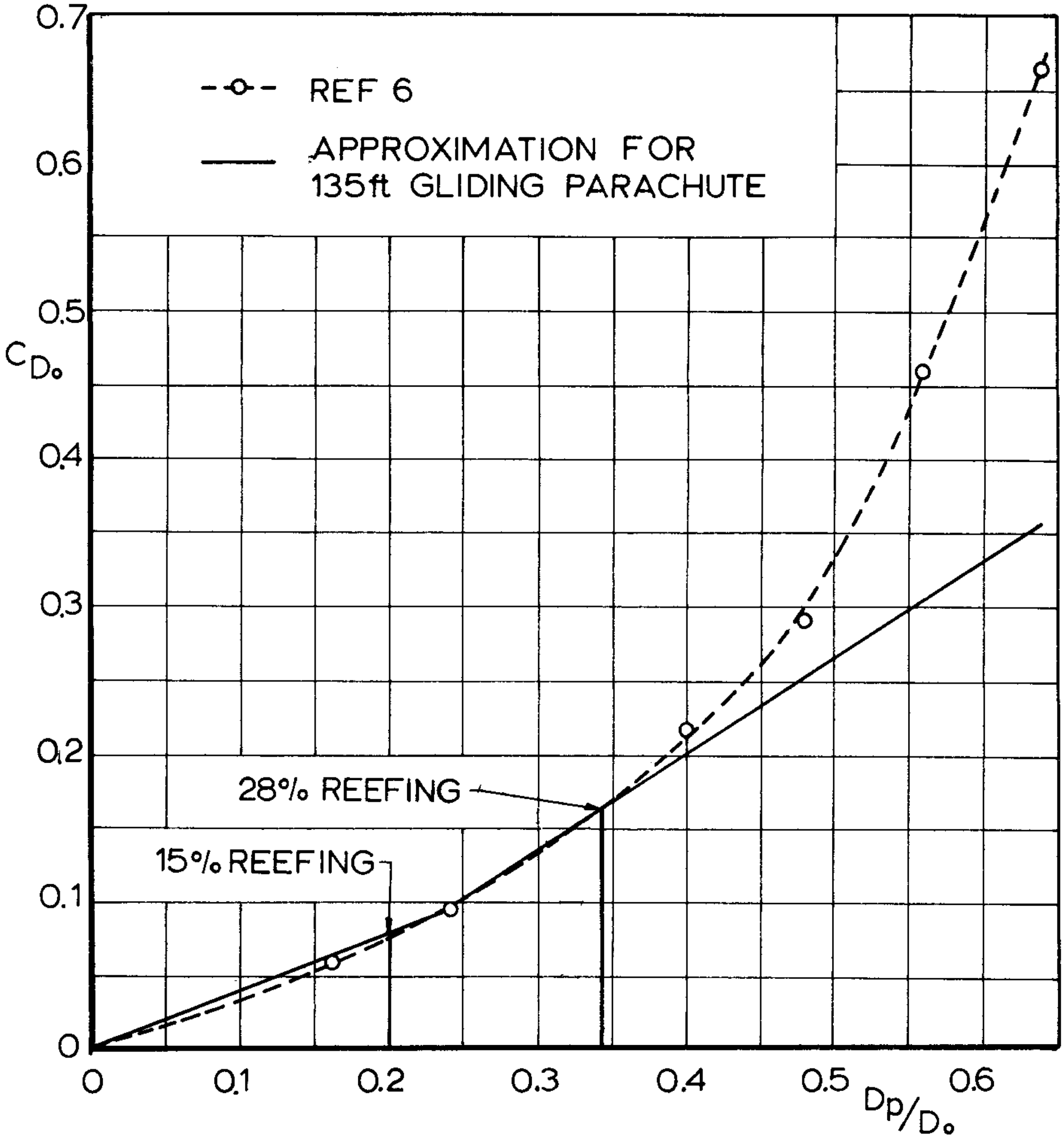

Fig 3 Drag Coefficient of Reefed Parachute

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high surface loading, and Ref 3 indicates a decrease of drag coefficient with increasing loading. The drag coefficient for the reefed parachute was assumed to follow the data given in Ref 6 as seen in Fig 3. Thus, reefing line diameters of 15% and 28% of D_o correspond to drag areas of 1130 ft^2 and 2431 ft^2, respectively.

In Figs 4a and 4b one notices a period of 2 seconds between the instant of extraction parachute release and the complete deployment of the main parachute. This interval is assumed in view of experience with similarly sized parachutes. Furthermore, one notices an assumed linear drag area-time growth during the periods of inflation followed by certain coasting times of the inflated but reefed parachutes assumed to be t_c = 2 seconds. The time t = 0 in this system is the time at which the load clears the airplane.

The linear drag area-time relationship was chosen because of the following facts. Reference 8 suggests such a function, and this statement is based on Ref 9 which showed that for an approximate opening shock calculation which disregards apparent mass effects, the results differ very little when linear, parabolic or quadratic C_DS-time relationships are assumed. Furthermore, Ref 10 presents a method of opening shock calculation which is based on the momentum and continuity equations and incorporates apparent mass effects. This theory also assumes a linear C_DS-time function, and opening forces calculated for a 28-ft solid flat parachute agreed very well with measured data over a considerable weight, speed and altitude range.

The filling times for each phase of opening t_{f_I}, $t_{f_{II}}$, and $t_{f_{III}}$ were determined in the following manner. The theory presented in Ref 10 indicates that the quantity $V_o t_f / D_o$ assumes a constant value provided that the parachutes under consideration have dimensionless velocity-time functions which are identical and have the same effective porosity characteristics. The quantity $V_o t_f / D_o$ is considered to be a dimensionless filling distance, and the statement above is made strictly for complete parachute inflation in one step.

In Ref 11 French states more generally "a given parachute inflates in a fixed distance regardless of the velocity or altitude at which it is deployed and regardless of the weight that it carries."

To a certain extent French's statement is supported by experimental evidence reported in Ref 12 which shows

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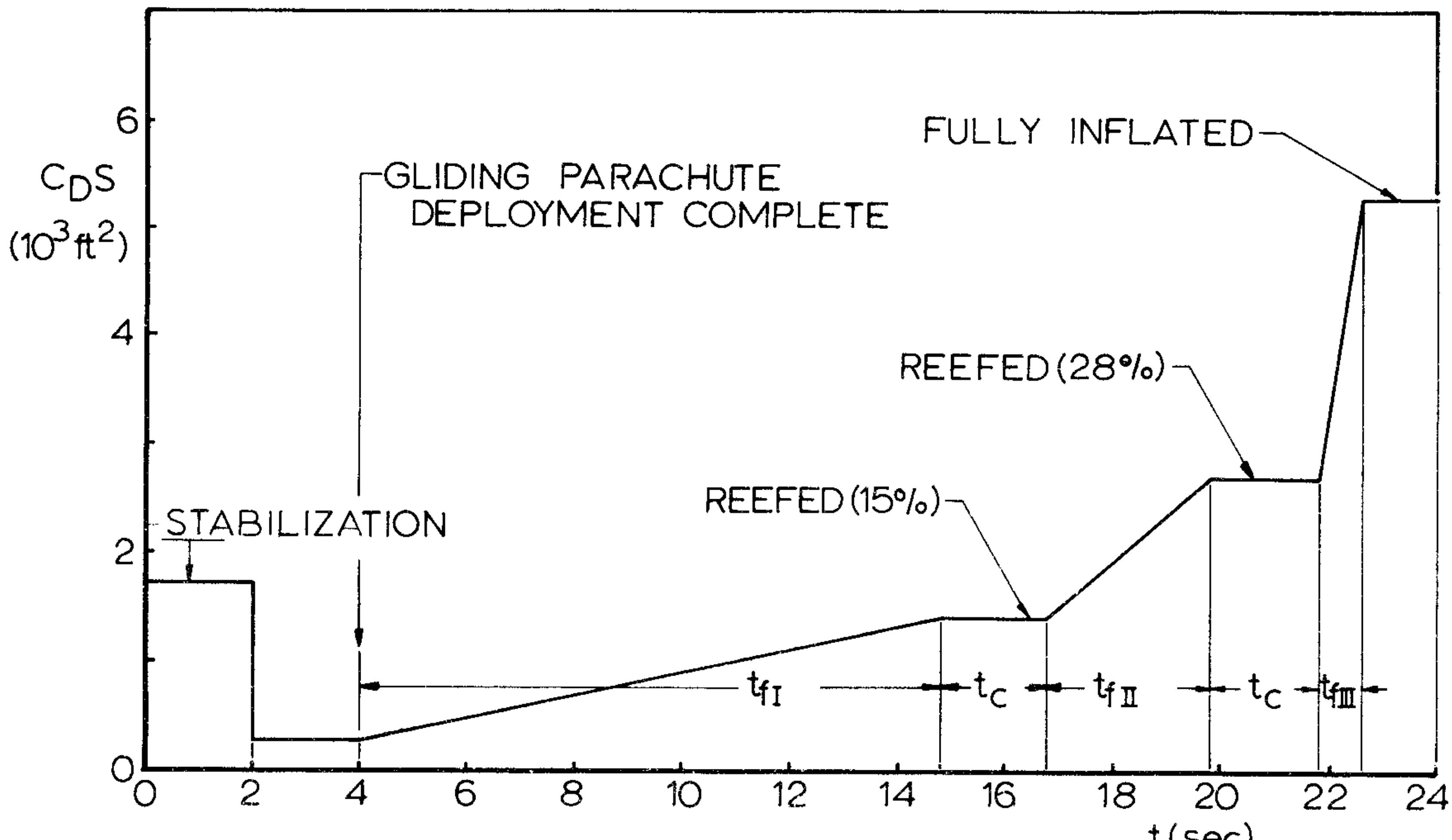

Fig 4a Drag Area - Time Relationship for Delivery System with 30,000 lb Load

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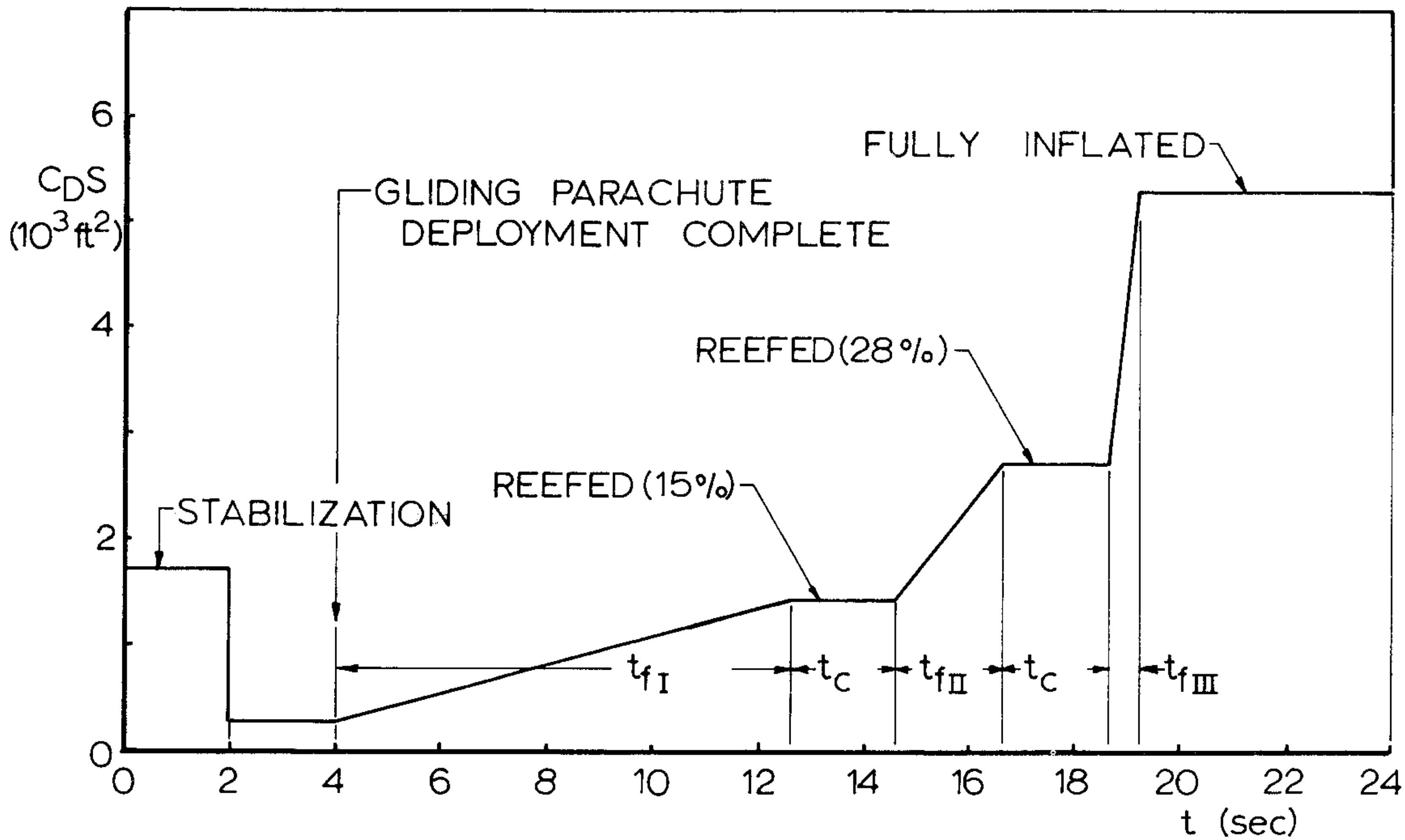

Fig 4b Drag Area - Time Relationship for Delivery System with 70,000 lb Load

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details of the inflation process of very lightly loaded parachute models in a wind tunnel.

In view of the lack of an analytical method of opening shock calculation for reefed parachutes, the experimental evidence and theoretical result concerning the constancy of the filling distance is extended to the calculation of opening shock of reefed parachutes. With this in mind the literature was searched for a recording of filling distance for reefed parachutes. References 4 and 5 contain information from which values of the quantities $V_o t_f/D_o$ can be extracted for reefed parachutes which corresponded approximately to the reefing line percentages selected for the layout of this recovery system. The filling times for each phase were then determined for the 135-ft gliding parachute by using the known quantities $V_o t_f/D_o$ and the system's velocity at the instant of disreefing as determined from a trajectory calculation. Table I shows the numerical values used in this procedure.

TABLE I

ESTIMATION OF OPENING TIMES OF THE
135-FT PARACHUTE IN ITS VARIOUS OPENING STAGES

Stage	Reefing d/D_o %	$V_o t_f/D_o$	Ref	t_f for 135-ft Parachute	
				30,000 lb sec	70,000 lb sec
I	15	11.94	5	10.8	8.6
II	28	3.26	4	3.0	2.0
III	Full Inflation	0.76	4	1.0	0.6

Figures 4a and 4b also indicate coasting phases with constant C_DS-values at the end of the inflation periods. The coasting phases are inserted because the calculated filling times, based on the experimental filling distances, probably differ from the actual filling times. Providing a time interval of coasting gives greater assurance that the parachute is actually fully inflated to its reefed stage before the parachute is disreefed to its successive stage. The trajectory calculation is carried out assuming that the C_DS-values change as schematically indicated in Figs 4a and 4b.

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The disreefings could be accomplished by reefing cutters which can be armed in various manners, for example, during the bag strip.

C. Trajectory and Opening Shock Estimation

Based on the parachute characteristics, the disreefing sequence and the derived times of inflation, composite trajectory calculations were performed. The drag area for the payload was determined from Ref 13, $C_DS_{load} = 265\ ft^2$, and added to the drag of the parachute. The velocity-time histories calculated in this manner are shown in Figs 5 and 8 for the two payloads. The force histories, assumed to follow the velocity squared law, and trajectory plots are shown in Figs 6, 7, 9, and 10. The equations used for trajectory analysis are shown in the appendix.

Maximum opening forces are indicated in Figs 6 and 9. These were calculated by a quasi steady state method as shown in Refs 8 and 9. Using this method one calculates first an instantaneous drag, $D = \rho/2\ V^2\ C_DS$ in which V and C_DS are instantaneous values obtained from the linear C_DS-time functions shown in Figs 4a and 4b and the trajectory analysis. The opening shock is then obtained by multiplying the instantaneous drag for $t = t_f$ with the so-called "K-factor." Reference 8 suggests a "K-factor" of 1.4 for solid cloth parachutes. This method of calculation was chosen, because no analytically oriented opening shock determination seems to exist for reefed parachutes. The instantaneous velocity used in this process is shown in Figs 5 and 8. The forces calculated in this manner are added to the drag of the payload to provide the maximum deceleration of the suspended weight. For both loads, it can be seen that the maximum opening shocks are less than 3 g.

In accordance with these trajectory calculations, steady gliding motion with a 45° glide angle is reached within an altitude loss of roughly 3500 ft for the 70,000 lb load, whereas the vertical and horizontal velocities amount to 64.2 ft/sec. For the 30,000 lb load the altitude loss is 3200 ft until steady gliding is reached with velocity components of 42.0 ft/sec.

It should be mentioned that the parachute and the payload must be aligned so that an axis of the load remains in the vertical plane through the horizontal velocity of the glide motion. This is important for the terminal deceleration as will be seen later. The alignment could be accomplished by means of torsional stiffness between the parachute and load, such as a geodetic suspension system, or by providing directional stability for the load, for example, with a trailing, aerodynamically stable parachute.

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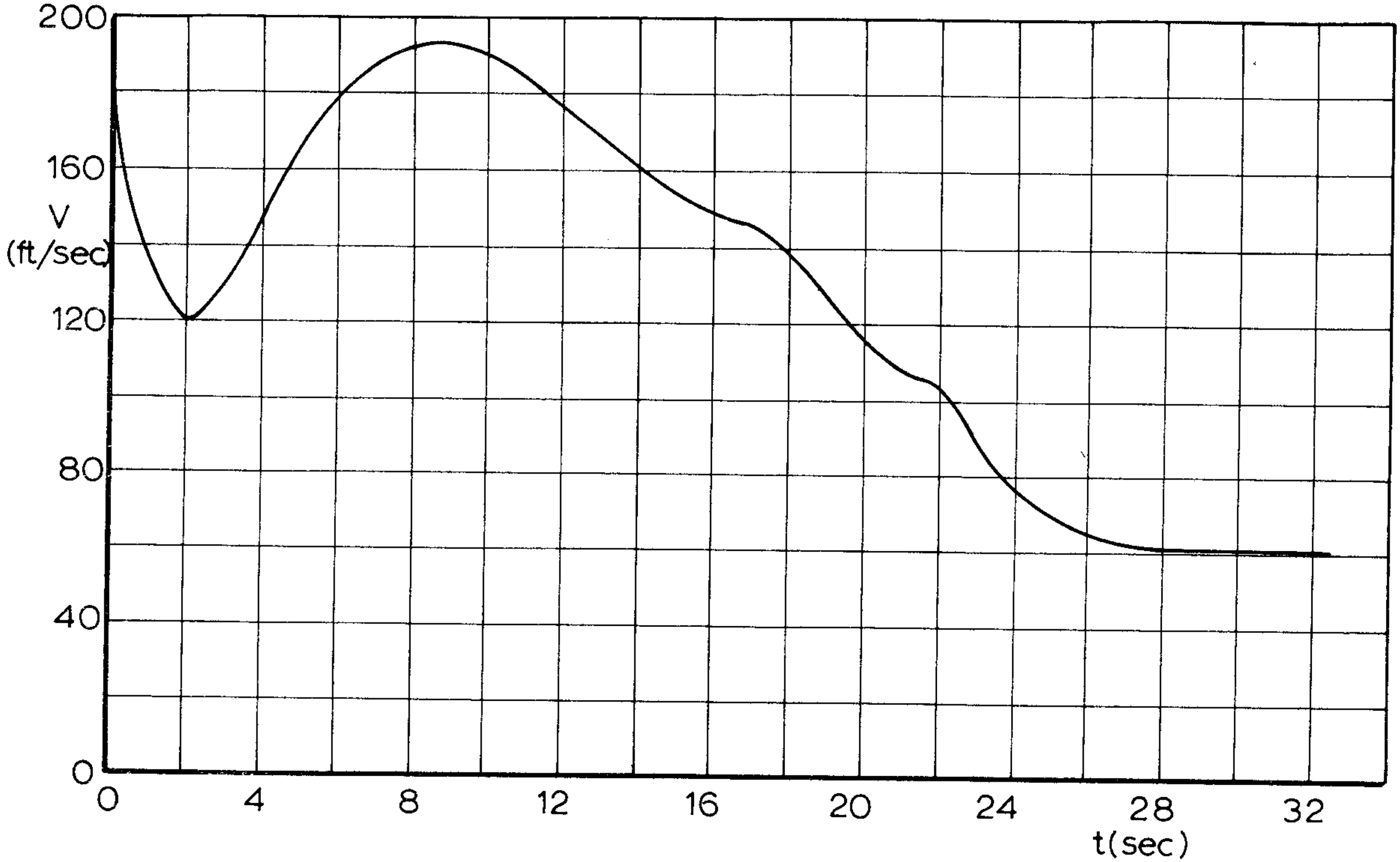

Fig 5 Velocity - Time History for 30,000 lb Load, Release Velocity = 253.5 ft/sec

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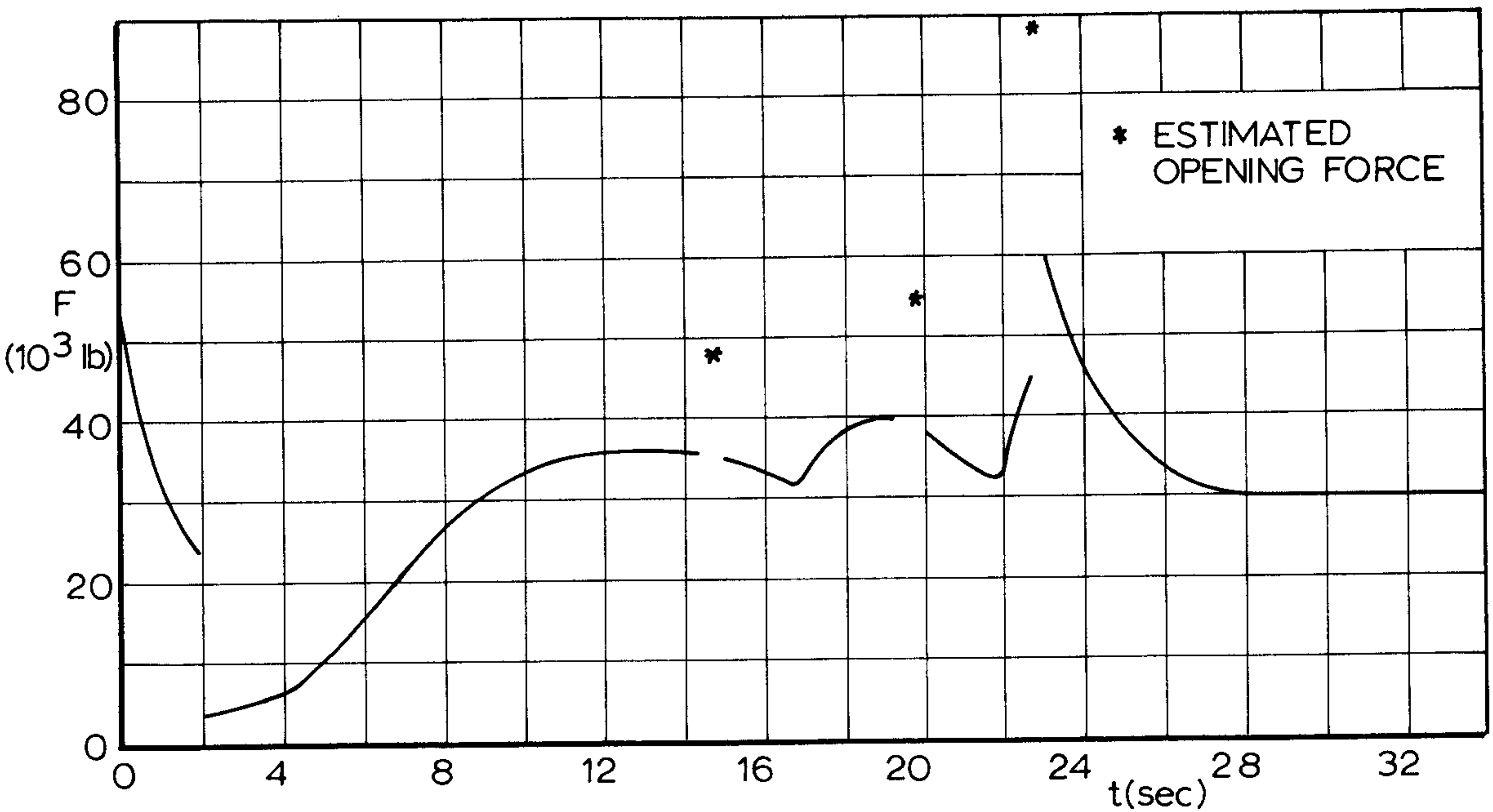

Fig 6 Force - Time History for 30,000 lb Load, Release Velocity = 253.5 ft/sec

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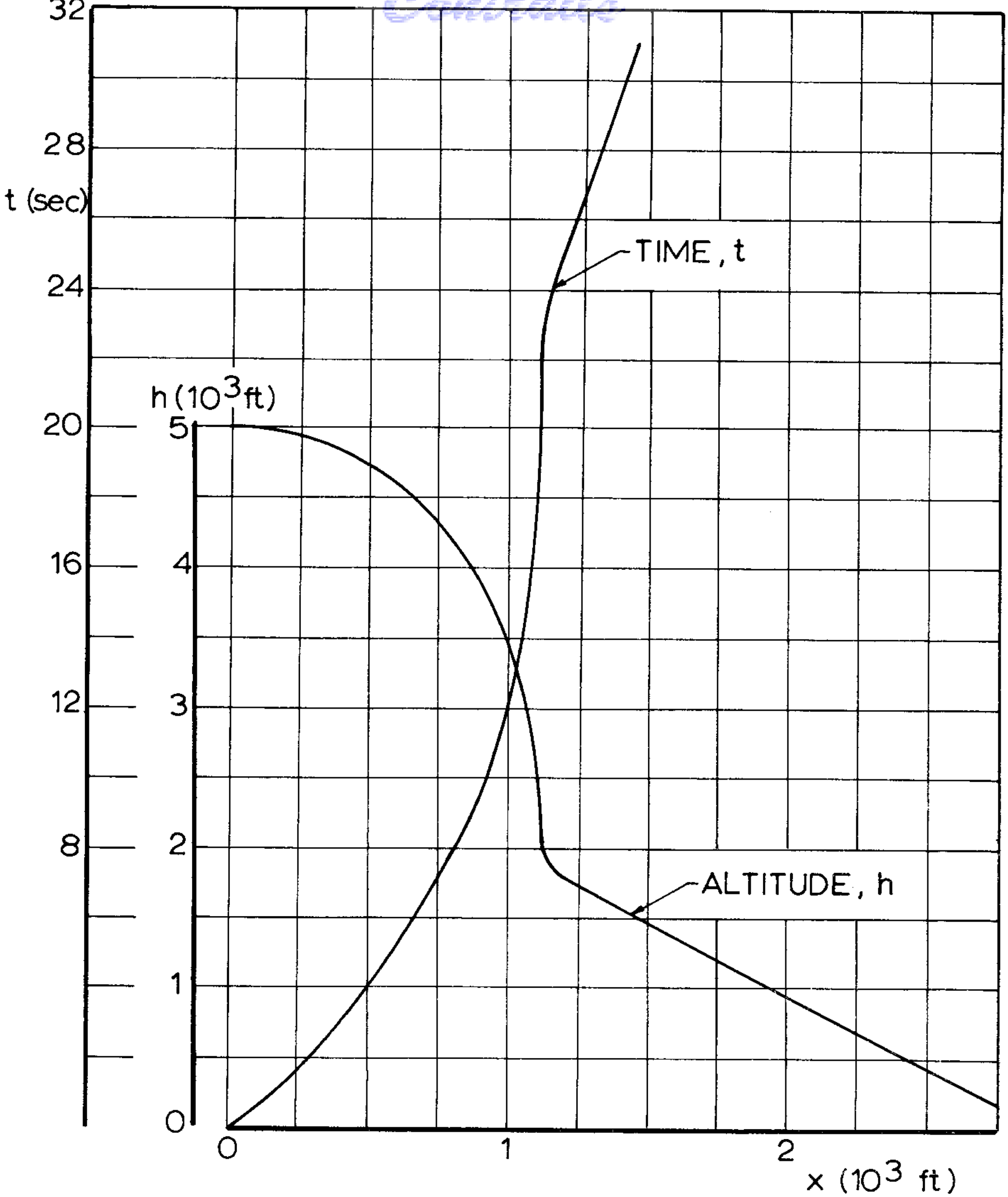

Fig 7 Altitude and Distance - Time History for 30,000 lb Load, Release Velocity =253.5 ft/sec

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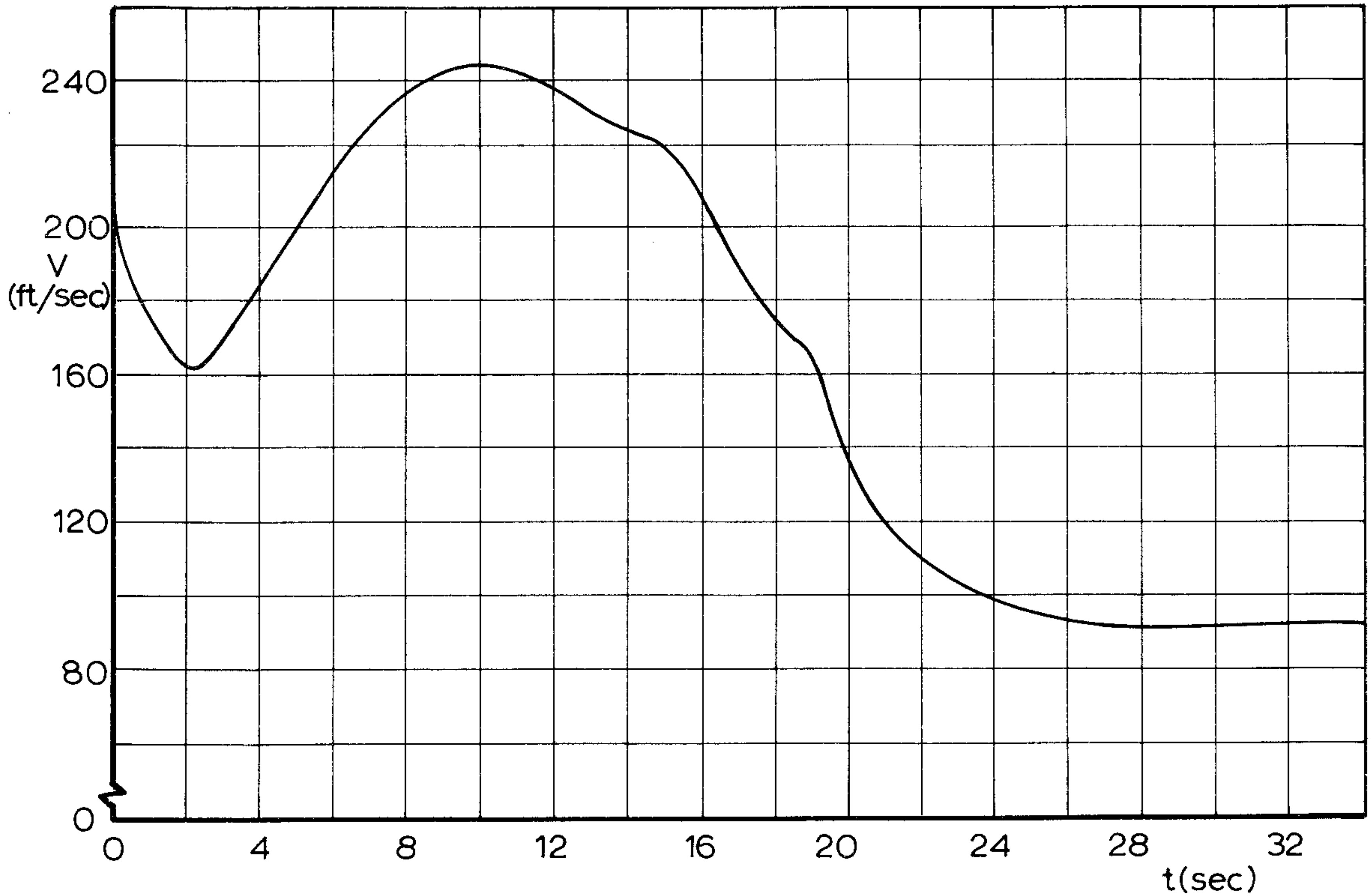

Fig 8 Velocity-Time History for System with 70,000 lb Load, Release Velocity = 253.5 ft/sec

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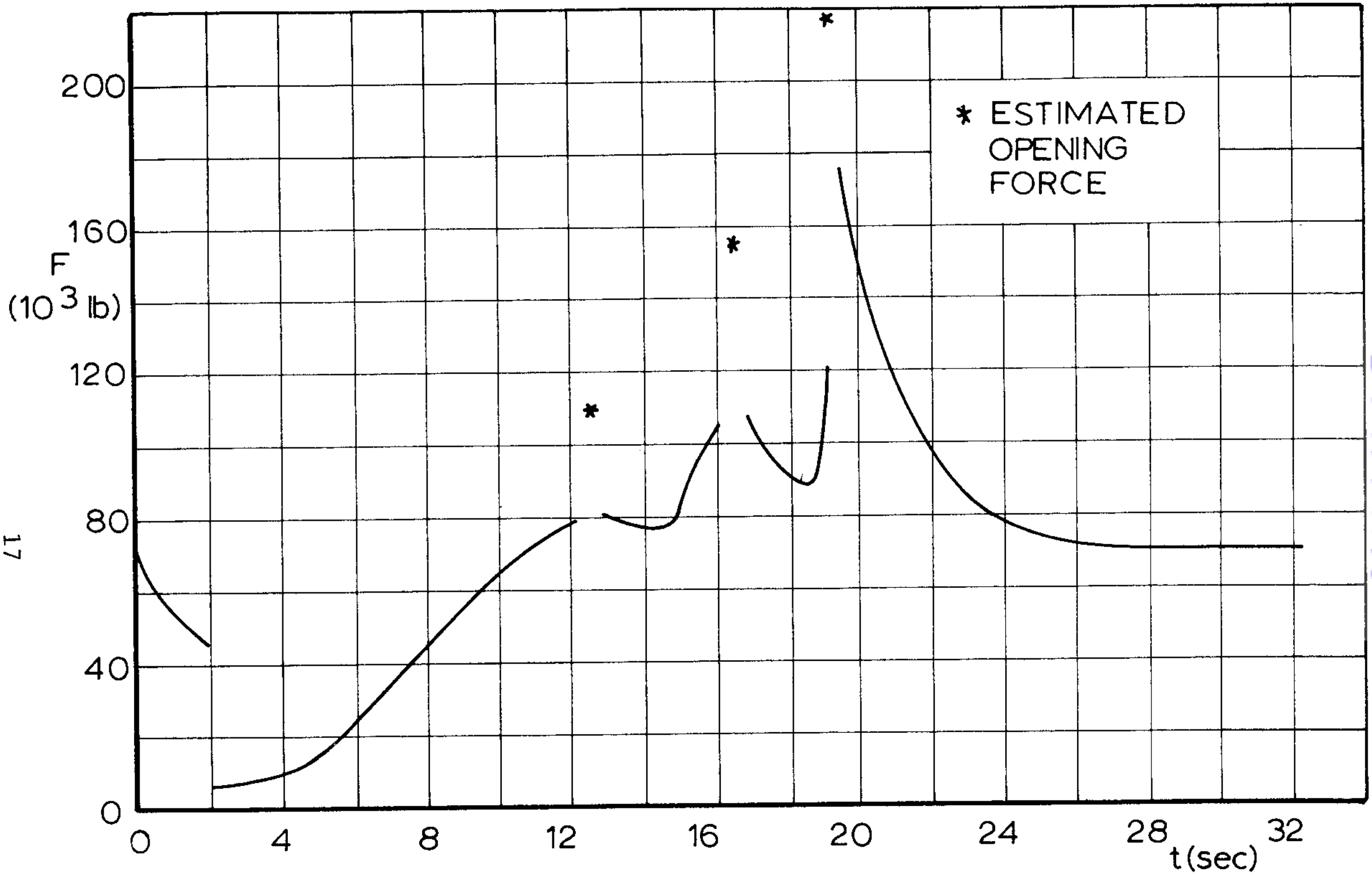

Fig 9 Force-Time History for System with 70,000 lb Load, Release Velocity = 253.5 ft/sec

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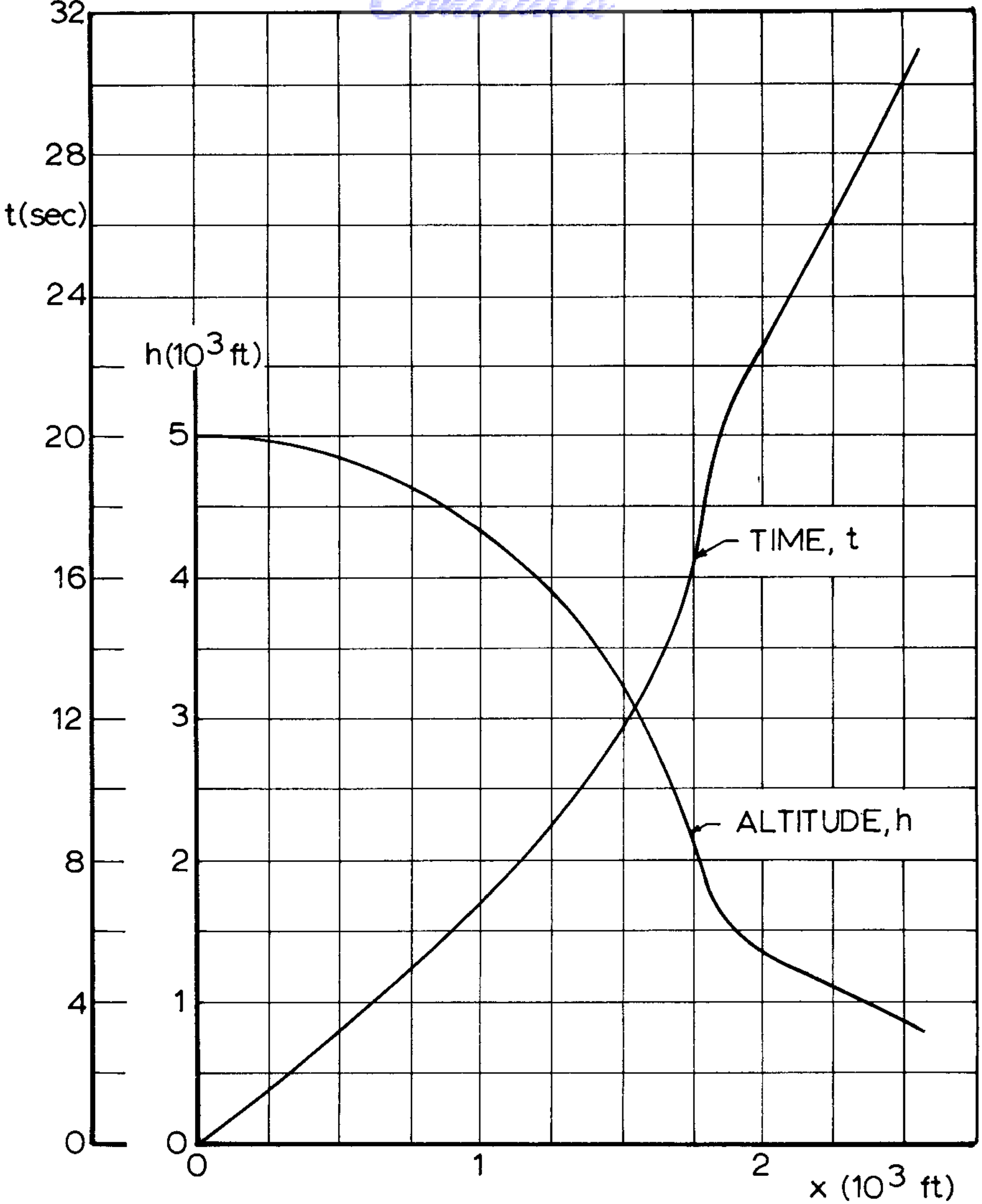

Fig 10 Altitude and Distance - Time History for System with 70,000 lb Load, Release Velocity = 253.5 ft/sec

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D. Terminal Deceleration

For both payloads the calculated terminal velocities are too high. However, in view of the state of the art it does not appear to be advisable to base the design layout on larger single parachutes. Clusters of parachutes do not appear to be feasible either because a cluster with defined gliding characteristics has not become known so far.

Therefore, it is envisioned to decelerate the load prior to the impact by means of retro-rockets. Vertical deceleration could be achieved by a system of rockets as described in Ref 14. Horizontally the system can also be decelerated by means of retro-rockets which could be attached to the platform or to the load itself.

Following the equations derived in Ref 15, the necessary impulse for deceleration of the vertical velocity to 25 ft/sec was calculated. For the 30,000-lb payload, an impulse of 33,450 lb-sec or a thrust of 43,395 lb for 0.772 sec will be required.

An impulse of approximately 136,500 lb-sec or a thrust of 236,600 lb for 0.577 sec would be required for vertical deceleration of the 70,000 lb load. The calculations are based on an assumed rocket action over a vertical distance of 25 ft. These figures include the impulse needed to overcome the effect of the apparent mass (Ref 15) and to compensate for a 35° deflection of the nozzle in order to divert the rocket exhaust from the load (see Appendix).

For horizontal deceleration, the rocket impulse required is merely equal to the necessary momentum change. For the 30,000 lb and 70,000 lb payloads the required impulses are 32,500 lb-sec, and 120,300 lb-sec, respectively, in order to reduce the horizontal velocity to 20 ft/sec in both cases.

Attention must be paid to the design of the terminal deceleration system so that the horizontal rocket force does not induce undesirable pendulum motion, because inertial forces of the included mass of the canopy and of the load will tend to move canopy and load in the gliding direction. This is a special problem and should be investigated separately.

E. Weight and Packing

Extrapolating the weights of smaller gliding parachutes, a 135-ft glider would weigh approximately 520 lb. The weight of the cluster of extraction parachutes amounts to approximately 180 lb, using data given in Ref 12 for a 28-ft ringslot extraction parachute. Based on information obtained

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from the author of Ref 14 the weight of retro-rocket systems capable of decelerating vertically and horizontally the loads of 30,000 and 70,000 lb amounts to 1230 lb and 3830 lb, respectively. These numbers were determined through comparison and extrapolation of known impulse and weight ratios. They also include 250 lb and 500 lb of weight for the structures needed for fastening and suspension of the rockets. These figures are also obtained from the same source.

Thus the total weight of the decelerator package would be in the range of 6.5-6.8% of the payload. This figure, however, does not include the weight of a possibly used platform, and the weights of bags, pilot parachutes and related hardware. However, it is estimated that the total weight of the delivery system is well below the amount specified as maximum.

Packing would follow a system as determined by engineering requirements related to the cargo aircraft. All components would be interconnected so that the system would perform as an integral unit as illustrated in Fig 1. The various required packages would contain the extraction/ stabilization parachutes, the glider, and the retro-rocket system. Established engineering methods and concepts are applicable. As shown before, a larger rocket system would be required for the heavier payload, but all other components would remain the same for both payloads.

F. Summary

In summary, this configuration appears to meet or to surpass the performance requirements specified and is within or close to the state of the art.

Also, control and guidance systems have been developed for gliding parachutes. This controllability is not further discussed in this study; however, it could be an important factor for actual aerial delivery systems of this type.

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IV. CONFIGURATION 2 - LIFT PRODUCING WINGS

Conventionally lift is developed by means of airfoils or wings. Therefore, a check will be made to determine whether the requirements for this aerial delivery system can be satisfied utilizing stubby wings which, while the load is in the airplane, would be folded against the side wall of the package.

The maximum possible area for wings is afforded by the area of the cargo containder side surfaces which amounts to approximately 448 ft^2. Assuming that a lift coefficient of 1.5 could be achieved, the wing area would provide a lifting area of $C_L S = 672\ ft^2$. To meet the requirements the lift to drag ratio, L/D, must be at least 0.8. Thus the drag area of the system cannot be larger than 538 ft^2. Under these conditions, steady state velocities of 171 ft/sec and 261 ft/sec would result for loads of 30,000 lb and 70,000 lb, respectively. Therefore, an additional system of parachutes or parachutes and retro-rockets would be necessary to decelerate the load to within the acceptable limits at impact.

The wings would have to be deployed during a stabilization phase similar to the one envisioned for Configuration 1. Mechanically the wing deployment is not a simple matter. In order to have a reasonable angle of attack between wing and the direction of glide, the cargo must be stabilized with respect to pitch, yaw, and roll. Pitch and yaw stability can possibly be achieved with a stabilizing parachute as schematically shown in Fig 11. However, it is highly questionable whether roll stability can be achieved with a parachute. Also, for torsional stiffness between parachute and cargo, an elaborate system of lines or some other means must be provided. Furthermore, the stabilization parachute is located in the wake of the cargo and its proper functioning is somewhat doubtful.

Thus this configuration would probably require a complex position control system incorporating elevators, ailerons and rudder, as well as sensing elements and servo motors. An arrangement to deploy the wings is needed, and either a very powerful retro-rocket system or a landing brake parachute with a somewhat smaller retro-rocket package must be provided. In view of these complex matters, this system is considered impractical, beyond the state of the art, and not feasible at this time.

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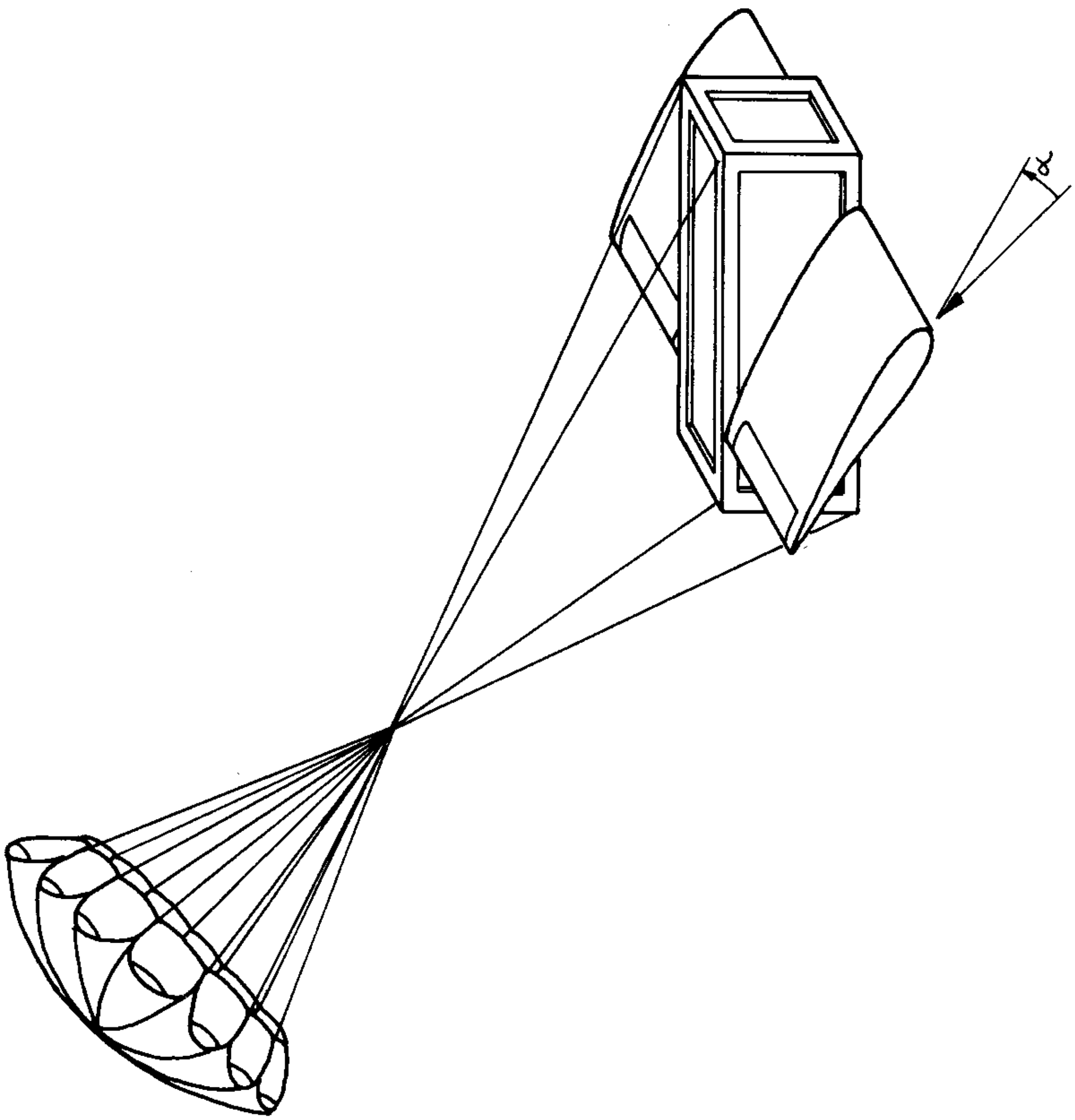

Fig 11 Scheme of Winged Glider

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V. CONFIGURATION 3 - LIFTING BODY

The concept of Configuration 3 includes an inflatable body which is rigidized by internal pressure and constructed in such a way that it performs as a so-called lifting body. Figure 12, taken from Ref 17, illustrates such a lifting body, and the following performance data are also obtained from the same reference.

Aside from any problems which would be involved in fabrication of such a device, the main disadvantage of this system is the high velocity obtained even from very large lifting bodies. The lifting body shown in Ref 17 has a relatively high lift to drag ratio, namely, L/D = 2.8 at an angle of attack of 9^{o}, with $C_L = 0.38$, and $C_D = 0.136$. A similarly shaped body enclosing the 70,000 lb payload and having various spans would produce the descent rates shown in Fig 13. The horizontal velocity would be 2.8 times these values. The length of the body is 2.1 times the span.

Thus it can be seen that a lifting body as developed in Ref 17 would need to have an enormous size to meet the impact velocity conditions. Even the smaller sizes indicated in Fig 13 are quite large and in addition would require a separate terminal decelerator.

Of course, one can alter the lift to drag ratio by means of a brake parachute. This, however, would require considerable development effort, whose success is very uncertain. A terminal decelerator system would also be required.

Finally one could think of developing another type of lifting body which would be more suitable for the given problem. Very likely this would lead to layer wings and approach the Configuration 2 based on lifting wings. This too would require an intensive development effort.

From these figures, it can be seen that a lifting body configuration is beyond the state of the art and would very probably be an impractical delivery system.

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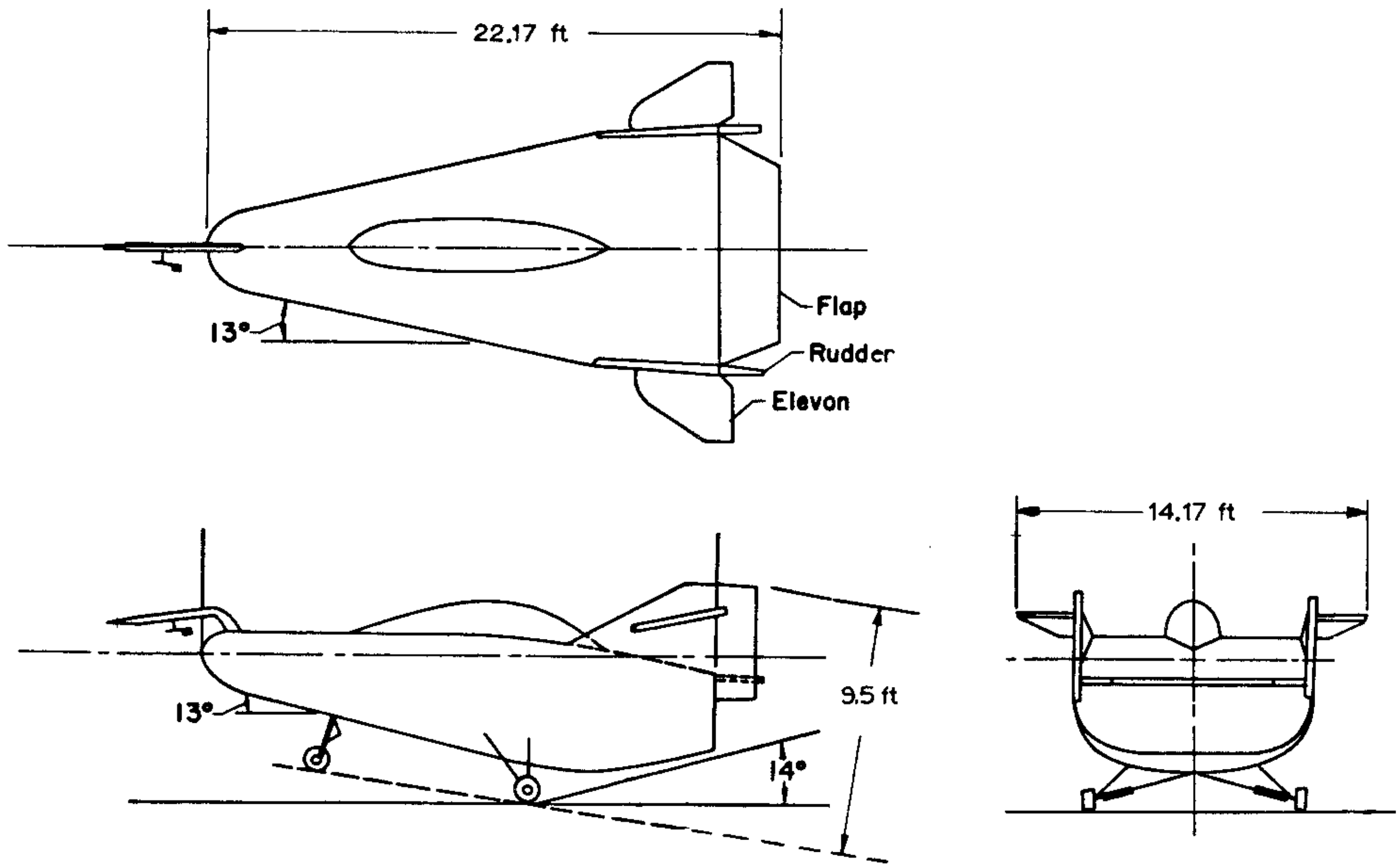

Fig 12 . Sample of Lifting Body, M2 - F1, Ref 13

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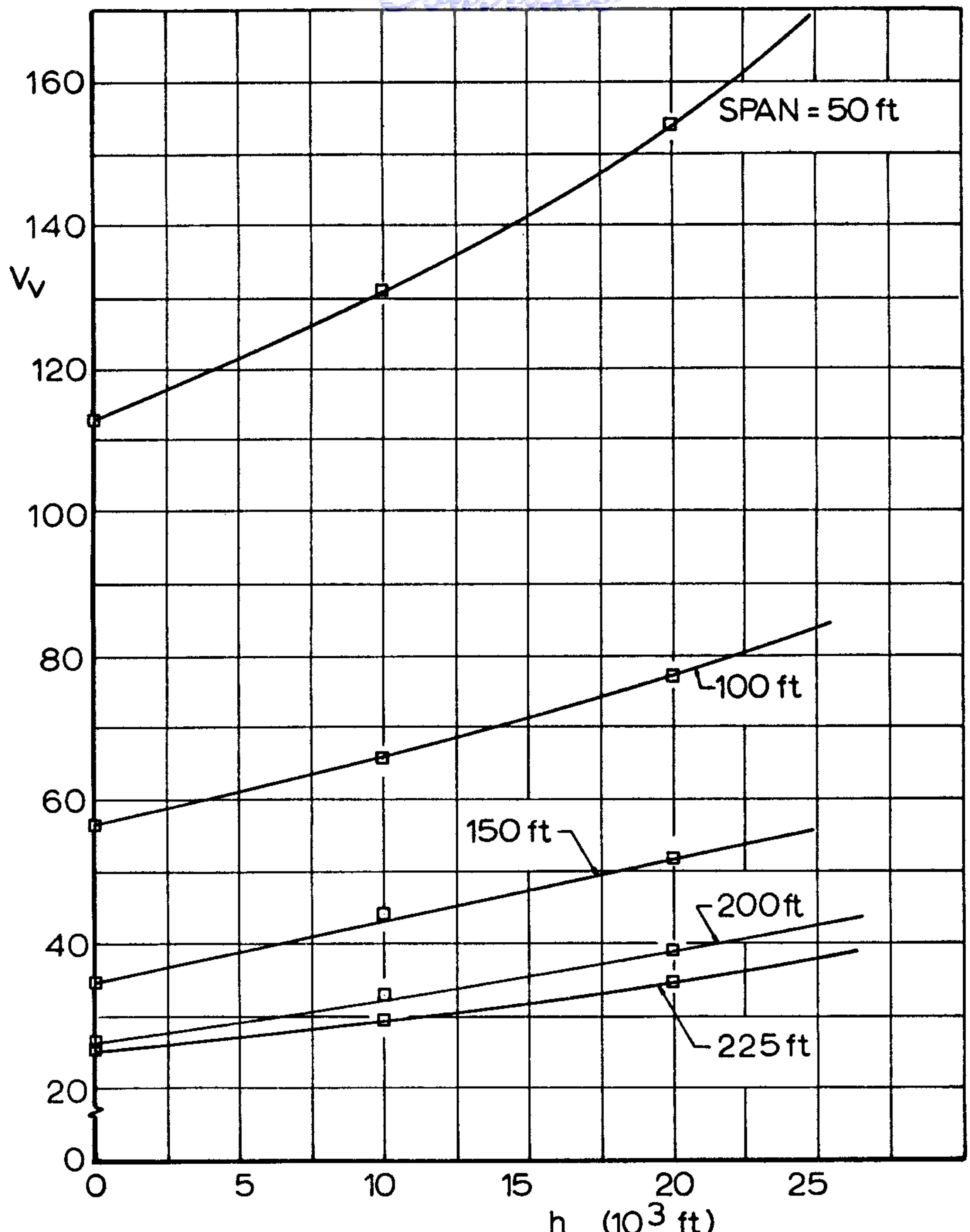

Fig 13 Rates of Descent for Lifting Bodies (M2-F1), $\alpha = 9°$, $L/D = 2.8$, $C_{D_{eff}} = 1.21$ (obtained from Ref 13)

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VI. CONFIGURATION 4 - ROTOR

Rotors are widely used for the development of lift. For the delivery of a heavy load from a high initial speed the main advantage of a system incorporating a rotor would be the mechanical strength of the rotor. Therefore, Refs 18, 19, 20, and 21 were reviewed to determine performance characteristics of a rotor.

A characteristic feature of a rotor is the fact that at high lift to drag ratios the lift and drag coefficients become quite small (Fig 14), and operating in the high L/D region requires very large rotors. Also the horizontal velocities are very high.

For example, at the maximum lift to drag ratio in Fig 14, the lift coefficient amounts to approximately 0.08. Thus the rotor drag coefficient is roughly 0.011, and when combined with the cargo container drag area of 265 ft^2 this system would produce a descent rate of approximately 30 ft/sec and 20 ft/sec for a 70,000 lb and 30,000 lb load respectively. The diameter of this rotor would be 135 ft. The horizontal velocities would be 217 ft/sec and 142 ft/sec, respectively, and this system would require a reefed brake parachute during the gliding phase which would be disreefed shortly before impact.

There would eventually be the possibility of using the rotational energy for a flare maneuver (Ref 21). However, this would require specific sensing and control elements and a servo mechanism. Also, a performance calculation can only be made after design details of the rotor blades are established.

Employing a lower lift to drag ratio would simplify and improve the operation somewhat. By extending the limits shown in Ref 18 slightly, the condition corresponding to an angle of attack of 20° could be met. Then the rotor would have a lift to drag ratio of 2.5, a lift coefficient of 0.6 and a drag coefficient of 0.24. A 135-ft rotor operating under these conditions would have approximately the required descent rate, 32 ft/sec for a 70,000 lb load and 21 ft/sec for 30,000 lb load. The horizontal velocities, 73 ft/sec and 48 ft/sec would be approximately equivalent to those obtained with the gliding parachute of Configuration 1 and could be reduced by a horizontal retro-rocket impulse.

The size of the rotor cannot be significantly reduced, if it is used to provide the required vertical impact velocities. For example, a 100-ft rotor would produce descent rates of roughly 42 ft/sec and 28 ft/sec for 70,000 lb and 30,000 lb loads, and horizontal velocities of 98 ft/sec and 64 ft/sec, and these conditions would require terminal decelerators.

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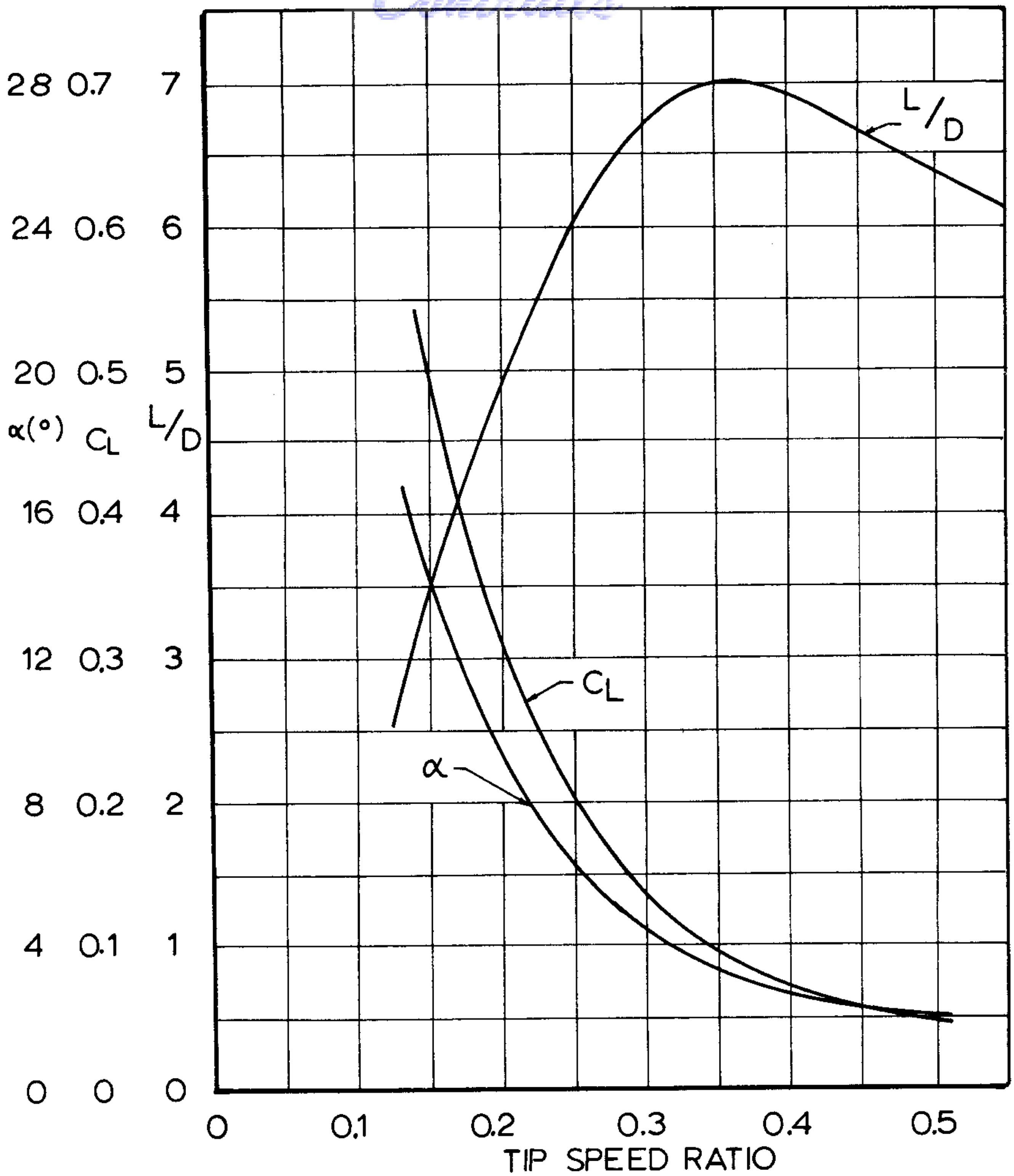

Fig 14 Typical Performance Diagram for a Rotor (Ref 18)

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In general, higher vertical speeds are accompanied by higher horizontal velocities. This could be improved by means of a trailing drogue parachute which also would provide some yaw and pitch stability. However, how well this system would function cannot be judged.

A strong disadvantage of this configuration is the size of the rotor. Packing limitations would require the blades to be folding or telescoping and constructed from 4 or 5 segments. Under the aerodynamic loads the structural integrity of such a device is a difficult problem.

A stabilization phase would be necessary for the deployment of the rotor and a rotor deployment mechanism is probably needed. The stability of the system during its glide phase is questionable and would probably require extra study and development work.

The performance characteristics shown in Refs 18, 19, and 20 are based on rotors ranging from 1 ft to 24 ft span, loads up to only 900 lb, and surface loadings which are much smaller than those proposed here; however, for the purpose of this analysis, they may be considered applicable.

In view of the complex composition of rotor devices and the great uncertainties of functioning, this configuration does not show sufficient feasibility to warrant further description and a more detailed analysis at this time.

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VII. MISCELLANEOUS CONFIGURATIONS

A configuration incorporating a single large gliding device was considered impractical because of very high bulk and weight characteristics.

Various other systems which have been used or could be used to produce lift were considered as gliding devices for possible delivery systems. These systems included balloons and high lift-to-drag gliding parachutes such as volplanes, parawings, parafoils, etc. The balloon type would require giant balloons and long periods to inflate. In addition they would be, at this time, very unpredictable in their ability to produce a given lift to drag ratio. In view of the required L/D-ratio in the order of unity, the use of devices having much higher L/D-ratios is not justified because of the added design complexities and cost. Therefore, they were not considered in detail.

In general, design concepts which were not felt to be within the state of the art or whose composition appeared too complex, allowing, of course, for certain developmental work, were only carried to the point where their feasibility appeared to be very doubtful.

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VIII. CONCLUSIONS

The recovery system denoted as Configuration 1 shows a feasibility as a deployable gliding aerodynamic decelerator design applicable to the recovery of large payloads. This system meets the requirements outlined in Section II, and it appears that the development of such a system is not an unrealistic task.

The components for this system have been successfully used, with the exception of the large size gliding parachute and that part of the retro-rocket system designed to retard the horizontal motion. Development of a large gliding parachute, such as described, could be directed toward furthering the capability of existing parachutes; for example, the solid flat circular parachute, the triconical parachute, the ParaSail parachute, or some other such device could be developed in a 135-ft prototype capable of the performance characteristics described in Section III. The development of a rocket system for horizontal deceleration is not anticipated to be any more of a problem than the development of a large gliding parachute.

In summary, it appears that such a delivery system could be developed with a reasonable amount of effort.

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APPENDIX

Trajectory Analysis

The equations for the trajectory analysis described in Section III,A incorporated the trajectory angle as the independent variable. This was also done with the analysis described in Section III,C for the period before the gliding parachute deployment was initiated, since a constant drag area was assumed to act until then. The equations are:

$$\Delta V = \left[\tan\alpha + \frac{\rho C_D S}{2W_S}\frac{V^2}{\cos\alpha}\right] V\,\Delta\alpha$$

$$\Delta h = -\frac{1}{g} V^2 \tan\alpha\ \Delta\alpha$$

$$\Delta x = -\frac{1}{g} V^2 \Delta\alpha$$

$$\Delta t = -\frac{1}{g}\frac{V}{\cos\alpha}\Delta\alpha$$

After the gliding parachute inflation, lift was assumed to act, and the independent variable was necessarily changed to time, since in this situation a steady state trajectory angle eventually exists which does not change. Time was also used as the independent variable during the inflation for simplicity in working with the time varying drag areas, but no lift was assumed until the parachute was fully inflated. The equations for this phase are

$$\Delta\alpha = -g\left[\frac{\cos\alpha}{V} - \frac{\rho C_L S}{2W_S} V\right]\Delta t$$

$$\Delta V = -g\left[\sin\alpha + \frac{\rho C_D S}{2W_S} V^2\right]\Delta t$$

$$\Delta h = V\sin\alpha\ \Delta t$$

$$\Delta x = V\cos\alpha\ \Delta t$$

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The initial conditions were (a) for W_s = 30,000 lb: trajectory angle = 0^o, altitude = 5,000 ft, $V_o \leq$ 180 ft/sec. (b) for W_s = 70,000 lb: trajectory angle = 0^o, altitude = 5,000 ft, V_o = 200 ft/sec.

The drag area-time function was determined during the opening by a linear growth from the particular reefed condition to the following reefed or fully open condition over the filling time calculated as described in the text.

Necessary inputs are the initial conditions, W_s, $V_o t_f / D_o$ for each reefing stage, $C_D S$ before and after each reefing stage, and $C_L S$ for the inflated parachute.

The increments for the independent variables were chosen so that the corresponding velocity changes would not exceed a value of approximately 3%.

Retro-rocket Deceleration

The thrust and time of rocket action required for deceleration of the loads as described in Section III,E were calculated as follows. The altitude loss over which the rockets act, Δh, was assumed to be 25 ft and the required final velocity, V_1, was 25 ft/sec.

The formula for the thrust (vertical component) to weight ratio (used in this report) as developed in Ref 15 is

$$\frac{T}{W_s} = \frac{e^{2\Delta h/(v_e^2/G)} \left(\frac{V_1}{V_e}\right)^2 - e^{2\Delta h/(v_e^2/G)}}{1 - e^{2\Delta h/(v_e^2/G)}}$$

The time of action is shown in Ref 15 to be

$$t_1 = \frac{V_e}{G} \frac{1}{\sqrt{T/W_s - 1}} \sin^{-1}\left\{\left(1 - \frac{V_1}{V_e}\right) \frac{T/W_s - 1}{T/W_s \left[\left(\frac{V_1}{V_e}\right)^2 + \frac{T}{W_s} - 1\right]}\right\}$$

In the above equations, v_e is the equilibrium velocity of the system and $G = \dfrac{1}{\frac{m_a}{W_s} + \frac{1}{g}}$ includes the apparent mass effect.

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In Ref 15 the thrust is assumed to be constant for the entire time of action so that the impulse is given by

$$I = T \cdot t_1$$

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) University of Minnesota Minneapolis, Minn 55455	2a. REPORT SECURITY CLASSIFICATION 2b. GROUP

3. REPORT TITLE

Conceptual Studies of Aerodynamic Glider-Decelerator Combinations for Heavy Loads

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Report - Feb 1970 - Nov 1971

5. AUTHOR(S) (First name, middle initial, last name)
Helmut G. Heinrich
David P. Saari

6. REPORT DATE August 1972	7a. TOTAL NO. OF PAGES 36	7b. NO. OF REFS 21

8a. CONTRACT OR GRANT NO. F33615-68-C-1227 b. PROJECT NO. 6065 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFFDL-TR-72-6

10. DISTRIBUTION STATEMENT

Distribution limited to U. S. Government agencies only; (Test and Evaluation; 4 August 1971). Other requests for this document must be referred to the AFFDL/FER.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY AFFDL/FER WPAFB, Ohio 45433

13. ABSTRACT

Several systems for aerial delivery of large payloads with a gliding capability are composed and analyzed. For the gliding and landing phases these systems incorporate gliding parachutes, wings, lifting bodies, rotors, and retro-rockets. The feasibility of the systems is discussed and recommendations are made based on the results of the investigations.

DD FORM 1 NOV 65 1473

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gliding Parachute						
Air Drop						
Heavy Loads						
Retro-Rocket						
Lift Producing Concepts						

☆U.S.Government Printing Office: 1972 — 759-485/018

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