BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B69 09008

SUBJECT: Gliding Parachutes for Land Recovery of Space Vehicles
Case 730

DATE: September 8, 1969

FROM: W. H. Eilertson

ABSTRACT

A survey of gliding parachute recovery systems under development shows that some of them have sufficient gliding capability (L/D) to allow pinpoint landing. Data is presented on their reliability,weight, volume and state of development.

The required gliding performance is a function of reentry vehicle guidance and control accuracy at main parachute deployment and the deployment altitude. For example the Apollo Command Module (CM) (targeting capability is 20 n.mi. CEP at 10,750 ft altitude) requires and L/D of 5.80 for pinpoint landing.

None of the gliding parachutes presently under development possess this capability. However, if the deployment altitude for the same CEP is increased to 20,000 ft the L/D requirement reduces to 3. The parachute gliding performance however, must be greater than this value (approximately 3.5) to offset the lower L/D of a semi-ballistic shaped payload (Apollo). Several of the gliding parachutes possess this level of L/D (3.5). If they could be designed to deploy at 20,000 ft. altitude, then pinpoint landings would be feasible for semi-ballistic configurations.

It is also pointed out that providing a large diameter rigid leading edge using inflatable booms or a "de Haviland boom" to some of the gliding parachutes could result in moderate increases in L/D.

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MEMORANDUM FOR FILE

INTRODUCTION

Of major concern to any manned space program is the mode of landing system employed to return the crew safely to earth. Over the past decade parachute systems have been exclusively used on manned spacecraft such as Mercury, Gemini, and currently the Apollo. While operationally successful systems, they leave much to be desired when a logistics spacecraft is considered because of a desire to recover these spacecraft on land as opposed to water. This requires the parachute system to possess gliding capability ($L/D > 0$) to offset entry ranging errors and ground winds. Impact attenuation possibly using rockets and landing gears must also be provided to prevent damage at touchdown (on runway or cleared ground areas).

This memorandum will review the recovery requirements of both the Apollo system and an earth landing logistics system. The later half contains a survey of current parachute systems under development as to their state of development, performance, reliability, and weight.

APOLLO RECOVERY SYSTEM REQUIREMENTS

Current Apollo recovery has been restricted to water landing after full scale test results indicated that spacecraft tumbling after ground impact would result in excessive loads on the crew and the spacecraft.[1] Water landing is restricted to maximum sea state of 4 under emergency conditions. A nominal splashdown occurs in a sea state of 3. Emergency earth landings are allowed but are restricted to 30 knot winds, 15 degree ground slopes and altitudes below 5,000 feet. Automatic operation of the recovery system is provided for an incapacitated crew. Avoidance of ground obstables, excessive ground slopes or ability to land in high winds is not possible with the Apollo recovery parachutes because they have no gliding or steering capability.

APOLLO RECOVERY SYSTEM DESIGN

The Apollo landing system (Figure 1) is based on vertical descent utilizing current parachute technology. A landing impact attenuation system is used consisting of a crew couch shock absorbing system and a crushable toe ribbed structure at the touchdown area of the CM (Figure 2).

The recovery system is activated nominally at 25,000 feet with the ejection of the CM apex cover and deployment of two 16.5 feet diameter drogue chutes. The drogue chutes are deployed at a dynamic pressure ranging from 83 to 204 psf. The maximum load imparted to the CM at drogue deployment is 40,000 lbs or about 3 g's.

The main recovery parachutes consist of three 83.5 feet diameter ring sail parachutes. Operation of any two results in a satisfactory rate of sink less than 38 fps at sea level. They are deployed by 7.2 feet diameter pilot chutes at a dynamic pressure from 30 to 80 psf and at altitudes from 2,500 to 18,000 feet (nominally at 10,750 feet). Two reef stages of 6 and 10 second intervals are utilized to limit the maximum load imparted to the CM to 43,400 lbs (3.6 g's).

The landing impact is attenuated by allowing the crew couches inside the CM to stroke 18.5 inches eyeballs down, 16.5 inches eyeballs in, 4.5 inches eyeballs side deceleration and 5 inches eyeballs up deceleration. Also a crushable ribbed structure is provided at the touchdown area of the CM for emergency earth landings.

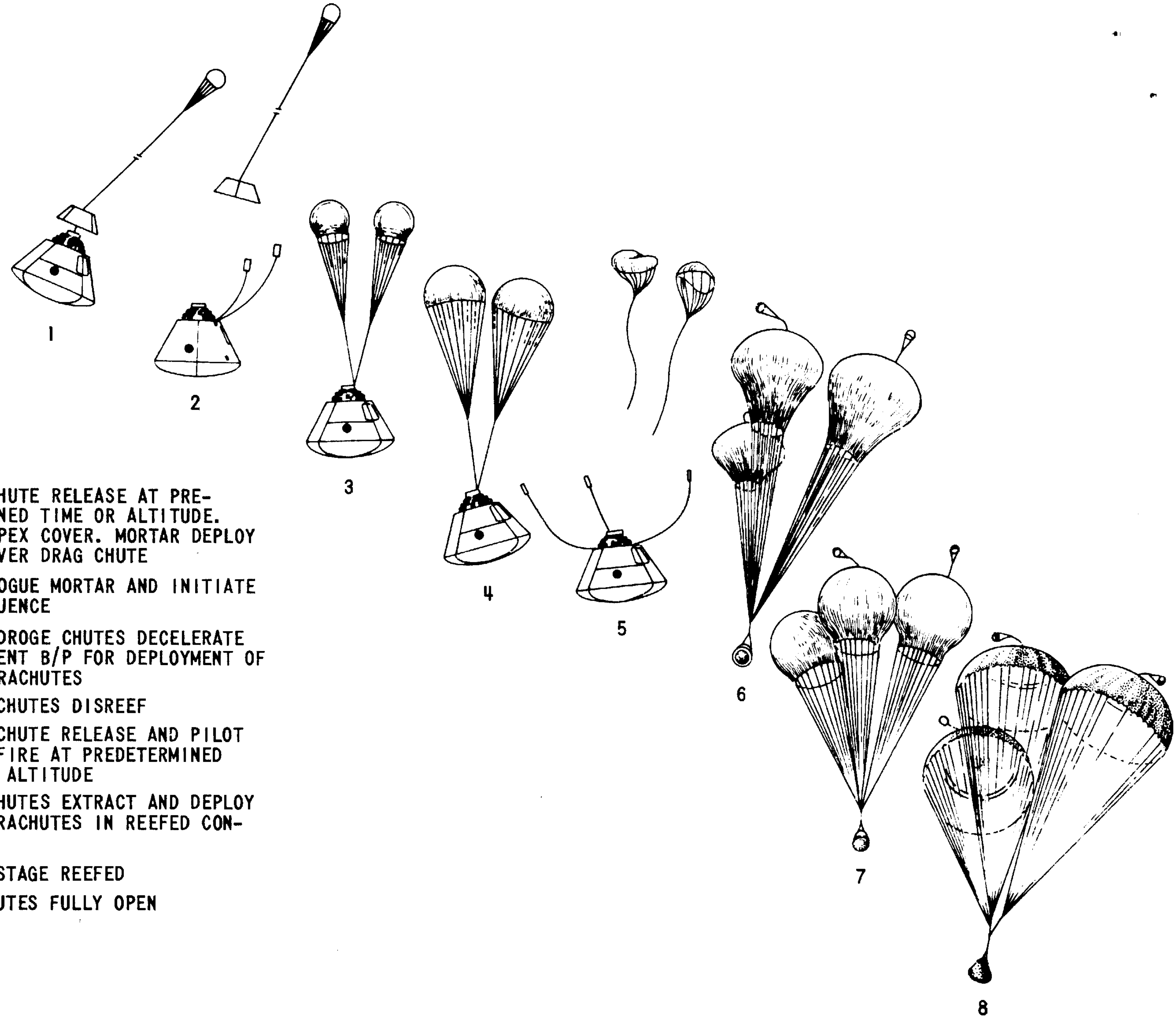
For water landing a flotation bag system maintains correct stable CM attitude (apex up) until crew egress.

APOLLO RECOVERY SYSTEM WEIGHT

The Apollo landing system weights are as follows:

As of April 1, 1968

Parachute System (drogues, mains, risers pilot chutes, release mechanisms, mortars)	708 lbs
Impact Attentuation (crew couch attenuation system, crushable ribs, etc.)	161 lbs
Flotation bag and pneumatic system	59 lbs
Total landing system weight	928 lbs



1. BRAKE CHUTE RELEASE AT PRE-DETERMINED TIME OR ALTITUDE. EJECT APEX COVER. MORTAR DEPLOY APEX COVER DRAG CHUTE
2. FIRE DROGUE MORTAR AND INITIATE ELS SEQUENCE
3. REEFED DROGE CHUTES DECELERATE AND ORIENT B/P FOR DEPLOYMENT OF MAIN PARACHUTES
4. DROGUE CHUTES DISREEF
5. DROGUE CHUTE RELEASE AND PILOT MORTAR FIRE AT PREDETERMINED TIME OR ALTITUDE
6. PILOT CHUTES EXTRACT AND DEPLOY MAIN PARACHUTES IN REEFED CONDITION
7. SECOND STAGE REEFED
8. MAIN CHUTES FULLY OPEN

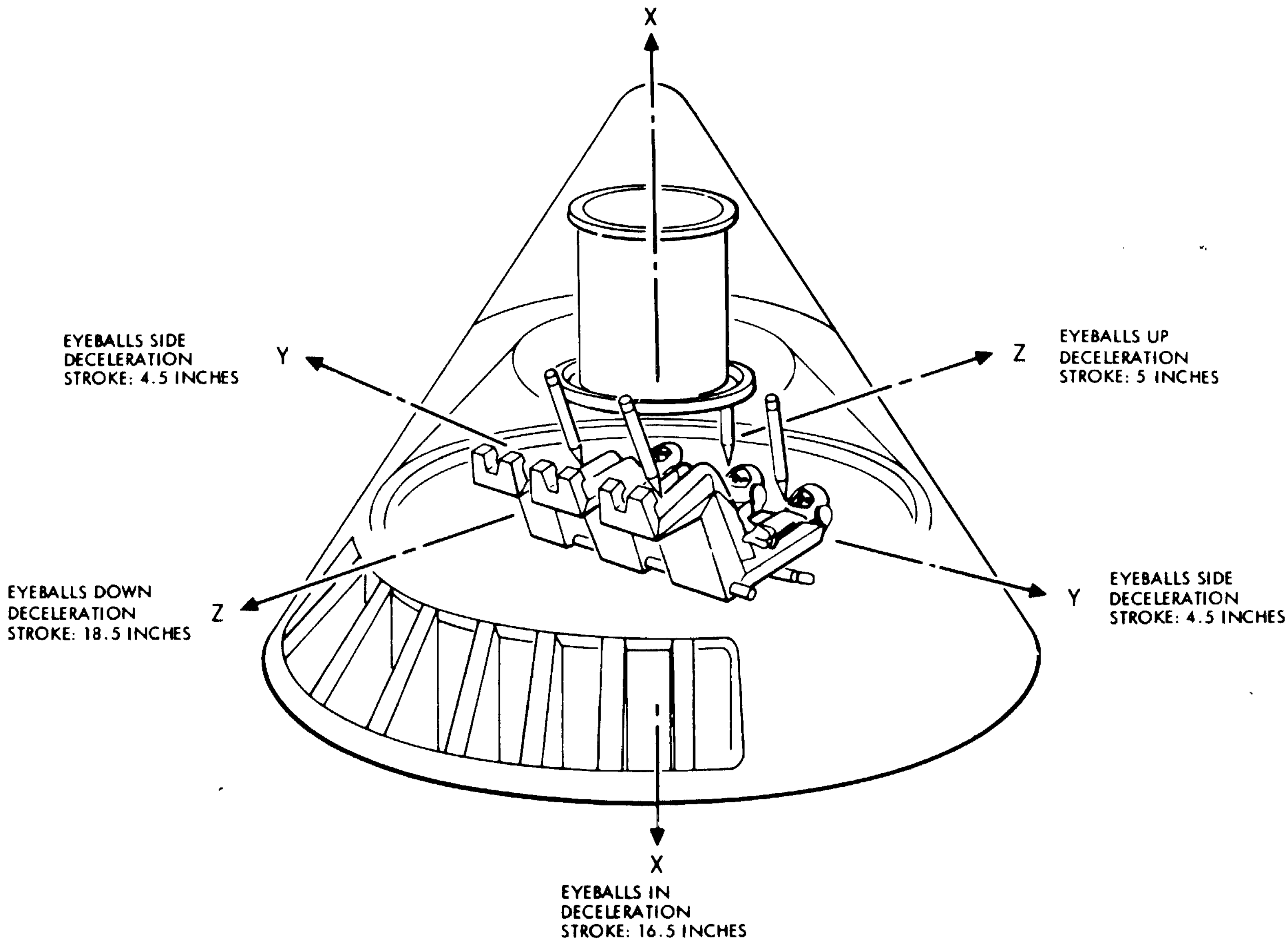


FIGURE 2 - APOLLO IMPACT ATTENUATION SYSTEM SCHEMATIC

This weight represents 7.7 percent of spacecraft 106 recovery weight (12,092 lbs).

APOLLO RECOVERY SYSTEM RELIABILITY AND COST

The landing system reliability apportionments are .999939 for crew safety and .999925 for mission success. The system is undergoing continuing drop testing. Failures have occurred on off nominal design conditions simulating high altitude abort (a failed drogue riser impacted and destroyed the second drogue causing loss of the test vehicle). Problems still under investigation are:

- complete system radiation tests,
- cold welding of parachute material under long term vacuum storage,
- dense packing of chutes causing minor material abrasion,
- increasing drogue riser cable diameter to increase factor of safety.

The Apollo landing system costs including development and testing for 13 units is $7,052,938. An additional unit would cost approximately $250,000. This data was obtained from Mr. D. Kelly, MAP-5, NASA Headquarters.

LOGISTICS SYSTEM REQUIREMENTS

In order for a logistics spacecraft to make safe operational landings on a routine basis, it appears necessary that a new system design accommodate primary earth landings with a maximum degree of crew safety and possible sapcecraft reuse. Also to be compatible with abort requirements a water landing capability must be provided. Therefore, it is apparent that the Apollo vertical descent concept must be modified to accomplish satisfactory earth landings with a logistic spacecraft.

For maximum volumeteric efficiency and to allow variation in crew/cargo mix an impact attenuation system not dependent on an attenuated crew couch as in Apollo is desired. This system design must provide an impact load profile and dynamic characteristics which can be tolerated by the crew and, under normal landing conditions, would not impose loads on the spacecraft that are larger than boost and reentry loads.

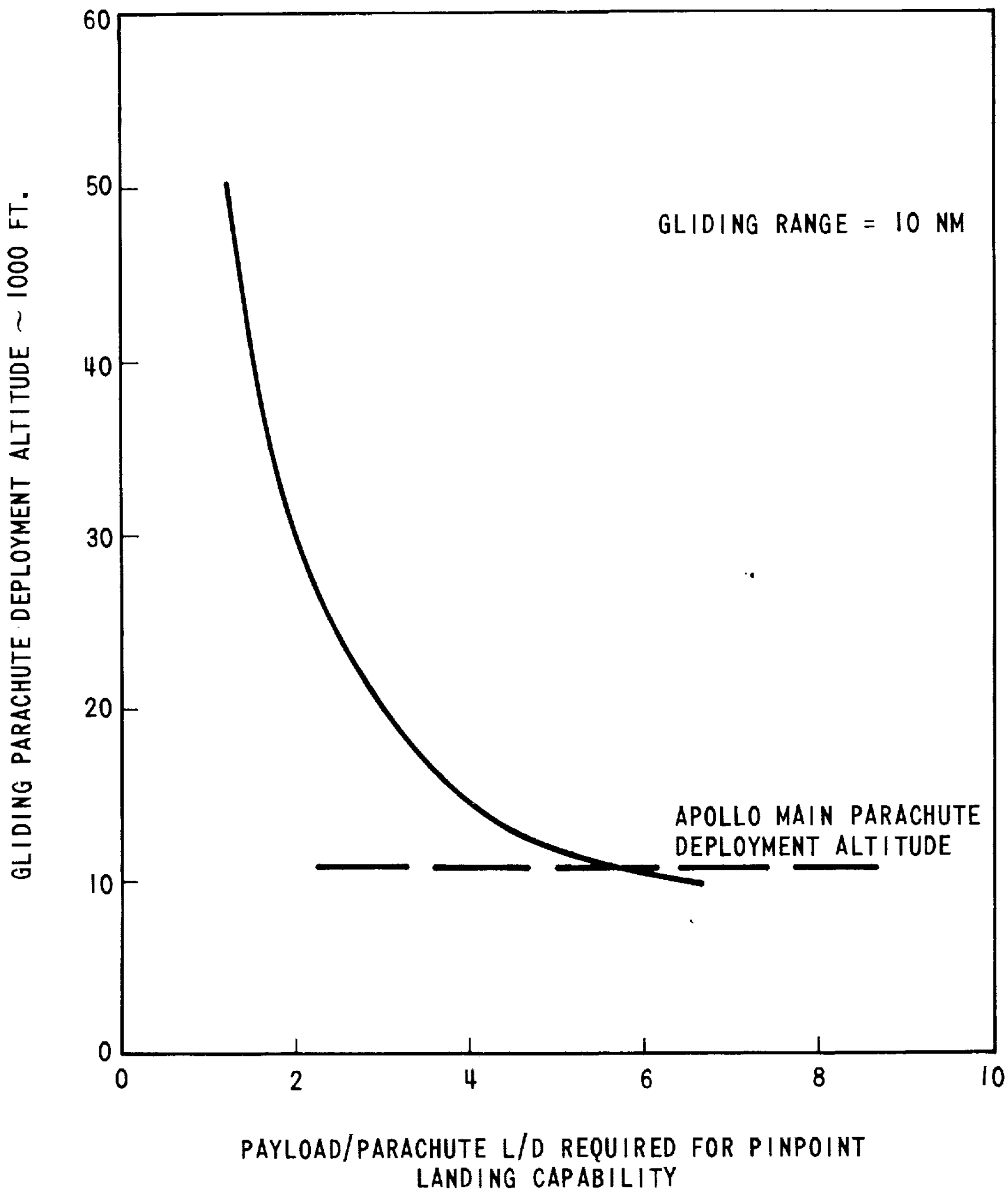


FIGURE 3 - REQUIRED L/D vs. DEPLOYMENT ALTITUDE

A certain degree of control during descent is essential to permit selection of a landing site free of ground obstructions, to avoid excessive ground slopes, and to negate high winds. This implies active crew participation for the nominal recovery case. In the event the crew is disabled, the recovery system must be designed to function automatically. These requirements are similar to the Gemini Paraglider recovery philosophy.

For design purposes, the maximum design ground wind should be 20 knots (34 fps) nominally (this is representative of 95 percent wind profile for the maximum steady winds which occur at the Woomera, Australia landing site) and 30 knots (51 fps) during mission abort.

RECOVERY SYSTEM GLIDING PERFORMANCE REQUIREMENTS

The gliding performance required of a recovery system for pinpoint landing capability is a function of parachute deployment altitude and the ability of an entry guidance system to minimize dispersions during entry so that the circle of error probability (CEP) is as small as possible at main chute deployment. For example, dispersions during autonomous inertial navigation from deorbit for the Apollo CM results in a maximum CEP diameter at altitudes below 25,000 feet of approximately 20.0 n.mi. This means that a recovery system would have to be able to glide a maximum of 10 n.mi. to reach its preselected target. The Apollo entry guidance capability is representative of the current state-of-the-art of semi-ballistic configurations and will therefore be used to define the lift-to-drag ratio, (L/D), requirements for recovery systems used on these configurations. The relationship between deployment altitude and required L/D for the Apollo entry guidance capability is shown in Figure 3. However, the Apollo main recovery parachute does not open until a much lower altitude is reached (10,750 feet), because time is required for the drogue chute to reduce velocity for safe operational deployment of the main parachute. Required L/D from this lower altitude (10,750 feet) would be 5.80. If we can increase the deployment of the main recovery parachute to 20,000 feet altitude, the required L/D reduces to 3.0. The L/D in these discussions includes the effects of both the parachute and the payload.

OPERATIONAL STEERABLE GLIDING PARACHUTE DESIGNS

In recent years several steerable parachute concepts have been developed to an operational level of confidence that also possess a gliding capability (L/D greater than zero).

They are the Parasail (Figure 4), the Cloverleaf (Figure 5), the Parawing (Figure 6), the Sailwing (Figure 7), the Parafoil (Figure 8), and the Volplane (Figure 9). Performance comparisons of these systems are tabulated in Table 1 and a more detailed description of the individual designs and development status is given in Appendix A.

GLIDING PARACHUTE L/D PERFORMANCE

The range of L/D of gliding parachutes is of interest since the higher the value of L/D the greater the gliding range from a given deployment altitude. As noted previously, the deployment of a parachute recovery system at 20,000 feet requires an L/D of only 3.0 for a recovery system, including the effects of the payload on L/D, capable of a pinpoint landing based on a guidance and navigation system capability equivalent to Apollo. This recovery system requires a parachute L/D of approximately 3.5 since the payload (Apollo shape) detracts from the total recovery system L/D. Going to higher deployment altitudes decreases the required L/D, but the opening shock loads of the main parachute increase accordingly.

GLIDING PARACHUTE STEERING CAPABILITY

All of these systems possess excellent steering capability with maximum turning rates of 50 degress per second or greater (Table 1). Fifteen degrees per second has been found to be adequate in cargo recovery systems using gliding parachutes.

GLIDING PARACHUTE CARGO LOADING (W/S)

For gliding parachute systems, horizontal velocity as well as sink rate is influenced by canopy loading (weight, W, divided by parachute projected area, S, in pounds per square feet). The relationships between sink rate, horizontal velocity, L/D and canopy loading is presented in Figure 10 for steady state flight conditions at sea level. The flight path angle, γ, is defined as the $\tan^{-1}\left[\frac{1}{L/D}\right]$. Also during steady state flight, weight is equal to the vertical component of the aerodynamic force, C_R. ($C_R \approx C_L$ for $L/D > 8.0$).

As shown in Figure 10, for a wind penetrating capability of 30 knots (51 fps) a canopy loading of 3 psf or more is required. Most of the parachutes exhibit a maximum canopy loading of less than 3 psf (Table 1). The Apollo recovery system, with zero lift to drag capability, requires a canopy loading below one psf to obtain a low vertical velocity (25 fps). Its wind penetrating capability is zero fps. Its resulting canopy area is large at 16,440 ft^2 for three parachutes. The remaining parachute systems

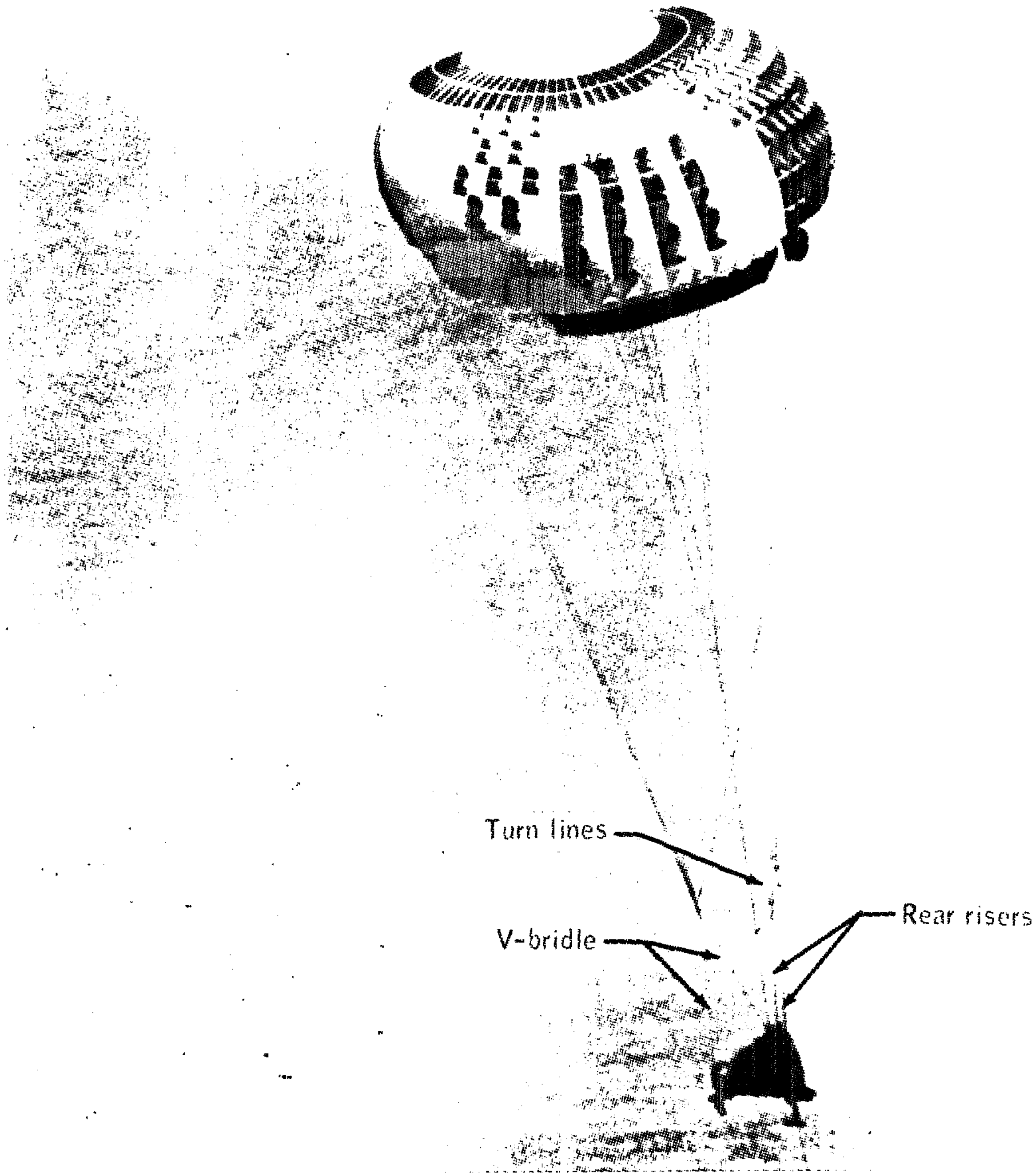


FIGURE 4 - PARASAIL IN FREE FLIGHT

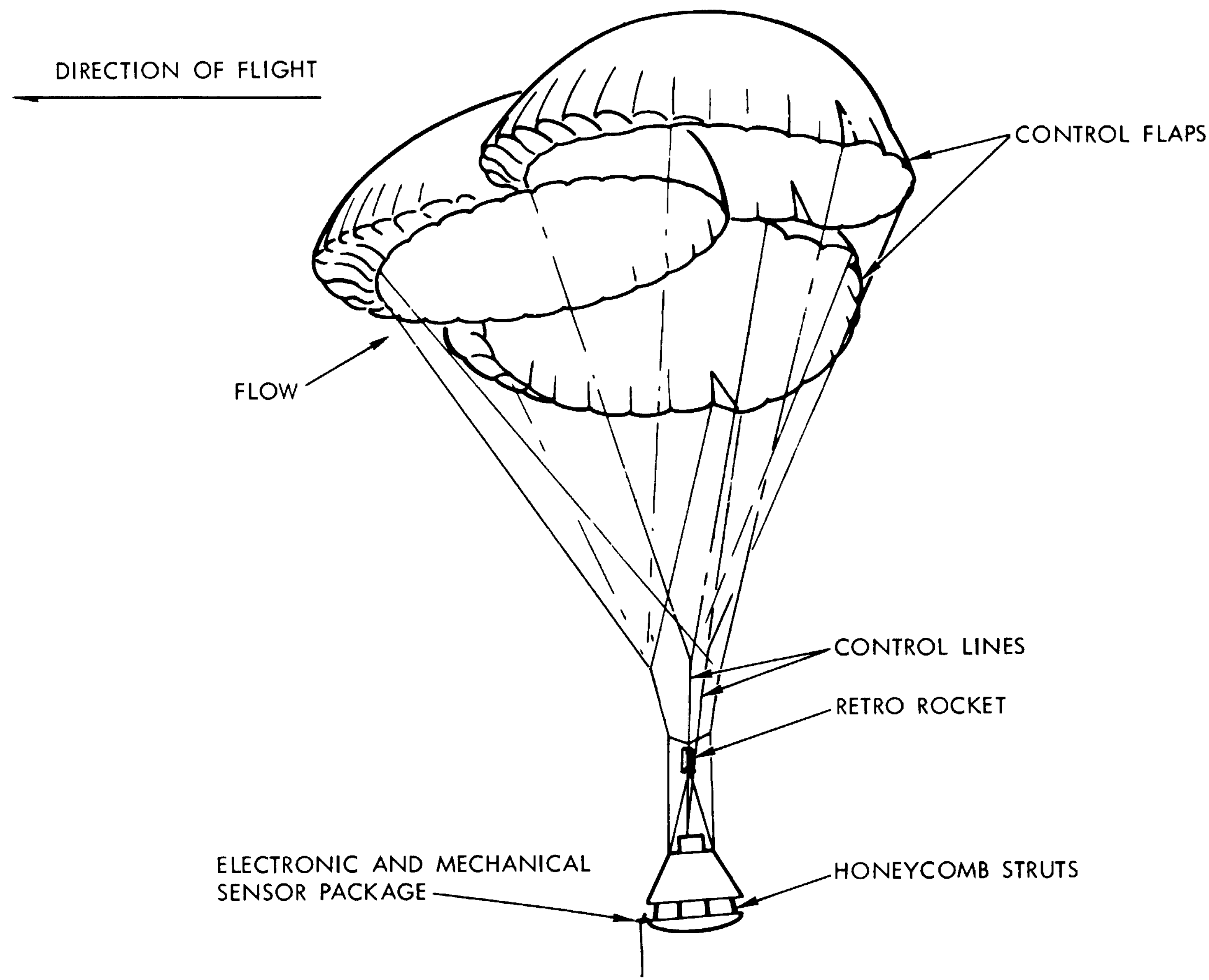


FIGURE 5 - CLOVERLEAF PARACHUTE CONFIGURATION

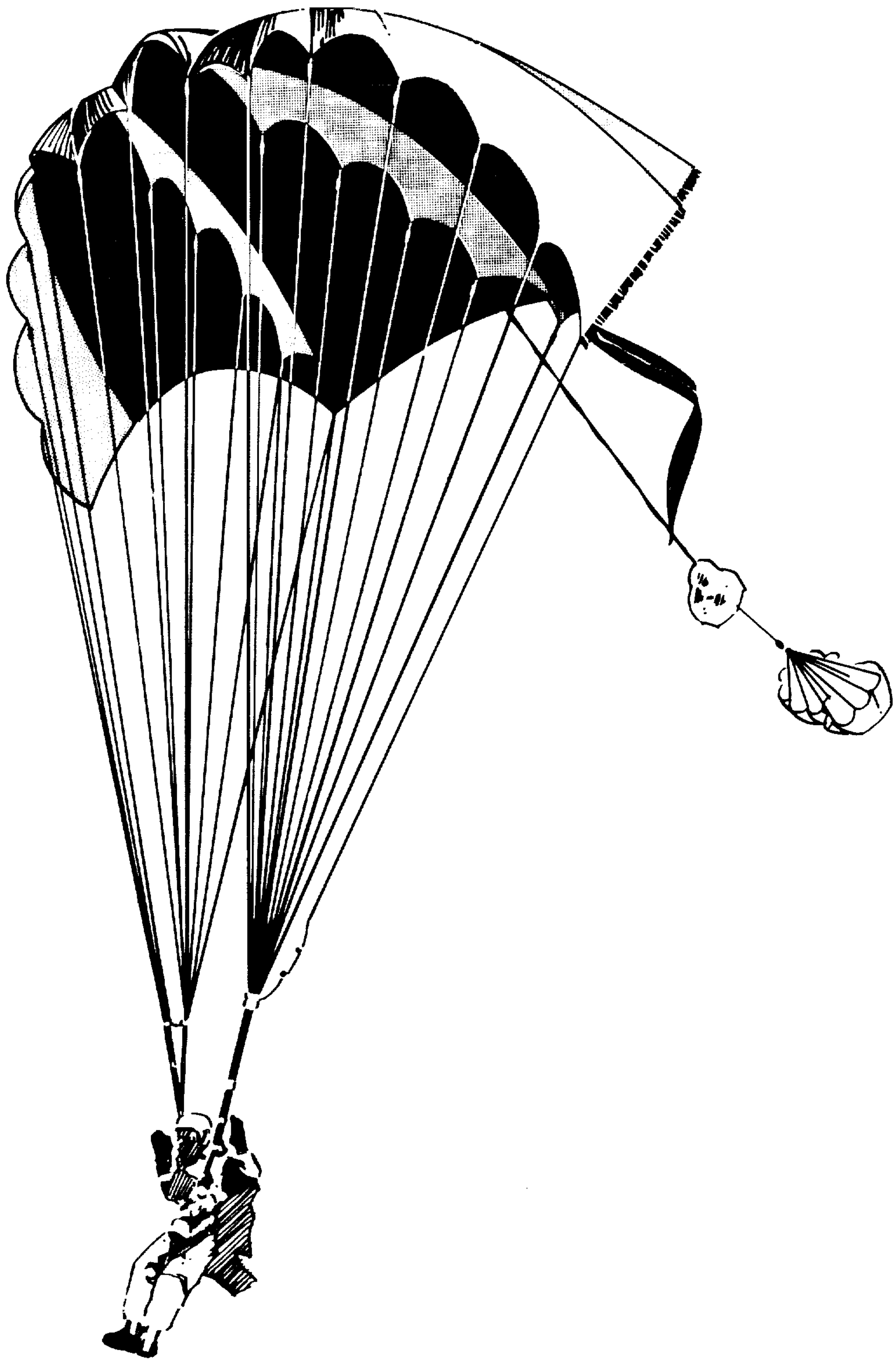


FIGURE 6 - PARAWING IN FREE FLIGHT

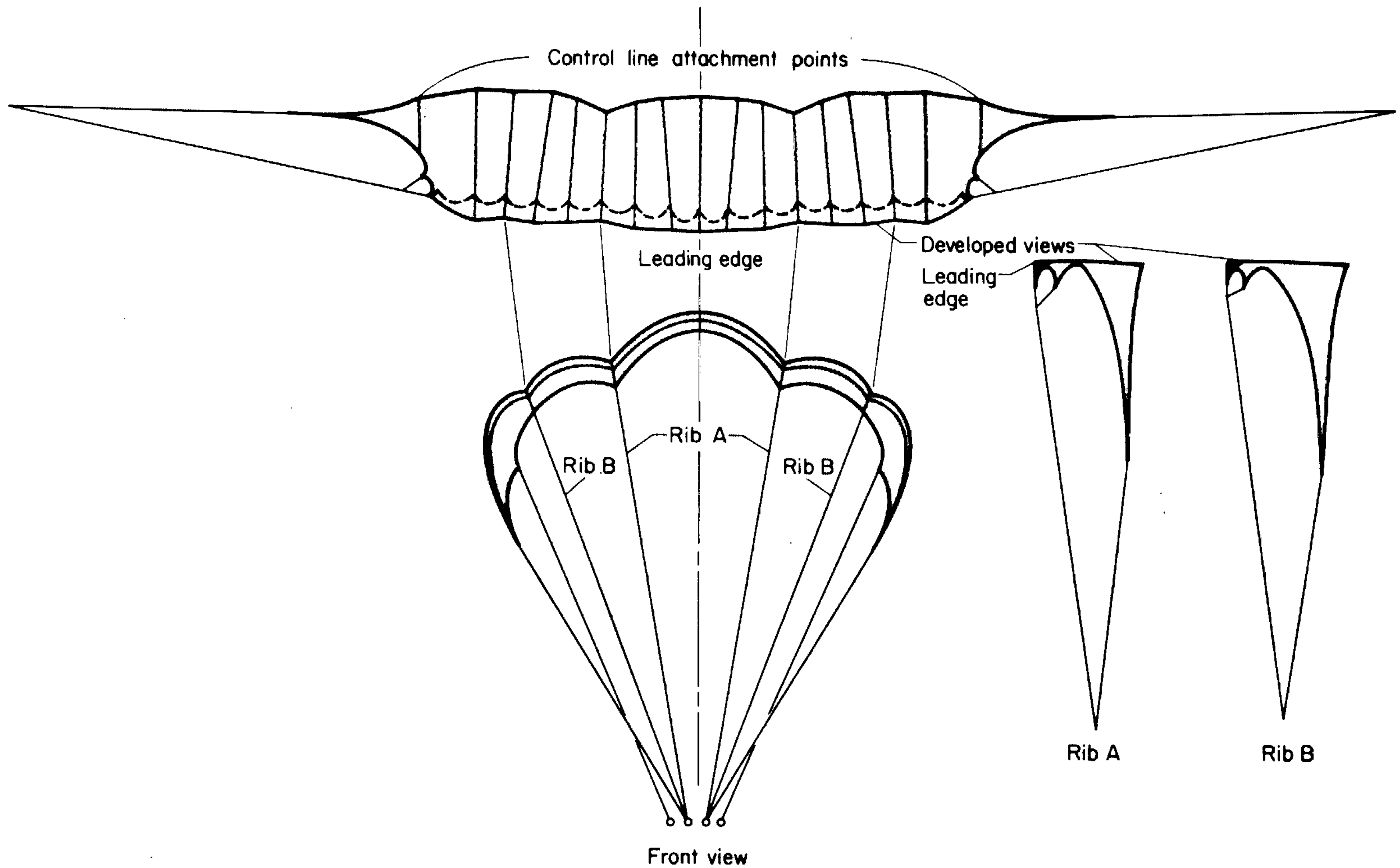


FIGURE 7 - SAILWING

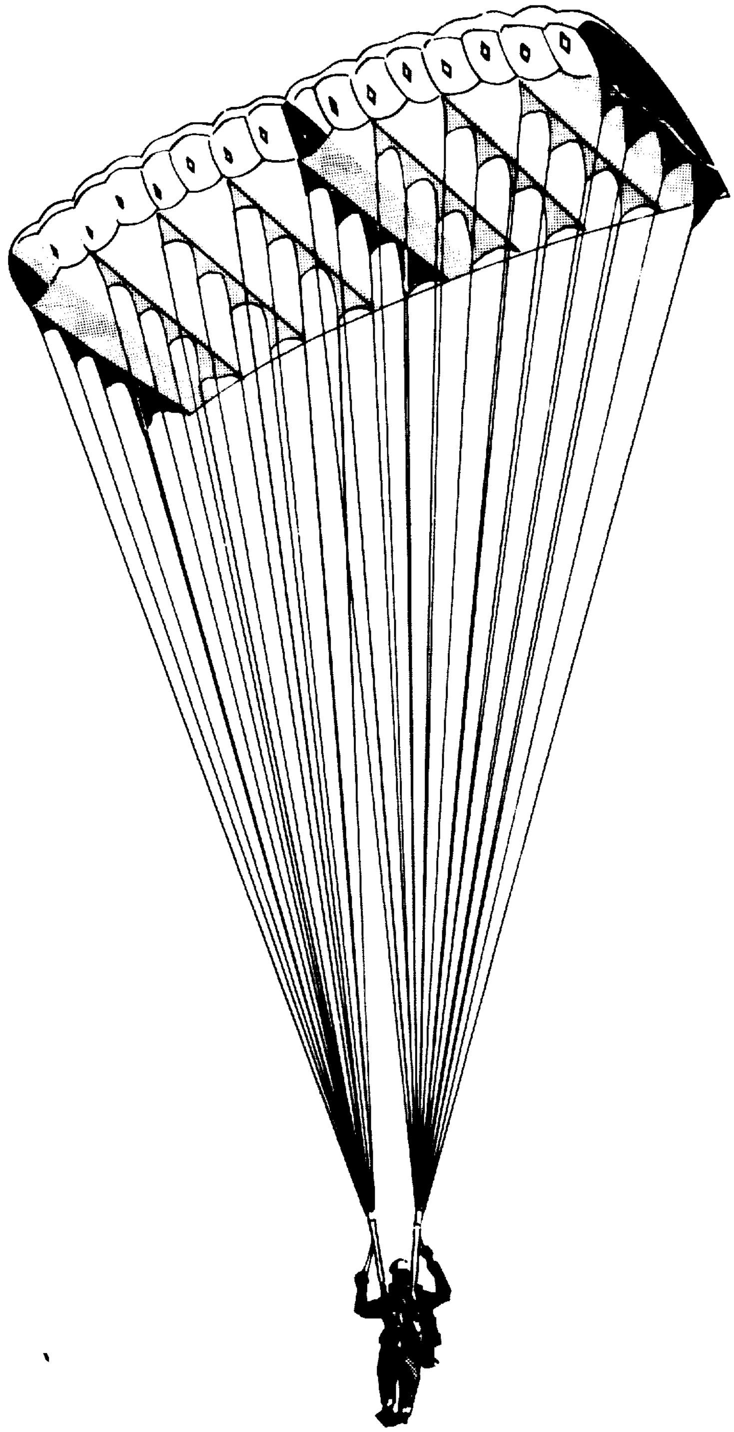


FIGURE 8 - PARA-FOIL IN FREE FLIGHT

FIGURE 9 - VOLPLANE IN FREE FLIGHT

TABLE 1

COMPARISON OF RECOVERY PARACHUTES

Parachute Type	L/D Range	Max. Turning Rate, deg/sec	Max. Canopy Loading, psf	Max. Rate of sink, fps	Max. Deploy. Dynamic Press., psf	Reliability	Status
Ringsail (used on Apollo)	0	0	0.792	38.	80	.999939	Operational
Parasail	0 to 1.20	50.	1.24	29	72	High	Operational
Cloverleaf	0 to 2.0	50	2.0	32	50	High	Operational
Parawing[1]	1.3 to 2.1	60	2.7	15.4	75	High	Under Developmer
Sailwing	1.8 to 2.2	72	2.0	20	50	Undetermined	Under Developmer
Para-Foil[2]	2.5 to 3.3	50	2.7	15.4	120	High	Under Developmen
Volplane	3.0 to 4.3	50	1.5	8	50	High	Under Developmen

NOTES:

1. Parawing data based on single keel version of Reference 11. Twin keel version of Reference 10 has L/D max. of 3.30. Deployment dynamic pressure calculated for 150 knots at 500 ft.

2. Data for aspect ratio 3.0 Para-Foil of Reference 7. Modifications to the airfoil upper surface near the leading edge have resulted in maximum L/D's of 4.0 during free flight.

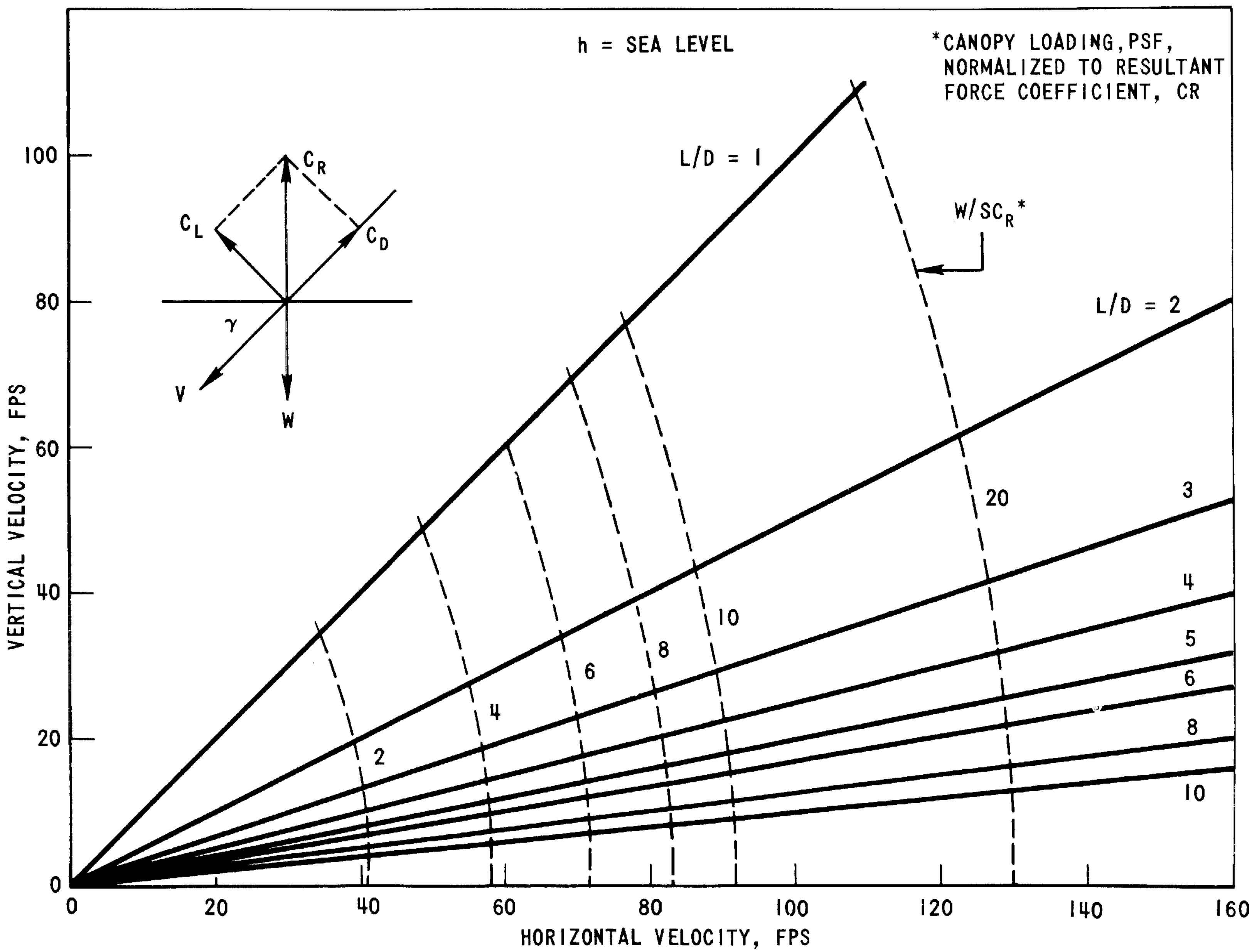


FIGURE 10 - VERTICAL AND HORIZONTAL VELOCITY AS A FUNCTION OF L/D AND CANOPY LOADING

in Table 1 exhibit canopy loadings below 3 psf. This is primarily due to the fact that higher canopy loadings distort the aerodynamic shape resulting in reduced aerodynamic performance (lower L/D). The use of a rigid boom in the leading edge might allow the canopy loading to increase without the attendant canopy distortion.

Desirable landing characteristics are high horizontal velocities to permit wind penetration, and low sink rates. To achieve these characteristics, high L/D and higher canopy loadings are necessary.

GLIDING PARACHUTE RATE OF SINK

A parachute configuration with an L/D of 4.0 (see Figure 10) can land at a rate of sink (vertical speed) of 10 fps with a canopy loading of 2 psf or at 20 fps with a canopy loading of 8 psf. Note the increase in horizontal landing speed from a value of 40 fps (23.5 knots) to 80 fps (47 knots). This increase provides adequate wind pentrating capability. The lower L/D configurations such as the single keel Parawing, and Sailwing if designed for low rates of sink (with canopy loadings below 2 psf) have horizontal speeds below 40 fps. This makes them undesirable from a wind penetration capability standpoint.

Maximum rates of sink listed in Table 1 vary from 38 fps for Apollo with one chute collapsed to 8 fps for the Volplane reported in Reference 2 with a wing loading of 1.5 psf. At higher levels of vertical velocity, impact attenuation must be provided to prevent structural damage and injury to the crew. Studies indicate that for non-gliding systems landing rockets can attenuate the vertical speeds sufficiently and more reliably than other approaches (Reference 1 and 3). Flared landings to horizontal flight prior to touchdown require L/D modulation which some of the parachute systems exhibit to a limited degree (Para-Foil and Volplane). However, these systems do suffer from canopy collapse problems at low angles of attack, and to early stall at higher angles, that render their reliability in this mode questionable. The use of leading edge stiffeners could open up their L/D modulation capability and possibly make them capable of flared landings.

GLIDING PARACHUTE DEPLOYMENT DYNAMIC PRESSURE AND OPENING SHOCK LOADS

In most parachute system designs a drogue chute is initially employed to reduce the terminal velocity to a level that insures safe and dependable opening of the main parachute. For gliding parachutes that use a low porosity fabric for the canopy, a terminal velocity is required that results in a lower dynamic pressure. Tradeoff studies comparing the drogue chute weight versus the main canopy weight (Reference 4) shows that a terminal dynamic pressure of 50 psf results in lower opening loads on the main canopy with a low drogue chute weight. (The Apollo drogue parachute terminal dynamic pressure is 64 psf.) Table 1 shows that all of the parachute systems tested to date have successfully deployed at this pressure (50 psf) or higher.

Another important effect is deployment altitude on opening shock loads. In Reference 4 it is stated that a 10 to 20 percent increase in opening shock loads can be expected when a parachute is deployed at 20,000 feet as compared to 10,000 feet at the same dynamic pressure. Hence, the adoption of pinpoint landing criteria with its higher deployment altitudes could necessitate a structural change in both the payload basic structure and the parachute to adapt the system to the higher opening shock loads.

GLIDING PARACHUTE RELIABILITY AND OPERATIONAL STATUS

Reliability for these systems has been excellent except for the Sailwing which experienced deployment problems earlier in the program. Recent improvements in reefing techniques have been successful. In personnel jumps the highest confidence level stated is for the Volplane (Reference 2).

The development status of the various systems listed in Table 1 are given as operational if a system has been developed and is operating successfully. It should be emphasized, however, that the Ringsail parachute system for the Apollo is the only system successfully developed and operational for spacecraft recovery weights of 13,000 lbs. More work would be required to bring the other systems up to this level.

GLIDING PARACHUTE WEIGHT AND VOLUME TRENDS

A comparison of the weights and volumes of the various main canopy systems are presented in Figures 11 and 12. The weights are based on actual design values and extrapolated to

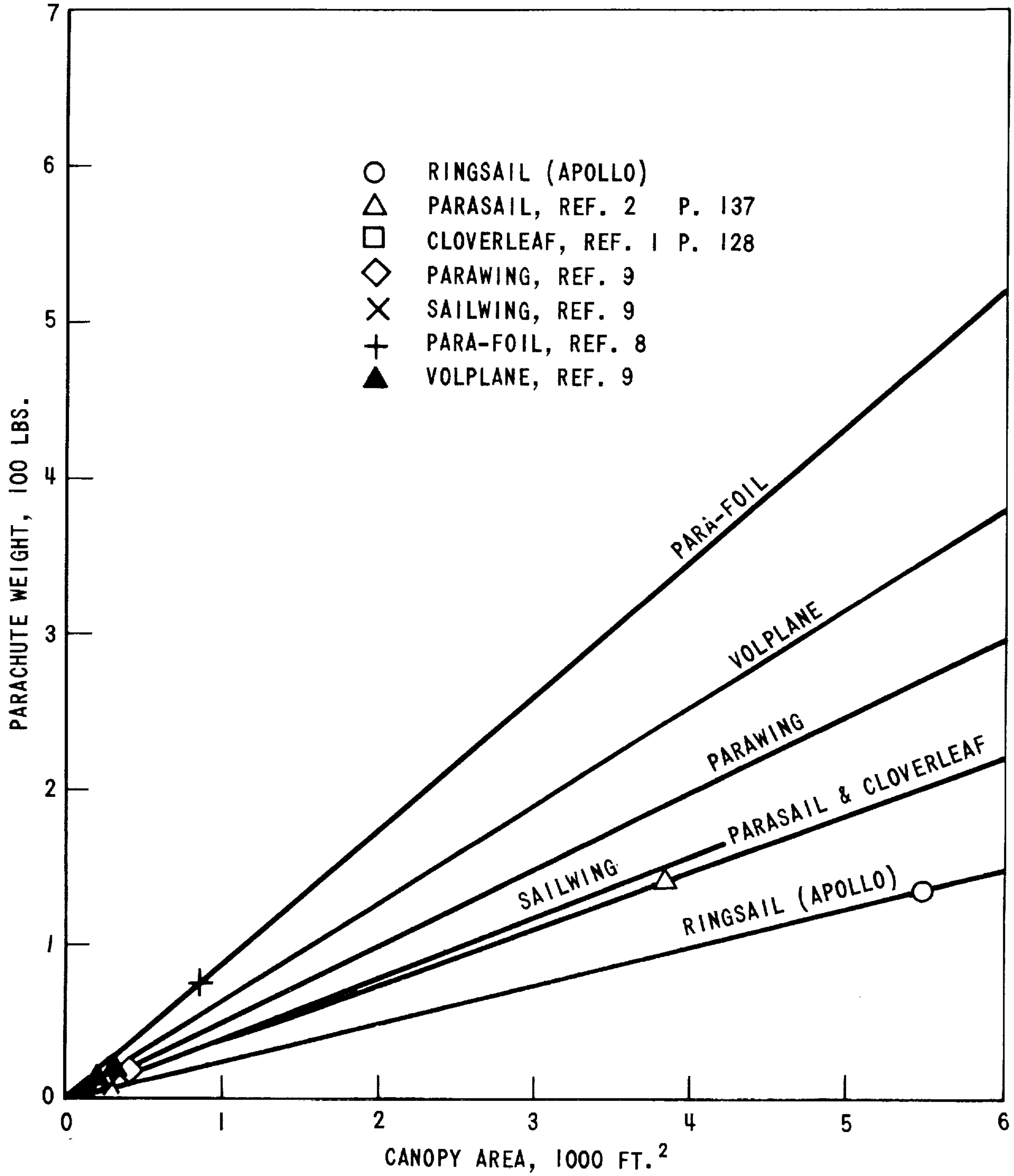


FIGURE 11 - PARACHUTE WEIGHT TRENDS

PACKING DENSITY = 34.5LB/FT.^{3}

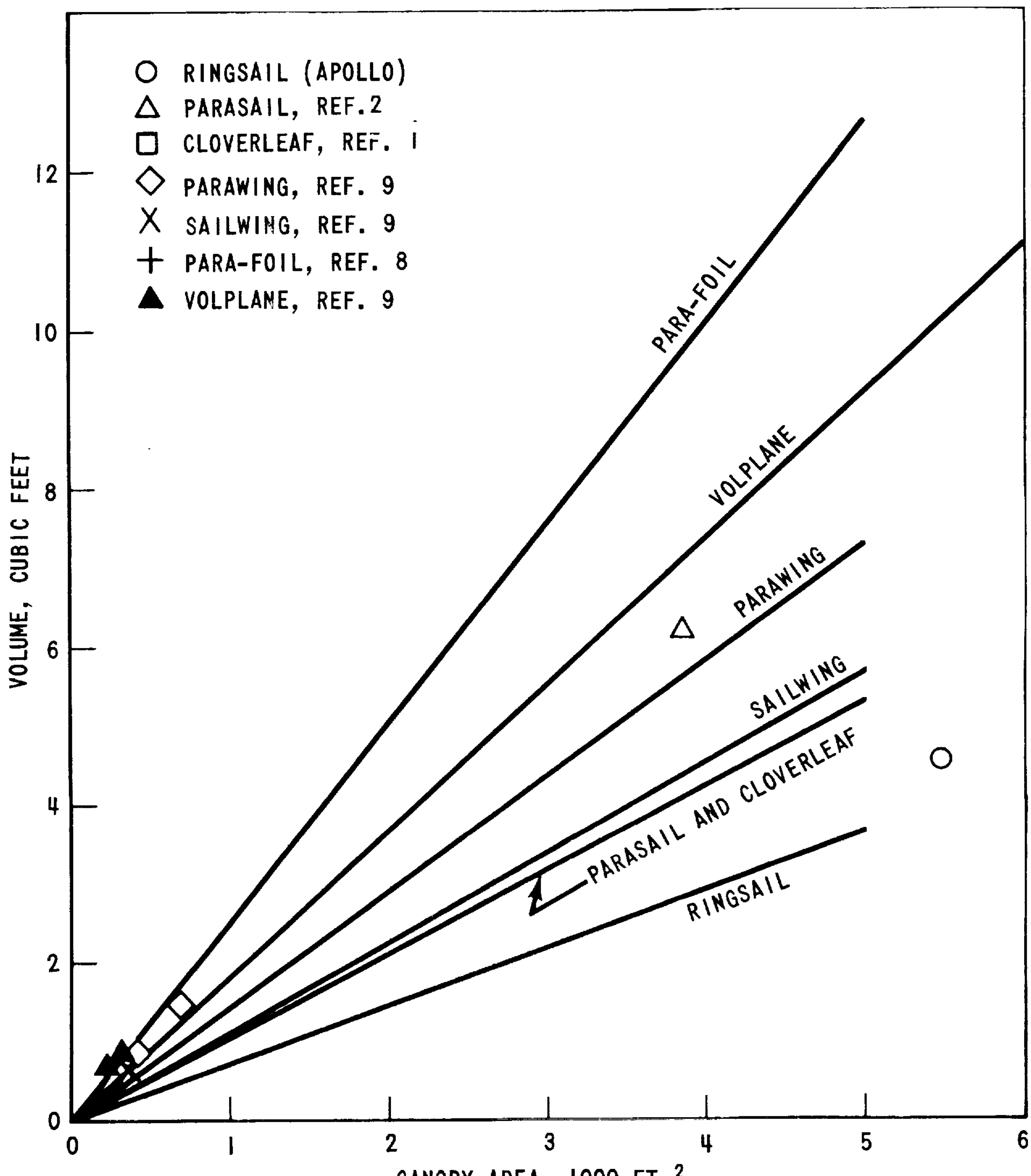


FIGURE 12 - PARACHUTE VOLUME TRENDS

higher and lower canopy areas. Therefore, the data presented should be used with caution as factors such as deployment dynamic pressure, velocity and canopy loading can vary considerably to affect the actual canopy weight for a given canopy area. The weight curve does show an increase in weight as the L/D capability of the various systems increase, with the Para-Foil, with an L/D maximum of 4.0, showing the highest weight trend. This is to be expected since the lifting canopies use heavier, low porosity, ployurethane coated fabrics.

The volume requirements also vary consideraly as shown in Figure 11. A constant packing density of 34.5 lbs/ft^3 was used as this value is reported (Reference 4) to be the maximum density allowable for damage free packing. Actual volumes reported in the references for each system are plotted also for comparison. They show that for the developed systems, packing densities less than 34.5 lbs/ft^3 were used. As before actual design considerations can result in volumes different than those shown in the figure.

GLIDING PARACHUTE AERODYNAMIC PERFORMANCE

A comparison of the L/D and lift (C_L) capability of the various gliding parachutes is presented in Figure 13. Also shown is the performance capability of a rigid wing of aspect ratio (AR) 1.5 and zero leading edge sweep ($\Lambda_{LE} = 0°$) using an NACA 23021 airfoil derived from Reference 5. This is a 21 percent thick airfoil which compares with the Para-Foil used for sounding rocket recovery of Reference 6. The L/D maximum of 9.0 for the rigid wing is considerably higher than the all flexible canopies shown in Figure 12. The Para-Foil has the highest performance with an L/D approaching 4.0 as reported in Reference 6. The Langley data (Reference 7) for the Para-Foil at the same aspect ratio shows much lower performance. This discripancy is probably due to Reynolds number effects between windtunnel and free flight and configuration differences (Reference 6 Para-Foil has a different airfoil shape).

Of interest is the grouping of the Parawing, Sailwing and Cloverleaf data at the same level of C_L and L/D. Based on rigid wing capability an L/D maximum of 3.0 would be the limit expected for these all flexible systems at a low aspect of 1.50. The addition of a payload shape can reduce the L/D capability of these canopies. Semi-ballistic shapes (Apollo) have subsonic L/D of about 1.0 whereas lifting bodies values are much higher (3 to 5).

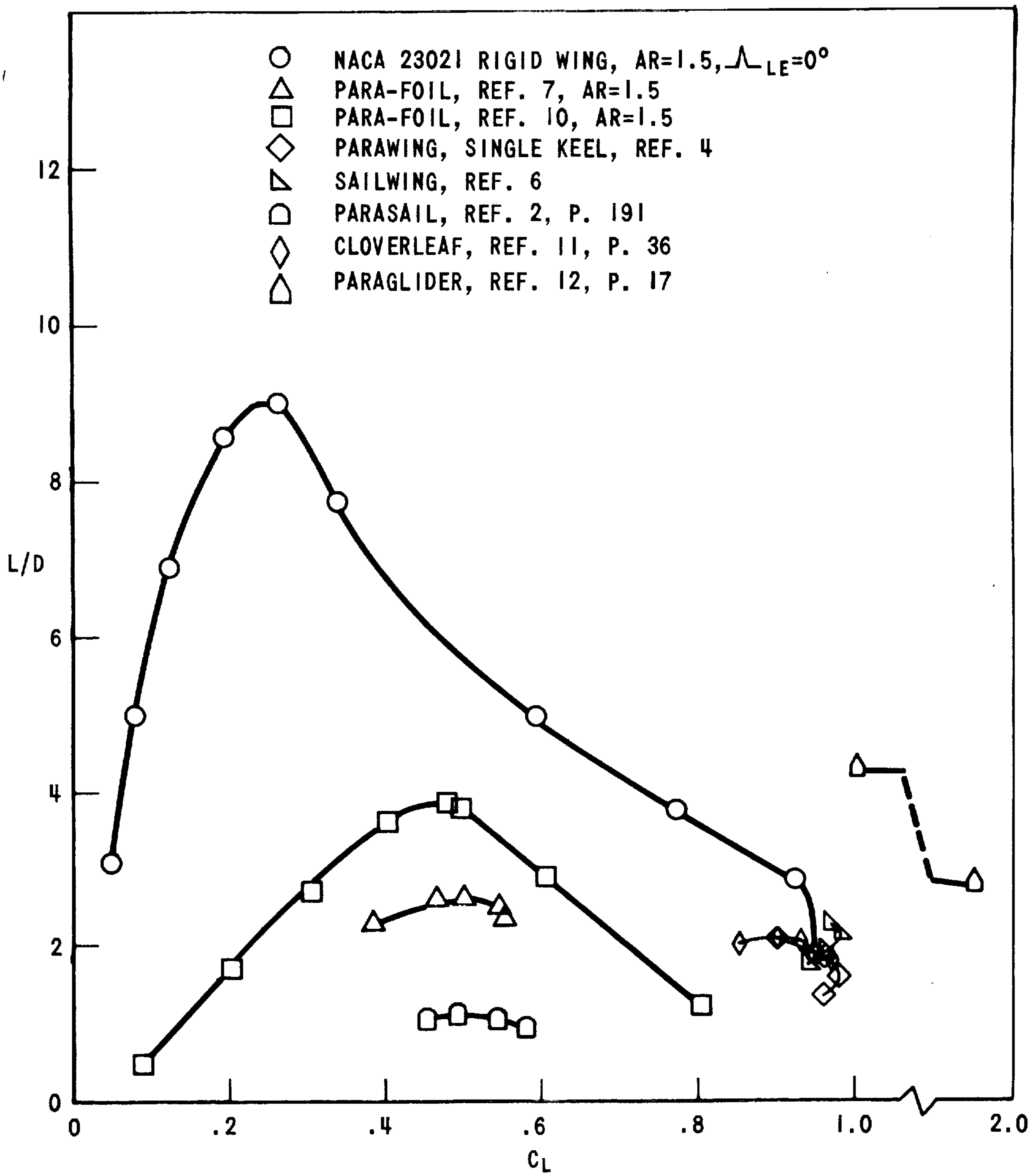


FIGURE 13 - RECOVERY SYSTEM AERODYNAMIC PERFORMANCE

Also shown is data for a semi-flexible Paraglider of Reference 8 with rigid inflatable leading edges. Considerable improvement in L/D and lift is shown. In combination with a Gemini vehicle (Reference 14) the max. L/D varied from 2.4 to 3.5 over a control range of lift coefficient from .8 to 1.65; the wing loading was 7.3 psf. However, this system proved to be unstable dynamically at low and high angles of attack. It was also a high weight and volume system. Recovery system weights approached 20 percent of the spacecraft vehicle weight (Reference 1). It does point out the advantages of large diameter rigid leading edges that can also increase the performance of the more rectangular platforms such as the Para-Foil and the Volplane. Wind tunnel data for the Volplane is not available at the present time and therefore does not appear in Figure 12.

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REFERENCES

1. "Ballistic Orbital Support Operations Study," Volume V, Escape and Recovery Systems, North American Aviation, Inc. SID65-179-5 March 30, 1965.

2. "Live Testing of Various Gliding Devices," E. D. Vickery, Pioneer Parachute Co., AIAA Paper No. 68-933, September, 1968.

3. "Gemini Land Landing System Development Program," TN D-3869, March, 1967.

4. "Land Landing System Technical Summary, " North American Avaition, SID65-1544-1, February 18, 1966.

5. "USAF Stability and Control DATCOM," D. E. Hook, J.W. Carlson, Douglas Aircraft Co., October, 1960, Contract AF 33(616)-6460.

6. "Controlled Recovery of Payloads at Large Glide Distances, Using the Para-Foil," C. F. Knapp and W. R. Barton, Sandia Laboratories, SC-R-67-1049, November, 1967.

7. "Analysis of Lift and Drag Characteristics of Ram-Air-Inflated All Flexible Winge Tested in the Langley Full Scale Tunnel," M. O. McKinny, NASA Langley Research Center, LWP-602, April 24, 1968.

8. "Low Speed Wing-Tunnel Tests of a Large Scale Inflatable Structure Paraglider," B. Gamse, K. W. Mort, P. F. Yaggy, Ames Research Center, NASA TN D-2859, June 1965.

9. "Status of Research on Parawing Lifting Decelerators," W. C. Sleeman, Jr., and Thomas G. Gainer, NASA Langley Research Center, AIAA Paper No. 68-967, September, 1968.

10. "Parawing Precision Aerial Delivery System," J. E. Forehand, and H. Q. Bair, AIAA Paper No. 68-958, September, 1968.

11. "Wind-Tunnel Investigation of the Static Aerodynamic Characteristics of a Multilobe Gliding Parachute," by G. M. Ware and C. E. Libby, NASA TN D-3856, June, 1967.

12. "Wind-Tunnel Investigation of the Static Aerodynamic Characteristics of a Multilobe Gliding Parachute," by G. M. Ware and C. E. Libby, NASA Langley Research Center NASA TN D-4672, July, 1968.

REFERENCES (CONTINUED)

13. " A Review of Para-Foil Programs," J. D. Nicolaides, University of Notre Dame, R. J. Speelman III, U. S. Air Force Flight Dynamics Laboratory, and G. L. C, Menard, U. S. Naval Aerospace Recovery Facility, September, 1968 (to be published by AIAA).

14. "The Effect of Aerodynamic Characteristics on the Flare and Landing of Low L/D Glide Vehicles," C. R. Faulders, E. R. Lekawa and R. L. McNary AIAA Paper No. 67-575. August, 1967.

APPENDIX A

Parasail Steerable Parachute

The Parasail steerable parachute (Figure 4) was designed in France by Mr. Pierre Le Moigne and is a gliding parachute based upon the jet exhaust principle (Reference 3). The Parasail has an operational L/D maximum of 1.2 (excluding payload) and possesses high turning rate capability of 70° per second. The variable L/D configuration with extended trailing flap has however experienced stability problems. It also requires a third control motor for pitch flap control in addition to the two motors required for turn control. A standard ring sail parachute used on Apollo could be used as a backup chute since it would be too complicated to provide for a redundant storable chute control system. Deployment of the Parasail is rapid and therefore it can be used during pad abort situations. At a canopy loading of 2 lbs per square foot an L/D of 1.2 would result in a forward glide speed of 30 fps (17.8 knots) with no wind. This forward velocity capability could be used therefore to offset winds up to 17.8 knots which is considerably short of the 30 knot maximum design wind. The vertical rate of descent at this wing loading and L/D is 30 fps which requires an impact attenuation device to prevent crew injury or spacecraft structural damage. A lower wing loading will result in lower vertical velocities but will also reduce the horizontal wind negating velocity capability.

Parasail Full Scale System

A full scale investigation of a Parasail recovery system has been completed at MSC[3] and demonstrated the recovery of a Gemini spacecraft at an unprepared landing site and on water. A Parasail, 70 ft. in diameter, with a wing loading of 1.24 psf resulted in a rate of sink of 29 fps at 5000 ft. altitude. Maximum forward speed was 30 fps indicating a Parasail/Gemini configuration L/D of 1. The recovery system weighed 12% of the entry vehicle weight (569 lb.) with the existing Gemini landing gear (310 lbs) representing the greatest weight component. Two turn control motors were utilized to give a maximum turning rate of 25 degrees per second. No pitch control was provided. Two landing rockets, weighing 80 lbs., burning for 1.5 seconds reduces the rate of sink from 29 fps to zero fps nominally. The Gemini landing gear, composed of three tricycle arranged oleo-pneumatic shock absorbers coupled with struts and skids, is included in the recovery system to attentuate the off nominal descent velocity remaining (up to 10 fps) after rocket fire and to provide a stable touchdown system during slideout. The Parasail is disconnected at touchdown. A conventional ring sail parachute is used for backup.

Fourteen full scale tests were performed. Nine over water, two crane drops on land and three air drops over land. The water drops were successful except for the second drop where premature disreef due to reefing line failure resulted in high loads on the parasail breaking several suspension lines. The damaged parachute was separated and the back-up parachute recovered the test vehicle intact. This incident did demonstrate the back-up system satisfactorily. Flights 6, 7, and 8 deployed satisfactorily but with no control due to incorrect turn line length. The two crane drops over ground were successful in demonstrating the rocket attenuation capability. They also demonstrated that severe ground erosion takes place at low forward speeds due to the rocket exhaust and it could be detrimental to the space vehicle structure. The three full scale air drops over land were to evaluate system performance in flight and landing operations. The first test failed due to a turn cable failure. The vehicle landed in a turn maneuver and rolled over. The peak g's encountered were only 8 g's which is considerably below the allowable for man-rated landings (20-g's). The second test failed due to the air drop method imparting a 100 degree pitchup which fouled the front parachute risers on the nose gear. When the vehicle pitched down one leg of the front riser failed, cutting six suspension lines which caused a built in left turn. Also a double malfunction of the De Havilland boom altitude sensors occurred resulting in a no rocket attenuation landing. Resulting impact of forces exceeded human tolerances. Fixes on the parachute system and the altitude sensors resulted in a successful flight on drop number three. The vehicle was launched at 12,200 ft. altitude, at 127 fps velocity. The dynamic pressure at chute deployment was 72 psf. The vehicle was maneuvered 2 miles cross country to the primary landing zone. The gear touched down 40 feet after rocket ignition and the vehicle slid another 55 feet. Maximum accelerations recorded during the landing were approximately 4.8 g's. Surface winds were light and variable, 1 to 2 knots.

Operational performance studies show that this low L/D system does not possess point landing capability but requires a 20 n. mi. diameter unprepared landing zone 90 percent free of obstacles and having no more than a 5 degree slope.

This is based on a 3 sigma dispersion study of the spacecraft guidance and navigation system with single station tracking. It has the inherent capability to attenuate winds up to 17.5 knots (a 30 knot wind attenuation is desired), sufficient steering control to avoid obstacles and can align with the wind with a relatively simple visual system.

Cloverleaf Steerable Parachute

The performance of steerable parachutes was improved in 1963 with the development of the cloverleaf parachute (Figure 5). Wind tunnel and free flight tests of this configuration have demonstrated L/D ratios in excess of 2.0 with good stability and turn control characteristics. Control system loads are substantially greater than the Parasail because turn control is accomplished by warping the trailing edge flaps rather than opening cover flaps on the sides of the Parasail. The Cloverleaf's variable L/D ratio potential (0 to 2.0) permits greater freedom of approach during descent and allows for horizontal velocity modulation to provide for a specific vertical velocity component at landing. The Cloverleaf system can be deployed in a nongliding mode (zero L/D) for vertical descent recovery even if the crew is disabled or if the control system is inoperative. At a canopy loading of 2 psf the vertical descent would be 40 fps at zero L/D.

In Reference 1, a Cloverleaf recovery system was analyzed for an Apollo capsule payload of 12,500 lbs. The chute diameter was 96.5 ft. corresponding to a canopy loading of 2 psf. The selected nominal L/D ratio for landing was 0.7 which results in a vertical velocity component of 32 fps and a horizontal velocity of 20 fps. This allows the vehicle to land at the same vertical velocity within its stability envelope (maximum ground speed is 20 fps heat shield down) for any wind velocities between 0 and 40 fps (but is below the required L/D of approximately 3.0 for a point landing). For emergency winds up to 51 fps (30 knots) the pilot can elect to land at an increased L/D ratio. This will result in a change in vertical velocity, however.

A 103 ft. diameter ringsail parachute which results in the same vertical velocity for abort (40 fps) was chosen as the back-up chute. This simplifies the impact attenuation design considerably. This chute possesses very short filling times creating high inflation loads. However, fast inflation is a highly desirable feature for any emergency system. By proper reefing, it has been calculated that inflation loads can be held to 3 g's.

Impact attenuation concepts considered with the Cloverleaf recovery system included a Gemini type landing gear concept combined with retro rockets, and an Apollo configuration(apex up) with and without extended heat shields plus retro rockets. The impact attenuation system chosen was the Apollo configuration with an extended heat shield and riser suspended retro-rockets. The Gemini landing gear concept (on Apollo configurations) has a limited landing stability wind envelope due primarily to the smaller landing gear spacing dimensions as compared to Gemini shapes that possess an extended nose gear due to the extended Gemini R & R can. The fixed heat shield concept was rejected because it required internal couch attenuation which displaces useable volume and results in an undesirable c. g. shift.

The system estimated weight for a 6 and 9 man modified Apollo configuration is:

	6 man	9 man
Drogue Assembly	72	108
Main Cloverleaf Assembly & Control	210	330
Backup Chute Assembly	112	150
Retrorocket Assembly	150	200
Impact Attenuation Assembly	60	75
Water Stabilization Assembly	21	47
Control, Sensor, Display	20	20
Misc., Sequence Controller	14	14
Total ELS Weight, lbs.	659	944

This represents 5.3% and 7.6% of the 12,500 lb. entry vehicle weight for 6 and 9 man crew size respectively.

Parawing

The Parawing gliding parachute (Figure 6) is a delta planform all flexible steerable system possessing an L/D capability of 2.1 for the single keel version to 3.3 for the twin-keel configuration.[9,10] A slotted single keel configuration that possesses lower opening shock characteristics possesses an L/D capability of 2.0. Typical aerodynamic characteristics for the single keel Parawing are shown in Figure 14 from Reference 11. Note that this configuration is stable in pitch over a canopy angle of attack range (15 degrees) but with a resulting limited range of lift variation. Above angles of attack of 35 degrees the Parawing is directionally unstable and has negative effective dihedral. For these reasons the Parawing is essentially a constant L/D recovery device operating at a fixed angle of attack. Steering is obtained by pulling down on the wing tip suspension lines. Relatively high turning rates (75 degrees per second) are obtained in this manner.

The Parawing has very fast opening and deployment times which is desired during a pad abort situation at launch but also results in high opening g loads as shown in Figure 15. Attempts to reduce the opening loads thru reefing and using slotted Parawings have been successful in reducing the load from 25 down to 4 g's. Continuing work should result in a system with an opening load no greater than 3 g's as on Apollo.

Technical development of an operational Parawing recovery system is proceeding along two paths. One is a contract being worked for the Langley Research Center by Northrop-Ventura to develop a 12,000 $ft.^2$ Parawing to recover a payload of 15,000 lbs. at a deployment dynamic pressure of 180 psf. This program is scheduled for completion during 1969. Plans to test the Parawing at MSC using radio controlled instrumented vehicles weighing 5000 and 15,000 lbs. are to follow. Concurrently research on the use of Parawings for precision aerial delivery of cargo is being sponsored by the U. S. Army under contract to Goodyear Aerospace Corporation and is reported in Reference 10. The Army prefers the twin keel Parawing because of its higher L/D. They have added a catenary to the keels which provides more directional stability with less sideslip. Eventually, an operational system capable of delivering a 500 lb. payload within 100 ft. of the target from an altitude as high as 30,000 ft. at deployment speeds up to 150 knots will be made available to the Army field forces.

Sailwing

The Sailwing gliding parachute (Figure 7) is a rectangular planform of high aspect ratio, all flexible steerable system, possessing a maximum L/D of 2.20 (Reference 12). Typical aerodynamic data for this configuration is presented in Figure 16 at zero slideslip. Note that the Sailwing is stable in pitch over a small angle of attack range, from

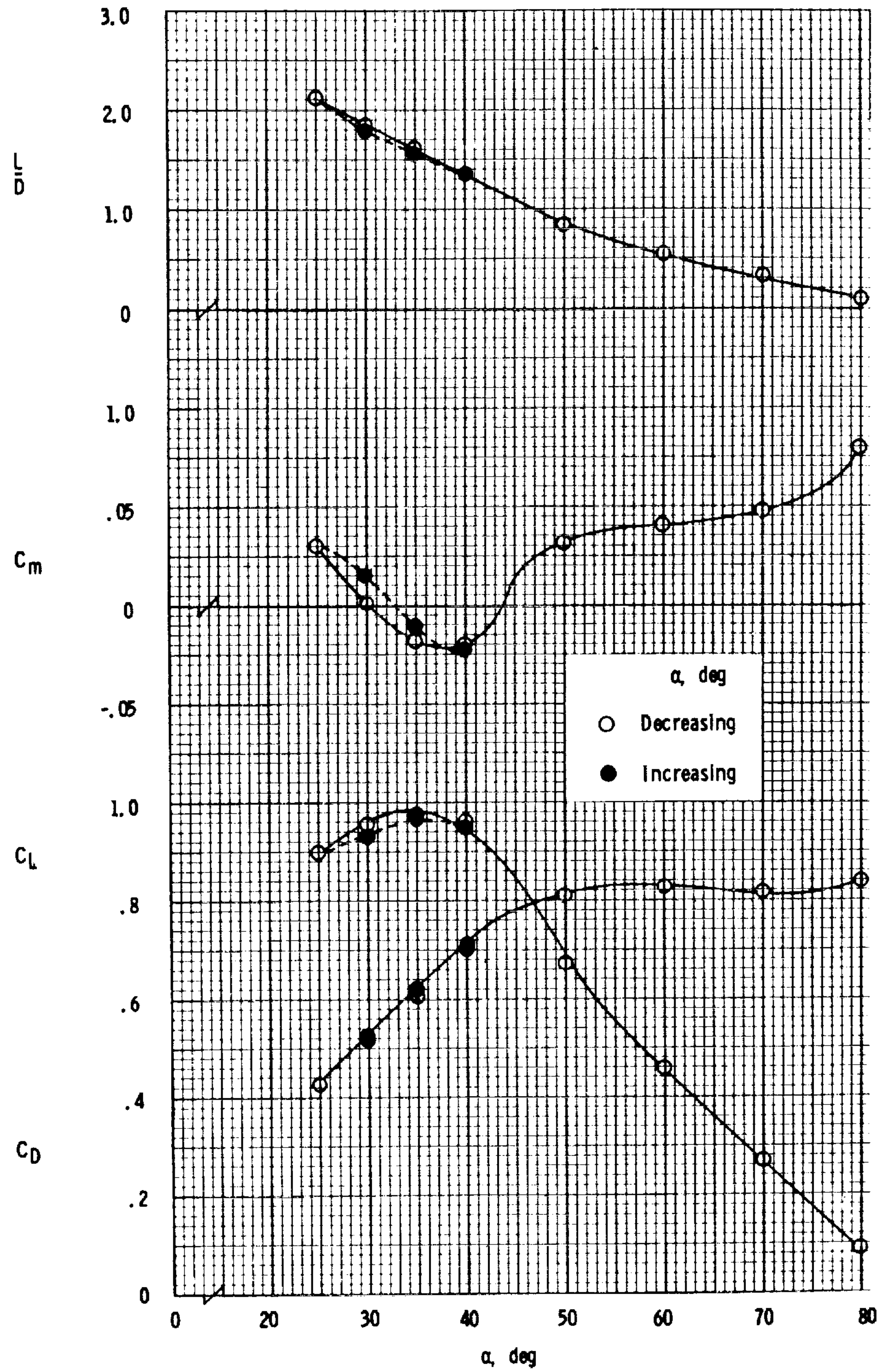

FIGURE 14 - PARAWING LONGITUDINAL CHARACTERISTICS
$\beta = 0°$; q=1.0 LB/SQ FT (47.9 NEWTONS/SQ METER)

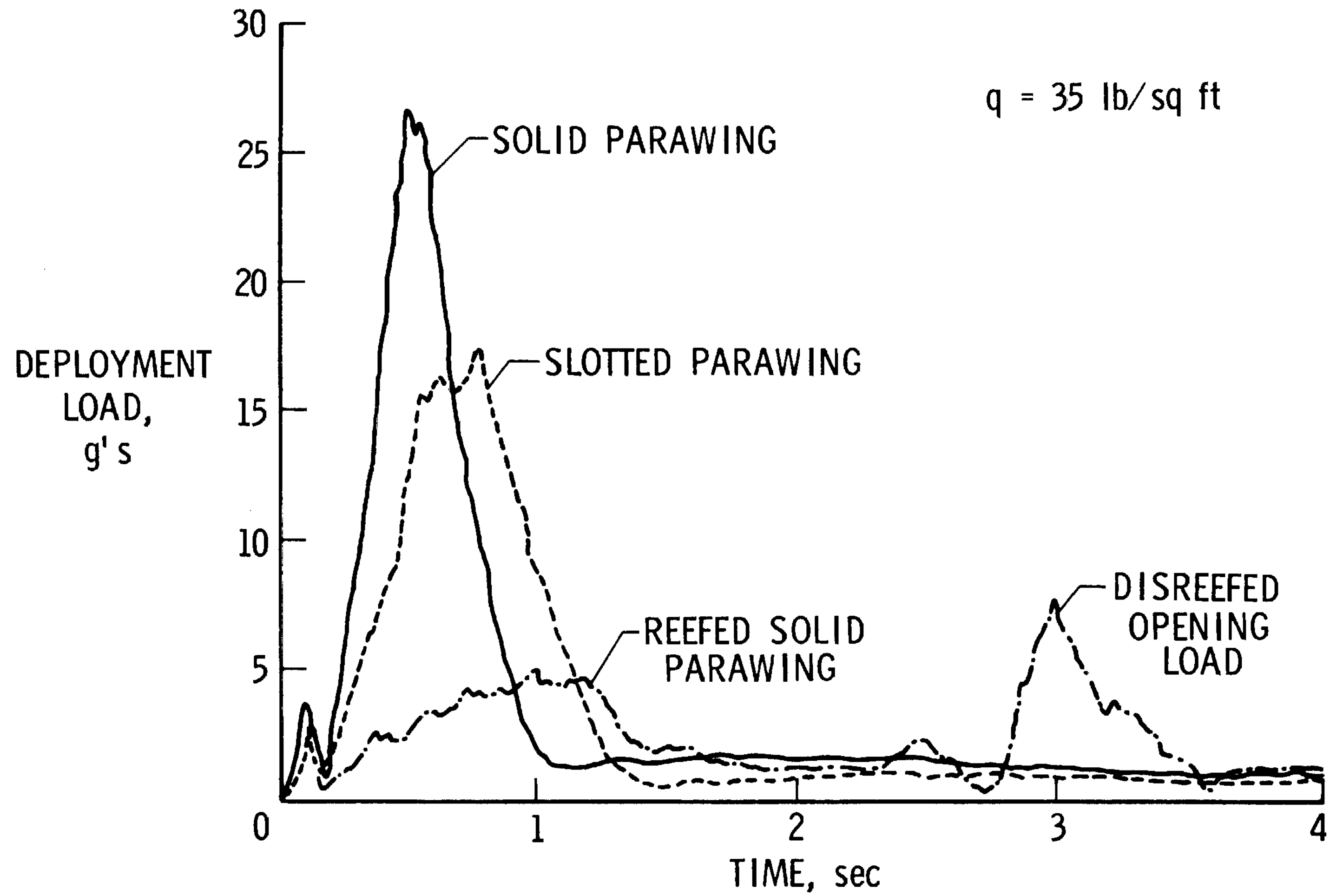

FIGURE 15 - DEPLOYMENT LEAD TIME HISTORIES FOR PERSONNEL PARAWINGS

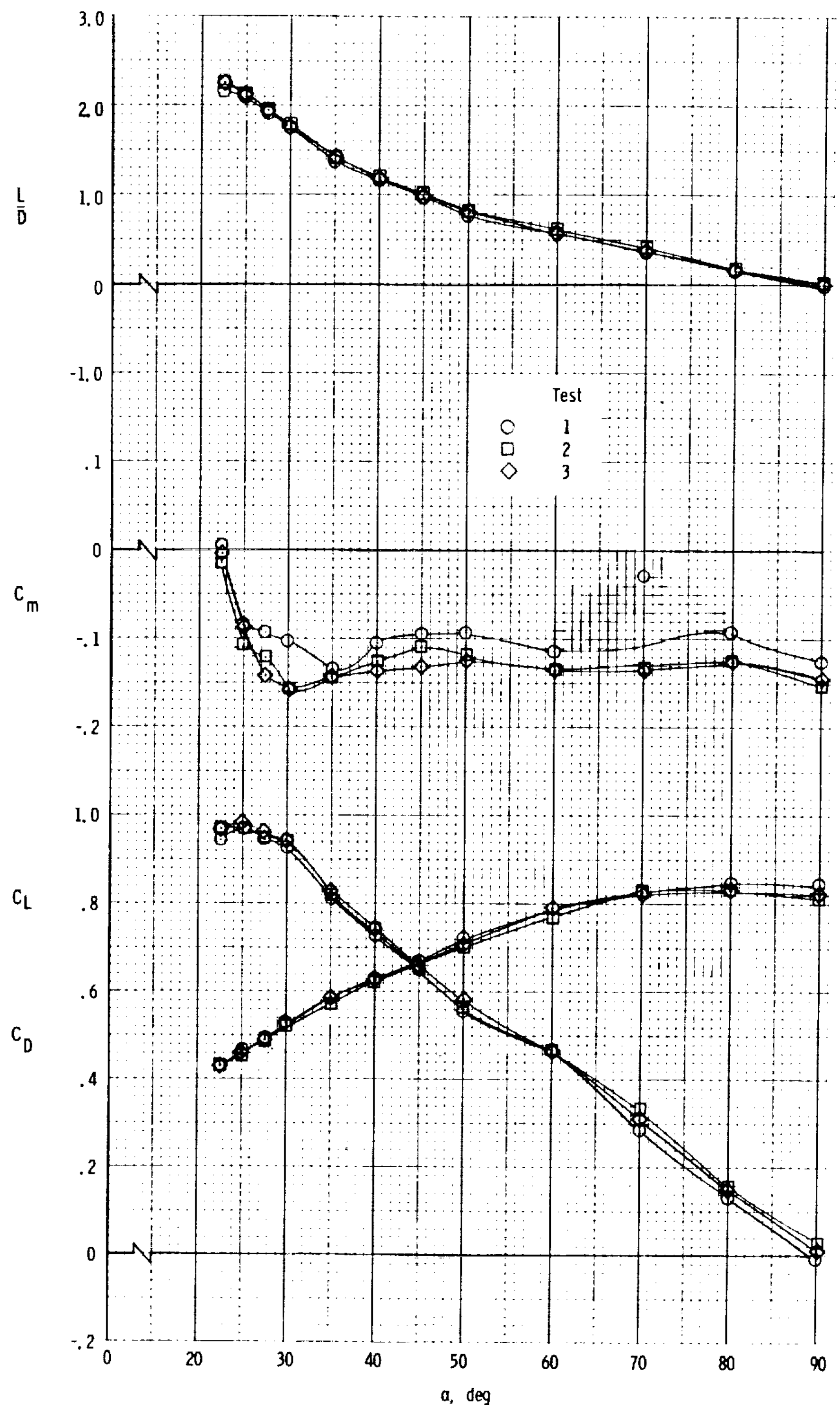

FIGURE 16 - SAILWING LONGITUDINAL AERODYNAMIC CHARACTERISTICS

$\beta = 0°$

22.5 to 30 degrees. In this angle of attack range the configuration is directionally stable and has positive effective dihedral. The minimum angle of attack is 22.5 degrees; below this angle the canopy will not remain inflated.

A typical fabric used to form the canopy is 1.6 ounce-per-square-yard rip stop nylon cloth with an acrylic coating which reduces the porosity. Twelve suspension lines carry the air loads through catenery curtains which also act as ribs to aid in maintaining a predetermined chordwise camber in the canopy. Two control lines attached at the trailing edge of the canopy are shortened to provide pitch control or individually for steering.

Deployment of the Sailwing has been difficult due to its large spanwise shape resulting in leading edge tuckunders. Proper reefing techniques, however, can reliabily prevent this from happening.

Technical development of the Sailwing is currently under the auspices of NASA Manned Spacecraft Center, Houston Texas. Mr. William Lofland, of the Atmospheric Descent Mechanics Section is currently engaged in testing the Sailwing to improve its L/D and to increase its deployment reliability.

Para-Foil

The Para-Foil (Figure 8) is a rectangular planform parachute with a cellular structure relying on ram air inflation. It has an airfoil cross section of about 22 percent chord thickness with an open leading edge. It is a completely nonrigid, self inflating flying wing, capable of being packed and deployed like a conventional parachute. Free flight tests at Sandia Laboratories indicate that the Para-Foil can attain maximum L/D near 4.0 with modification of the airfoil shape. Wind tunnel test data from Reference 7 shows a variation of L/D max. varying from 2.5 for aspect ratio 1.0 wing to 3.3 for an aspect ratio of 2.5 shown in Figure 17. Several factors detract from the attainment of higher L/D and these are high profile drag of the suspension lines (this system requires many more than the Parawing of Sailwing), high profile drag of the open nose of the airfoil, high induced drag caused by the open nose, and early stall evidently due also to the open nose of the airfoil.

Steering rates up to 120 degrees per second have been achieved using a control line to collapse the outboard cell at the leading edge.

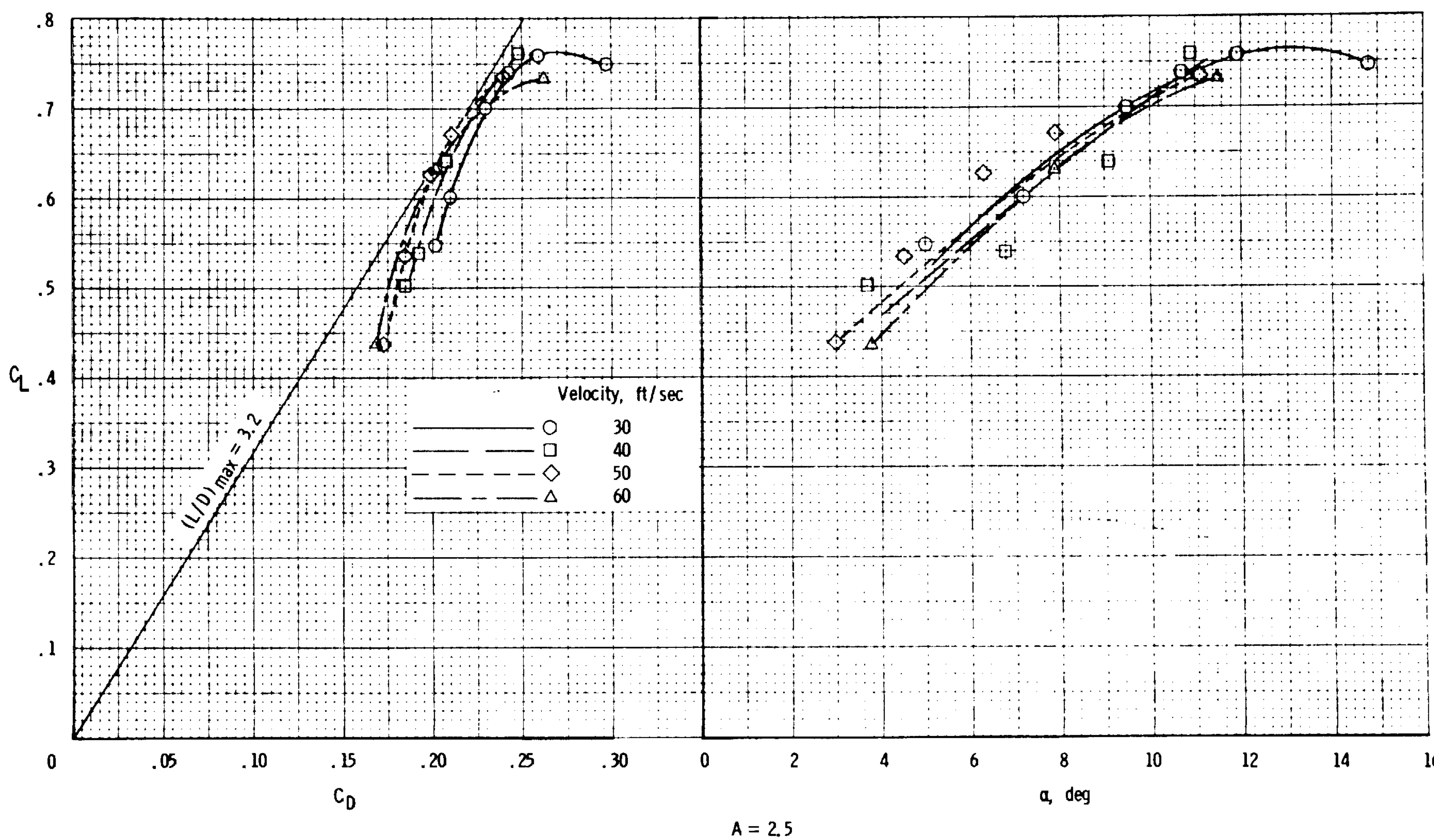

FIGURE 17 - PARA-FOIL LONGITUDINAL AERODYNAMIC CHARACTERISTICS

Angle of attack can be varied from 4 to 12 degrees by shifting the c.g. resulting in an L/D variation of 2.7 to 3.2 for an aspect ratio of 2.50. This allows the Para-Foil to be flared during landings to a horizontal flight path. In personnel jumps with the Para-Foil, landings have occurred at zero vertical and horizontal velocity by flaring just prior to touchdown.

Technical development of the Para-Foil has been underway at the University of Notre Dame under the direction of Dr. John D. Nicholaides, Chairman and Professor of the Department of Aerospace Engineering, since late 1964 when the inventor, Domina Jalbert, brought his idea to the university for study and development. Contracts with Notre Dame have resulted in several applications of the Para-Foil as a high altitude kite to aid in the alignment of Apollo tracking ship radars under contract to NASA Goddard Space Flight Center, as a meteorological instrument kite for the U. S. Army Electronics command at White Sands Missile Range and the Atmospheric Research Laboratory of Colorado State University. Sandia Corporation developed a sounding rocket recovery systems using a 72 square foot Para-Foil with an aspect ratio of 2.0 designed to recovery a 150 lb payload. It used an automatic homing guidance system to steer the Para-Foil from a deployment altitude of 9000 feet and a deployment dynamic pressure of 120 pounds per square feet. The U. S. Navy at the Naval Aerospace Recovery Facility, El Centro, California, is currently testing a 360 $ft.^2$, aspect ratio 2.0, Para-Foil for pilot recovery from jet aircraft at speeds up to 300 knots (KIAS) and altitudes to 20,000 ft. To date, this program has experienced an average landing L/D of 3.0 with an average rate of sink of 10 fps.

The U.S. Air Force Flight Dynamics Laboratory is currently developing a cargo delivery system using the Para-Foil (Reference 13). Their objective is to design and develop an operational system capable of delivering payloads up to 2,000 lbs. from an altitude as high as 15,000 ft., deployment speeds up to 130 knots, and to use an automatic homing guidance system to deliver the payload on target.

Volplane

Earlier this year, the Pioneer Parachute Co. came up with a modification to the Para-Foil where they joined the lower surface of each cell to the upper surface near the mid-chord. They call this design the Volplane (Figure 9). The basic planform is rectangular and control is accomplished by deflection of the trailing edge in the desired direction of turn. Personnel jumps with a 312 $ft.^2$ Volplane (aspect ratio of 2.0) resulted in an L/D max. of 4.30 (Reference 2). As a comparison, personnel jumps by the same company with the Parawing and Sailwing resulted in L/D max values of 2.14 and 3.08, respectively. It was reported by Pioneer that the Volplane opening characteristics are positive and orderly with no idiosyncracies reported. The opening shock of the Volplane unreefed was reported similar to the reefed Parawing and Sailwing. Opening reliability has been 100% successful but on relatively fewer jumps than on the Parawing. The Volplane is reported to be less sensitive to control line movement than the Parawing and Sailwing. It also possesses excellent dynamic stability. Reaction time for a turn are normal and turning rates are relatively slow (50 deg. per second as compared to 60 and 72 deg. per second for the Parawing and Sailwing, respectively). Stalls with the Volplane are comparatively mild. Release of the control lines causes an immediate recovery, which is as mild as the stall.

A much larger range of L/D modulation was reported for the Volplane than for the Parawing or Sailwing during the live jumps. Extensive portions of the flight can be made at any desired L/D value between 0.8 and 4.3. The Volplanes' flaring capability was reported to be excellent with timing for a good landing (50% reduction in total velocity) not very critical.

BELLCOMM, INC.

Subject: Gliding Parachutes for Land Recovery of Space Vehicles - Case 730

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