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NASA Project Apollo Working Paper No. 1026

PROJECT APOLLO
LANDING SYSTEMS APPLICABLE
TO
APOLLO SPACECRAFT

[redacted]

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SPACE TASK GROUP

Langley Field, Va.

August 14, 1961

N70-76130
(ACCESSION NUMBER)
36
(PAGES)
TMX-65225
(NASA CR OR TMX OR AD NUMBER)
(THRU)
Nm
(CODE)
(CATEGORY)
FACILITY FORM 602

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PROJECT APOLLO
LANDING SYSTEMS APPLICABLE TO APOLLO SPACECRAFT

Prepared by: John W. Kiker
John W. Kiker
AST, Flight Systems

James K. Hinson
James K. Hinson
AST, Flight Systems

Authorized for Distribution:
Robert R. Gilruth, Director

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SUMMARY

A standard or cluster parachute landing system can be rapidly developed for Project Apollo using existing hardware or with minor modification to present hardware. The steerable parachute overcomes some of the performance disadvantages of the standard and cluster parachute systems while retaining the same high degree of reliability. A steerable parachute would be the next logical step in advancing the state of the art in landing systems. The parawing and rotor systems are feasible concepts that will require a long lead time to develop; however, the performance potential of both systems warrant their consideration for Project Apollo.

Air bags, skirt extensions, or crushable structures are methods of impact attenuation that can be developed within an adequate time period when used with either of the parachute landing systems. Discrete shock absorbers hold the most promise when used in conjunction with another impact attenuation method.

The use of retrorockets for the final stage of descent in conjunction with landing systems other than rotors show promise of reducing the impact attenuation problem.

INTRODUCTION

The Project Apollo command module will require some form of auxiliary landing system to reduce the touchdown velocity to a value within human tolerance. In an effort to insure selection of the best possible system, a study of landing systems and techniques was initiated. The landing systems considered ranged from presently available hardware to interesting but impracticable proposals.

The purpose of this paper is to consolidate general information on the landing systems which show the most promise for possible application to the Apollo capsule. The descent systems are analyzed from the standpoint of development time, performance, packaging and deployment, complexity, weight and volume, and, to a limited extent, general design considerations. Systems presented are the standard parachute, multiple parachutes, steerable parachutes, rotary wing, parawing and retrorockets. Performance of these systems is widely varied from the standpoint of vertical and horizontal velocity at impact, as well as to degree of control over vehicle impact attitude. Thus, some of the landing devices considered require impact shock attenuation systems to reduce landing accelerations and an accurate comparison of the landing devices is not possible without their inclusion. For this reason a qualitative description of several possible shock attenuation systems is presented.

The first part of this paper describes and discusses some advantages and limitations of the specific landing and impact attenuation systems considered. The remaining portion of the paper is directed towards application of these systems to Project Apollo. No attempt is made in this paper to propose a final system for the Apollo capsule nor to "rate" the systems relative to one another beyond the presentation of available data and discussion of some of the significant properties of each. Some of the most promising landing techniques are presently in a neophyte stage of development.

SYMBOLS

C_D	drag coefficient
C_{D_O}	parachute drag coefficient based on flat constructed area
C_L	lift coefficient
D	drag in pounds
g	gravity
L	lift in pounds
R_R	radius of rotor
R_C	maximum radius of capsule
V_v	vertical velocity in feet per second
V_h	horizontal velocity in feet per second
α	angle of attack in degrees
W	weight in pounds
$\frac{W}{A}$	rotor disc loading, weight divided by rotor disc area

SYSTEMS EVALUATION

Parachutes

Standard parachute.- The standard parachute is a single symmetrical, noncontrollable drag device. Through the years, much effort has been applied to development of the parachute canopy design. Most of this effort has been directed toward improvement of one or more of the following characteristics: drag coefficient, stability, opening characteristics, canopy strength, weight, volume, and ease and cost of fabrication. Several distinct parachute designs have been developed, each of which is superior in one or more of the listed areas. The canopy designs which have been most widely used in manned systems or are being considered for such use are as follows:

Solid flat circular - The basic canopy design from which most of the important parachute types have evolved is solid flat circular. This canopy is constructed as a flat circular plate with a center vent, and consists of solid textile triangular gores stitched together laterally, the joints forming the main radial seams. (See fig. 1.)

Flat extended skirt - This design consists of a flat circular center, to which is added a flat annular ring having an outer diameter equal to the diameter of the circular center and a width designated as a percent of this diameter. Nomenclature for the canopy includes the nominal diameter, percent skirt extension and canopy type; for example, a 56-foot, 10-percent flat extended skirt canopy. The inflated extended skirt canopy is shown in figure 2.

FIST ribbon - This canopy is flat circular in design and composed of concentric ribbons supported by a number of radial ribbons and smaller radial or vertical spacing tapes. The inflated ribbon canopy is shown in figure 3.

Ring slot - This canopy is flat circular in design and consists of wide concentric fabric strips with intervening air slots. The number and width of slots varies with canopy diameter and application. (See fig. 4.)

Ring sail - The ring-sail canopy is very similar to the ring-slot canopy in basic construction. Like the ring slot, the ring sail consists of wide concentric fabric strips separated by air slots. The ring-sail canopy is constructed as a quarter sphere rather than flat circular, and the slots in each gore are crescent-shaped (except in the crown), rather than trapezoidal as in the ring slot.

Specific performance characteristics of the five canopy designs are compared in table I.

Selection of the best canopy design for a specific system application will depend on the primary system requirements. Opening reliability and low rate of descent are required for any manned application. Beyond these basic requirements, the relative importance of pendulum stability, opening force limitations, and weight and volume usually dictate the final canopy selection. (See ref. 1 for detailed parachute design data.)

The single parachute system is by far the most easily adapted to a specific vehicle design. It lends itself to the use of a single attachment point which simplifies disconnect of the chute at impact. The parachute system is not basically an integral part of the recovered vehicle and thus has little influence on the vehicle design.

The single standard parachute system is the most highly developed and most reliable landing system currently available. It has been used for many years for aerial delivery of personnel and cargo, and as a final landing state for recovery of missiles and space vehicles, including the Project Mercury manned space capsule. In order to achieve an acceptable rate of descent with the Apollo vehicle, a single chute of approximately 100 feet in diameter will be required. Parachutes of this size are widely used, both singly and in clusters, for aerial delivery of cargo. Experimental single parachutes of diameter up to 200 feet have been built and tested, but the problems associated with the fabrication, packaging and deployment of these larger chutes, together with the extremely long inflation times, make them impractical.

While the standard parachute landing system has much to offer in simplicity, reliability, and low weight and volume, the performance of such a system is rather severely limited. To keep the weight and volume within reason, sinking speeds on the order of 30 feet per second must be tolerated. The standard parachute is at the mercy of prevailing winds, and horizontal impact velocities equal to wind velocities must be expected. Pendulum stability of the lightweight, relatively high drag, parachutes is generally poor, and the additional vehicle horizontal velocity due to these oscillations must be considered in the vehicle design criteria.

The standard parachute has no translational or rotational capability, and is not capable of any flare maneuver to reduce the impact sink speed.

Knowing the design deployment conditions, the maximum parachute opening forces can be estimated with reasonable accuracy. Transfer of the parachute loads to the vehicle structure can be through the single attachment point, and while this may not be the most desirable situation, at least the vehicle structural requirements are readily predictable.

Through use of proper deployment methods and selection of suitable reefing or staged inflation configurations, the opening forces can be maintained below any reasonable limit. However, lower opening forces are achieved at the expense of increased inflation time. Since the altitude available for operation of the landing sequence during escape of the vehicle from the launch pad is limited, some trade-off is usually required between reduced opening forces and reduced inflation time.

The standard parachute system is passive except for pilot backup of the deployment sequence. Pilot technique is not applicable except in the monitoring of these events.

The parachute compartment should be located such that unobstructed deployment is accomplished in a direction opposite to the vehicle flight direction. It is desirable but not mandatory for the recovery vehicle to be in a stable attitude prior to landing-chute deployment. The shape of the parachute deployment bag is not critical as long as the deployment end is larger than or as large as the other sections of the bag. Thus, there are no serious restrictions on the stowed parachute configuration. If volume is limited, the parachute can be pressure packed to densities on the order of 0.20 $lb/in.^3$ with no adverse effects on deployment. (Nominal hand-packed density is about 0.13 $lb/in.^3$.)

The weight of a single landing parachute system, including an independent backup system, is on the order of 6 percent of the total landing weight. This is based on a 30-foot-per-second rate of descent at impact, which is generally felt to be excessive for a manned vehicle without some form of impact acceleration attenuation. The acceptable human tolerance of 20g to 25g and rate of onset of 20,000g per second has been used as a basis for requiring an impact attenuation system. The weight of the impact attenuation system necessary to meet the human tolerance requirement is approximately 3 percent of the landing weight. This must be considered when comparing the complete parachute landing system to more elaborate systems.

Multiple standard parachutes.- The problems associated with the use of very large single parachute systems resulted in multiple parachute systems being developed for landing heavy payloads. Clusters of two to six large parachutes have been used extensively for aerial delivery of heavy cargo and recovery of the larger missiles and drones. Figure 5 shows a typical two-chute cluster. A cluster parachute system for the Apollo vehicle could be rapidly developed using existing hardware or with minor modification to present hardware.

All of the canopy designs discussed under single parachute systems could be used in a multiple chute application. However, the extended skirt and flat circular canopies have been used most extensively in clusters. Limited experience has been gained with a clustered ribbon, ring-slot, and ring-sail chutes, but indications are that these designs also perform quite satisfactorily in multiple systems.

The clustered parachute system is easily adapted to a given vehicle design and need not be designed as an integral part of the vehicle except for the shape of the stowed system.

The effective drag area of the clustered parachute system is somewhat less than the combined theoretical drag area of the single canopies, due to interference between the canopies. The loss in drag area depends on the number of canopies used and the length of individual risers. Generally this loss is from 5 to 10 percent of the total drag area necessitating a weight increase of this order for comparable sink speeds. The multiple chute system will require slightly greater weight and volume than a comparable single chute system.

The multiple chute system is subject to wind drift, but pendulum stability of the system is excellent. The standard clustered chute system has no translational or rotational capability.

Opening forces for the multiple parachute system can be calculated with some accuracy using standard methods and can be reefed. The cluster chute system is passive and pilot technique consists only of monitoring the deployment sequence.

With proper control of deployment and initial inflation, the reliability of the multiple parachute system approaches that of the single parachute. Although it appears that no detailed comparative reliability analysis has been performed to date, many parachute specialists feel that a cluster of three parachutes, designed such that proper operation of any two chutes will provide an acceptable rate of descent, is more reliable than a system of large single main and reserve parachutes deployed independently, where others believe a single chute with a backup chute for emergence is the best.

Except for the considerations stated under the standard single parachute, there are no restrictions on the shape of the multiple parachute packs. To utilize the advantages in handling and packing offered by the multiple chute system and to insure proper deployment of the individual parachutes, the parachutes must be stowed in separate deployment bags. The bags should be connected to a common deployment system to insure near simultaneous line stretch and initial inflation. In general, it is necessary to temporarily reef the chutes to further insure even inflation; however, in the case of the Apollo system, reefing would probably be necessary at any rate to reduce the opening forces.

Steerable parachutes.- Steerable parachute canopies have been developed specifically for use of pararescue personnel and smoke jumpers. Several types of steerable personnel canopies have been used for these applications, all of which achieved translation and rotational capability by controlled expulsion of the entrapped air.

Most of the steerable parachutes tested to date have incorporated a split or vented gore to direct a portion of the entrapped air mass outward. This type of chute normally has a fixed glide angle with rotational control only. This rotational control is achieved by distorting the canopy to redirect the flow of air through the vented gore. Most of the steerable personnel canopies have been evolved by modification of standard flat circular or extended skirt canopies.

The present steerable personnel parachutes achieve a glide of about 9 feet per second at a rate of descent of about 20 feet per second. On some of the canopies, rates of turn of about 36° per second are possible.

Intensive effort is currently being applied to development of larger steerable parachutes and to increasing the horizontal glide capability. (Refs. 2 and 3).

Recent emphasis on some translational capability during final descent of space vehicles has led Radioplane, a Division of Northrop Corporation to apply serious effort towards improvement of present steerable parachute capabilities. Their approach has been to use a controllable flapped area rather than the conventional split gore. (See fig. 6.) In addition to the controlled L/D this design shows promise of the attainment of higher maximum L/D ratios and adaptability to larger parachutes. Some degree of success in this effort has been reported. The standard ring-sail canopy has been modified by the addition of a control flap which can be opened or closed to vary L/D or opened differently to achieve rotation.

An L/D of approximately 0.7 has been demonstrated with the flapped ring-sail canopy at a rate of descent of less than 30 feet per second.

It is felt that this canopy can achieve an L/D approaching or equal to 1.0 with low descent velocities but actual L/D variation with descent rate and maximum possible L/D have yet to be established. The flapped parachute will make possible some reduction of horizontal velocity due to wind drift. The maximum horizontal velocity will, of course, depend on design vertical velocity and maximum L/D at that descent velocity. Pendulum stability of the flapped ring sail appears to be comparable to that of the standard ring sail ($\pm 10^{\circ}$).

The steerable parachute will produce opening forces comparable to the standard chute and can similarly be reefed.

The flapped parachute is not capable of a flare maneuver to reduce vertical velocity at impact but the pilot will be able to rotate the system "into the wind" and vary L/D to obtain near zero ground speed. The pilot must be provided with a suitable control system, some knowledge of the wind profile near ground level, and acceptable visual or other indications of vehicle motion relative to the ground. This is a relatively low L/D parachute and does not permit a great amount of range control; however, some capability for avoidance of local obstacles will be present. Figure 7 shows an early model of a glide-sail parachute.

Reliability of the existing steerable personnel parachutes is comparable to that of the standard personnel chutes. Reliability of the steerable ring sail will have to be demonstrated, but it is felt that addition of the control flap will not seriously affect the opening characteristics or structural integrity of the proven ring-sail design.

The steerable parachute is packaged and deployed in the same manner as the standard chute. The primary difference between the steerable and standard parachutes with regard to incorporation into a specific vehicle is the necessary control linkage.

Weight and volume of the steerable parachute canopy is comparable to the standard parachute. However, some additional weight and volume will be required for the control system.

Some form of impact attenuation is required and this weight has to be considered in the final selection of a landing system.

Parawing

The parawing is another type of descent system which has been investigated. The parawing is best described as a flexible, nonporous, fabric or metal wing glider. The flat platform has the appearance of a delta wing aircraft. The leading edges and keel are rigid members equal in length. The leading edge is swept back 45° in the flat out or planform. In flight, the leading edges are generally swept from 50° to 55°. (See fig. 8.) This system concept is an attempt to incorporate some of the good parachute features, namely reliability, storability, and light weight while attempting to overcome the parachute performance drawbacks of high vertical rates of descent and limited range capability. The parawing is presently in a very early stage of study although a considerable amount of qualitative data have been obtained. There presently are not sufficient data to isolate completely the design parameters nor adequately define all problem areas associated with its application to Apollo.

Preliminary drop and wind-tunnel tests conducted by NASA Langley Research Center using nonporous fabric models have indicated for range considerations a maximum $L/D \approx 4$ was obtainable when flying at angle of attack of 22° and a $C_L = 0.5$. For the flare maneuver, a $C_L = 1.18$ at an $\alpha = 43^\circ$ is considered possible. (See fig. 9.) Typical horizontal landing velocities at various wing loadings for both the flare and no-flare conditions are shown in figure 10. The corresponding vertical velocity for the no-flare condition is also shown.

A major structural problem is anticipated due to the unpredictable transient loads during deployment, the loads resulting from the interaction of the capsule and parawing, and the behavior of the flexible suspension system. Considerable development of the parawing landing system is required since the behavior of the system does not readily lend itself to analytical solution.

Control of model parawings has been accomplished either by the use of conventional aircraft-type elevator and rudder controls or by shifting the capsule fore, aft, or sideward. The use of conventional controls, while desirable for stability, complicates the already difficult deployment problem, increases the required storage volume, and adds weight. Although this type of control system would be much simpler to apply, the resultant shift in center of gravity may not be compatible with the stability of the parawing-payload combination. Drop tests of an erected model-payload combination have indicated this problem may be serious.

The problems of packaging and deploying a parawing are unknown and will require a major development effort. An inflatable structure is attractive when the criteria of ease of storage and small volume is considered. However, it is handicapped by the problems of structural loads, inflation, gas storage, and deployment. Development of metal folding or telescoping structures holds promise in overcoming the anticipated problems of the inflatable structures. Methods for deploying the parawing from the Apollo capsule will be dictated, in part, by the packaging and rigging techniques. From the presently available data, it appears that positive stabilization of the capsule will be necessary to achieve reliable parawing deployment regardless of the type. The best deployment procedure for an inflatable structure appears to be to deploy the glider uninflated parallel to the free stream with the nose attached to the capsule, inflate keel and leading edges and develop glider, and mechanically rotate glider to a positive angle of attack. A metal structure parawing will follow the same general type of deployment sequence as for the inflatable parawing but will be accomplished mechanically. The time required to deploy a parawing will probably make it unacceptable for pad abort.

At the present state of development of the parawing, a close weight estimate cannot be made. However, it appears that a system without emergency backup will exceed 12 percent of the recovery weight. Volume requirements for a single parawing having a wing loading of 7 is expected to be 3 cubic feet per 1,000 pounds of recovered weight assuming a design load factor of 4.

The final reliability of the parawing cannot be predicted at the present state of development. It does appear that with the additional problems associated with the parawing, it probably will not approach the reliability of the parachute systems.

Rotor Systems

Helicopter rotor systems have been highly developed; however, there has been little effort expended towards developing an autorotational landing system suitable for recovery of space vehicles. The established success of other landing systems has generated a general lack of interest in developing a rotor system, particularly since the rotor system will require considerable development effort to overcome anticipated stability, storage, and deployment problems. Furthermore, until the manned space programs were initiated, there has not been an urgent requirement for the performance advantages of the rotor over that of the parachute. Some progress has been made by industry in landing small payloads (200 to 250 pounds) using folding and telescoping blade rotor systems. Flexible metal and fabric rotors have been investigated; however, it does not appear possible to develop these rotors within the Project Apollo time scale. The U.S. Air Force presently has an active contract with Kaman Aircraft Corporation to further develop rigid rotor landing systems.

A rotor system has the important performance advantage of zero horizontal and vertical velocity at touchdown. No other landing systems within the present state of the art can independently match this performance. A rotor system's maneuverability is obtained by cyclic and collective pitch controls. A lift-to-drag ratio of 4 is obtainable with rotors alone which makes it competitive with the parawing and other lifting body configurations. The evident lack of dynamic stability of a rotor system is undesirable; however, like the helicopter, it can probably be adequately controlled by proper design. Rotor structural design has been well-defined by the helicopter industry and should present no problem once the blades have deployed and are rotating. The loads imposed on the blades during deployment have not been analyzed. A first look indicates an incremental deployment may be necessary to prevent designing the system to an unnecessarily high load factor just to take care of the deployment mode.

To understand the actual flight problem associated with rotor systems, flight demonstrations were accomplished where autorotation landings were performed with helicopters which ranged in gross weight from 2,350 to 31,000 pounds and where the disc loadings varied from 2.3 lb/ft^2 to 7.6 lb/ft^2. The descent rate is a function of the disc loading as shown in figure 12. These flight demonstrations were convincing evidence that unless automatic, a full autorotation landing is virtually impossible unless performed by a proficient helicopter pilot during daylight, over land, with adequate cockpit visibility and good weather conditions.

The reliability of a rotor landing system has yet to be established. It appears reasonable to assume that once the blades have been deployed it will be comparable to a helicopter in autorotative flight. However, there are insufficient test data on deployment of rotors. There is evidence from the limited data that are available that capsule stabilization within ±10° is necessary before any degree of deployment reliability can be expected. Once stabilized, all blades must be deployed simultaneously. Like all other landing systems, it is desirable to provide a backup emergency system. This could present a very difficult design problem. Shaped pyrotechnic charges can possibly be used to jettison the blades allowing deployment of the emergency system.

Packaging of a rotor landing system presents somewhat the same problem as for a rigid keel parawing. Blade stowage can probably best be accomplished by folding or telescoping the blades, then either trailing or storing them within the capsule. Heat protection for either blade position can be costly from a weight standpoint. Deployment would be accomplished by jettison of the heat protection cover and mechanically rotating the blades into the airstream. Deployment and packaging of a rotor system will require a major development program. Storage and deployment problems may be lessened by development of flexible rotor systems.

The best estimates indicate a rotor system alone will weigh 12 to 15 percent of the recovery weight, volume requirements will approximate 12 ft^3 per 1,000 pounds of recovery weight.

Retrorockets

For lunar landings, a reaction braking system will be required as the lack of a sensible atmosphere rules out the use of drag devices. The retrorocket has also received some consideration as a primary earth landing system and appears basically to be competitive with atmospheric decelerators in weight and volume. The design of the retrorocket for a primary landing system (with initial rate of descent at 300 to 500 feet per second) is extremely critical. The impact velocity is sensitive to errors in ignition times, thrust alinement, and to changes in capsule weight. To make such a system practical, a variable thrust rocket with thrust vector control would be required. Auxiliary capsule stabilization during the retrofire maneuver would probably be required. As the initial rate of descent is reduced, the retrorocket system becomes more practical, and the use of the retrorocket in conjunction with aerodynamic decelerators shows much promise. The retrorocket offers a lightweight method for reducing impact velocity and impact attenuation requirements.

A parachute retrorocket system optimized for weight and volume would approximate a parachute rate of descent of 70 feet per second. It appears more logical to design for a rate of descent below 40 feet per second where, with careful capsule design, a retrorocket failure could be tolerated. A detailed analysis of this application of retrorockets is included in reference 6.

Impact Attenuation

The landing of low L/D vehicles without means of flaring will require some method of shock attenuation at the time of impact on either land or water to protect both the capsule and its payload. A cursory investigation has been conducted in an attempt to establish some of the better methods of absorbing the kinetic energy of the capsule at impact. A brief description, some advantages and disadvantages of air bags, skirt extensions, crushable structure, and discrete shock absorbers, are presented.

An air bag is a gas-filled, flexible, inelastic container used individually or in clusters. Shock absorption is obtained by bleeding of the gas from the bag at a prescribed rate. An air bag or multiple bags have the advantages of being tolerant of attitude at touchdown, function satisfactorily under conditions of low horizontal velocity, and operate independent of direction at impact. The major disadvantages are its weight, stowage volume, water stability effects and design complexity. Figure 12 shows an air bag in operation. References 4 and 5 present design data.

An impact skirt is presently used on the Mercury capsule for attenuation. It is representative of all applications of impact skirts and can be described as a flexible, nonporous, fabric material, cylindrical-shaped attenuation device. One end is attached to the bottom of the capsule and the other to the backside of the heat shield. The skirt has numerous orifices located on the cylindrical section of the skirt. The skirt is stowed between the heat shield and the bottom of the capsule which extends the skirt prior to impact. Attenuation is obtained by the orifice metering of the escaping air. (See fig. 13.) The impact skirt has the advantage of being within the state of the art, operates satisfactorily with some horizontal velocity of the capsule at impact, is multidirectional, and acts as an anchor for increased water stability. The major disadvantages of skirts are the weight, complexity of design, proper storage, and inefficiency.

Crushable-type structures have been used in many applications for attenuation. The greatest use of crushable structure has probably been by the U.S. Army in connection with their aerial drops of equipment and supplies. A few of the more common forms of crushable structures are honeycombed metal or other materials, foamed plastics, and low-density woods.

Crushable structures have the advantages of being passive, efficient, light in weight, and readily stored. The disadvantages that are apparent are the high g deceleration, high onset rate, and volume requirement.

Discrete shock absorbers are attractive for some applications. The discrete shock absorber considered would be similar in design and operation to the automobile shock absorbers. For Project Apollo, the main consideration has been given to the use of discrete shock absorbers on the astronaut's couch, thereby reducing the primary attenuation requirement for the complete capsule.

The advantages of the discrete shock absorbers are that they are within the present state of the art, the characteristics are predictable, and they are light in weight. Disadvantages of using this method of attenuation as the primary means of reducing the impact shock are the concentrated loads at the attachment points of the shock absorbers, and the feature of being undirectional in operation.

MISSION CONSIDERATIONS

The Apollo mission of manned earth orbital and manned lunar reconnaissance provides the guidelines for a landing and impact attenuation system. These missions for the spacecraft establish the landing system requirements of abort both from the launch pad up to maximum velocity, the highest obtainable degree of reliability, land and water landing capability, and when possible, provisions for avoiding local hazards.

The Apollo missions lead to the trade-off of advantages and disadvantages of horizontal versus vertical descent landing systems. Horizontal landing vehicles of the higher L/D type have certain criteria that are necessary to the execution of a safe nonpowered horizontal landing. These are a proficient pilot, adequate landing site, good visibility, and a control system. The major obstacles associated with conducting a safe horizontal landing are darkness, rough terrain, adverse weather, and for water landings, a high sea state. The primary advantages of horizontal landing space vehicles appear to be range control and the possibility of reducing the impact problem by use of a flare maneuver.

The numerous mission abort possibilities and subsequent landing areas make the vertical descent landing system attractive. Furthermore, a safe landing is not so dependent upon the condition of the crew.

Generally speaking, there are less problems associated with a safe touchdown utilizing a near-vertical descent landing rather than a horizontal landing.

CONCLUDING REMARKS

General information on three configurations of parachutes, rigid rotors, parawing, and retrorockets has been presented to assist in the selection of an optimum landing system. It was found the standard and clusters of standard parachutes in the sizes required for Project Apollo have already been developed. However, since they are not controllable, they do not meet the Apollo requirements. A controllable personnel parachute has been developed and is presently being used by U.S. Air Force pararescue teams. It appears feasible to adopt and improve the controllable principal to a larger diameter parachute for landing of space vehicles. Both the split gore and glide-sail parachutes show promise. The parawing and rotors are landing system concepts in early stages of development which have an L/D performance advantage of approximately four times that of a parachute. Considerable effort will be required to develop either the rotor or parawing. However, their increased range performance may justify this effort.

Impact attenuation of the capsule and crew can be accomplished by air bags, skirt extensions, crushable structure, or discrete shock absorbers. Each method has certain advantages and disadvantages dependent upon the selected descent system. The use of retrorockets for further reducing sinking speed is a new and promising approach to the problem.

The landing system combination that shows the most promise for rapid development is the steerable parachute-retrorocket combination. Other systems such as the parawing and rotors show greater performance possibilities but will require longer development times.

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TABLE I.- AVERAGE PARACHUTE PERFORMANCE CHARACTERISTICS

Canopy type	Drag coefficient C_{D_o}	Opening shock factor	Angle of oscillation	Opening reliability
Solid flat circular	0.75	2.0	±30°	Excellent
Flat extended skirt	.70	1.8	±20°	Without reefing good
FIST ribbon	.50	1.05	±3°	Good
Ring slot	.60	1.05	±7°	Good
Ring sail	.72	1.10	±10°-15°	Excellent

Figure 1. - Solid flat circular parachute.

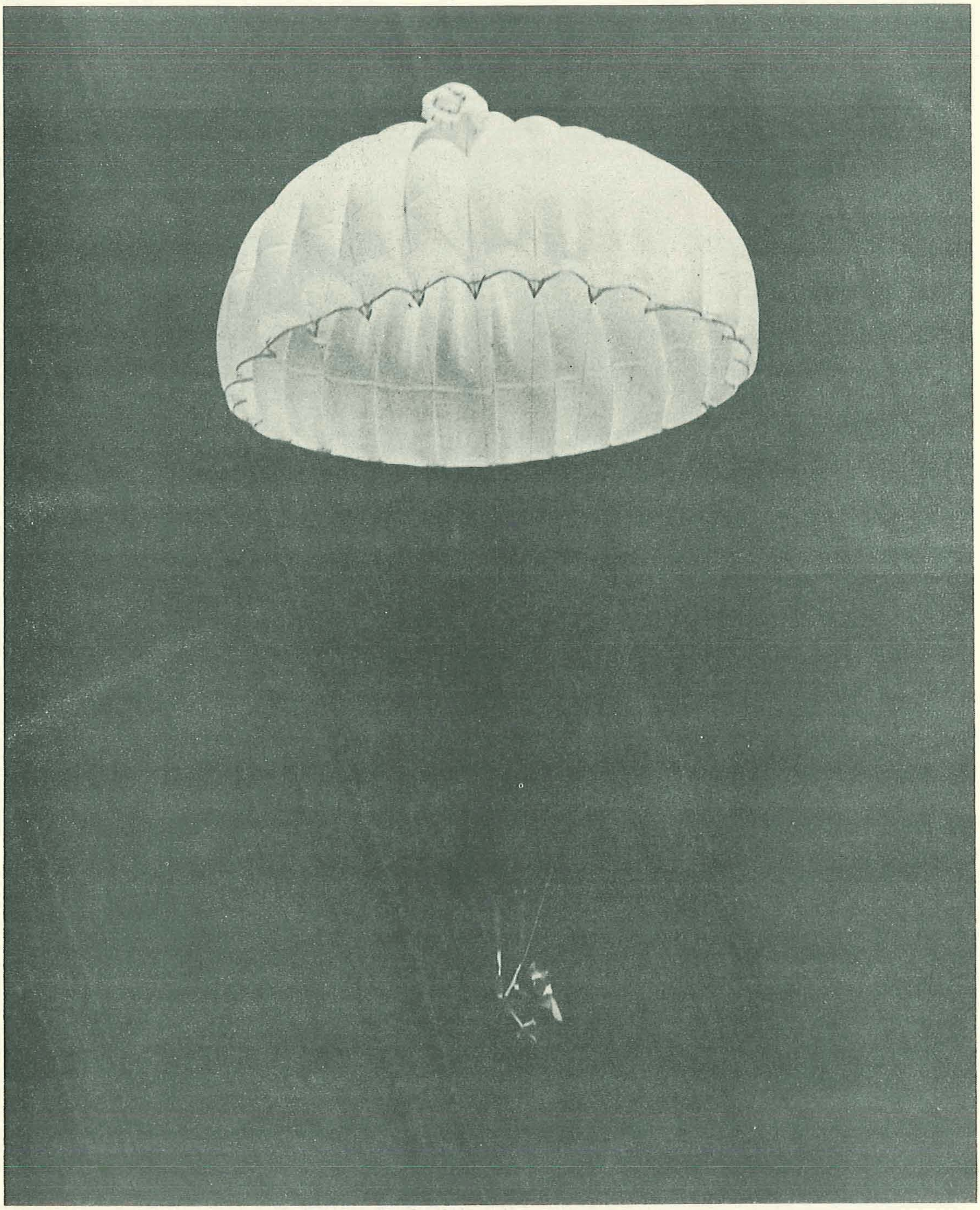

Figure 2. - Flat extended skirt parachute.

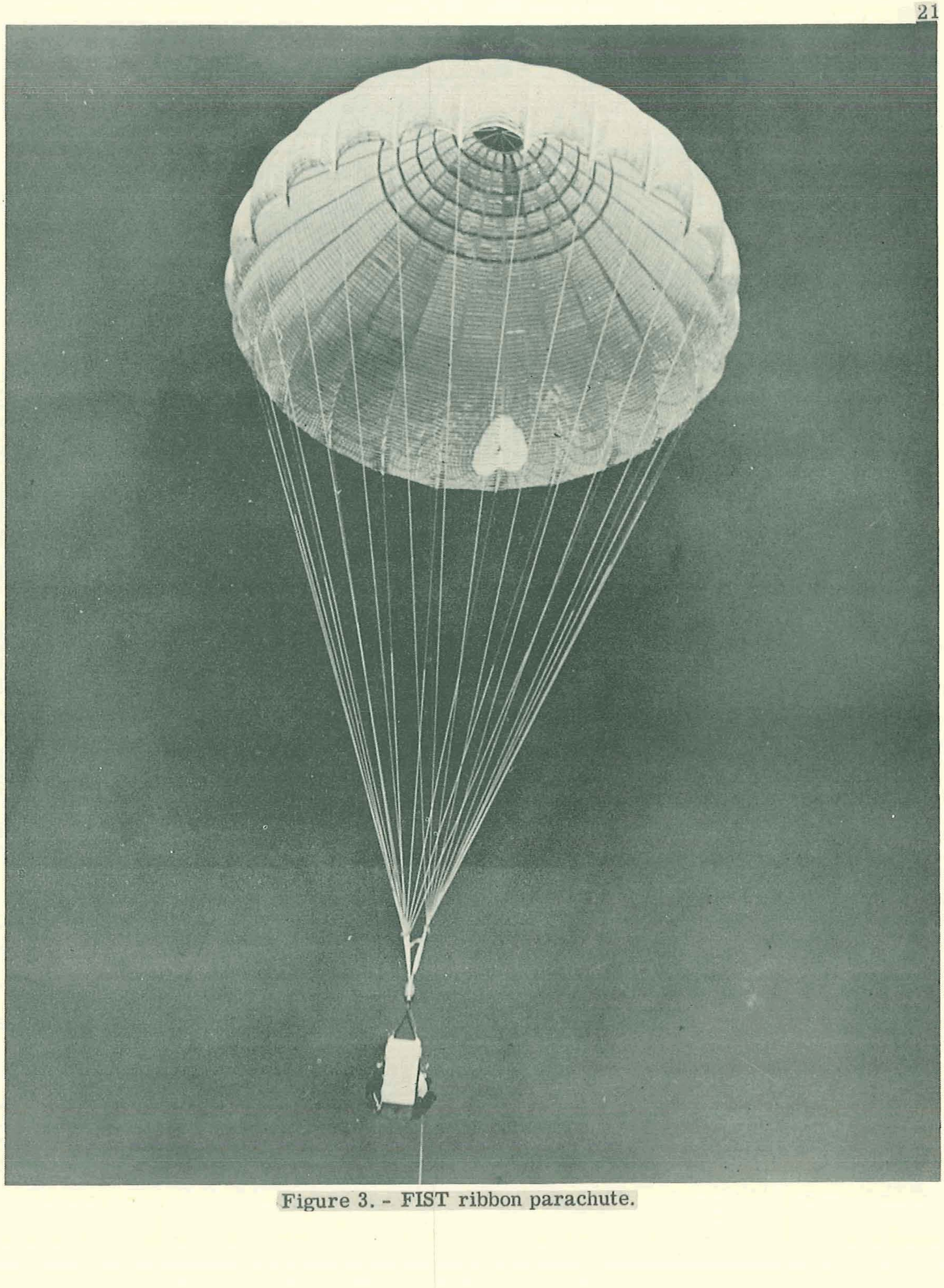

Figure 3. - FIST ribbon parachute.

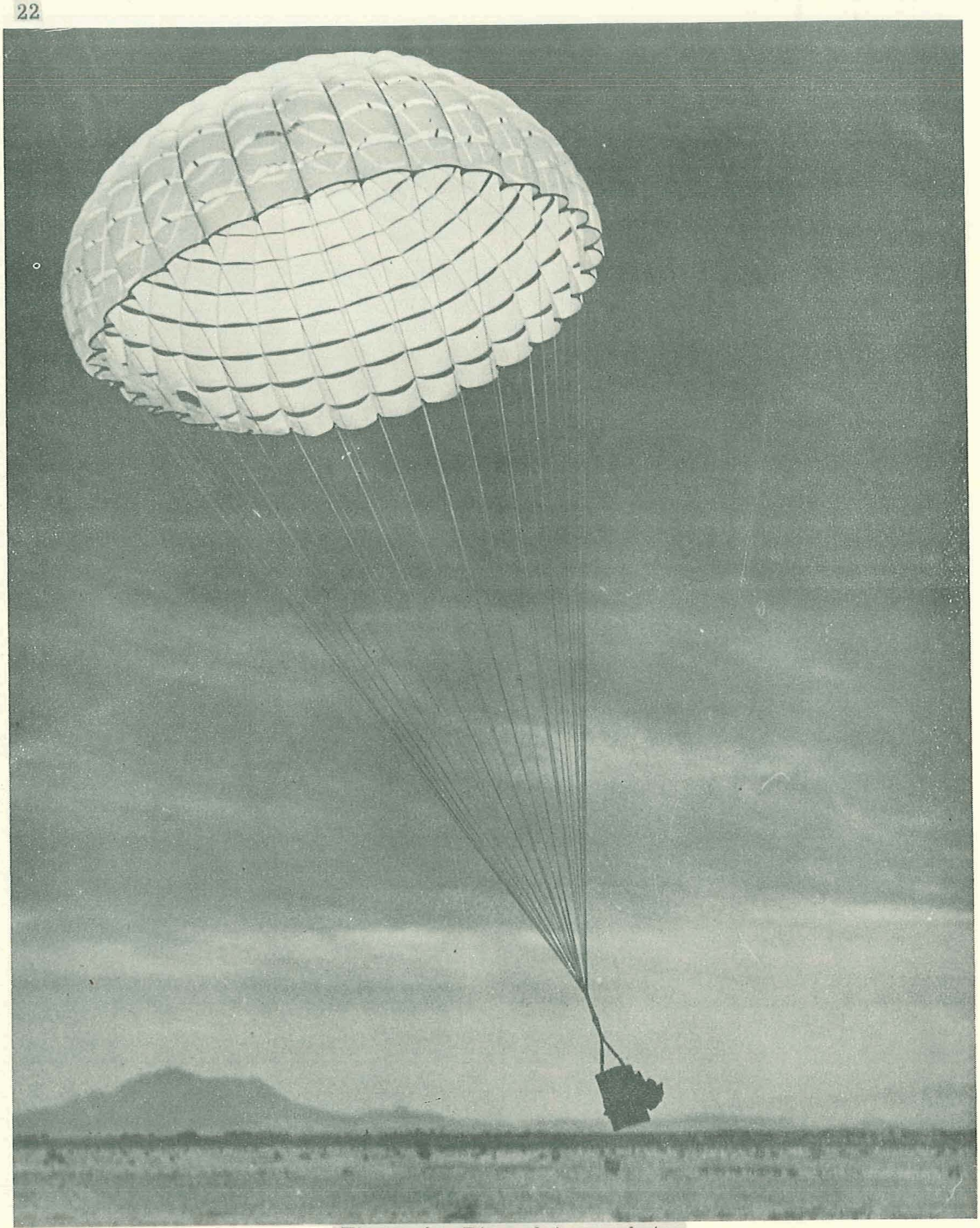

Figure 4. - Ring-slot parachute.

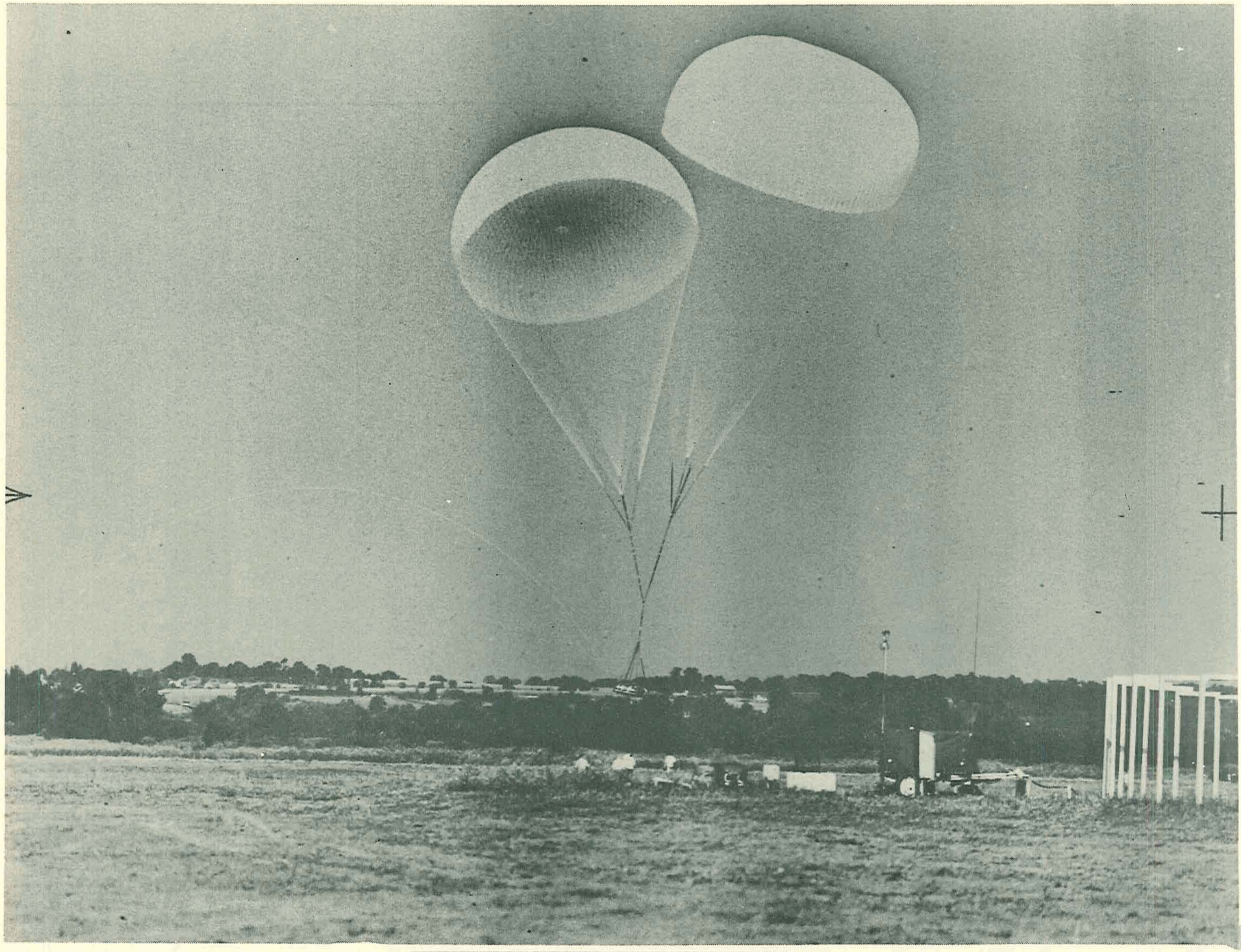

Figure 5. - Multiple parachutes.

Figure 6. - Split gore parachute.

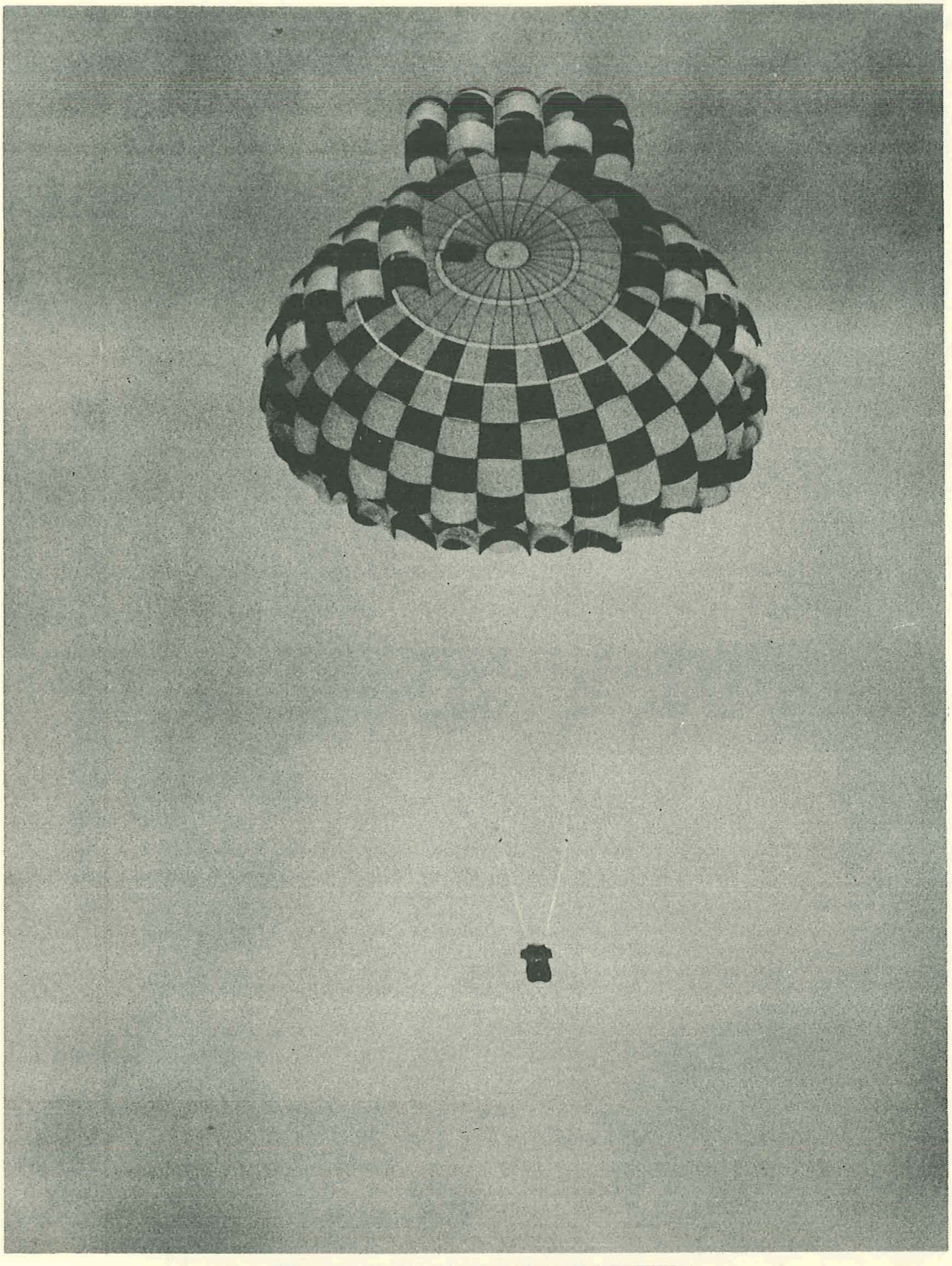

Figure 7. - Controllable flap parachute.

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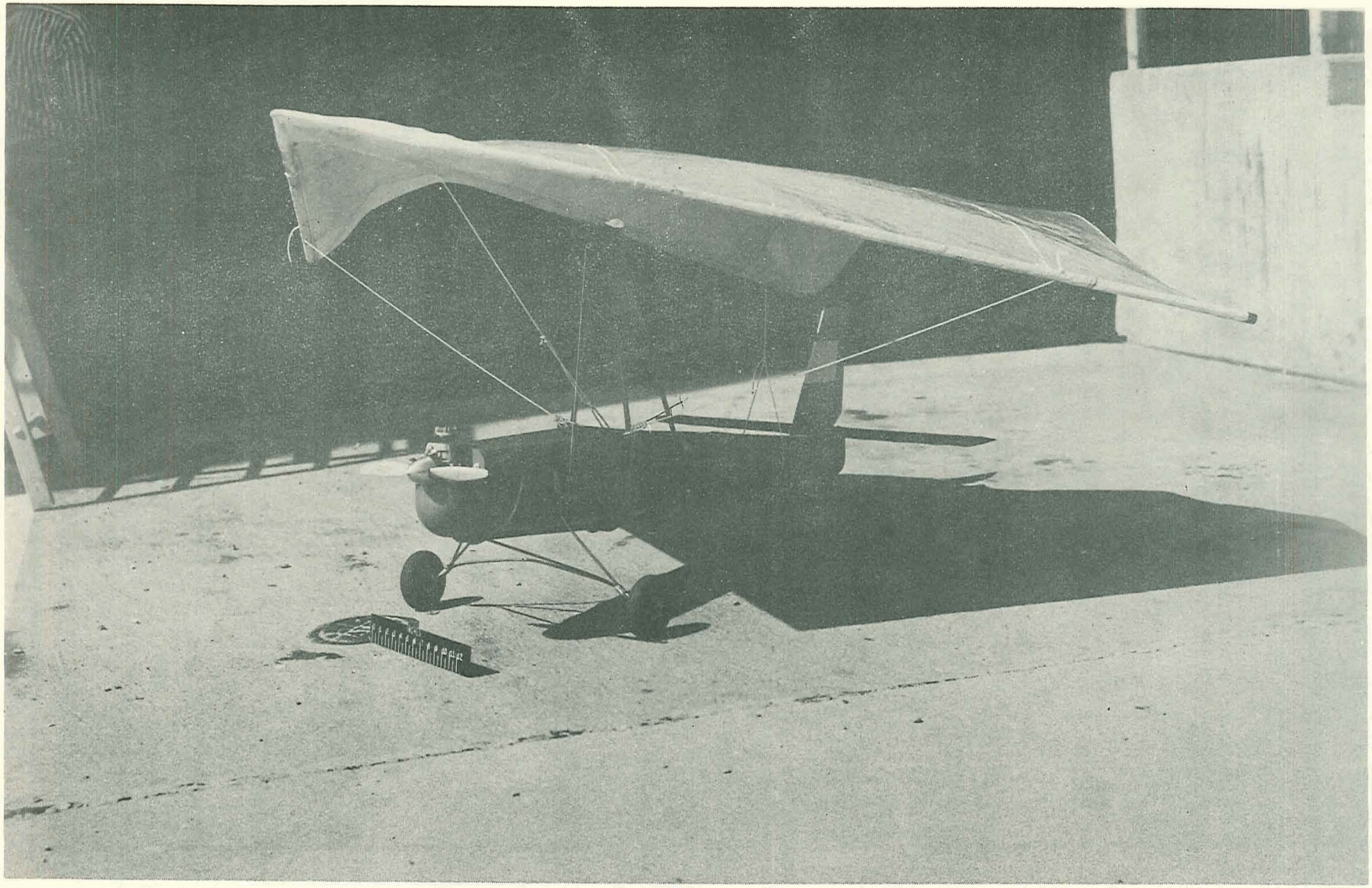

Figure 8. - Radio control model parawing.

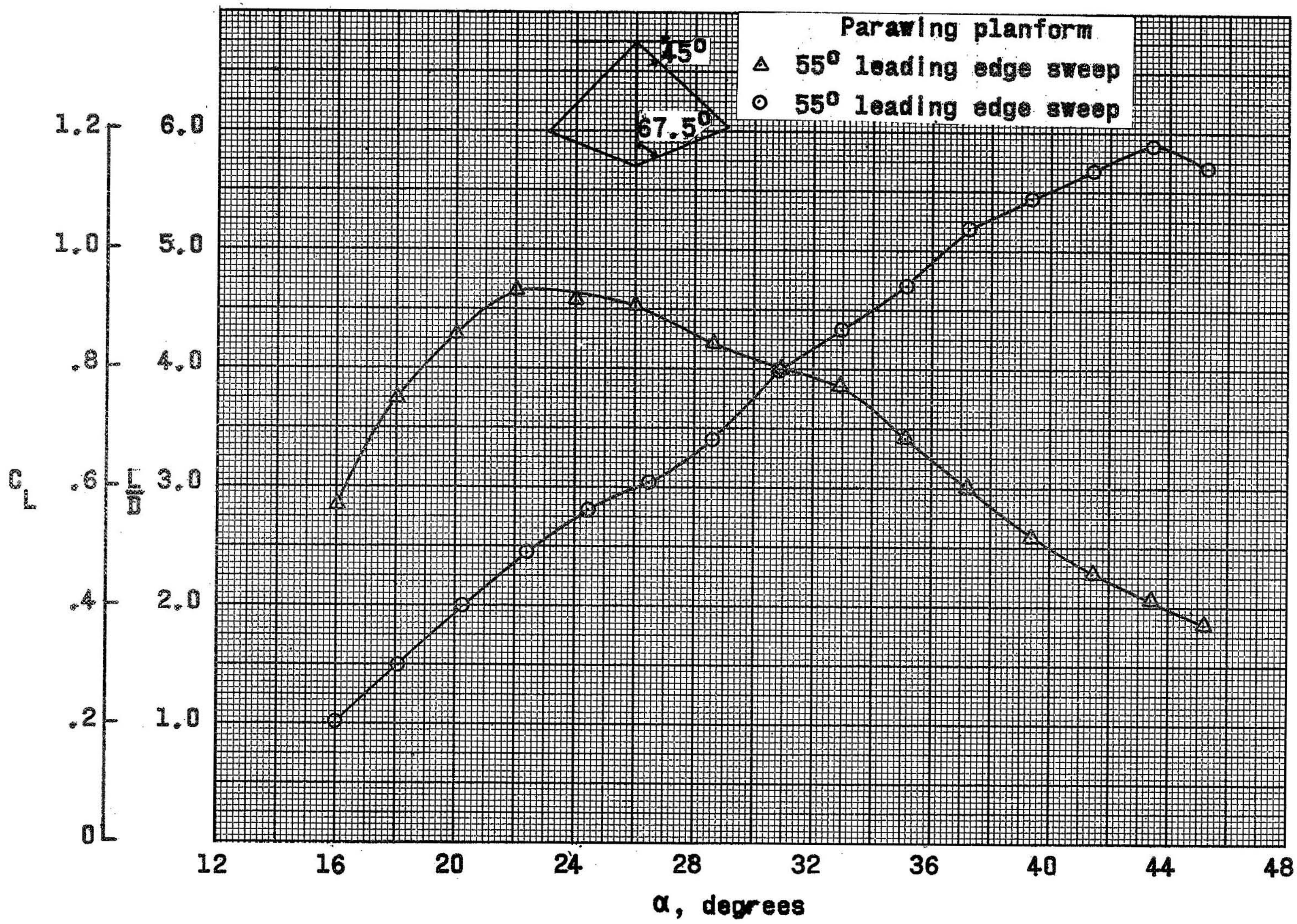

Figure 9.- Parawing L/D and C_L vs angle of attack.

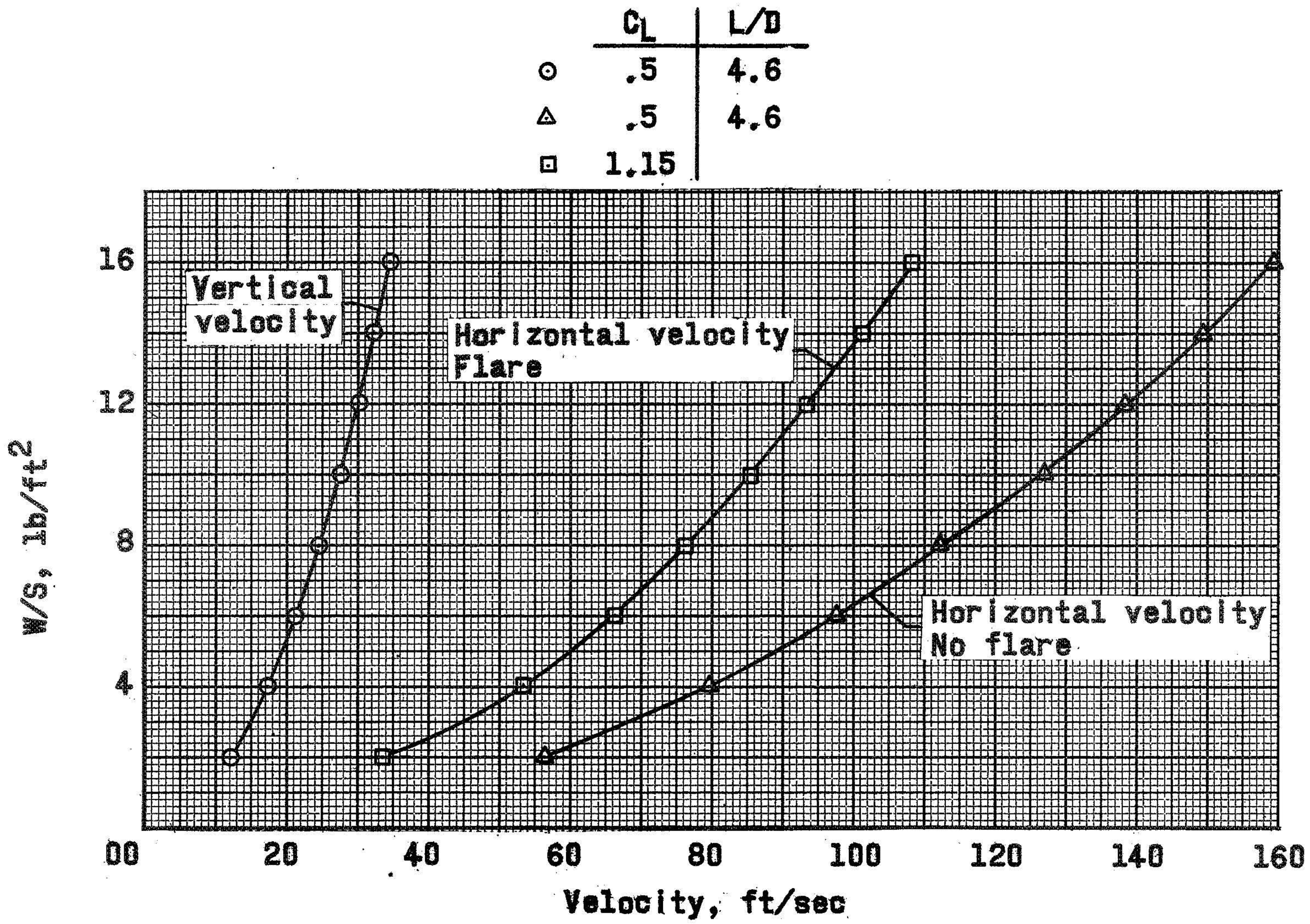

Figure 10. - Parawing horizontal and vertical velocity vs wing loading.

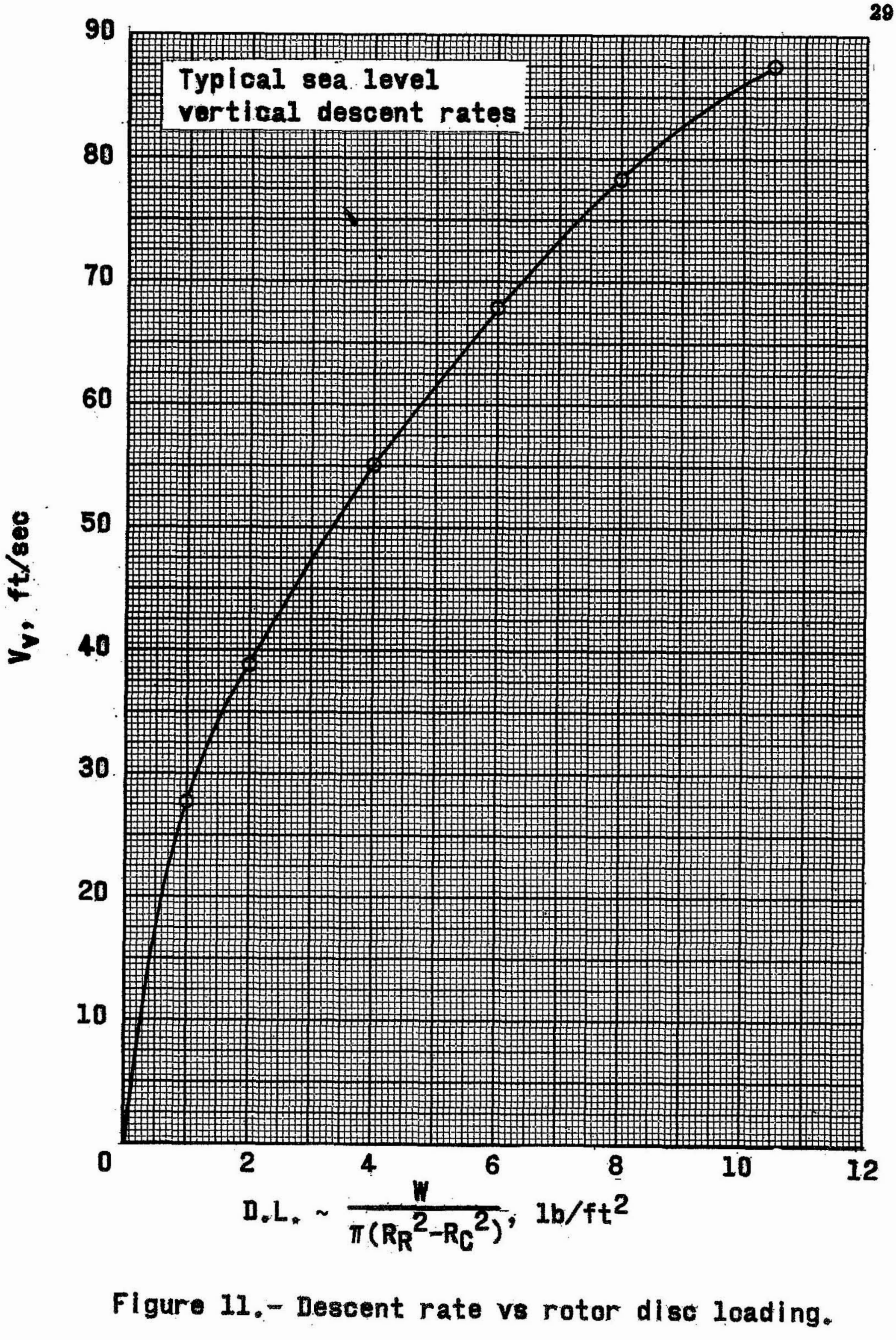

Figure 11.- Descent rate vs rotor disc loading.

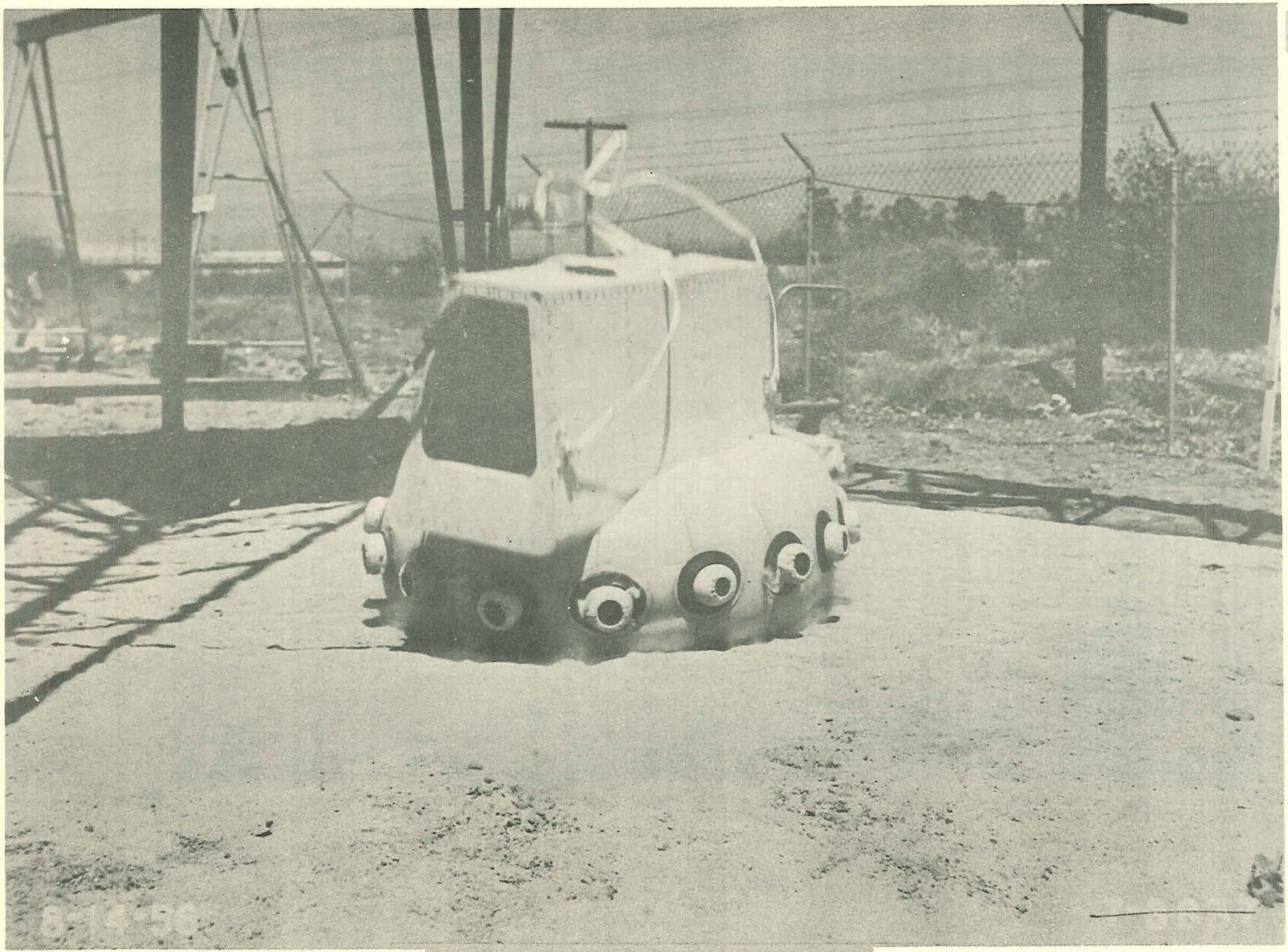

Figure 12. - Air bag impact attenuation.

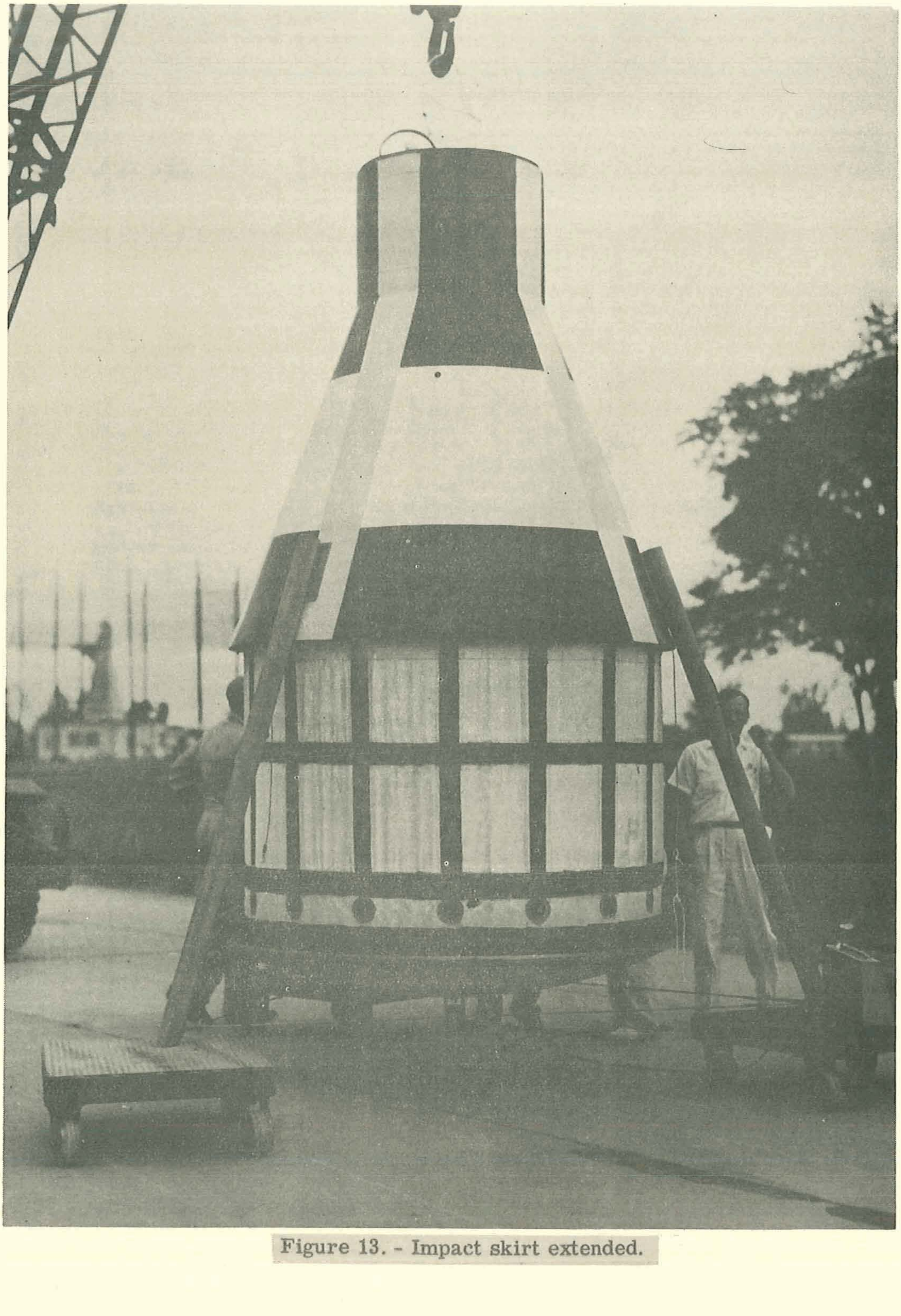

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Figure 13. - Impact skirt extended.