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TECHNICAL NOTE

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PRELIMINARY INVESTIGATION OF A PARAGLIDER

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Langley Field, Va.

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SUMMARY

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A preliminary investigation of the aerodynamic and control characteristics of a flexible glider similar to a parachute in construction has been made at the Langley Research Center to evaluate its capabilities as a reentry glider.

Preliminary weight estimates of the proposed vehicle indicate that such a structure can be made with extremely low wing loading. Maximum temperatures during the reentry maneuver might be held as low as about 1,500° F.

The results of wind-tunnel and free-glide tests show that the glider when constructed of nonporous material performed extremely well at subsonic speeds and could be flown at angles of attack from about 20° to 90°. At supersonic speeds the wing showed none of the unfavorable tendencies exhibited by conventional parachutes at these speeds, such as squidding and breathing. Several methods of packing and deploying the glider have been successfully demonstrated.

The results of this study indicate that this flexible-lifting-surface concept may provide a lightweight controllable paraglider for manned space vehicles.

INTRODUCTION

Current studies of vehicles to put a man in space and return him safely emphasize the need for a recovery device that has low weight and small area during the launching phase, low acceleration and temperature during the reentry phase, and the stability, control, and performance required to glide to a predetermined site and make a safe landing at a low or moderate speed.

The first author of this paper, Francis M. Rogallo, has for several years been experimenting with a flexible-lifting-surface concept that promises to satisfy many and possibly all of the aforementioned requirements. Among the flexible configurations developed were stable and controllable gliders that could be rolled or folded into compact bundles. Of the many possible applications of the flexible-lifting-surface concept, one of interest to the NASA and the one treated in the exploratory study reported herein is the controllable, lightly loaded flexible glider for the recovery of manned capsules and equipment from space.

In this study several different gliders were investigated at the Langley Research Center to determine their stability, control, performance, ability to be packed like parachutes, and opening characteristics at subsonic speeds. Free glides and deployments were made at low speeds, and wind-tunnel tests were made at both subsonic and supersonic speeds. Motion pictures were taken during some of the tests. A motion-picture film supplement has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this paper, on the page immediately preceding the abstract and index pages.

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This report discusses the results of the experiments and of some preliminary calculations of temperatures, accelerations, dynamic pressures, velocities, and the altitude, time, and distance relationships during reentry of some very lightly loaded gliders.

SYMBOLS

C_D	drag coefficient, D/qS
C_L	lift coefficient, L/qS
c	root chord, ft
D	drag, lb
g	gravitational acceleration, 32.2 ft/sec^2
h	altitude, ft
h_o	initial altitude, ft
L	lift, lb
L/D	lift-drag ratio
l'	distance, miles

M	Mach number
q	dynamic pressure, $\frac{1}{2}\rho V^2$, lb/sq ft
S	vehicle wing area (fabric area)
T	temperature, $^{\circ}$F
t	time, sec
V	velocity relative to air, ft/sec
W	vehicle weight, lb
W/S	wing loading
α	angle of attack of rigid member at plane of symmetry, deg
γ	entry angle
ρ	density, slugs/cu ft

GENERAL DESCRIPTION OF PARAGLIDER

The glider consists of a flexible wing with a load suspended beneath it on cables. A sketch of the general configuration is shown as figure 1. Control of such a vehicle is achieved by changing the center of gravity of the glider with respect to the wing. Moving the payload to the rear causes an increase in the angle of attack. Turns to the left or right are accomplished by moving the payload left or right with respect to the wing. Gliders thus far flown have exhibited excellent stability and can be controlled to very high angles of attack.

The principal advantage of such a scheme lies in the fact that the structure carries loads primarily in tension and, as a result, can be constructed with a minimum of weight. The reentry glider as initially conceived was to be constructed of a wire gauze coated with a high-temperature silicone sealant. A reasonable weight for a practical single-ply cloth is about 10 ounces per square yard. If this value is used, a wing with inflatable shroud lines and leading edges of about 2 feet in diameter and an area of 1,500 square feet would weigh about 250 pounds. If the wing area is increased to 3,000 square feet and the diameter of the leading edges and shroud lines is left at 2 feet, the wing and shroud lines would weigh about 700 pounds. For the case of an earth satellite reentry a capsule might have a gross weight of about 1,400 pounds to carry a payload of 200 pounds. The values quoted are estimates only and are not intended as absolute. Improvements in weight can be expected as experience is gained in weaving the lighter weight high-temperature glass fibers into cloth.

REENTRY CALCULATIONS

As a first step in evaluating the paraglider concept in a practical application as a reentry vehicle, calculations were made by using equations of motion involving two degrees of freedom. These equations represent an entry into the earth's atmosphere at a constant angle of attack. For these calculations the range of variables and initial conditions are as follows:

W/S	0.25, 0.50, and 1.00
L/D	0.577
h_o, ft	400,000
γ, deg	-1

The temperature used in these calculations is the stagnation-point temperature and is obtained by using Romig's formula (ref. 1) for heat transfer to a hemisphere. The hemisphere considered is at the apex of the glider. A characteristic radius of 1 foot was assumed. The emissivity constant was taken as 0.80, and the glider was assumed to receive solar radiation at a temperature of 580° R. Time histories of the resultant acceleration, radiation equilibrium stagnation-point temperature, dynamic pressure, velocity, and distance were evaluated. The main results of these calculations are shown in figure 2.

Figure 2(a) shows the resultant acceleration encountered, which never exceeds about 1.6g for the L/D and entry angle assumed. The effect of decreasing wing loading is to force the accelerations to occur at higher altitudes as seen in figure 2(b). Since density is lower at higher altitudes, the maximum temperature encountered (stagnation point) is lower as the wing loading decreases. The effect of wing loading on stagnation-point temperature is shown in figure 2(c). Dynamic-pressure variations with time are presented in figure 2(d). Under the conditions assumed the dynamic-pressure peak is approximately 1.25 times the wing loading.

The main point to be brought out in these figures is the fact that low wing loading enables the reduction of temperature during reentry and, as a result, enables the designer to use lighter structures and possibly more common materials. Wing loadings should therefore be kept as low as possible for this glider.

EXPERIMENTAL STUDIES

For most of the experimental studies the glider was constructed with rigid leading edges and keel. This type of construction was used because it simulated the inflated leading edges and keel without the difficulties associated with inflated structures. Recent free glides of a glider with inflated leading edges and keel substantiated the fact that the rigid structure does simulate the inflated structure.

Low-Speed Aerodynamic Characteristics

Exploratory wind-tunnel tests of the glider were made in the Langley 300-MPH 7- by 10-foot tunnel at a Reynolds number of about 0.5×10^6 per foot to determine the longitudinal aerodynamic characteristics of flexible lifting surfaces. A photograph of the model and the installation is shown as figure 3. The model was constructed of 0.016-inch-sheet aluminum alloy and was supported along its streamwise diagonal by a rigid (angle-iron) member. Shroud lines from the leading edges of the model were attached to a strut below the rigid member.

A summary of the data obtained in tests of this aluminum-alloy model is presented in figure 4. Corrections applied to these data were those due to the stream boundaries as outlined in reference 2. Drag tares to account for the shroud support strut were also applied to the data. These tests were limited to an angle of attack of 40° by the model support mechanism in the tunnel. It should be pointed out that the lower angle of attack and lift coefficient shown in the figure were possible only because of the stiffness in the model used; normally these models, when constructed of flexible materials, tend to be limited in operation to an angle of attack greater than 15°. A series of tests were made to determine the influence of altering the confluence point; a value of 0.75c below the keel was found to be satisfactory. As will be noted, the highest values of L/D shown in the figure correspond to glide-path angles of about 8°. This glide-path angle is in general agreement with free-flight glides where gliding angles estimated at about 10° have been observed for nonporous flexible lifting surfaces. Glides with lifting surfaces made of porous nylon fabric were inferior. In the free-flight tests the effect on L/D of changing the rigging slightly (due to a physical shift of the center of gravity) was of the second order. Therefore, the values of figure 4 are not necessarily modified to any great extent due to trimming the glider if the trim is accomplished by a change in the center-of-gravity location.

Control Characteristics

A series of control tests was made with the model in a restrained flight condition in the 17-foot test section of the Langley 300-MPH 7- by 10-foot tunnel. The model used for these control tests was constructed of 1/4-mil-thick Mylar film with tubular, stiff leading edges and keel. The model was tethered to a post in the tunnel floor and "flown" in the stream by an operator beneath the tunnel floor. Control was achieved by lengthening and shortening the shroud lines. This model was successfully operated in restrained flight at angles of attack from about 20° to 90° (fig. 5). There was a tendency, however, toward neutral stability at the higher angles of attack and it is uncertain whether this phenomenon was due to the towing instability encountered in this type of test (where the suspension point is fixed) or to the reduction of stability due to the relatively rearward movement of the suspension point (center of gravity) relative to the surface. Whatever the reason, the resultant motion although less stable was controllable under the conditions of the test. The results of these tests are included in the motion-picture film supplement to this paper.

High-Speed Aerodynamic Characteristics

Inasmuch as the most severe requirements for such a vehicle may lie in the region of extremely high speeds, preliminary tests were made at a Mach number of about 1.89 in the Langley 4- by 4-foot supersonic pressure tunnel. The Reynolds number of these tests was about 0.5×10^6 per foot. The wings used in these tests consisted of a membrane fabricated of nylon (parachute cloth) having a porosity of about $120 \frac{\text{cubic feet}}{\text{square feet-minute}}$ and leading edges of 3/8-inch steel rod loosely connected at the apex. It was estimated that the adhesive used in construction of the wings reduced the porosity of the 45° swept wing to about $100 \frac{\text{cubic feet}}{\text{square feet-minute}}$ and that of the 55° swept wing to about $50 \frac{\text{cubic feet}}{\text{square feet-minute}}$. A sketch of the model and support is shown in figure 6. Since the tests were preliminary in scope, no special effort was made to refine the support system and, as a result, the absolute value of the data shown in figure 7 is less reliable than the data in figure 4. However, values of L/D of about 1.0 are in evidence (fig. 7). It seems reasonable to assume that more careful design of the model support and the installation of a membrane with much less porosity should yield values of L/D considerably higher; subsequent data, not presented, have indicated values of L/D higher than those shown herein. However, if larger diameter shroud lines are used, the value of L/D would be reduced. Figure 8 shows typical schlieren photographs taken during these tests. It should be pointed out that the wing used during these tests was absolutely flutter free and exhibited none of the unfavorable tendencies which have appeared in supersonic tests conducted with parachutes, such as squidding and breathing. Tests made at transonic speeds in the Langley 8-foot transonic pressure tunnel showed that the model was also flutter free in this speed regime.

Deployment Characteristics

Demonstration of the deployment characteristics of flexible-lifting-surface gliders have been made in the 17-foot test section of the Langley 300-MPH 7- by 10-foot tunnel and in free flight.

Two methods of deployment were demonstrated in the wind tunnel - the cover-eject method in which a 7-foot-span model was used and the cover-retract method in which a 5-foot-span model was used. Sequence photographs of the wind-tunnel tests of these two methods of deployment are presented in figure 9. Both wings had membranes fabricated of parachute nylon and aluminum tubular leading edges and keels.

Free-flight deployment of a 28-inch-span model was demonstrated by using a hand-launching technique. The wing used for this demonstration had a membrane of parachute nylon and steel-tape leading edges and keel and was capable of being rolled up and stowed in a relatively small compartment.

Free-flight deployment of a 7-foot-span model was demonstrated at the Langley landing-loads track by using the cover-retract method and also by ejecting the model from a tube by use of a gas generator. The gas-generator ejection system was also installed in a low-altitude-rocket vehicle at the NASA Wallops Station and free-flight deployment, as well as glides of the model from the rocket vehicle to the ground, was demonstrated. The models used in the deployment demonstrations at the Langley landing-loads track and at the NASA Wallops Station had aluminum tubular leading edges and keels; the membranes were made from a lamination of parachute nylon and 1/4-mil-thick Mylar coated with aluminum to a thickness of approximately 2,200 angstroms.

CONCLUDING REMARKS

Results of wind-tunnel and free-glide tests of a flexible glider show that the glider when constructed of nonporous material performed extremely well at subsonic speeds and could be flown at angles of attack from about 20° to 90°. At supersonic speeds the wing showed none of the unfavorable tendencies exhibited by conventional parachutes at these speeds, such as squidding and breathing. Several methods of packing and deploying the paraglider have been successfully demonstrated.

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Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., May 24, 1960.

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1. Romig, Mary F.: Stagnation Point Heat Transfer for Hypersonic Flow. Jet Propulsion. (Technical Notes), vol. 26, no. 12, Dec. 1956, pp. 1098-1101.

2. Gillis, Clarence L., Polhamus, Edward C., and Gray, Joseph L., Jr.: Charts for Determining Jet-Boundary Corrections for Complete Models in 7- by 10-Foot Closed Rectangular Wind Tunnels. NACA WR L-123, 1945. (Formerly NACA ARR L5G31.)

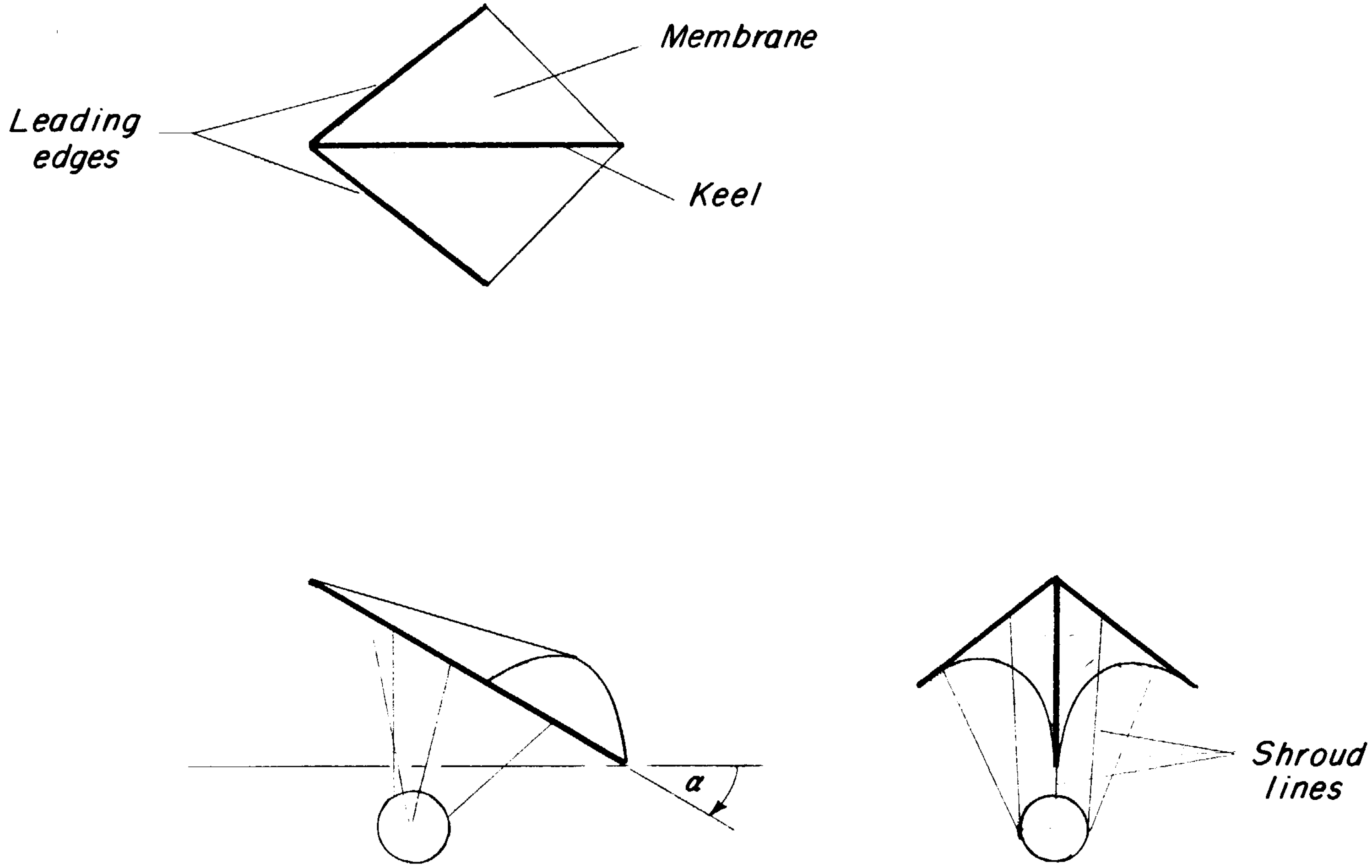
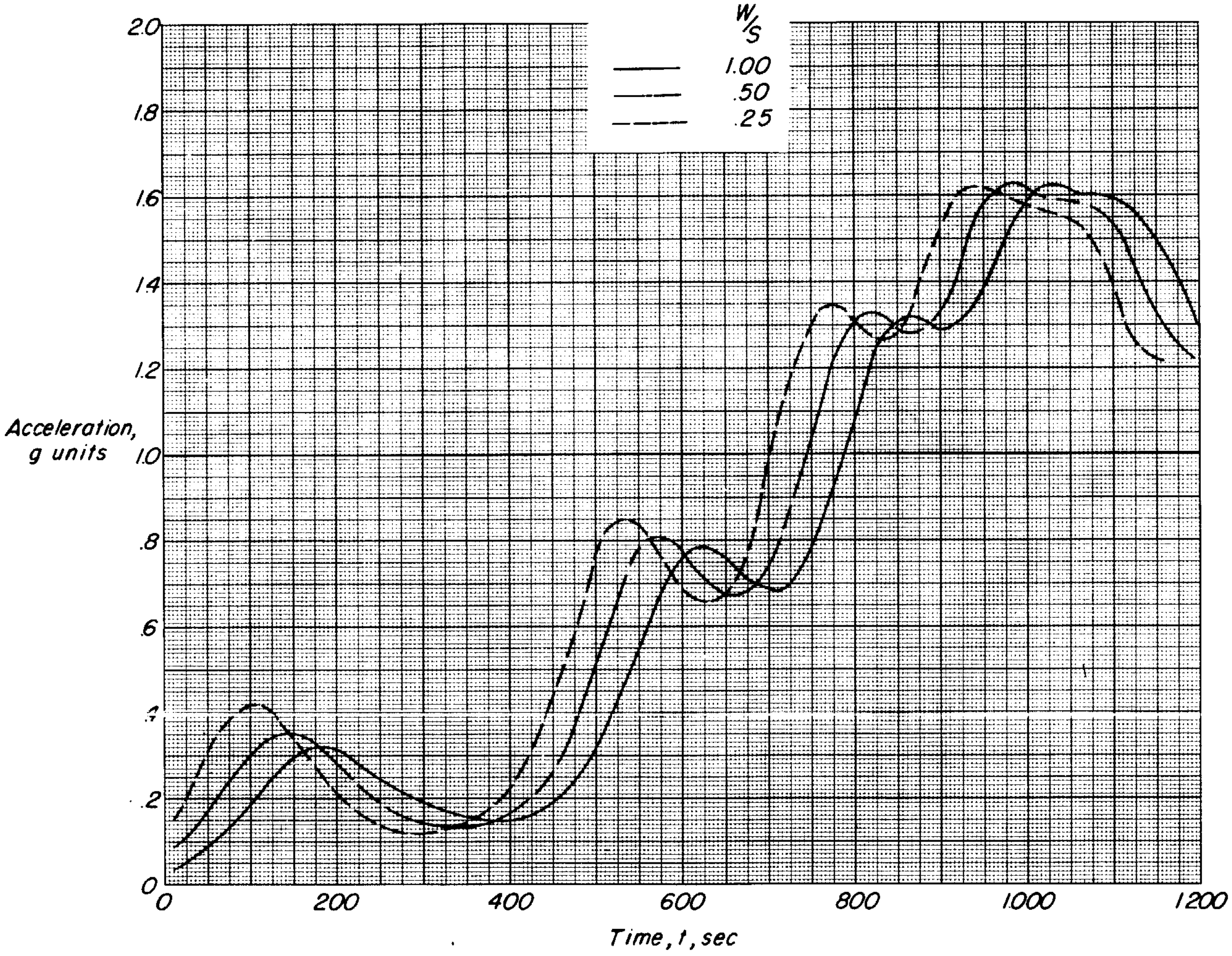
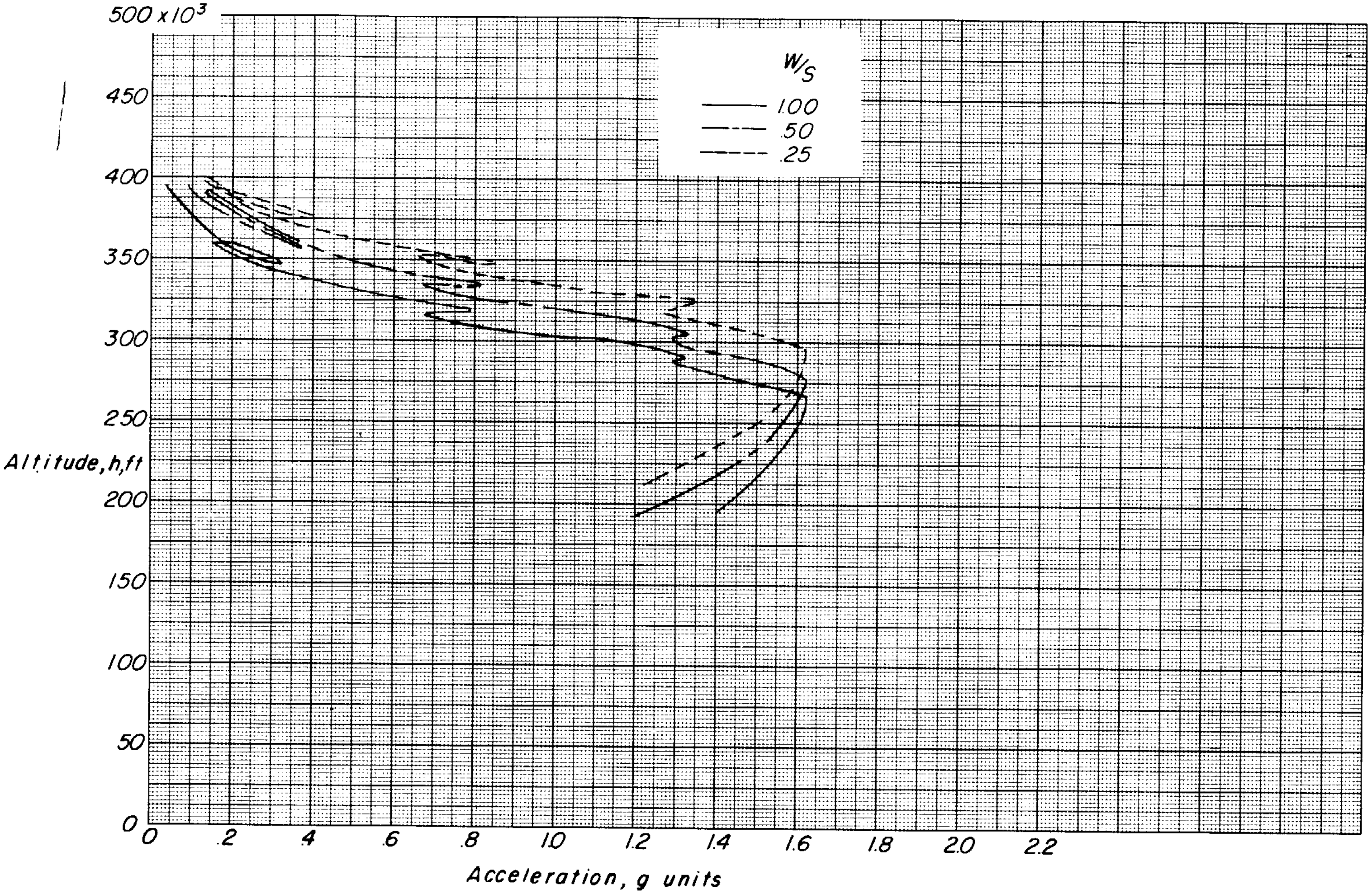


Figure 1.- Sketch of general configuration of paraglider.



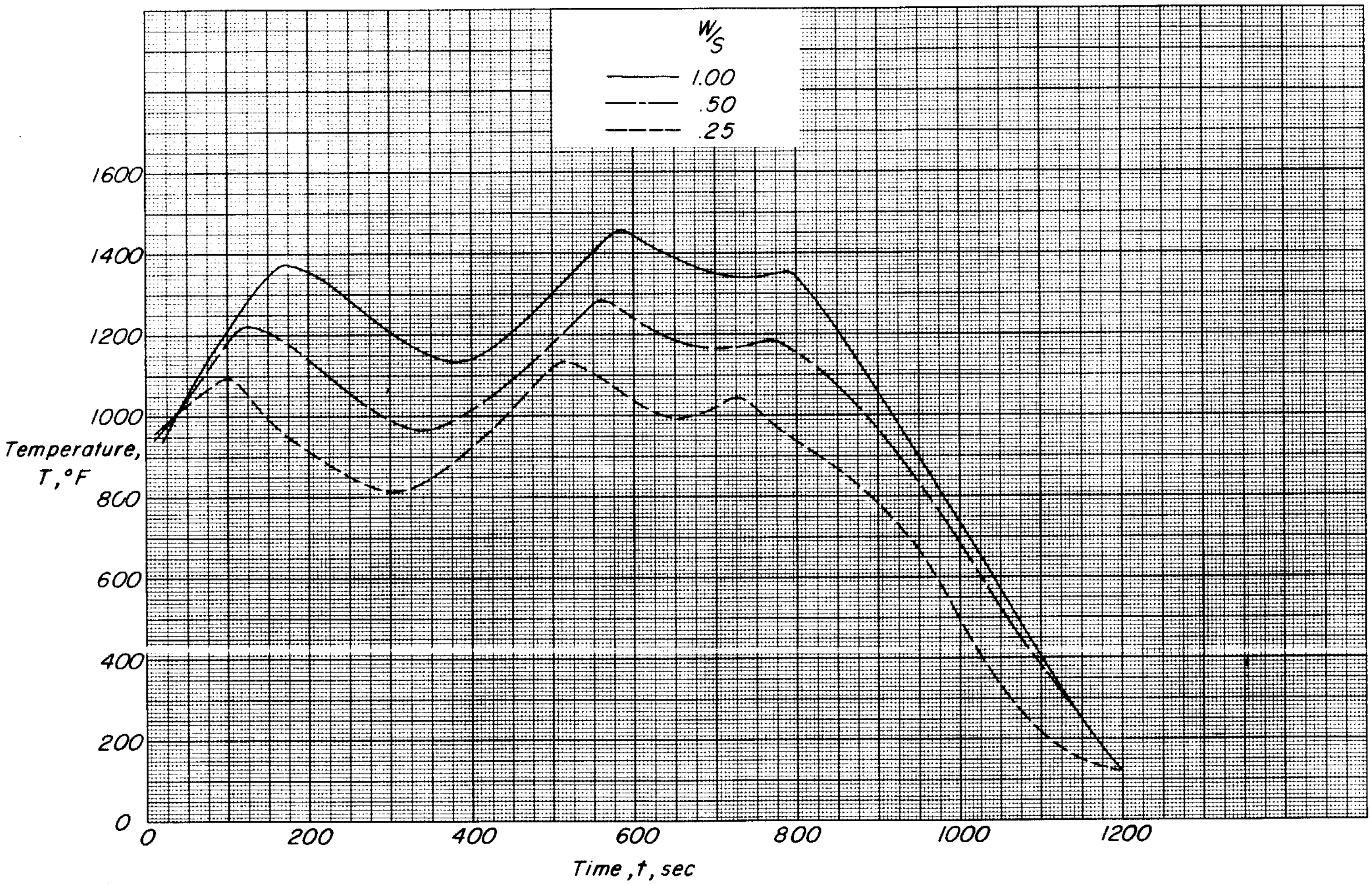
(a) Time history of resultant acceleration.

Figure 2.- Effect of wing loading on an assumed reentry.



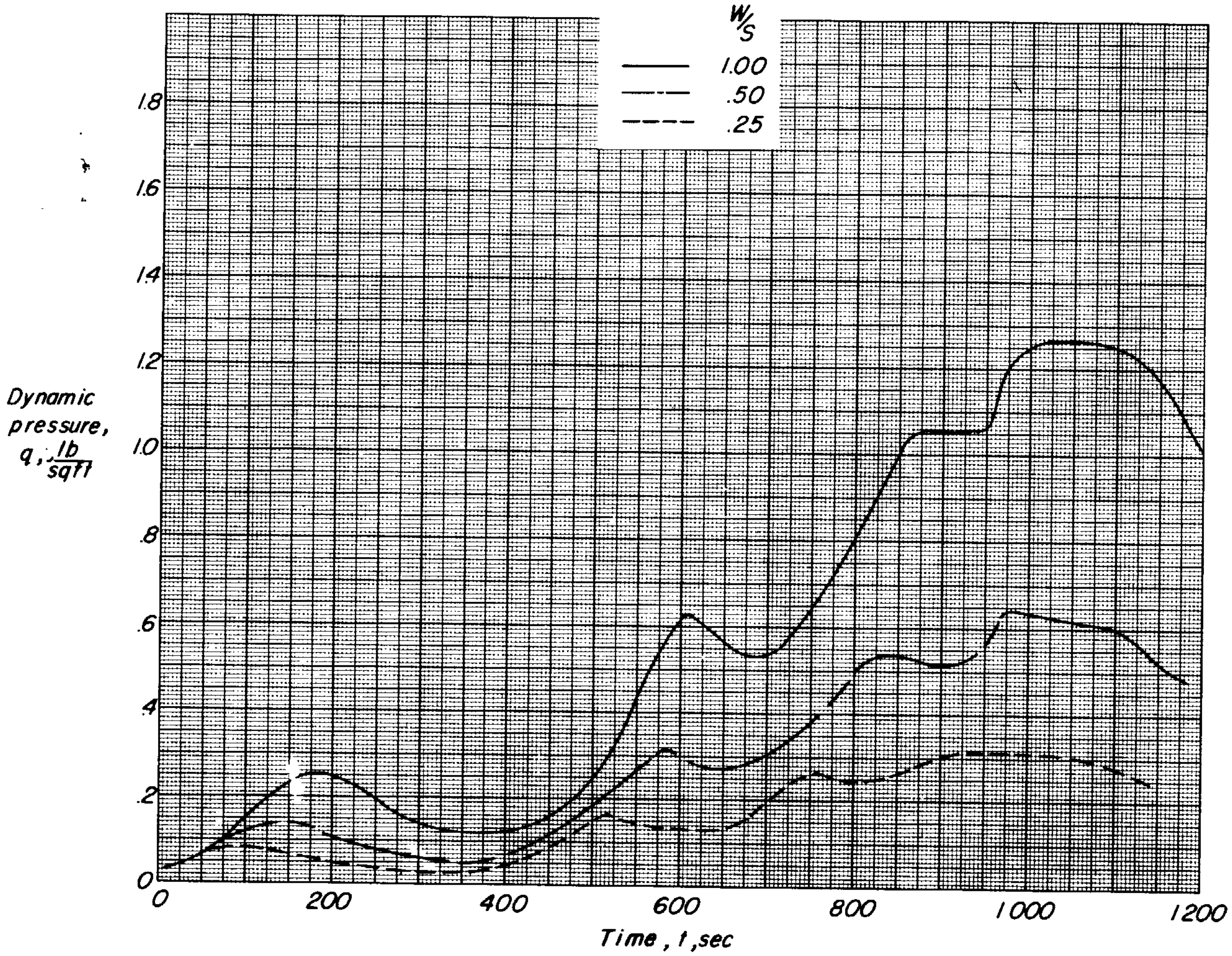
(b) Variation of altitude with acceleration.

Figure 2.- Continued.



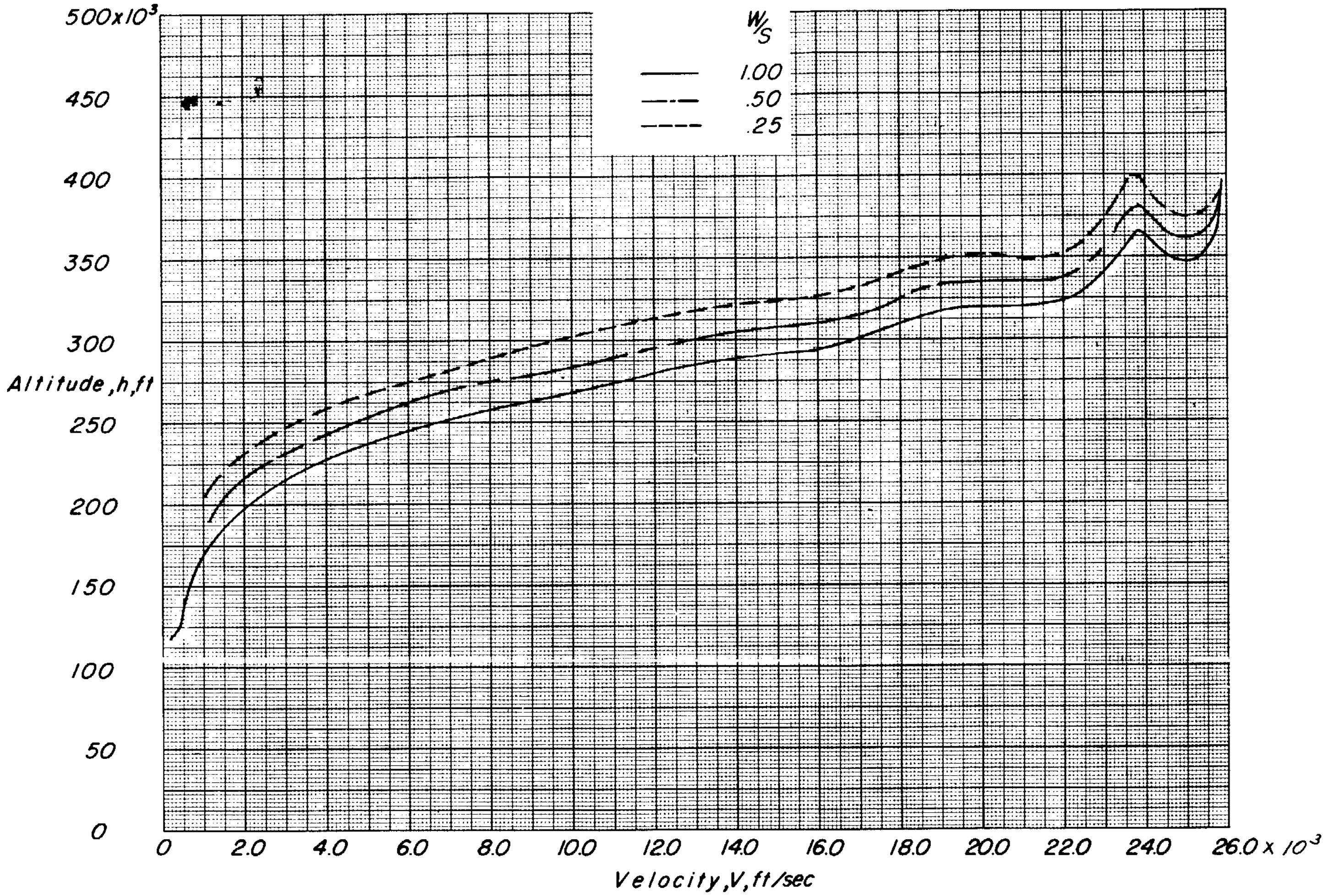
(c) Time history of stagnation-point temperature.

Figure 2.- Continued.



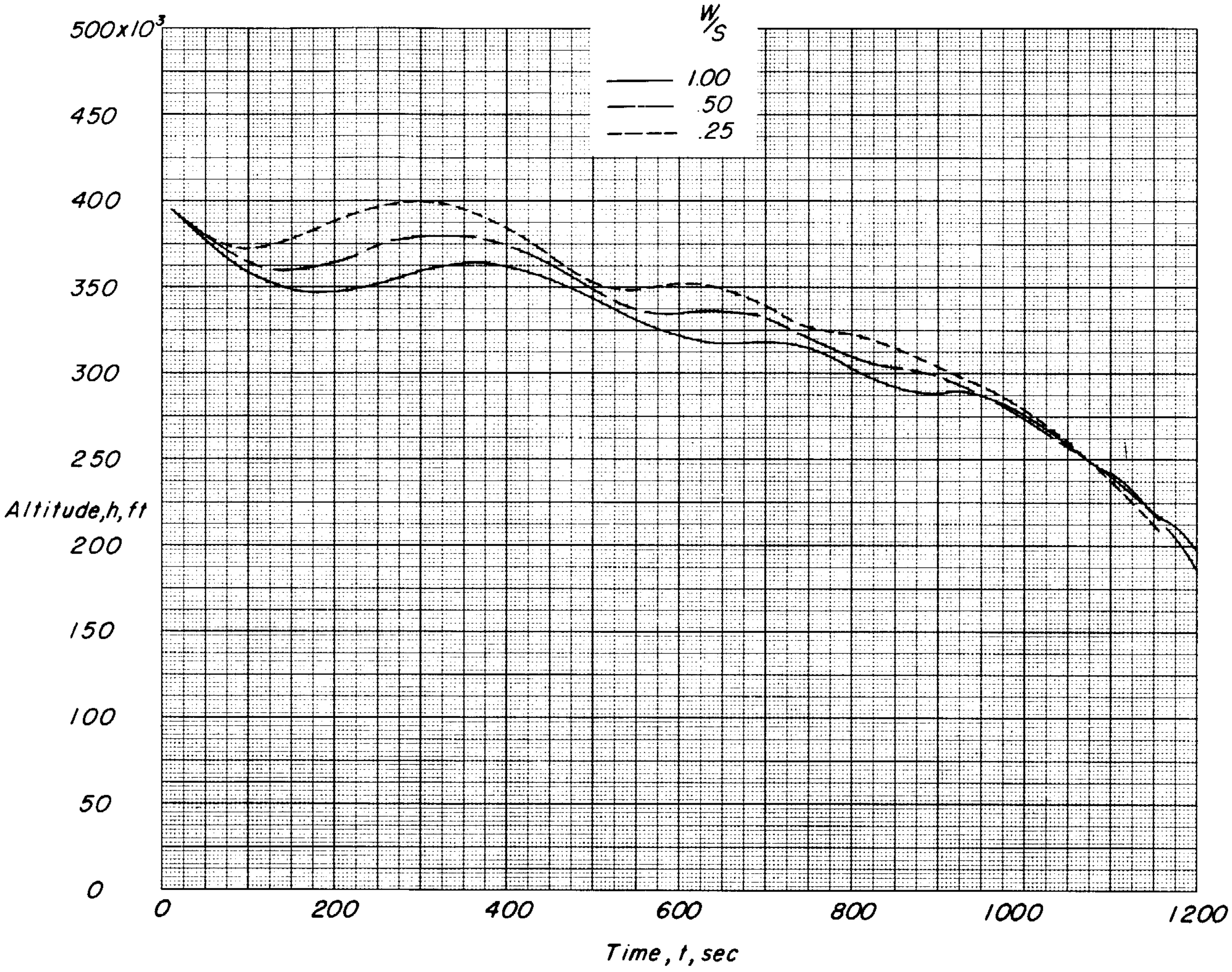
(d) Time history of dynamic pressure.

Figure 2.- Continued.



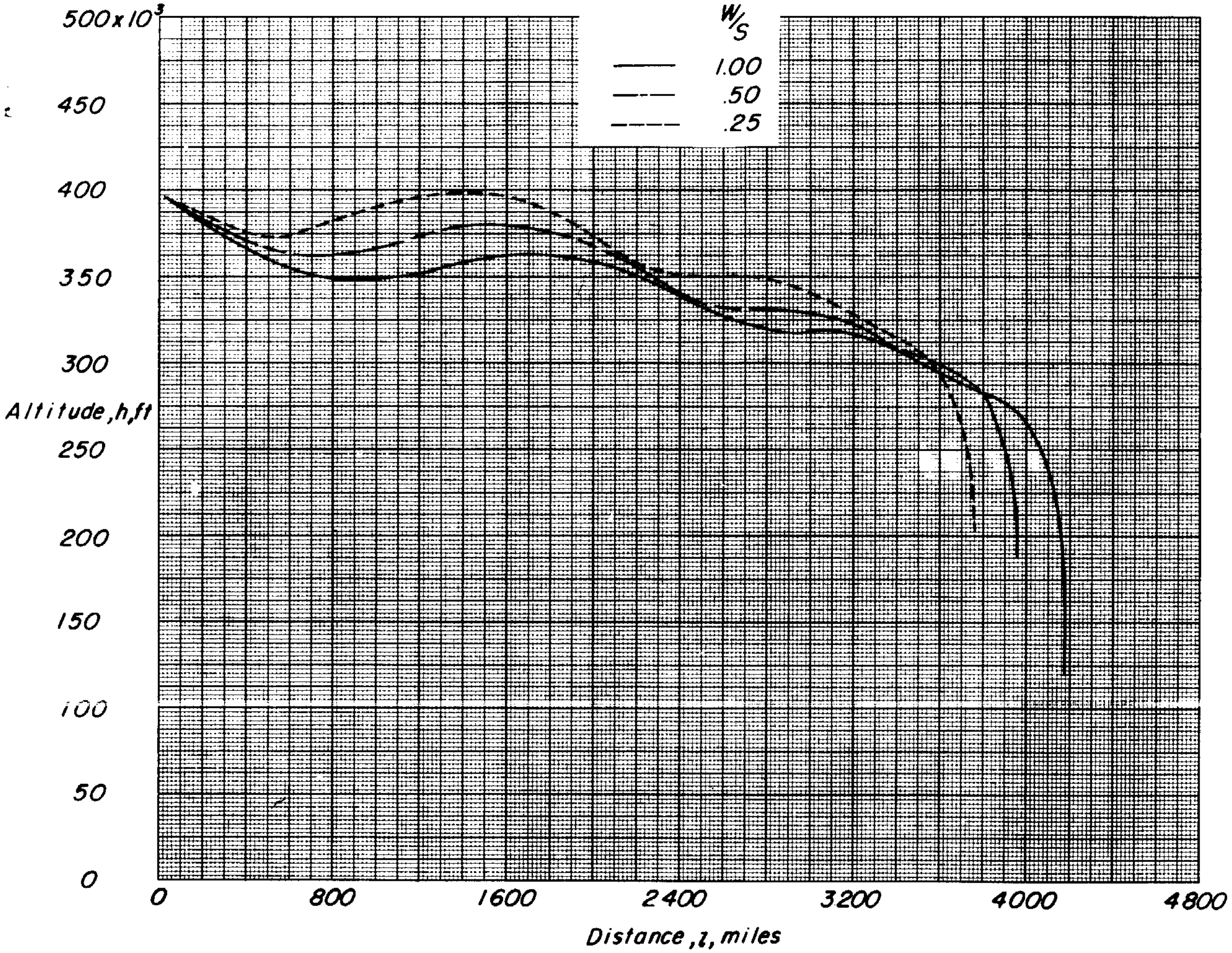
(e) Effect of velocity on altitude.

Figure 2.- Continued.



(f) Altitude time history.

Figure 2.- Continued.



(g) Flight-path profile.

Figure 2.- Concluded.

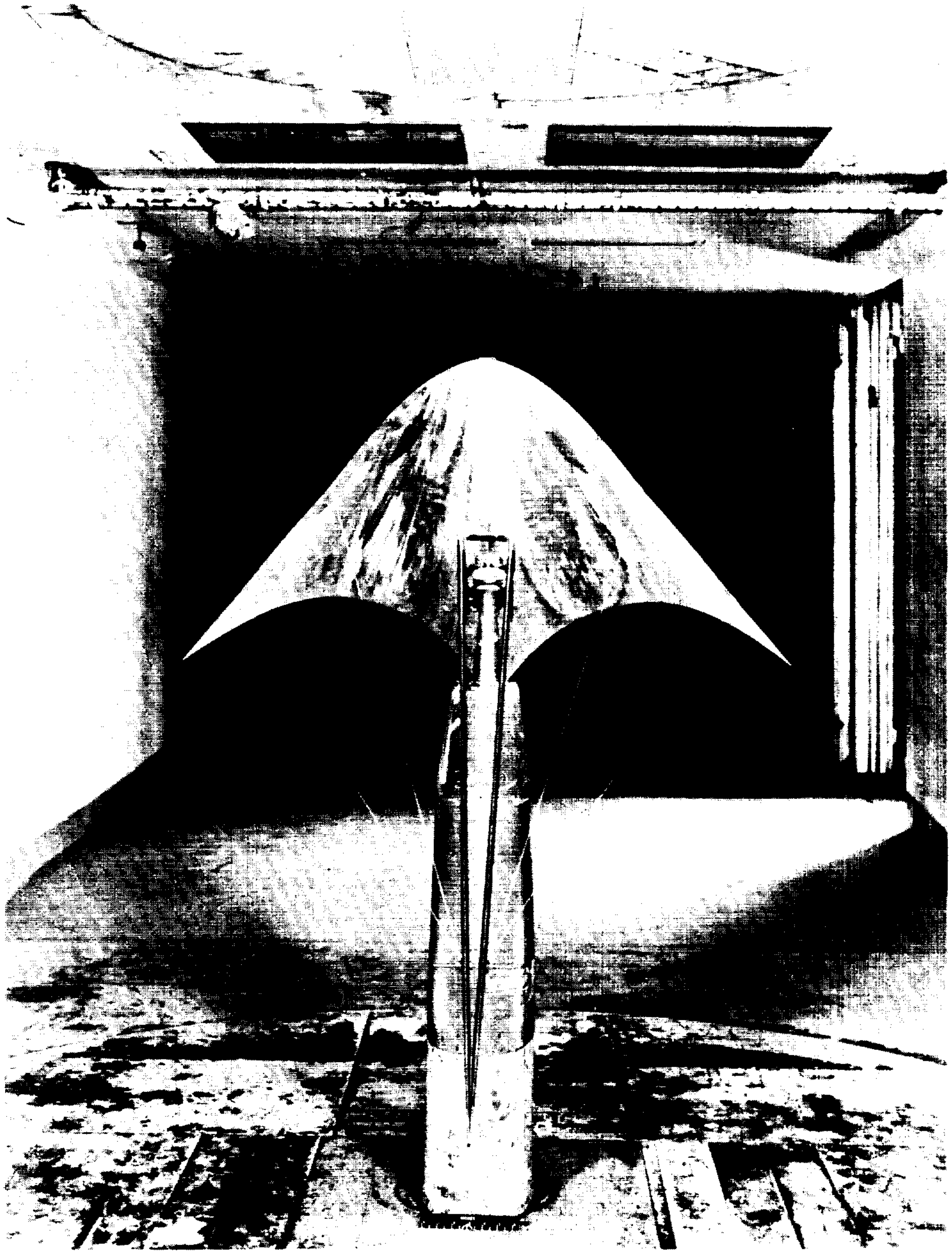


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Figure 3.- Aluminum-alloy model in the Langley 300-MPH 7- by 10-foot tunnel.

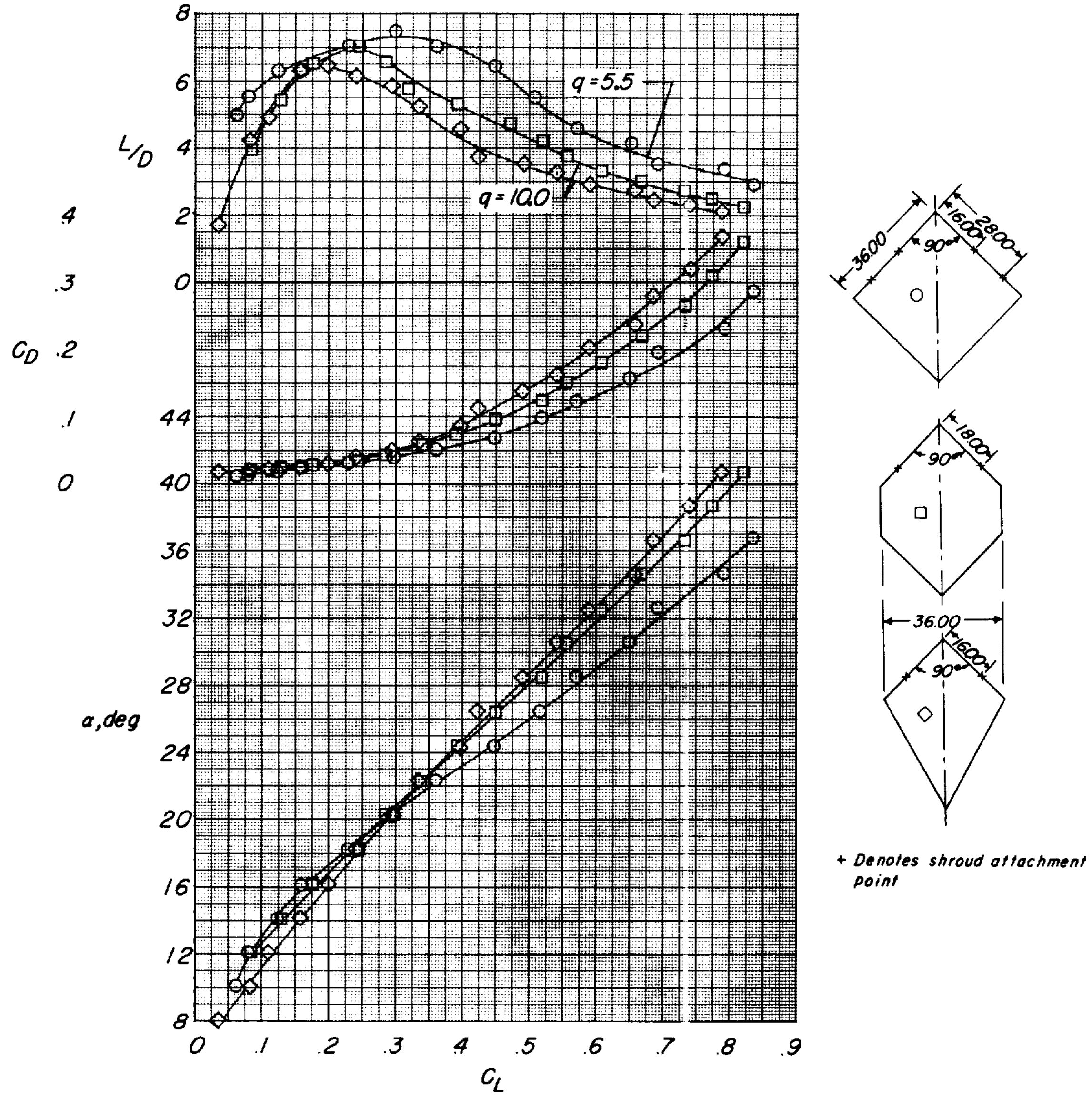

Figure 4.- Effect of glider plan form on the longitudinal aerodynamic characteristics of the aluminum-alloy model.

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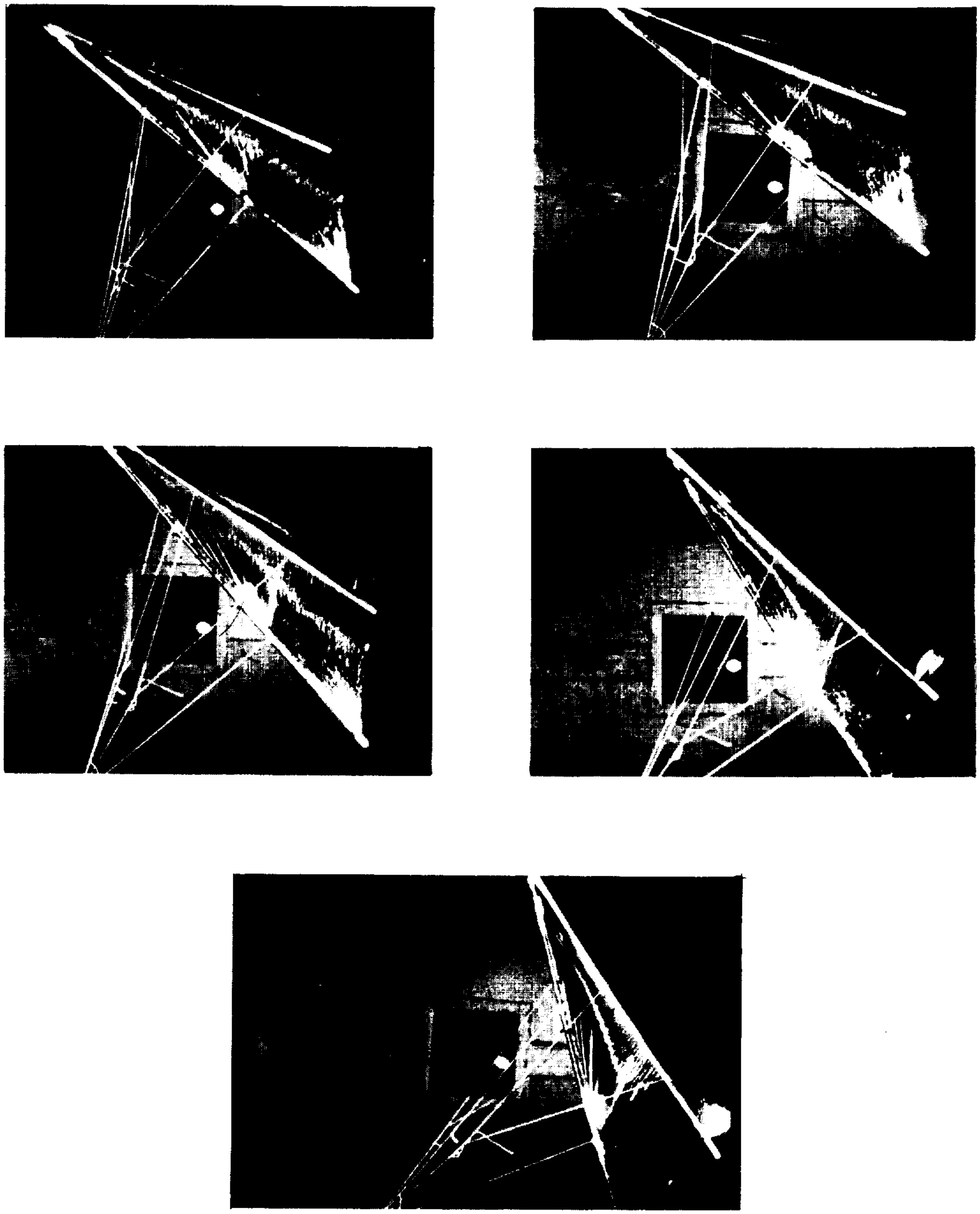

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Figure 5.- Sequence photographs of model in restrained flight, demonstrating attitude range.

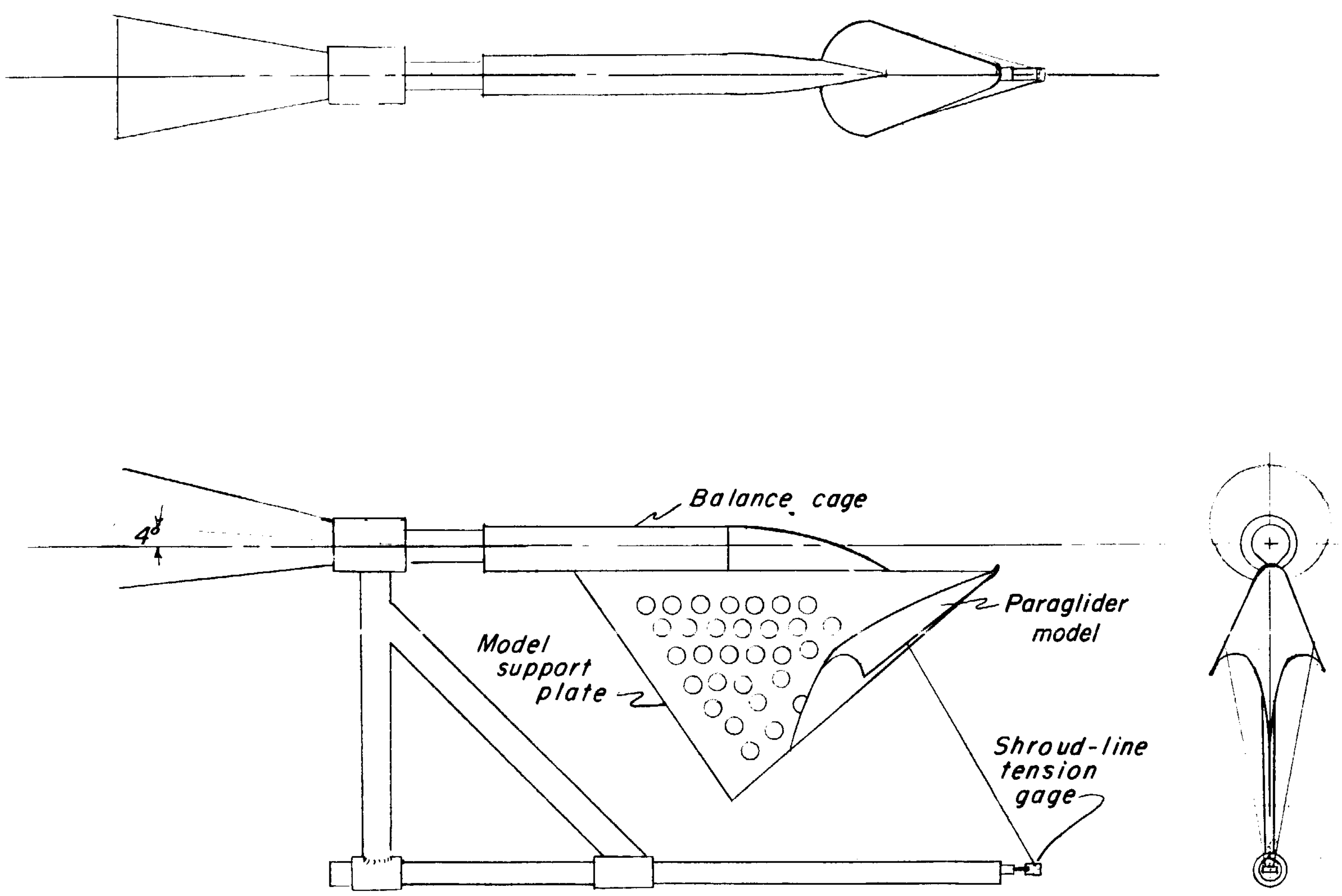

Figure 6.- Sketch of model and model support used in supersonic paraglider tests.

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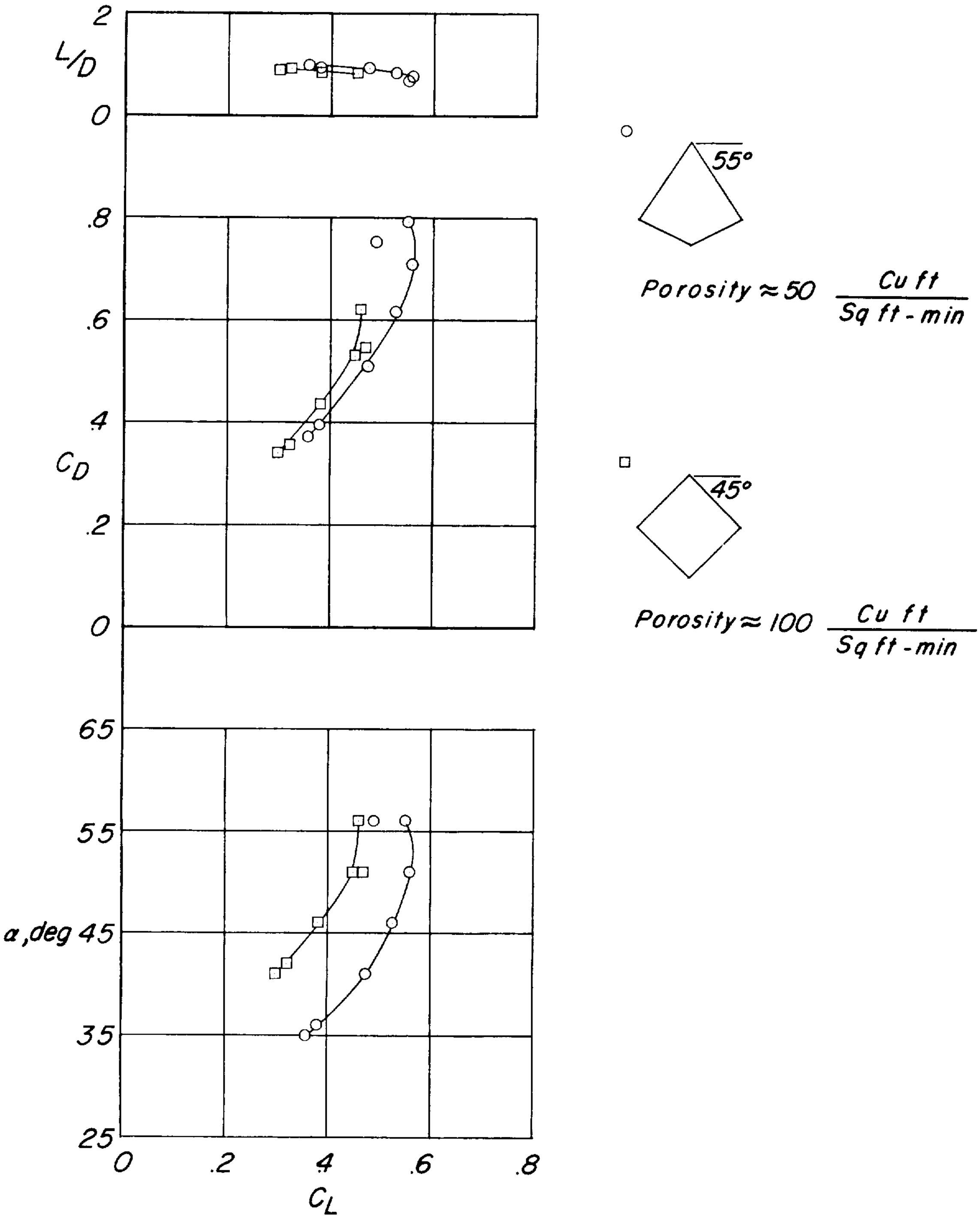
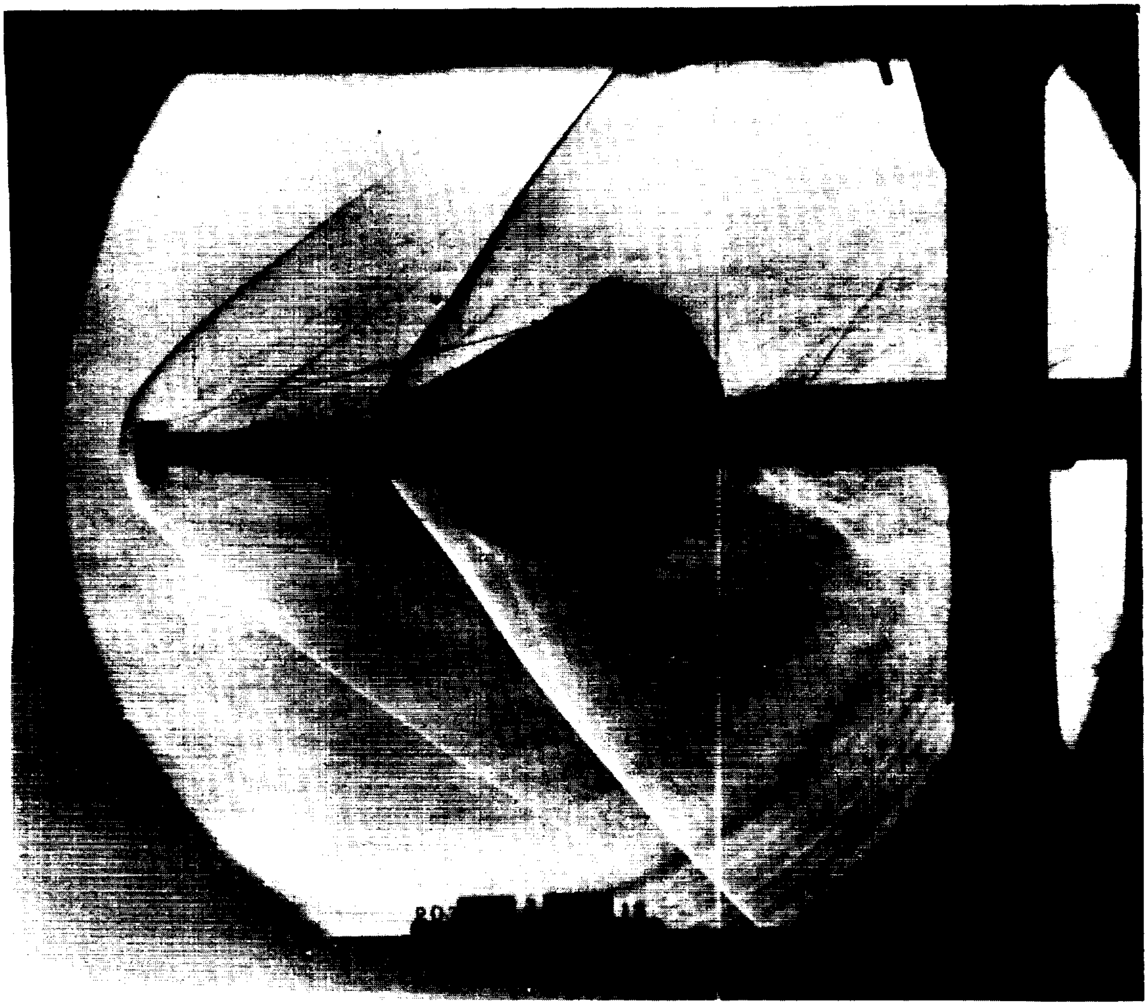


Figure 7.- Aerodynamic characteristics of porous paragliders at $M = 1.89$.



(a) Plan view.

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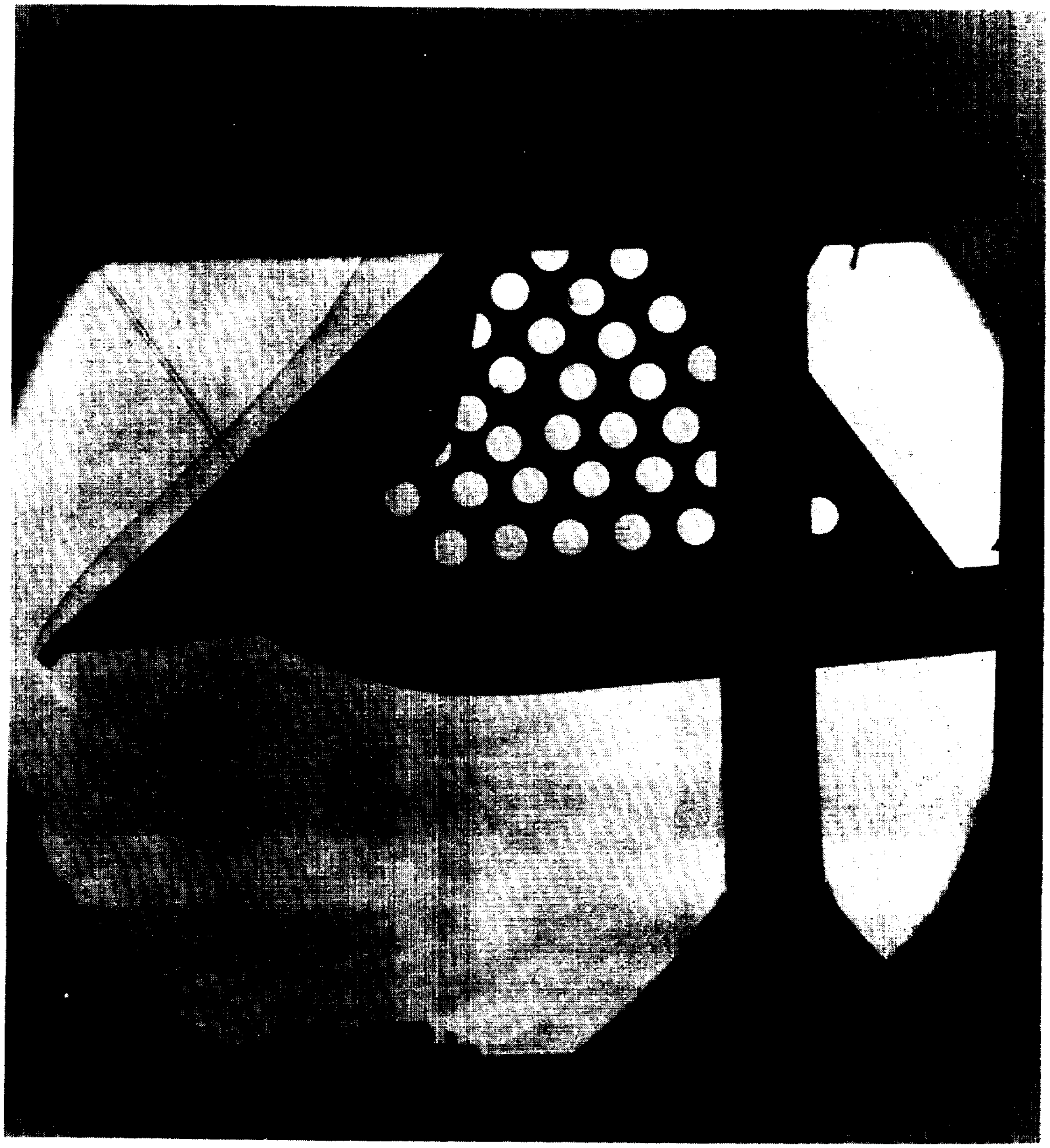
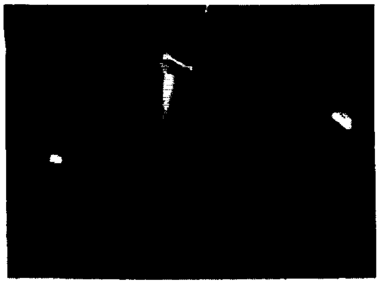
Figure 8.- Typical schlieren photographs of the model in the Langley 4- by 4-foot supersonic pressure tunnel. $\alpha = 44^\circ$; $M = 1.89$.



(b) Side view. L-60-2450

Figure 8.- Concluded.



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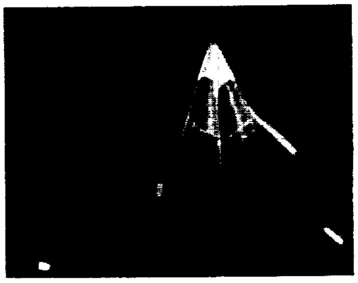

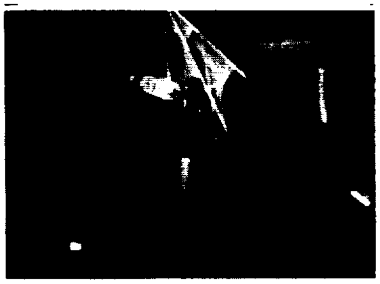

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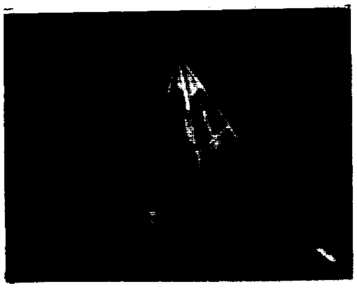
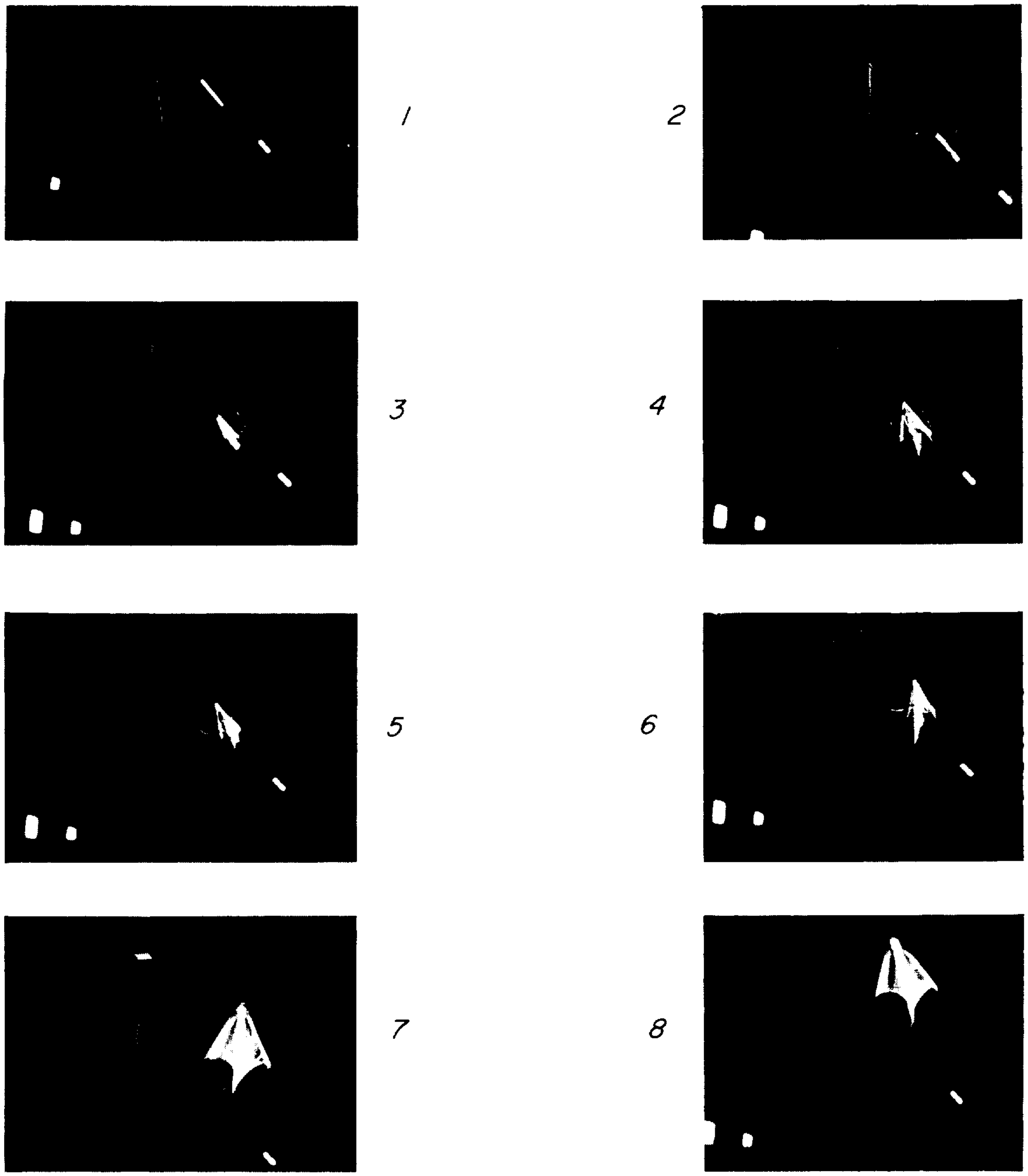


(a) Cover-eject tests. L-60-2451

Figure 9.- Sequence photographs from deployment tests in the 17-foot test section of the Langley 300-MPH 7- by 10-foot tunnel.



(b) Cover-retract tests. L-60-2452

Figure 9.- Concluded.