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FLIGHT TEST OF A 40-FOOT-NOMINAL-DIAMETER MODIFIED RINGSAIL PARACHUTE DEPLOYED AT A MACH NUMBER OF 1.64 AND A DYNAMIC PRESSURE OF 9.1 POUNDS PER SQUARE FOOT

By Clinton V. Eckstrom, Harold N. Murrow,
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Langley Research Center
Langley Station, Hampton, Va.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A ringsail parachute, which had a nominal diameter of 40 feet (12.2 meters) and reference area of 1256 square feet (117 meters^2) and was modified to provide a total geometric porosity of 15 percent of the reference area, was flight tested as part of the rocket launch portion of the NASA Planetary Entry Parachute Program. The payload for the flight test was an instrumented capsule from which the test parachute was ejected by a deployment mortar when the system was at a Mach number of 1.64 and a dynamic pressure of 9.1 pounds per square foot (43.6 newtons per meter^2). The parachute deployed to suspension line stretch in 0.45 second with a resulting snatch force of 1620 pounds (7200 newtons). Canopy inflation began 0.07 second later and the parachute projected area increased slowly to a maximum of 20 percent of that expected for full inflation. Because the parachute never reached the full-open condition, the large drag force (opening load) normally associated with parachute inflation did not develop. The difference in rotation between the spinning payload and the deployed canopy has normally resulted in some twisting of the payload attachment bridle and riser system in previous tests of this series. During this test, the suspension lines also twisted, primarily because the partially inflated canopy could not restrict the twisting to the attachment bridle and risers. This twisting of the suspension lines hampered canopy inflation at a time when velocity and dynamic-pressure conditions were more favorable. It is concluded that the most probable cause of the failure of the parachute to inflate properly was excessive total porosity (geometric open area and cloth permeability) in the crown area of the canopy.

INTRODUCTION

Parachutes have been used for many applications through the years; however, requirements for operations at high altitudes and low density have been rather recent. Very little information is available concerning deployments at supersonic velocities combined with relatively low dynamic pressures. Programs such as Voyager for soft landings of instrumented capsules on Mars will require data on operational characteristics of decelerators at these conditions. Earth simulation of deployments at supersonic Mach numbers combined with low dynamic pressures can be achieved at altitudes above 100 000 feet (30.5 kilometers). (See ref. 1.)

For the present test of this series in the Planetary Entry Parachute Program (PEPP), the test item was a 40-foot-nominal-diameter (12.2 meters) parachute of ringsail configuration modified to provide a total geometric porosity of 15 percent of the reference area. This parachute was the third of ringsail design tested in the program. Prior to this test, 31.2- and 85.3-foot-nominal-diameter (9.5 and 26 meters) modified ringsail parachutes had been tested and results are given in references 2 and 3. Results for a 30-foot-nominal-diameter disk-gap-band parachute also tested in the program are reported in reference 4.

The desired conditions for the present test were an unreefed deployment, a Mach number of 1.6, and a dynamic pressure of 10 pounds per square foot (479 newtons per meter^2). For reference, it may be noted that deployment conditions of the earlier tests were a Mach number of 1.39 and a dynamic pressure of 11 pounds per square foot (527 newtons per meter^2) for the 31.2-foot-diameter (9.5 meters) ringsail parachute (unreefed) and a Mach number of 1.15 and a dynamic pressure of 6 pounds per square foot (287 newtons per meter^2) for the 85.3-foot-diameter (26 meters) ringsail parachute (reefed deployment). For all PEPP tests, the objectives are to observe the dynamics of the parachute deployment and inflation and to measure opening shock loads, parachute drag efficiency, and stability characteristics.

Motion-picture film supplement L-981 is available on loan; a request card and a description of the film are included at the back of this paper.

SYMBOLS

$C_{D,o}$ nominal drag coefficient

D_o nominal diameter, $\left(\frac{4S_o}{\pi}\right)^{1/2}$, feet (meters)

g acceleration due to gravity, feet per second^2 (1g = 9.80665 meters per second^2)

M Mach number

q_∞ free-stream dynamic pressure, pounds per square foot (newtons per meter^2)

S_o nominal surface area of parachute canopy including openings such as slots and vents, feet^2 (meters^2)

S_p projected canopy area, feet^2 (meters^2)

$S_{p,f}$ projected area for a fully inflated canopy, feet^2 (meters^2)

t time from vehicle lift-off, seconds (exceptions: t - 24 and t + 2 hours)

t' time from mortar firing, seconds

Δp differential pressure

TEST SYSTEM

The payload was carried to the test point by means of an Honest John – Nike rocket vehicle. A photograph of the vehicle configuration is presented in figure 1, and a brief discussion of the launch vehicle system is presented in reference 2. A radio command system was used to start a programer which, in turn, initiated the firing of the parachute deployment mortar. A real-time visual display of the variation of velocity with altitude for the payload, such as is described in references 1 and 2, was used in conjunction with Mach number and dynamic-pressure grids to determine the proper time for transmitting the radio command signal.

A diagram of the test payload is presented in figure 2. The test payload weight including the test parachute system was 239 pounds (108 kilograms). Onboard instrumentation consisted of a tensiometer placed in the parachute riser line, a ±75g range accelerometer alined with the longitudinal axis of the vehicle, two ±5g range accelerometers mounted perpendicular to the longitudinal axis, an attitude reference system, and two cameras. The attitude reference system, commonly referred to as a gyro platform, was included to record payload motions in pitch, yaw, and roll. One camera was mounted in a pod on the payload (fig. 2) and pointed aft to record parachute performance. The second camera was mounted in the nose of the payload and pointed forward so that it would provide data on payload motions relative to Earth during the descent portion of the test. The tensiometer, accelerometer, and gyro-platform measurements were telemetered to ground receiving stations and recorded on magnetic tape. Camera film was obtained from the recovered payload.

In addition to the data-gathering instrumentation, a C-band transponder was included in the payload to facilitate radar tracking as well as a beacon which could be located directionally by receiving equipment onboard the recovery airplane. The payload also contained two auxiliary parachutes which could be deployed by radio command at any time after payload separation if the performance of the test parachute (as observed on the real-time radar plotting-board display) was such that the anticipated impact velocity of the payload would be greater than about 80 feet per second (24 meters per second).

TEST PARACHUTE

The test parachute was a modified ringsail design having a total reference area S_o (including geometric open areas) of 1256 square feet (117 meters^2) and a nominal diameter D_o of 40 feet (12.2 meters). The normal in-flight projected diameter of the parachute when fully inflated would be about 27 feet (8.2 meters).

The ringsail parachute had 36 gores and 36 suspension lines with 4 rings and 6 sails per gore. Figure 3 shows the dimensional details of a gore and the general parachute-payload configuration. The major modification to the standard ringsail design was the removal of one sail (from the seven which would normally exist) to provide the desired total geometric porosity or open area of 15 percent of the reference area S_o. This open area was distributed as follows: 0.43 percent in the vent, 1.84 percent in the slots between the rings (for a total geometric crown porosity of 2.27 percent), 9.47 percent from the omitted sail, and 3.26 percent in the scoops formed by the sail panels.

The test-parachute canopy rings and sails were fabricated of 1.0-ounce-per-square-yard (34 grams per meter^2) dacron material with the exception of the first ring which was fabricated of 2.0-ounce-per-square-yard (68 grams per meter^2) dacron material to strengthen the vent area. The upper edge of the first ring (the vent edge) was also reinforced with three layers of dacron tape having a rated tensile strength of 550 pounds (2450 newtons). The lower edge of the first ring and both upper and lower edges of rings 2, 3, and 4 were also reinforced with a single layer of this dacron tape. The upper and lower edges of sails 5, 6, 7, 8, and 10 and the upper edge of sail 11 were reinforced with a single layer of dacron tape having a rated tensile strength of 300 pounds (1335 newtons). The lower edge of sail 11, which is the canopy skirt edge, was reinforced with a single layer of 550-pound (2450 newtons) dacron tape. The panels in each ring were first joined at the gore edges by a French fell seam. The rings were then joined by 550-pound (2450 newtons) radial gore tapes to form the canopy. The radial gore tapes were continuous across the vent and were a double thickness across the missing sail. The suspension lines, which were 40 feet long (12.2 meters), were coreless braided dacron having an actual tensile strength in excess of 550 pounds (2450 newtons).

The parachute attachment system was approximately 11.5 feet (3.5 meters) in length and, as shown in figure 3, consisted of an upper riser, an explosive-bolt-actuated disconnect link, an intermediate riser, a tensiometer, and a bridle. The upper riser was 4 feet (1.2 meters) in length and the intermediate riser was $2\frac{1}{4}$ feet (0.7 meter) in length. The tensiometer and the disconnect link were each approximately 1/2 foot (15 centimeters) long. The bridle consisted of three legs, each of which was 4 feet long (1.2 meters), which joined at the upper end to form a single line for a length of 1/4 foot (8 centimeters). The bridle provided a three-point attachment to the payload.

The weight of the test parachute (including the upper riser which was permanently attached) was 33.0 pounds (15 kilograms). The total weight of the parachute system attached to the payload was 38.7 pounds (17.6 kilograms). The parachute was packed to a density of 40 pounds per cubic foot (641 kilograms per meter^3) in a cylindrical dacron bag which was closed with a mouth tie. No canopy or suspension-line holders or restraints were used inside the deployment bag except for a break line from the apex of the canopy to the bottom of the bag. The entire deployment bag, including the petal-type mouth closure, was lined with teflon cloth to prevent friction burning during deployment. The mortar deployment method used is described in reference 2.

The parachute was equipped with a system of lines which allowed it to be reefed after the data period was completed. This system of lines was termed a "post-reefing" system since the parachute was not reefed until the actual test was completed. The post-reefing system was activated during descent by the explosive-bolt-actuated disconnect link in the parachute attachment system. This disconnect link allowed the payload to drop away from the parachute. As the payload dropped, it pulled two lines leading to the skirt of the canopy. These lines passed through reefing rings on the skirt of the canopy and drew in the skirt to form a reefed canopy configuration the same as a standard reefing system would provide. The extent of reefing attained was determined by the length of a secondary riser (one end attached to each half of the separated disconnect link) which controlled the distance the payload could drop below its initial position. Post-reefing was used to increase the parachute descent rate; this descent rate increase reduced the total flight time and the corresponding drift due to winds.

The packed parachute and deployment bag were subjected to a temperature of 125° C for 90 hours. This heat cycle is representative of part of the sterilization requirements for equipment to be used in interplanetary spacecraft and was included in the test requirements so that any effects on parachute deployment and performance would be present in these tests.

RESULTS AND DISCUSSION

Test Data

The flight test vehicle was launched at 11:45 a.m. m.d.t. on May 9, 1967, at White Sands Missile Range, New Mexico. Figure 4 presents the sequence of events and the recorded times for significant flight events. Time histories of altitude and relative velocity for the first 360 seconds of the flight are shown in figure 5. The payload was in the ascent portion of the flight trajectory at the time the parachute was deployed ($t = 60.42$ seconds). The C-band transponder in the payload failed shortly after vehicle lift-off; however, the radars did skin track the payload for the first 71 seconds of the flight. The portion of the trajectory shown in figure 5 between $t = 71$ seconds and $t = 222$ seconds was computer simulated and was based on a calculated average value of $C_{D,o}S_o$ for the main parachute, known drag area values for the recovery parachutes, and event times. Altitude at apogee was about 157 000 feet (47.9 kilometers). Tracking cinetheodolites provided the data from $t = 222$ seconds to $t = 360$ seconds.

Measured atmospheric data from meteorological sounding rockets launched at t - 24 hours and t + 2 hours were used with radar and telemetered data to determine the time histories of payload true airspeed and Mach number (fig. 6) and of dynamic pressure (fig. 7). By definition, the initiation of the deployment sequence or time of deployment corresponds to mortar firing ($t' = 0$ in the figures). Parachute deployment was initiated at a true airspeed of 1732 feet per second (528 meters per second) or $M = 1.64$ and a dynamic pressure of 9.1 pounds per square foot (436 newtons per meter^2) at an altitude of 136 500 feet (41.6 kilometers) above mean sea level.

As shown in figure 6, the payload velocity increased slightly immediately after initiation of the deployment sequence because of the reaction of the payload to firing the mortar. The velocity decay was very slow since the parachute did not inflate properly. From an analysis of the aft camera film, it was determined that the test parachute began inflation immediately but the canopy projected area increased very slowly. Figure 8 presents the parachute projected area ratio, as determined from the camera film, for the first 2 seconds after mortar firing. The maximum projected area attained in the first 2 seconds was approximately 20 percent of that expected for a fully opened parachute. As a result of the small drag area developed, the payload-parachute velocity was supersonic for about 7.5 seconds.

The time history of force transmitted through the riser line as measured by the tensiometer during the deployment period is presented in figure 9. The first peak force of 1280 pounds (5700 newtons) at $t' = 0.16$ second is attributed to riser and bridle deployment. The second peak force of 1620 pounds (7200 newtons) occurred at $t' = 0.45$ second and was the snatch force corresponding to suspension line stretch.

Because the parachute did not inflate properly, the sudden rise in drag normally associated with the parachute-canopy opening process did not develop and, therefore, the snatch force was the greatest force recorded. The maximum tensiometer force developed after line stretch was 970 pounds (4315 newtons) at $t' = 1.65$ seconds.

Figure 10 presents the data obtained from the longitudinal accelerometer in the payload. Positive longitudinal accelerations imposed by the firing of the mortar are not shown but were an average of 30g for 0.02 second. The peak decelerations of 7.4g at $t' = 0.16$ second and 9.0g at $t' = 0.45$ second correspond to the peak loads noted on the tensiometer data. Since the data fall within only 12 percent of the full range on the accelerometer, a large noise-to-signal ratio is evident from figure 10.

Analysis of Parachute Performance

Extensive examination of the aft camera film showing the parachute deployment sequence gave no indication of any item which would have prevented proper inflation of the canopy. Selected frames from this film showing ejection, line stretch, partial inflation, and twisting of the suspension lines are presented in figure 11.

As mentioned previously, the time from mortar firing to suspension line stretch was 0.45 second; therefore, an average ejection velocity of 114 feet per second (35 meters per second) was achieved which indicated normal mortar operation. The test parachute began inflation immediately after deployment but never reached the full-open condition. The canopy remained partially inflated but did not spread the suspension lines enough to prevent the spinning payload from twisting the suspension lines in addition to the riser and the bridle system. This twisting of the suspension lines definitely hampered inflation of the canopy at any later time. On previous flights where canopy inflation was rapid, the twists had been contained within the riser and bridle system and had not affected parachute performance.

Because the parachute was only partially inflated, the drag efficiency was very low. Values of drag coefficient $C_{D,o}$ based on the nominal reference area S_o varied between 0.04 and 0.14 (average value of 0.09) for the first 5 seconds of the test.

Examination of the parachute at the recovery site indicated that the parachute had ejected from the mortar with no damage, no lines were broken or entangled, and the post-reefing operation had been performed. A more thorough examination revealed two small tears in the canopy cloth but nothing was found which could have mechanically restrained the canopy from inflating. All lines were found to be of the correct length and it was verified that the system was properly rigged.

A review was made of those items relating to the aerodynamics of the system which may have caused squidding or only partial inflation of the parachute. Information from wind-tunnel results concerning the effects of shock-wave fluctuations on parachute oscillations and on inflation stability is presented in reference 5. It was determined from the tests of several parachute configurations that at a Mach number of 1.6 a parachute should have a geometric open area of 15 percent or more of the reference area to prevent violent oscillations due to shock-wave fluctuation but less than 35 percent of the reference area to assure proper inflation stability. The proper distribution of the open area was not discussed in the reference. It is to be noted that the geometric open area of the ringsail flight-test parachutes in the present program (refs. 2 to 4) has been 15 percent of the reference area and was therefore within the boundaries established for stable operation based on the conclusions of reference 5. However, there is a significant difference in test conditions inasmuch as models tested in the wind-tunnel experience sustained exposure to supersonic flow, whereas the flow conditions are changing rapidly for the PEPP test parachutes in free flight. For all PEPP ringsail tests, no high-frequency changes in parachute frontal area or shape were noted such as would be expected with shock-wave fluctuations. Therefore, shock-wave effects are not believed to have been a significant cause of the failure of the test parachute to inflate properly.

The following critical design parameters governing the capability of a parachute canopy to open or inflate are given in reference 6:

(a) Total porosity or permeability of the canopy

(b) Distribution of canopy porosity

(c) Shape of the canopy mouth opening during inflation

It is also stated in reference 6 that after canopy inflation begins, it will continue until equilibrium is attained between the volume of air flowing into the canopy through its mouth and that flowing out through the geometric openings (vent, slots, sails) and the fabric pores, or until equilibrium is reached between internal pressure and structural tension. If this equilibrium condition is reached at some intermediate step of inflation, then a "critical" condition exists and full inflation does not occur. Generally, the parachute will open subsequently if the velocity is reduced. Therefore, the term "critical opening velocity" is used to define the velocity at which a squidding canopy develops normal inflation. It is also noted in reference 6 that geometrically porous canopies of the ribbon family (ringslot design included) are sensitive to variations in total porosity since the total porosity required for stability is close to the critical limit for inflation.

A comparison of the 40-foot-diameter (12.2 meters) ringsail parachute with the 31.2-foot-diameter (9.5 meters) ringsail parachute used in an earlier test revealed the following differences:

(a) The geometric crown porosity of the 40-foot-diameter (12.2 meters) parachute was greater than that of the previously tested 31.2-foot-diameter (9.5 meters) parachute (ref. 2) which opened properly. It is to be noted that by general design procedure the percentage of porosity in the crown area of the canopy is decreased as the size of the parachute is increased; however, the crown porosity of the 31.2-foot-diameter (9.5 meters) parachute was less than standard for ringsail design. Also, it is known that not all previously used ringsail parachutes of large size have had low crown porosity. Low-porosity cloth has been used in some instances to improve canopy inflation. Alternatively, in some instances the crown porosity has been increased to slow down the canopy inflation process and thereby reduce the parachute opening shock or maximum opening load.

(b) The entire canopy including the crown area (with the exception of the first ring) was fabricated of material having a nominal permeability several times that of the parachute cloth used in the previously tested 31.2-foot-diameter (9.5 meters) parachute, as given in the following tabulation:

Test parachute	Nominal permeability
40-ft-diam ringsail (12.2 m)	700 $ft^3/ft^2/min$ at 1/2 inch H_2O Δp ($214\ m^3/m^2/min$ at 1.27 cm H_2O Δp)
31.2-ft-diam ringsail (9.5 m)	162 $ft^3/ft^2/min$ at 1/2 inch H_2O Δp ($49.5\ m^3/m^2/min$ at 1.27 cm H_2O Δp)

It is known that the permeability or effective porosity of cloth decreases as atmospheric density decreases. Reference 7 provides data on the variation of the effective porosity of several standard nylon parachute materials as a function of atmospheric density and differential pressure across the cloth. Unfortunately, data are not available for materials similar to the high-porosity material used in the 40-foot-diameter (12.2 meters) test parachute. However, it may be possible that even with the decrease in effective porosity, the permeability of the 1-ounce-per-square-yard (34 grams per $meter^2$) material was too great.

It, therefore, appears that the most probable cause of the failure of the test parachute to inflate properly was excessive total porosity in the crown area of the canopy. The contributing factors were the rather high geometric open area in the crown and the high-permeability cloth used for the canopy.

CONCLUSIONS

From an analysis of the data, the following conclusions have been made concerning the flight test of the 40-foot-nominal-diameter (12.2 meters) modified ringsail parachute:

1. Mortar ejection and deployment to suspension line stretch were normal for this test.

2. The test parachute attained a maximum frontal area of about 20 percent of that expected for a fully opened parachute.

3. There was no indication of any damage or mechanical restraint which would have prevented proper inflation of the parachute canopy immediately after deployment.

4. The spinning payload caused twisting of the suspension lines which hampered further inflation at a later time even though a wide range of velocity and dynamic pressure was experienced.

5. The most probable cause of the failure of the parachute canopy to inflate fully was that the total porosity (geometric open area and cloth permeability) was greater than that allowable for the crown area of the canopy.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 17, 1967,
709-08-00-01-23.

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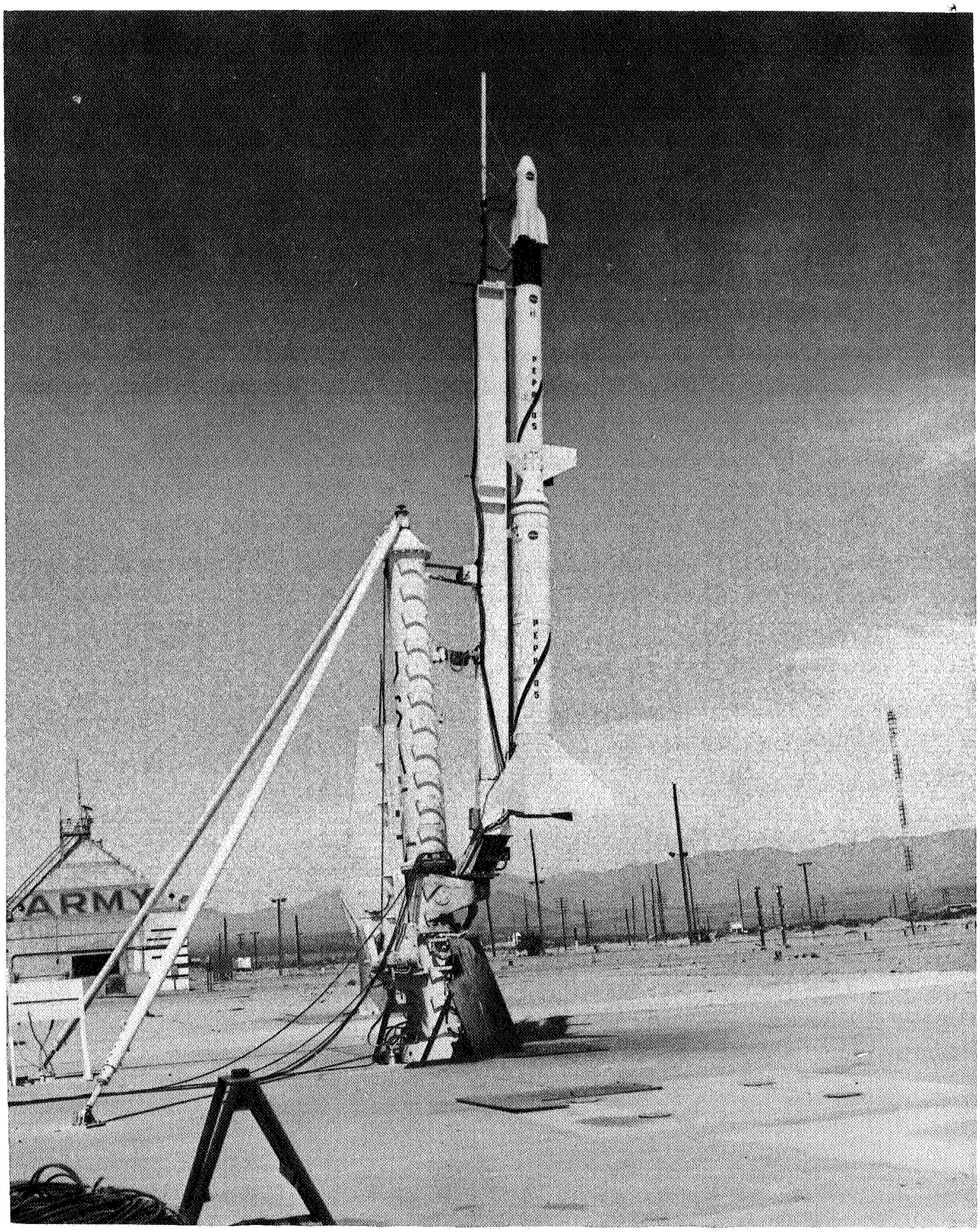


Figure 1.- Vehicle configuration. U.S. Army photograph. L-67-6624

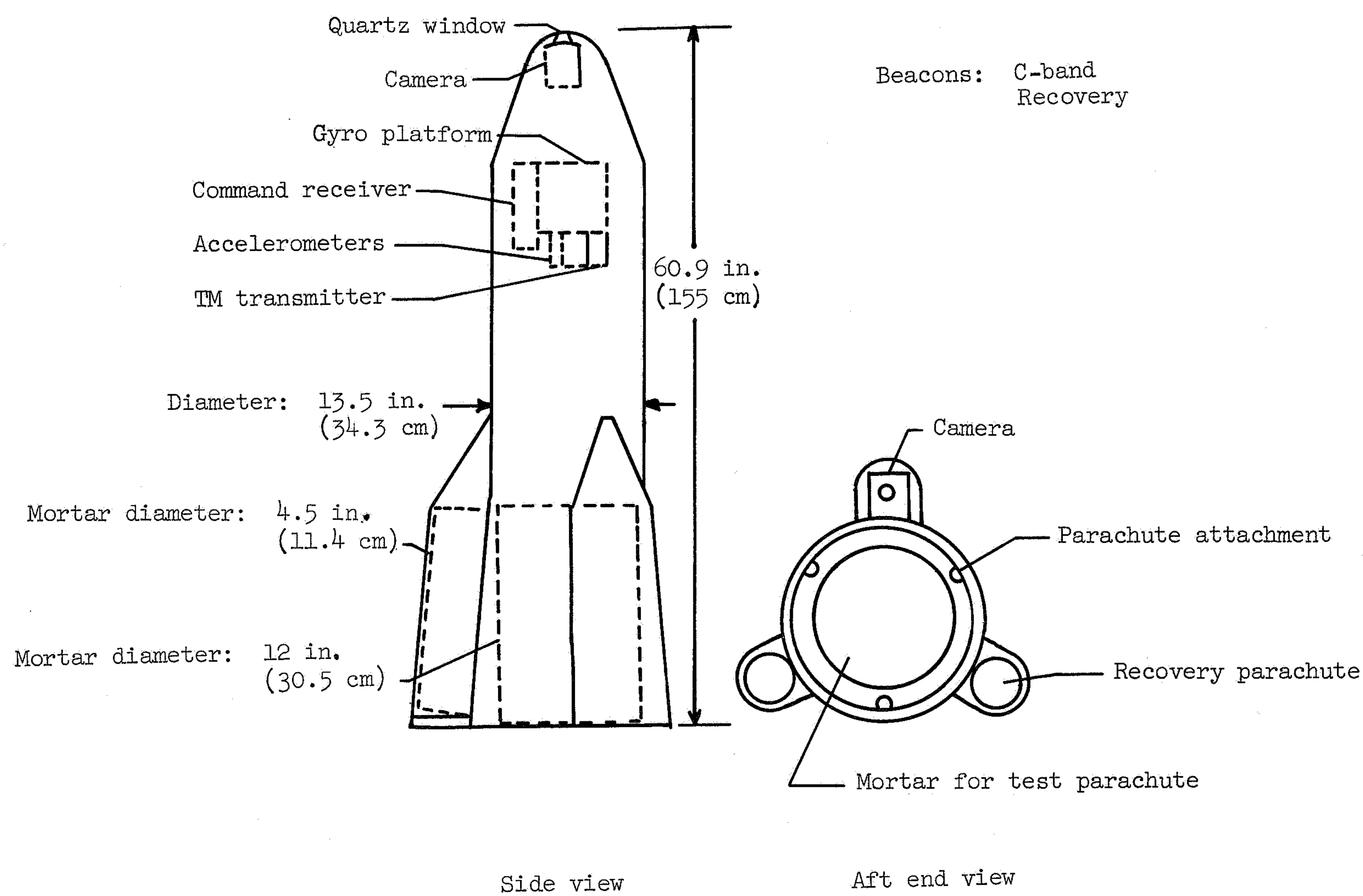


Figure 2.- Test payload.

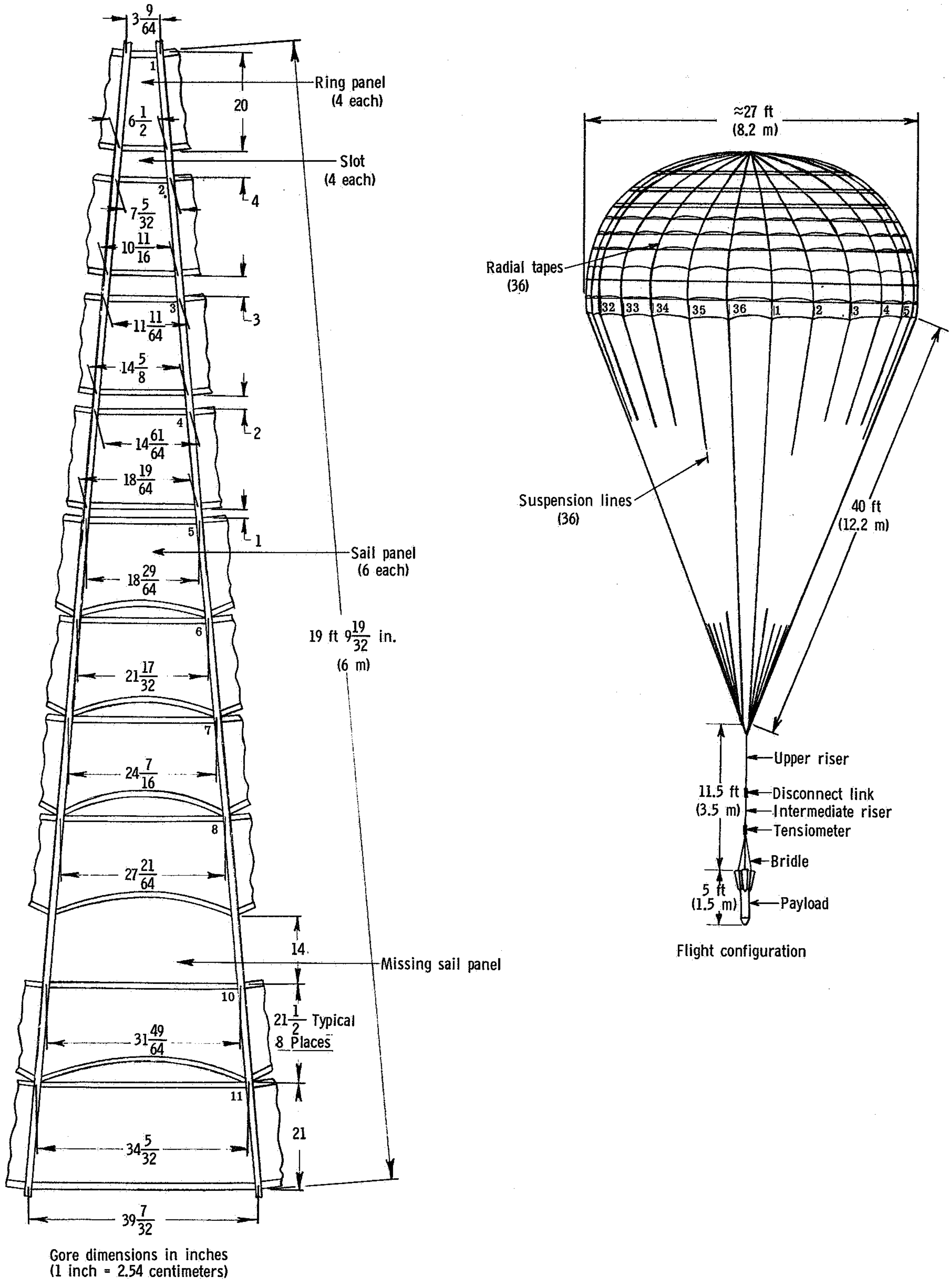
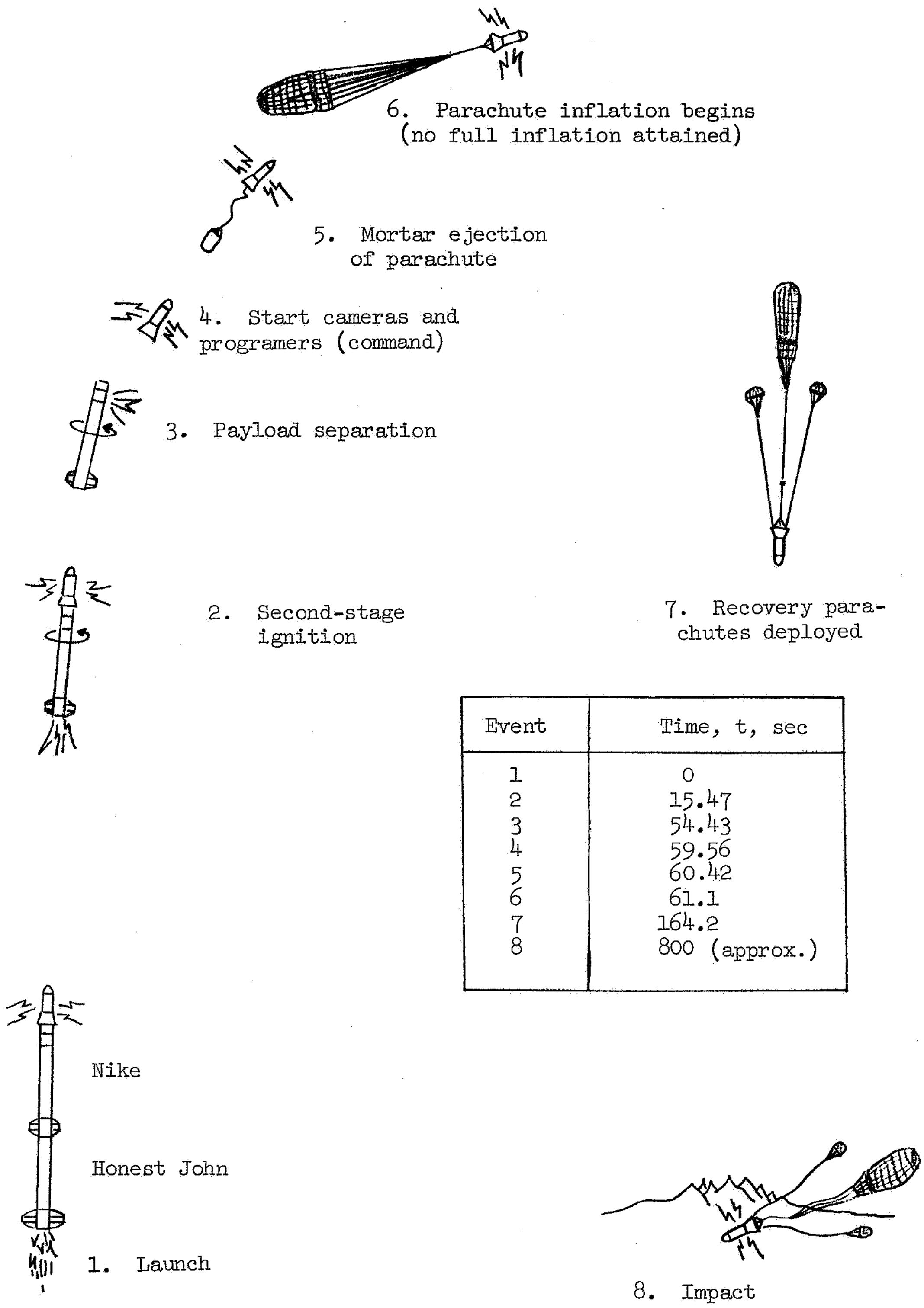


Figure 3.- Ringsail-parachute configuration.



Event	Time, t, sec
1	0
2	15.47
3	54.43
4	59.56
5	60.42
6	61.1
7	164.2
8	800 (approx.)

Figure 4.- Flight sequence of events.

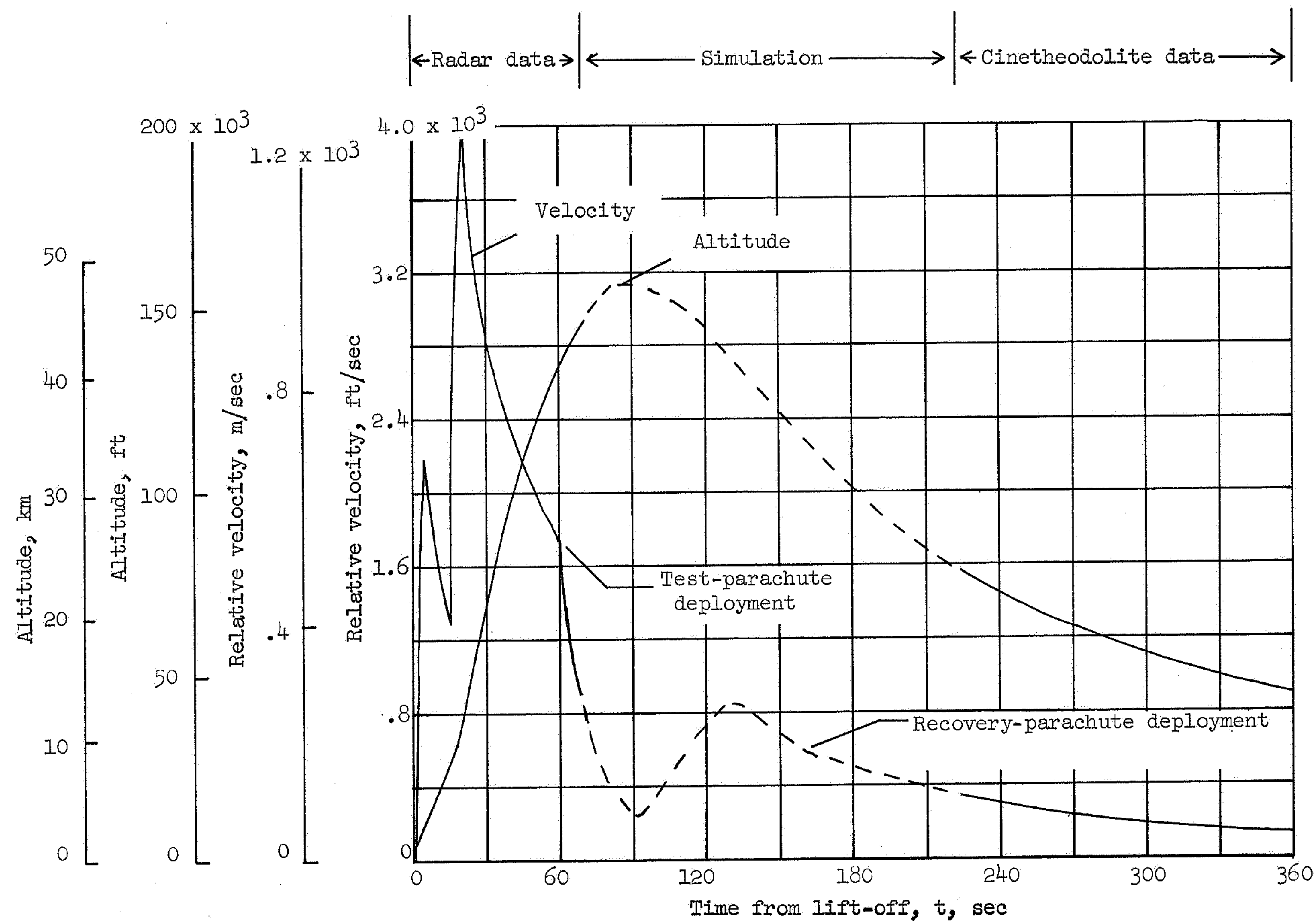


Figure 5.- Time histories of altitude and relative velocity.

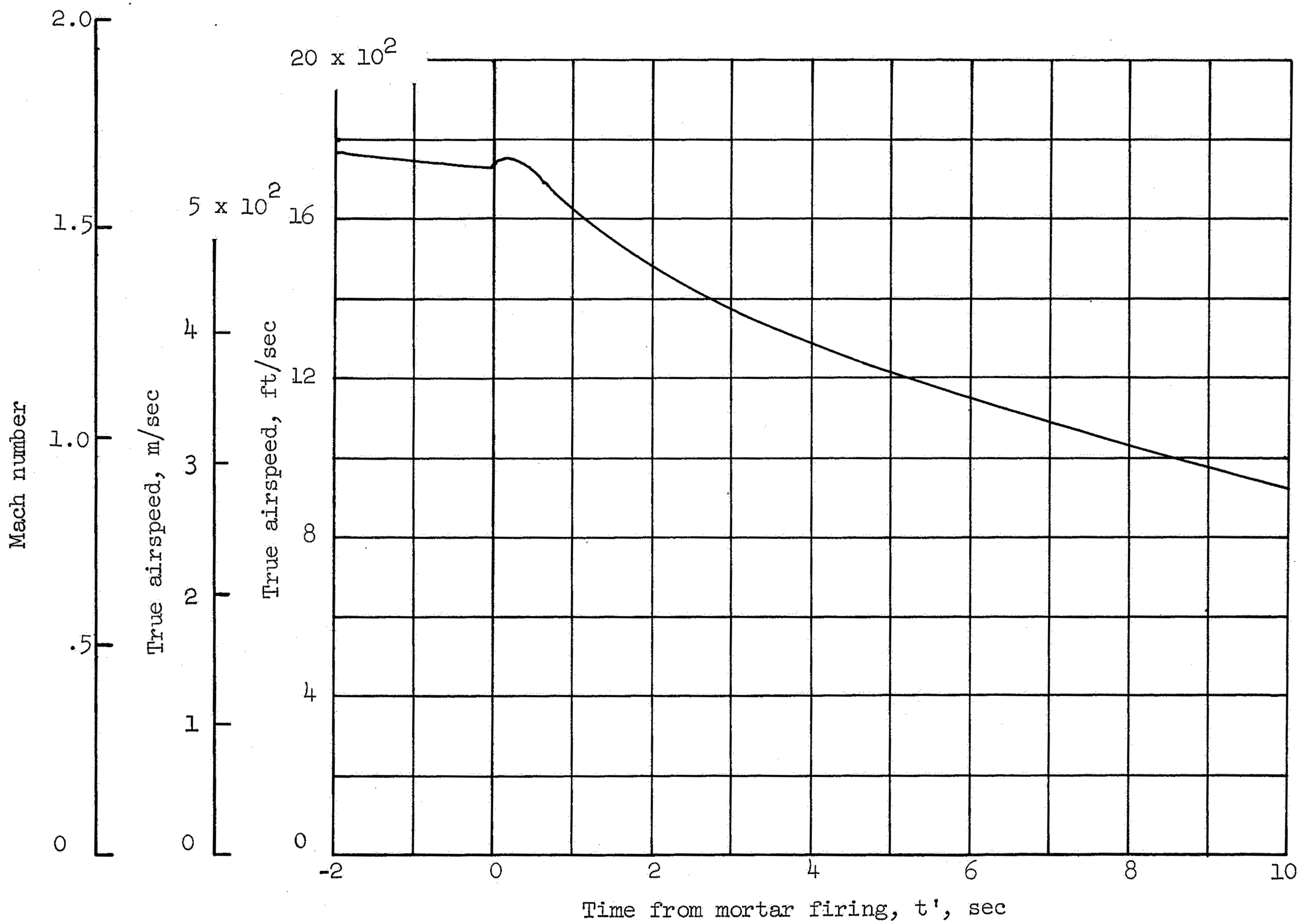


Figure 6.- Time history of Mach number and true airspeed.

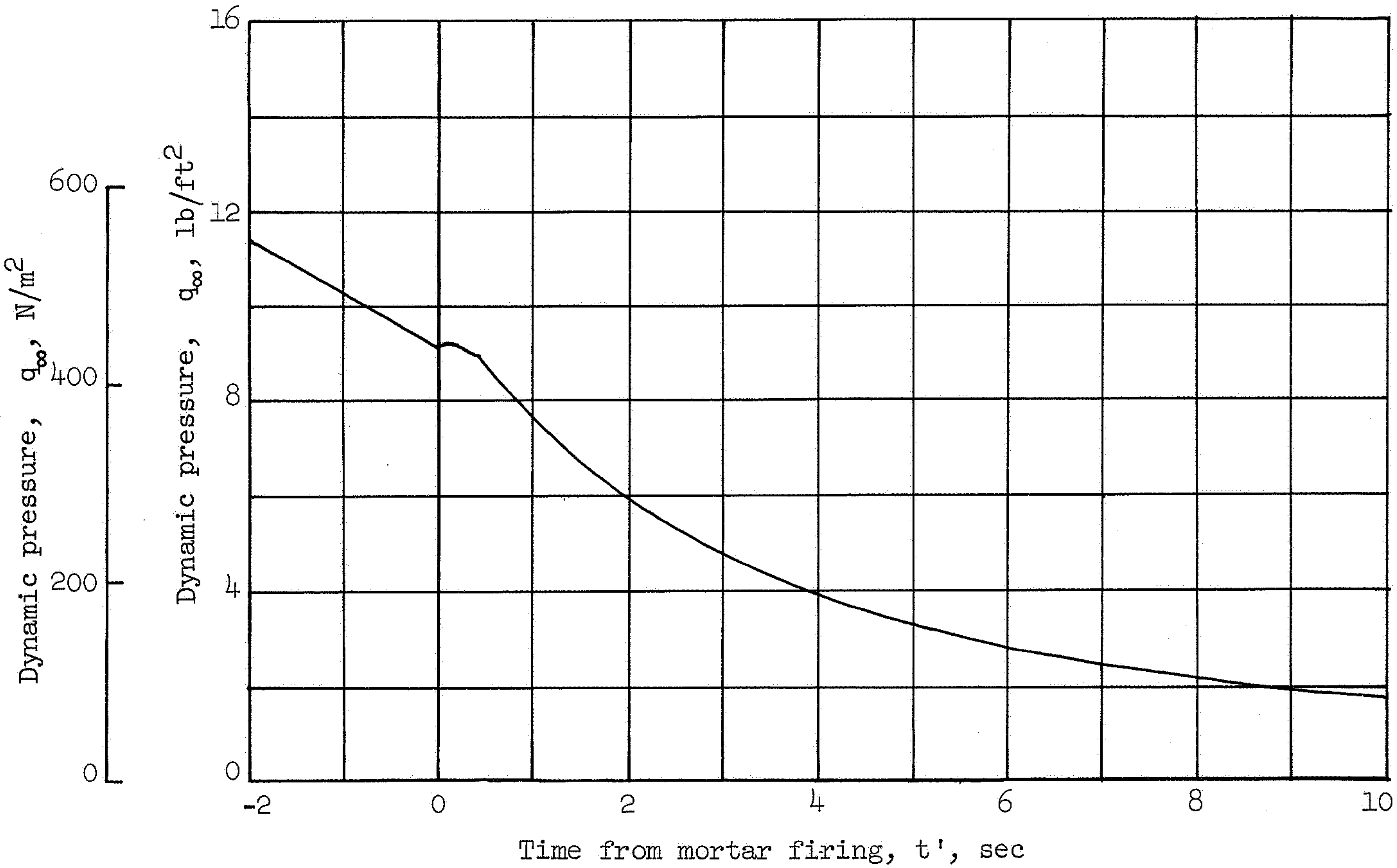


Figure 7.- Time history of dynamic pressure.

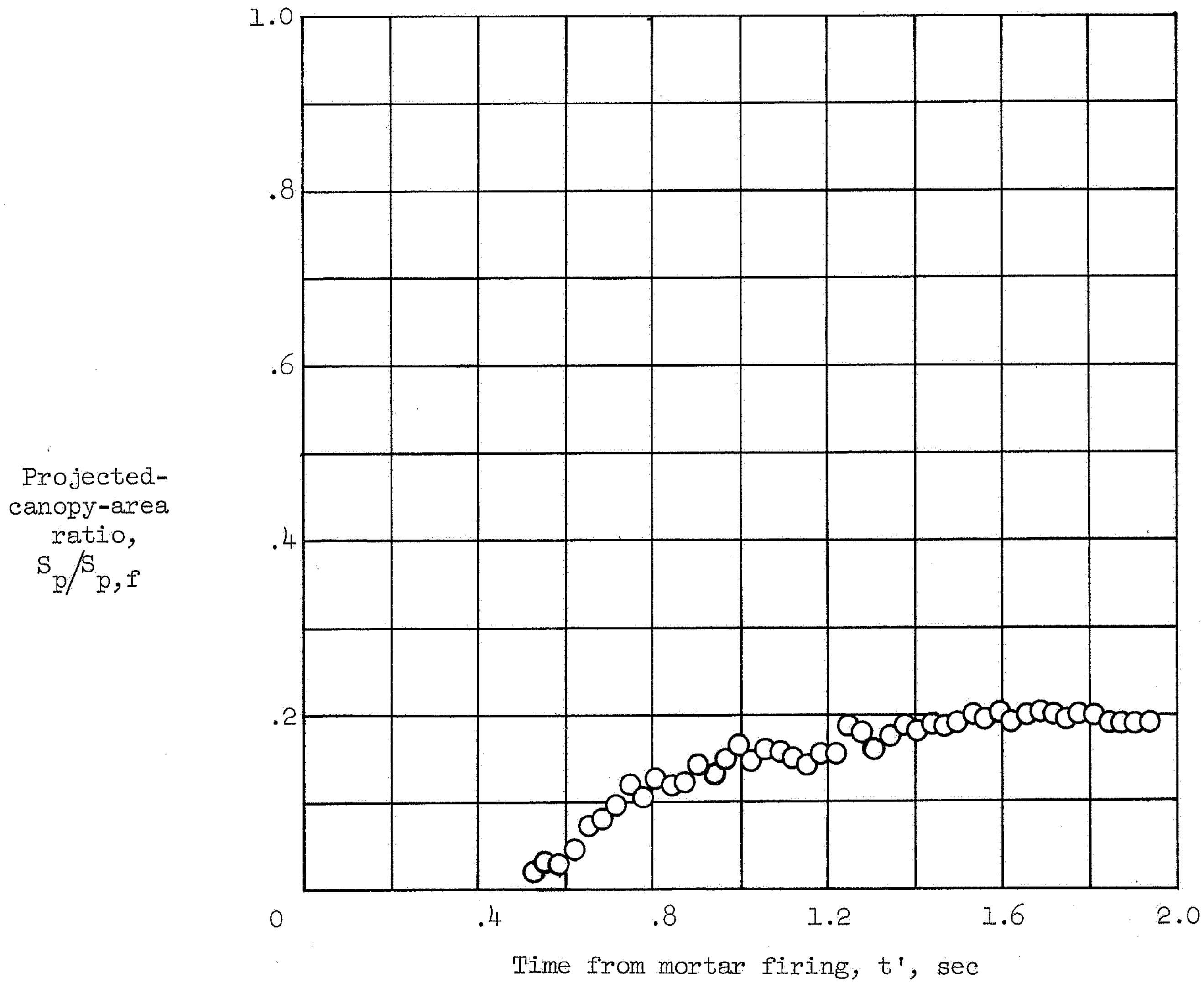


Figure 8.- Variation of parachute projected area ratio with time during inflation (based on aft camera film).

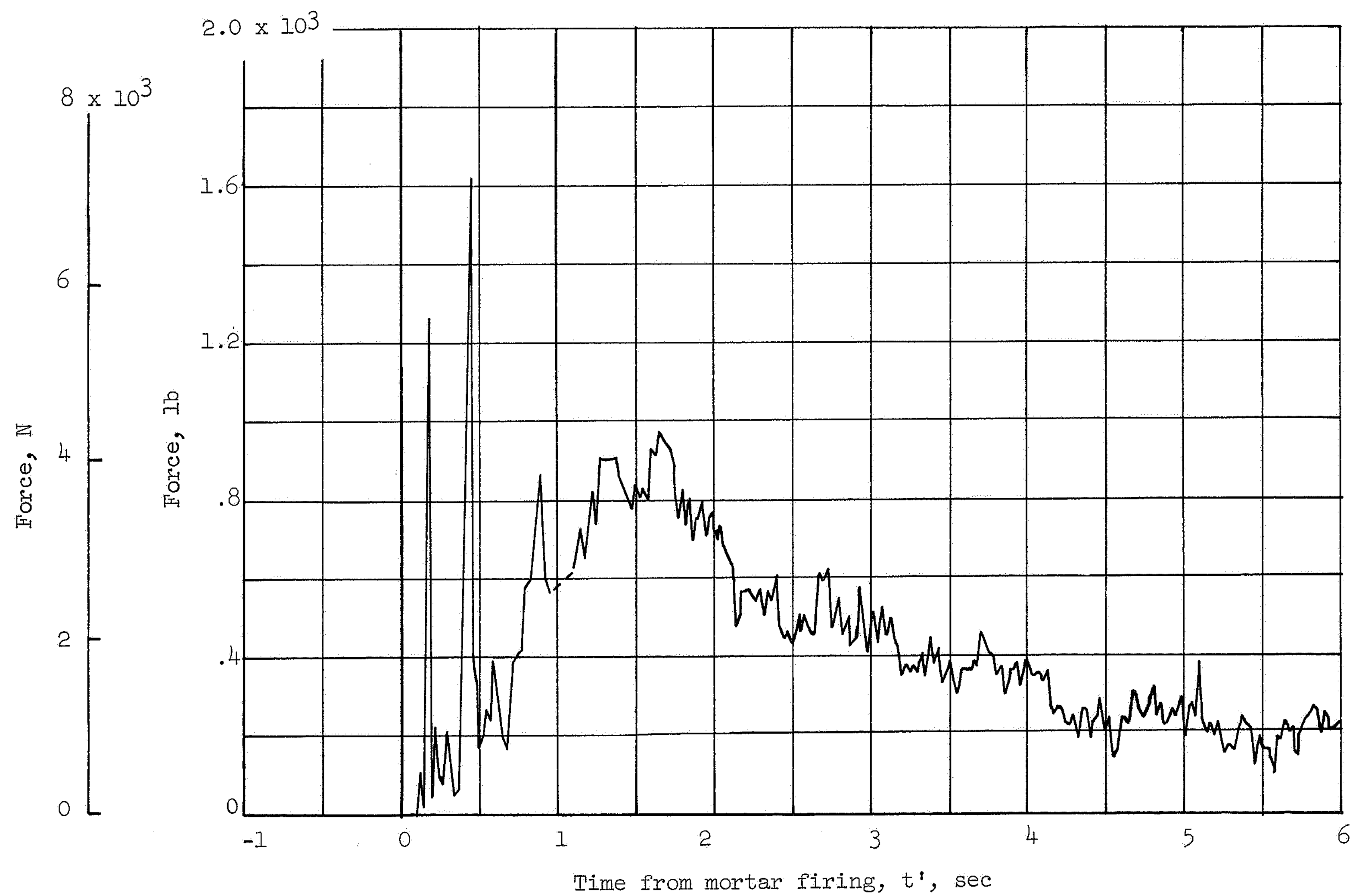


Figure 9.- Time history of force measured by tensiometer.

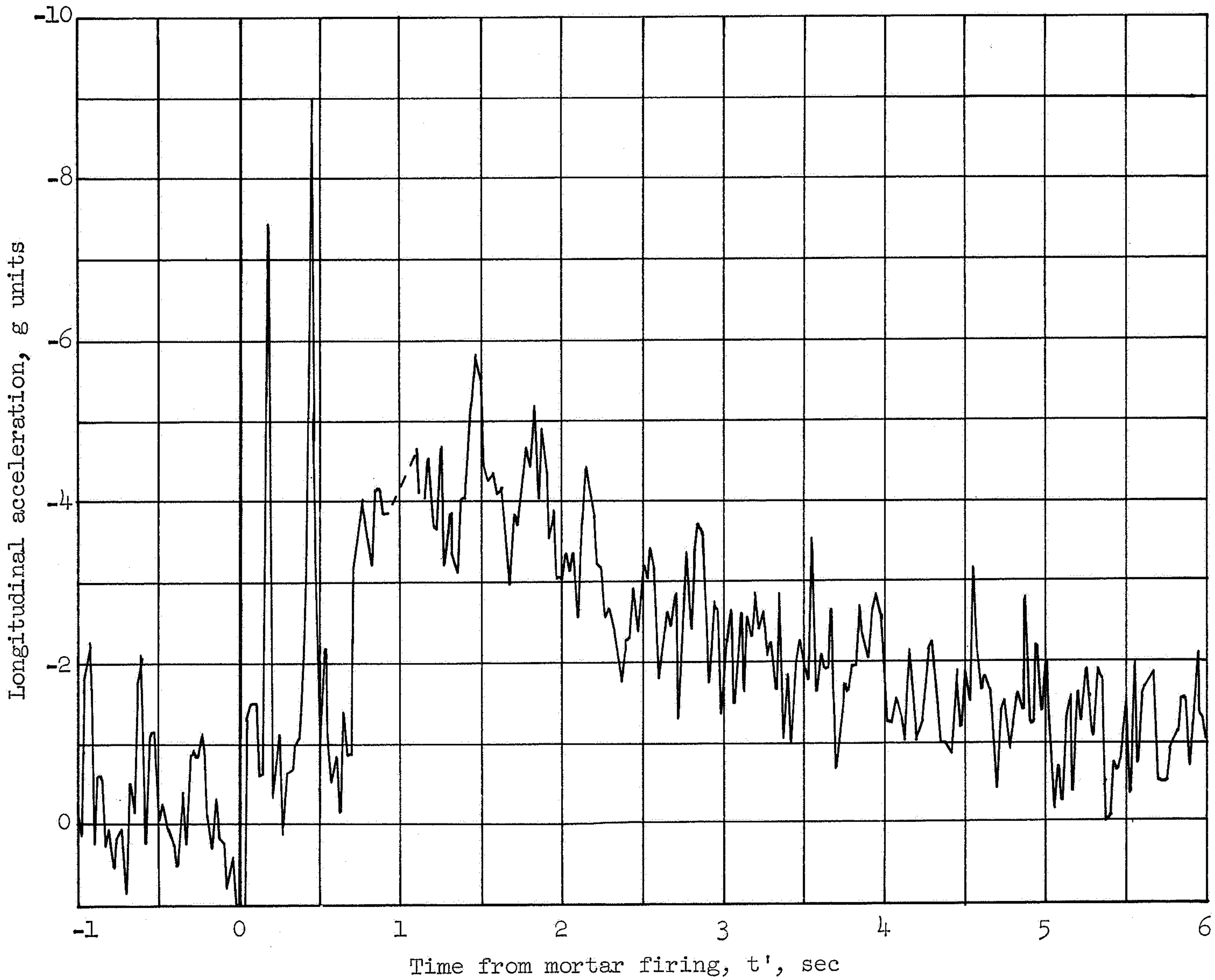
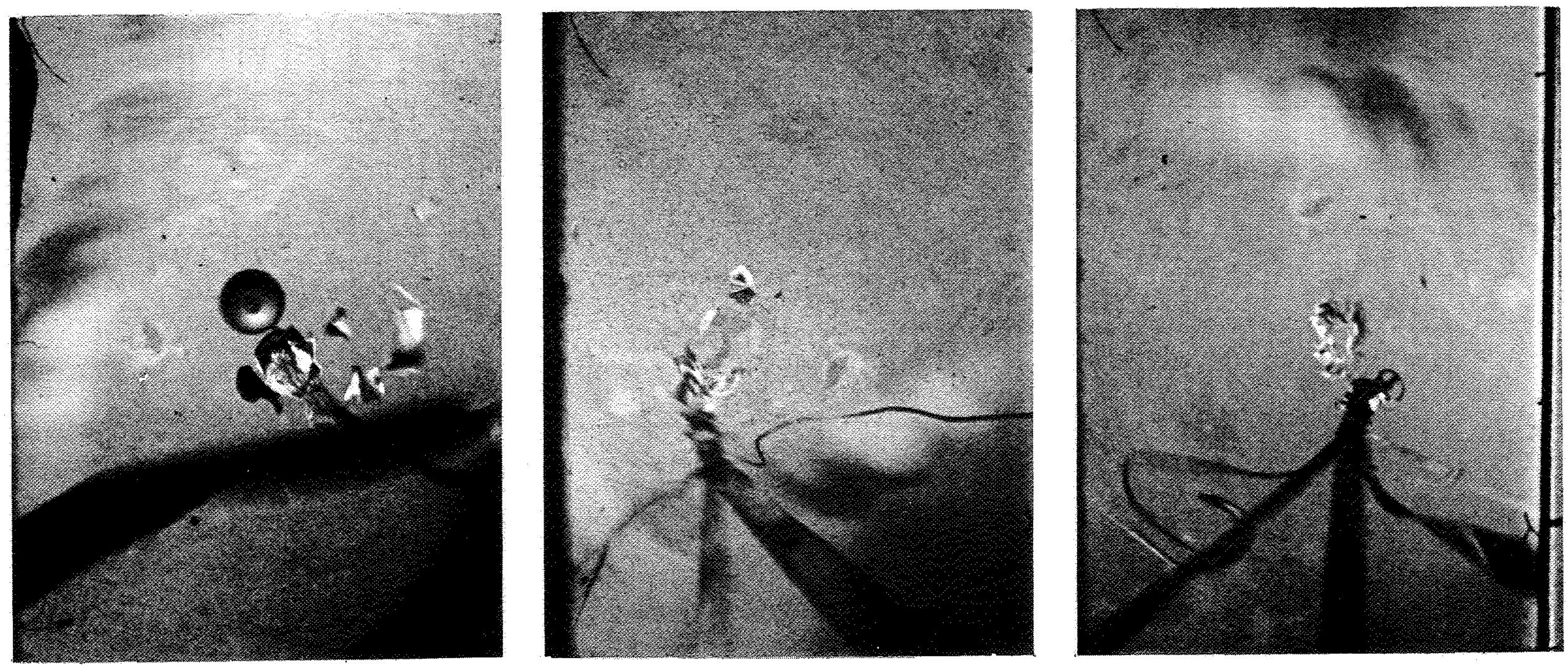


Figure 10.- Time history of acceleration during deployment.



t' = 0.125 sec   t' = 0.45 sec   t' = 0.60 sec

(a) Deployment.

L-67-8714

Figure 11.- Onboard camera photographs of parachute performance during deployment and inflation sequence.

t' = 0.75 sec

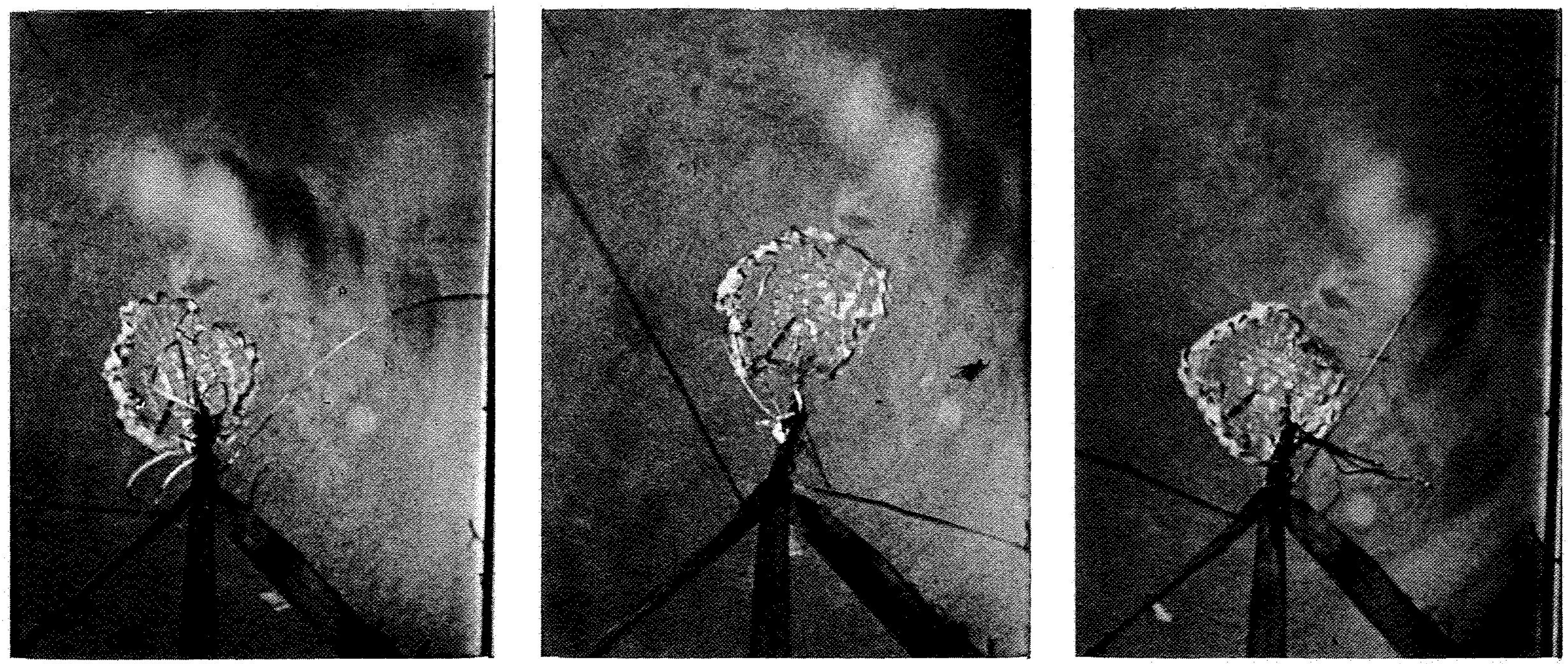
t' = 1.00 sec

t' = 1.25 sec

L-67-8715

(b) Partial inflation.

Figure 11.- Continued.

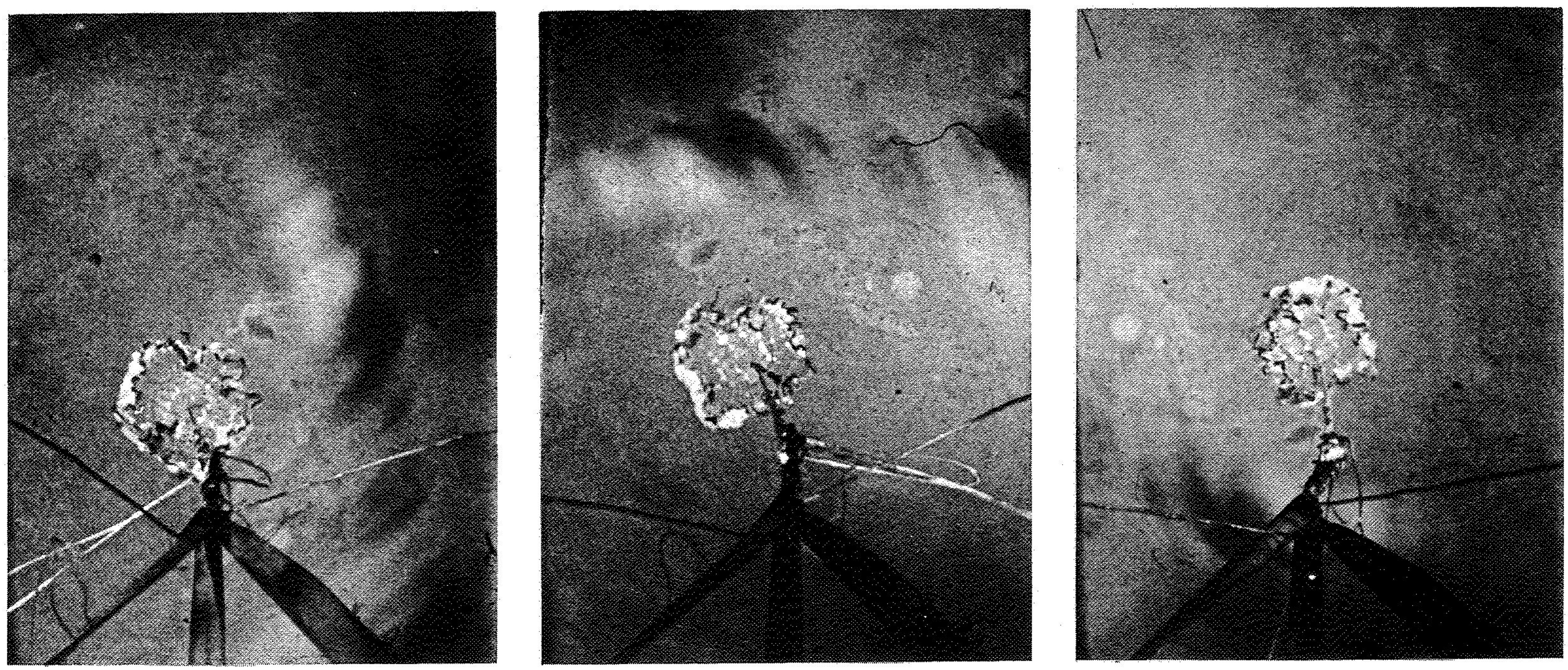


$t' = 1.50$ sec $t' = 1.75$ sec $t' = 2.00$ sec

L-67-8716

(b) Continued.

Figure 11.- Continued.

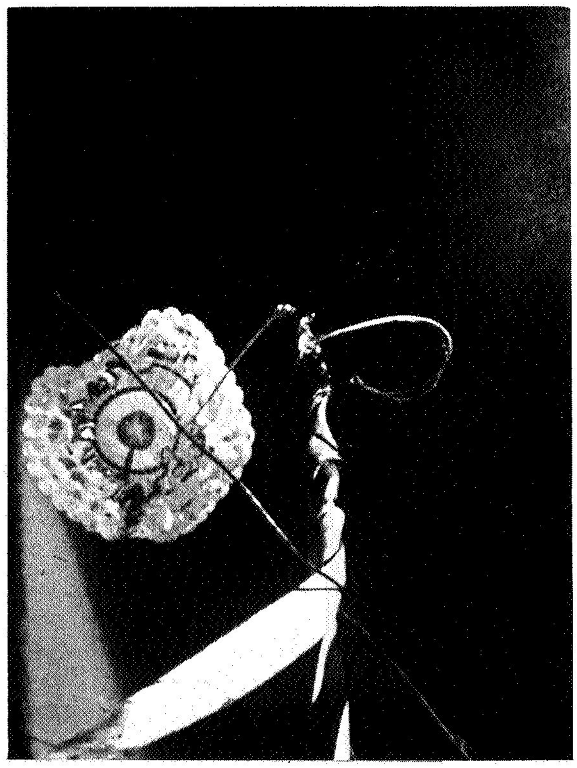


t' = 3.00 sec   t' = 4.00 sec   t' = 5.00 sec

L-67-8717

(b) Concluded.

Figure 11.- Continued.



t' = 35.00 sec

(c) Parachute at apogee. L-67-8718

Figure 11.- Concluded.

NASA-Langley, 1967 —— 31 L-5878

A motion-picture film supplement L-981 is available on loan. Requests will be filled in the order received. You will be notified of the approximate date scheduled.

The film (16 mm, 4 min, color, silent) shows the parachute deployment and the subsequent failure of the parachute to inflate properly. Deployment of the two emergency conical ribbon recovery parachutes is also shown just prior to the end of the film. The film, which was obtained from a camera pointed aft from the payload, was taken at a speed of 32 frames per second.

Requests for the film should be addressed to:

Chief, Photographic Division
NASA Langley Research Center
Langley Station
Hampton, Va. 23365

CUT

Date ____________

Please send, on loan, copy of film supplement L-981 to TM X-1484

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Name of organization

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Street number

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City and State Zip code

Attention: Mr. ______________________

Title ______________________