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LOW-SPEED DYNAMIC-MODEL INVESTIGATION OF APOLLO COMMAND MODULE CONFIGURATIONS IN THE LANGLEY SPIN TUNNEL

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SUMMARY

An investigation has been conducted in the Langley spin tunnel to determine the dynamic stability of the Apollo command module at low subsonic speeds, both with and without drogue parachutes. The investigation consisted of tests to determine (1) the dynamic stability of the command module alone, (2) the motion of the command module during the deployment of a drogue parachute, (3) the effect of various drogue-parachute configurations on the stability of the command module, and (4) the effect of modifications to the command module to prevent an apex-forward trim condition.

The results of the investigation indicated that the command module with blunt end forward was dynamically unstable and could go through rather violent gyrations such as large oscillations, tumbling, and spinning motions if the reaction controls should fail. The command module alone with the apex end forward was dynamically stable and would trim at an angle of attack of about 40° and glide steeply in large circles. Deployment of a drogue parachute would quickly stop any tumbling motions of the command module, and the damping of the residual motions was considerably more rapid if the parachute were attached to the command module by means of a 4-point bridle-type attachment than if it were attached by a 1-point attachment. The motions of the command module with the drogue parachute deployed and attached by means of the design 1-point attachment system frequently consisted of large-amplitude oscillations and of rapid rotation about the symmetrical axis. The use of a properly designed 3-point or 4-point bridle-type attachment, however, would result in much more satisfactory stability. A drogue parachute size of about 14 to 15 feet (4.3 to 4.6 meters) diameter (based on a drag coefficient of 0.55) seemed to be optimum. An apex-forward trim condition on launch abort could be prevented by having the launch escape system attached to the command module and fitting the launch escape system with canard surfaces or with a parachute to cause the configuration to rotate 180° to a blunt-end-forward condition without tumbling.

INTRODUCTION

At the request of the NASA Manned Spacecraft Center and, as part of a continuing interest in the dynamic stability of vehicles in vertical descent, an investigation utilizing dynamically scaled models has been conducted in the Langley spin tunnel to determine the dynamic stability characteristics of the Apollo command module at low subsonic speeds, both with and without drogue parachutes. Results of similar investigations in the Langley spin tunnel of models of Mercury and Gemini spacecraft are presented in references 1 and 2, respectively.

At the time of the present investigation, it was intended that two drogue parachutes be used as a retardation and stabilization device for the Apollo command module after entry. Although both parachutes would be deployed simultaneously, primarily for reliability purposes, one parachute was actually intended to be adequate, and the other was considered as a backup system. Prior to the deployment of the drogue parachutes, the command module would be stabilized by a reaction control system; and, because of the center of gravity of the vehicle being offset from the axis of symmetry, the command module would have a glide capability. When the reaction control system is shut off, the parachutes would be deployed (at an altitude of about 25 000 feet (7625 meters) and at a Mach number of about 0.5) and would remain attached to the vehicle until the main parachutes were deployed at an altitude of about 12 000 feet (3660 meters). Thus, a drogue-parachute configuration would be needed that would provide proper stability for the spacecraft during a portion of the entry.

The present investigation consisted of tests to determine: (1) the dynamic stability of the command module alone; (2) the motion of the command module during the deployment of a drogue parachute, and (3) the effect of various drogue-parachute configurations on the stability of the command module. Brief tests also were performed to investigate methods of preventing an apex-forward trim condition of either the command module or the launch escape system. These tests included the use of strakes, fins, and a drogue parachute.

SYMBOLS

The body system of axes as used on the Apollo command module are shown in figure 1. The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating the two systems are given in reference 3.

A projected area of command module based on maximum diameter, $\pi d^2/4$, ft^2 (m^2)

d	command module maximum diameter, ft (m)
g	acceleration due to gravity, 32.17 ft/sec^2 (9.80 m/sec^2)
I_X, I_Y, I_Z	moments of inertia about X, Y, and Z body axes, respectively, slug-ft^2 (kg-m^2)
m	mass, slugs (kg)
R	radius, in. (cm)
W	weight, lb (kg)
X,Y,Z	body axes
x_c	distance along X body axis measured from command module station 0 (see fig. 2), in. (cm)
y_c	distance along Y body axis measured from XZ plane, in. (cm)
z_c	distance along Z body axis measured from axis of symmetry, in. (cm)
x_{cg}	distance of center of gravity along X body axis measured from command module station 0, in. (cm)
y_{cg}	distance of center of gravity along Y body axis measured from XZ plane, in. (cm)
z_{cg}	distance of center of gravity along Z body axis measured from axis of symmetry, in. (cm)
x_1	distance along X body axis of launch escape system measured from launch escape system station 0, in. (cm)
α	angle of attack of command module (see fig. 3), deg
θ	pitch angle of symmetrical axis of command module with respect to vertical ($\theta = 0^{\circ}$ when blunt end of command module is downward), deg

μ relative density, $m/\rho Ad$

ρ air density, slugs/ft^3 (kg/m^3)

FULL-SCALE RECOVERY SYSTEM

A sketch of the full-scale design drogue parachute system is shown in figure 4. This system consists of two ribbon parachutes 13.7 feet (4.2 meters) in diameter permanently reefed to a diameter of 8.5 feet (2.6 meters). It is intended that either of the two drogues be capable of retarding and stabilizing the command module satisfactorily; thus, one of the drogues is actually a backup system. However, both drogues are to be deployed at the same time because of considerations of reliability and also to take advantage of the added drag and stabilizing force of the two drogues if both drogues deploy. The two drogues are attached to the spacecraft at a single point – in an offset location just above the main parachute deck. The center of gravity is offset from the symmetrical axis on the opposite side from the attachment point. This combination of offset center of gravity and offset attachment point results in a 25° tilt of the spacecraft.

MODELS

SPACECRAFT

A drawing of the full-scale Apollo command module which hereafter, unless otherwise noted, will be referred to as the spacecraft, is presented in figure 2 and shows the dimensional characteristics of the earth-launch and entry configurations of the spacecraft. The earth-launch configuration is considered to be the spacecraft with the apex cover of the forward heat shield on, and the entry configuration is considered to be the spacecraft with the apex cover off. The apex cover must be off in order that the drogue parachute may be deployed. A photograph of one of the models of the spacecraft in the entry configuration is presented in figure 5, and a photograph of this spacecraft model with a drogue parachute undergoing tests in the Langley spin tunnel is shown in figure 6. The models tested were 1/11.54- and 1/28-scale dynamic models of the entry configuration ballasted for simulated test altitudes of both sea level and 15 000 feet (4575 meters), and a 1/28-scale dynamic model of the earth launch configuration ballasted for a simulated test altitude of sea level. From practical test considerations of the wind-tunnel operation it was necessary to test the models at a simulated altitude of 15 000 feet (4575 meters) rather than the desired altitude of 25 000 feet (7625 meters). The mass and inertial characteristics of the full-scale spacecraft and the values simulated by the various loadings of the models are presented in table I. In this table two different loadings

(loadings 1 and 2) are indicated as representing the normal entry condition. This situation resulted from the fact that during the course of testing the model, the mass characteristics of the full-scale command module changed somewhat. These mass changes did not appear to affect the results of the investigation.

DROGUE PARACHUTES

The drogue parachutes used on the models were of a stable, flat, circular design constructed of 400-porosity material. Porosity is defined as the volume of air in cubic feet that will flow through 1 square foot of cloth in 1 minute at a pressure of 1/2 inch of water. The parachutes were not actual scale models of the ribbon parachutes likely to be used on the Apollo command module, but the results are interpreted in terms of the size of the unreefed full-scale ribbon parachute required to duplicate the scaled-up drag of the model parachute. The parachutes generally were attached to a riser representing a 64-foot (19.5-meter) full-scale riser which is the length intended for use on the actual full-scale vehicle. In turn, the riser was attached to the spacecraft at a single point or by a bridle. The bridle consisted of two or more relatively short lines (about 9.6 feet or 2.9 meters long, full scale) attached to the spacecraft.

Although the full-scale design drogue parachute system utilizes two parachutes, it was decided to take a conservative approach in the conduct of the model tests; and thus most of the tests of the model were made with only a single drogue parachute to represent the condition in which only one of the two drogues deployed successfully.

MODIFIED EARTH-LAUNCH CONFIGURATIONS

The earth-launch configuration was tested with various modifications intended to prevent the occurrence of an apex-forward trim condition. The modifications were as follows:

(1) strakes (fig. 7)

(2) basic launch escape system (fig. 8)

(3) launch escape system with canard surfaces added (figs. 9 and 10(a))

(4) launch escape system with drogue parachute added (fig. 10(b))

(5) launch escape system tower with a special fin added (fig. 11)

TESTS

The tests were conducted in the Langley spin tunnel which is an atmospheric wind tunnel with a vertically rising airstream in the test section and a maximum airspeed of approximately 90 ft/sec (27.4 m/sec). A more detailed description of the tunnel is presented in reference 4.

SPACECRAFT ALONE

Tests were made of the spacecraft without a drogue parachute to determine the stability of the spacecraft alone and to determine means of preventing an apex-forward trim condition. All these tests were made on the 1/28-scale model in the earth-launch configuration (that is, with the apex cover on) and with the model ballasted for a simulated test altitude of sea level. Tests were made with the spacecraft model alone launched in both the blunt-end-forward and apex-forward conditions. The method of testing the model alone was to launch the model in both an apex-forward and blunt-end-forward condition with as little disturbance as possible to determine the ensuing motions and trim attitudes.

Tests were also made with the various modifications previously described under the section "Modified Earth-Launch Configurations" added to the basic spacecraft model to determine means of insuring that the spacecraft not have an apex-forward trim point, but that it turn to a blunt-end-forward trim condition regardless of the launch attitude. The technique of testing the model equipped with strakes (earth-launch configuration) was to launch it with the apex forward ($\alpha = 0^{\circ}$) and also to launch it at about $\alpha = 40^{\circ}$ with the center of gravity on the windward side, which was approximately the trim attitude under dynamic conditions. When the model was equipped with the tower or with the launch escape system, it was launched with the apex forward and was also launched at about $\alpha = 5^{\circ}$ with the center of gravity on the windward side.

SPACECRAFT DURING DROGUE PARACHUTE DEPLOYMENT

Tests were made with the 1/28- and 1/11.54-scale models in which a drogue parachute was deployed to determine the effectiveness of deployment of the parachute in terminating initial spinning and/or tumbling motions of the spacecraft. These tests were made with a single drogue parachute representing a 14.6-foot-diameter (4.5 meter) full-scale parachute. Tests were made with the parachute riser attached to the spacecraft in the 1-point design attachment configuration and also with the riser attached to the spacecraft by a 4-point bridle attached to the periphery of the parachute deck.

For the drogue-parachute deployment tests, the model was launched into various spinning and/or tumbling motions and then the drogue parachute was deployed. During the deployment study, the parachute and its various lines were folded and held against the top or apex end of the model and the parachute was released and inflated by the airstream rather than being ejected by a mortar as in the case for the full-scale vehicle. The study thus did not determine the drogue-parachute deployment characteristics, but rather determined the effects of successful deployments on the motions of the spacecraft.

SPACECRAFT WITH DROGUE PARACHUTE DEPLOYED

Tests were made to determine the stability of the spacecraft with the drogue parachute already deployed. These tests were made with the 1/11.54-scale model in the entry configuration (that is, with the apex cover removed). Most of the tests were made with the model ballasted for a simulated test altitude of sea level, but a few tests were made with the model ballasted for a simulated test altitude of 15 000 feet (4575 meters) to determine the effect of altitude on the stability of the spacecraft-parachute combination. Most of the tests were also made with a single drogue parachute to represent the critical condition in which only one parachute had deployed successfully, but a few tests were made with both parachutes deployed to provide a comparison of the single and dual parachute configurations.

The object of most of these tests with the parachute already deployed was to determine the effect on the stability of the spacecraft of various parachute attachment configurations intended to improve the stability. Specifically, modifications of parachute attachment configurations were made to hold the spacecraft at several widely spaced points to provide better resistance to oscillations and to hold the spacecraft more level to prevent rotation. The modified configurations consisted of four basic attachment configurations which had 1-point, 2-point, 3-point, and 4-point attachments. Also, three basic locations of the parachute riser were tested and consisted of positioning the riser over the symmetrical axis of the spacecraft, over the center of gravity of the spacecraft, and over a point outboard of the center of gravity such that the spacecraft would tend to remain level when in free fall. Unless otherwise noted, a swivel was used at the juncture of the riser and bridle to insure that the results were not altered by the twisting of the multiple lines of the bridle. Some typical attachment configurations are shown in figure 12. Altogether 59 different parachute attachment configurations were tested.

In some tests in this part of the investigation, the center of gravity of the entry configuration was varied from the normal position (indicated in fig. 2) in both the vertical and horizontal directions.

The method of testing the model with the drogue-parachute predeployed was to hold the parachute erect in the tunnel until it became inflated and supported the model, and then to push the model toward the center of the tunnel. The model was sometimes launched with as little disturbance as possible to determine the motions of the model that were self-excited. At other times, the model with predeployed drogue parachute was launched with a spinning motion about the symmetrical axis to determine the effectiveness of the drogue parachute in terminating this motion. There were two reasons for launching the models with the parachute predeployed and with rotation. One reason was that without prerotation the model glided and wandered in the tunnel and, in many cases, struck the tunnel net, and thus made it difficult to allow sufficient time for any tendency of the model to rotate to manifest itself. The second reason was that the model sometimes had two spinning modes, one with a low rate of rotation and the other with a high rate of rotation. In such a case, the model may only reach low rates of rotation from self-excitation, but when a large rotary input is applied to the model, it may continue to rotate rapidly even after the prerotation effects have disappeared.

REDUCTION OF DATA

Visual observations and motion pictures were made of the behavior of the spacecraft in its various configurations. Typical motions of the spacecraft (rates of rotation and amplitude of oscillations) were determined by measuring these quantities as recorded on the motion-picture film. The amplitudes of the oscillations of the spacecraft were measured only when the oscillations were in approximately the same plane as the projected picture. Thus, since the spacecraft generally rotated, it was not possible to get continuous measurements of the oscillation angles to present a continuous time history. The procedure that was followed in reducing the data for the case of the spacecraft with the drogue parachute predeployed was to read the amplitude of the oscillation whenever possible, and to present values of maximum amplitude encountered and an average amplitude. Oscillations of the spacecraft normally varied during the same test run. For example, during a typical run, a series of both small and large oscillations were encountered. When this situation occurred, the average amplitude presented herein was the average of the series of the large oscillation angles. The decision to present an average only of the large oscillation angles was based on the assumption that the series of large oscillations are more critical and thus more important than the lower oscillation values when considering their effect on the design of the spacecraft.

Similarly, in determining the rate of rotation of the spacecraft with the drogue parachute predeployed, only the maximum values are presented since these values are considered to be the most important ones. These values should not be considered as exact but rather as being indicative of the rotary motions.

During the deployment of the drogue parachute the pitch angles of the spacecraft during a tumbling condition were measured from the time the drogue parachute was deployed until the oscillation angles had reduced considerably and became almost constant.

Continuous measurements of the angles were possible since they were approximately in the same plane as the motion picture.

The oscillation angles presented in the tables are considered to be measured within $\pm 1^{\circ}$. The accuracy of measuring the weight and mass distribution of the dynamic models shown in table I is believed to be within the following limits:

Weight, percent	±1
Center-of-gravity location, x_{cg} and z_{cg}, percent	±1
Moments of inertia, percent	±5

RESULTS AND DISCUSSION

A motion-picture film supplement showing some typical results of the tests has been prepared and is available on loan. A request card form and a description of the film will be found at the end of the paper.

In the discussion of results, all dimensions shown are in terms of full-scale values. The dimensions of the parachute are given on the basis of an assumed drag coefficient of 0.55 based on the laid-out-flat diameter. This value of drag coefficient was used because it is a representative value for a ribbon parachute which is the type proposed for the Apollo spacecraft. If parachutes with a drag coefficient of other than 0.55 are used (such as a reefed ribbon parachute), an adjustment in the diameter of the parachute should be made such that the product of the area and drag coefficient of the parachute is unchanged.

Unless otherwise noted, rotation of spacecraft is about its symmetrical axis.

SPACECRAFT ALONE

Results of Dynamic Tests

The test results for the spacecraft alone in the earth-launch configuration (table I, loading 1) indicated, in general, that the spacecraft alone with blunt end forward was dynamically unstable. In various cases, the spacecraft glided, oscillated, tumbled, or entered spinning motions about its symmetrical axis, although tumbling was the most common type of motion. If the spacecraft was launched gently with the blunt end forward, it would glide because of the offset center of gravity and would simultaneously start to oscillate between angles of attack of approximately 0° and 45°, while descending at about 160 ft/sec or 48.7 m/sec (sea level rate). In some instances, the oscillations would increase until the spacecraft tumbled. These results would seem to indicate that the spacecraft had a statically stable trim point at an angle of attack of about 23° but was dynamically unstable.

When the spacecraft was launched gently into the vertical airstream with the apex forward, it would trim at an angle of attack of about 40° and would glide in large circles while descending at about 210 ft/sec (64.0 m/sec). In this attitude, therefore, the spacecraft apparently was both statically and dynamically stable.

Analysis of Longitudinal Characteristics

In order to make a more thorough analysis as to why the various motions of the spacecraft occurred, reference was made to the results of low-speed static and oscillatory force tests of a model of an Apollo command module presented in reference 5. The reference center of gravity for these force-test data is in approximately the same location as that used in the present investigation; thus the results of reference 5 may be analyzed directly.

For the case in which the blunt base of the spacecraft was forward, the results of the static wind-tunnel tests of reference 5 indicated that it had a trim point in pitch at an angle of attack of about 28° and was statically stable longitudinally about this trim point, but that the normal-force-curve slope $\left(C_{N_{\alpha}}\right)$ was negative. The results of the forced-oscillation tests indicated that from $\alpha = 10^{\circ}$ to 40° (or $\alpha = 170^{\circ}$ to 140°, respectively, if the reference axes of ref. 5 are used), the spacecraft had no damping in pitch. This combination of characteristics would be expected to cause the spacecraft to be unstable dynamically. Thus, the results from reference 5, in general, substantiate the results obtained in the present investigation where the spacecraft was descending with the blunt base forward.

For the case in which the spacecraft was tested with apex forward, the data of reference 5 indicate that it was longitudinally stable statically and would trim at an angle of attack of about 50°. The results presented in this reference also indicated that the spacecraft had damping in pitch at angles of attack up to 40°, although the values were low. Hence, fairly good agreement was obtained between the results of the present investigation and those of reference 5.

SPACECRAFT DURING DROGUE PARACHUTE DEPLOYMENT

Typical results obtained when deploying a 14.6-foot-diameter (4.5 meter) drogue parachute in the original 1-point design attachment configuration (fig. 12(a)) for a simulated altitude of sea level are shown in figure 13(a). In this case the parachute was deployed while the spacecraft was tumbling about its Y body axis. This time history shows that, although the tumbling motion was stopped, large-amplitude oscillations would ensue and continue for some time.

When the spacecraft was launched with a combination of a tumbling motion about its Y body axis and a spinning motion about its X body axis or symmetrical axis, the deployment of the parachute was not very effective in terminating these motions quickly. No time history could be obtained for this case, but the characteristic motions are shown in the film supplement. On a few occasions, for this type of launch, the resulting final motion was a fairly fast rate of rotation approximately about the symmetrical axis (X body axis) of the spacecraft.

For a single attachment point, it appears that whether the final or residual motion is predominantly oscillatory or rotary is dependent on the attitude or motions of the spacecraft at the time the parachute becomes inflated.

In order to show the effect of parachute attachment configuration on the motion of the spacecraft during and after deployment of the parachute, the riser was changed from the 1-point attachment to a 4-point attachment; for the 4-point attachment configuration, the riser was attached to the periphery of the parachute deck with a four-line bridle such that the riser was over the center of gravity of the spacecraft as illustrated in figure 12(n). Typical results obtained when deploying the parachute are shown in figure 13(b). When the parachute was deployed while the spacecraft was tumbling, the tumbling was terminated and the ensuing oscillations damped more quickly than when the 1-point design attachment configuration for the parachute was used.

Deployment of the parachute when the spacecraft was launched with a combination of tumbling and spinning motions was effective in terminating these motions initially although some oscillation did ensue and the damping of the rotation was somewhat slow.

Thus, the deployment of a drogue parachute will quickly stop any tumbling motions of the command module, but the damping of the residual motions will be considerably more rapid if the parachute is attached to the command module with a 4-point bridle-type attachment rather than with a 1-point attachment. The difference in effectiveness of the two-drogue-parachute attachment configurations is considered to be partly due to the direct effect of the attachment in damping the initial large-amplitude motions but is also considered to be a reflection of differences in the stability of the spacecraft with the drogue parachute deployed.

SPACECRAFT STABILITY WITH DROGUE PARACHUTES DEPLOYED

Typical Results

Typical results obtained from tests performed to determine the effectiveness of various drogue parachute attachment configurations in stabilizing the Apollo command module are presented in table II. The drogue parachute configuration, unless otherwise noted, consisted of a parachute with a diameter of 14.6 feet (4.5 meters), a riser length of 64 feet (19.5 meters), and a bridle length of 9.6 feet (2.9 meters).

Prior to discussion of the results of the tests of the various attachment configurations in detail, it is desirable to make some generalizations of the results of the tests. One result was that the 3- and 4-point parachute attachment configurations were considerably more satisfactory than the 1- and 2-point attachment configurations in providing stability for the spacecraft; that is, minimizing the tendency of the spacecraft to rotate and oscillate. A 3-point bridle-line attachment of the parachute is the simplest configuration which will make it possible to take full advantage of the available restoring force of the parachute to limit the oscillations about any horizontal axis; and a 3-point attachment appears to provide as much stability to the spacecraft as a 4-point attachment. A second result was that the greater the longitudinal tilt of the spacecraft, the greater was its tendency to glide and rotate. A third result was that the spacecraft was extremely sensitive to lateral tilt (tilt about Z axis) in that as little as $1/4^{\circ}$ of lateral tilt would start the spacecraft rotating in a direction opposite to the direction of tilt. For example, tilt to the right would make the spacecraft rotate to the left, as viewed from above. Normally, the greater the lateral tilt angle the more quickly the rate of rotation would increase to its steady-state value. Since it was practically impossible to adjust the bridle lines so that the spacecraft was perfectly level laterally, the spacecraft generally would rotate slowly to the right or left when the rotation was self-excited while oscillating slightly. In many cases, after the spacecraft was prerotated, it would continue to rotate relatively rapidly for one direction of rotation, whereas it would slow down or not continue to rotate for the opposite direction of rotation. This effect, relatively fast rotation in one direction and little or no rotation in the opposite, seemed to be the result of lateral tilt of the spacecraft. It also was noted while the spacecraft were rotating, that if the oscillations built up to a large enough amplitude, the spacecraft would stop rotating. However, in many cases, after the rotation ceased, the oscillations would diminish and then the rotation would start again and the cycle would be repeated. It seemed that this type of behavior was the result of a transfer of energy from one mode of motion to the other.

Design (1-Point) Attachment Configuration

The results of the tests to determine stability of the spacecraft in the original design 1-point parachute attachment configuration (fig. 12(a)) are presented in table II, test conditions 1 to 5. The results indicated that the spacecraft had a marked tendency to glide because of the tilt of the spacecraft. This characteristic was not a bad one in itself but indirectly increased the tendency of the spacecraft to rotate, as will be explained later. In a few tests the spacecraft developed only mild oscillations and rates of rotation, but in most cases the oscillations would build up to large amplitudes (approximately ±35°) and the rotation of the spacecraft about its symmetrical axis occasionally built up to high rates (approximately 66 revolutions per minute, full scale).

The maximum rates of rotation reached appeared to be about the same with only one parachute deployed or with two parachutes deployed (table II, test conditions 2 and 5). With regard to the rate of rotation results, it would appear that the behavior of the spacecraft was no worse with only one parachute deployed than it was with two parachutes deployed. This was not exactly the case, however. With both parachutes deployed the rate at which the motion built up to objectionably large rates of rotation was lower than it was for a single parachute. Since it is intended that the spacecraft operate for only about 30 seconds with the drogue parachutes prior to the deployment of the main parachutes, the time required for the motions to build up is important. The two-drogue-parachute system is therefore considered to be more satisfactory than the single-drogue-parachute system. The fact that the rotation built up more slowly with both parachutes deployed was not believed to be the result of the greater stability of a clustered parachute arrangement, but was believed to be the result of the slower descent rate of the spacecraft with both parachutes deployed; that is, the airspeed was lower and thus the aerodynamic forces exciting the unstable motions were much smaller.

No statistical data, in general, were taken on the time required for the oscillations or rate of rotation to build up to excessive values which may cause unsatisfactory deployment of the main parachutes and/or subject the crew to excessive accelerations. These effects are discussed in more detail later. In a few tests the increase in rate of rotation was very rapid and excessive values were reached within a period of time corresponding to 30 seconds full scale. The achievement of excessive rates of rotation and oscillation angles evidently depended upon the exciting disturbances encountered. No intentional disturbances, other than normal tunnel airstream turbulence, were given during the tests except in a few cases where intentional rotation was given the spacecraft and except during the deployment tests where the drogue parachutes were deployed under severe conditions of tumbling and spinning. It should be noted, however, that for most of the tests, the increase in rate of rotation was low so that excessive values would not be reached during the approximately 30-second period of time that the spacecraft might be expected to operate with the drogue parachutes deployed.

Analysis of Rotational Characteristics

The tendency of the spacecraft to rotate about an axis coinciding approximately with its X body axis has been analyzed and is believed to result from the aerodynamic asymmetries caused primarily by the tilt of the spacecraft and the offset center-of-gravity location. The explanation is as follows. The spacecraft is assumed to be descending with the blunt end forward (downward). If the spacecraft sideslips to the right or left, either as a result of a lateral tilt or a sidewind, it develops an aerodynamic rolling moment about the X body axis which initiates the rotation. This aerodynamic rolling moment which corresponds to the dihedral effect of an airplane (that is, a rolling moment due to sideslip) has been shown to exist by wind-tunnel tests of models of the Apollo spacecraft (ref. 5).

Based on this analysis, it would be expected that gliding tendencies of the spacecraft could provide a source for additional sideslip. This increased sideslip angle will lead to larger aerodynamic rolling moments acting on the spacecraft which, in turn, will increase the tendency of the spacecraft to rotate.

On the basis of the foregoing analysis, the spacecraft would not have this tendency to rotate if it were in a level attitude with the center of gravity on the symmetrical axis. This conclusion is verified by the results of tests conducted to determine the effect of center-of-gravity location on the stability characteristics of the spacecraft with an attached parachute. These results, which will be discussed in detail later, indicated that when the center of gravity was placed on the symmetrical axis of the spacecraft and the parachute was attached to the center of the top of the spacecraft, the spacecraft showed little tendency to rotate.

This tendency of the spacecraft to rotate is an insidious characteristic in that rotation does not always occur. Some asymmetry is required to start the rotation. Such an asymmetry might result from uneven ablation of the heat shield, tilt of the spacecraft, or a side gust. The point is that rotation might not be encountered on any one particular test, or in any specific number of tests, but is always a possibility on the next test.

Modified Configurations

Effect of parachute attachment configurations.- In addition to the tests of the original design drogue parachute attachment configuration, many other attachment configurations were tested which were intended to provide improved stability. In general, the object of the modifications, such as the typical ones shown in figure 12, was to suspend the spacecraft at several widely spread points to provide better resistance to oscillations and to hold the spacecraft more nearly level to prevent or minimize rotation — in accordance with the foregoing analysis of the cause of the rotation. All the modified configurations with the exception of three (figs. 12(b), 12(c), and 12(g)) afforded some improvement in stability over the original design 1-point attachment configuration. The 3- and 4-point attachment configurations, however, were considerably better in providing stability than the 1- or 2-point attachment configurations and, in fact, were the only attachment configurations considered to give satisfactory stability. With the 3- and 4-point attachment configurations, it was possible to reduce the maximum amplitudes of the oscillations to low levels (less than $\pm 15^{\circ}$) and to reduce the maximum rates of rotation to low levels (less than about 25 revolutions per minute). There was no significant difference in the stability of the spacecraft when the three basic locations of the parachute riser were used although the riser location that kept the spacecraft more level reduced slightly the tendency of the spacecraft to rotate.

Effect of twin parachutes.- The results of brief tests (see table II, test condition 5) conducted with twin parachutes 14.6 feet (4.5 meters) in diameter with separate risers attached to a common point on the spacecraft have already been presented as part of the discussion of the original design configuration. Another method of attaching twin parachutes 10.4 feet (3.2 meters) in diameter to the spacecraft consisted of placing them in the longitudinal plane of the spacecraft and attaching one parachute riser to the tip of the pitch-control jets and the other to the periphery of the parachute deck ahead of the center of gravity (fig. 12(p)). The results of tests for this configuration indicated the spacecraft would glide slightly and oscillate in a low range of angles both in the lateral and longitudinal plane (table II, test condition 11). In some instances, the spacecraft rotated slowly, but in other instances it rotated very rapidly. Although the risers of the parachutes would entwine because of the rotation, the parachutes never showed any tendency to collapse. Results of brief tests conducted without the use of a swivel connected to the risers of the parachutes indicated no noticeable difference in the motions of the spacecraft. In fact, in some cases the risers became completely entwined up to the point where they joined the suspension lines of the parachutes, but the suspension lines never became entwined and the parachutes consequently did not collapse.

Effect of parachute diameter.- Typical results of the tests conducted to determine the effect of drogue parachute diameter on the stabilization of the spacecraft in vertical descent are shown in table II, test conditions 16 to 18. For this condition a 4-point attachment was used with the riser over the center of gravity. These results indicated that the amplitude of the oscillation of the spacecraft was reduced somewhat as the parachute diameter ranged from 12.5 to 16.7 feet (3.8 to 5.0 meters). Increasing the parachute diameter did not appear to affect appreciably the final rate of rotation, but it did increase the time required to attain the final rate of rotation. The results indicated that a 14- to 15-foot-diameter (4.3- to 4.6-meter) parachute would be suitable for stabilizing the spacecraft. Parachutes smaller than the suggested size generally allowed the spacecraft to exhibit larger oscillations and a greater tendency to rotate; and larger parachutes than the suggested size do not appear to be necessary since they do not offer any significant advantages to offset the disadvantages of increased parachute weight, volume, and loads.

These results do not appear to be consistent with the results obtained when the original design 1-point attachment configuration was used (see table II, test conditions 1 to 3), in which case parachute size did not seem to affect appreciably the amplitude of the oscillations of the spacecraft. It was not possible, however, for the original design attachment configuration to determine the effect of parachute diameter on the motions of the spacecraft because the motions generally were so violent that they tended to mask these effects.

Effect of center-of-gravity location.- The effect of varying the location of the center of gravity on the stability of the spacecraft is shown in table III. These tests were conducted with a 14.6-foot-diameter (4.5-meter) parachute and with an attachment configuration similar to that shown in figure 12(j). In this configuration a bridle is attached to the spacecraft at four points on top of the airlock. The results indicated that when the center of gravity was not located on the axis of symmetry, the spacecraft had a tendency to rotate. When the center of gravity was located on the symmetrical axis, however, the spacecraft had no tendency to rotate although it did oscillate slightly (test conditions 1 and 2). This result supports the previous analysis of the cause of the spacecraft rotation. The vertical position of the center of gravity, over the range of the test, did not appear to have any significant effect on the tendency of the spacecraft to rotate or oscillate either for the case of center-of-gravity locations on the symmetrical axis or offset from this axis.

Effect of altitude.- Tests were made on the 1/11.54-scale model using the normal entry configuration (table I, loading 2) to determine the effect of altitude on the stability of the spacecraft in vertical descent and the results are presented in table II (test conditions 4, 5, 6, and 7). A comparison of the results at sea level (table II, test condition 2) and at an altitude of 15 000 feet (4575 meters) (table II, test condition 4) indicates that the amplitude of the oscillations and the rate of rotation were approximately the same.

MODIFIED EARTH-LAUNCH CONFIGURATIONS

During an abort flight condition the spacecraft will be moving with the apex forward. In this attitude the command module has an apex-forward trim condition and since for certain abort conditions the dynamic pressure will be very high on the apex cover, it will be impossible to jettison the apex cover in order that the drogue parachute may be deployed to provide stabilization and deceleration of the spacecraft. It has therefore been proposed to modify the spacecraft to cause it to turn from the apex-forward trim condition to a blunt-base-forward trim condition. The modification, however, should not cause the spacecraft to tumble since this condition would lead to other problems. All the following tests were conducted at a simulated altitude of 15 000 feet (4575 meters) except the tests utilizing strakes which were conducted at a simulated altitude of sea level.

Basic Launch Escape System Retained

Results of brief tests of the spacecraft with the launch escape system attached but with no modification indicated that in some instances the configuration would trim in an apex-forward condition at a very low angle of attack and not diverge which, of course, was unsatisfactory (table IV, test condition 1). At other times the spacecraft would turn about 180° and would not tumble, but in this condition (blunt base forward) the spacecraft would tilt and rotate about the flight path (which, in this case, was vertical) with the top of the spacecraft inclined toward the flight path.

Launch Escape System With Canard Surfaces

The results of the tests of the command module with the launch escape system with canard surfaces attached are presented in table IV, test condition 2. These results indicate that the canard surfaces consistently caused the spacecraft to turn about 180° and did not cause the spacecraft to tumble. After the spacecraft with the launch escape system still attached was descending blunt base forward in the tunnel, the spacecraft, however, would start to oscillate and then, on occasion, it would tilt and rotate about the flight path, the top of the spacecraft being inclined toward the flight path. It is felt, however, that if the launch escape system and apex cover were jettisoned just after the spacecraft turned 180°, there would be no problem in getting the drogue parachute deployed.

Drogue Parachutes on Launch Escape System

The tests with a drogue parachute attached to the launch escape system were made for two sizes of drogue parachutes 14.6 feet (4.5 meters) and 10.0 feet (3.1 meters) in diameter. The results, which are presented in table IV, test conditions 3 and 4, indicated that either the large or small parachutes would cause the spacecraft to turn 180° rapidly and not tumble. After it had turned to the blunt-base-forward condition, the spacecraft would rotate slowly and oscillate. The oscillations, however, were small and were slightly smaller for the larger parachute than for the smaller one. The spacecraft appeared to be more stable in the blunt-base-forward condition when a parachute was attached to the launch escape system than when it was equipped with canard surfaces.

Tower Plus Fin

The results of these tests for the tower-plus-fin configuration indicated that this modification would cause the spacecraft to turn initially approximately 180° (table IV, test condition 5). In some instances, however, the spacecraft immediately would continue to rotate and commence tumbling. At other times, after it diverged, it would oscillate, tumble, or spin rapidly in a flat attitude.

Strakes on Spacecraft

The results of the tests of the spacecraft with strakes are presented in table IV, test conditions 6 to 9. The results indicated that for certain sizes and locations of the strakes, the spacecraft when descending with the apex forward ($\alpha = 0^{\circ}$) or at about $\alpha = 60^{\circ}$ would diverge from the apex-forward trim condition; but in every case in which the spacecraft diverged, it would tumble.

SUGGESTED DROGUE PARACHUTE SYSTEMS

There appeared to be several possible drogue parachute systems which would limit the spacecraft oscillations to an average of about $\pm 15^{\circ}$ or less and which would hold the spacecraft nearly level and thereby minimize the tendency of the spacecraft to rotate. It appears advisable to use a drogue parachute about 14 to 15 feet (4.3 to 4.6 meters) in diameter (based on a drag coefficient of 0.55) and a bridle consisting of at least three lines, the bridle being attached to the periphery of the top of the airlock or to the periphery of the main parachute deck with the confluence point of the bridle over the center of gravity or between the center of gravity and the axis of symmetry of the spacecraft. (See figs. 12(j) to 12(n) for examples.)

HUMAN FACTORS

The discussion so far has been concerned primarily with the stability of the spacecraft with the drogue parachutes deployed. The stability of the spacecraft in this condition is of concern for two reasons: first, because excessive oscillation or rotation of the spacecraft which may cause unsatisfactory deployment of the main parachutes and, second, because of human factors such as motion sickness and the possibility of subjecting the crew to excessive accelerations.

In connection with the human factors, a comparison has been made of the maximum rate of spacecraft rotation about the symmetrical axis and the maximum frequency and amplitude of the oscillations for the original design 1-point parachute attachment configuration (table II, test condition 2) and a 4-point attachment configuration (table II, test condition 17). The data indicate that the rate of rotation of the spacecraft for the 1-point attachment configuration is much greater than that of the 4-point attachment configuration (66 rpm and 15 rpm, respectively). The frequency of the oscillations is of the order of 1 cycle per second for either of the configurations, but the amplitude of the oscillations is much larger for the original design 1-point-attachment configuration, ($\pm 36^{\circ}$) than for the 4-point-attachment ($\pm 10^{\circ}$) configuration.

These results indicate that the human factors of the problem should be a cause for concern, particularly the possibility of having excessive accelerations at the heads and feet of the crew which would result from the maximum rates of rotation previously given in table II. These accelerations were determined by calculating the centrifugal forces at the heads and feet of the crew by using the maximum rates of rotation about the symmetrical axis of the spacecraft. Additional motions, such as oscillations superimposed on this rotary motion probably would make the effects of the accelerations worse. The sketch on the left in figure 14 shows accelerations for the original design 1-point attachment and the sketch on the right shows the accelerations for the 4-point-attachment configurations. Relatively modest accelerations are indicated for the 4-point-attachment configuration because of the low rate of rotation, but for the 1-point-attachment configuration the figure shows accelerations at the head which would ordinarily be of grave concern. The reason that the seriousness of these high accelerations at the head cannot be determined at present is the unusual situation in which the accelerations are in one direction at the head and the other direction at the feet. The effect of such accelerations, however, should be investigated.

SUMMARY OF RESULTS

The results of low-speed tests conducted in the Langley spin tunnel on dynamic models of Apollo command module configurations are summarized as follows:

1. The spacecraft alone with blunt end forward was dynamically unstable and could go through some rather violent gyrations such as large oscillations, tumbling, and spinning motions if the reaction controls should fail.

2. The spacecraft alone with the apex end forward was dynamically stable and would trim at an angle of attack of about 40° and glide in large circles.

3. Deployment of a drogue parachute would quickly stop any tumbling motions of the command module, and the damping of the residual motions was considerably more rapid when the parachute was attached to the command module by means of a 4-point bridle-type attachment than when it was attached with a 1-point attachment.

4. With the original design 1-point-parachute attachment configuration, the spacecraft may experience excessive oscillations and rates of rotation.

5. The use of 3-point or 4-point bridle-line attachment configurations can result in much lower amplitude of the oscillations and much lower rates of rotation than were encountered with the design 1-point-attachment configuration. These improvements result from the fact that the bridle makes it possible to take greater advantage of available restoring force of the parachute to limit the oscillations and to hold the spacecraft

more level in order to reduce its tendency to rotate. The results achieved with a 3-point-attachment configuration were as satisfactory as those achieved with a 4-point-attachment configuration.

6. In conjunction with the 3-point or 4-point bridle-line arrangement, it appears desirable to use a drogue parachute about 14 to 15 feet (4.3 to 4.6 meters) in diameter – based on a drag coefficient of 0.55.

7. Location of the center of gravity of the spacecraft on the symmetrical axis and attachment of the parachute to the center of the top of the spacecraft practically eliminated the tendency of the spacecraft to rotate. Movement of the center of gravity vertically for the range tested had no appreciable effect on the oscillations of the spacecraft.

8. Retention of the launch escape system, with either a drogue parachute or canard surfaces attached to it, appeared to be the most satisfactory means of preventing an apex-forward trim condition during launch abort.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 15, 1967,
124-07-03-09-23.

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TABLE I.- MASS AND INERTIA CHARACTERISTICS FOR THE LOADINGS OF THE FULL-SCALE APOLLO COMMAND MODULE AND FOR LOADINGS TESTED ON THE MODEL

[Model values are converted to corresponding full-scale values and moments of inertia are about the center of gravity]

Loading number	Configuration	Weight, W, lb (kg)	Center-of-gravity location, in. (cm)			Relative density, μ		Moments of inertia, slug-ft^2 (kg-m^2)		
			x_c	y_c	z_c	Sea level	15 000 ft (4 572 m)	I_X	I_Y	I_Z
	Apollo command module values									
1	Normal entry.	9 000 (4 086)	38.0 (96.5)	-1.2 (-3.05)	7.0 (17.8)	70.6	112.44	3 769 (5 110)	2 961 (4 014)	2 879 (3 903)
2	Normal entry. Drogue parachute deployed. 265 lb (120 kg) ablation material burned off.	8 107 (3 681)	45.9 (116.6)	0	9.3 (23.6)	63.85	101.49	3 693 (5 007)	2 906 (3 940)	3 021 (4 096)
3	Command module with escape rocket and tower.	12 789 (5 806)	115.0 (292.1)	-1 (-2.50)	5.8 (14.7)	100.58	159.89	4 474 (6 066)	45 281 (61 392)	45 082 (61 122)
4	Command module with tower and fin.	9 893 (4 491)	47.6 (120.9)	-0.2 (-.51)	7.5 (19.1)	77.78	123.64	4 343 (5 888)	5 023 (6 810)	4 850 (6 576)
5	Command module in earth-launch condition.	8 990 (4 081)	43.8 (111.3)	0.5 (1.27)	7.9 (20.1)	70.68	112.36	4 186 (5 675)	3 571 (4 842)	3 569 (4 839)
	Model values, 1/11.54-scale									
1	Normal entry.	9 038 (4 103)	35.77 (90.9)	0	6.90 (17.5)	71.0	------	3 670 (4 976)	3 009 (4 080)	2 988 (4 051)
2	Normal entry. Drogue parachute deployed. 265 lb (120 kg) ablation material burned off.	8 370 (3 800)	44.71 (113.6)	0	9.04 (23.0)	65.87	------	3 744 (5 076)	2 923 (3 963)	3 015 (4 088)
7	Normal entry. (Loading no. 1) with center-of-gravity variation.	9 133 (4 146)	24.8 (63.0)	0	6.23 (15.8)	71.8	------	3 474 (4 710)	2 934 (3 978)	3 007 (4 077)
8		9 082 (4 123)	25.8 (65.5)	0	0	71.4	------	3 168 (4 295)	2 614 (3 544)	2 931 (3 974)
9		9 106 (4 134)	38.80 (98.6)	0	0	71.6	------	3 165 (4 291)	3 148 (4 268)	3 465 (4 698)
10		9 119 (4 140)	39.9 (101.3)	0	6.43 (16.3)	71.7	------	3 503 (4 749)	3 607 (4 890)	3 665 (4 969)
	Model values, 1/28-scale									
1	Normal entry.	7 869 (3 573)	40.99 (104.1)	0	4.56 (11.6)	61.82	98.27	3 618 (4 905)	3 633 (4 926)	3 314 (4 493)
5	Command module in earth-launch condition.	9 051 (4 109)	45.05 (114.4)	0	7.92 (20.1)	71.19	------	4 026 (5 458)	4 255 (5 769)	4 239 (5 741)
3	Command module with escape rocket and tower.	12 816 (5 818)	115.36 (293.0)	0	5.43 (13.8)	------	160.29	4 526 (6 136)	43 820 (59 411)	42 773 (57 992)
4	Command module with tower and fin.	9 041 4 105	73 22 (186.0)	0	5.85 (14.86)	------	113.17	3 304 (4 480)	7 591 (10 292)	7 854 (10 648)
6	Command module with tower only.	9 843 (4 469)	53.34 (135.5)	0	7.56 (19.2)	------	123.64	3 613 (4 899)	7 087 (9 609)	6 701 (9 085)

TABLE II.- EFFECT OF DROGUE PARACHUTE ATTACHMENT CONFIGURATION AND DROGUE PARACHUTE DIAMETER ON DYNAMIC STABILITY OF COMMAND MODULE IN VERTICAL DESCENT

[Model values converted to corresponding full-scale values; parachute size based on drag coefficient of approximately 0.55]

Test condition	Parachute attachment configuration			Parachute diameter, ft (m)	Mass loading number (see table I)	Test altitude, ft (m)	Velocity, ft/sec (m/sec)	Maximum rate of rotation, rpm		Oscillation angle, deg		Remarks
	Number of points	Location	Figure					Self-excited	Prerotated	Average	Maximum	
1	1	Original design	12(a)	12.5 (3.7)	1	Sea level	197 (60)	27	35	±35.0	±65.0	
2	1	Original design	12(a)	14.6 (4.5)	1	Sea level	187 (57)	66	30	±36	±65.0	The high maximum rate of rotation shown for the self-excited case was not typical and occurred on only one of many tests.
3	1	Original design	12(a)	16.7 (5.1)	1	Sea level	175 (55)	35	35	±30	±55.0	The rotation built up more slowly in this case than for the case of test condition 2; and maximum rate of rotation may not have been achieved because of model bumping the tunnel wall.
4	1	Original design	12(a)	14.6 (4.5)	2	15 000 (4 572)	238 (73)	6	83	±30	±65	Model was difficult to test at this and other simulated 15 000-foot-altitude conditions. The tests were therefore short, and maximum values of oscillation amplitudes and rate of rotation may not have been obtained.
5	1	Original design two risers	12(o)	2 parachutes 14.6 (4.5)	2	15 000 (4 572)	198 (61)	60	No tests	±35	±60	For this case (2 parachutes), however, the rate of rotation increased much more slowly than for test condition 2 (1 parachute).
6	1	Top of airlock over symmetrical axis	12(b)	14.6 (4.5)	2	15 000 (4 572)	232 (71)	27	27.0	±43	±65.0	
7	1	Top of airlock over center of gravity	12(c)	14.6 (4.5)	2	15 000 (4 572)	232 (71)	25	16.0	±53.0	±68.0	
8	1	Top of airlock outboard of center of gravity	12(d)	14.6 (4.5)	2	Sea level	183 (56)	6	0	±37.0	±58.0	The rotation of the spacecraft stopped after prerotation because large oscillations ensued as the rotation decreased and these oscillations caused the rotation to stop. For the self-excited condition, the rotation increased slowly to small values and for this condition there were no large oscillations to reduce the rotation to zero.
9	2	Top of airlock both points outboard of center of gravity	12(f)	14.6 (4.5)	2	Sea level	183 (56)	8	----	±15.0	±24.0	When it was prerotated in one direction, model eventually stopped rotating; however, sufficient data were not available to determine whether rotation would cease when the model was prerotated in the opposite direction.
10	2	Top of airlock one point forward (outboard of center of gravity) and second point aft of center of gravity	12(e)	14.6 (4.5)	2	Sea level	183 (56)	9	14	±20.0	±36.0	Motions of spacecraft were fairly steady although occasionally motions became somewhat oscillatory.
11	2	One riser for each chute. One on front and one on tip of pitch control jets	12(p)	2 parachutes 10.5	2	Sea level	190 (58)	116	116	±31	±60	Spacecraft oscillated about one parachute attachment point and then about the other. The rate of rotation was the fastest encountered in any of the tests.

TABLE II.- EFFECT OF DROGUE PARACHUTE ATTACHMENT CONFIGURATION AND DROGUE PARACHUTE DIAMETER ON DYNAMIC STABILITY OF COMMAND MODULE IN VERTICAL DESCENT – Concluded

[Model values converted to corresponding full-scale values; parachute size based on drag coefficient of approximately 0.55]

Test condition	Parachute attachment configuration: Number of points	Parachute attachment configuration: Location	Parachute attachment configuration: Figure	Parachute diameter, ft (m)	Mass loading number (see table I)	Test altitude, ft (m)	Velocity, ft/sec (m/sec)	Maximum rate of rotation, rpm: Self-excited	Maximum rate of rotation, rpm: Prerotated	Oscillation angle, deg: Average	Oscillation angle, deg: Maximum	Remarks
12	3	Near original design (spacecraft tilted 25°)	12(g)	14.6 (4.5)	1	Sea level	190 (58)	11	70	±10.0	±13.0	Motions of spacecraft were generally steady and mild. However, spacecraft had strong gliding tendencies which made it difficult to observe its oscillation and rotational tendencies because the vehicle struck the tunnel wall frequently. When it was prerotated, the spacecraft rotated very rapidly.
13	3	Top of airlock over symmetrical axis	12(h)	14.6 (4.5)	1	Sea level	187 (57)	12	25	±15.0	±22.0	
14	3	Top of airlock over center of gravity	12(i)	14.6 (4.5)	1	Sea level	187 (57)	25	25	±10.0	±17.0	
15	4	Top of airlock over symmetrical axis	12(m)	14.6 (4.5)	1	Sea level	187 (57)	12	12	±10.0	±16.0	
16	4	Top of airlock over center of gravity	12(j)	12.5 (3.7)	1	Sea level	200 (61)	28	28	±17.0	±25.0	
17	4	Top of airlock over center of gravity	12(j)	14.6 (4.5)	1	Sea level	187 (57)	15	25	±10.0	±18.0	
18	4	Top of airlock over center of gravity	12(j)	16.7 (5.1)	1	Sea level	174 (53)	24	30	±6.0	±13.0	
19	4	Top of airlock over center of gravity; two cantilever beams used	12(k)	14.6 (4.5)	2	Sea level	187 (57)	5	18	±10.0	±22.0	
20	4	Top of airlock outboard of center of gravity	12(l)	14.6 (4.5)	2	Sea level	183 (56)	7	25	±13.0	±27.0	
21	4	On periphery of parachute deck over symmetrical axis	12(m)	14.6 (4.5)	1	Sea level	187 (57)	20	35	±10.0	±25.0	
22	4	On periphery of parachute deck over center of gravity	12(n)	14.6 (4.5)	1	Sea level	187 (57)	12	25	±10.00	±20.0	

TABLE III.- EFFECT OF CENTER-OF-GRAVITY LOCATION ON THE DYNAMIC STABILITY OF THE COMMAND MODULE WITH PARACHUTE ATTACHED IN VERTICAL DESCENT

[Model values converted to corresponding full-scale values; parachute size based on drag coefficient of approximately 0.55. Diameter of parachute is 14.6 feet (4.5 meters) and riser is attached at four points on top of airlock over center of gravity. Lateral location of center of gravity y_{cg} is zero. Test altitude is zero]

Test condition	Mass loading number (see table I)	Center-of-gravity location, in. (cm)		Velocity, ft/sec (m/sec)	Maximum rate of rotation (self-excited), rpm (*)	Oscillation angle, deg	
		x_c	z_c			Average	Maximum
1	7	21.3 (54.1)	0	187 (57)	0	±7	±15
2	8	34.7 (88.1)	0	187 (57)	0	±8	±12
3	9	21.3 (54.1)	6.5 (16.5)	187 (57)	11	±7	±10
4	10	36.7 (93.2)	6.6 (16.8)	187 (57)	17	±11	±15

*For all tests where the spacecraft was prerotated, sufficient time was not allowed for the spacecraft rotation to slow down to a steady value; thus, a column for the prerotated case is not presented in this table.

TABLE IV.- EFFECT OF COMMAND MODULE MODIFICATIONS ON APEX-FORWARD TRIM PROBLEM

[Model values converted to corresponding full-scale values. Lateral location of center of gravity y_{cg} is zero. Spacecraft launched apex forward except where noted]

Test condition	Configuration	Figure	Velocity, ft/sec (m/sec)	Center of gravity, in. (cm) x_c	Center of gravity, in. (cm) y_c	Mass loading number (see table I)	Test altitude, ft (m)	Results
1	Command module with launch escape system	8	375 (114.3)	115.0 (292.1)	5.4 (13.7)	3	15 000 (4 572)	Spacecraft trimmed at an angle of attack of about 5° for a short period of time; then it pitched up to a blunt-end-forward condition and went into a flat spin at a tilt angle of about 60°. It also rotated slowly around its symmetrical axis.
2	Command module with launch escape system and with canard surfaces on nose of rocket	9 and 10(a)	375 (114.3)	115.0 (292.1)	5.4 (13.7)	3	15 000 (4 572)	Spacecraft pitched up immediately and had no tendency to trim apex forward. It spins blunt end forward at an angle of attack of from 10° to 40°. When the spacecraft was nearly vertical, it rotated about the symmetrical axis at about 16 rpm.
3	Command module with launch escape system and with 14.6-foot (4.5-m) parachute and 7-foot (2.1-m) towline on rocket	10(b)	285 (88.9)	115.0 (292.1)	5.4 (13.7)	3	15 000 (4 572)	Spacecraft pitched up immediately and assumed a stable blunt-end-forward trim condition at an angle of attack near 0°.
4	Command module with launch escape system and with 7-foot-diameter (2.1-m) parachute and 7-foot (2.1-m) towline on apex of rocket	10(b)	320 (97.5)	115.0 (292.1)	5.4 (13.7)	3	15 000 (4 572)	Spacecraft pitched up immediately to a blunt-end-forward condition and then continued to oscillate about $\pm 10^{\circ}$ while rotating slowly about the symmetrical axis.
5	Command module with tower and fin	11	375 (114.3)	51.3 (130.3)	7.5 (20.1)	6	15 000 (4 572)	When launched with tower forward, the spacecraft pitched up rapidly and would not continue tumbling but went from a tumbling to a spinning, and to an oscillating motion. Also it may spin about the symmetrical axis.
6	Command module with strakes	7(a)	250 (76.2) to 320 (97.5)	47.1 (119.6)	7.9 (20.1)	1	Sea level	When launched with apex forward, the spacecraft pitched up and began tumbling. When launched with apex forward but tilted at an angle of 60°, spacecraft pitched up but less quickly.
7	Command module with strakes	7(b)	250 (76.2) to 320 (97.5)	47.1 (119.6)	7.9 (20.1)	1	Sea level	Spacecraft occasionally would trim apex forward near an angle of attack of 0° and glide in large circles. On other occasions, it would pitch up more slowly than for run 6 and would then begin to tumble.
8	Command module with strakes	7(c)	250 (76.2) to 320 (97.5)	47.1 (119.6)	7.9 (20.1)	1	Sea level	Spacecraft tumbled immediately and continued to tumble.
9	Command module with strakes	7(d)	250 (76.2) to 320 (97.5)	47.1 (119.6)	7.9 (20.1)	1	Sea level	In some cases spacecraft tumbled immediately and in other cases it would trim apex forward for a brief period of time and then tumble. Also, spacecraft occasionally would trim apex forward and rotate slowly about the symmetrical axis.

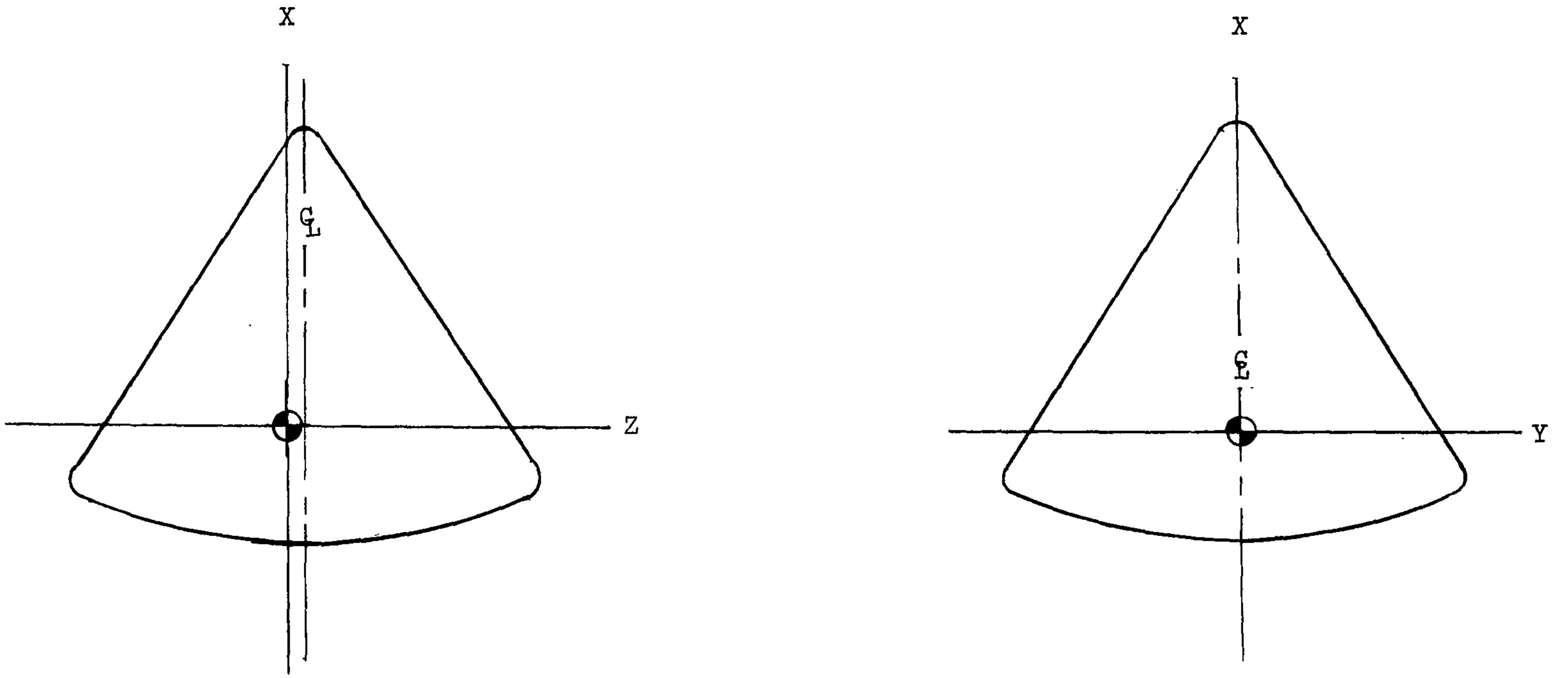

Figure 1.- Body system of axes as used on Apollo command module.

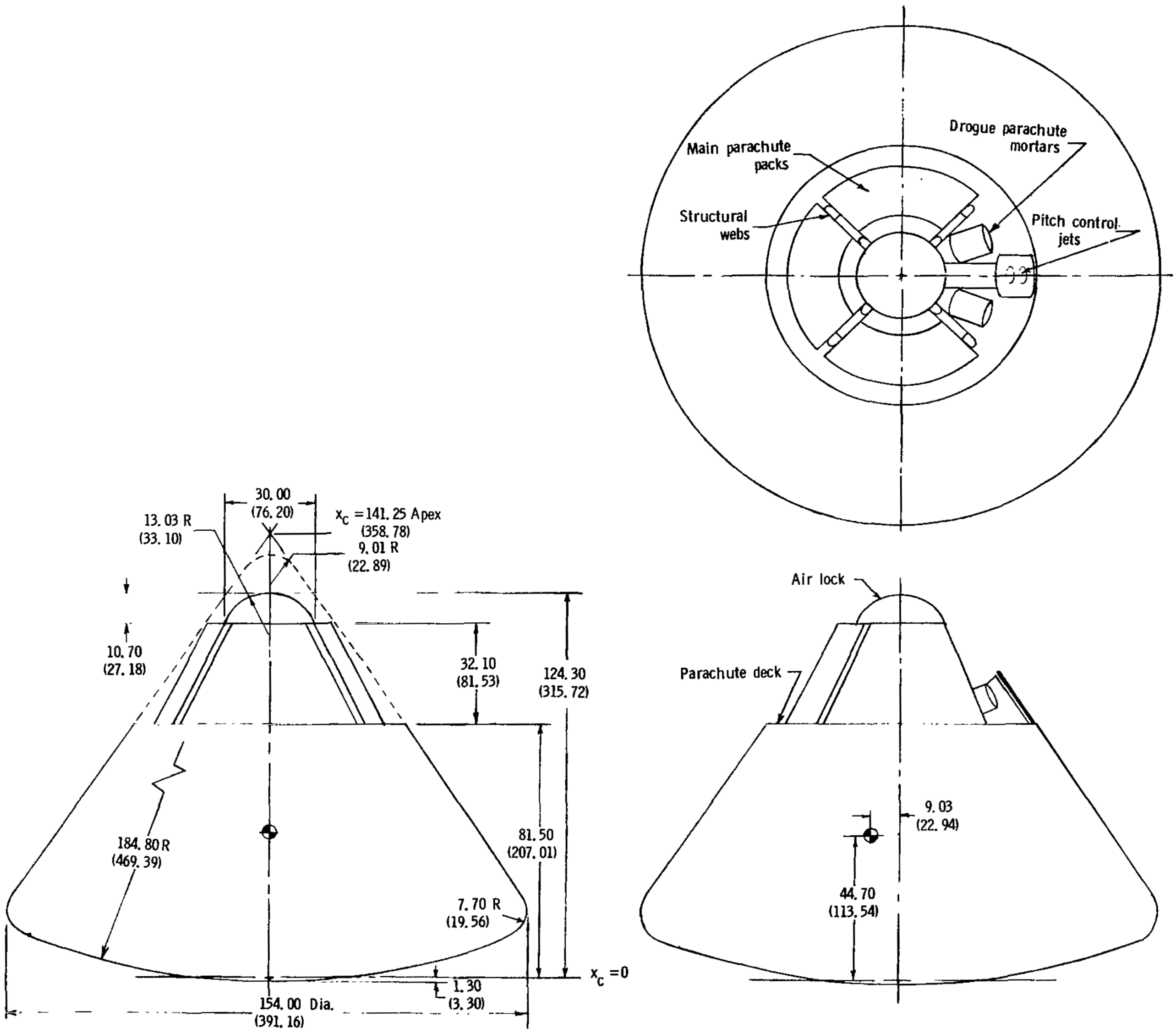

Figure 2.- Drawing of Apollo command module in entry configuration. Dotted line shows apex cover attached to module for the earth-launch configuration. All dimensions given are full scale. Initial dimensions are in inches and parenthetical dimensions are in centimeters. Center-of-gravity position shown is for a typical loading.

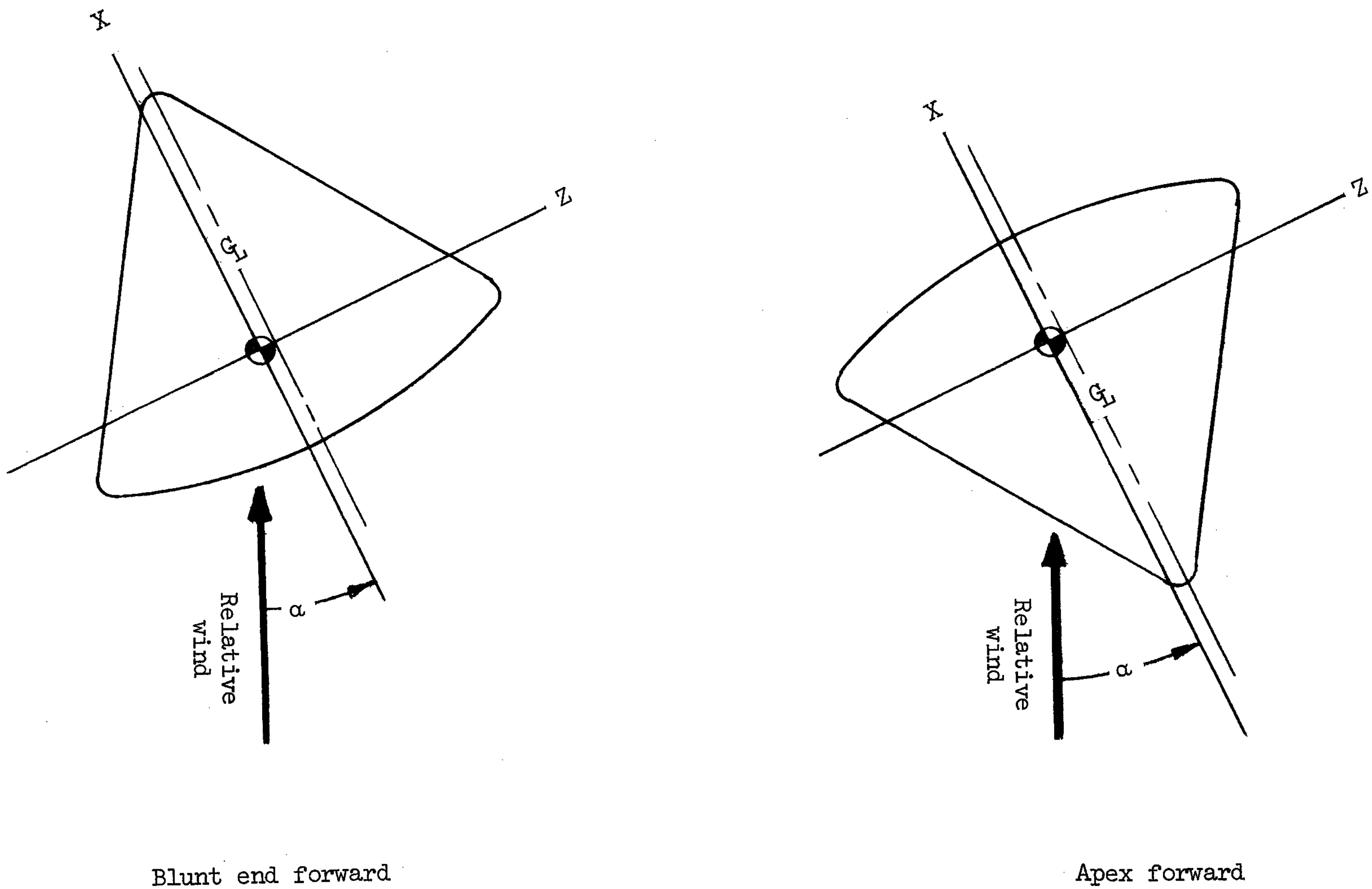

Figure 3.- Definition of angle of attack as used on Apollo command module.

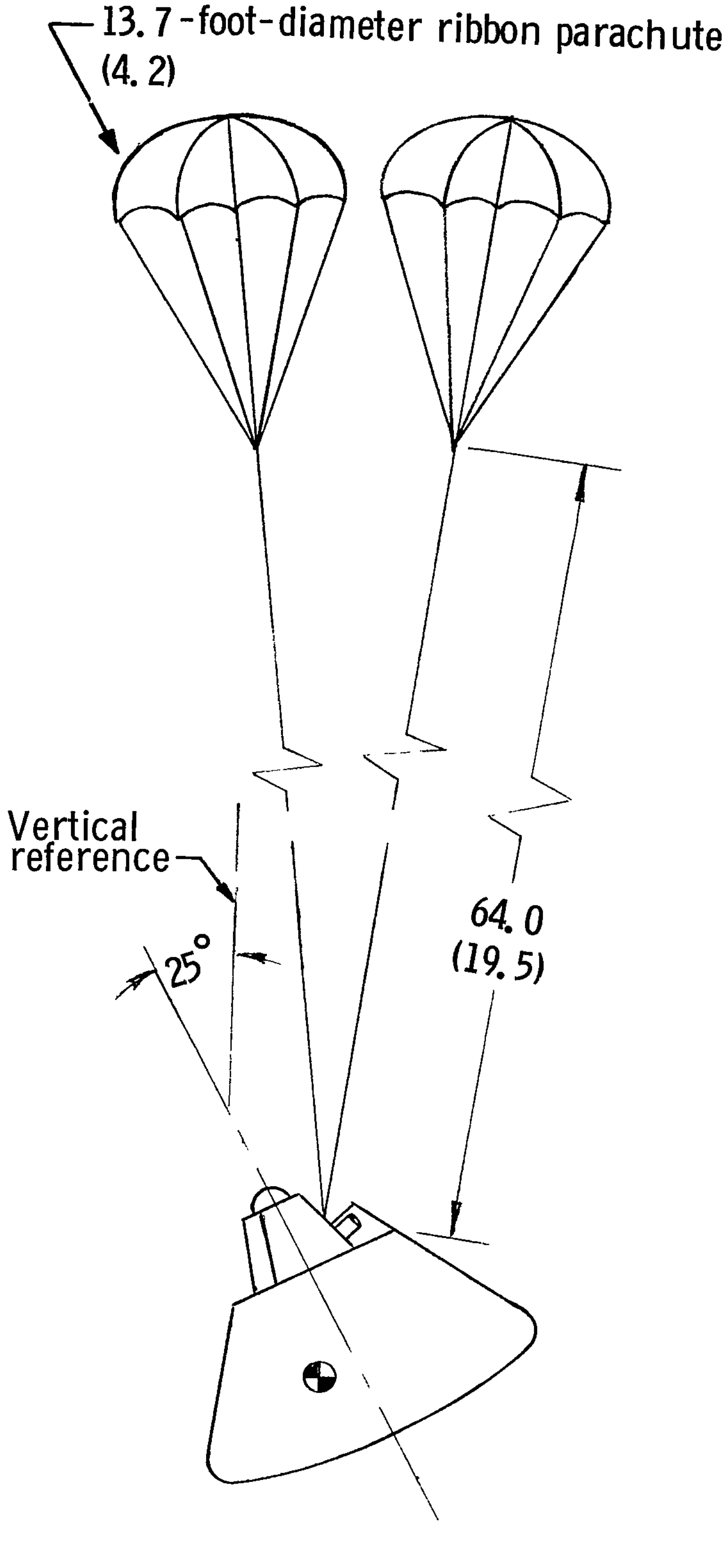

Figure 4.- Sketch of full-scale design drogue parachute system. Initial dimensions are in feet; parenthetical dimensions are in meters.

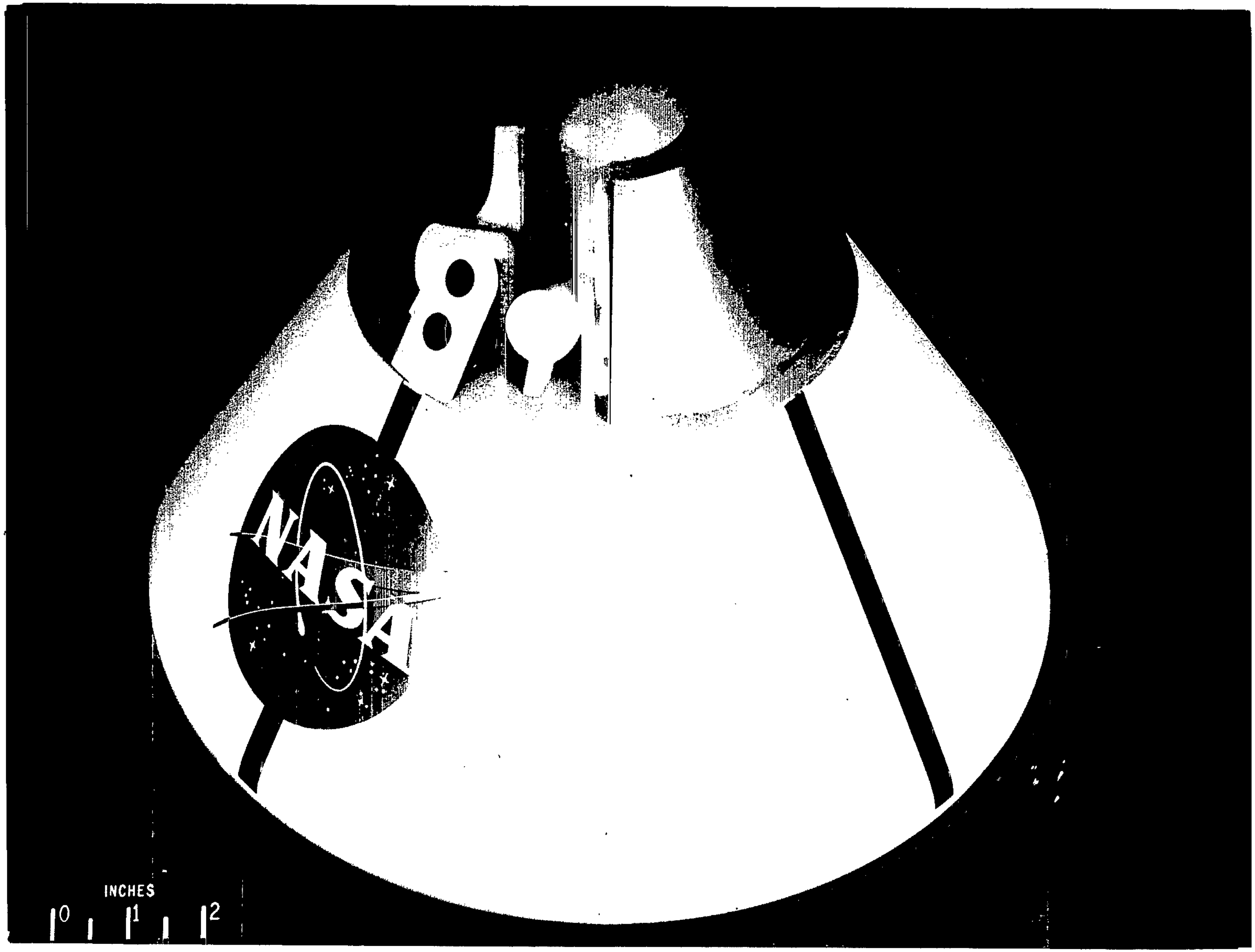

Figure 5.- The 1/11.54-scale model of the Apollo command module in entry configuration. L-62-7907

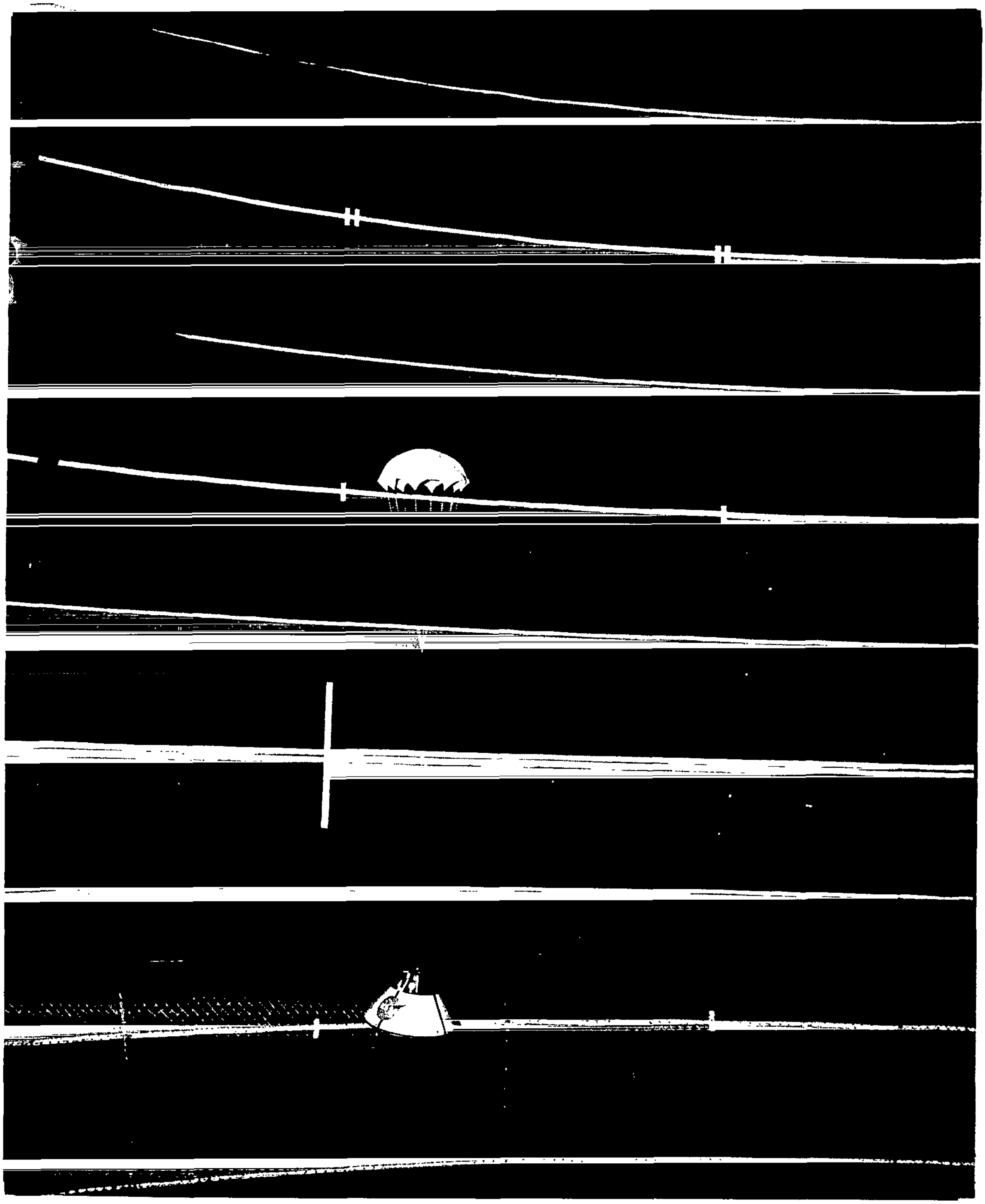

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Figure 6.- The 1/11.54-scale model of the Apollo command module with drogue parachute being tested in the Langley spin tunnel.

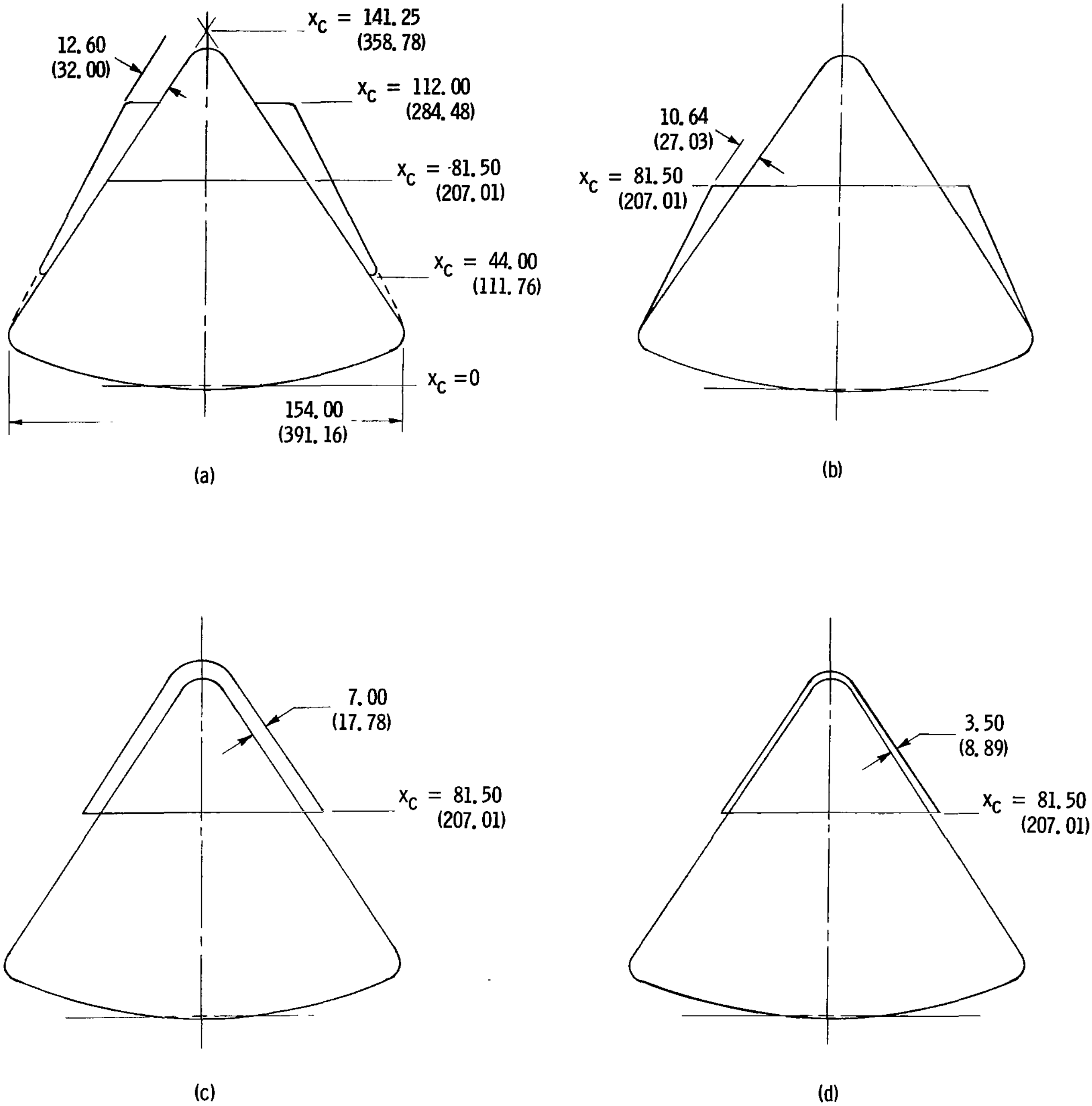

Figure 7.- Typical strakes tested. Dimensions are full scale. Initial dimensions are in inches and parenthetical dimensions are in centimeters.

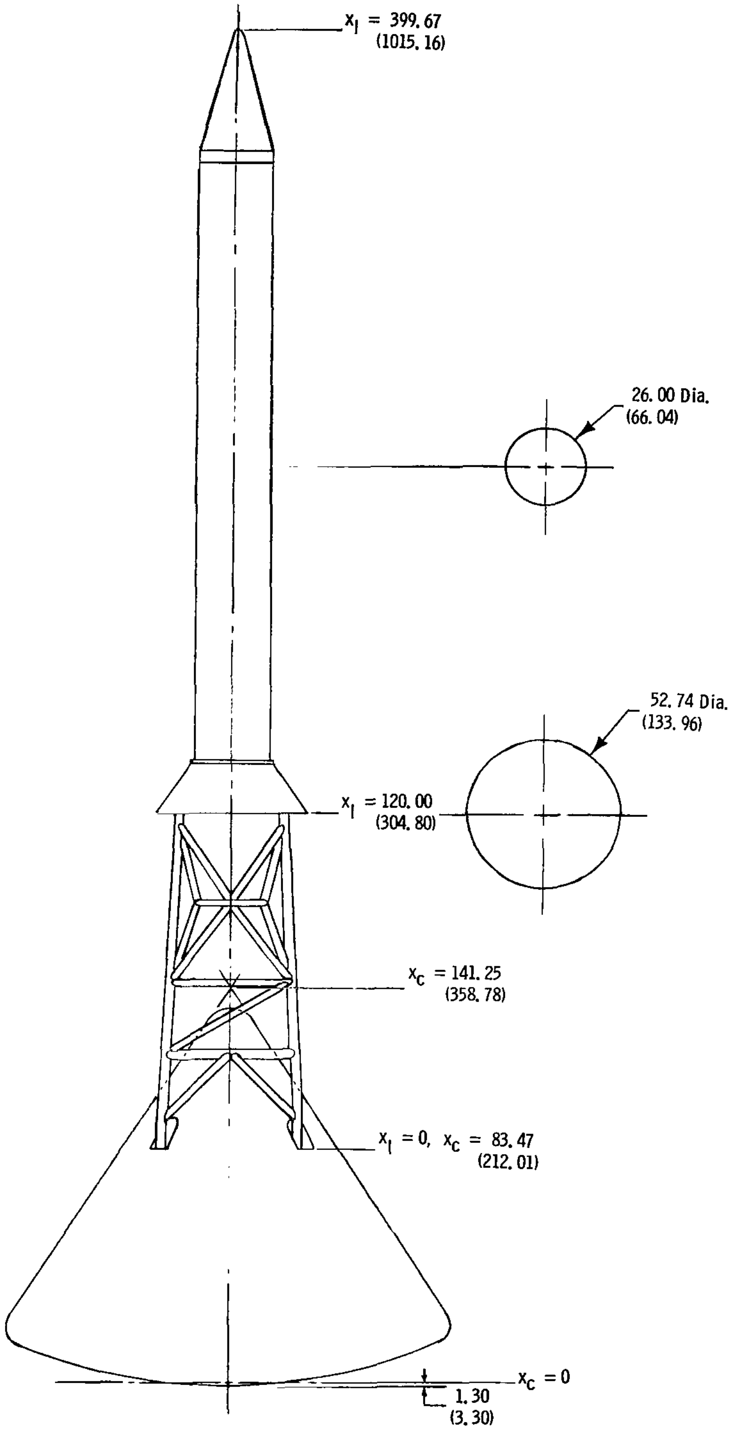

Figure 8.- The Apollo command module with the launch-escape system. Dimensions given are full scale. Initial dimensions are in inches and parenthetical dimensions are in centimeters.

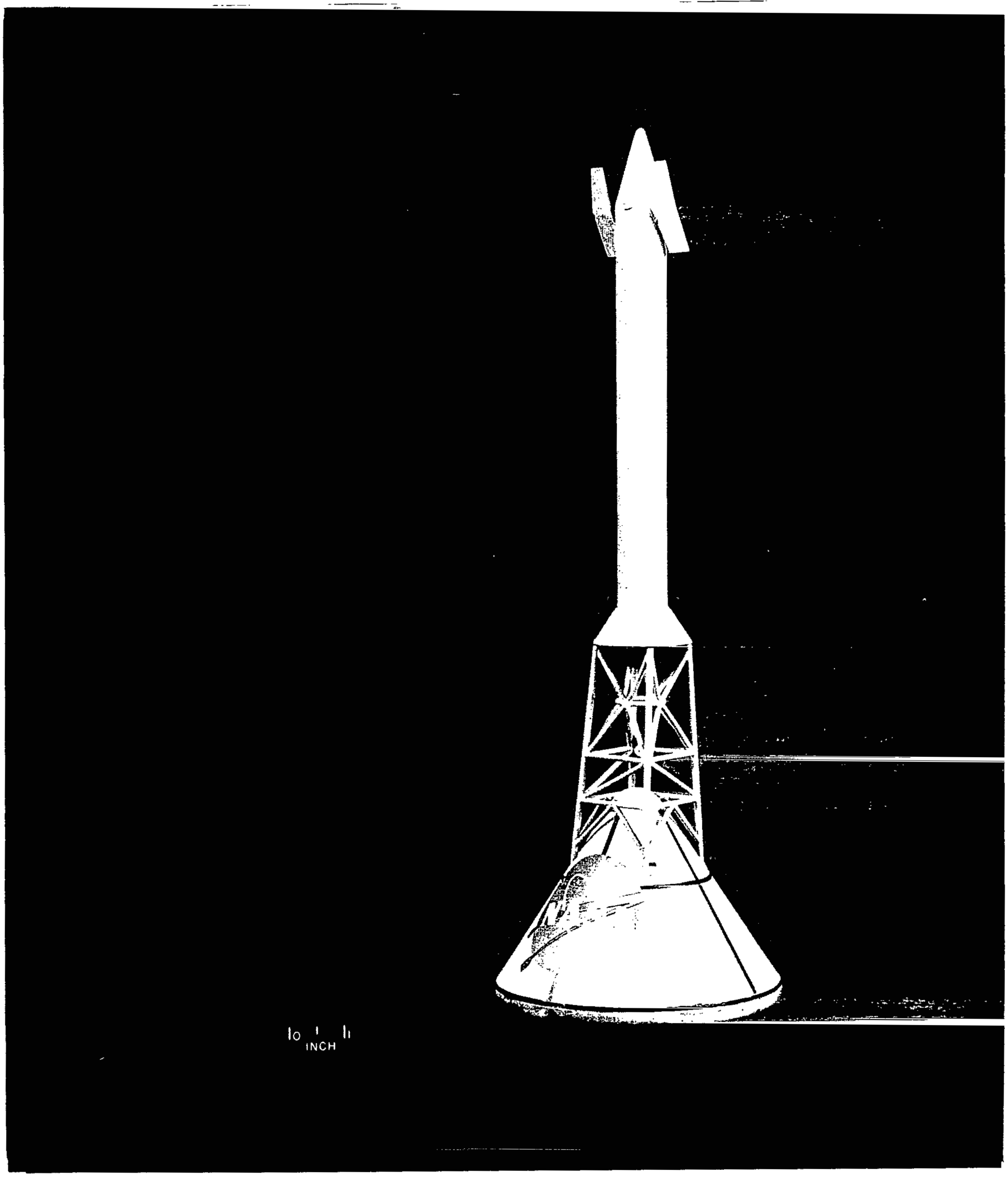

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Figure 9.- The 1/28-scale model of the Apollo command module with the launch-escape system with canard surfaces attached.

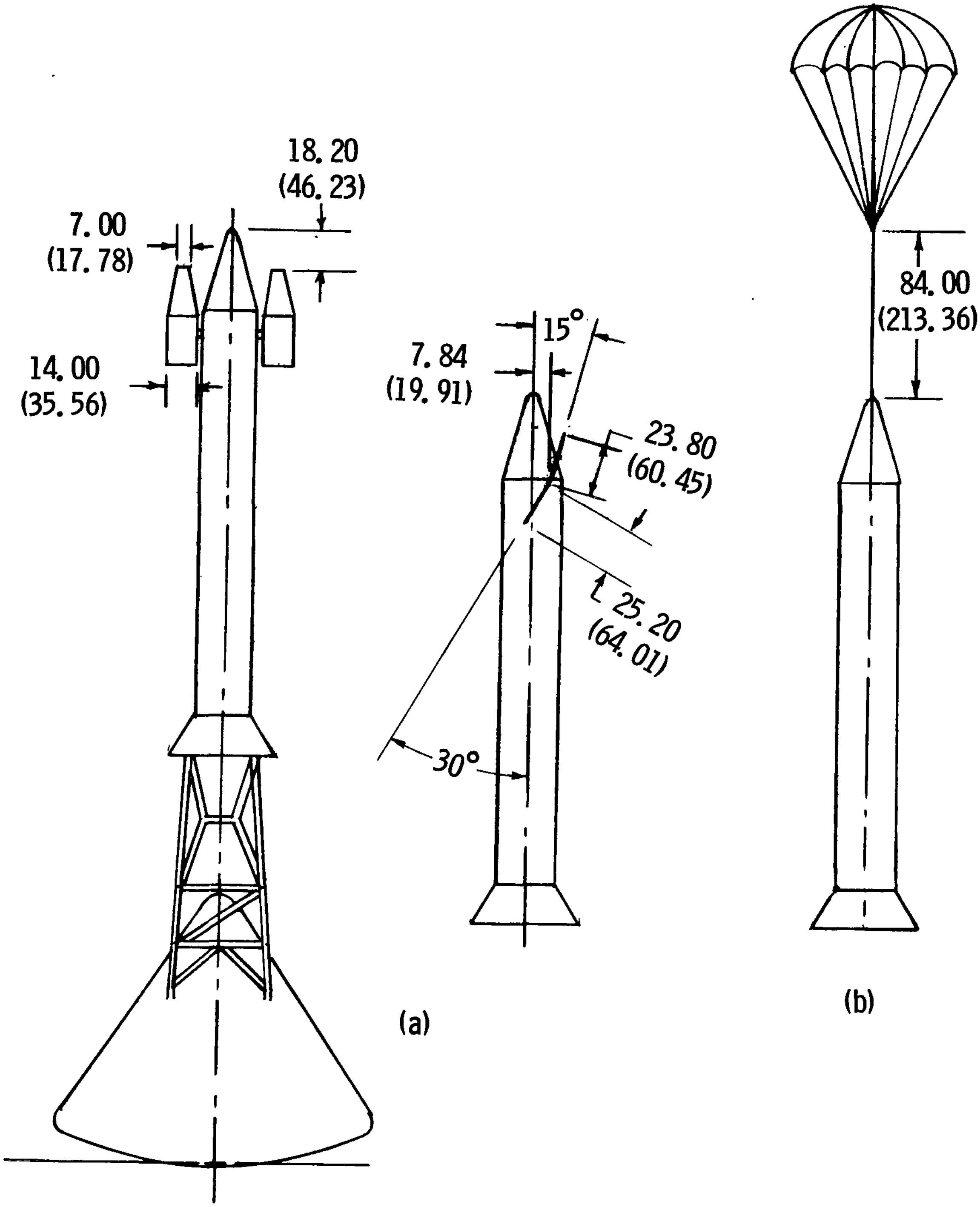

Figure 10.- Canard surfaces and drogue parachute attached to launch-escape system. Dimensions given are full scale. Initial dimensions are in inches and parenthetical dimensions are in centimeters.

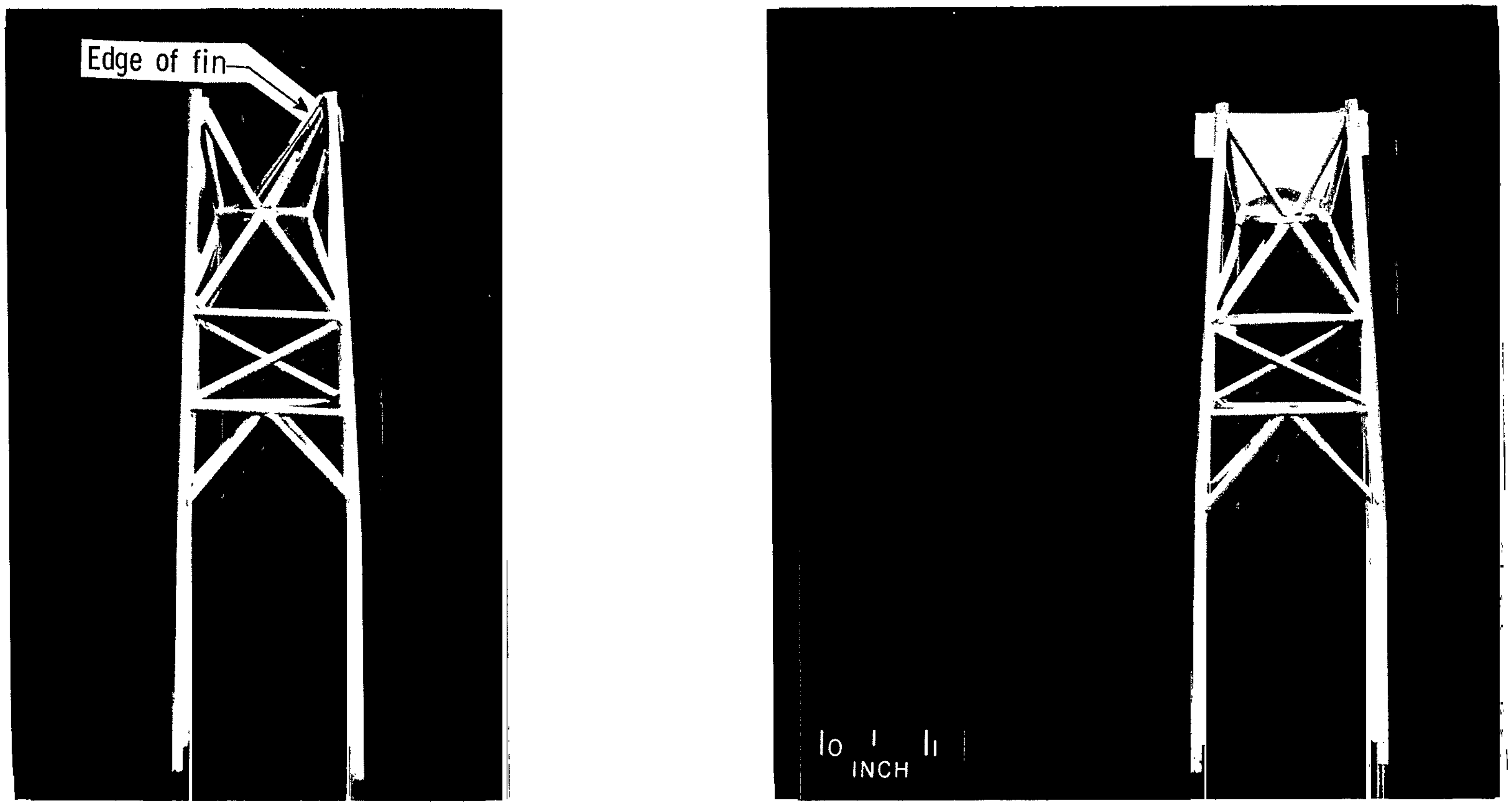

Figure 11.- Tower with fin.

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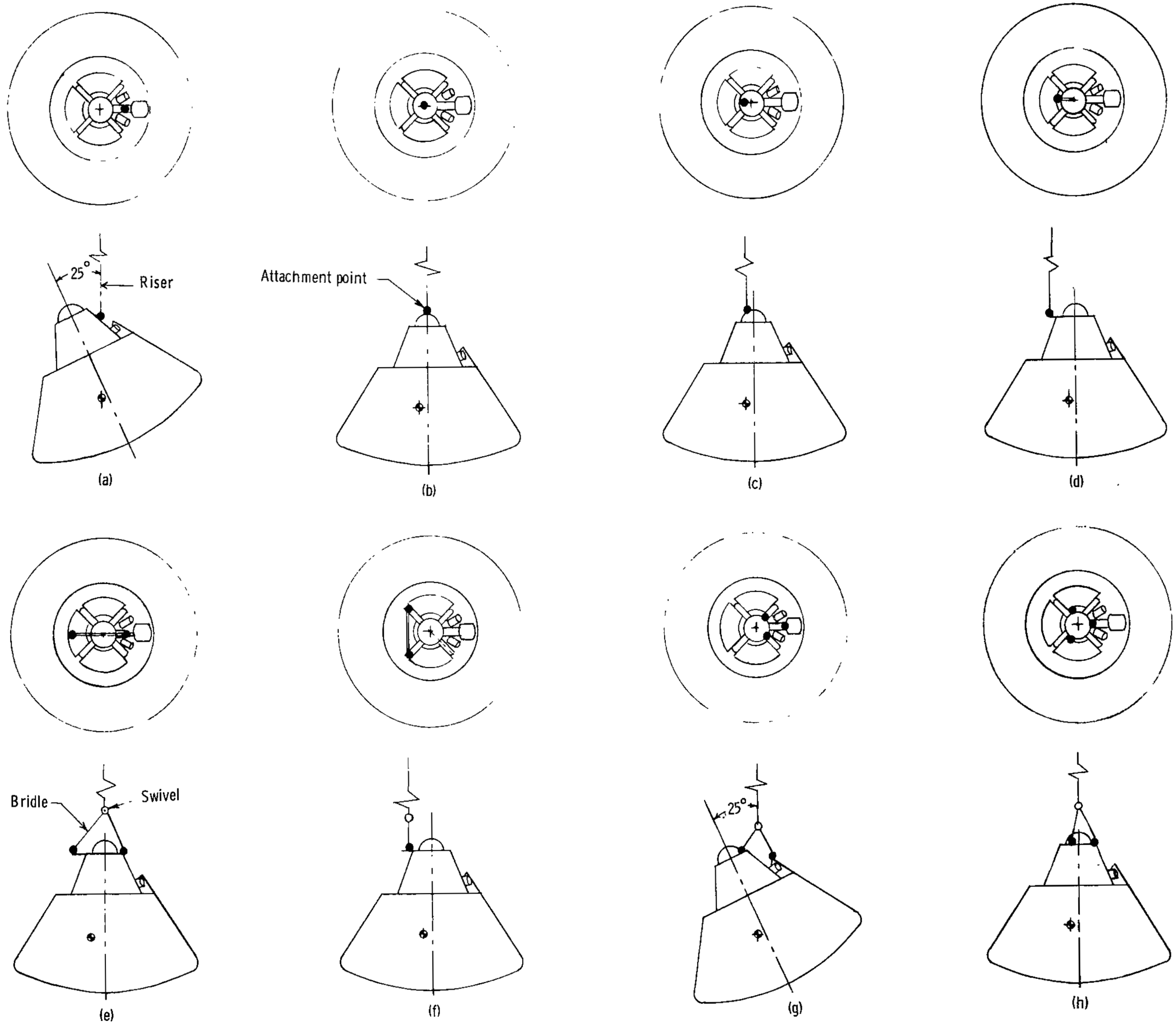

Figure 12.- Typical drogue parachute attachment configurations. Dots indicate attachment points of drogue parachute.

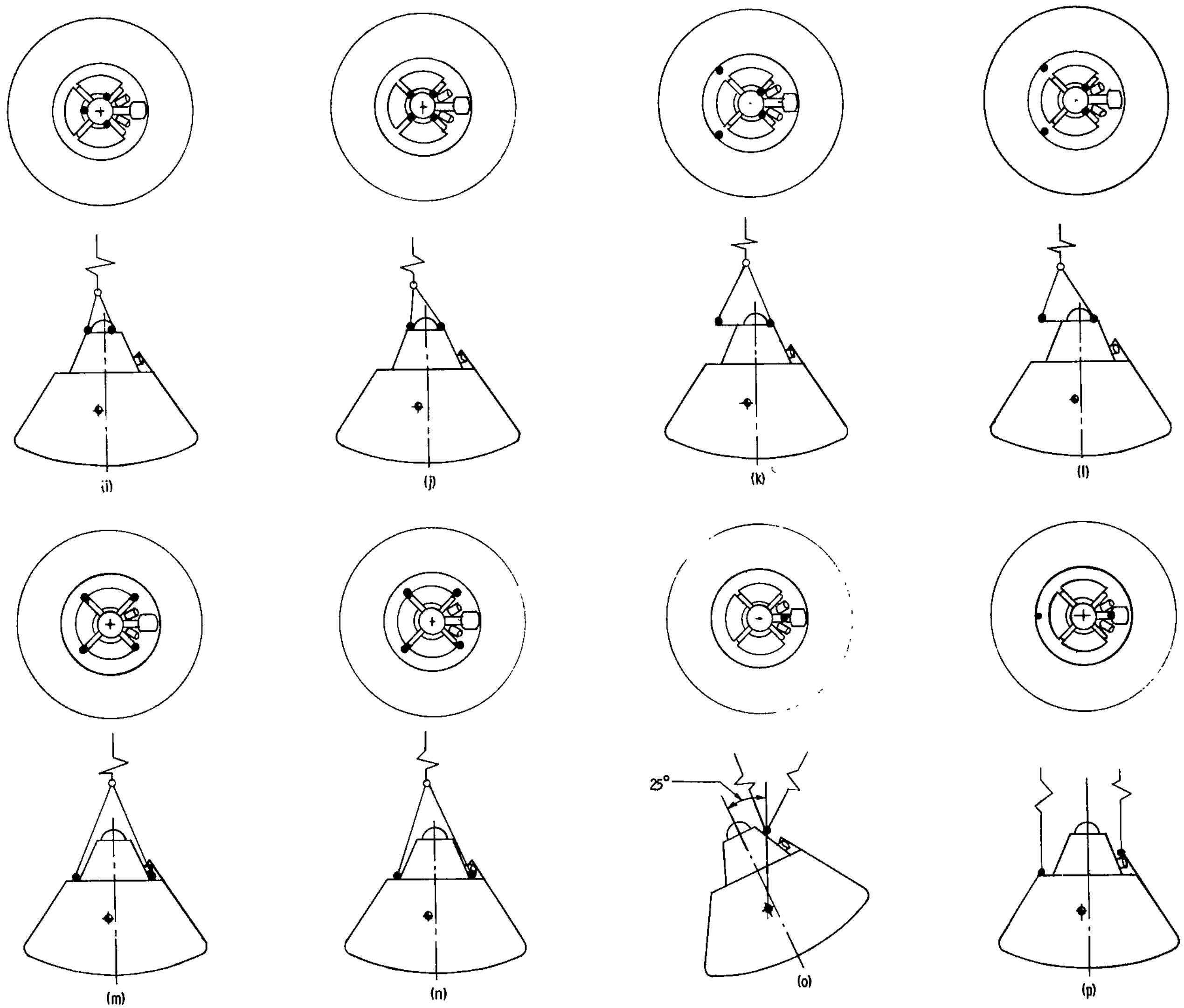

Figure 12.- Concluded.

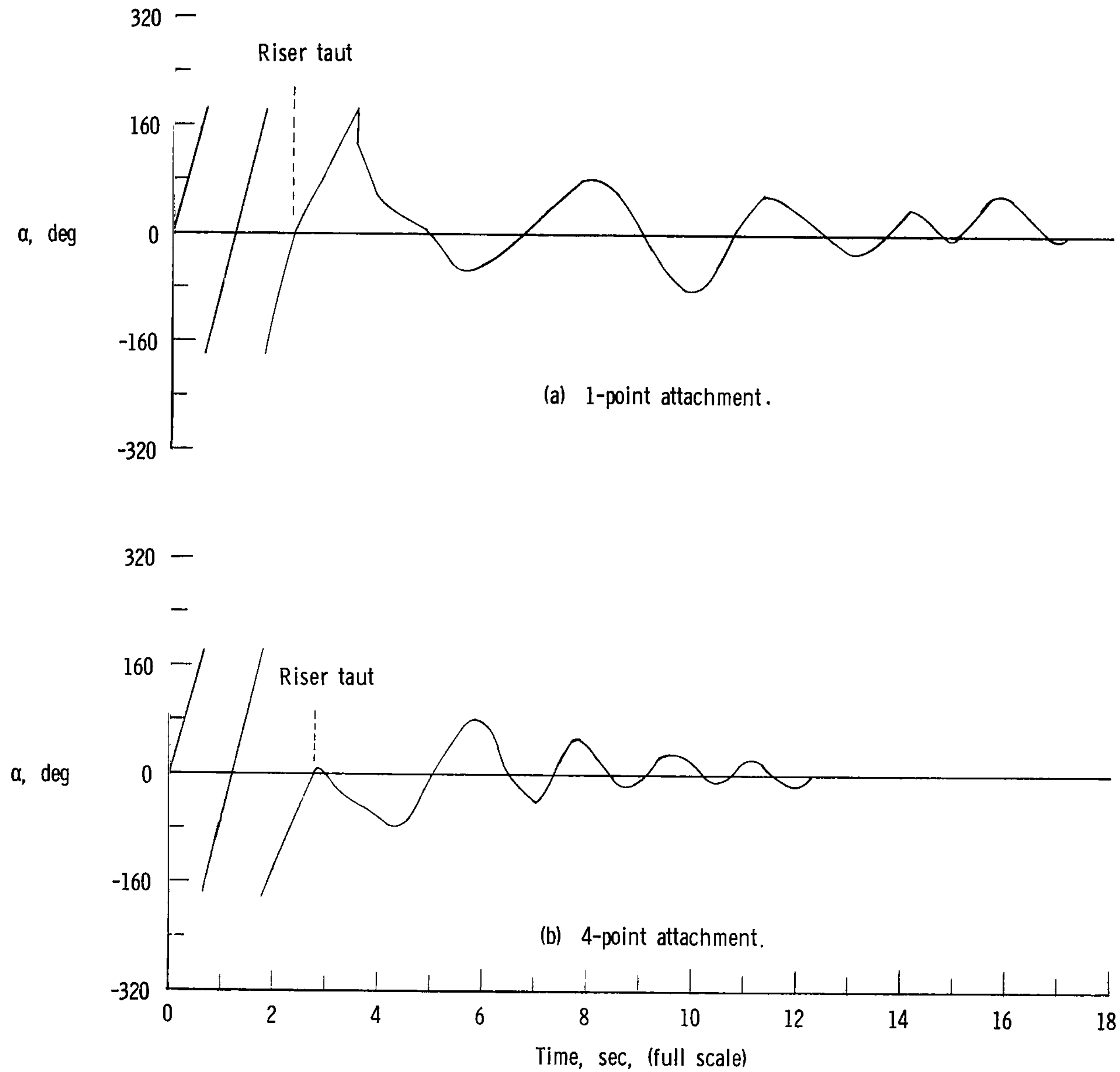

Figure 13.- Typical time histories showing effect of drogue parachute attachment configuration on motion of spacecraft during and after deployment of parachute. Parachute was deployed from a tumbling condition of spacecraft at time zero.

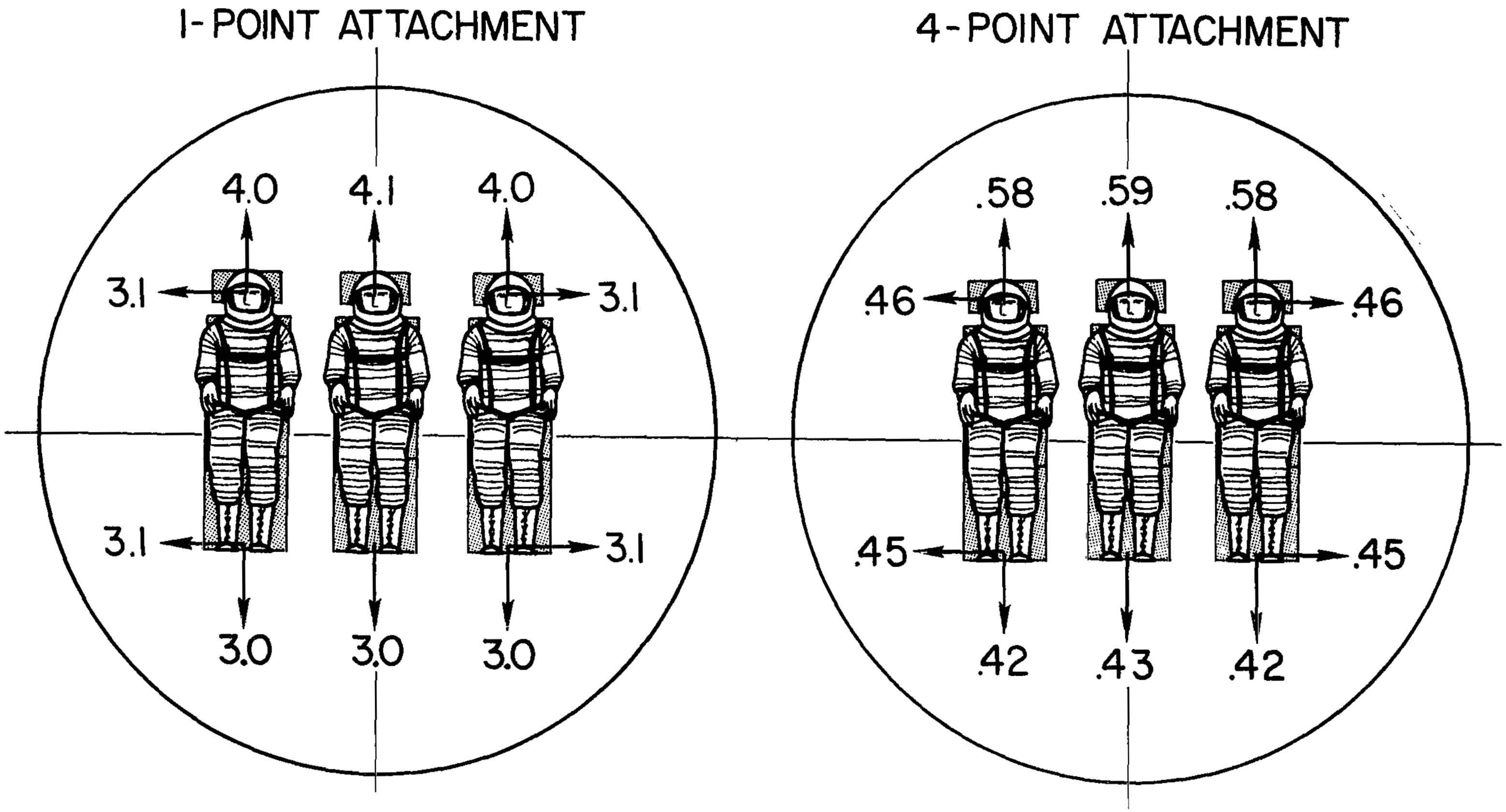

Figure 14.- Maximum acceleration in g units on crew due to spacecraft rotation about symmetrical axis for two different drogue parachute attachment configurations.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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