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by Euclid C. Holleman

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SUMMARY

Flights to high altitude with the X-15 research airplane have successfully demonstrated that a pilot can control lifting entry into the atmosphere. Flights were made with two airplane configurations and with several types of reaction and aerodynamic controls.

The pilots' performance in these flights was similar with all of the reaction control systems tested--angular acceleration, angular acceleration with damping, and rate command--and was comparable to the performance of the automatic hold systems. The pilots evaluated the reaction control task with all systems as satisfactory. For a range of altitude from 200,000 feet to 354,200 feet, the entry control task with attitude command with damping, rate command, and hold was rated satisfactory. The entry acceleration environment did not affect the pilot's performance. Neither the controllability of the entry nor the pilot's evaluation of the task was degraded by the more severe entries.

With the preflight procedures established for the X-15 program, control of range to the landing site has been accomplished easily by the pilots. Flights to high altitude have been planned with 50 to 100 nautical miles of excess range, and the pilots have been able to judge and control excess range by modulating angle of attack and using speed brakes to insure landing at the desired landing site.

INTRODUCTION

The X-15 airplane is the first piloted airplane designed for atmospheric entry and hypersonic flight research. As such, it is capable of investigating flight problems at extremely high altitudes and at high speeds in an actual entry flight environment characterized by high acceleration forces and both rapid and large changes in airplane response characteristics.

In a flight program designed to explore the entry control characteristics of the X-15 airplane, 12 flights to approximately 200,000 feet or greater were made, thus providing piloted entry experience from high altitude. Two airplane configurations and several different reaction and stability augmentation controls were used.

This paper summarizes the high-altitude X-15 flight experience, which culminated in a flight to an altitude of 354,200 feet. Discussed are the basic stability, control, and handling characteristics of the airplane, the cockpit displays, and the operational techniques that enabled it to be successfully flown to and recovered from high altitudes without special piloting aids other than stability augmentation. Flight experience to moderately high altitudes with the airplane equipped with interim rocket engines is discussed in reference 1.

The symbols used in this paper are defined in the appendix.

AIRPLANE AND SYSTEMS

Airplane

The X-15 is a single-place, rocket-powered airplane (figs. 1 and 2) designed for flight at hypersonic speeds and extreme altitudes. It is carried aloft under the right wing of a B-52 aircraft and is launched at an altitude of about 45,000 feet and a Mach number of about 0.80. After launch, the X-15 performs a powered flight mission followed by a deceleration glide before vectoring for a landing at Edwards Air Force Base, Calif. With this operational technique, the airplane is capable of a Mach number of 6 and can be flown to and recovered from an altitude in excess of 300,000 feet.

Flights to high altitude have been made with two airplane configurations--lower movable ventral on, and lower ventral off (fig. 2). The stability and control and physical characteristics of these configurations are presented in detail in reference 2. The static-stability derivatives of the basic airplane (lower ventral on) indicate that the vehicle should be stable throughout the flight envelope; however, near a Mach number of 3.0 and an angle of attack of 10° the airplane was uncontrollable without damping augmentation and with the pilot controlling bank angle normally. An analysis of this instability revealed the cause to be an unfavorable combination of the yawing moment due to aileron deflection and the dihedral effect, which was subsequently alleviated by removing the lower movable ventral (ref. 3). The change, although producing lower static-directional stability and rudder effectiveness, resulted in a more controllable airplane with damping augmentation inoperative, particularly at high angles of attack.

Aerodynamic control is provided through conventional aerodynamic surfaces; however, the horizontal tail provides both pitch and roll control. The aerodynamic control surfaces are actuated by irreversible hydraulic systems. Artificial feel is provided for control feel. A conventional center stick, a right-side-located controller, and rudder pedals provide aerodynamic control. The controller, although designed for use in high-acceleration environments, was used by the pilots throughout the aerodynamic flight regime. A left-side-located three-axis controller is also provided for use with the reaction control system. This control system is described in detail in reference 4.

Augmentation Systems

To provide adequate handling qualities over the aerodynamic operating envelope of the X-15 airplane, aerodynamic damping augmentation about all three axes is necessary. The two systems designed for this purpose are a conventional stability augmentation (damper) system, referred to as SAS, and the adaptive flight control system, referred to as AFCS. Detailed descriptions of these systems may be found in references 4 and 5 (SAS) and 6 to 8 (AFCS).

Stability augmentation system.- The SAS provides auxiliary aerodynamic damping by actuating the aerodynamic control surfaces to oppose the rotational velocity of the airplane. For the basic airplane configuration, an interconnect damper loop (termed yar) provides a crossfeed yaw-rate signal into the roll control surfaces. With the ventral-off configuration, the yar interconnect is undesirable and, therefore, not used. Because of a need for redundancy, a backup augmentation system has been designed and installed in the roll modes of the two X-15 airplanes that are equipped with stability augmentation systems.

Adaptive flight control system.- The AFCS used in the other aircraft is a model-following, rate command system. The principal features of the system are: self-adjusting gains, rate-command control by the pilot, hold or attitude command modes of operation, normal-acceleration command and limiting, and automatic blending of aerodynamic and jet reaction controls. Most of the high-altitude flights were made with this system because of its inherent high performance, fail-safety features, and high reliability.

Reaction Controls

Four modes of operation--angular acceleration command with and without reaction augmentation damping, angular rate command, and attitude command or hold--are available with the reaction control system (see refs. 6 to 9). All the modes have been used during flights to extremely low dynamic pressure. The basic reaction control system is dualized for redundancy. Damping augmentation has been provided by paralleling one channel of the basic system with an electronically controlled rate damper and is available only when reaction control thrust is not commanded by the pilot.

The reaction controls for the airplane equipped with the adaptive flight control system may be operated in any combination of three modes: the basic angular-acceleration-command mode activated by the separate three-axis controller, an angular rate command mode integrated with the aerodynamic controls, and an attitude hold or attitude command mode also integrated with the aerodynamic controls.

Displays

A photograph of the pilot's display is shown in figure 3. The three-axis attitude indicator (center) is the primary instrument for displaying airplane pitch, roll, and yaw attitude to the pilot. A pitch-attitude vernier is provided on the left side of the indicator for more accurate display of pitch attitude. A display giving dynamic pressure is located above the attitude indicator, and immediately above the dynamic-pressure display is a timer which displays elapsed engine thrust time. Early in the program when inertial velocity was not yet considered to be reliable, thrust time was used as a cue to shut down the engine.

Angle of attack and sideslip are presented on the cross bars of the three-axis attitude indicator. Actual readings of α and β are not given on the indicator, but the angle-of-attack bar may be set as a vernier for establishing entry angle of attack. At high altitude where the sideslip indication is unreliable, the sideslip bar may be switched to present heading change. Angle of attack is also presented on a dial gage to the left of the attitude indicator. Above the angle-of-attack dial is a presentation of normal acceleration.

Conventional pressure-derived airspeed and altitude are displayed to the left of the angle-of-attack dial for use at Mach numbers less than 2 and altitudes less than 80,000 feet. Velocity, altitude, and rate of climb, derived from the inertial reference platform, are displayed in the upper-right corner of the panel. A display of roll rate was included as a secondary display for use in the event the augmentation system failed.

The X-15 airplanes are operated only during contact flight conditions, so no guidance displays, with the exception of heading, are provided for the pilot.

OPERATIONAL PLAN

The philosophy of the X-15 flight-test program, as stated in reference 10, was to expand the flight envelope to the maximum speed and altitude as rapidly as practical and to obtain, simultaneously, as much research data in hypersonic flight as possible. The envelope-expansion program has been performed on an incremental performance basis; that is, each successive flight is designed to go to a slightly higher speed or altitude than the previous flight. This approach permits a reasonable extrapolation of flight-test data from one flight to the next and builds a backlog of pilot experience.

The flight plan for a typical altitude mission is shown in table I, and the time history of a flight to an altitude of 285,000 feet is shown in figure 4. Immediately after launch, the pilot opens the throttle to 100-percent thrust and rotates the airplane until the limiting condition of 2g or 10° of angle of attack is reached. This condition is maintained until the desired exit pitch angle (42°) is attained. Thereafter, the pitch vernier on the three-axis ball allows the pilot to fly a constant pitch attitude to within 1°. At the extreme pitch angles, the pilot must rely entirely on his displays, since contact flight is inaccurate and impractical. The inertial-system indications of velocity and altitude and the radar altitude callouts from the ground provide the pilot with additional cues. Final velocity or engine shutdown time and exit pitch attitude are the two quantities that the pilot must control effectively during the powered portion of the flight in order to control maximum altitude.

After engine shutdown during the low-dynamic-pressure portion of the flight, the pilot uses the reaction controls, on cue from the three-axis attitude indicator, to control the airplane attitude. The airplane is in a ballistic trajectory and only attitude is controllable. The desired entry angle of attack is established by using the reaction controls. As dynamic pressure builds up, angle of attack is maintained until normal acceleration increases to the level required for pullout. This acceleration is held until level flight is achieved and a glide to the landing site is established. The pressure instruments (altitude, airspeed) are used after the airplane reaches Mach numbers less than 2 and altitudes less than 80,000 feet to perform the approach and landing.

Pilot Preparation

Before each flight, the pilot practices the proposed flight plan using the six-degree-of-freedom X-15 fixed-base simulator. Both the pilot and the ground controller become familiar with the required piloting techniques and timing of the proposed flight plan. The desired flight is "flown" several times, and changes suggested by the pilot are incorporated into the flight plan. After the pilot is thoroughly familiar with the flight plan, flights slightly off the desired are flown to acquaint him with the effect of variations in critical control parameters. In addition, simulated emergency conditions are practiced, and anticipated emergencies that might result from malfunctions of the engine, inertial platform, flow-direction sensor, radio or radar, and stability augmentation system are rehearsed. Failures that do not affect the flight are distinguished from those that cause alteration to the flight plan. An extreme failure may dictate that the flight plan be abandoned, with safe recovery of the airplane and pilot the only objective.

Ground Controller

Although the pilot is in complete control of the flight, the ground monitoring station performs an important function in support of the flight operation. The monitor station is equipped with displayed radar and selected channels of telemetered data. The ground controllers monitor subsystem operation, captive flight track, engine operation, flight track, stability and control parameters, pilot's physiological factors, airplane energy to insure recovery, and, in an emergency, direct air search and rescue.

Since all the flights considered herein were made without on-board energy-management display for the pilot, the ground controllers furnished information to the pilot as required. A simplified system, based on the energy-management footprint concept and consisting of a family of curves for points along the projected track, was used to give the ground controller an indication of the range capability of the airplane at any time during the flight so that he could relay information to the pilot. The procedure has been satisfactory for all the flights; however, a ground-based real-time computation of energy has been mechanized and will be displayed as range capability for future flights.

RESULTS AND DISCUSSION

Two series of buildup flights were made. During the first, an altitude of 314,750 feet was reached with the basic airplane configuration. The second series was made with the ventral-off configuration, and an altitude of 354,200 feet, the maximum altitude obtained to date, was reached.

The altitude and velocity of flights to high altitude considered in this paper are shown in figure 5; detailed information concerning the flights is presented in tables II and III. The boost portion of the flight to high altitude is analyzed in reference 11. As indicated in table III, the pilot did not always control to the desired altitude; however, during most of the flights he was able to control as accurately as the information displayed to him allowed. The boost-acceleration environment did not affect the pilot's performance.

High-Altitude Experience

During the flights to high altitude, aerodynamic controls were used until their effectiveness became low; the transition to reaction controls was then made. Below a dynamic pressure of 10 lb/sq ft, the reaction controls provided more control than could be obtained with aerodynamic controls (fig. 6). However, the aerodynamic controls require large surface deflections which provide effective trimming moments during low-dynamic-pressure flight but are not especially useful as damping devices.

Time histories of representative flights with reaction controls are presented in figures 7(a) to 7(h). Summarized in the figures and in table II is the experience with several types of control systems: acceleration command, rate command, and attitude command or hold operation for various piloting tasks. The tasks are shown as heavy lines. Table II also includes the pilot ratings of the reaction controls and piloting tasks and gives an estimate of the reaction control propellant used and the frequency of control utilization. Simulator studies (ref. 12) have shown that the effective use of reaction controls is a function of piloting experience and technique. This was particularly true with acceleration command reaction controls where the controlled quantity is two integrations removed from the immediate response to control. It is possible, therefore, that some of the data presented herein were, of necessity, obtained before the pilots had progressed to a steady performance level; however, in all cases, the pilots had sufficient practice on the simulator to be very familiar with the simulated reaction control piloting task.

Evaluation of acceleration command control.– Figure 7(a) presents data from a flight to a peak altitude of 217,000 feet in which acceleration command reaction controls were used. The minimum dynamic pressure was 3.4 lb/sq ft. This was the pilot's first flight at low dynamic pressure. The piloting task called, initially, for maintaining zero angle of attack. A 5° change in angle of attack was requested at maximum altitude; however, the desired angle was overshot. Also, a 14° angle of attack for entry was requested but again was not achieved. The effect of the airplane aerodynamics is shown by the sinusoidal oscillation of the airplane response in both pitch and yaw. The disturbance in pitch is probably the result of reaction controls, but the aerodynamic restoring moments of the airplane help sustain the airplane motions. No control was used in yaw; however, oscillatory motions are evident, probably initiated by the aileron control. Control at low dynamic pressure was more difficult than at zero dynamic pressure. The aerodynamic controls used by the pilot and the SAS are also included, inasmuch as during most of the flight the aerodynamic controls were almost as effective as the reaction controls.

Evaluation of rate command control.– Data from a flight to an altitude of 223,700 feet in which rate command reaction controls were used are shown in figure 7(b). The minimum dynamic pressure was 2.9 lb/sq ft. Close control of bank angle is indicated, at the expense of a high number of control inputs. The desired flight plan in pitch was not followed closely, but the requested entry angle of attack was established and held. No pilot or automatic control inputs were observed in yaw, since the pilot was evidently satisfied with the airplane heading and the rates developed were less than the system threshold. Total reaction control fuel used was significantly less than that used during the previously described flight with the acceleration command control system (fig. 7(a)). Although the two flights were made by different pilots, both rated the control tasks as generally satisfactory.

Effect of reaction damping.– Figure 7(c) presents data from a flight at low dynamic pressure in which the acceleration command reaction controls were used together with reaction damping augmentation. For this flight the pilot was asked to control pitch and bank angle within 8° of 0 to obtain pilot-performance data applicable to a future stellar-photographic program with the X-15. Thus, the pilot had a clearly defined objective, and the control task was successfully accomplished within the desired limits. This flight was made by a third X-15 pilot who, at the time, had accumulated most of the reaction control experience achieved during the program. Total control fuel used was higher than with the rate command system but less than with the acceleration command system. The pilot considered the effectiveness of the control system for the given control task to be excellent.

Comparison of manual and automatic controls.– Figures 7(d) and 7(e) provide a comparison of control tasks during flights to an altitude of about 250,000 feet (design altitude) where the minimum dynamic pressure was less than 1 lb/sq ft. The rate command and hold reaction control features of the adaptive control system were used in the flight depicted in figure 7(d). Initially, angle-of-attack hold was used. Bank angle and heading were controlled manually as maximum altitude was approached; the hold modes were used during entry. Bank angle was controlled precisely but required careful monitoring. Angle of attack and pitch angle were not closely controlled except prior to entry. Aerodynamic control inputs are also evident since, with blended controls, aerodynamic control is commanded with the same stick movement that commands reaction control.

Figure 7(e) shows a similar flight with manual control through the acceleration command system. The excursions in the controlled quantities show that the airplane motions were not controlled as closely by the pilot with the acceleration command control system as the combined pilot-autopilot controlled the flight of figure 7(d). At maximum altitude the pilot was asked to bank to approximately 30° to evaluate the effectiveness of the ballistic control system. The angle reached was 28°. The lack of reaction damping is evidenced by the oscillatory motions. The pilot was not able to damp the airplane oscillation in yaw.

In both flights the pitch reaction control inputs were predominantly up in order to maintain pitch attitude and to establish entry angle of attack. With the rate command system, the pilot was content to allow slow excursions in yaw; whereas, with the acceleration command system, he attempted to minimize the excursions in yaw. With the rate command system, the bank angle was held within 5°, but at the expense of many control inputs. With the acceleration command system, the pilot was asked to bank to and stabilize at an angle of -30° and then return to 0°. Both pilots successfully performed the bank control task assigned. With the two systems the control fuel used was about the same for the roll control task. For the yaw stabilization task, much more control fuel was used with the acceleration command controls. The control task with the more sophisticated controls was rated as substantially improved over that with the simpler acceleration command system. Although the reaction control inputs are shown to be the same amplitude for pitch, roll, and yaw, the roll reaction control thrust is lower and, so, consumes less control fuel.

Presented in figure 7(f) are data from a flight to an altitude of 271,700 feet with a minimum dynamic pressure of less than 1 lb/sq ft. Rate command controls were used by the pilot to control the airplane manually. The pitch and yaw modes illustrate loose but effective containment of the motions with little expenditure of control fuel. The flight was flown by the most experienced X-15 pilot. Bank angle was closely controlled with many control inputs. It is interesting to note that the pilot rated the roll-control task superior to the pitch and yaw modes, which were controlled less closely. The total control fuel used was much less than for some of the lower-altitude flights. The reduction is attributed, for the most part, to the pilot's greater experience in using the reaction controls.

Flights above 300,000 feet.- Near-maximum use was made of the automatic control features of the adaptive control system in the first flight to an altitude greater than 300,000 feet (fig. 7(g)). Roll and heading hold were used during the entire flight, and bank angle was controlled within close limits. Although a heading of 205° was specified, the heading hold accepted by the pilot was about 4° less. Few control inputs were required in this control mode. An angle of attack of 10° was requested during the final phase of climbout, although at the extreme altitude the angle of attack was expected to be unreliable because of the extremely low dynamic pressure. From maximum altitude to the acquisition of reentry angle of attack, pitch-attitude hold was engaged and the system held pitch angle to within 2° to 3° of the desired value. As was expected with hold modes in operation, the control system operation was evaluated as satisfactory even in yaw where some drift was allowed. However, reaction control fuel consumption was relatively high, especially in the pitch channel (table II).

A compromise between automatic hold and manual rate command control (fig. 7(h)) was used during a flight to 347,800 feet in which the minimum dynamic pressure was calculated to be about 0.01 lb/sq ft. Roll and yaw hold was used, and the system performance was rated satisfactory in holding bank angle to within 5°. The primary task was control of the pitch mode, which was accomplished manually by the pilot using the rate command control system. Average piloting error in pitch and entry angle of attack was about 5°. More reaction control fuel was used in the mode controlled manually, but the pilot evaluated control in all three modes as excellent.

Summary of Reaction Control Experience

Flight experience with the X-15 airplane has indicated that the pilot uses reaction controls to surprisingly high levels of dynamic pressure, where aerodynamic controls would be several times more effective than reaction controls. For example, reaction controls have been used at dynamic pressures as high as 200 lb/sq ft on exit and 500 to 600 lb/sq ft on reentry. This technique appears to be peculiar to the X-15 operation, in which dynamic pressure decreases at a high rate during exit and builds up rapidly during reentry. Rates of change of dynamic pressure from about 30 to 60 lb/sq ft/sec have been observed during entries from high altitudes. During these critical control times, the pilot used whatever control seemed most effective to accomplish the control task. The pilots have used the reaction controls effectively to damp the airplane oscillatory motions during entry at relatively high dynamic pressure. These controls apply a pure moment with less lag and, so, do not excite unwanted responses. The adaptive system reaction controls, by design, also operate in regions of rapidly changing and high dynamic pressure, since these control regions are critical for controllability, as is discussed later.

As noted previously, table II summarizes the flight experience obtained with reaction controls. Although total fuel used does not necessarily reflect the efficiency or controllability of a system closed by a pilot, the total fuel and control inputs are shown and include experience at all levels of dynamic pressure. For these flights the pilots were thoroughly rehearsed on the fixed-base simulator; nevertheless, these data must be considered to be preliminary because of the limited total experience in these flight regimes.

Fuel consumption.— As might be expected, the reaction control fuel consumption in regions of high dynamic pressure was high and was not representative of that required to stabilize in low-dynamic-pressure regions for which the reaction controls were designed. In order to compare reaction fuel consumption in regions of low dynamic pressure, a tabulation was made of the use of the reaction controls in regions of dynamic pressure less than 5 lb/sq ft. Figure 8 indicates the time available for evaluation of the reaction controls in this range of low dynamic pressure and shows the maximum available control time to be of the order of 3 minutes. It is also apparent that for the range of the flights the only valid comparison is on a rate-of-fuel-usage basis rather than total fuel consumed.

The reaction control fuel used per second for stabilizing tasks in flight regions with a dynamic pressure less than 5 lb/sq ft is shown in figure 9 for the four reaction control systems tested. Compared are fuel rates for pitch, roll, and yaw control. In view of the paucity of data, the fuel rates for pitch and roll control were comparable. The pilots appeared to be the least concerned with close control in yaw (heading), but indicated that the yaw task would be as difficult as pitch and roll if the pilot chose to control this quantity closely. This is substantiated in the figure by the experience shown for the acceleration command system. Fuel consumption of the rate command controls and the automatic hold controls, which comprise most of the data, was comparable. The limited results obtained with the various systems obviate more detailed comparisons.

The reaction-system fuel requirement for damping appeared to be about one half that expended with manual control. The expenditure of fuel for augmentation appears to be justified when the superior pilot rating assigned the augmented controls is considered. These data are discussed in more detail later.

Pilot performance.— Although the amount of reaction control fuel used may give some indication of the effectiveness of the system, a performance measure is also needed to indicate the effectiveness of the pilot—system in accomplishing the desired control tasks. The desired airplane attitudes were indicated on the example time histories of the high-altitude flights presented in figure 7. The average absolute error during these flights at low dynamic pressure is summarized in figure 10. Performance is summarized only for that part of the flight in which the pilot was asked to control to a specified attitude. From these meager data, it appears that slightly less average error was achieved by the automatic hold mode of operation; however, acceptable control performance for the X-15 high-altitude missions was obtained with all systems. Larger average errors were evident in the pitch control, as might be expected, since the steep exit and entry angles required near-continuous compensation to control pitch attitude, simply as a result of the flight trajectory. Roll errors were apparently closely controlled, inasmuch as they are more easily detected by using cockpit displays and external visual cues. Although the pilots could control yaw angle closely, they did not choose to control as closely as the automatic system.

Pilot ratings.— To summarize the flight experience with the reaction control systems, the pilot ratings of the piloting task and control systems are summarized in figure 11. Although all the piloting tasks with the control systems were rated as satisfactory, the control task with the more sophisticated systems (rate or attitude command) was rated as slightly improved over the simpler "acceleration command" system.

Considering the overall evaluation of the reaction control systems tested, the simplest system--the acceleration command reaction control--although satisfactory for the design goals of the program, must be rated somewhat less effective than the other control systems. Fuel consumption could be high depending on control technique, yet the control errors (fig. 10) were not significantly greater than with the other systems. The pilots rated the acceleration command system, however, as slightly inferior to the other systems. Although the hold modes were appreciated for the roll and yaw controls, a preference for manual control of pitch--the primary mode of control--was expressed.

Evaluation of Entry Flight Control

An airplane capable of a maximum Mach number of about 6.0 reenters the atmosphere from high altitude steeply at a large negative flight-path angle. This maneuver is challenging to the pilot, since it is flown at a relatively high angle of attack and under rapidly changing conditions of dynamic pressure and velocity, with the associated changes in aircraft stability and response. A time history of the most severe entry experienced to date (i.e., from the highest altitude) with the X-15 is shown in figure 12(a) in terms of dynamic pressure and dimensional aerodynamic derivatives. Figure 12(b) shows the lateral-directional and longitudinal undamped natural frequency and damping (unaugmented). With Mach number nearly constant, the increase in the dimensional derivative is primarily the result of the rapid change in dynamic pressure; however, the basic airplane characteristic motion, even at high dynamic pressure, is lightly damped. The rapid change in the stability and control sensitivity of the basic airplane with the light damping (unaugmented) was predicted from the flight simulator tests to be a severe control task, near the limit of the control capability of the pilot.

With the augmented control system operating, the primary piloting task during entry is one of trimming the stabilizer to an angle that will result in the desired angle of attack for entry as dynamic pressure builds up. With this technique, the pilot makes corrections only to the airplane's attitude to limit the normal acceleration to the desired value during entry.

X-15 entry experience from high altitudes is summarized in table III, which includes a comparison of the planned and actual flight parameters and pilot ratings of the entry control task. Representative entries from these flights to high altitude are presented in figure 13 to illustrate the X-15 entry characteristics and the piloting control task with the various control systems available in the X-15 airplane.

Figure 13(a) presents an entry from an altitude of 226,400 feet with the conventional controls (manual attitude command in pitch and yaw and roll rate command in roll) with damping augmentation. Speed brakes were extended 20° for decreased range during the entry and increased directional stability, especially at high angles of attack. Maximum entry normal acceleration was 3.6g and dynamic pressure was 1360 lb/sq ft. Control was performed manually, using longitudinal trim to establish the angle of attack for entry.

A similar entry from an altitude of 223,700 feet flown with the adaptive rate command control system is shown in figure 13(b). Peak entry acceleration was about 4g normal and 1.5g longitudinal. An angle of attack of approximately

20° was held until dynamic pressure and the resulting acceleration buildup dictated a reduction to about 5°. Maximum entry dynamic pressure was 1215 lb/sq ft.

A comparison of the two entries (figs. 13(a) and 13(b)) shows similar controllability with the two types of control systems--the conventional control system with SAS and the adaptive control system. The reaction augmentation control system (ref. 9) was used for the initial part of the entry from 226,400 feet (fig. 13(a)), and the adaptive control system, which provides rate command reaction control, was used during the early portion of the entry from 223,700 feet. Establishing entry angle of attack was a simple task with either control system. The lower ventral had been removed for these flights.

Figures 13(c) and 13(d) present data for entries from the design altitude of 250,000 feet with the conventional and the adaptive control systems. For the entry of figure 13(c), the airplane was not equipped with reaction augmentation, so the conventional acceleration command controls were used during the early part of the entry. The entry with the adaptive control system (fig. 13(d)) was, for the most part, made using the system hold modes. The ventral-on airplane configuration was used for both flights, and the speed brakes were extended 35° for the entry of figure 13(c) to reduce the range. The lateral-directional controllability with the adaptive control system, with the hold modes α, φ, and ψ functioning, was superior to the entry with the conventional controls with the lower-gain stability augmentation system. With the low-gain damper system, a lateral-directional oscillation of larger amplitude is evident during the initial part of the dynamic-pressure increase. However, each pilot rated the control task as satisfactory.

Other evaluations of the adaptive control system were obtained on the flights shown in figures 13(e) and 13(f). The entry from 285,000 feet (fig. 13(e)) was flown manually but with the rate command controls with the ventral-off configuration. The entry from 314,750 feet (fig. 13(f)) was made using angle-of-attack, bank, and heading hold in the ventral-on configuration. Speed brakes were extended 20° for the flight shown in figure 13(e) and 35° for the flight in figure 13(f). The controllability of the manually controlled entry (fig. 13(e)) appeared to be superior to that with the attitude command or hold mode. Although ventral-on and additional speed-brake extension increased the directional stability of the airplane, both factors made the airplane less controllable in roll. On the basis of these results, additional wind-tunnel tests, simulator controllability studies, and system reliability considerations, it was decided to fly the remainder of the exploration program of the high-altitude capability of the X-15 with the airplane equipped with the adaptive control system and with the lower ventral removed.

The entries from the two highest altitude flights to date are presented in figures 13(g) and 13(h). These flights were flown manually in pitch with the adaptive control system. The lower ventral was removed, and the speed brakes were extended 20° for increased directional stability. Controllability was rated very satisfactory in both the low- and the high-dynamic-pressure regions. An entry angle of attack of about 25° was held through acceleration buildup to about 5g. There is no evidence of the lateral-directional oscillation characteristics that were found to be objectionable during the entries from 250,000 feet with the ventral-on configuration.

Summary of Entry Experience

Although the flight data that have been obtained are not sufficient to determine the entry angle of attack and normal acceleration required for recovery of the X-15 from high altitude, simulated flight data are available to indicate these requirements (fig. 14) both for the clean airplane from an altitude of 250,000 feet and the airplane with speed brakes extended from altitudes of 250,000 feet and 350,000 feet.

The X-15 entry pullout requirements, from the simulator, for the design altitude of 250,000 feet and a velocity at maximum altitude of 4450 ft/sec are shown in figures 14(a) and 14(b). The simulator minimum velocity at maximum altitude was selected to be the average of the illustrated flights to 250,000 feet. For verification, the peak entry acceleration and dynamic pressure from figures 13(c) and 13(d) are included, although the entry velocities were not identical. Nevertheless, the flight and simulator data, including the average angle of attack during entry, agree.

Similar requirements for entry from 350,000 feet with the speed brakes extended 20° are presented in figure 14(c). The limited flight experience is included and compares well with the predicted entry angle of attack, normal acceleration, and dynamic pressure.

The performance and the controllability of the X-15 airplane have, in general, been closely predicted by the X-15 complete six-degree-of-freedom flight simulator (ref. 13). The simulation used the generalized equations of motion (ref. 14) referenced to the airplane body axes.

Entry profiles.- From these simulated flights, it is apparent that the recovery to level-flight altitude is a strong function of entry angle of attack and, to a lesser extent, the normal acceleration held for pullout. The combination of angle of attack and pullout acceleration determines the peak value of dynamic pressure during entry. As dynamic pressure builds up, a reduction in angle of attack and vertical acceleration is required to avoid pulling up instead of establishing a controlled glide. The entry experience obtained during the X-15 entries from high altitude is summarized in figures 15 to 18.

The time accumulated at elevated g during entries (fig. 15) has ranged from minimal time at 5g to nearly 10 minutes at 1.5g.

Summarized in figures 16(a), 16(b), and 16(c), respectively, are the ranges of Mach number, dynamic pressure, and angle of attack encountered during the entry and terminal glide from the high-altitude flights. Since flights to higher altitude require more time than those to lower altitude, the time base of the entry and ranging data presented was shifted to aline the increase in entry dynamic pressure. Maximum Mach numbers (fig. 16(a)) during entry ranged from 4.25 to 5.4. As planned, subsonic Mach numbers were used during the glide-to-base portions of the flight and resulted in increased range.

The maximum dynamic pressure obtained during entry is dependent on the maximum altitude, angle of attack, and the piloting technique used during entry. Figure 16(b) shows the range of entry dynamic pressure to be from 800 lb/sq ft to 1800 lb/sq ft. The dynamic pressure during the glide to return to base was lower and varied from 200 lb/sq ft to 400 lb/sq ft.

During the aerodynamic portions of flights to high altitude, the angle of attack varied over a range of about 0° to 28° during entry (fig. 16(c)). Since an angle of attack of about 10° results in near maximum lift-to-drag ratio (approximately 2.5), it appears that the X-15 flights were planned and flown without the need for flying maximum L/D. Glide angles of attack flown were generally less than that for maximum L/D.

Pilot evaluations.- Pilot ratings of the entry control task with the various control systems are presented in figures 17(a), (b), and (c) as a function of maximum dynamic pressure, average angle of attack, and maximum normal acceleration. In only one instance (fig. 17(c)) was an entry control task rated poorer than satisfactory, and no degradation in pilot rating is indicated over the range of entry parameters obtained. Also, no preference for a particular aerodynamic control system is indicated. Although the yaw hold mode on one flight was rated by the pilot to be less satisfactory than manually flying the airplane, adjustments to the system's dead band have resulted in a system considered to be completely satisfactory.

Control of range.- Maximum range attained during entry flight was obtained during the flight to an altitude of 354,200 feet (fig. 18). For this entry, the speed brakes were extended 20° for increased directional stability at high angles of attack. The total range to landing pattern high key, which is nominally an altitude of 30,000 feet and a Mach number of 0.8, was approximately 270 nautical miles. The duration of entry was only about 3 minutes.

The lift-to-drag ratio for the X-15 airplane at supersonic speeds is presented in figure 19 to indicate the range of lift-drag ratio available to the pilot through control of the speed brakes. Data are shown for an angle of attack of 10°, which gives approximately maximum L/D. Additional values of L/D below the maximum value can be obtained by the pilot through control of angle of attack; however, extensive use of this control would result in unwanted excursions in the flight path. Although angle of attack is normally used for long-range control, the speed brakes may be used for either long- or short-range control, such as during approach and landing.

This flexibility in controlling range during entry by the use of speed brakes and turning flight is illustrated in figure 20, which compares an entry from an altitude of 354,200 feet with various simulated flight data for the same mission. During the flight shown, the pilot used speed brakes intermittently at his own discretion. A range of about 200 miles is available to the pilot from maximum altitude at a velocity of 4300 ft/sec, but with speed brakes the forward range can be reduced to about 140 miles. If a 2g turn is used for a 180° change of heading, the forward range can be minimized to about 85 miles. Pilot comments indicate that the landing site can be observed from the highest altitude reached to date and from a range of 160 miles; however, corrective control toward the site cannot be made until the entry is nearly completed.

Yet, through careful flight planning, only one incident has occurred that resulted in marginal recovery at the selected landing site. On this occasion, the pilot nearly overflew the landing site by "bouncing" on entry.

The recovery and ranging plan for flights from high altitude to a high key position of $h = 30{,}000$ feet and $M = 0.8$ over the Edwards landing site is illustrated in figure 21. The flights to high altitude with a minimum velocity at maximum altitude of 4000 ft/sec to 5000 ft/sec are planned with 50 to 100 miles of excess range to insure landing at the desired landing site. Compared to the actual flight experience (crosshatched region) is the minimum recovery range for Edwards landings. Range for entry from altitudes greater than 200,000 feet is planned to be greater than 180 nautical miles; flights to 100,000 feet require a range of 150 nautical miles or less.

Additional information concerning the pilot's control of range during recovery and landing of the X-15 airplane is summarized in reference 15.

CONCLUSIONS

Piloted flights to high altitudes have been successfully accomplished with several different control systems in two X-15 airplane configurations. The performance of the pilot and his evaluation of the control tasks during the low-dynamic-pressure and entry portions of high-altitude flight have been analyzed to indicate the effectiveness of the control used and the severity of the control task. These flight tests led to the following conclusions:

1. The pilot's performance during flight at low dynamic pressure was similar with all of the reaction control systems tested--angular acceleration, angular acceleration with damping, and rate command--and was comparable to the performance of the automatic hold systems. The pilots evaluated the reaction control task with all of the systems as satisfactory; however, they preferred the automatic hold modes in roll and yaw and manual control in pitch. Reaction control fuel usage was generally higher with the less sophisticated acceleration command control system.

2. For the entry control task from altitudes of 200,000 to 354,200 feet all of the aerodynamic controls--attitude command with damping, rate command, and attitude hold--were rated satisfactory by the pilots. The entry acceleration environment did not affect the pilots' performance.

3. With the preflight procedures established for the X-15 program, no range control problems have been experienced during terminal glide to the landing site. The pilots have been able to judge and control excess range by modulating angle of attack and using speed brakes to insure landing at the desired landing site.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., December 23, 1965.

APPENDIX

SYMBOLS

All quantities are referenced to an airplane body-axis system.

a_x longitudinal acceleration of airplane center of gravity, g units

a_y transverse acceleration of airplane center of gravity, g units

a_z vertical acceleration of airplane center of gravity, g units

b wing span, feet

C_L lift coefficient, $\frac{\text{Lift force}}{\bar{q}S}$

$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha}$

C_l rolling-moment coefficient, $\frac{\text{Rolling moment}}{\bar{q}Sb}$

$C_{l_p} = \frac{\partial C_l}{\partial \left(\frac{pb}{2V}\right)}$

$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$

$C_{l_\delta} = \frac{\partial C_l}{\partial \delta}$

C_m pitching-moment coefficient, $\frac{\text{Pitching moment}}{\bar{q}Sc}$

$C_{m_q} = \frac{\partial C_m}{\partial \left(\frac{qc}{2V}\right)}$

$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$

$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial \left(\frac{\dot{\alpha} c}{2V}\right)}$

$C_{m_\delta} = \dfrac{\partial C_m}{\partial \delta}$

C_n yawing-moment coefficient, $\dfrac{\text{Yawing moment}}{\bar{q}Sb}$

$C_{n_r} = \dfrac{\partial C_n}{\partial\left(\frac{rb}{2V}\right)}$

$C_{n_\beta} = \dfrac{\partial C_n}{\partial \beta}$

$C_{n_\delta} = \dfrac{\partial C_n}{\partial \delta}$

C_Y side-force coefficient, $\dfrac{\text{Side force}}{\bar{q}S}$

$C_{Y_\beta} = \dfrac{\partial C_Y}{\partial \beta}$

c wing mean aerodynamic chord, feet

D drag force, pounds

g acceleration due to gravity, feet/second^2

h geometric altitude, feet

I_X moment of inertia referred to roll body axis, slug-foot^2

I_Y moment of inertia referred to pitch body axis, slug-foot^2

I_Z moment of inertia referred to yaw body axis, slug-foot^2

L lift force, pounds

$L_p = \dfrac{\bar{q}Sb^2}{2V\ I_X} C_{l_p}$, per second

$L_\alpha = \dfrac{\bar{q}S}{mV} C_{L_\alpha}$, per second

$L_\beta = \dfrac{\bar{q}Sb}{I_X} C_{l_\beta}$, per second^2

$L_\delta = \dfrac{\bar{q}Sb}{I_X} C_{l_\delta}$, per second^2

M Mach number

$M_q = \frac{\bar{q}Sc^2}{2V\ I_Y} C_{m_q}$, per second

$M_\alpha = \frac{\bar{q}Sc}{I_Y} C_{m_\alpha}$, per second^2

$M_{\dot{\alpha}} = \frac{\bar{q}Sc^2}{2V\ I_Y} C_{m_{\dot{\alpha}}}$, per second

$M_\delta = \frac{\bar{q}Sc}{I_Y} C_{m_\delta}$, per second^2

m mass, slugs

$N_r = \frac{\bar{q}Sb^2}{2V\ I_Z} C_{n_r}$, per second

$N_\beta = \frac{\bar{q}Sb}{I_Z} C_{n_\beta}$, per second^2

$N_\delta = \frac{\bar{q}Sb}{I_Z} C_{n_\delta}$, per second^2

p rolling velocity, radians/second

q pitching velocity, radians/second

$\bar{q}$ dynamic pressure, pounds/square foot

r yawing velocity, radians/second

S wing area, square feet

t time, seconds

V true velocity, feet/second

$Y_\beta = \frac{\bar{q}S}{mV} C_{Y_\beta}$, per second

α angle of attack, degrees

β sideslip angle, degrees

γ flight-path angle, degrees

Δ incremental change

δ	control deflection, degrees
ζ	damping ratio
θ	pitch angle, degrees
φ	bank angle, degrees
ψ	heading angle, degrees
ω	undamped natural frequency, radians/second

Subscripts:

a	aileron
e	entry
h	horizontal stabilizer
max	maximum
min	minimum
o	initial
r	recovery to level flight
v	vertical stabilizer
θ	pitch reaction control
φ	roll reaction control
ψ	yaw reaction control

A dot over a symbol indicates a derivative with respect to time.

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TABLE I.– TYPICAL X-15 FLIGHT PLAN

X-15 Flight Request

Flight No.: 3-20-31 Scheduled date: June 27, 1963

Pilot: Major Robert Rushworth

Purpose: Altitude buildup, evaluate horizon scanner, infrared experiment, and ultraviolet experiment

Launch: Delamar Lake on magnetic heading of 214° with adaptive flight control system on "adaptive" damper but with roll hold on, reaction controls "auto," both ballistic control systems "on," and heading vernier switch on "standby."

Item	Time, sec	h, ft	V, ft/sec	α, deg	$\bar{q}$, lb/sq ft	
1	0	45,000	790	2	145	Launch, light engine, increase to 100-percent thrust, and rotate the airplane until 2g is attained.
2	15	45,000	1400	11	440	Maintain 2g until θ = 42°.
3	29	50,000	2900	11	530	At θ = 42°, engage θ hold, use vernier trim to maintain θ = 42°.
4	79	150,000	5100	7	60	Shut down the engine at V = 5100 ft/sec and disengage θ hold.
5	86	180,000	5000	7	8	Switch heading vernier to $\Delta\psi$.
6	170	278,000	4250	--	0.2	At maximum altitude extend the speed brakes to 20°. Roll into 30° left bank and release the controls. Maintain θ = -5° until α = 23°.
7	243	188,000	5000	23	10	At α = 23° turn roll hold off and switch heading vernier to "standby." Maintain α = 23° until normal acceleration = 5g.
8	282	85,000	4600	20	600	Maintain a_z = 5g until $\dot{h}$ = -700 ft/sec. Maximum entry $\bar{q}$ = 760 lb/sq ft.
9	290	76,000	3900	15	760	At $\dot{h}$ = - 700 ft/sec push over to α = 3°, extend speed brakes to 35°, and vector to high key. Turn reaction control switch and engine master switch "off."
10						At high key use speed brakes as required. Pressurize the tanks at 17,000 feet and check flap and "squat" circuit breakers in.
11						After landing slide out, before auxiliary-power-unit shutdown, cycle flaps, set stabilizer trim to zero, and turn all data "off."

TABLE II.– SUMMARY OF FLIGHTS WITH REACTION CONTROLS

Pilot	h_{max}, ft	Reaction-control systems	Piloting modes			Piloting task	Ballistic control pilot rating			Reaction-control fuel used, lb						Total reaction control fuel, lb	Reaction-control inputs					
										θ		φ		ψ			θ		φ		ψ	
			θ	φ	ψ		θ	φ	ψ	Up	Down	Right	Left	Right	Left		Up	Down	Right	Left	Right	Left
A	193,600	Rate command θ hold	m[a] h[b]	m	m	Roll to 30° right bank, maintain for 30 seconds. At h_{max}, engage θ hold at $\theta = 0°$.	1.5	1.5	1.0	55.6	1.8	0.3	5.1	10.0	1.9	[c]74.7	62	4	4	46	20	4
A	209,400	Rate command φ, ψ hold	m	h	h	With φ and ψ hold on, maintain $\alpha = 6°$. At h_{max}, roll into 30° left bank and release. Maintain $\theta = 0°$ until $\alpha = 20°$. Maintain $\alpha = 20°$.	1.0	1.0	1.2	1.0	2.0	2.3	3.3	0	0.2	8.8	3	11	19	37	0	1
B	217,000	Acceleration command	m	m	m	Maintain $\alpha = \beta = 0°$ to h_{max}. At h_{max}, rotate to $\alpha = 5°$ and hold, then to $\alpha = 0°$. Maintain $\alpha = 14°$ for entry.	4.0	2.0	2.0	----	----	----	----	----	----	84.0	17	51	11	14	0	0
C	223,700	Rate command	m	m	m	Maintain $\alpha = 5°$ manually. At h_{max}, maintain $\theta = 0°$ until $\alpha = 20°$. Maintain $\alpha = 20°$ for entry.	3.0	1.5	2.0	8.5	6.7	3.9	4.9	0	0	24.0	17	20	38	52	0	0
A	226,400	Acceleration command damping	m	m	m	Maintain α until $\theta = 0°$, then $\theta = \varphi = 0° \pm 8°$. At h_{max}, maintain $\theta = 0°$ until $\alpha = 20°$.	1.0	1.0	1.7	30	15.6	2.2	5.2	4.1	14.9	72.0	80	42	16	38	11	40
B	246,700	Rate command α, θ, φ, ψ hold	m h	h	h	Hold $\alpha = 8°$, $\varphi = 0°$, $\psi = 205°$ until h = 200,000 feet, then maintain $\theta = 0°$ manually. At h_{max}, engage θ hold at $\theta = 0°$. At $\alpha = 20°$, engage α hold.	1.0	1.0	1.0	18.5	0.8	6.7	8.0	0.4	4.2	38.6	37	2	53	75	1	4
A	247,000	Acceleration command	m	m	m	Maintain $\alpha = 10°$. At h_{max}, bank $\varphi = -30°$. At h = 180,000 feet, establish $\alpha = 18°$ for entry.	3.0	1.0	3.0	17.7	5.5	5.0	6.4	14.2	14.2	63.0	72	39	29	38	31	31
A	271,700	Rate command	m	m	m	Maintain $\alpha = 6°$. At h_{max}, maintain $\theta = 0°$ until $\alpha = 23°$, then maintain $\alpha = 23°$.	3.0	1.0	3.0	7.1	9.7	10.3	11.1	2.3	0.8	41.3	15	26	61	70	8	2
C	285,000	Rate command φ, ψ hold	m	h	h	With φ, ψ hold on, manually control θ. At h_{max}, maintain $\theta = -5°$ until $\alpha = 23°$. Maintain $\alpha = 23°$, φ, ψ hold off for entry.	2.5	1.5	1.5	9.8	3.3	5.3	6.5	1.2	4.1	30.2	30	11	54	62	6	14
B	314,750	Rate command α, θ, φ, ψ hold	m h	h	h	With φ, ψ hold engaged, maintain $\alpha = 10°$ manually. At h_{max}, engage θ hold at $\theta = 0°$. At $\alpha = 23°$, engage α hold.	2.5	1.0	1.5	35.3	3.1	8.2	11.3	0	10.6	68.5	62	12	56	96	0	24
A	347,800	Rate command φ, ψ hold	m	h	h	φ, ψ hold on. At h_{max}, maintain $\theta = -20°$ until $\alpha = 23°$. Maintain $\alpha = 23°$ for entry. φ, ψ hold off during entry.	1.0	1.0	1.0	23.7	12.3	7.0	8.6	14.5	4.9	71.0	42	31	29	77	23	18
A	354,200	Rate command φ, ψ hold	m	h	h	φ, ψ hold on. At h = 330,000 feet, push over to $\theta = 0°$. Roll 45° to -45°. At h_{max}, maintain level flight and $\theta = -20°$. At h = 220,000 feet, establish $\alpha = 26°$ for entry with φ, ψ hold off.	1.2	1.0	1.2	17.5	14.0	6.3	3.4	5.1	8.0	[d]54.3	48	34	47	39	22	20

[a]Denotes manual piloting.
[b]Denotes automatic hold.
[c]Roll augmentation inadvertently turned off during entry.
[d]System freeze malfunction.

TABLE III.– SUMMARY OF ENTRY DATA

Pilot	Configuration		Control	Planned						Actual											Pilot rating					
	Ventral	Speed brakes		h_{max}, ft	$\bar{q}_{min}$, lb/sq ft	α_e, deg	a_z, g	$\bar{q}_{max}$, lb/sq ft	h, ft (level flight)	h_{max}, ft	$\bar{q}_{min}$, lb/sq ft	α_e		a_z, g		$\bar{q}_{max}$, lb/sq ft	h, ft (level flight)	γ_e, deg	V_o, ft/sec	V_{max}, ft/sec	Low $\bar{q}$			High $\bar{q}$		
												High	Average	High	Average						θ	φ	ψ	θ	φ	ψ
A	On	Extended	θ hold, adaptive[a]	220,000	9.0	20	---	-----	------	193,600	10.6	24	10	3.3	2.7	986	67,000	-17	5,150	5,300	---	---	---	1	1	1.5
A	Off	Extended	Manual adaptive	206,000	5.0	20	4.0	550	80,000	209,400	4.0	19	12	3.7	3.2	844	72,000	-28	4,390	4,760	1	1	1	1.5	1	1
B	On	Extended	Manual SAS (8,6,8)	200,000	7.0	14	4.0	1,000	72,000	217,000	3.4	13	12	3.7	3.4	1,436	61,000	-26	4,760	5,260	4	2	2	2	2	2
C	Off	Extended	Manual adaptive	220,000	6.0	20	4.0	630	84,000	223,700	2.9	19.5	18.5	4	3	1,215	61,000	-28.5	4,540	4,850	2.5	1.5	2.0	1.5	1.5	1.5
A	Off	Extended	Manual SAS (8,4,8)	220,000	6.0	20	4.0	630	84,000	226,400	2.0	20	18	3.6	3.2	1,360	54,000	-26	4,780	5,200	2	1	1.7	1	1	1
B	On	Retracted	α, φ, ψ hold, adaptive	250,000	[b]0.75	20	5.5	650	80,000	246,700	[b]0.6	19	16	4.4	3.5	1,086	72,000	-28.5	4,540	5,200	---	---	---	1	1	2
A	On	Extended	Manual SAS (8,6,8)	250,000	[b]1.0	18	5.0	1,150	70,000	247,000	[b]0.9	20.5	17	5	4	1,020	63,000	-29	4,360	5,110	2	3	4	1	1.5	1.5
A	Off	Extended	Manual adaptive	250,000	[b]0.6	23	5.0	625	82,000	271,700	[b]0.2	27	23	3.6	3.2	1,889	49,000	-29	4,920	5,640	---	---	---	1.5	3.0	1.5
C	Off	Extended	Manual adaptive	278,000	[b]0.2	23	5.0	760	76,000	285,000	[b]0.2	26	20	4.2	3.8	1,205	66,000	-35	4,070	5,000	2.5	1.5	1.5	2	1.5	1.5
B	On	Extended	α, φ, ψ hold, adaptive	282,000	[b]0.4	23	5.0	625	80,000	314,750	[b]0.03	22.5	20	5.1	4.9	1,186	65,000	-35	4,550	5,515	---	---	---	2	1	4
A	Off	Extended	Manual adaptive	315,000	[b]0.1	23	5.0	1,000	73,000	347,800	[b]0.01	26	23	4.8	4.3	1,362	66,000	-36	4,270	5,480	1	1	1	1.5	1	1
A	Off	Extended	Manual adaptive	360,000	[b]0.1	26	5.2	1,200	70,000	354,200	[b]0.01	26.5	25	5.2	4.5	1,207	68,000	-37	4,310	5,510	1.5	1	1.5	1	1	1

[a]Roll augmentation inadvertently turned off during entry.
[b]Best estimate.

Figure 1.– X-15 airplane.

E-7902

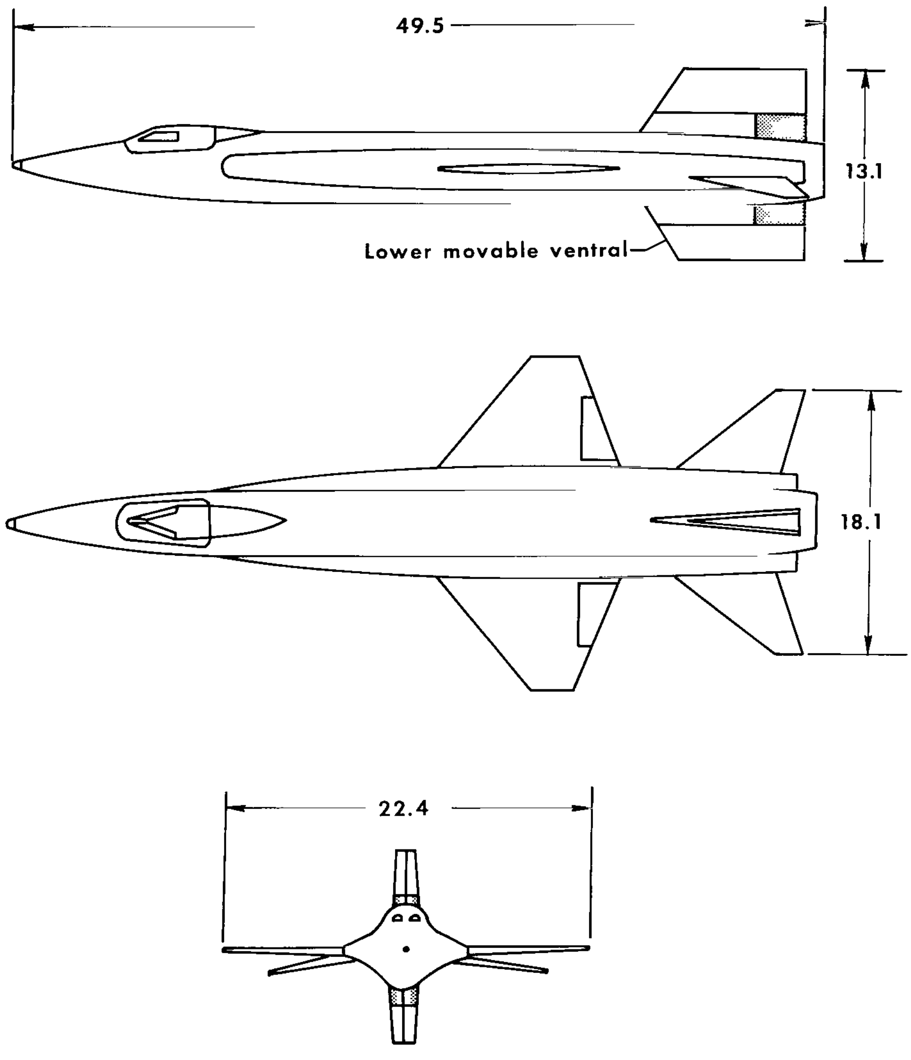
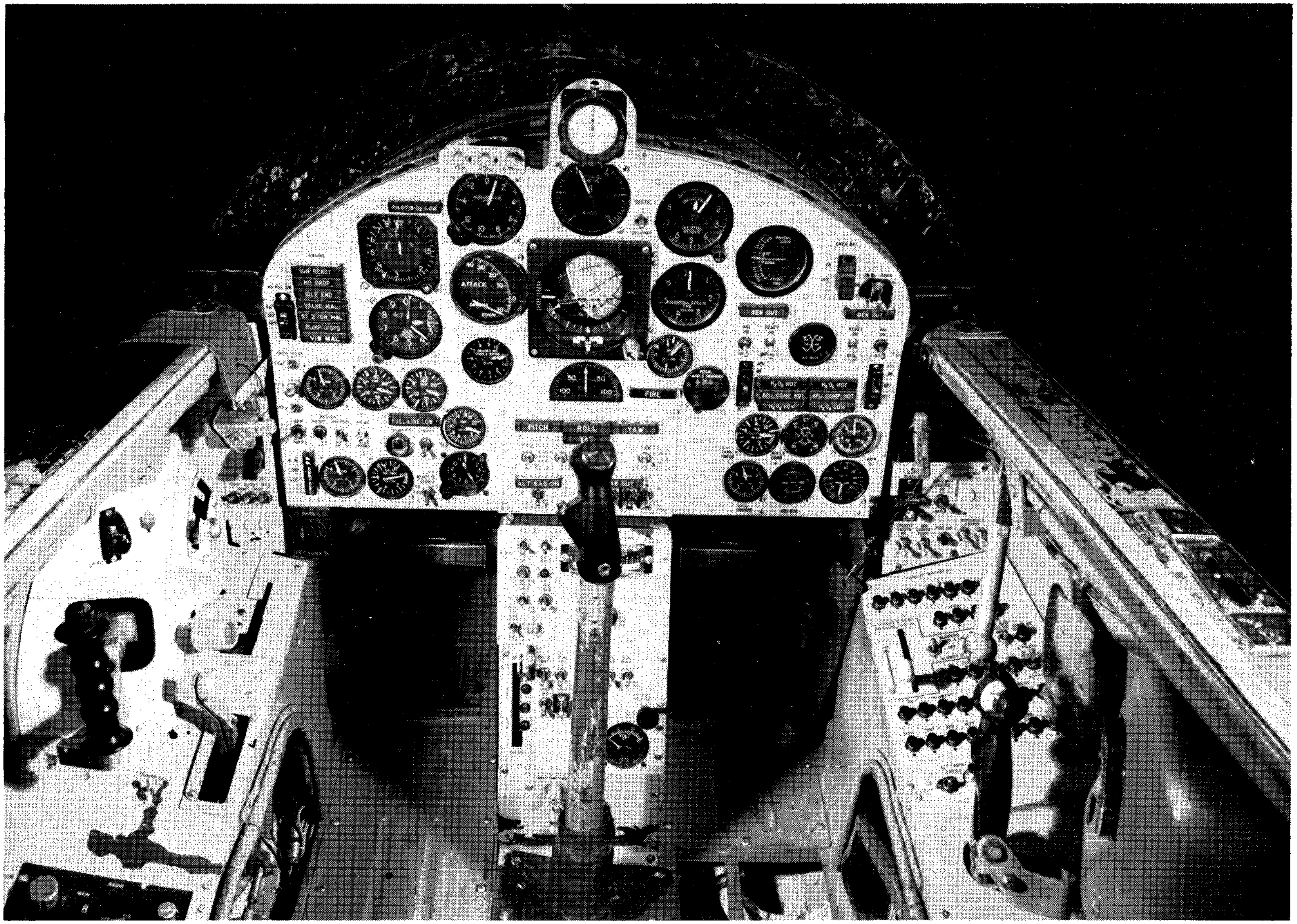


Figure 2.- Three-view drawing of the X-15 airplane. All dimensions in feet.



E-10542

Figure 3.– X-15 cockpit.

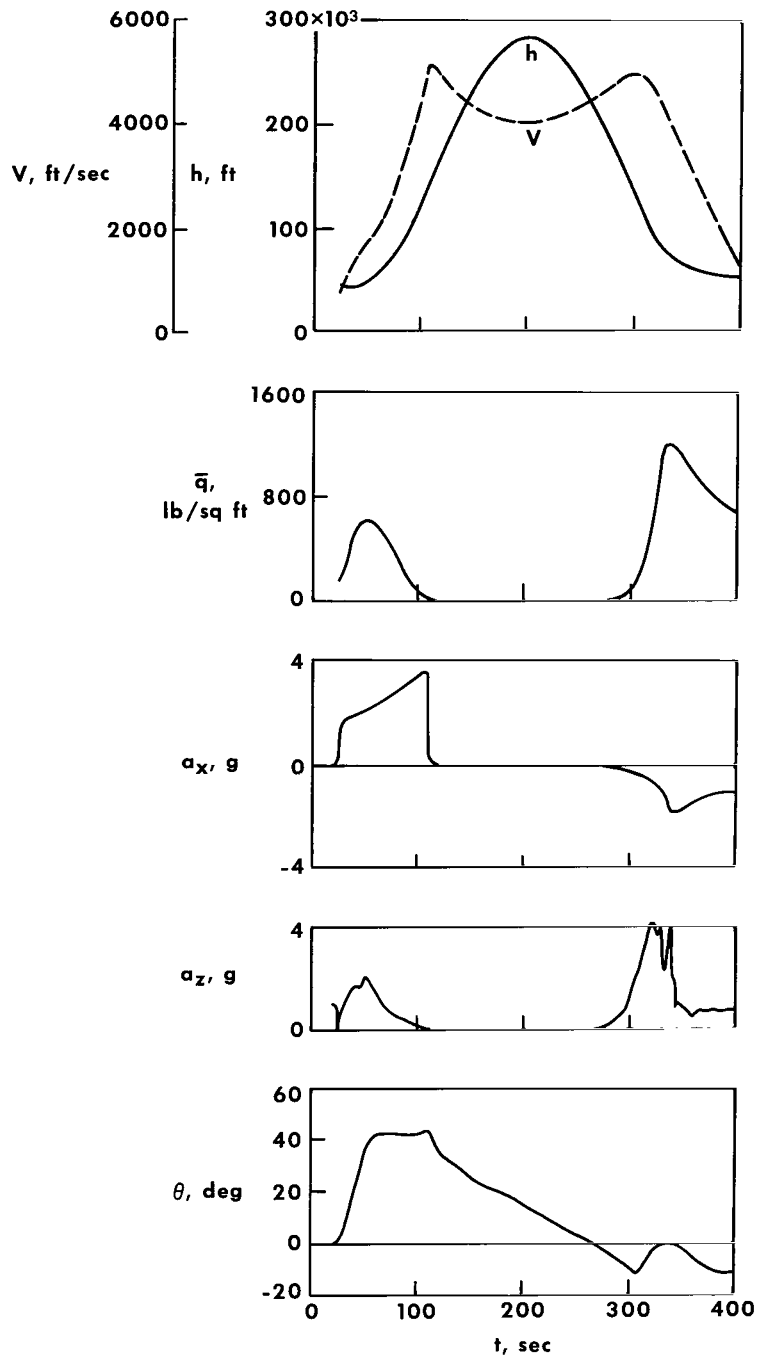


Figure 4.– Representative flight to high altitude.

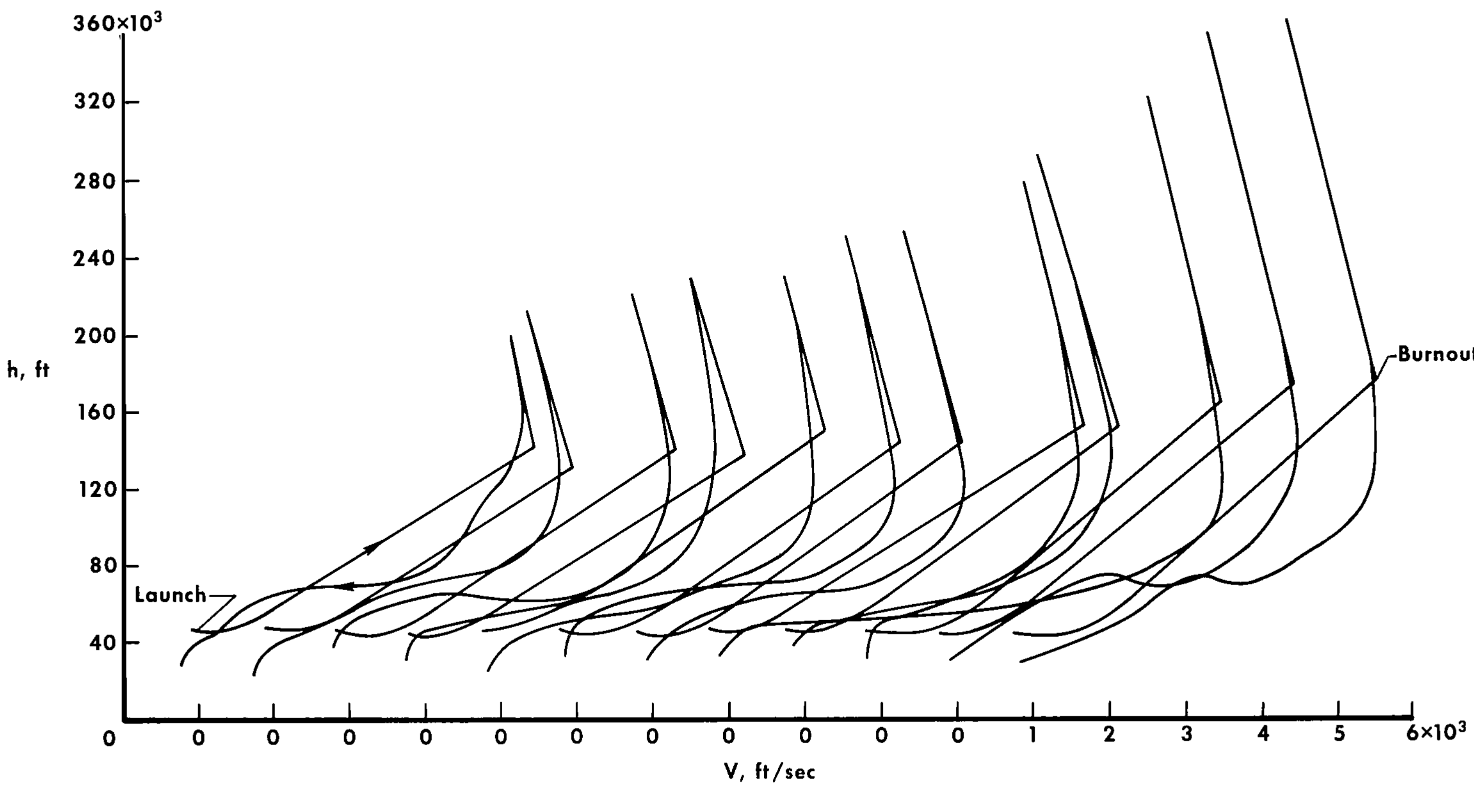


Figure 5.- X-15 altitude flights considered during this investigation.

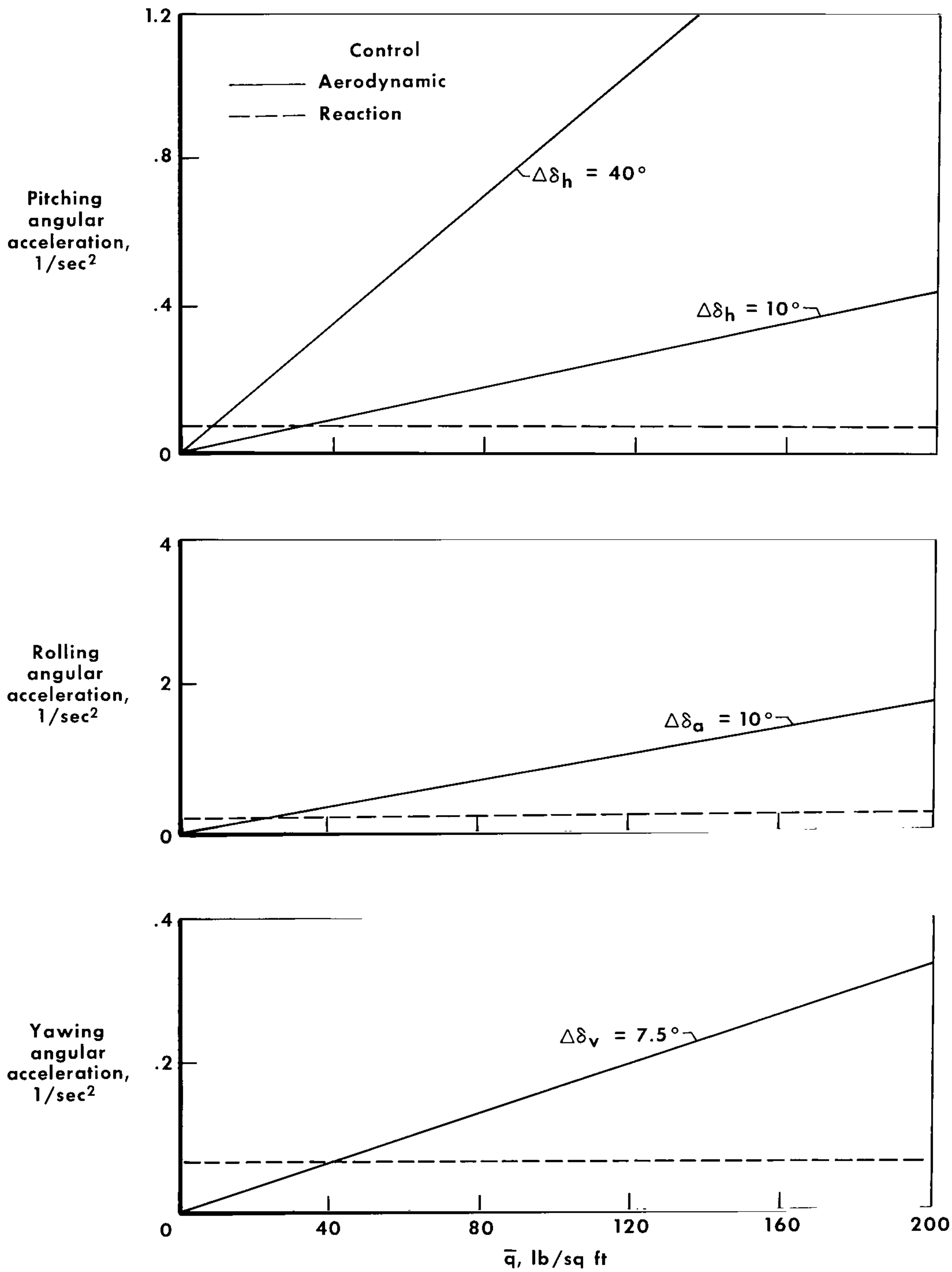
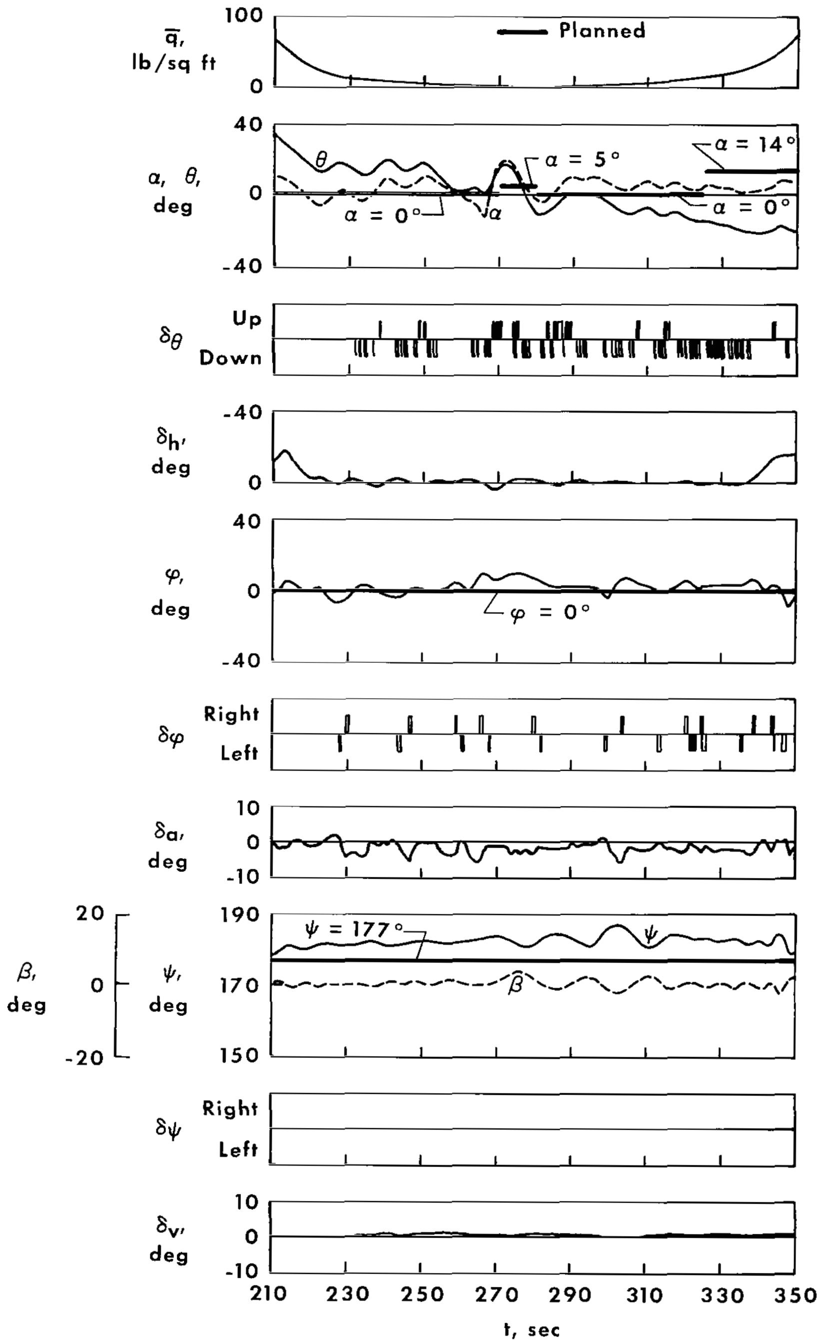
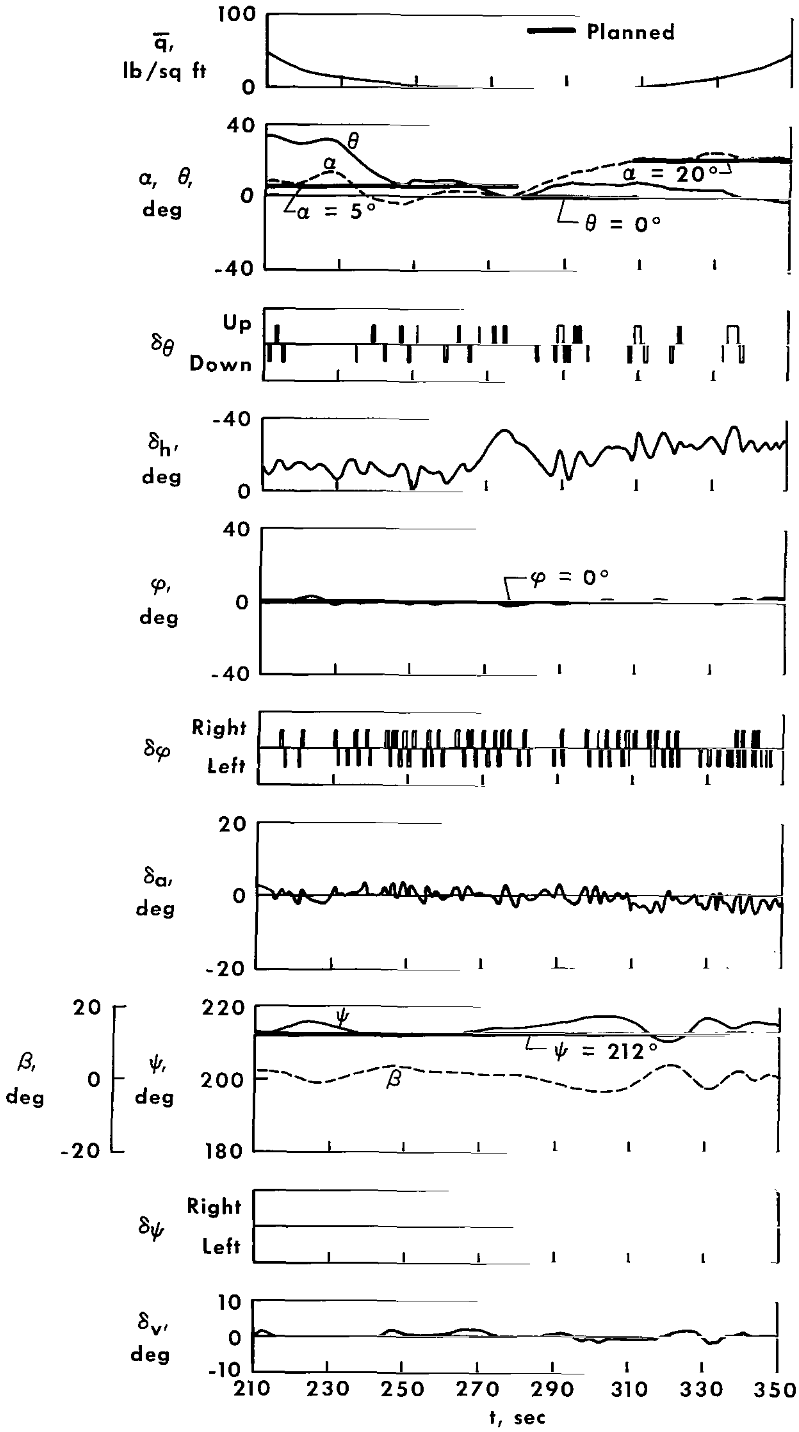


Figure 6.— Comparison of the aerodynamic and reaction control effectiveness. δ_h trimmed at -25° for α_e = 20°.



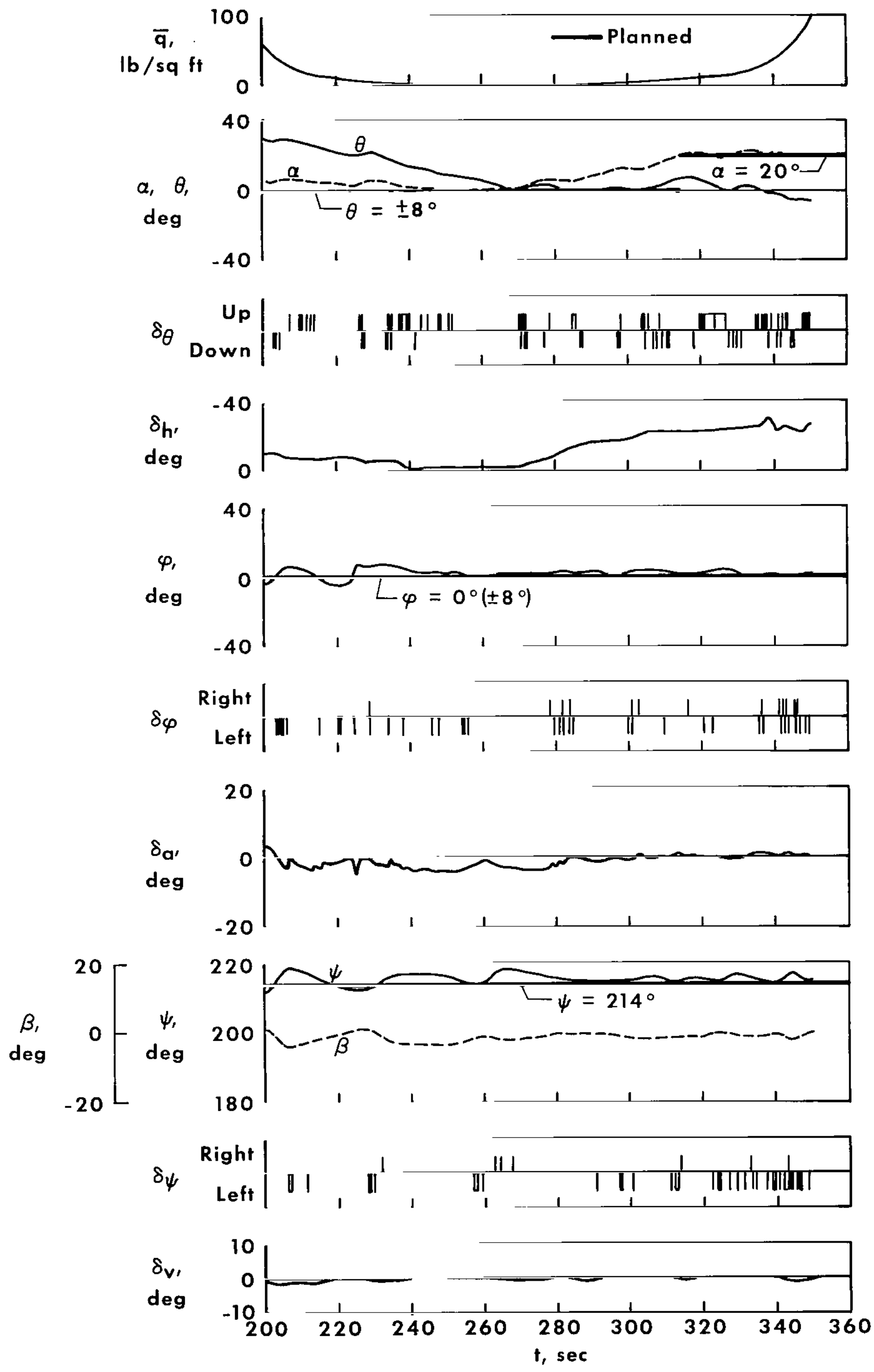
(a) Acceleration command controls manually operated, h_{max} = 217,000 ft, $\bar{q}_{min}$ = 3.4 lb/sq ft.

Figure 7.— Time histories of flights at very low dynamic pressure showing planned and actual values of airplane attitudes.



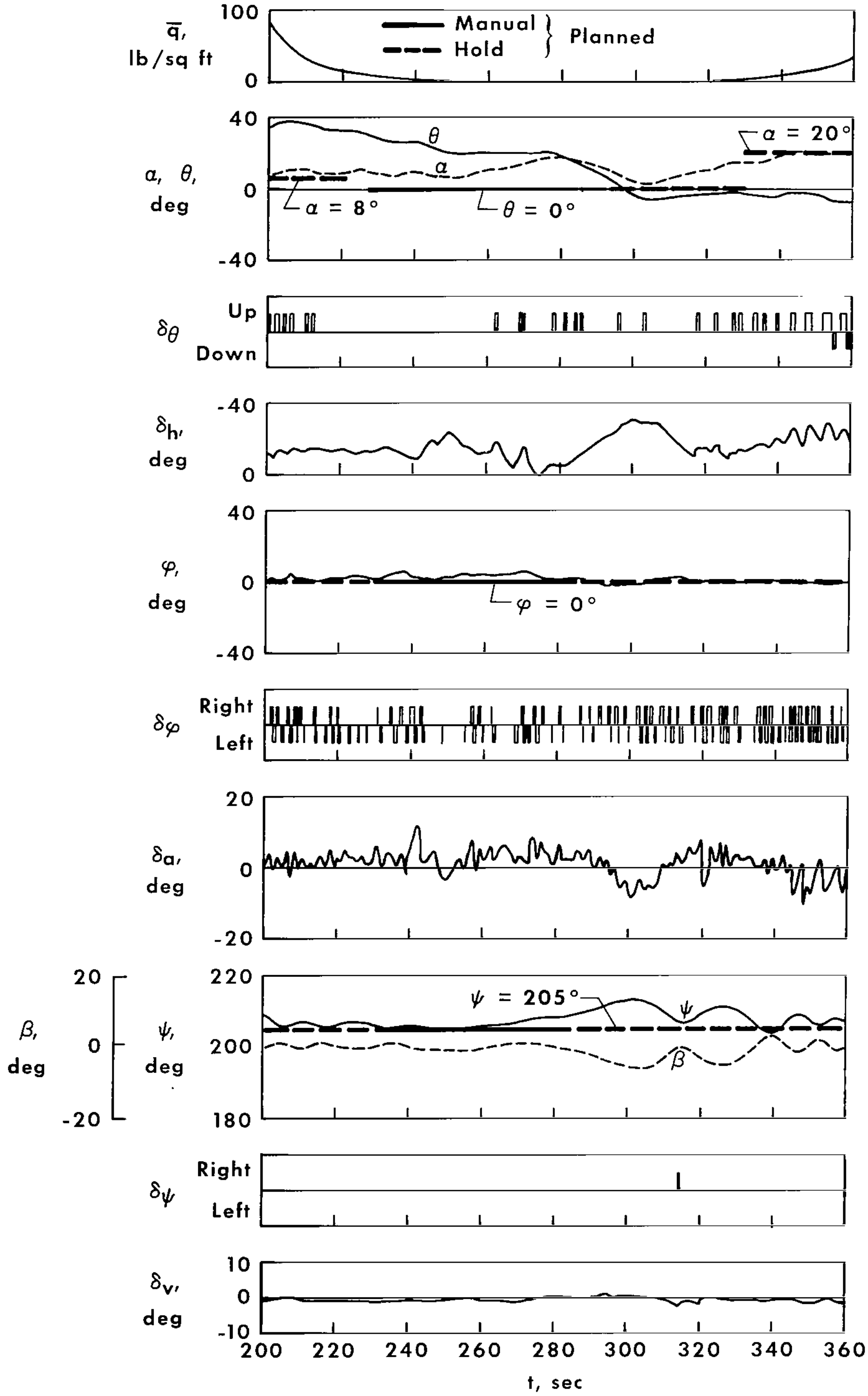
(b) Rate command controls manually operated, h_{max} = 223,700 ft, $\bar{q}_{min}$ = 2.9 lb/sq ft.

Figure 7.– Continued.



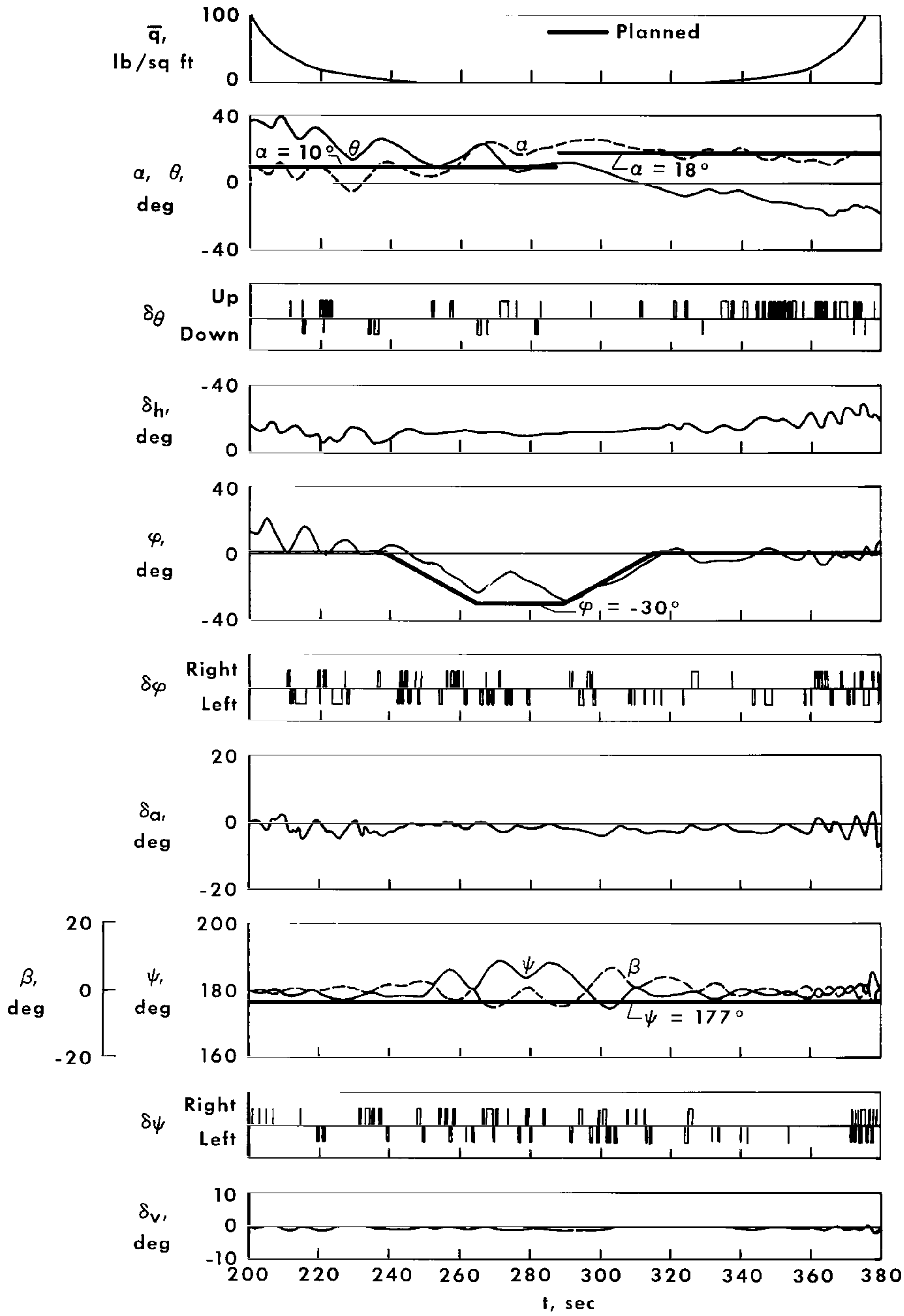
(c) Acceleration command controls with rate damping manually operated, h_{max} = 226,400 ft, $\bar{q}_{min}$ = 2.0 lb/sq ft.

Figure 7.- Continued.



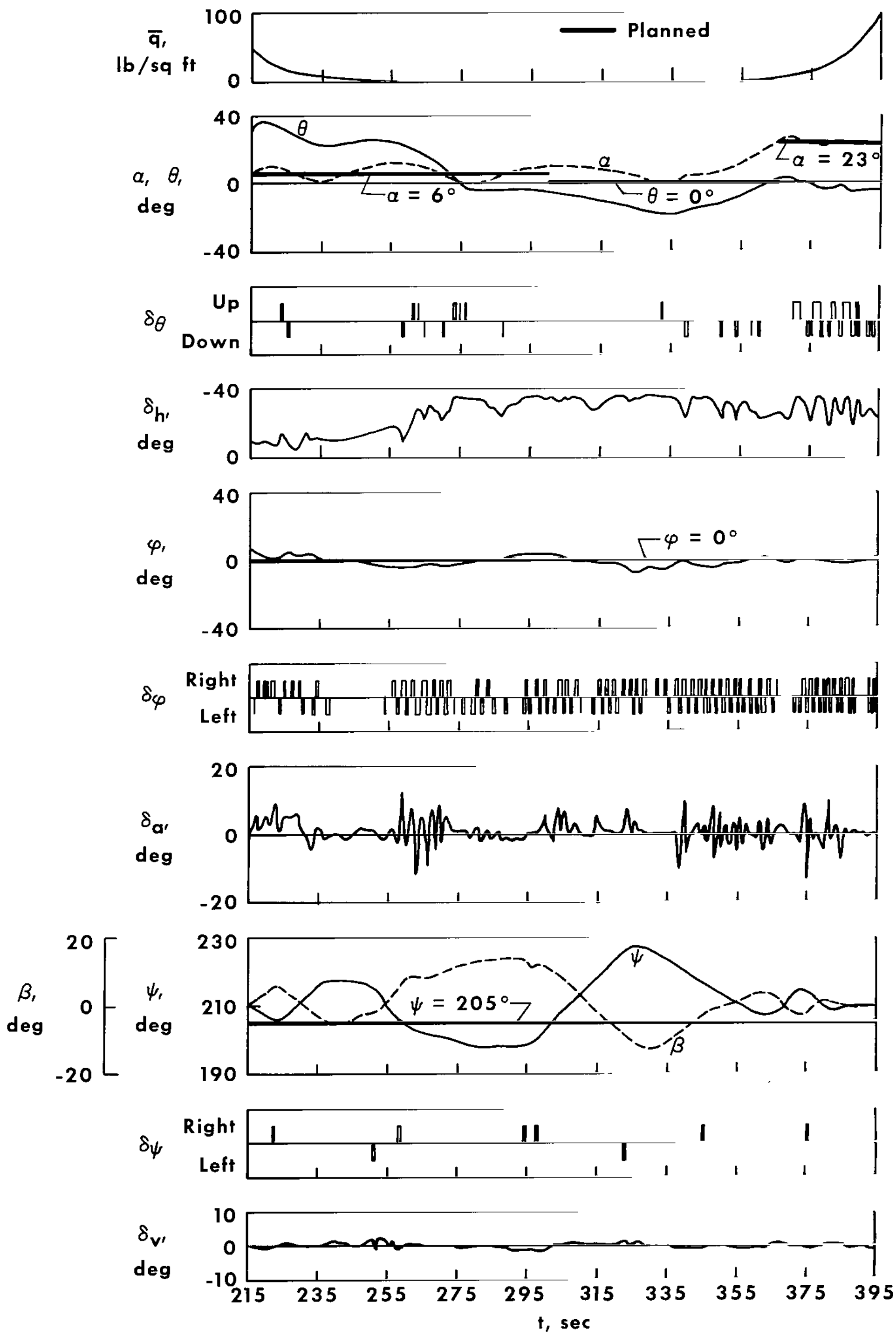
(d) Rate command and attitude command (hold) controls, h_{max} = 246,700 ft, $\bar{q}_{min} \approx 0.6$ lb/sq ft.

Figure 7.— Continued.



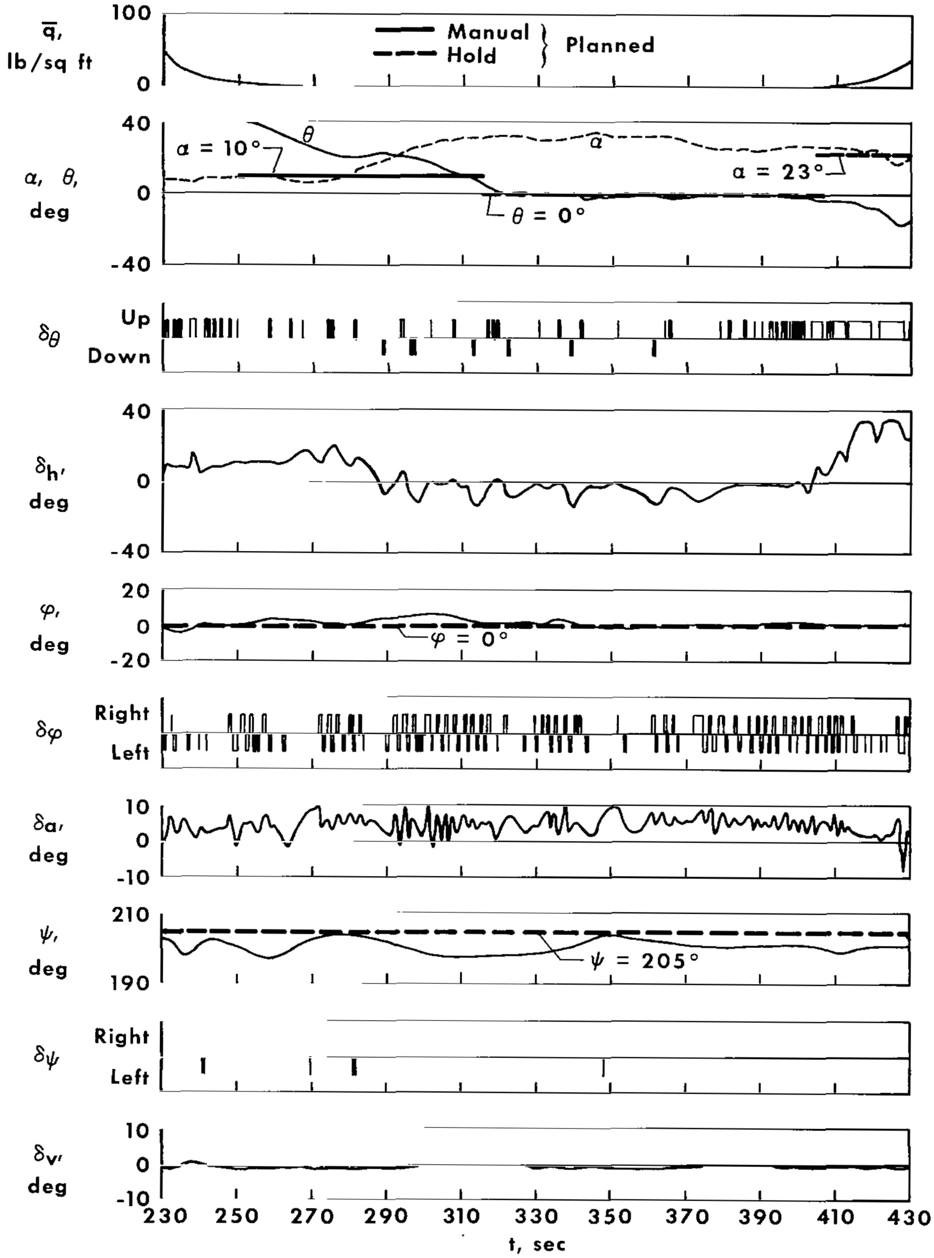
(e) Acceleration command controls manually operated, $h_{max} = 247{,}000$ ft, $\bar{q}_{min} \approx 0.9$ lb/sq ft.

Figure 7.– Continued.



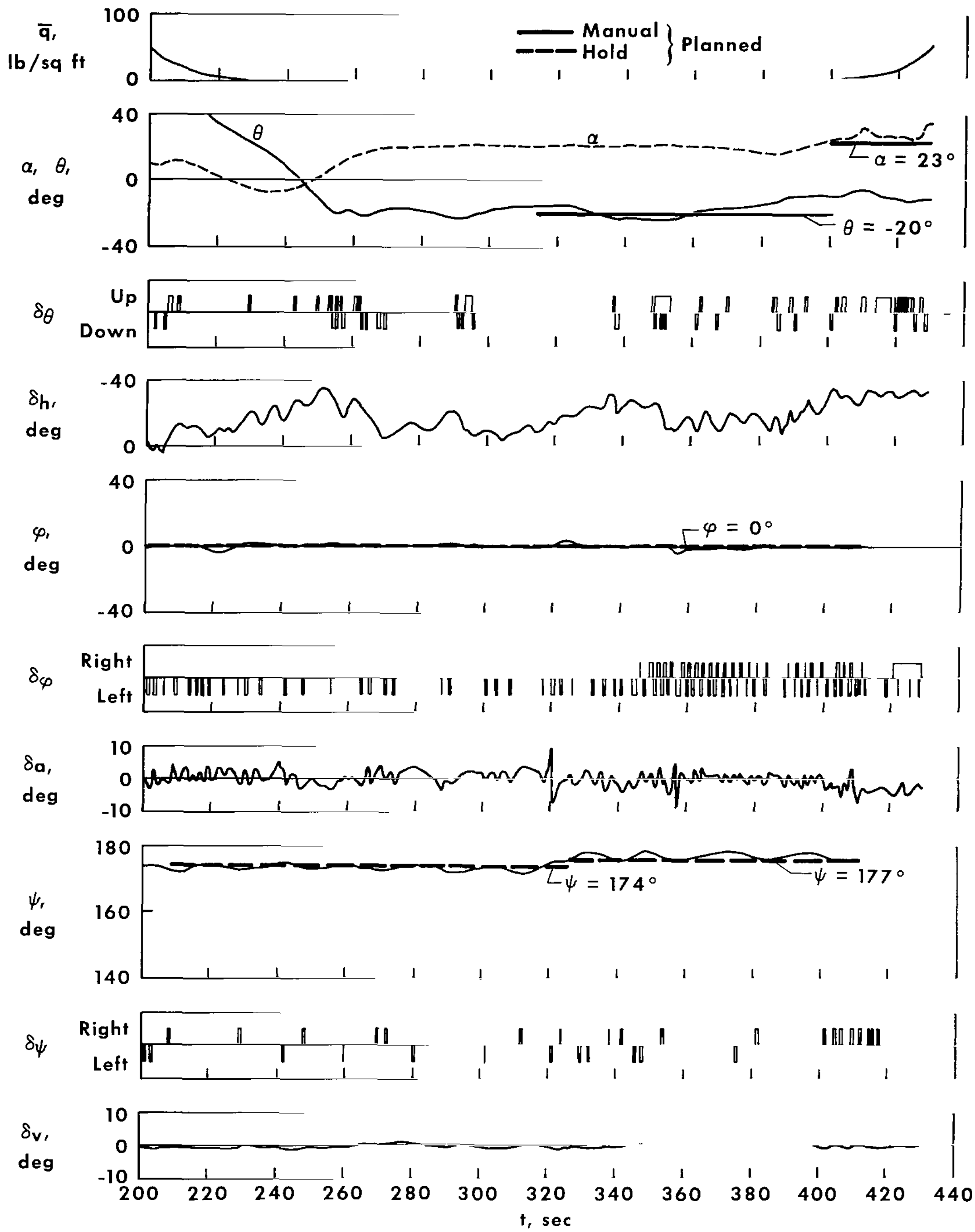
(f) Rate command controls manually operated, h_{max} = 271,700 ft, $\bar{q}_{min} \approx$ 0.2 lb/sq ft.

Figure 7.– Continued.



(g) Rate command and attitude command (hold) controls, h_{max} = 314,750 ft, $\bar{q}_{min} \approx$ 0.03 lb/sq ft.

Figure 7.— Continued.



(h) Rate command and attitude command (hold) controls, h_{max} = 347,800 ft, $\bar{q}_{min} \approx$ 0.01 lb/sq ft.

Figure 7.— Concluded.

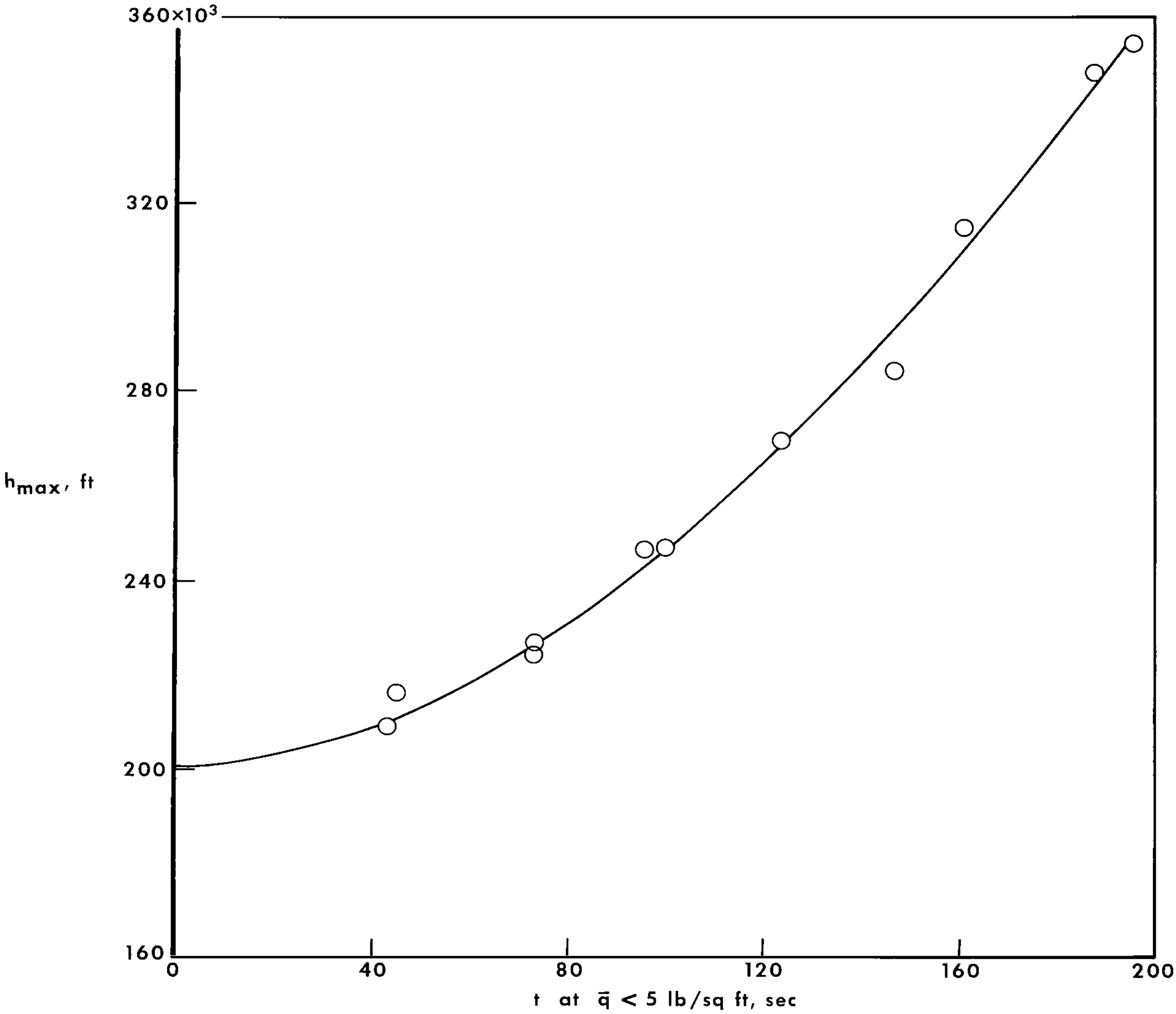


Figure 8.— Control evaluation time available at a dynamic pressure less than 5 lb/sq ft. Velocity at apogee approximately 4,500 ft/sec.

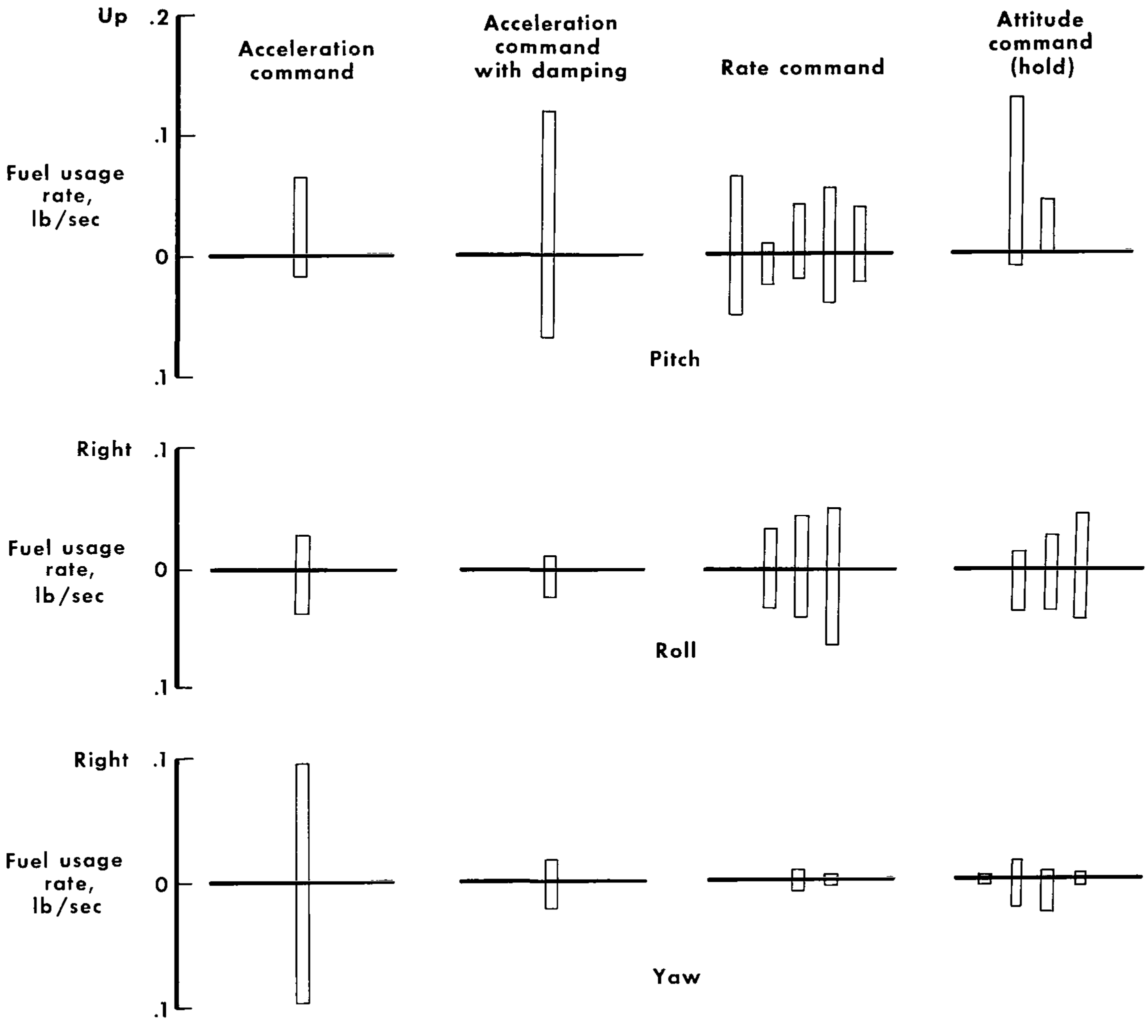


Figure 9.- Reaction control fuel used, with the various control systems, per second of operation at a dynamic pressure less than 5 lb/sq ft. Stabilizing control task.

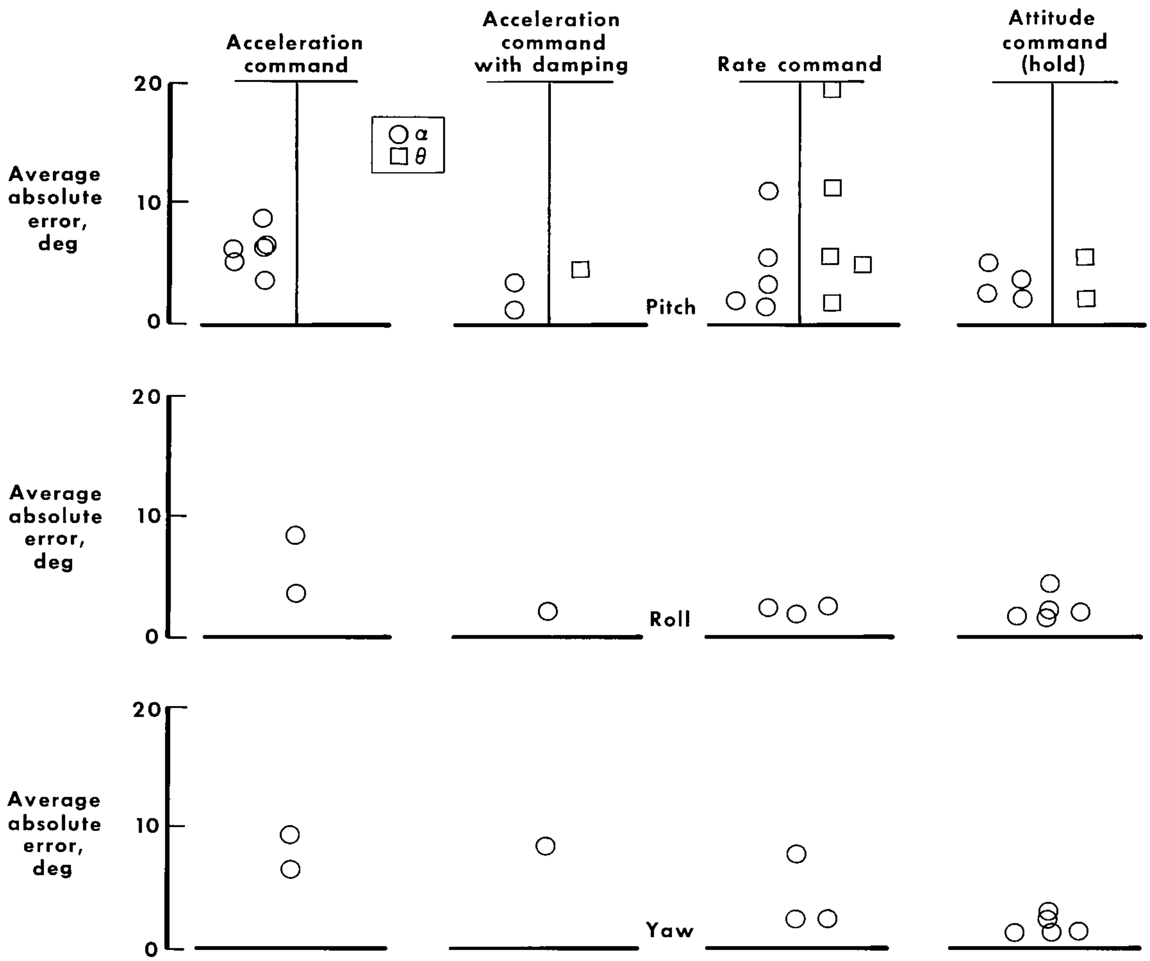


Figure 10.– Summary of reaction control performance (attitude error) with the various control systems for the X-15 control tasks.

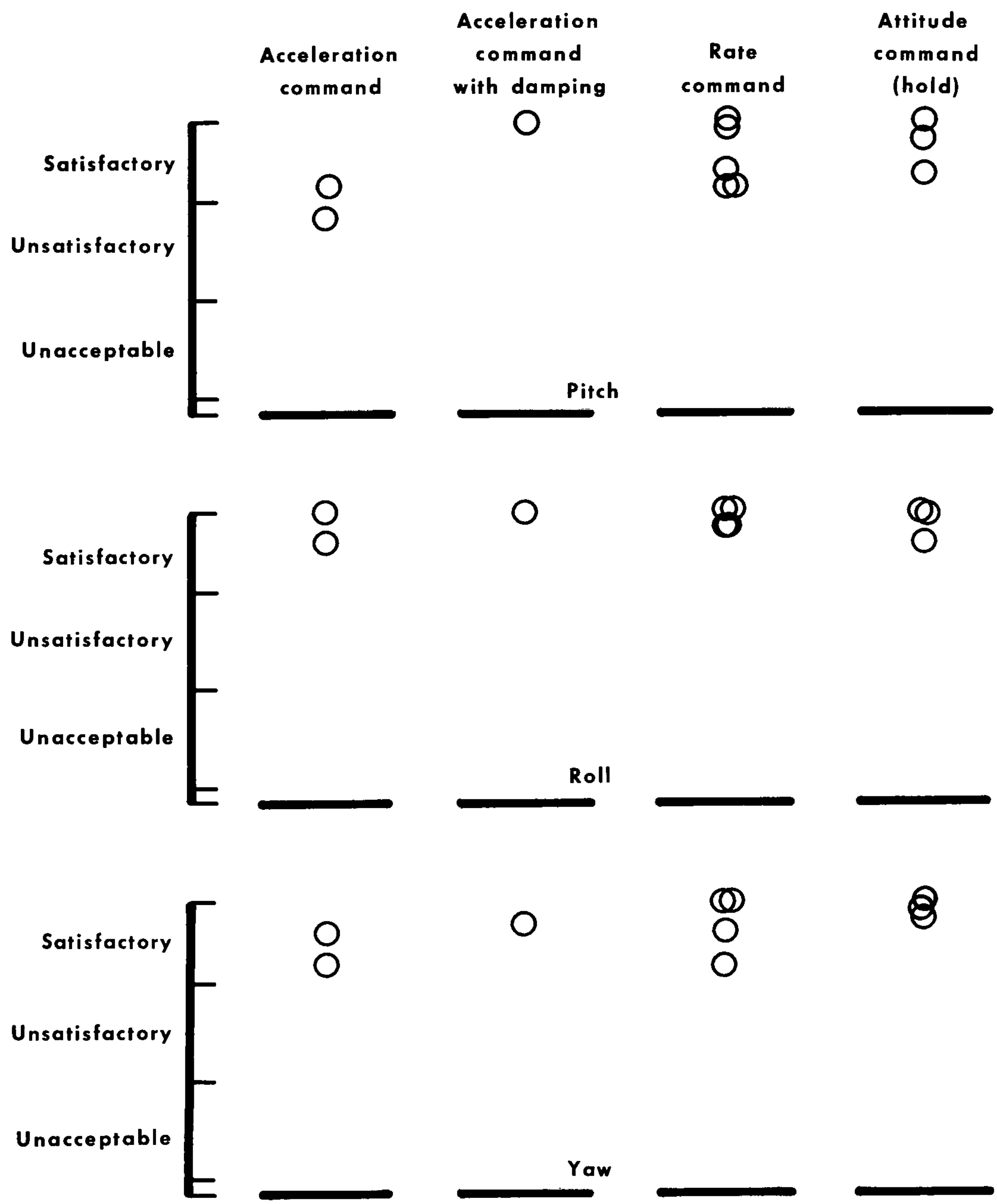
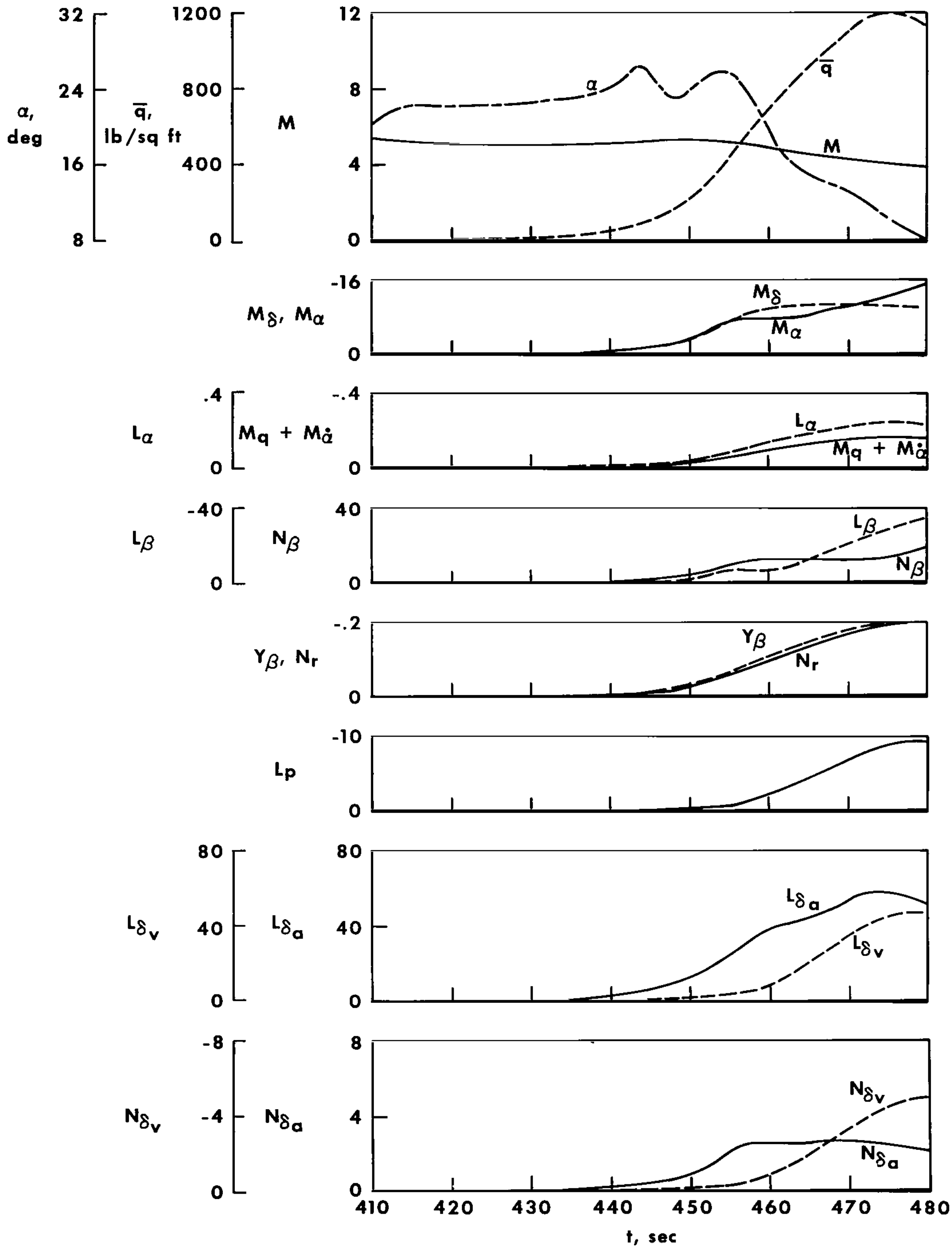
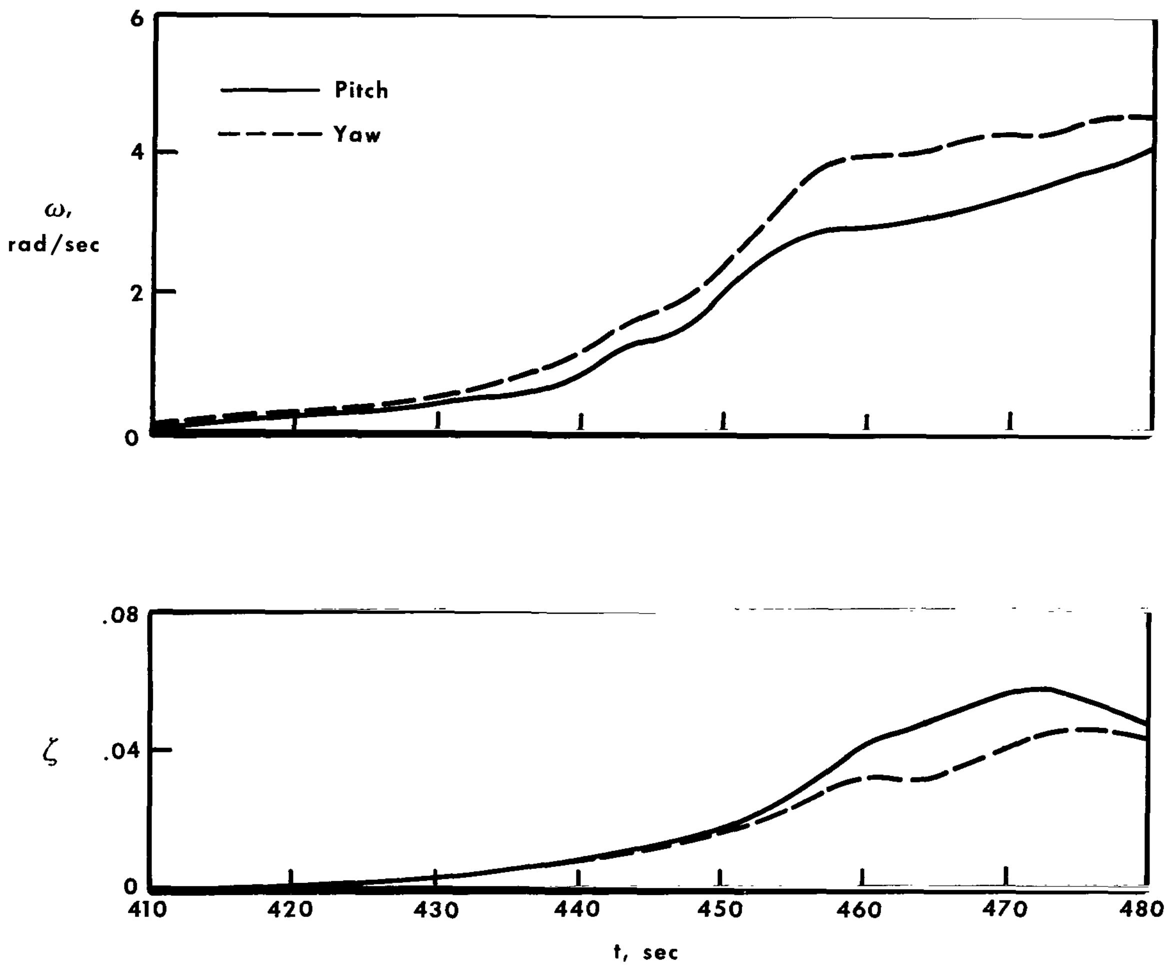


Figure 11.– Pilot rating of the X-15 low-dynamic-pressure control task with the various control systems.



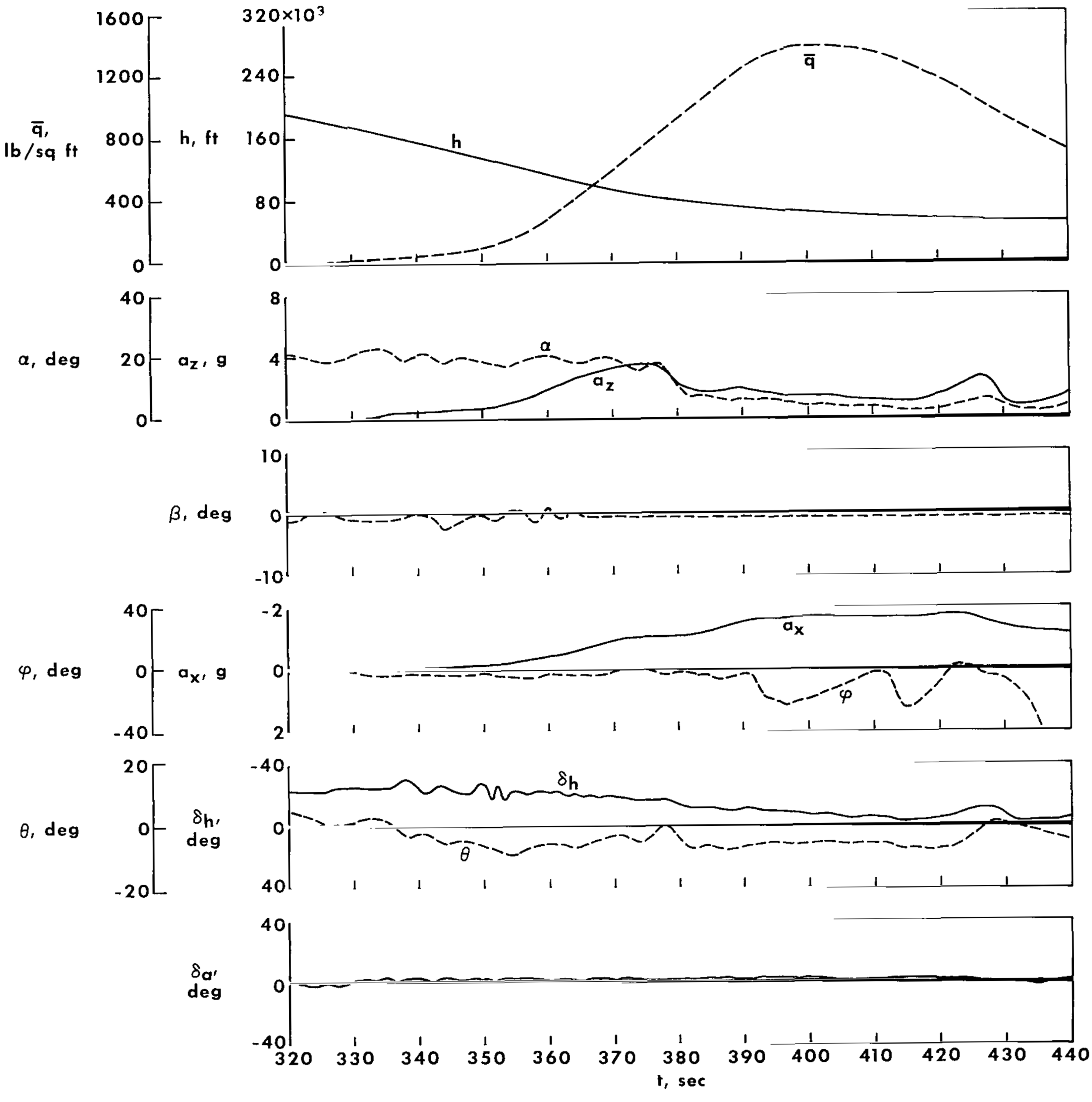
(a) Dimensional stability and control parameters.

Figure 12.— Variation of the X-15 aerodynamic parameters during entry from an altitude of 354,200 feet. Lower movable ventral off; speed brakes open 20°.



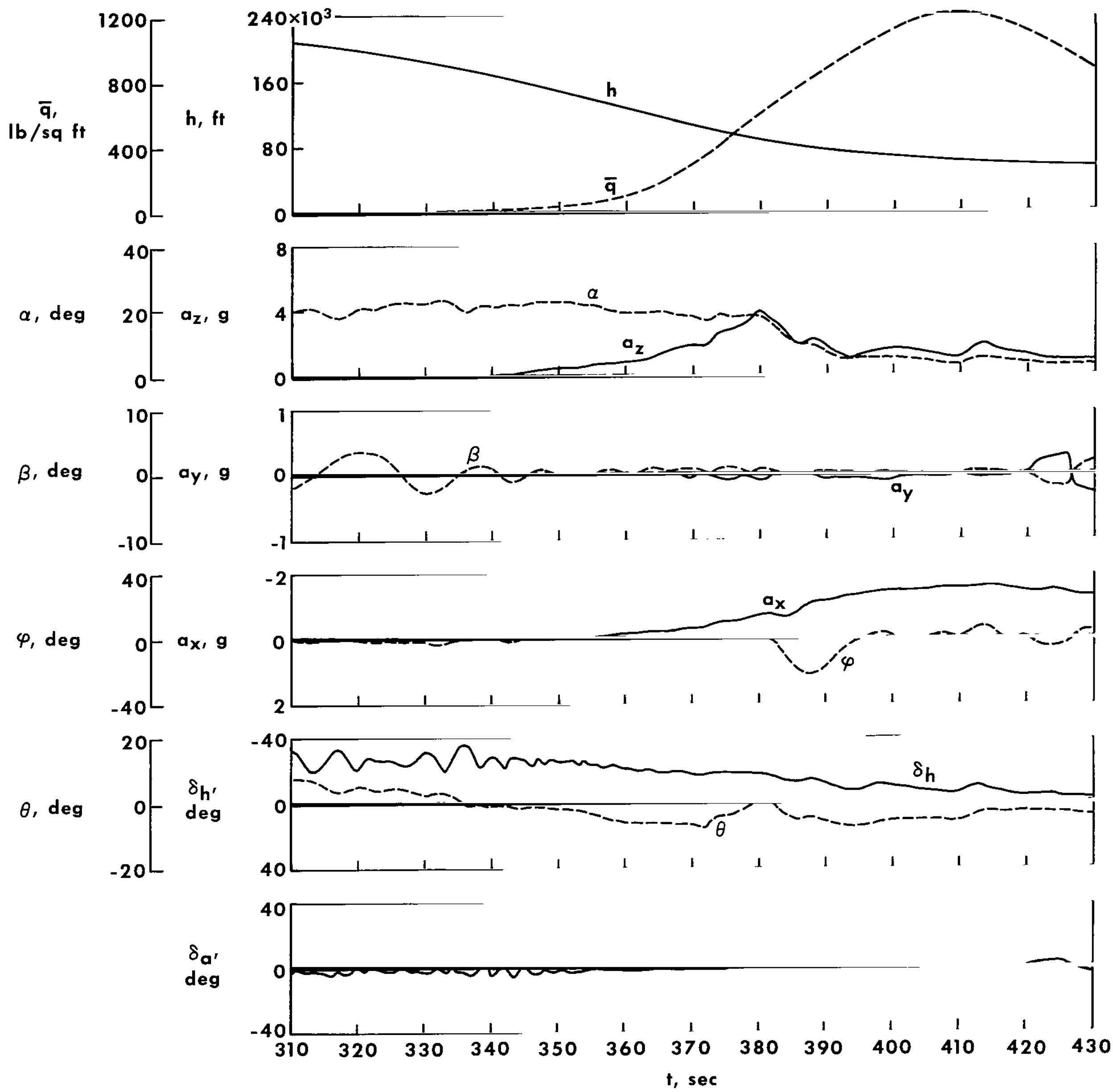
(b) Pitch and yaw undamped natural frequency and damping ratio.

Figure 12.– Concluded.



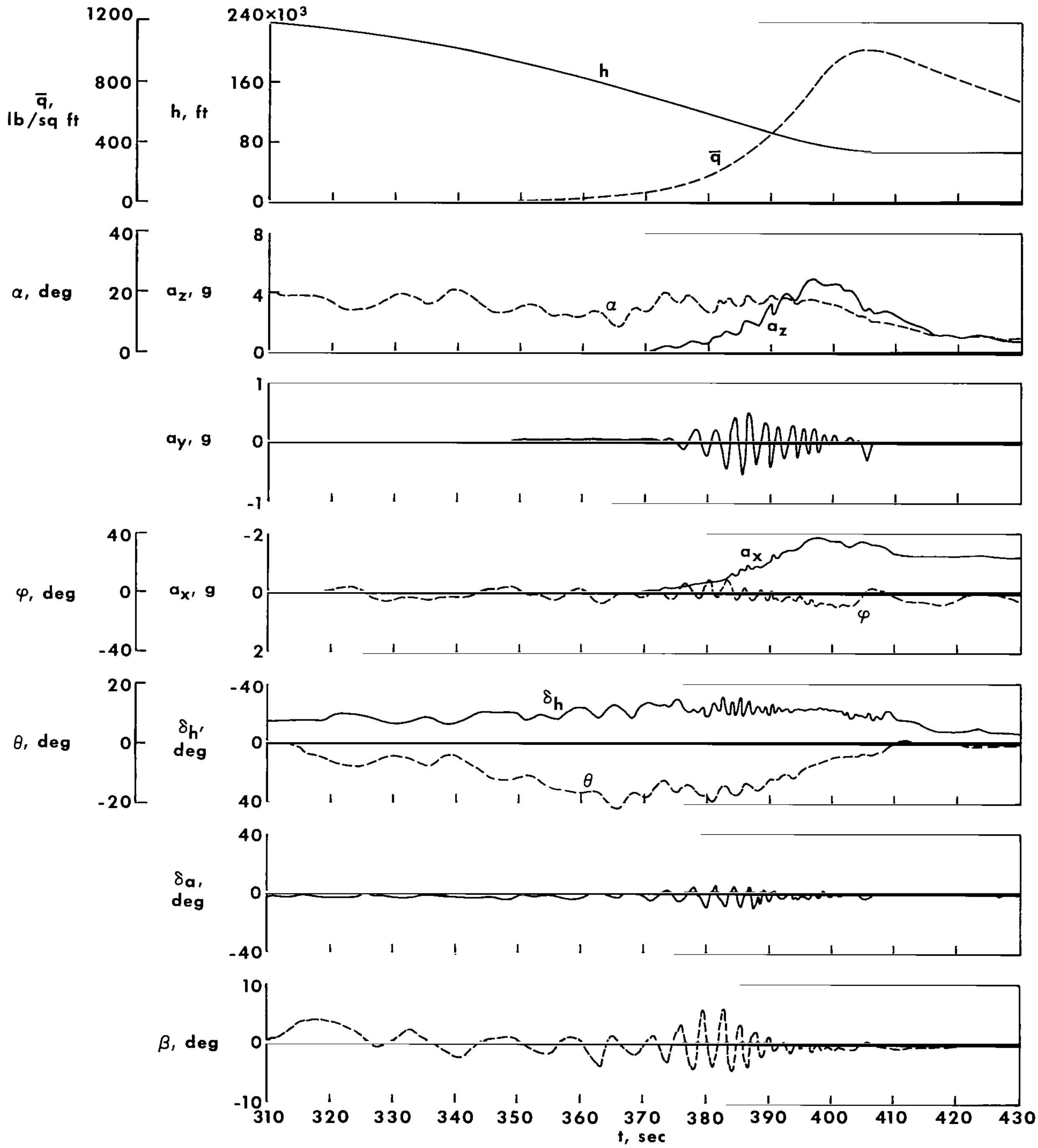
(a) Conventional aerodynamic controls, acceleration command with damping reaction controls, planned $\alpha_e = 20°$, planned $a_z = 4g$, ventral off, speed brakes extended 20°, $h_{max} = 226,400$ ft.

Figure 13.– Representative entries from high altitude with various types of aerodynamic and reaction controls.



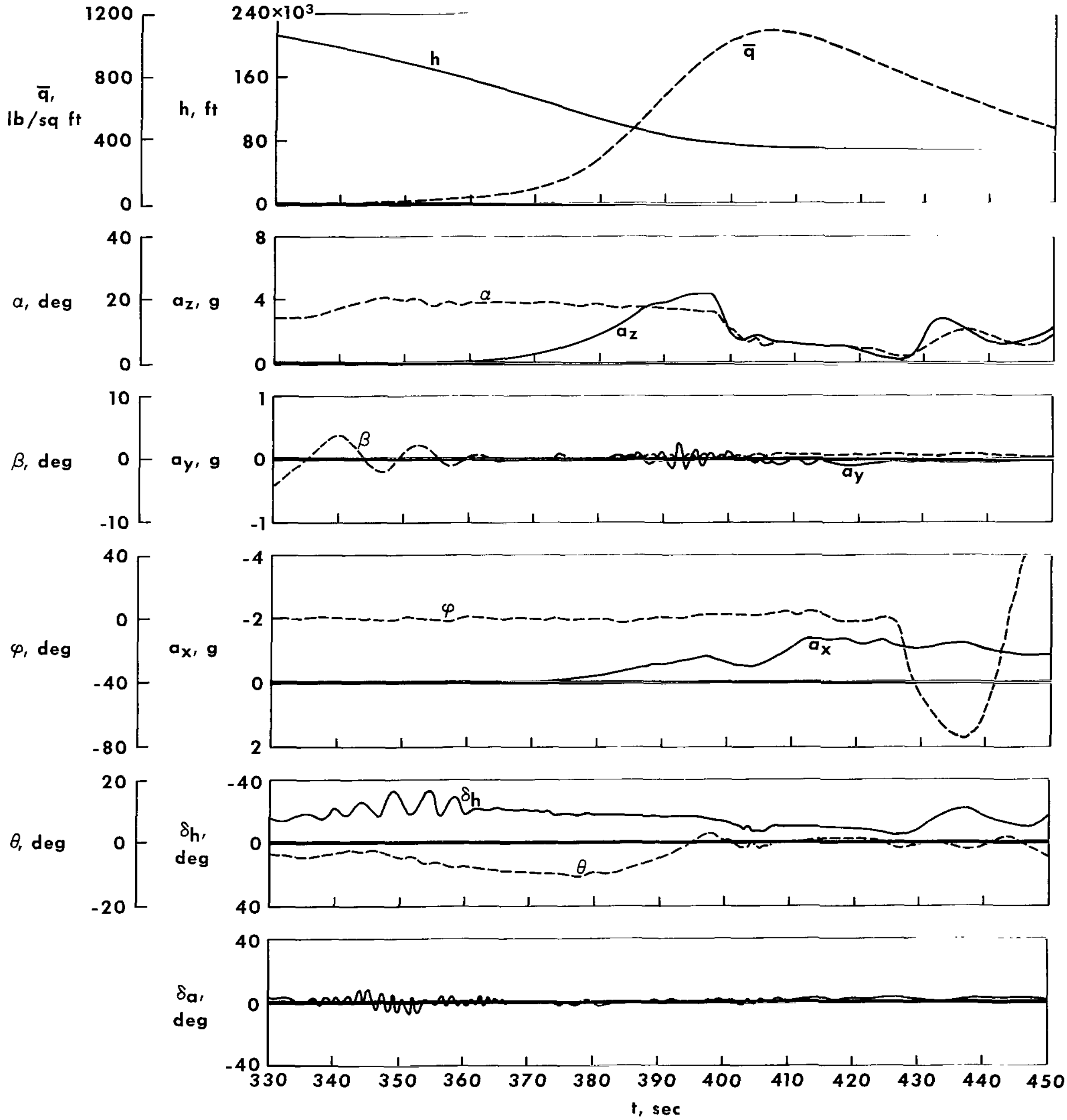
(b) Adaptive rate command controls, planned $\alpha_e = 20°$, planned $a_z = 4g$, ventral off, speed brakes extended 20°, $h_{max} = 223,700$ ft.

Figure 13.– Continued.



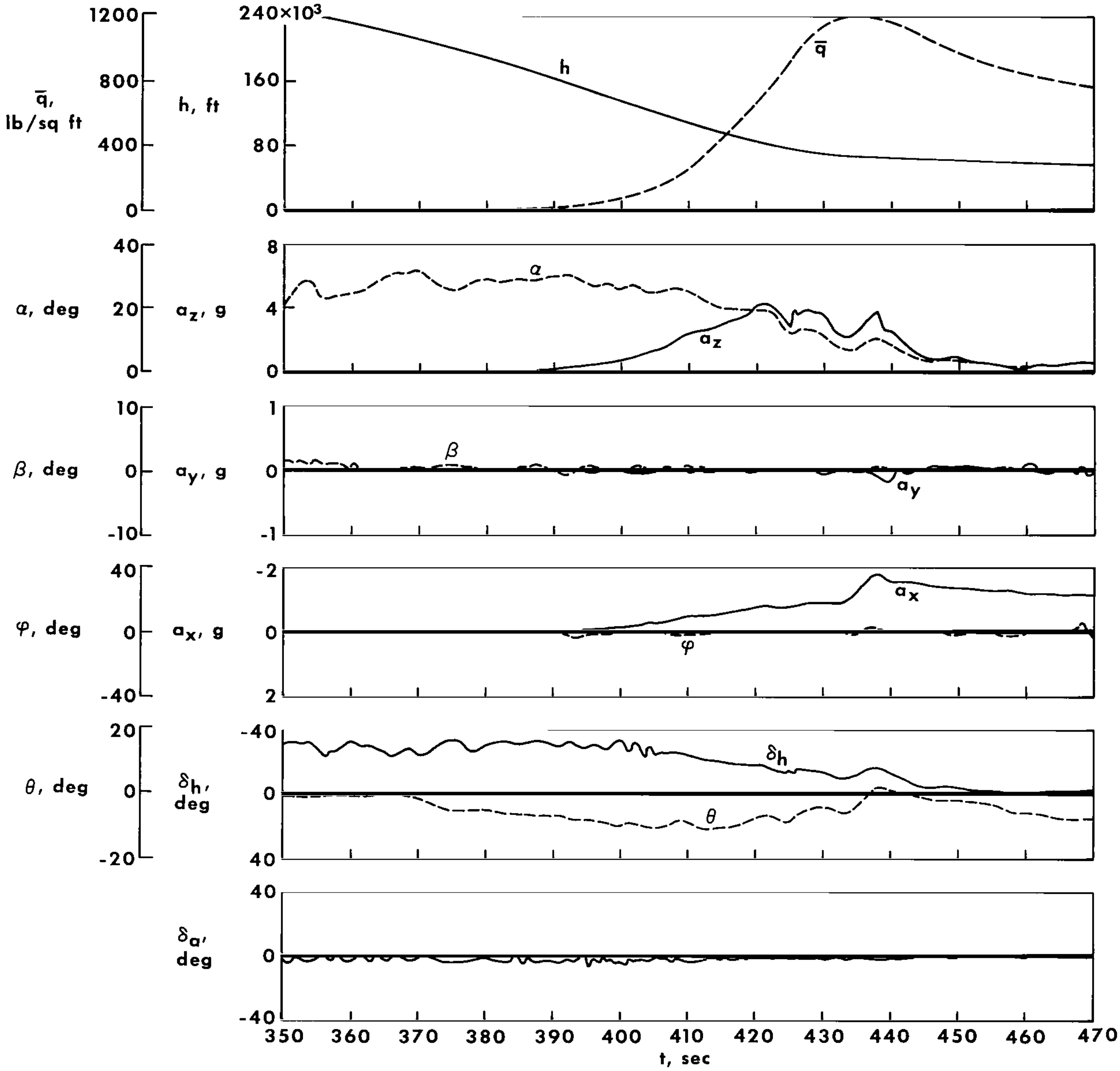
(c) Conventional aerodynamic controls, acceleration command reaction controls, planned $\alpha_e = 18°$, planned $a_z = 5g$, speed brakes extended $35°$, $h_{max} = 247,000$ ft.

Figure 13.- Continued.



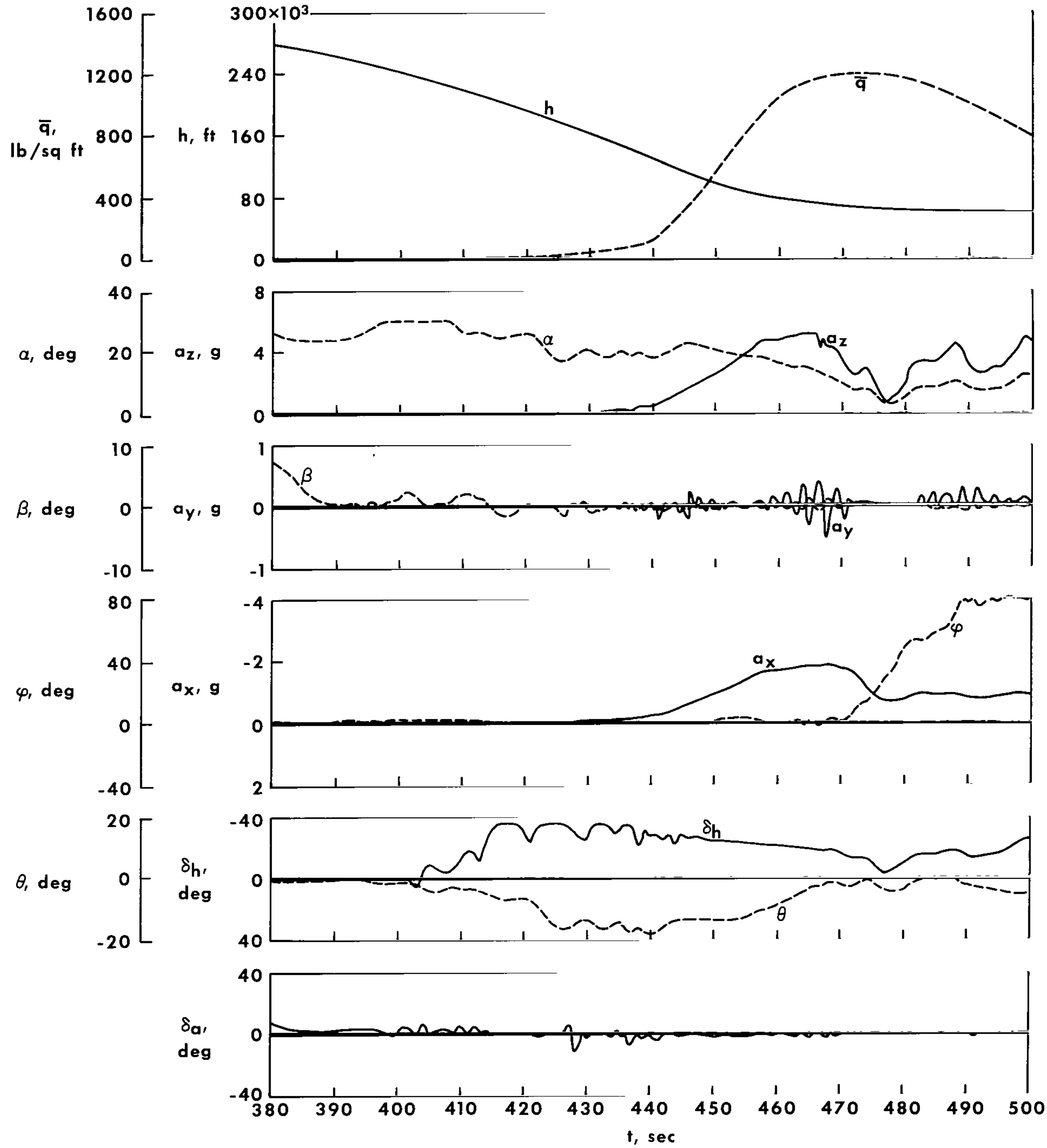
(d) Adaptive rate command controls, α, φ, ψ hold, planned $\alpha_e = 20°$, planned $a_z = 5.5g$, $h_{max} = 246,700$ ft.

Figure 13.— Continued.



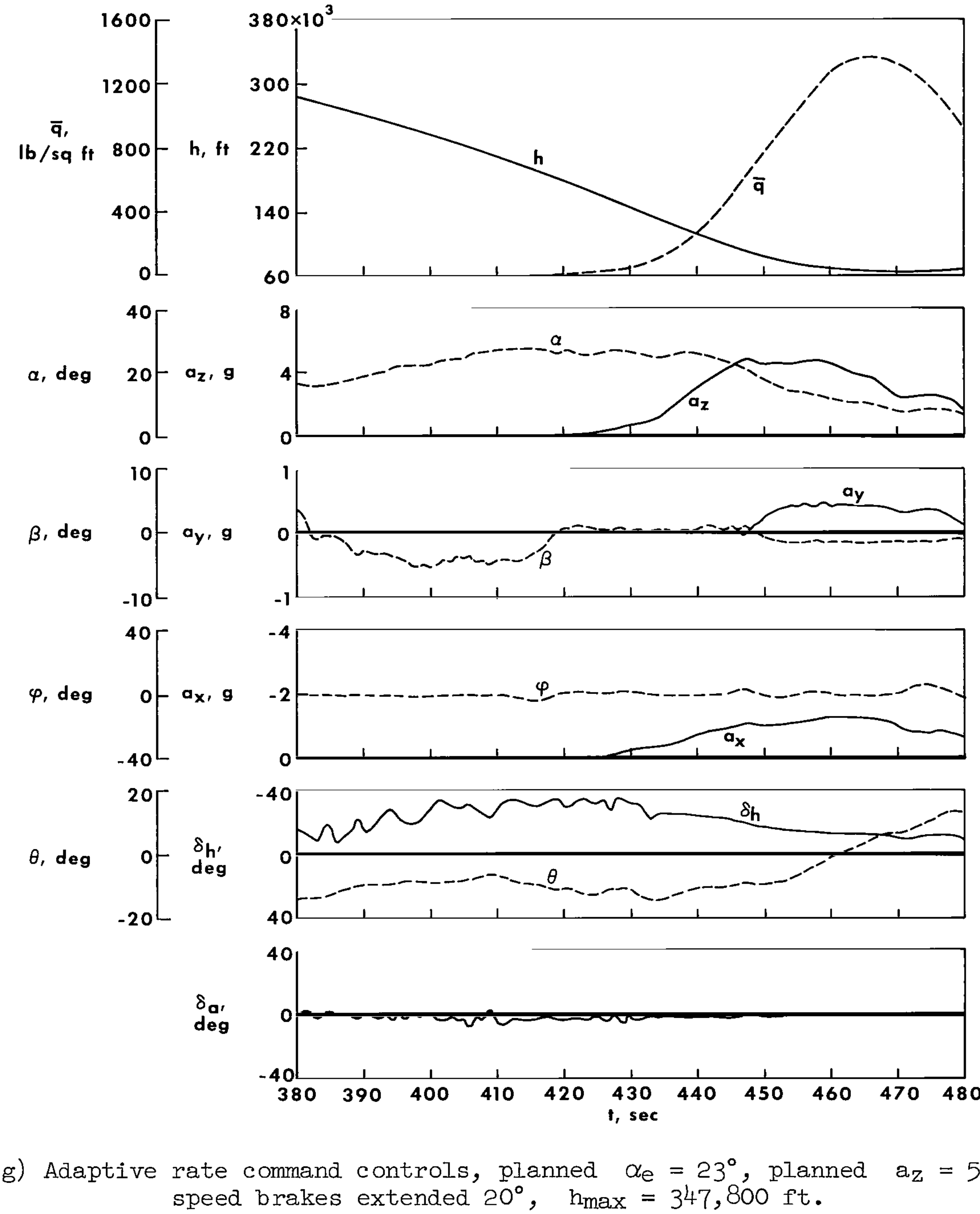
(e) Adaptive rate command controls, planned $\alpha_e = 23°$, planned $a_z = 5g$, speed brakes extended 20°, h_{max} = 285,000 ft.

Figure 13.— Continued.



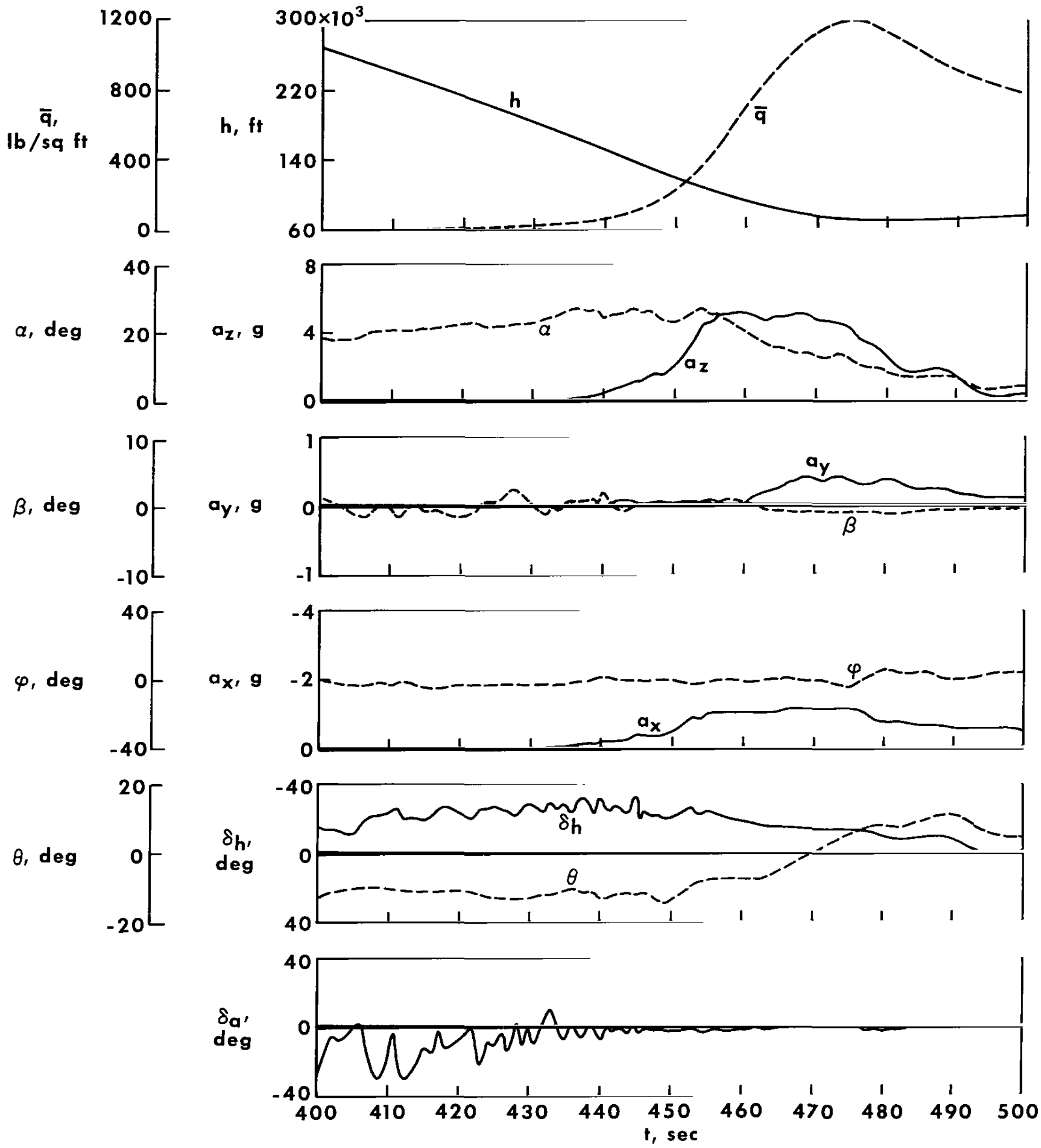
(f) Adaptive rate command controls, α, φ, ψ hold, planned $\alpha_e = 23°$, planned $a_z = 5g$, speed brakes extended 35°, $h_{max} = 314,750$ ft.

Figure 13.– Continued.



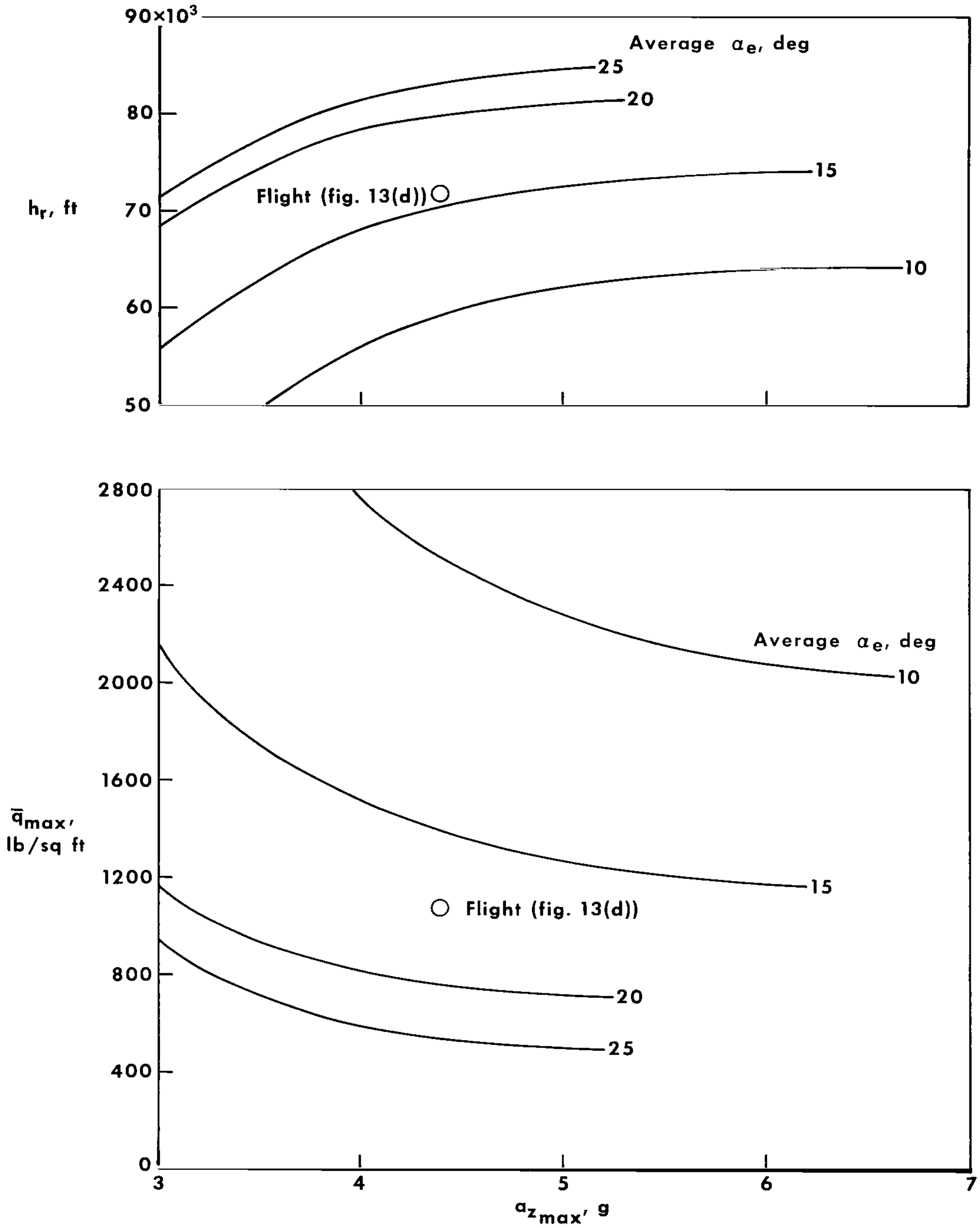
(g) Adaptive rate command controls, planned $\alpha_e = 23°$, planned $a_z = 5g$, speed brakes extended 20°, $h_{max} = 347{,}800$ ft.

Figure 13.– Continued.



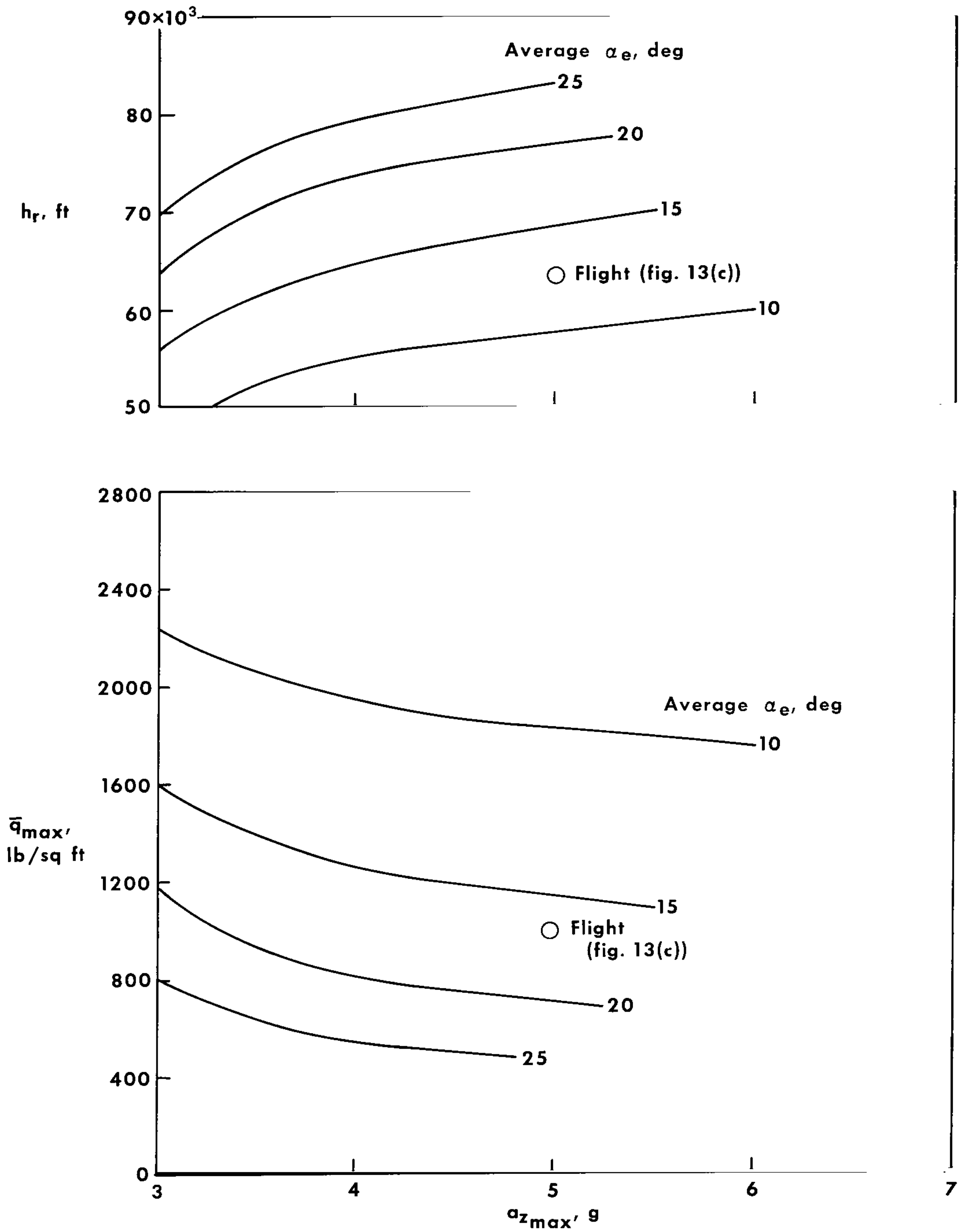
(h) Adaptive rate command controls, planned $\alpha_e = 26°$, planned $a_z = 5.2g$, speed brakes extended 20°, $h_{max} = 354{,}200$ ft.

Figure 13.— Concluded.



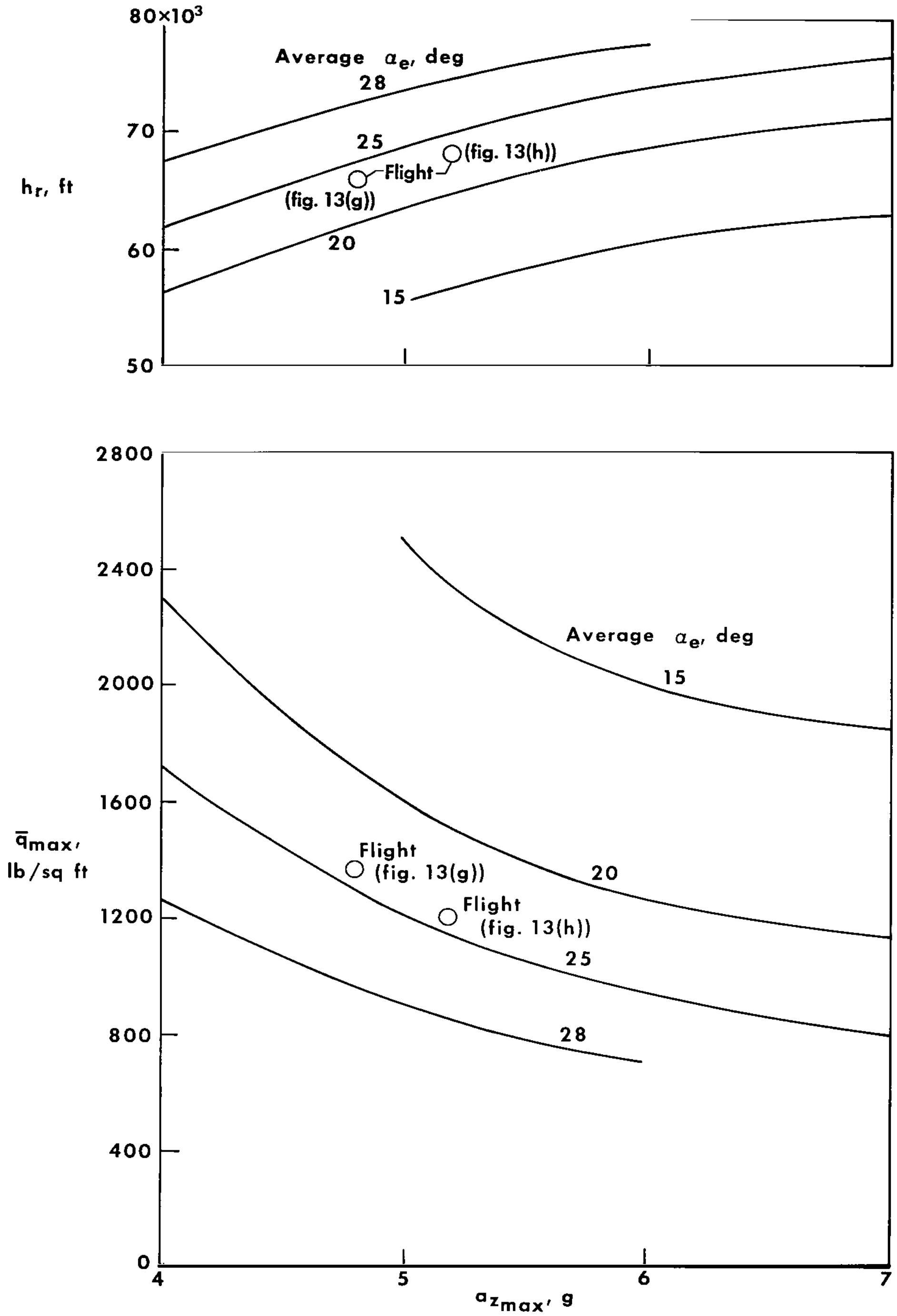
(a) h_{max} = 250,000 ft, V at h_{max} = 4,450 ft/sec, airplane weight = 15,000 lb, speed brakes closed.

Figure 14.— Entry recovery requirements for the X-15.



(b) h_{max} = 250,000 ft, V at h_{max} = 4,450 ft/sec, airplane weight = 15,000 lb, speed brakes extended 35°.

Figure 14.— Continued.



(c) h_{max} = 350,000 ft, V at h_{max} = 4,260 ft/sec, airplane weight = 15,000 lb, speed brakes extended 20°.

Figure 14.— Concluded.

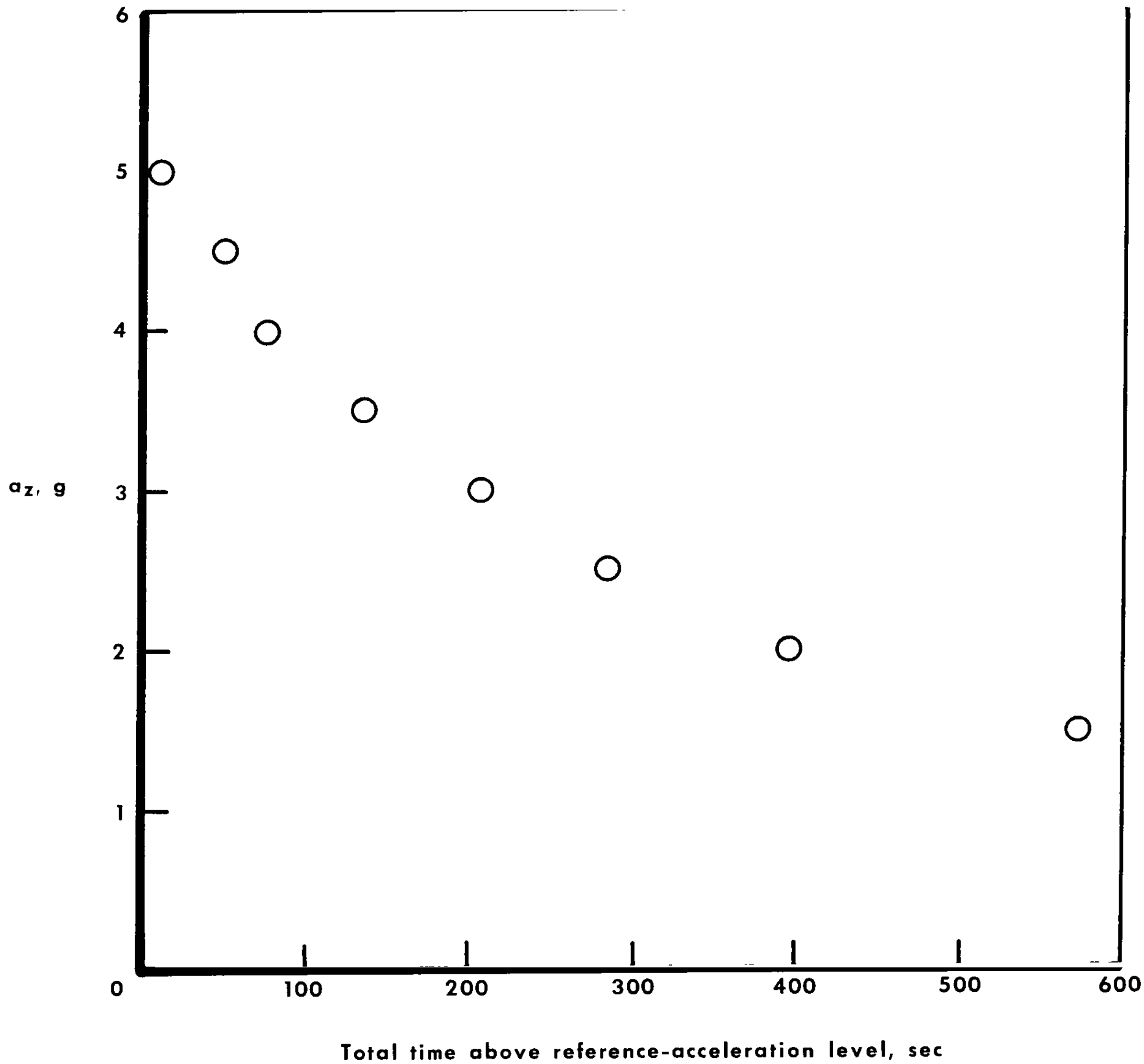
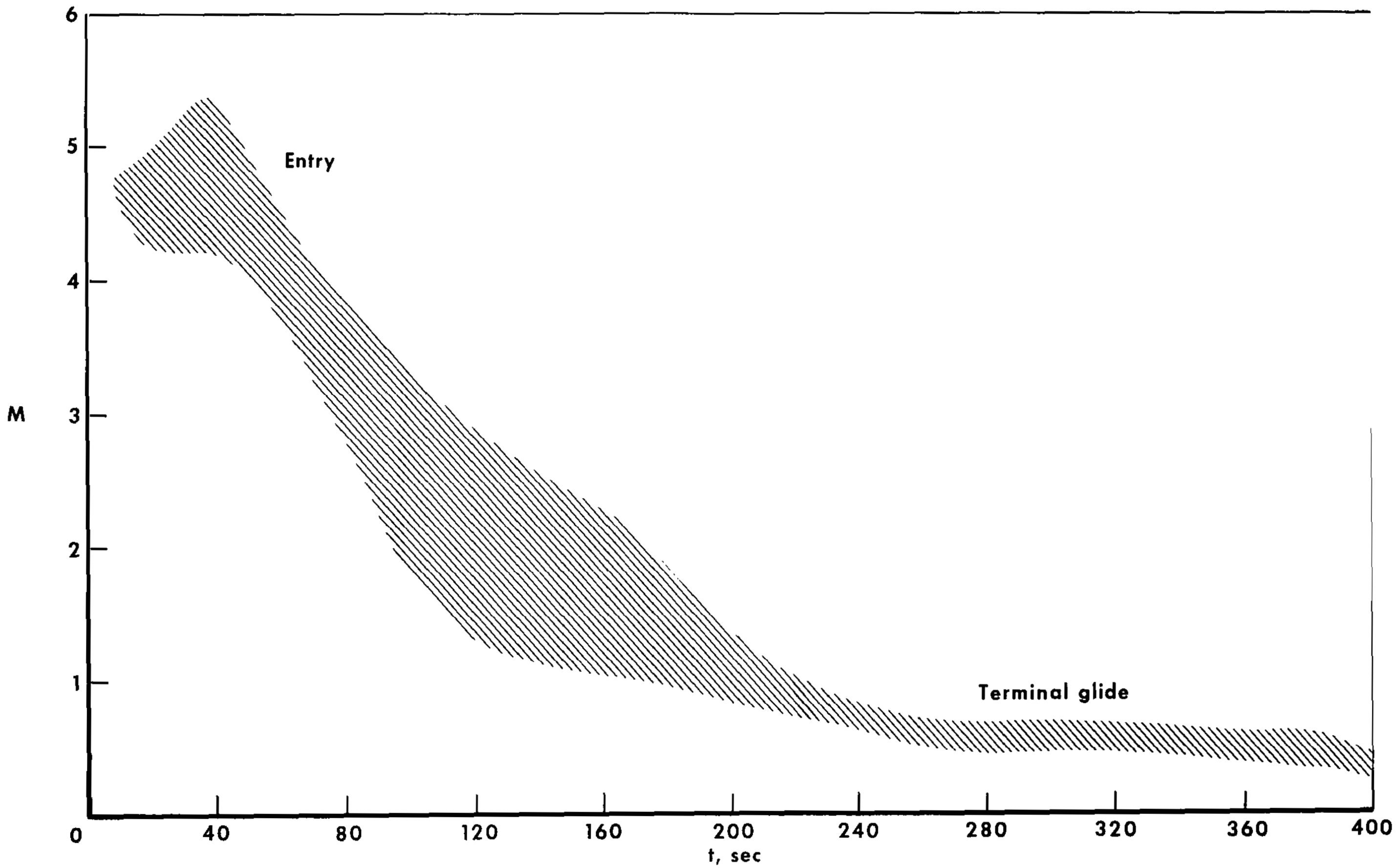
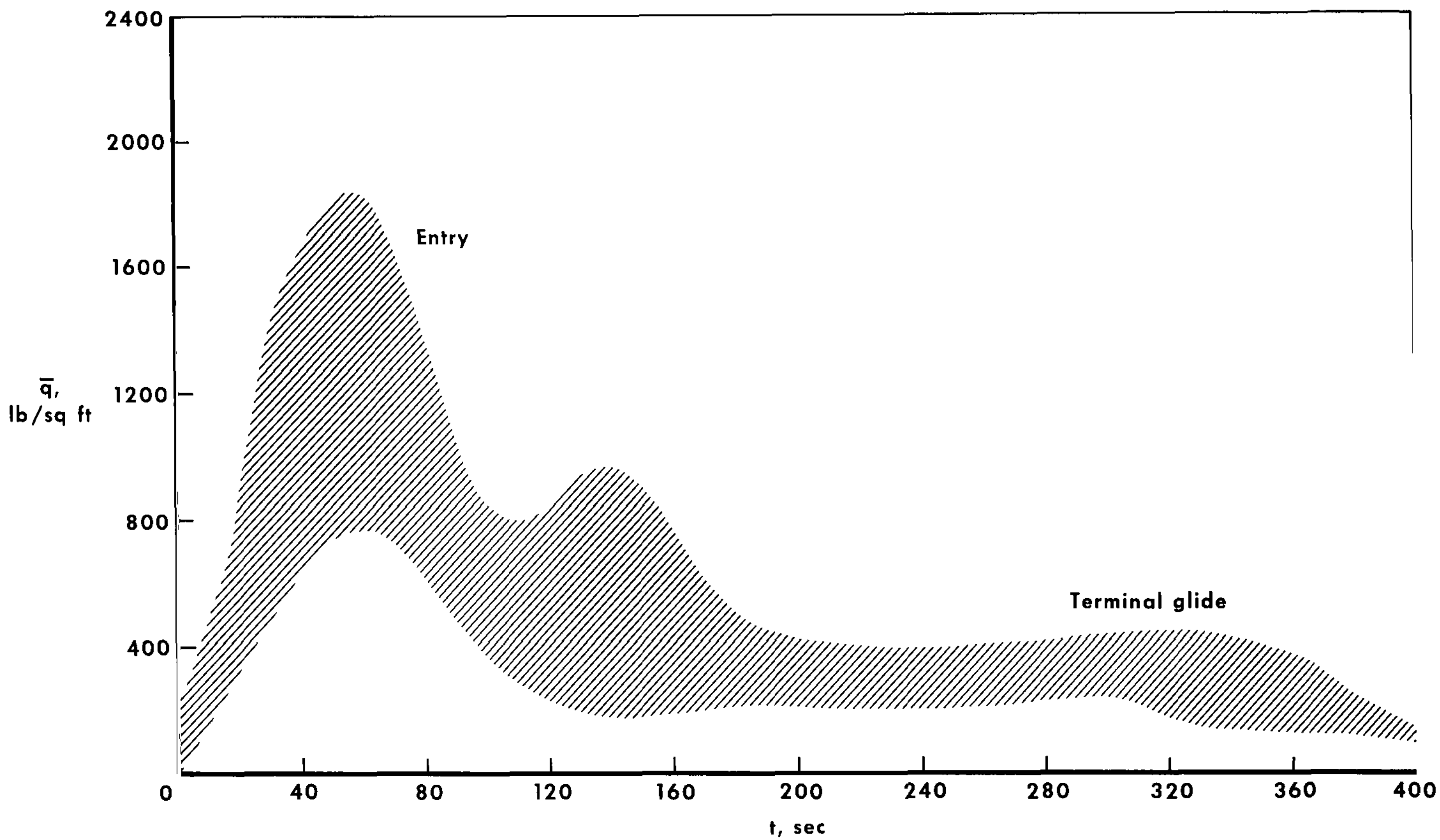


Figure 15.– Summary of normal acceleration experienced during entry from high altitude.



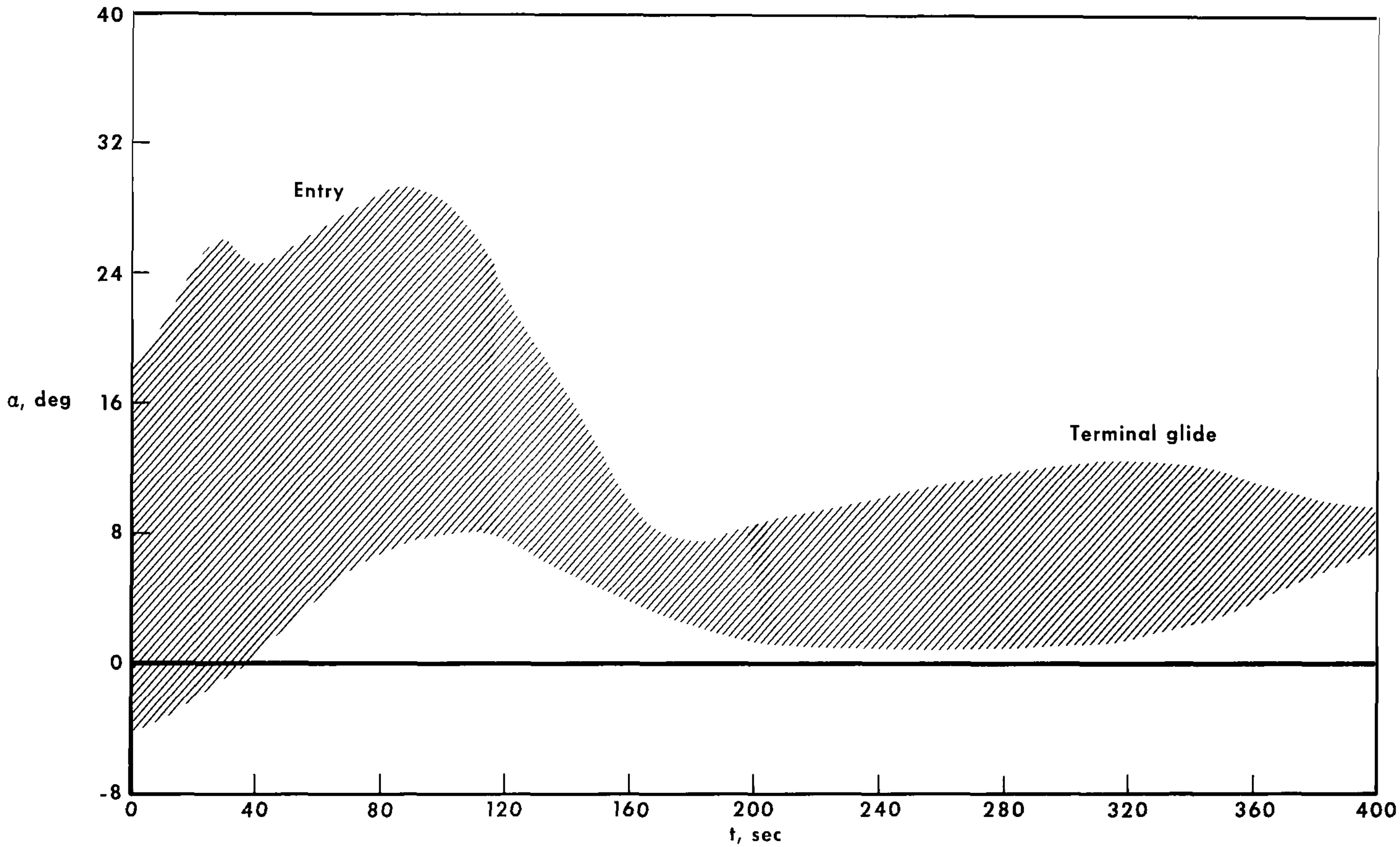
(a) Mach number.

Figure 16.- Summary of entry flight profiles.



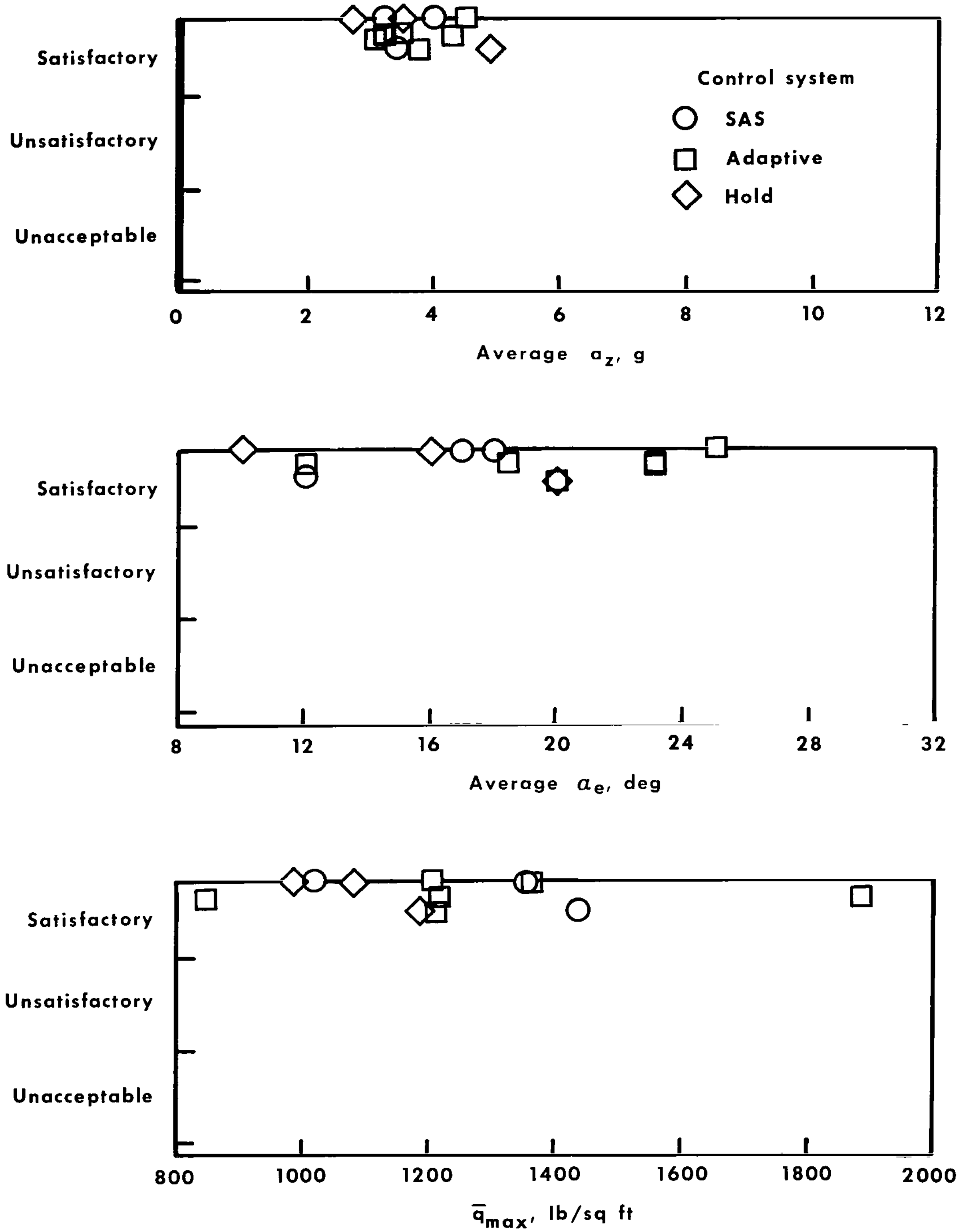
(b) Dynamic pressure.

Figure 16.– Continued.



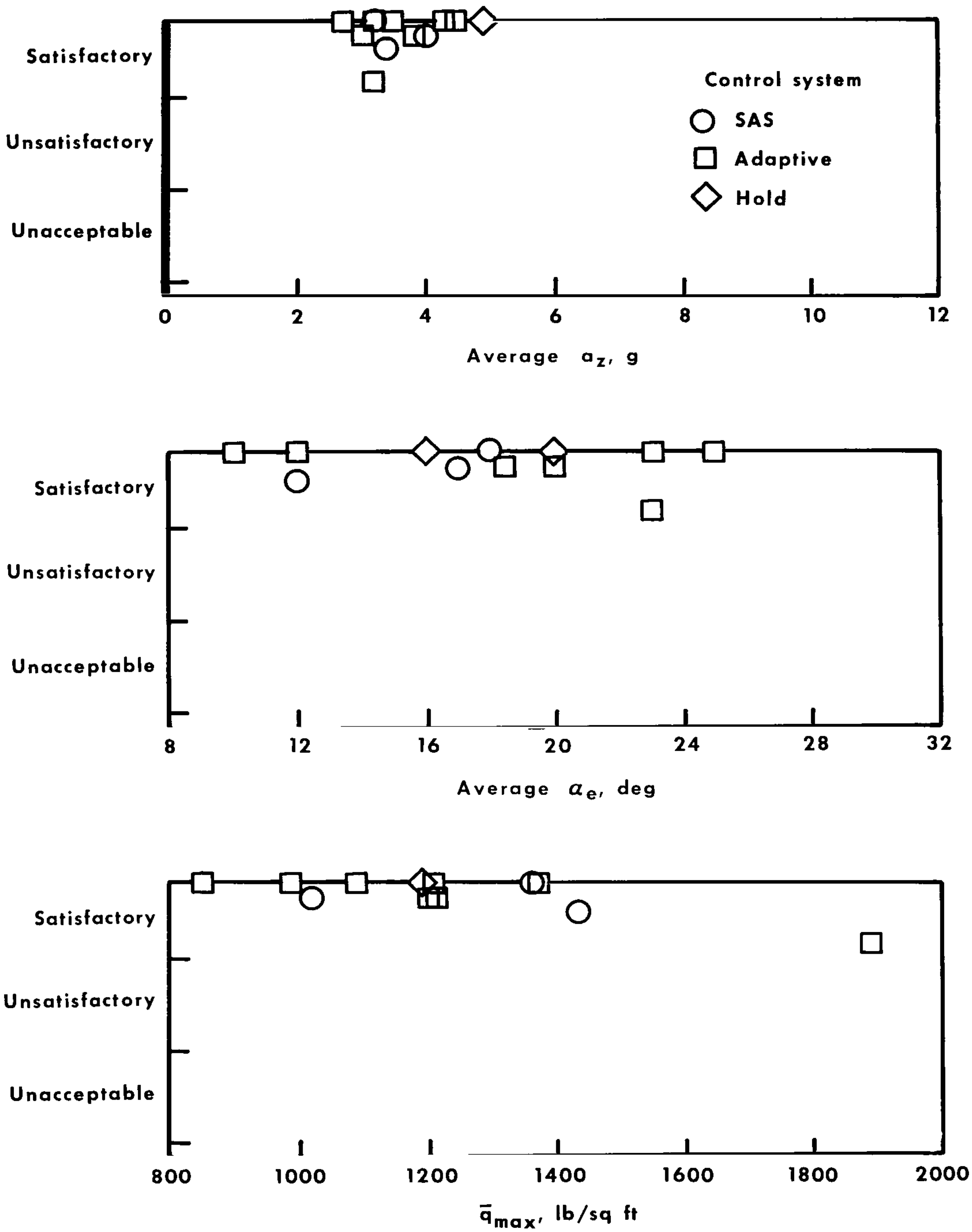
(c) Angle of attack.

Figure 16.– Concluded.



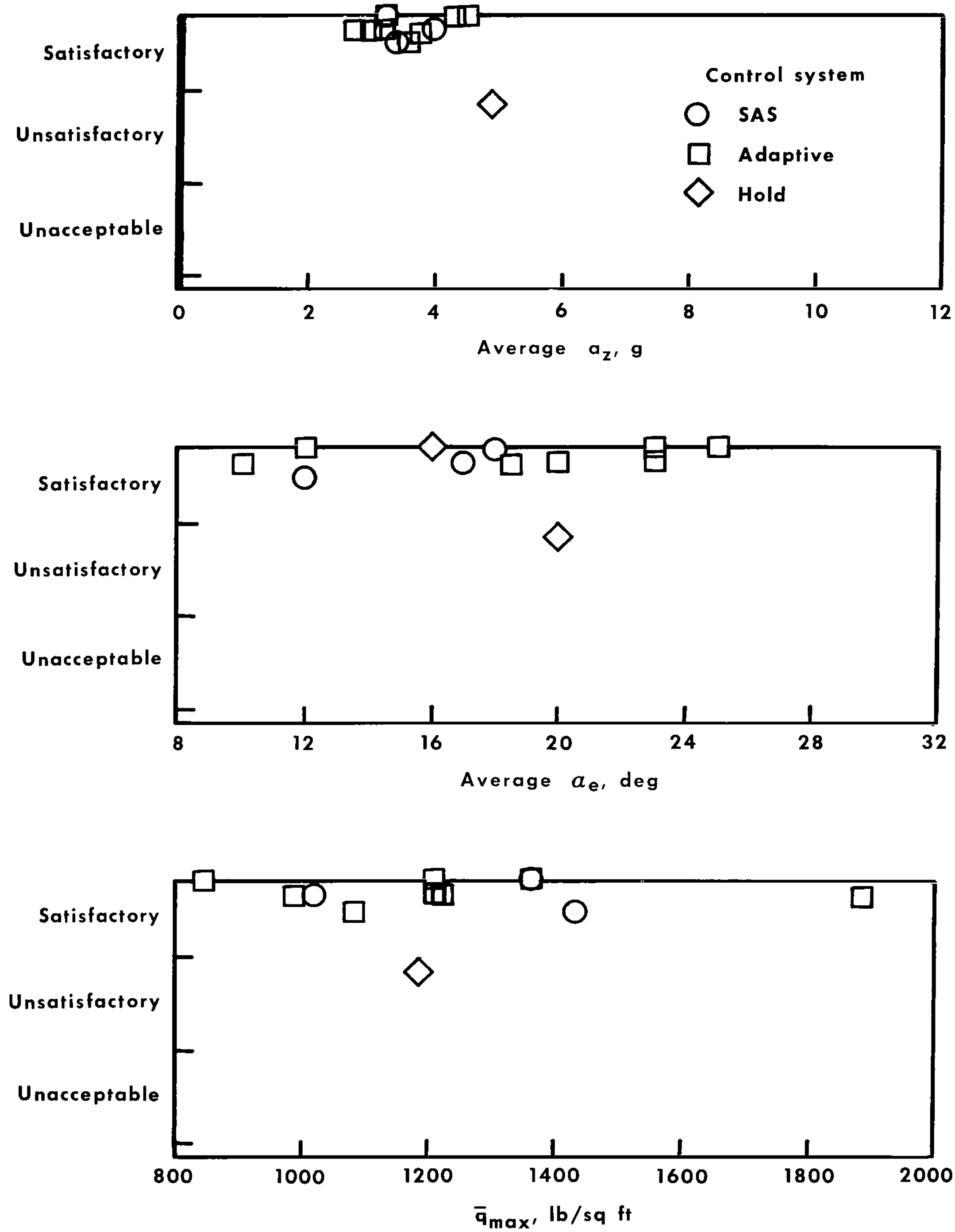
(a) Pitch mode.

Figure 17.— Summary of the pilot rating of the X-15 entry control task for the three aerodynamic control systems.



(b) Roll mode.

Figure 17.— Continued.



(c) Yaw mode.

Figure 17.– Concluded.

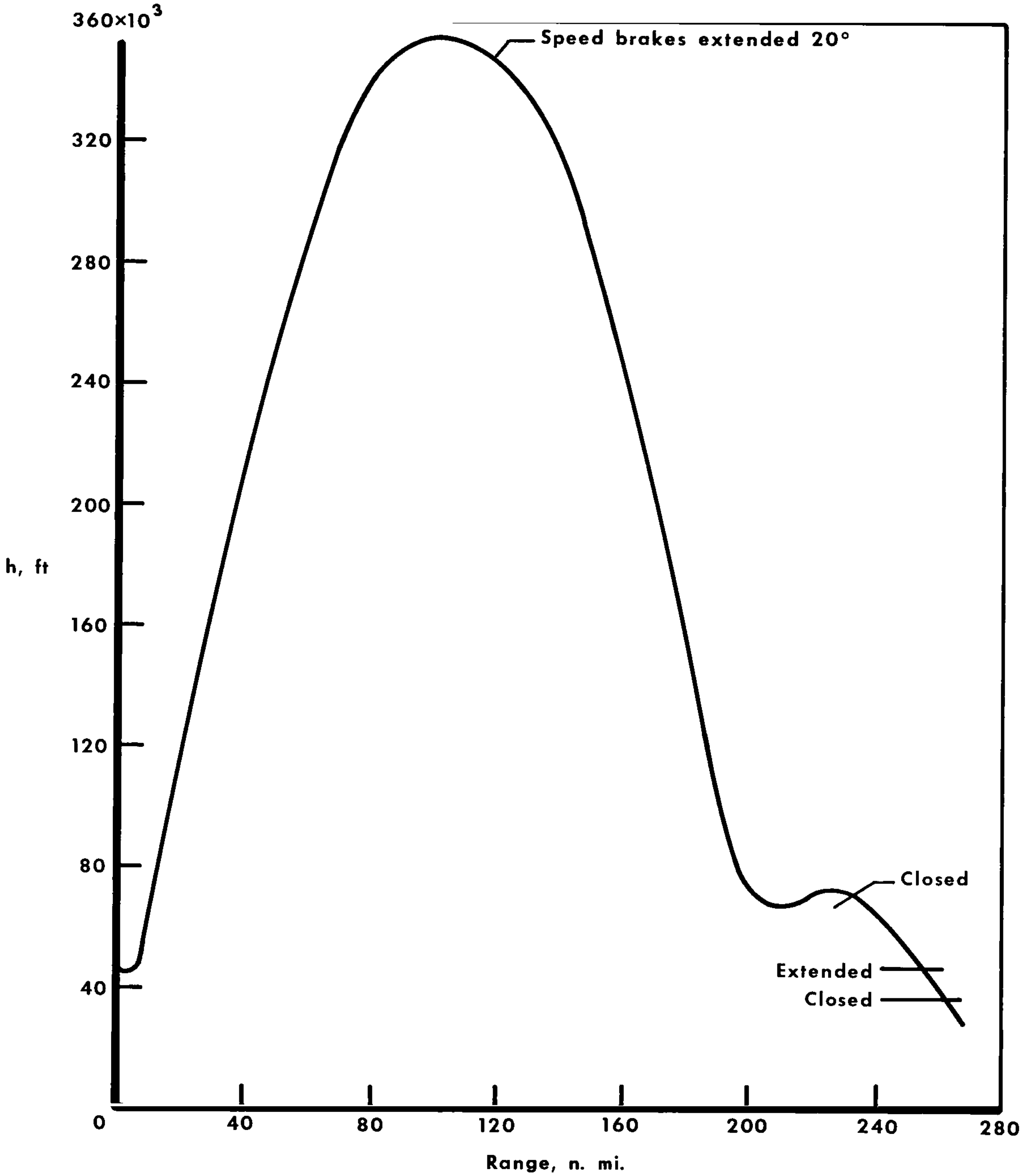


Figure 18.- Range required for recovery from an altitude of 354,200 feet.

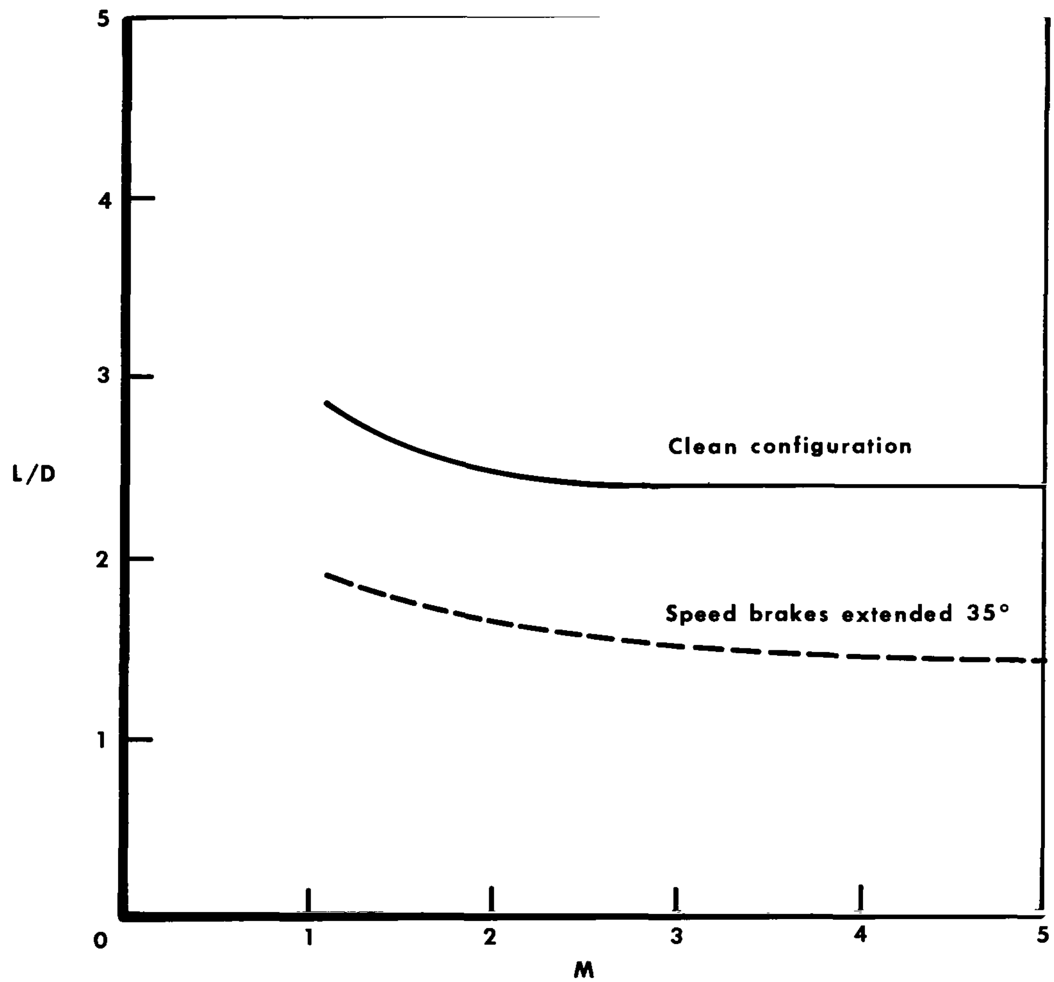


Figure 19.– Lift-drag ratio of the X-15 with and without speed brakes extended. Power off; $\alpha = 10°$.

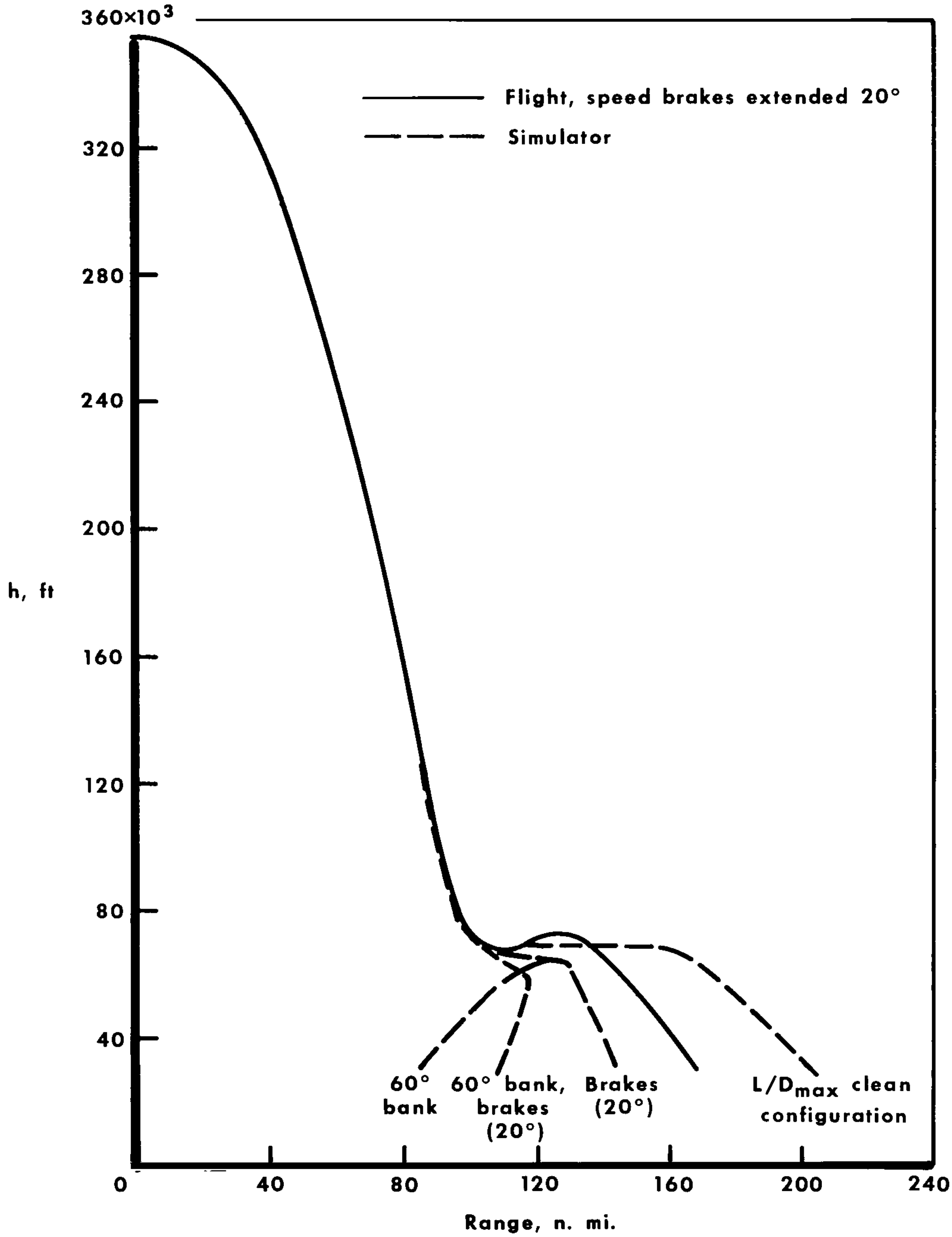


Figure 20.— Comparison of flight range capability with simulator-predicted capability. $V_o = 4,310$ ft/sec.

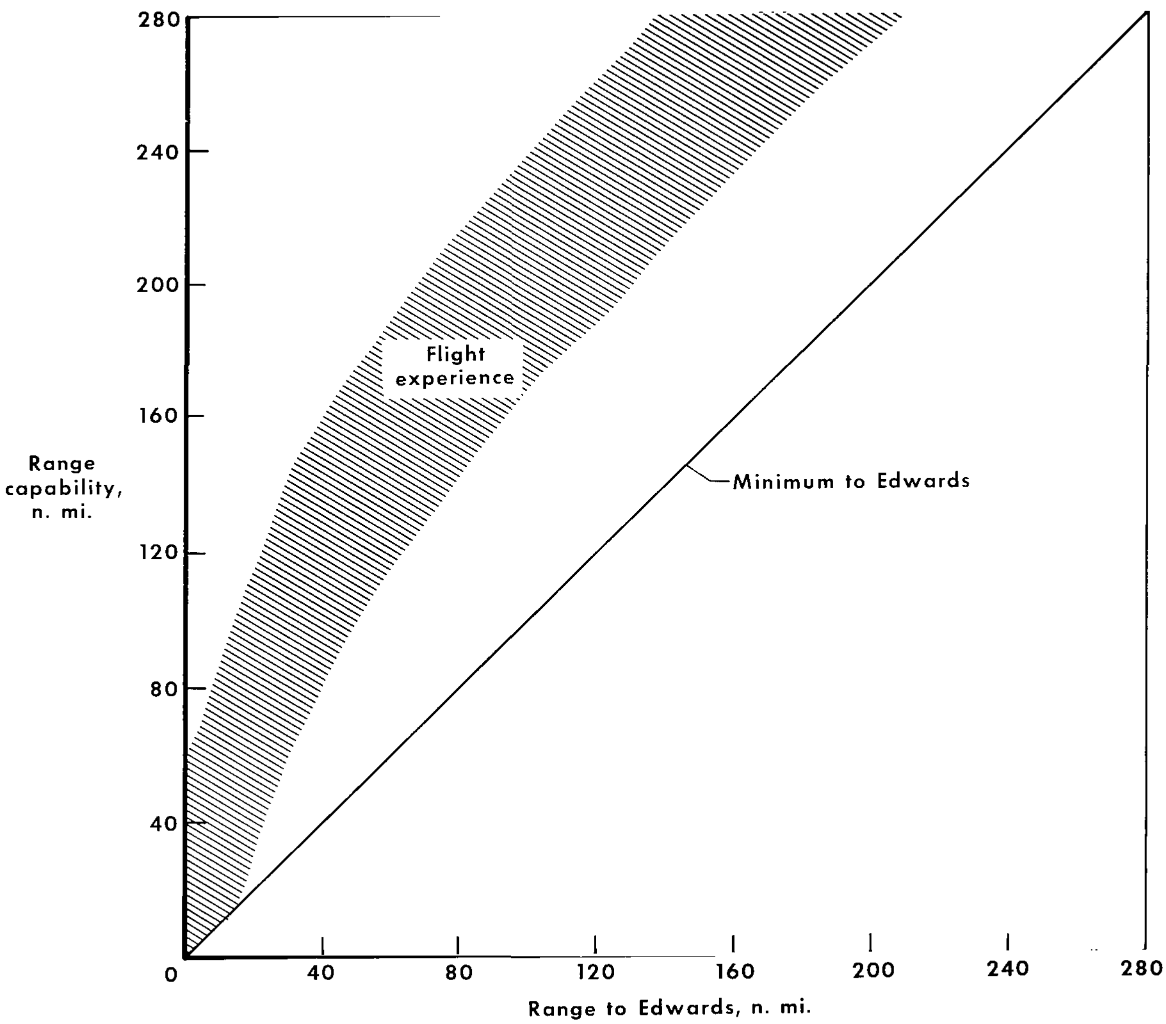


Figure 21.— Comparison of actual flight ranging experience with minimum required.

NASA-Langley, 1966 H-384

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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