Contributions of the X-15 Program to Lifting Entry Technology

EUCLID C. HOLLEMAN* AND ELMOR J. ADKINS†
NASA Flight Research Center, Edwards, Calif.

Entries from altitudes greater than 350,000 ft with the X-15 airplane have provided piloting experience and verification of predicted control characteristics and operational techniques. The airplane re-enters as a glider and duplicates several phases in the recovery of higher-performance vehicles, for example, transition from near-zero dynamic pressure to aerodynamic flight, and the terminal-area ranging and landing. During entries, reaction controls have been used to surprisingly high dynamic pressures. Rate command control provided satisfactory control, and hold modes were appreciated by the pilots for secondary control modes. With conservatively planned flights, the pilots have had no problem controlling range to base with contact navigation. Landmarks have been observed from above 300,000 ft and 160 miles range. The approach and landing of the low-lift-drag-ratio X-15 airplane has become routine, with relatively small dispersion in touchdown and slideout distance. The speed brakes have been an important control for regulation of ranging for landing; however, the pilots indicated that faster-acting speed brakes would allow more flexible operation.

Nomenclature

D = drag
g = acceleration due to gravity, ft/sec^2
L = lift
q = dynamic pressure, psf
α = angle of attack, deg
θ = pitch angle, deg
φ = roll angle, deg
ψ = yaw angle, deg

Introduction

ALTHOUGH the X-15 was not designed to investigate problems of orbital lifting entry,[1,2] it is the first research vehicle capable of lifting entry and piloted flight outside the sensible atmosphere. Sixteen flights have been made to high altitudes during which low dynamic pressures were experienced and entries were required for recovery. Altitudes up to 354,000 ft have been reached, with apogee velocities of about 4500 fps. Entry angles of attack as high as 26°, recovery normal accelerations to 5.5g, and dynamic pressures of 1500 psf were obtained. Because its speed capability is much lower than that of orbital vehicles (Fig. 1), the X-15 enters much more steeply. This results in shorter entry time (Fig. 2) and, in some respects, a more severe entry than would be expected with truly orbital vehicles. Piloted entries from high altitudes with several types of control systems have been made during the X-15 program. This experience has provided information that may be applicable to the entry problems of orbital vehicles.

This paper discusses the X-15 entry experience, and, on the basis of this experience, suggests some control-system requirements for lifting entry. Other contributions to entry technology, terminal guidance, simulation, approach and landing, and aerodynamic heating are also presented briefly. Inasmuch as the Mercury program has supplied significant control data at zero dynamic pressure, this region is not considered.

X-15 Control Systems

More than 90 research flights have been made with the X-15 airplanes, using four variations of reaction controls, three types of aerodynamic controls, and two airplane configurations (ventral fin on, and lower ventral fin off). When the original ventral-fin-on configuration exhibited undesirable augmentation-off control characteristics, the lower fin was removed. This resulted in somewhat lower directional stability but, what is more important, a configuration controllable by the pilot throughout the flight envelope with the damping augmentation inoperative.[3,4] Two of the X-15 airplanes were equipped with conventional aerodynamic control systems with three-axis stability augmentation.[5] The other airplane had an adaptive rate command control system, the Minneapolis Honeywell-96 system.[6]

Each airplane has reaction jets for control at low dynamic pressure. The X-15 reaction controls were designed to be used only when the aerodynamic control surface effectiveness is not sufficient to maintain the desired vehicle attitude. The basic system commands a roll acceleration of 5 deg/sec^2, and pitch and yaw accelerations of 2.5 deg/sec^2 for each of two systems. The X-15 system is completely dualized to provide the requisite fail safety for man-operated vehicles.

Reaction Controls

Four types of reaction control systems have been used on the X-15 in high-altitude flights. The basic reaction control system is a pure thrust command system but with thrust proportional to stick deflection outside of a dead zone of 15% of stick travel. A second type of system was provided by modifying the basic reaction control systems to include reaction rate damping. Two types of reaction control are available to the pilot with the MH-96 control system: a rate command reaction control for manual control, and an attitude hold control loop.

Aerodynamic Controls

Aerodynamic control[7] is provided in the X-15 through conventional aerodynamic surfaces using vertical surfaces for yaw

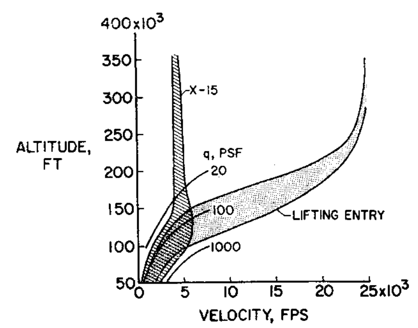

Fig. 1 Comparison of X-15 and lifting entry velocity; $L/D \approx$ 1 to 2.

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* Assistant Head, Manned Flight Control Branch. Member AIAA.
† Assistant Head, Vehicle and Systems Dynamic Branch.

control and the horizontal tail for both pitch and roll control. All the aerodynamic control surfaces are actuated by irreversible hydraulic systems. Control force is provided by bungee for pilot feel. Two systems, the stability augmentation (SAS), and the adaptive control provide the required damping augmentation about all three axes. The stability augmentation system[5] provides auxiliary aerodynamic damping by actuating the aerodynamic control surfaces to oppose the rotational velocity of the airplane. The adaptive system is much more sophisticated.

Some features of the MH-96 adaptive control system are: self-adaptive gain changing, rate command control, automatic trim, acceleration limiting, hold modes, automatic blending of aerodynamic and reaction controls, control-stick steering, and improved reliability and fail safety. More detailed system characteristics are available in the references cited. Flight tests of the system are discussed briefly in subsequent sections in an attempt to indicate the aerodynamic controls that will be required for lifting entry vehicles.

Contributions to Entry Technology

Entry Control Experience

The flexibility of the X-15 operation and the number of control systems available for evaluation have provided valuable flight experience which should be applicable to the design of future vehicles. Flight data have been obtained with attitude and rate command control systems and with attitude hold modes over a wide range of altitudes and dynamic pressures of interest.

Reaction-control experience

Flight experience at low dynamic pressure during entry has been obtained with four reaction-control systems: a simple acceleration or thrust command control system, acceleration command with rate damping, a rate command system, and the rate command system with hold modes. For the piloted control system, of equal importance are the effectiveness of the system configuration and the control fuel used during the control task. Figure 3 presents the low-dynamic-pressure portion of two X-15 entries from high altitudes with the pilot utilizing the acceleration command reaction-control system (Fig. 3a) and the rate command reaction-control system (Fig. 3b). Entry dynamic-pressure buildup to 600 psf is shown. The control tasks were similar. The pilot was asked to hold the heading angle to the desired value, the bank angle to zero, and the pitch angle constant until angle of attack equaled 20°, and then to hold angle of attack constant.

The pilot's inputs for the manual acceleration command control system are characterized by pulse-type operation. Although the rocket thrust response is proportional outside of the deadband, this feature of the system has neither been used nor appreciated by the pilots. They disliked the deadband in the system because it made precise control difficult. With the manual system, piloting technique is all important for reasonable reaction-control fuel consumption.

Although both control tasks were rated as satisfactory by the pilots (based on the Cooper scale[8]), it is apparent that the airplane motions in the low- and high-dynamic-pressure regions for the rate command system are controlled much nearer to the desired values. The pilot ratings, reaction-control fuel used, and the dynamic pressure at which the pilot last used the reaction controls (which is an important consideration in fuel consumption) for these entry control tasks, are shown in Table 1.

For this flight (Fig. 3b) the pilot did not choose to control the heading during entry, and the rates developed during the oscillation were slightly less than the deadband threshold of the MH-96 reaction control system. The motions were, however, damped by the aerodynamic damping system as dynamic pressure increased.

The reaction controls were used to much higher than expected dynamic pressures in these entries. An experienced pilot can use the manual thrust command effectively to damp airplane oscillations that tend to persist at low dynamic pressures. These oscillations would, of course, be damped by an augmented or rate command system. It appears that the pilot was using the acceleration command controls to high dynamic pressure for this purpose (Fig. 3a). From a piloting standpoint, reaction damping augmentation is especially desirable in regions of low dynamic pressure. The X-15 acceleration command reaction-control systems have been modified by adding rate damping. On the one flight that has been made with the system, it performed satisfactorily.

Although the entry experience with the reaction-control systems has been limited, the reaction-control fuel usage has been recorded and trends are indicated that may be of interest. Piloting and simulator experience is all important when considering fuel used to accomplish a control task with the manual thrust command reaction-control system. With this system, fuel usage has been relatively high, in fact, higher than designed for. The reaction-control fuel capacity required for the stabilization and angle-of-attack setup for en-

Table 1 Ratings of entry control tasks

	Acceleration command (Fig. 3a)	Rate command (Fig. 3b)
Pilot rating	Satisfactory (3)	Satisfactory (2)
Fuel used	63 lb	24 lb
Dynamic pressure at last pulse	330 psf	180 psf

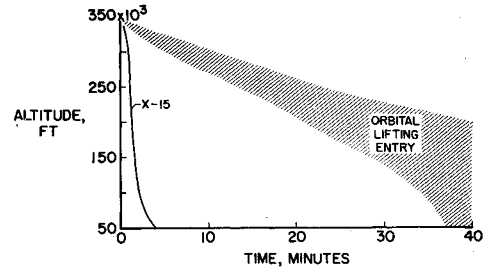

Fig. 2 Comparison of X-15 and orbital lifting entry time; $L/D \approx 1$ to 2.

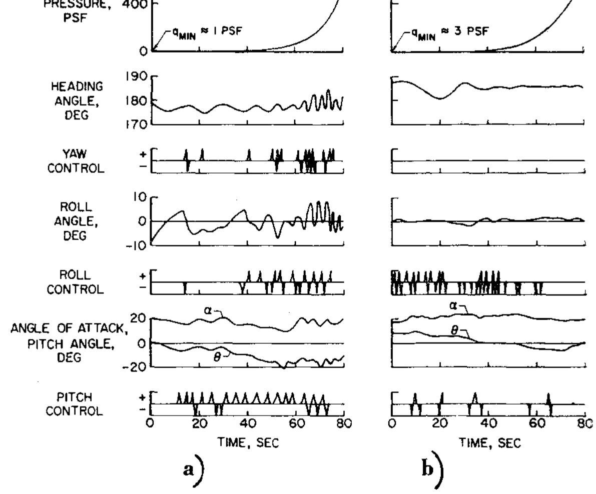

Fig. 3 Use of reaction controls, X-15 entries; a) acceleration command, b) rate command.

FLIGHTS	PILOTS	CONTROLS		PILOT RATINGS			ENTRY q, PSF	
		REACTION	AERODYNAMIC	θ	φ	ψ	MINIMUM	MAXIMUM
2	2	ACCELERATION COMMAND	ATTITUDE COMMAND AND DAMPING	3.5	1.5	2.5	≈ 0	1200
1	1	ACCELERATION COMMAND AND DAMPING	ATTITUDE COMMAND AND DAMPING	2.0	1.0	1.2	≈ 1	1360
5	3	RATE COMMAND	ADAPTIVE RATE COMMAND	2.1	1.2	1.8	≈ 0	1250
3	2	HOLD MODES, α, φ	HOLD MODES, α, φ	1.3	1.0	1.5	≈ 0	1000

Fig. 4 Entry control experience.

try control tasks was determined during simulated flights of the X-15 design altitude (250,000 ft) mission. During early altitude flights, it became apparent that more fuel was being used by the pilot than anticipated. Thus, a fuel transfer system was designed to enable the pilot to transfer fuel from the engine fuel-pump source to insure adequate reaction control fuel. Average fuel consumption has been about 90% of the design value, and on 40% of the entries usage was higher than predicted.

Flights with the MH-96 rate command system (Fig. 3b) have indicated that this system will be much more effective than the manual control system for control and stabilization during operation in a low-dynamic-pressure environment. However, with the rate command system, drift rate below the threshold level of the system can result in unwanted excursions in vehicle attitude. Control fuel, it appears, will be less than required for the manual thrust command system.

Flights to high altitude using the various attitude-hold features of the MH-96 reaction-control system resulted in precise control and somewhat less reaction-control fuel consumption than with the manual reaction-control system. The pilots have appreciated the reaction hold modes, especially in the secondary control modes such as roll.

The reaction controls have been used to much higher dynamic pressure than the value at which the effectiveness of the aerodynamic and reaction controls is equal. This value for the X-15 entry is approximately 50 to 75 psf. In some instances, dynamic pressures as high as 400 to 500 psf were reached before the pilot switched to aerodynamic controls. This operational technique has contributed to the high fuel consumption. Use of the reaction controls to high dynamic pressures may result from the rapid buildup in dynamic pressure which is peculiar to steep entries.

With manual reaction controls, some of the excess fuel consumed has been used effectively by the pilot as a damping device. This has been true especially in yaw where rapid, precisely timed inputs of the rudder control were impossible with the rudders but could be accomplished easily with a hand controller.

SAS experience

The stability augmentation system has provided satisfactory control for the pilot throughout the aerodynamic flight envelope of the airplane.[9] Entries have been made with the system from altitudes of approximately 250,000 ft, and control has been satisfactory, although not so precise as that provided by the MH-96 system (Fig. 3a).[4]

MH-96 experience

Except for specific flight tests to investigate the operation of the adaptive control system with portions of the system deactivated, all flights have been made using the complete adaptive control system, which includes the automatic gain changer. The gain changer sets the channel gains as high as possible, avoiding objectionable limit-cycle amplitudes. The pilots have rated the adaptive mode of control as excellent. The system provides positive control and good airplane damping throughout the aerodynamic flight envelope of the airplane, including entry flight.

Although there was some speculation among pilots and designers on the acceptability of the pitch-rate command control system, pilots have had no problem adapting to this type of system for any phase of the altitude flight from zero dynamic pressure to landing. The loss of the speed stability of the airplane has been noted by the pilots especially during the glide to the landing site when attention is required outside of the cockpit. Pitch-rate trim has been accepted only as a by-product of the system mechanization. With this trim, an extra display quantity—the longitudinal control surface position—was desirable, since the surface position is not related to the cockpit trim control position.

By means of the hold modes available to the X-15 pilot, an entire altitude flight, except for landing but including entry, can be flown automatically by resetting the hold modes to the desired values during specific phases of the mission. With the rapid changes that occur during the X-15 flights, little time is available to set the hold modes accurately. Often, when there has been insufficient time to trim to the desired hold attitude correctly, the pilots have overpowered the system. Some pilots have preferred to fly the prime control quantity (pitch attitude, for example) and allow the system to hold bank angle and heading. By design, the bank angle is held to zero if the hold mode is engaged when the bank angle is less than 7°. Thus, this mode does not require a precise set-in of the desired quantity.

The automatic trim provides full surface authority for the adaptive system. This is especially desirable in low-dynamic-pressure regions, and the pilots have appreciated the increased damping. For the short entry times of the X-15 airplane, it has not been possible to assess the effectiveness of the full surface authority of the system for trim at low dynamic pressures. However, for longer-time entries, this feature should be much more important in conserving reaction-control fuel.

The pilots consider the normal-acceleration limiter to be a highly desirable safety feature, because the acceleration required for entry approaches the airplane structural acceleration limit. For more extreme entries than have been flown in the program, the acceleration-limiting feature would be necessary, since higher accelerations would be required for longer periods of time for recovery.

The X-15 adaptive system has been very reliable. Only one component has failed in flight during two years of operation, which includes 21 flights covering a wide portion of the flight envelope. This failure did not degrade the performance of the system, but caused a small bias in yaw that was detectable by the pilot as only a slight directional mistrim. In 850 hr of total operating time on the flight system, only seven component failures have occurred, and five were the result of human error. This enviable reliability record can be attributed to good design and solid-state electronics. The system was designed and built around 1958–1959 state-of-the-art components; thus, subsequent improvements should make future systems more reliable.

The pilot evaluation of the X-15 over-all entry control task with the various systems is summarized in Fig. 4. Only the more extreme tasks are included. Although all the controls were rated satisfactory by the pilots, the more sophisticated systems were rated somewhat superior to the basic controls.

Entry Control Requirements

Reaction controls

What are the features in a reaction-control system that will enable the pilot to control effectively during entry? All of the X-15 pilots have endorsed the controls blending of aerodynamic and reaction controls activated by the same controller. The proportional-thrust command reaction control has not been appreciated by the pilots, nor have they used the control as a proportional control device.[10] In all instances, it has been used as an on-off control. The use of rate command reaction controls resulted in much more precise control and, apparently, consumed less fuel. The reaction augmentation was appreciated by the pilots. For entries of the type considered herein, the pilots have used reaction controls to dynamic pressures several times higher than expected. This resulted in the use of more reaction-control fuel during several entries than predicted or designed for. The deadband design of 15% of stick deflection was considered excessive by the pilots.

Aerodynamic controls

A careful examination of the flight records when the adaptive control system was used indicates that the fully adaptive gain-changer feature of the X-15 system may not be required for many flight regimes. Recognizing that the simplest system may be the best, a study was made utilizing the complete six-degree-of-freedom X-15 simulator and a breadboard adaptive control system that could be altered as desired. The rate command system at various forward-loop gains with model following and reaction-controls blending was used to investigate the controllability of the X-15 during entries from 360,000 ft. The pilot's task was primarily a pitch-axis task in which he was to hold an angle of attack of 25° until the normal acceleration reached about $5g$ and then to hold $5g$ until level flight was attained. Sideslip and roll attitude were to be held as close to zero as possible. These entries (Fig. 5) show very little difference in the pilot's ability to perform the maneuver, except for the entry at the lowest gain setting. In this entry, larger deviations occurred in all three controlled parameters. The pilot felt that excessive and continuous attention was required at the lower gain, whereas the moderate-gain and adaptive-gain entries were almost equally acceptable. These simulated entries compare well with an actual flight entry from 354,200 ft (right side of Fig. 5) in which the adaptive control system was flown manually by the pilot.

The results of this study are summarized in Fig. 6 in terms of pilot opinion of the entry control task for each of the systems investigated. From these data it is apparent that successful entries can be accomplished with either of the systems and that acceptable piloting performance and ratings are obtained with the moderate fixed-gain rate command system. It is interesting to note that the pilot ratings for actual flight are somewhat better than those for the simulator tests. Also, the pilot stated that controlling the airplane was somewhat easier in flight than on the simulator because of the additional visual and motion stimuli available in flight and the better mechanical condition of the airplane control system than the simulator.

It should be remembered that the X-15 entry is severe from the standpoint of rate of change of parameters and that it is conceivable that even systems with lower gains may be acceptable for higher-performance vehicles with longer-time entries. Certainly, the fixed-gain concept should be considered for manual control.

Some of the controls that have contributed to the success of the X-15 program may not be required for the orbital lifting entry vehicle, for example, the adaptive gain changer, which initially prompted the adaptive design concept. Perhaps the most important reason for including the gain changer would be for fail safety. With this feature, certain system failures may occur without degrading system performance. For lifting entry vehicles, however, the pilot may have time to recognize such system malfunctions and switch to backup modes, by virtue of the longer entry time available. It is of interest to note that present design trends appear to be toward the triply redundant system, which would eliminate the need for the gain changer for fail safety.

The rate command control can provide satisfactory control and damping over the wide range of aerodynamic characteristics from orbital speed to landing and, therefore, appears to be the logical choice for the primary control system of a lifting entry vehicle. The companion rate trim has not been so widely accepted, but, if properly mechanized, will provide acceptable trim. Full utilization of the capabilities of the pilot or pilots would probably remove the requirement for automatic trim, since some member of the crew could monitor this quantity during the long entry times. Similarly, the acceleration-limiting feature may not be required; the onset of acceleration for these entries will be much slower than in the X-15 entry. During certain abort situations, however, acceleration limiting may be desirable. Detailed studies of the mission and abort situation will be required to define the desired acceleration limiting.

Hold modes will certainly be desirable to reduce crew workload during the entry and perhaps provide more precise control of flight path for energy management and aerodynamic-heating considerations. Automatic switching of aerodynamic and reaction controls may not be required, inasmuch as time will be available for manual switching. By monitoring such factors as control effectiveness and reaction-control fuel consumption, it should be obvious when switching is required.

Reliability and fail safety will be as vital in the design of this system as in the X-15 adaptive system, although in a somewhat different manner. Design reliability must be based on much longer operating time for a mission but perhaps for fewer missions. Fail-safety philosophy applied in past manned-system designs should be adhered to.

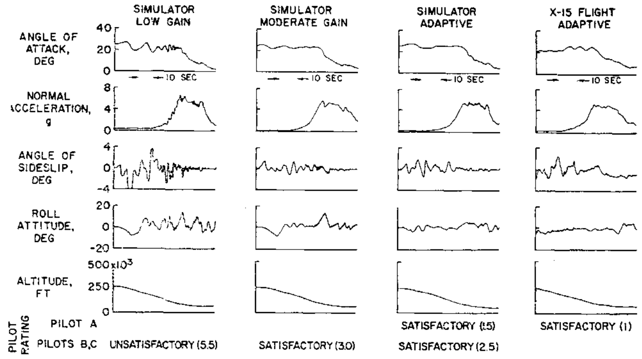

Fig. 5 Controllability during X-15 entries: entry from 360,000 ft, rate-command control.

Entry Simulation

In preparation for the X-15 program, several simulation programs[11, 12] were conducted to prepare the pilots for the extreme altitude and speed missions of which the X-15 is capable. As the program has progressed, the six-degree-of-freedom fixed-base simulator has been relied upon heavily for many operational aspects. The simulator has been used by the pilots to practice each flight.[13] Thus, as a by-product of the program, data have been obtained that aid in defining

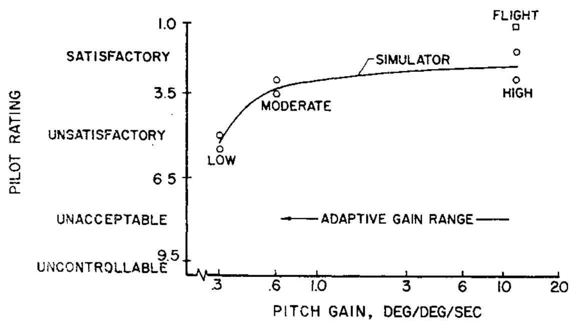

Fig. 6 Effect of damper gain on entry control: entry from 360,000 ft, rate-command control.

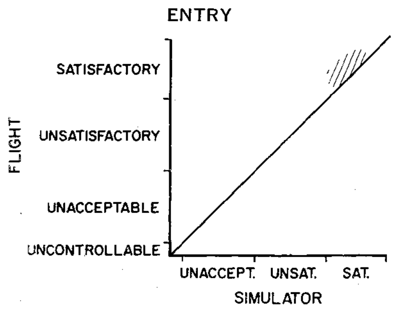

Fig. 7 Correlation of flight and fixed-base simulator.

the simulator requirements for high-performance airplanes. After X-15 flights, the pilot's opinions of the entry control task in flight and on the fixed-base simulator have been compared. Such a comparison is presented in Fig. 7. As expected, controllability was rated slightly higher in flight than on the fixed-base simulator. None of the kinesthetic cues of flight are duplicated on the simulator, and, of course, there is greater motivation in flying the actual airplane. However, the mechanics of the entry control task on the simulator were rated similar to the flight control task.

The initial X-15 pilots were exposed to the entry control task on a moving-base simulator that duplicated the entry acceleration environment. Although the pilots did not think it was necessary to prepare for each X-15 flight in this manner, exposure to the expected acceleration did give them confidence that they could perform the control task under the acceleration environment. The performance of pilots with and without the centrifuge experience, however, has been equally acceptable.

Navigation and Recovery

Ranging and navigation

As important for safe recovery as the control of vehicle attitude for stabilization during entry is the control of the rate of dissipation of energy, or control of the range of the vehicle. Although ranging is not the problem with the X-15 that it will be with the orbital entry vehicle, similar energy management controls must be exercised by the X-15 pilot for successful recovery of the vehicle after atmospheric entry.

For high-altitude X-15 flights requiring entries for recovery, the maximum range from launch to landing has been about 280 miles, which occurred on the highest altitude mission made to date. To illustrate the range capability[4] of the airplane, several entries were flown on the simulator. During steep, short-time entries, the modulation of lift-drag ratio has very little effect on range until recovery to level aerodynamic flight is achieved (Fig. 8). During pullout to level flight, the pilot controls range by modulating the vehicle lift-drag ratio or by turning flight. Certainly, cockpit display of the range capability of the vehicle during entry will be required for orbital lifting entry vehicles. Such a display has

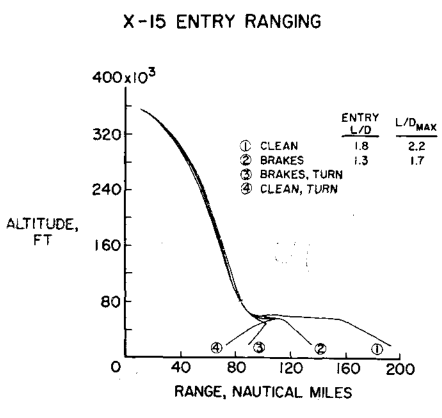

Fig. 8 X-15 entry ranging.

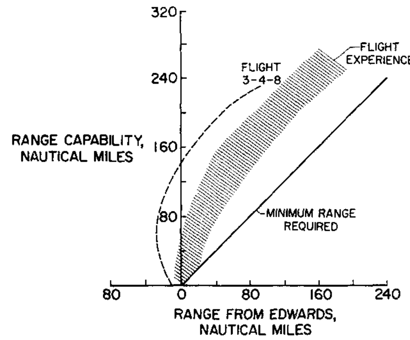

Fig. 9 X-15 terminal-guidance experience.

not been necessary in the X-15; however, a mechanization is planned for future use by the X-15 pilots.

The X-15 flights have been planned conservatively.[13] A ground controller monitors the flights and, with precomputed range tracks and flight radar range data, suggests flight-path control changes to assure safe ranging of the airplane following an entry. By plan, all flights have been under visual flight rules (VFR). Although much of the research information requested must be obtained by flying a precise instrument flight plan, terminal ranging has been by visual piloting. Of course, it is the pilot who must judge finally on the attitudes and configurations flown. Missions are planned and practiced to acquaint the pilot with all flight-plan variations likely to be encountered in flight. The pilots have indicated that they can see the landing site under the VFR conditions and can identify the site from the maximum altitude attained (350,000 ft) and from a range of 160 miles.

The X-15 entries have been planned with some 80 to 100 miles excess range during the nonaerodynamic phase of flight and some 40 to 60 miles excess range in the aerodynamic phase (Fig. 9). By modulating flight path and lift-drag ratio, the pilots have had no difficulty arriving over the landing site at a nominal high key of 20,000 ft and a Mach number of 0.8. The operational envelope of the X-15 flights (cross-hatched area) is compared to the minimum range required to return to Edwards Air Force Base (solid line). On only one occasion has the recovery been marginal (dashed line). In this situation, the pilot, engrossed in checking onboard systems, ballooned slightly during pullout and nearly overflew the landing site. But, with a call from the ground monitor, he performed a steep turn and was able to land on the south end of the lake rather than on the north lakebed as planned.

Key factors in the control of range have been angle of attack and speed brakes. By flying the angle of attack for maximum lift-drag ratio, the pilot can achieve maximum range; by modulating speed brakes and by turning flight, minimum range is obtained. Although the effectiveness of the speed brakes (which have a drag increment[14] approximately equal to the $\alpha = 0°$ drag of the vehicle) in reducing range is considered to be satisfactory by the pilots, they have expressed a desire for more flexibility in the operation of the brakes. The present brake system is relatively slow acting, about 5° of brake deflection per sec. This results in a rate of change of drag coefficient of about 0.01/sec or an increment in lift-drag ratio of about 0.2/sec. A faster-acting speed brake, particularly in closing, would allow more precise control of range in the approach to landing. A speed-brake closure rate twice as rapid as the present rate is desired by the pilots. In addition to being used as a range-control device, the speed brakes have been used to increase the directional stability of the airplane in flight attitudes where the level of stability was critical. Also, they have been used to modulate over-all performance during engine operation to enable the pilots to obtain more precise flight research data.

With the X-15, there have been no ranging and recovery problems in operating VFR. Terminal navigation has been

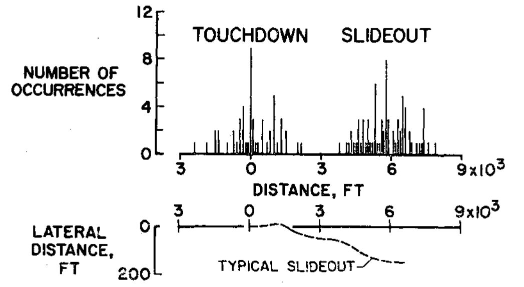

Fig. 10 Runway requirements for low L/D landings.

by contact flight with ground monitoring. Instrument flight rules (IFR) entry and VFR recovery require only a clear-weather recovery area of about 200 miles around the intended landing site. This has been the usual mode of operation of the X-15, inasmuch as the entire altitude flight plan requires instrument flight through atmospheric entry. The pilot then navigates VFR to arrive over the landing site at the desired high-key position for approach and landing.

Approach and landing

Successful recovery of an entry vehicle requires a safe landing at the desired landing site. In 1958, a program was initiated specifically to determine a satisfactory technique for accurately and repeatedly landing low-lift-drag-ratio airplanes,[15, 16] in particular, the X-15. The low lift-drag ratio and high wing loading of the X-15, for example, combine to produce, in the landing approach, one of the most challenging aircraft to land.

Since the steep approach of entry vehicles has defied successful ground-based simulation, a flight program was conducted with airplanes having similar characteristics. This program proved to be of great value to the X-15 pilots in acquainting them with the approach and landing expected of this class of vehicles. Now, after many landings, this phase of the flight has become routine and spot landings are requested of the pilots. These requests serve two purposes: they help to prepare the pilots for emergency landings; and they provide data on the landing requirements for future vehicles. Touchdown dispersion with the X-15 is shown in Fig. 10. Touchdown has occurred within $\pm 2{,}500$ ft of the desired zero point, and 70% of the nonemergency landings have occurred within $\pm 1{,}000$ ft of the desired point. Slideout, also shown in Fig. 10, has ranged from about 4000–8700 ft. Although the pilot has little directional control of the X-15 below 100 knots, lateral slideout has nominally been about 200 ft, but values as high as 2000 ft have been recorded for crosswind landings on a damp lakebed. However, with effective nosewheel steering, it appears that low-lift-drag-ratio gliders with speed brakes for drag modulation could be landed successfully on 2- to 3-mile runways. X-15 touchdown vertical velocity has averaged 3.4 fps, with a range of 0.5 to 9.5 fps.

Most of these approaches have been from a high-key position of 20,000 ft and a Mach number of 0.8, with a circular overhead approach pattern.[15] This type of pattern[17] has been preferred for visual landing approaches, as all of the X-15 approaches have been. The straight-in approach has the advantage of reducing pilot judgment requirements, since only drag modulation is necessary to insure the proper airspeed. Instrument approaches with lifting entry vehicles may require straight-in approaches or perhaps some technique not yet developed. Certainly, new displays will be required for these steep, high-rate-of-descent IFR approaches and high landing speeds.

Of somewhat more importance for the lifting entry vehicle than for the X-15 airplane is the external visibility required to land vehicles with low lift-drag ratios and high wing loadings,[18] since the problems of heat protection will be much more complex than with the X-15. The X-15 pilot has 180° of peripheral vision and about 17.5° of forward vision, 10° up and 7.5° down. With this field of vision and with the assistance of an escort airplane, the X-15 landings have become routine. Actually, in the landing attitude the pilot's downward vision is limited to about 0° by airplane attitude. Two landings have been made with reduced vision on one side when the cockpit glass had shattered as a result of aerodynamic heating. For one of these landings, the entire side glass panel was opaque.

Aerodynamic Heating

Aerodynamic-heating results that have been obtained during the X-15 program are not presented in detail herein; however, more complete data are included in Refs. 19 to 22. Although aerodynamic heating has not been a problem on any of the X-15 entries, by virtue of the design temperature of 1200°F, predictions of aerodynamic heating on the airplane have been made for each of the altitude entry missions. The temperature-prediction process developed for this program involves three digital-computer programs. First, the local flow is computed for the conditions expected during the flight. The computed local flows are used to calculate the aerodynamic heat transfer to the airplane surfaces. Then, the differential equation describing the time-dependent heating of the thin-skinned areas is integrated to give skin temperature as a function of time during the flight. Finally, the aerodynamic-heating inputs are used to calculate the transient heating of internal structural areas where heat transfer is by conduction and/or radiation.

Figure 11 compares the calculated and measured wing temperatures during an X-15 altitude flight to 315,000 ft. The present prediction methods were arrived at by using empirical coefficients developed to modify the basic theoretical calculations and improve the actual prediction process. The X-15 entries made to date are not temperature limited, as orbital entries would be expected to be; however, temperature-prediction methods for the X-15 appear to be acceptable and should provide additional insight into the aerodynamic heating of the orbital entry vehicle.

Additional Contributions of the X-15 Program

In addition to the operational contributions to entry technology already discussed, the X-15 program has made many other contributions, although perhaps more subtle. For example, at least up to Mach numbers of 6, the measurement and prediction methods used to determine the stability and control derivatives[23] of complicated configurations have been verified with actual flight-determined derivatives. Both pilots and designers have gained increased confidence in the methods of predicting handling qualities and the levels of stability required at hypersonic speeds. All of the maneuvers required of entry vehicles have been performed by the X-15 pilots, using a side-located controller, in an acceleration en-

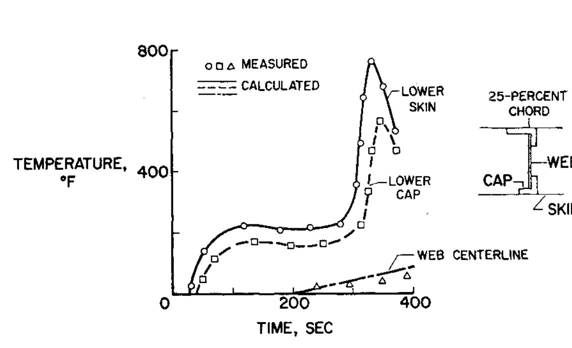

Fig. 11 Comparison of calculated and measured temperatures: flight to 315,000 ft.

vironment as hostile as would be expected during orbital entry.

Airplane systems[24] have been designed and made to function in all of the environments that will be operational for the lifting entry vehicle. Pilots have proved that the human can control effectively in many flight regimes from zero g to high g. For the X-15 program, the pilot was integrated into the design far earlier and more completely than with any previous design. The success of this program attests to the wisdom of including the pilot in a program at its beginning.

Although the degree of aerodynamic heating at some locations on the airplane was predicted, other locations sustained heat damage during routine flight. Locations such as landing-gear doors require much better seals than originally believed. Also, skin or structural junctures where the boundary layer was tripped resulted in much higher heat loads, sometimes buckling the skin.[20] Skid-type landing gear[25] proved satisfactory; however, this type of gear, it appears, required a new design criteria because of the radically different rebound reaction loads that are experienced with the gear in this rearward location.

Finally, the X-15 program has demonstrated that an incremental-performance-buildup flight program in which flight and system operational experience can be gained pays large dividends in providing a more successful over-all operation.

Concluding Remarks

Sixteen successful X-15 entries from high altitudes—the most extreme from 354,200 ft—have provided confidence that lifting entries can be made with higher-performance entry vehicles.

The X-15 program has offered the opportunity to assess and resolve the problems of controls, displays, and operational methods required for steep short-time entries from high altitudes. Such entries are predicted to be more severe from a controllability standpoint than entries with a lifting entry vehicle. The contact flight ranging and recovery of the low-lift-drag-ratio, high-wing-loading X-15 airplane have become routine.

Although instrument flight approach and landing of lifting entry vehicles is feasible, some research effort will be required to develop operational methods and required displays.

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