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THE X-15 AIRPLANE—LESSONS LEARNED

William H. Dana*
NASA Dryden Flight Research Facility
Edwards, California

Abstract

The X-15 rocket research airplane flew to an altitude of 354,000 ft and reached Mach 6.70. In almost 200 flights, this airplane was used to gather aerodynamic-heating, structural loads, stability and control, and atmospheric-reentry data. This paper describes the origins, design, and operation of the X-15 airplane. In addition, lessons learned from the X-15 airplane that are applicable to designing and testing the National Aero-Space Plane are discussed.

Nomenclature

a_n	aircraft normal acceleration vector
a_R	resultant aircraft acceleration vector
a_x	axial aircraft acceleration vector
g	acceleration caused by gravity, ft/sec^2
h	altitude, ft
M	Mach number
NACA	National Advisory Committee for Aeronautics
NASP	National Aero-Space Plane
t	time, sec
V	velocity, ft/sec

Introduction

The X-15 airplane flew to an altitude of 354,000 ft and reached Mach 6.70. Over a 9-yr period, the three X-15 airplanes flew almost 200 flights and made major contributions to the understanding of aerodynamic heating, hypersonic stability and control, control outside the atmosphere, and lifting reentry to the atmosphere of the Earth. Because of these contributions, the late Dr. Hugh L. Dryden called the X-15 "the most successful research airplane in history."

This paper describes the origins, design, and operation of the X-15 airplane. In addition, lessons learned from this airplane that are applicable to designing and testing the National Aero-Space Plane (NASP) are discussed.

Research completed by Wendell H. Stillwell is gratefully acknowledged as the basis for this paper.[1] Use of trade names or names of manufacturers in this paper does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

Origin and Design

The beginnings of the X-15 airplane were in 1952. It was the year of the first flights of the F-86F and the YB-52. The aeronautical community was struggling to increase aircraft speeds from Mach 1.5 to 2. People of vision, however, already were looking to the higher speeds and altitudes that would eventually lead to orbital flight. For in 1952, the National Advisory Committee on Aeronautics (NACA) recommended an increase in research dealing with flight to speeds from Mach 10 to 12 and to altitudes from 12 to 50 miles.

In 1954, NACA submitted to the Air Force-Navy-NACA research airplane program a technical proposal for a hypersonic research airplane. The plan was accepted. In December 1954, the Air Force issued invitations to industry for the design and manufacture of a hypersonic research airplane. Several contractors submitted proposals with maximum speeds from Mach 6 to 7. North American Aviation, Incorporated, Inglewood, California, won the contract, and the result was the X-15 airplane.

The X-15 program called for production of three airplanes designed for a speed of Mach 6.6 and an altitude of 250,000 ft. The Mach 6.6 represented the maximum speed that state-of-the-art structures could support. An altitude of 250,000 ft was an arbitrary design point which would force adequate attention to exoatmospheric control and to reentry techniques.

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*Aerospace Research Pilot.

Vehicle Description

Figure 1 shows a three-view photograph of the X-15. This 50-ft long airplane had a wingspan of 22 ft, weighed 33,000 lb at launch, and weighed 15,000 lb when empty. The flight control surfaces were hydraulically actuated and included all-moveable elevators and all-moveable upper and lower rudders. The lower rudder extended below the landing gear and had to be jettisoned before landing. Speed brakes were located on the aft end of the fixed portion of the vertical fins, and the landing flaps were on the trailing edge of the wing. No ailerons were used. Roll control was achieved by differential deflection of the horizontal tail.

All three X-15 airplanes were delivered with simple rate-feedback damping in all axes. The X-15 no. 3, however, was extensively damaged during a ground-engine run before the airplane ever flew. When rebuilt, this X-15 was fitted with a self-adaptive flight control system. This system included command augmentation, self-adaptive damper gains, several autopilot modes, and blended aerodynamic and ballistic controls.

The X-15 airplane was designed as a hot structure; that is, the structure served as a heat sink for aerodynamic heat loads. These loads could have been reduced by insulation or by cooling, but the hot structure offered a more attractive concept in terms of knowledge to be gained in the areas of aerodynamic heating and elastic behavior. The structural material was Inconel X®. Slightly heavier than steel, this nickel-chromium alloy was selected because of its load-carrying capability at high temperatures. The exterior surface of the airplane was painted black to increase reradiation of aerodynamic heat loads.

Figure 2 shows the X-15 engine. This engine was an XLR-99 single-chamber rocket that produced 60,000 lb of thrust and burned 18,000 lb of liquid oxygen and anhydrous ammonia in 85 sec. These propellants were fed by a steam-driven turbopump. The source of the steam was hydrogen peroxide decomposed by passing through a silver screen catalyst bed. Gaseous helium provided the tank pressure to feed the propellants to the engine turbopump. In addition, two steam turbines, called auxiliary power units, furnished hydraulic pressure and electrical power for the X-15. Their propellant was also decomposed hydrogen peroxide. Liquid nitrogen was used to cool the payload bay, cockpit, windshields, and nose. Steam rockets in the nose and wings provided attitude control when the airplane was out of the atmosphere.

Figure 3 shows the cockpit. Three flight controllers are outlined in white. The center stick provided conventional pitch and roll control and was intended for use after engine burnout. Mechanically linked to the center stick was a right-hand controller used during the boost. When the pilot used the side controller, the back of the right elbow was braced to disallow aft movement. This arrangement prevented the mass of the pilot's forearm and hand from causing spurious pitch inputs in the acceleration field that exists during boost. A three-axis ballistic controller on the left side of the cockpit was mechanically linked to steam rockets in the nose and wings.

On the instrument panel was an attitude indicator whose source was inertially derived. Inertial velocity, altitude, and rate-of-climb data were also provided. Barometric instruments included an altimeter and a combined Mach-airspeed indicator. These instruments were usable below approximately 75,000 ft and were used mainly in the traffic pattern. Angle-of-attack and sideslip indicators were provided. The source of these two instruments was selectable, inertial for high-altitude flight and barometric for the end of the mission.

Operations

The X-15 airplane was actually the second stage of a two-stage system (Fig. 4). The first stage was a B-52 bomber, specially modified for the program. This bomber carried the X-15 uprange into Nevada, pointed it towards Edwards, California, and launched it at an altitude of 45,000 ft and at Mach 0.8.

Figure 5 shows a typical X-15 mission. In this case, the airplane was launched approximately 200 miles from Edwards, California. The engine was lit immediately after launch and burned for approximately 85 sec. During that period, the engine would boost the X-15 to an altitude of 160,000 ft and to a speed of Mach 5.4. The X-15 would then coast to 250,000 ft, reenter the atmosphere, and glide to a landing on the dry lake at Edwards, California. A typical X-15 flight lasted 11 min, including approximately 4 min in the traffic pattern.

The X-15 first flew on June 8, 1959, and within 3 yr had completed all the objectives of the original research program. It reached Mach 6.06, which because of weight growth was less than the Mach 6.6 design speed, but it also reached an altitude of 354,000 ft, some 40 percent higher than the program goal of 250,000 ft. The altitude capability was made possible by the blended aerodynamic and reaction controls of the self-adaptive flight control system in the X-15 no. 3. Only X-15 no. 3 flew significantly above 250,000 ft. The following subsections address some of the problems that were anticipated for the X-15 before the first flight and describe how the X-15 fared in these areas.

Atmospheric Exit and Entry

The mechanics of atmospheric exit and entry were quite straightforward. The pilot flew a constant pitch-attitude until engine burnout. Then an angle-of-attack schedule (a low angle of attack to peak altitude and a high angle of attack for

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reentry) was flown. Reentry angle of attack varied from 15° to 26°, depending on peak altitude.

Some aeromedical effects of interest occurred during boost. One was the ability of the pilots to function in the acceleration during boost. After engine light, the pilot was under 2-g, chest-to-back acceleration which increased to approximately 4 g at burnout. The pilots believed that 4 g were about enough. Test pilot Milton Thompson once said, "The X-15 was the only aircraft I ever flew where I was glad when the engine quit."

The fact that the X-15 pilots were willing to call 4 g of axial acceleration a limit when fighter pilots of today fly and fight in much higher normal acceleration environments may have been a result of another phenomenon concerning X-15 power-on flight—phantom pitch rate perceived during the boost. In the absence of a horizon reference, pilots tend to define down as the direction that acceleration forces them. When X-15 pilots lost sight of the horizon during pullup, acceleration along the flightpath gave them the sensation of pitching steeply upward. Figure 6 illustrates this phenomenon. As acceleration increased during fuel burn, the pilot had the sensation that the X-15 was rotating even more steeply upward. This phenomenon was a fundamental sensory illusion for which there was no cure. Strict reference to the flight instruments was required until engine shutdown to prevent the pitch rate illusion from ruining the flight profile.

Entry was a less-demanding pilot task. There was no acceleration caused by thrust, and the horizon was in view throughout. At constant angle of attack, the normal acceleration gradually increased to 5 g and then was maintained there (usually for a period of about 15 sec) until the X-15 had broken its fall. The X-15 pressure suit was equipped with an integral g suit.

Control Outside the Atmosphere

No serious problems developed in controlling the X-15 using the ballistic control rockets. Care had to be exercised to keep angular rates small because the task could become confusing for the pilots when they attempted to control all three axes simultaneously. The main problem with ballistic flight was that the airplane was neutrally stable. As a result, the pilot was the only thing keeping the X-15 pointing down the flightpath. The X-15 no. 3 aerodynamic and ballistic controls were blended automatically through the autopilot. One feature of this autopilot was a heading-hold mode; so as far as the pilot was concerned, X-15 no. 3 was directionally stable while ballistic.

Control at Zero Gravity

Neither control problems at zero gravity nor any other problems related to weightlessness occurred. The pilots did not become nauseous, as later occurred in the Apollo program. There was one humorous incident. The pilot hit the latch on the checklist binder while shutting down the engine and thereby released 27 pages of checklist. These pages floated around the cockpit for 2 min before the weightlessness ended.

Aerodynamic and Structural Heating

The X-15 airplanes were exposed to surface temperatures as high as 1350 °F during this program. All of the airplanes exhibited minor buckling of the exterior skin. During the rocket-boost phase of the flight, when the aircraft was accelerating and heating rapidly, the pilot could hear this skin buckling. As test pilot Joseph A. Walker observed, "The airplane crackled like a hot stove."

The leading edges of the wing were formed in several pieces and had small slots between segments to allow thermal growth. These slots tripped the boundary layer and caused high temperature and skin buckling downstream of the slots. The slots were eventually capped and an additional rivet was added behind the slot to solve the problem. Figure 7 shows the skin buckle following flight to Mach 5.28. The modified slot is also shown.

On two occasions, the right outside window pane crazed and forced the pilot to fly and land with only left-hand vision. Figure 8 shows damaged window glass following flight to Mach 6.04. This crazing was caused by buckling of the window frame. The Inconel X® frame was replaced with one made of titanium. The replacement frame had less thermal expansion and thereby prevented further recurrences of window crazing.

Simulation

A fixed base analog simulator was used extensively for planning X-15 flights and for pilot practice. Every flight was preceded by from 10 to 20 hr of simulation of normal and emergency procedures. This simulator had to be continually updated with data gathered in flight. For example, early simulations based on wind-tunnel data indicated that the X-15 would be flyable with the lower rudder turned on and the roll damper turned off. Flight test proved this indication not to be the case, however. When the roll damper was turned off, a divergent dutch roll developed. Coincidentally, though, flight test also revealed that the lower rudder was not required for directional stability. The lower rudder was discarded. The X-15 airplane then became stable even with a roll damper failure, and the simulator was updated to reflect the actual aircraft characteristics.

Landing

Before the X-15 flight program began, considerable reservation about the ability of the pilots to consistently land a power-off, low lift-drag ratio airplane existed. The X-15, however, had good handling qualities and a large, variable-deflection speed brake, and it proved easy to land. The pilots used a circling approach which began at 30,000 to 50,000 ft above the runway and stayed high on profile until it was ensured that the airplane would reach the runway. Then, the speed brakes were used to descend to a nominal glideslope.

For drag reduction, the landing gear was left retracted until the landing flare was complete, and the aircraft was in level flight.

There were 196 successful landings in the program. The two landing accidents that occurred were related to system or structural failures and not to pilot error. The first accident (Fig. 9) happened early in the program. An engine explosion occurred during engine start, and the pilot was forced to land at the launch lake. Not all of the propellants jettisoned. In addition, the oil in the nose strut had become aerated. Thus, the airplane was heavyweight, and the nose strut did not provide the shock absorption for which it was designed. In spite of this structural failure, the damage was minor and the airplane was back in the air in 3 months with a modified nose strut that was able to handle landing loads.

Figure 10 shows the second landing accident. Once again, an engine failed. In this case, the fuel was jettisoned, but the landing flaps failed to extend. The landing was, therefore, fast. High download on the main gear after nosewheel touchdown combined with a faulty weld to cause the left main gear to fail. The airplane veered sideways and rolled over, damaging the wings, destroying the tail surfaces, and injuring the pilot, who suffered three crushed vertebrae. The pilot returned to flying status within 6 months and was soon back in the X-15 program. Rebuilding of this X-15 is described later in this subsection.

By 1963, the design objectives for the X-15 airplane had been met. For the last 6 yr of its life, this airplane served mainly as a testbed for other experiments. These experiments were usually space-related and varied from a pod that was carried on one wingtip with which it was attempted to capture a micrometeorite to a top-looking camera for stellar photography to a down-looking camera for aerial photography. Figure 11 is a photograph of the Colorado River Valley taken using a down-looking camera mounted on an X-15 airplane at an altitude of 220,000 ft.

The ramjet engine which was planned to be tested on the X-15A was the most interesting X-15 follow-on experiment. Figure 12 shows the X-15A which was rebuilt from the X-15 airplane that rolled on its back after the previously discussed landing gear failure. The fuselage was lengthened 29 in. to make room for a hydrogen tank which was to provide fuel for an air-breathing ramjet engine to be mounted on the ventral fin. The ramjet shown in Fig. 12 was a boilerplate dummy engine used to obtain performance and stability data before installation of a working ramjet. Similar to the lower ventral fin, the ramjet had to be jettisoned before landing.

The ramjet rode well. With the added structural weight and drag of the ramjet, however, the maximum speed of this configuration was just over Mach 5. Testing the ramjet at Mach 6 to 8 was desired. To accommodate this increased performance, two external fuel tanks were added. Figure 13 shows these droppable tanks which carried an additional 13,000 lb of propellants. The tanks were carried until empty at an altitude of approximately 70,000 ft and at Mach 2. Then the tanks were jettisoned, and the bare X-15 airplane had full internal fuel with which to accelerate from that starting point.

One flight was launched in the configuration shown in Fig. 13 and flown to Mach 6.33. The next flight was to exceed the original design speed of Mach 6.6, which meant that the structure had to be protected from the heat. A silicone elastomeric was sprayed over the exterior of the airplane (Fig. 14). This coating was designed to ablate during the high-Mach-number portion of the flight and to carry some of the heat load with it.

The white X-15 was flown one time to Mach 4.94 to check the integrity of the thermal protection. Then this airplane was flown in the configuration shown in Fig. 15 to Mach 6.70, the fastest speed achieved during the X-15 program. Charring of the ablative coating (Fig. 16) occurred on many areas of the X-15, but more serious damage occurred where the wake of the dummy ramjet impinged on the ventral fin. Portions of the skin of the ventral were burned through. In addition, the substructure and the subsystems enclosed in the ventral fin sustained substantial damage. The X-15A was returned to the North American Aviation, Incorporated, factory in Inglewood, California, for repair. Before repair of the damaged structure was complete, the X-15 program was canceled. The X-15A was never flown again, and the actual working ramjet was never flight tested. The flight resulting in all the heat damage occurred in October 1967.

In November 1967, X-15 no. 3 launched on what was to be a routine research flight to an altitude of 250,000 ft to evaluate a boost-guidance system and to conduct several additional follow-on experiments. During the boost, the airplane experienced an electrical problem which affected the flight control system and inertial displays. This problem distracted the pilot and may have caused other displays to be misinterpreted. At peak altitude, the X-15 began a yaw to the right, reentered the atmosphere yawed crosswise to the flightpath, went into a spin, and broke up at an altitude of 65,000 ft, killing the pilot. This tragic event, in retrospect, was the death knell for the entire project. Program management decided not to fly the X-15A again and to fly X-15 no. 1 only for calendar year 1968.

Lessons Learned

Numerous lessons learned from the X-15 are already standard practice in the industry. Examples of well-understood lessons include techniques for power-off landing of low lift-drag ratio airplanes and use of simulators for flight planning and pilot training. Other lessons are not so well-known. These lessons are offered here to anyone who can use them, but they are applicable mainly to those who will build the next hypersonic airplane; specifically, the people involved in the development of the National Aero-Space Plane.

The first lesson from the X-15 is to make the airplane robust. The X-15 survived some severe mistreatment during landings and still came back to fly another day. Examples exist of where the X-15 survived a major stress in spite of operating with a major malfunction. In June 1967, test pilot William J. (Pete) Knight launched in X-15 no. 1 on a planned flight to 250,000 ft. At Mach 4 and at an altitude of 100,000 ft during the boost, the X-15 experienced a complete electrical failure. This failure resulted in shutdown of both auxiliary power units and, therefore, loss of both hydraulic systems. Knight was eventually able to restart one of the auxiliary power units, but not its generator. By skillful use of the one remaining hydraulic system and the ballistic controls, Knight was able to ride the X-15 to its peak altitude of 170,000 or 180,000 ft, reenter the atmosphere, make a 180° turn back to the dry lake at Tonopah, Nevada, and deadstick the airplane onto the lakebed. All of these activities occurred without there ever flowing another electron through the airplane from the time of the original failure.

A hue and cry is to be expected from some that the National Aero-Space Plane (NASP) cannot afford the luxury of robustness; that to get into orbit the NASP will have to be highly weight-efficient; and that it will, therefore, have to forego the strength and redundancy margins which allowed the X-15 airplane to survive during adversity. An answer to these people is to build the first NASP with X-15 margins. Even at the expense of performance, these margins will serve well while researchers learn how to make the propulsion system operate and discover how to survive in the heating thicket of hypersonic flight. Someday with this knowledge in hand, it will be time to build a no-margins NASP. For now, seize all the margins that are obtainable. Such margins will be as needed today as they were with the X-15 airplane.

The second lesson from the X-15 is to conduct envelope expansion incrementally. The typical increment of speed increase for the original X-15 was approximately one-half of a Mach number. With this increment, it was easy to handle the heating damage that occurred in the original speed expansion phase. Again, protest from the NASP community is to be expected because when using one-half Mach number increments, it is a long flight test program to Mach 25. Indeed, the goal here is not to specify what size bite to take during the NASP envelope expansion but to offer the X-15A experience. In two consecutive flights carrying the dummy ramjet, the X-15A airplane was flown to Mach 4.94 and 6.70. The former flight exhibited no heat damage because of the wake of the dummy ramjet. The latter flight almost resulted in loss of the aircraft because of heat damage.

With that brief counsel for those who would follow in the path of the X-15, there is one more X-15 flight to be discussed. On October 24, 1968, X-15 no. 1 flew a successful research flight to an altitude of 250,000 ft to accomplish the 199th flight of the program. Two months of the year remained in which to pass the 200-flight milestone. However, a series of problems involving the experiment, the inertial reference system, and the weather combined to keep the X-15 airplane on the ground. Time finally ran out on the most successful research airplane in history.

Reference

[1]Stillwell, Wendell H., *X-15 Research Results*, NASA SP-60, 1965.

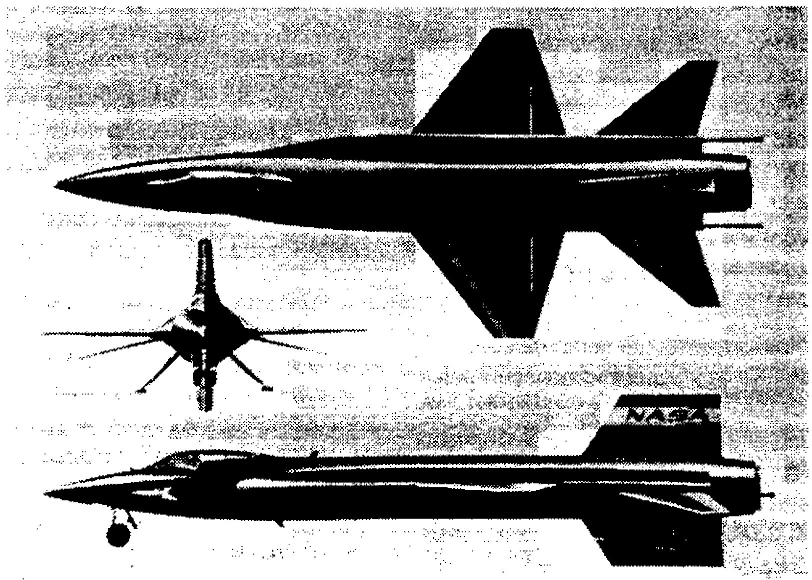

Fig. 1 The X-15 airplane.

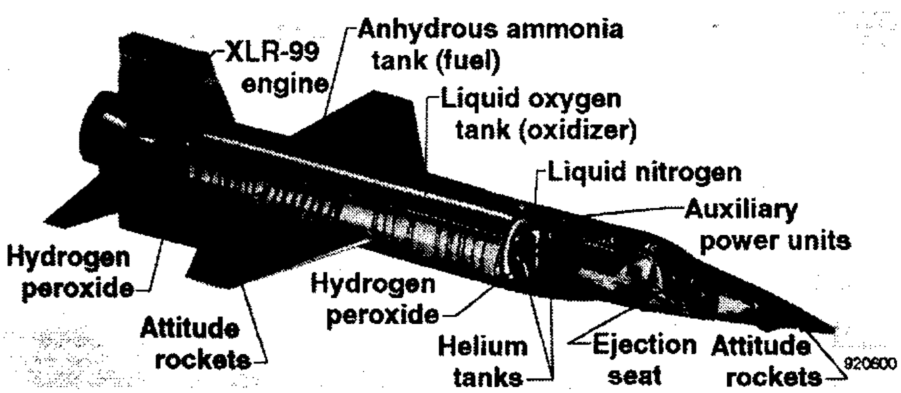

Fig. 2 The X-15 airplane configuration.

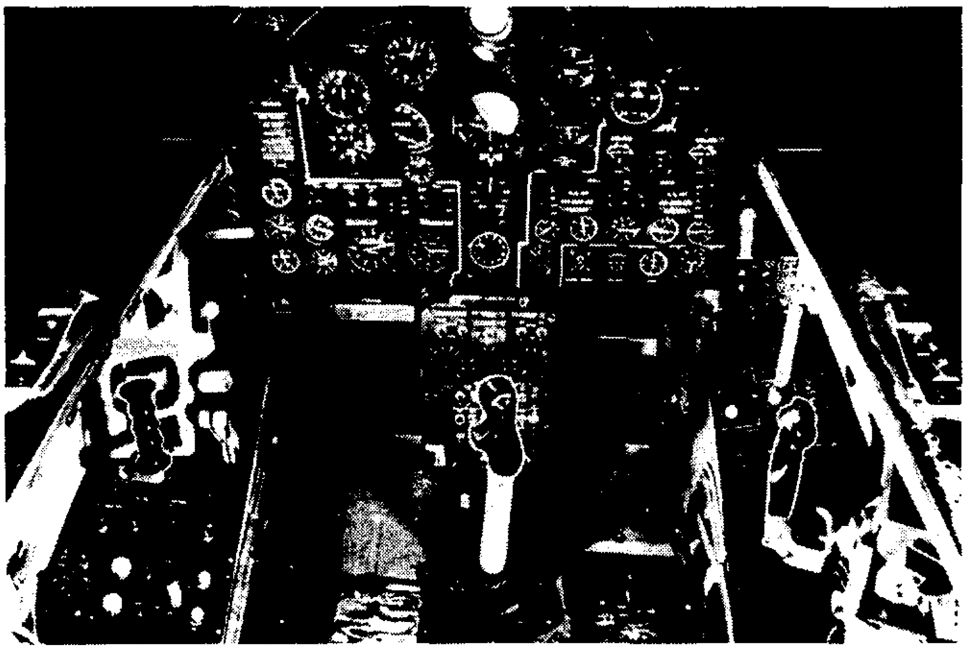

Fig. 3 The X-15 cockpit.

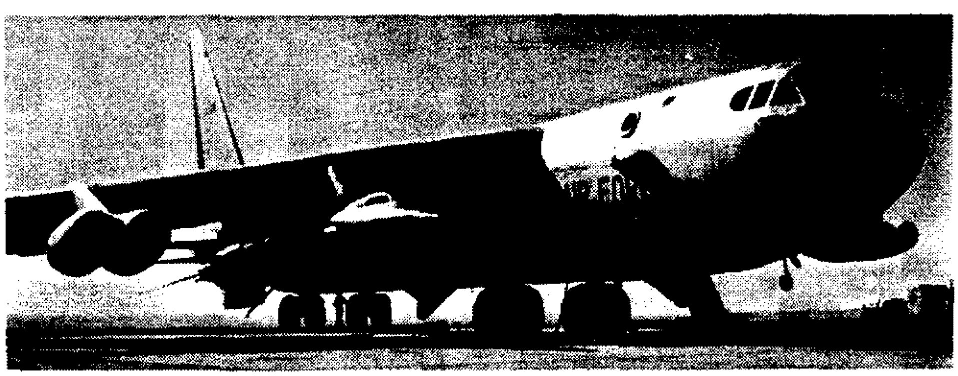

Fig. 4 A B-52 bomber modified for use as an X-15 airplane.

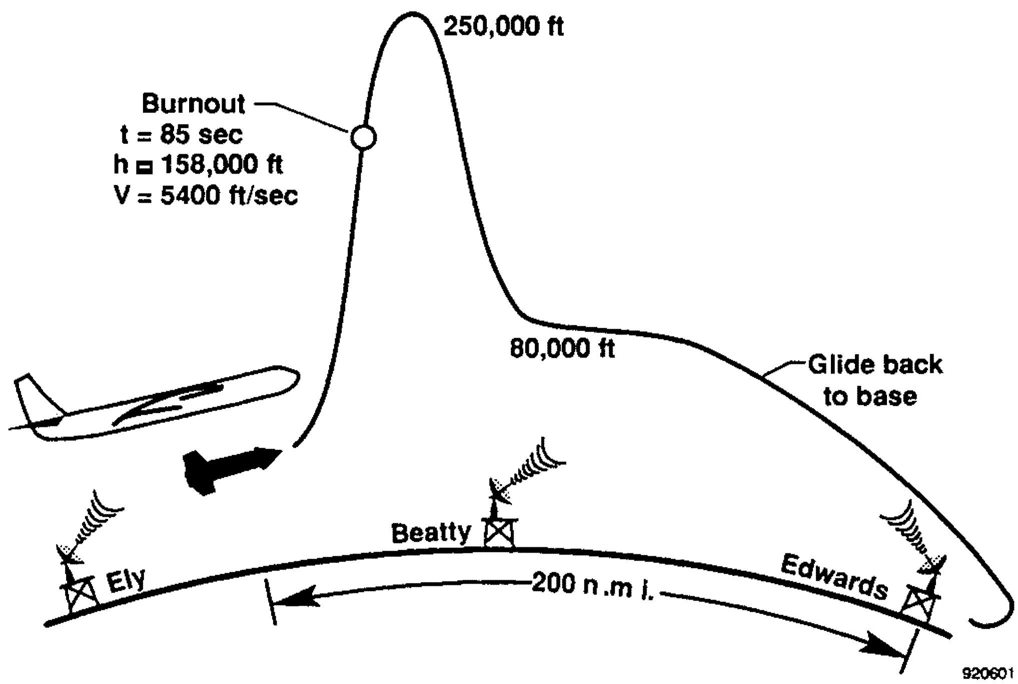

Fig. 5 A typical X-15 mission.

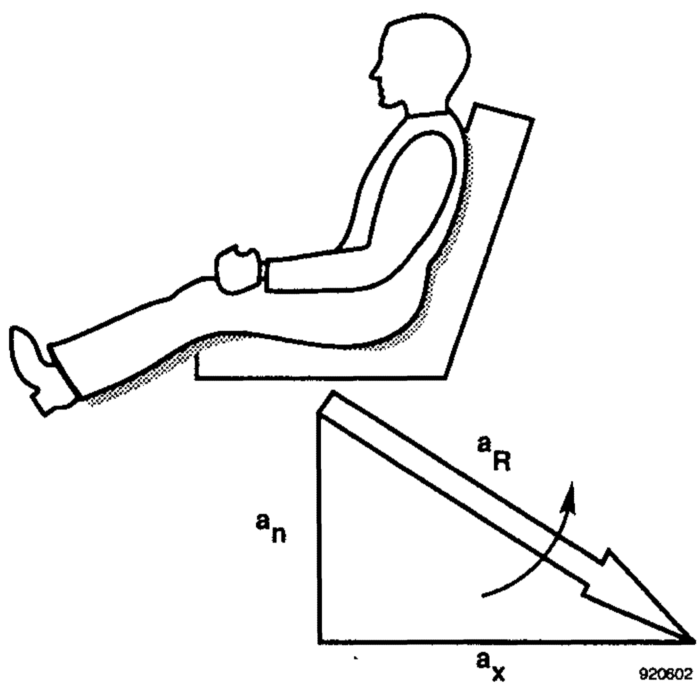

Fig. 6 Steep pitch phenomenon caused by acceleration.

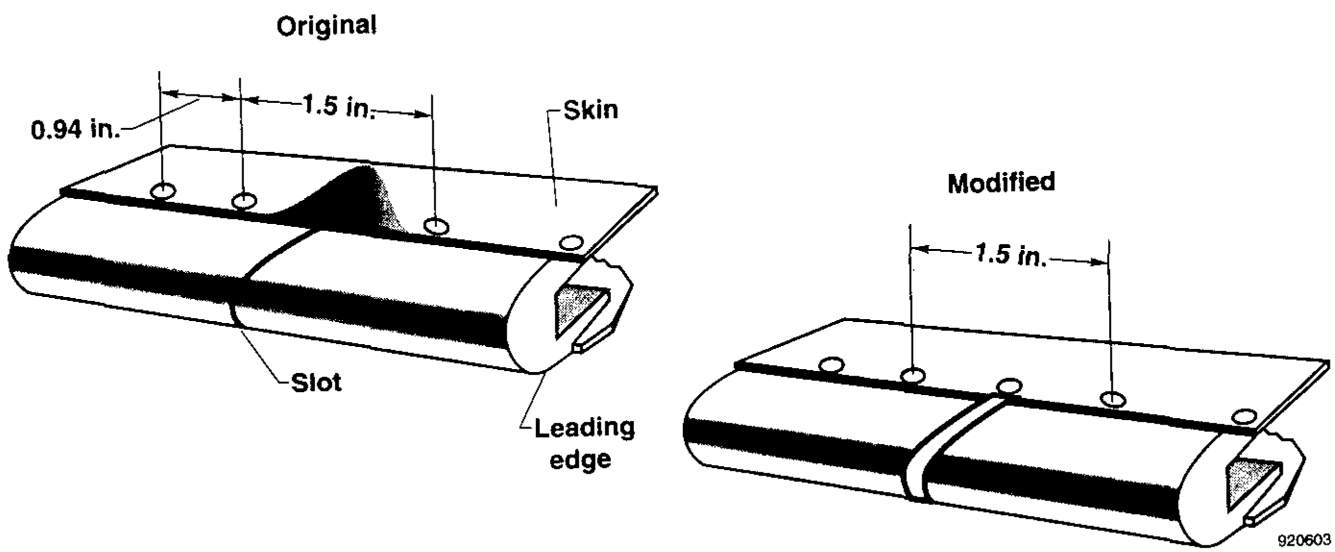

Fig. 7 Wing skin buckle following flight to Mach 5.28.

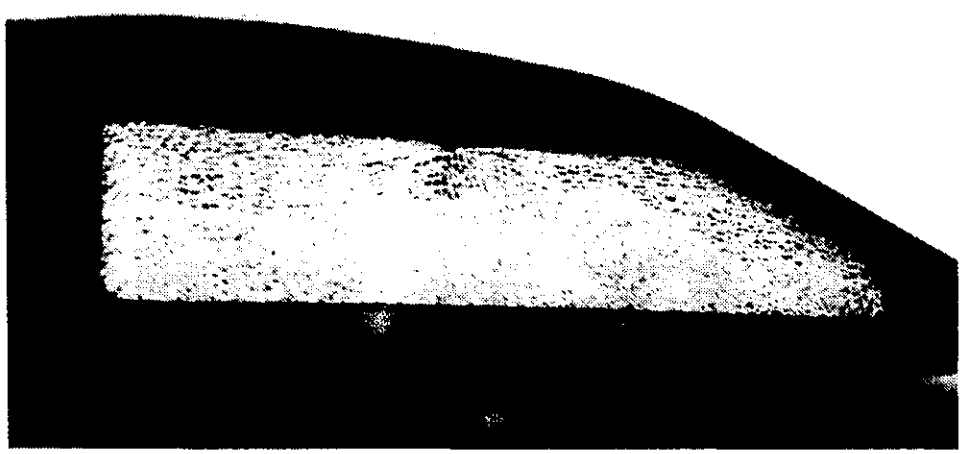

Fig. 8 Damaged right-windshield glass following flight at Mach 6.04.

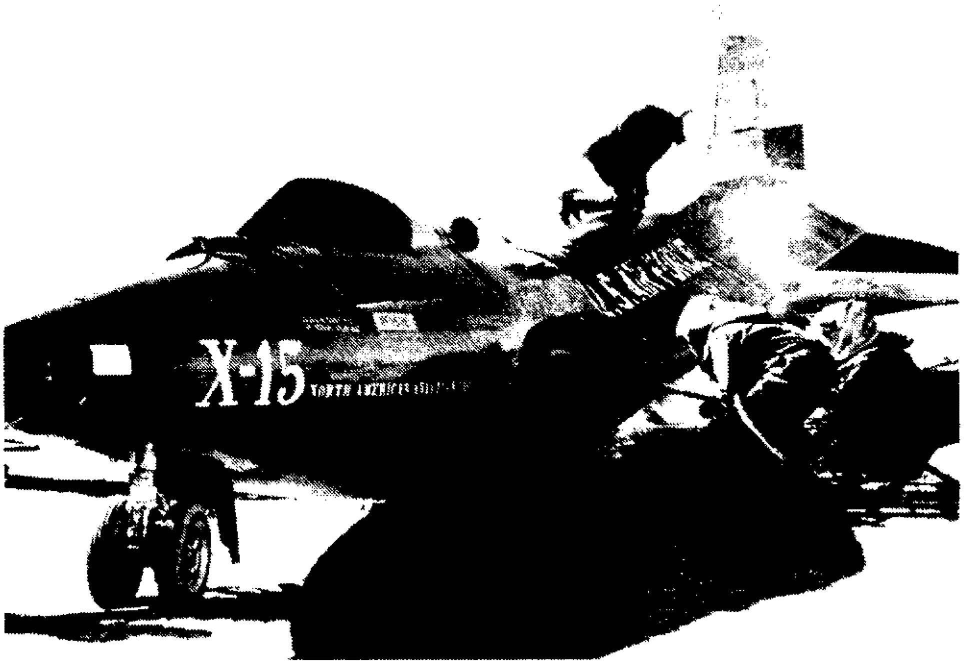

Fig. 9 First landing accident.

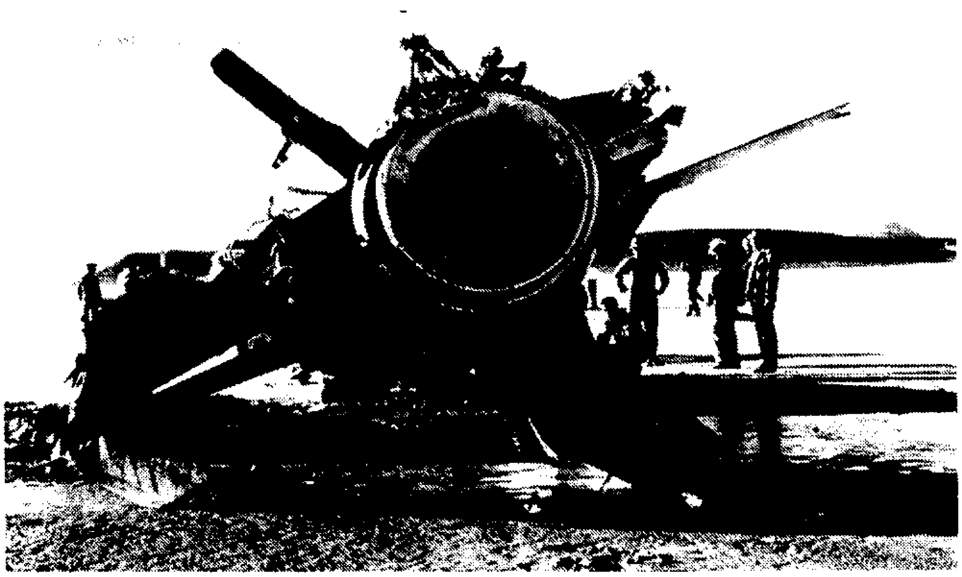

Fig. 10 Second landing accident.

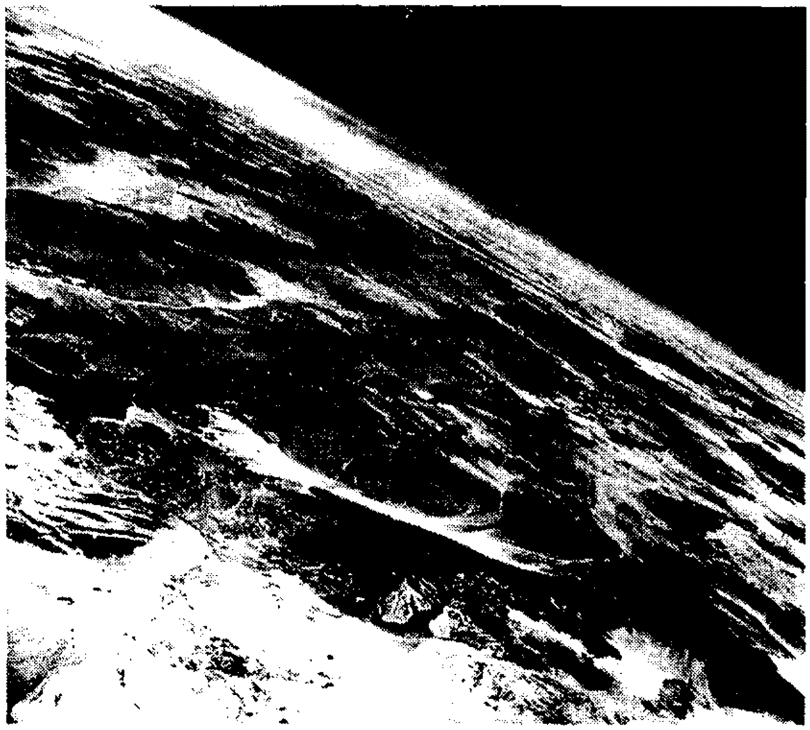

Fig. 11 Photograph of the Colorado River Valley taken using a down-looking camera mounted on an X-15 airplane at an altitude of 220,000 ft.

Fig. 12 The X-15A airplane.

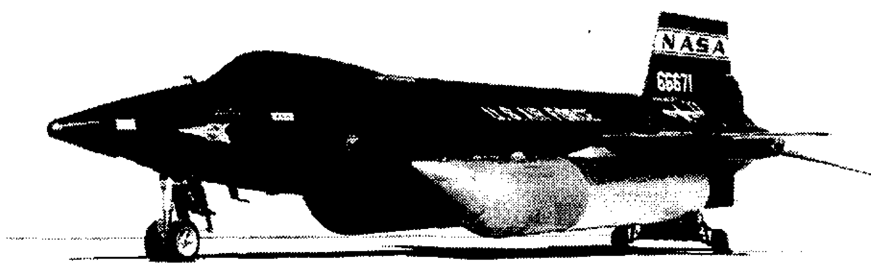

Fig. 13 The X-15A airplane with external, droppable fuel tanks.

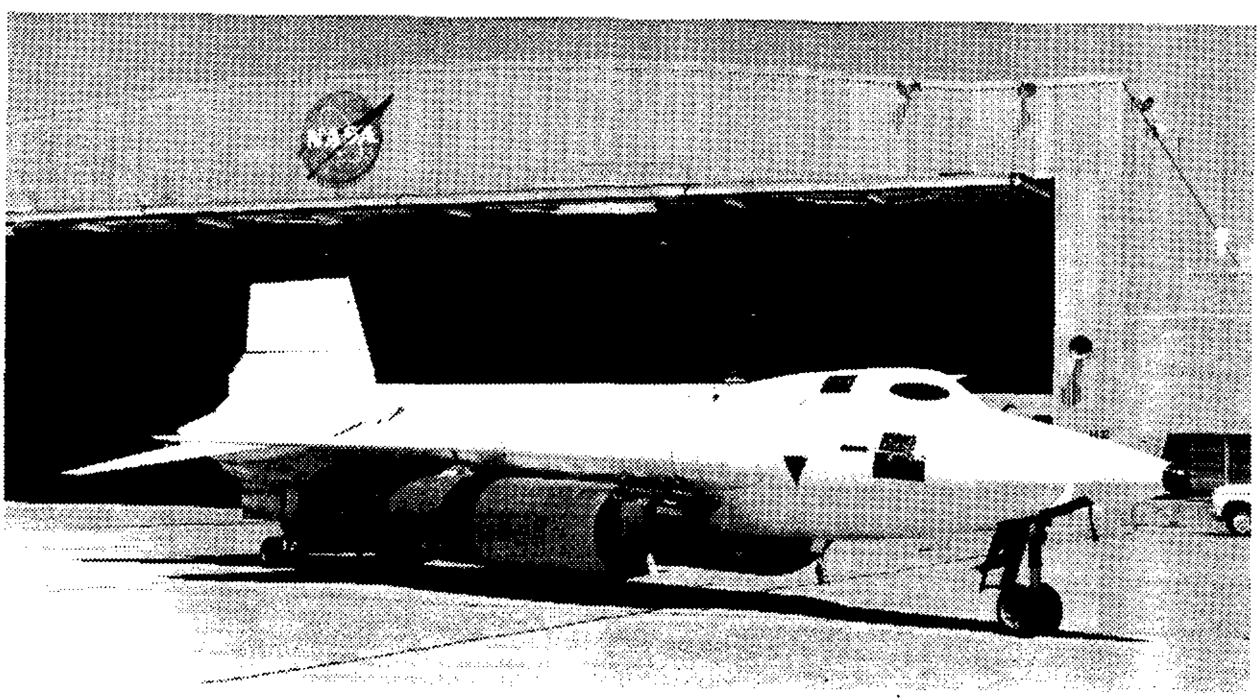

Fig. 14 The X-15A airplane with ablative coating.

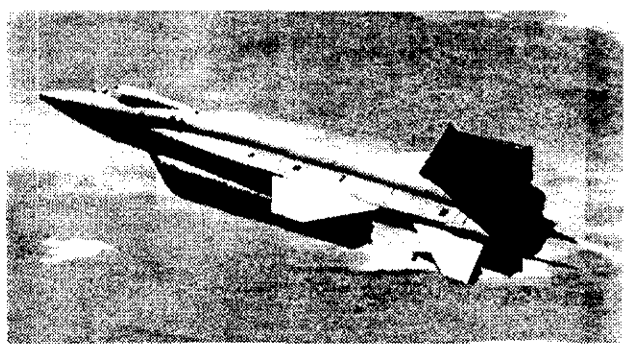

Fig. 15 The ablative-coated X-15A airplane in-flight.

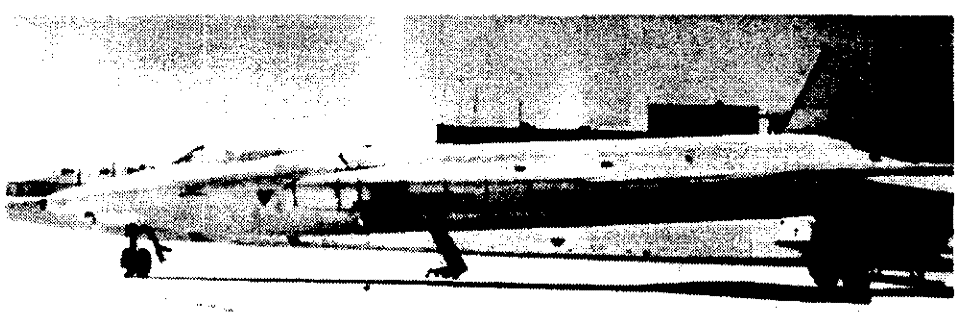

Fig. 16 Charring of the ablative coating on the X-15A airplane.