Robert G. Hoey

X-15 CONTRIBUTIONS TO THE X-30

Much of the technology benefit of a research airplane like the X-15 is gained before the first flight of the airplane; not the paper tradeoff studies, but meeting the challenge of designing, manufacturing, and integrating real hardware that works. The remaining lessons are learned during flight test. Many of the technology benefits of the X-15 have been extolled in past years as they apply to space flight (high altitude, 0 g) and lifting reentry (low L/D landings).

As an introduction to the X-30 presentation, I will highlight some of the less publicized flight test results from the X-15 program that might relate to sustained high-speed flight in the atmosphere.

I will cover four topics (fig. 1):

1. Energy management and range considerations,
2. The advantages of pilot-in-the-loop and redundant–emergency systems,
3. A summary of some of the aerodynamic heating problems that were encountered, and
4. Some comments on the advantages of an early flight test program and gradual expansion of the flight envelope.

The energy management for a typical X-15 flight is shown in figure 2. Most of the flights were conducted essentially in the vertical plane. It was most important to establish the proper heading toward Edwards during the first 20 sec after launch, very much like aiming in the direction of the target when firing a gun. The remainder of the powered portion of flight was used to establish the proper pitch angle and engine shutdown velocity, which again is akin to establishing the correct elevation and muzzle velocity of a gun. Once the X-15 engine was shut down, the trigger was pulled and the ballistics were pretty well established for the next few minutes of flight.

When we began to fly research flights in the airplane, the heating engineers wanted to obtain data at constant angle of attack, constant q, constant Mach, constant everything. Using the simulator, we determined that if we used the speed brakes, reduced thrust, and entered a 4-g turn, we could keep the airplane from accelerating. When we began looking at emergency considerations for these flights, we began to appreciate the enormous complexity of adding that third dimension, azimuth, to the flight plan. It was like swinging the gun wildly in azimuth just before pulling the trigger.

For the flight shown in figure 3, the initial heading was 30° off of the heading towards Edwards and the turn HAD to be completed pretty much as planned in order to return to Rogers lakebed. An early shutdown or flight control problem would have dictated a landing at Silver Lake, Three Sisters, or Cuddeback Lake. The turn was held for about 20 sec at about Mach 5, 80,000 ft altitude, and about 4 g. This produced a turn radius of about 36 nm. These heating research flight plans were severely constrained by the geography of the available emergency lakebeds; thus, only a few were flown. They probably caused as much uneasiness among the flight planners and control room personnel (not to mention the pilots) as many of the high altitude flights.

Obviously, the X-30 missions will involve much longer periods of sustained hypersonic turning flight with the attendant large radii and geography considerations.

In 1962, a very comprehensive, but little known, study was initiated by Bob Nagle at AFFTC to quantify the benefits of having a pilot and redundant–emergency systems on a research vehicle. Each individual malfunction or abnormal event that occurred after B-52 takeoff for the first 47 free flights of the X-15 was analyzed. The outcome of each event was forecast for three hypothetical models; one with only the pilot but no redundant–emergency systems, one with only the redundant–emergency systems but with no pilot, and one with neither the pilot nor redundant–emergency systems (i.e., single string, unmanned).

The results are summarized in figure 4. The unmanned, single-string system would have had 11 additional aborts and resulted in the loss of 15 X-15's. Not surprising is the fact that the pilot is of little value in a system without redundant–emergency systems. He must have some alternate course available in order to be effective. The redundant–emergency systems were also found to be of little value in an unmanned system primarily because the fault detection and switchover logic must presuppose the type of failure or event. For example, few designers would have built in a capability to handle an inadvertant nose gear extension at Mach 4.5.

Of more than academic interest was a parallel, but independent, study conducted by Boeing on the first 60 flights of their BOMARC missile, an unmanned, single-string, ramjet-powered interceptor. The authors collaborated on the ground rules for the study but not on the actual analysis. The similarity of the results as shown in figure 5 is striking, especially when considering that the X-15 study was projecting from a piloted, redundant design to an unpiloted, nonredundant design, and the BOMARC study was the reverse. The X-30 will have a crew on board, and mission success should be significantly enhanced if the appropriate levels of redundancy and emergency systems and proper crew integration are designed into the system.

The next series of figures depict sequentially some of the aerodynamic heating events that occurred during the initial envelope expansion of the X-15.

Our first "hands-on" awareness of the effects of aerodynamic heating occurred just above Mach 3 while the airplane was still flying with the -11 engines. The canopy lifted slightly at the front edge (due to differential pressure at altitude), allowing stagnation air to burn the rubber canopy seal with a resulting loss of cabin pressure. The fix was a narrow Inconel deflector strip which was riveted to the skin just forward of the canopy joint (fig. 6).

At about the same time, small spanwise buckles and local scorching were observed in some areas of the thin-skinned side tunnels. The fix was to segment the side tunnels fore and aft and insert expansion slip joints between each segment (fig. 7).

After a flight to about 4.5 Mach number, these aluminum instrumentation pressure lines in the nose wheel well (fig. 8) were observed to be melted and severed. The cause was a small gap in the nose wheel door seal which allowed a torchlike stream of hot boundary layer gas to enter the wheel well. The paint on the bulkhead behind the tubes (a cockpit pressure bulkhead) was badly burned and scorched but the bulkhead remained undamaged.

At 5.28 Mach number, the upper surface wing skins were locally buckled immediately behind the expansion slots in the leading edge. Flow through the slots and the tripping of the boundary layer had created a local hot spot on the wing skin. The fix was a thin Inconel cover over the slot which was welded to one side only (fig. 9).

On the maximum speed flight to Mach 6.04, the outer canopy glass shattered shortly after burnout (fig. 10). A small buckle in the retainer ring had created a local hot spot producing high stresses on the retainer as well as the glass itself. A redesign of the retainer ring with larger tolerances resulted.

The decision to attempt to expand the envelope to Mach 8 created many aerodynamic heating redesigns and surprises. The ablator–insulator material, although adequate for the job at hand, was time consuming to apply, difficult to handle, and created a measurable increase in drag after charring had started (obviously not a candidate for use on the X-30). Figures 11 and 12 show typical wear patterns.

The severe damage to the ventral (fig. 13) that occurred on the flight to 6.7 Mach number was the result of local shock interference. The solution to this problem would not have been of the "quick-fix" variety. The program was terminated before a redesign could be completed.

The lesson is NOT that the X-30 might encounter a broken windshield or buckled wing skin, but rather that aerodynamic heating problems tend to be localized effects and are often difficult to predict before flight. They also tend to be self-propagating. Although the X-15 was heavily instrumented, none of the aerothermo events described was evident from the instrumentation, real time or otherwise. The nature of an X-15 flight was that it was highly transient and the flight time at each new Mach condition was momentary. Each of the events described would have been much more severe if the flight condition had been sustained even for a few more seconds.

The chronology of the initial envelope expansion of the X-15 is shown in figures 14(a) and 14(b) for the first 2 1/2 years of the flight test program. The altitude envelope for the −11-powered airplane reached 136,500 ft in a little over a year. The first −99-powered flight was flown 18 months after the first glide flight and the design altitude was reached 16 months later. The −11-powered airplane exceeded Mach 3.0 within a year. The max speed flight to 6.04 was flown 11 months after the first flight with the −99 engine. About half the people on the program thought that this pace was too slow and that we should be more aggressive. The other half thought it was much too fast and that we should do more research along the way. The real benefit was the luxury to choose whatever pace we thought was right.

It is important to notice that the philosophy of the X-15 program was to let flight test distinguish between the "real" and the "imagined" problems. It was felt that in many cases a detailed preflight analysis of a potential "worry item" would have been unnecessarily expensive, time consuming, and possibly erroneous or misleading. The photos of heating damage were "worries" that turned out to be "real"; however, many of the "worries" never materialized. For example, the sharp corner at the inboard leading edge of the horizontal stabilizer was expected to reach very high temperatures if it extended beyond the fuselage boundary layer. The gaps at the inboard and outboard edge of the wing flap might have created severe local hot spots.

Unlike the space shuttle program where the reentry envelope had to be expanded from the top down on a single flight, the X-30 should be able to expand its flight envelope gradually from the bottom up very much like the X-15 program. Given the proper mix of pilot-in-the-loop, redundancy, system integration, and a flexible envelope expansion plan, the X-30 flight testing should be able to start sooner and with lower risk than might be projected by space-type systems planning.

The last figure (fig. 15) is merely a reminder that the X-15 and X-30 have another thing in common—simultaneous development of a new airframe and a new propulsion system. The odds that both will reach maturity at the same time are very slim. The decision to install interim engines in the X-15 allowed the test team to gather valuable data and experience with the airframe and its subsystems before encountering the unknown environmental effects of high altitude and high-speed flight. I recognize that the propulsion system and the aerodynamics for the X-30 are much more closely integrated than on any previous vehicle. Nevertheless, history shows that there is both technical and political value in getting SOME type of flight hardware into the air as quickly as possible.

X-15 CONTRIBUTIONS to the X-30

- ENERGY MANAGEMENT, RANGE CONSIDERATIONS
- PILOT-IN-THE-LOOP, REDUNDANT/EMERGENCY SYSTEMS
- AERODYNAMIC HEATING
- EARLY FLIGHT TEST, GRADUAL ENVELOPE EXPANSION

Figure 1. X-15 contributions to the X-30.

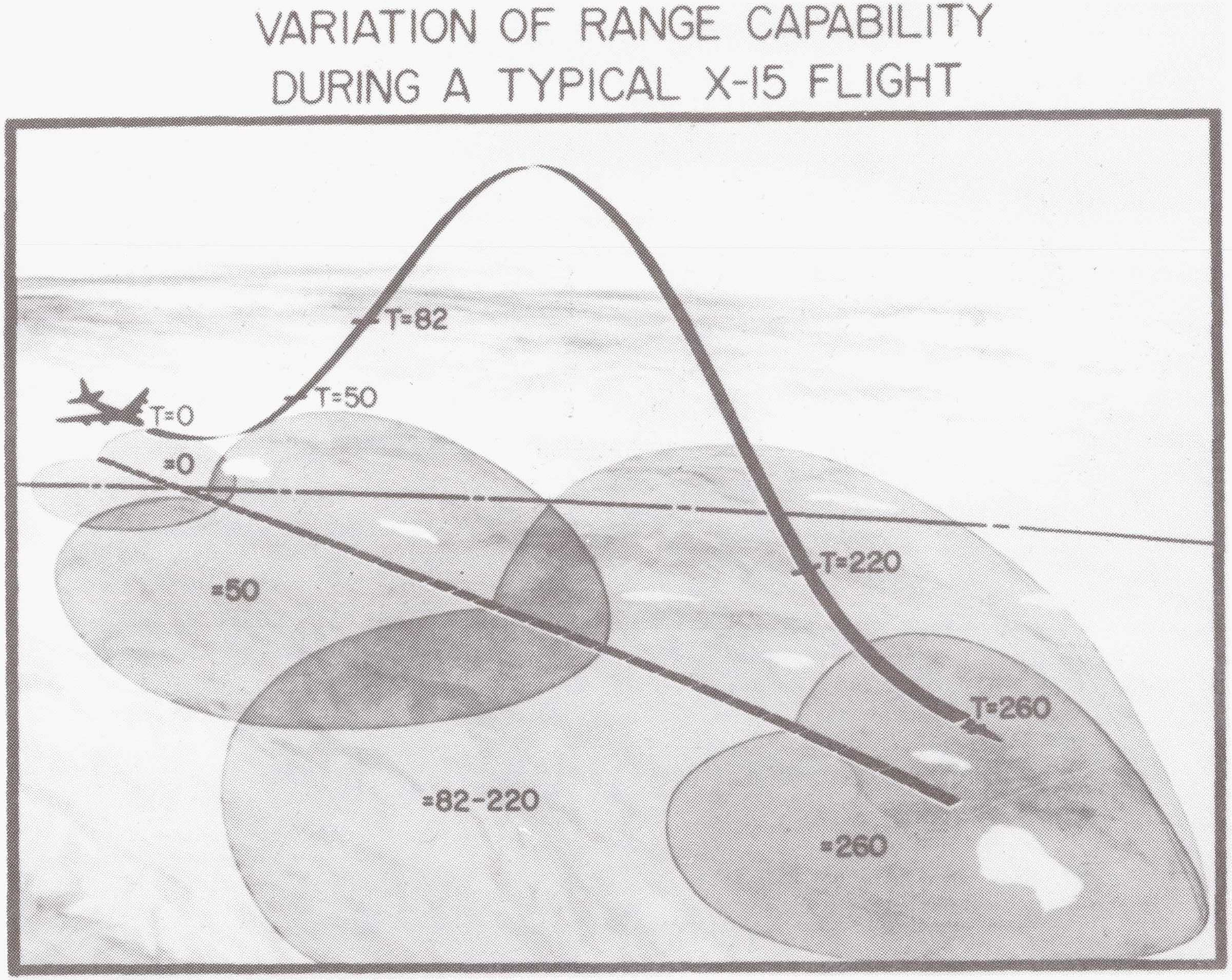


Figure 2. Variation of range capability during a typical X-15 flight.

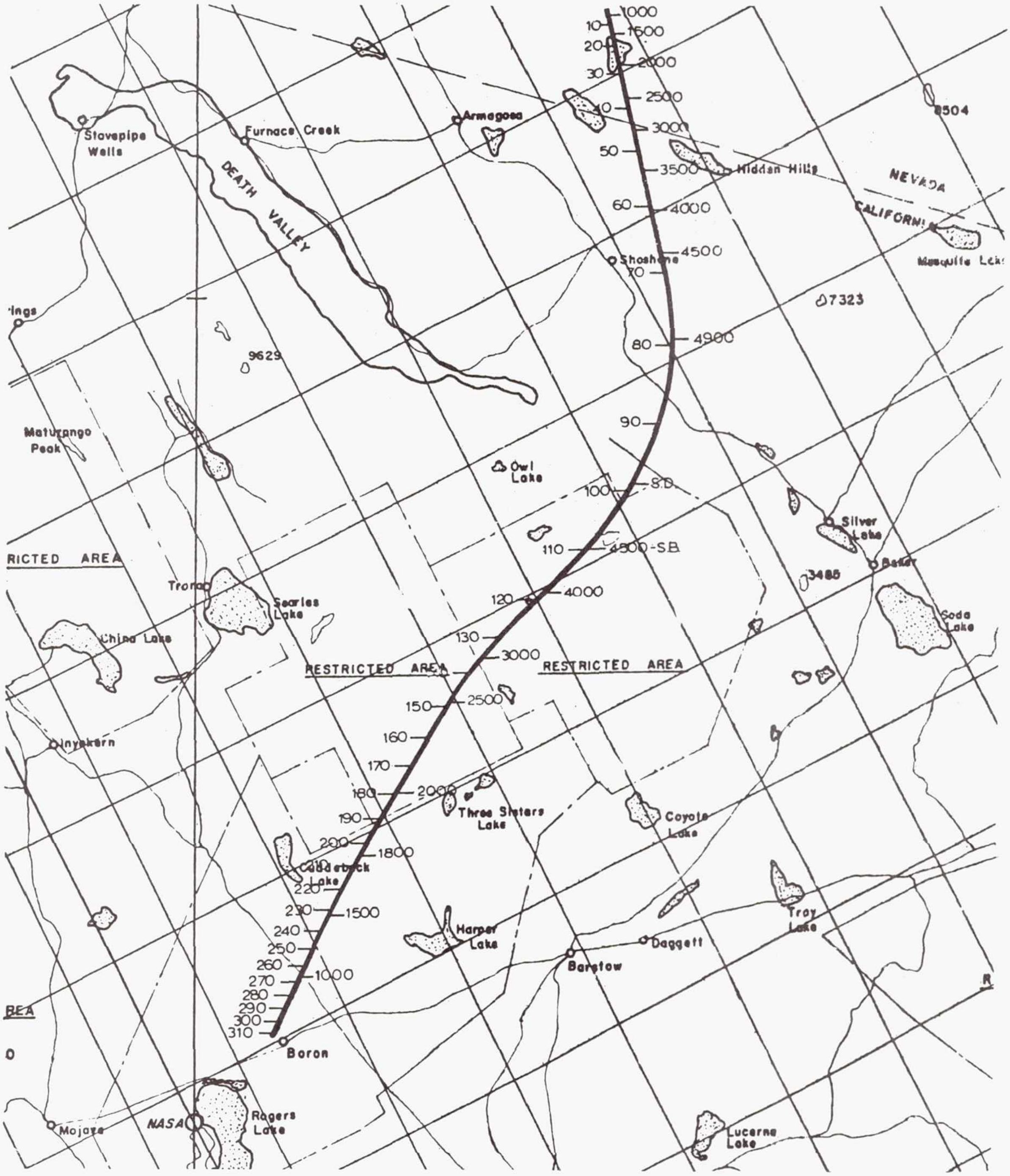


Figure 3. Flightpath of the X-15 aircraft for heating test.

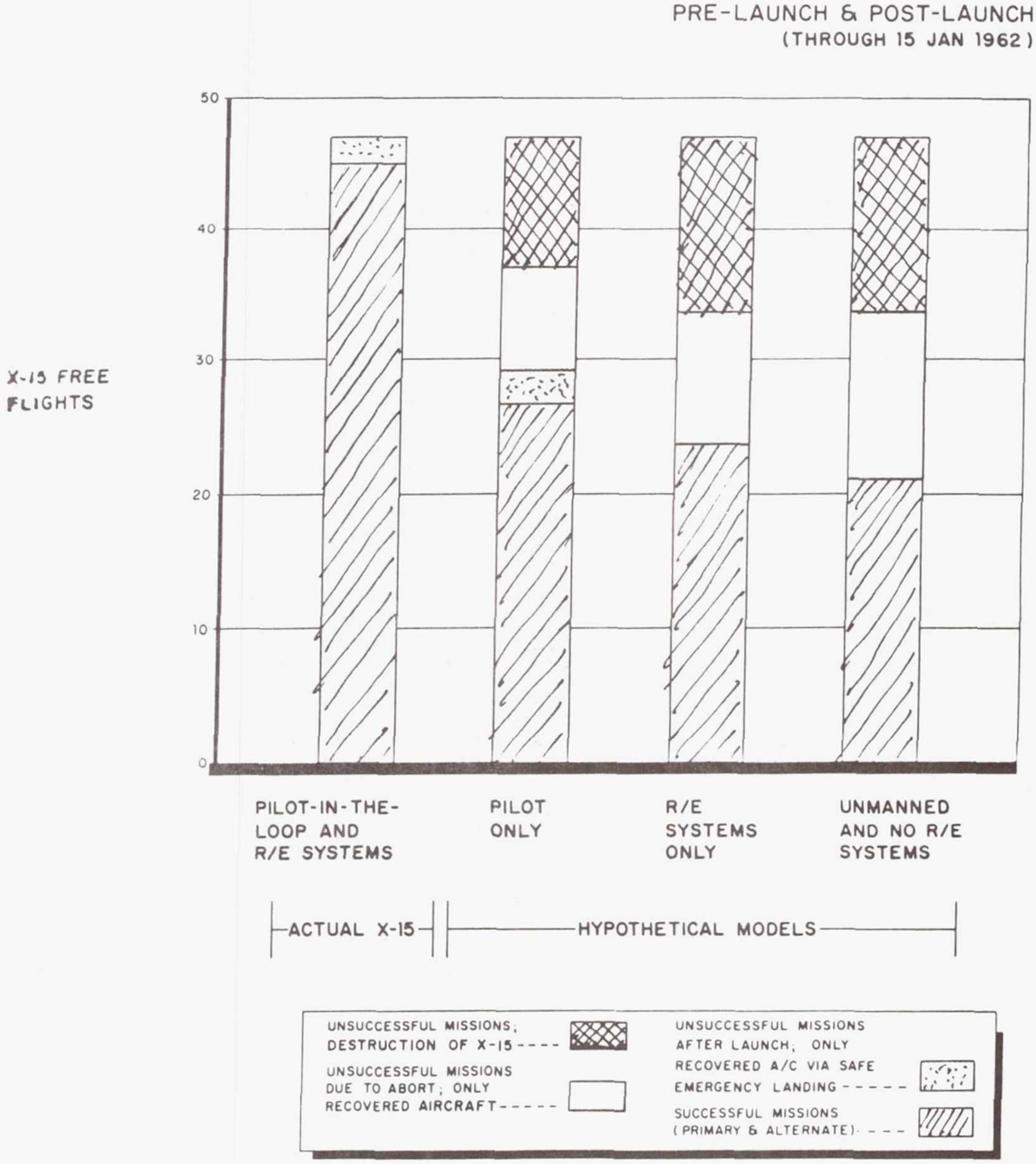


Figure 4. Total pilot-in-the-loop and R/E systems benefits.

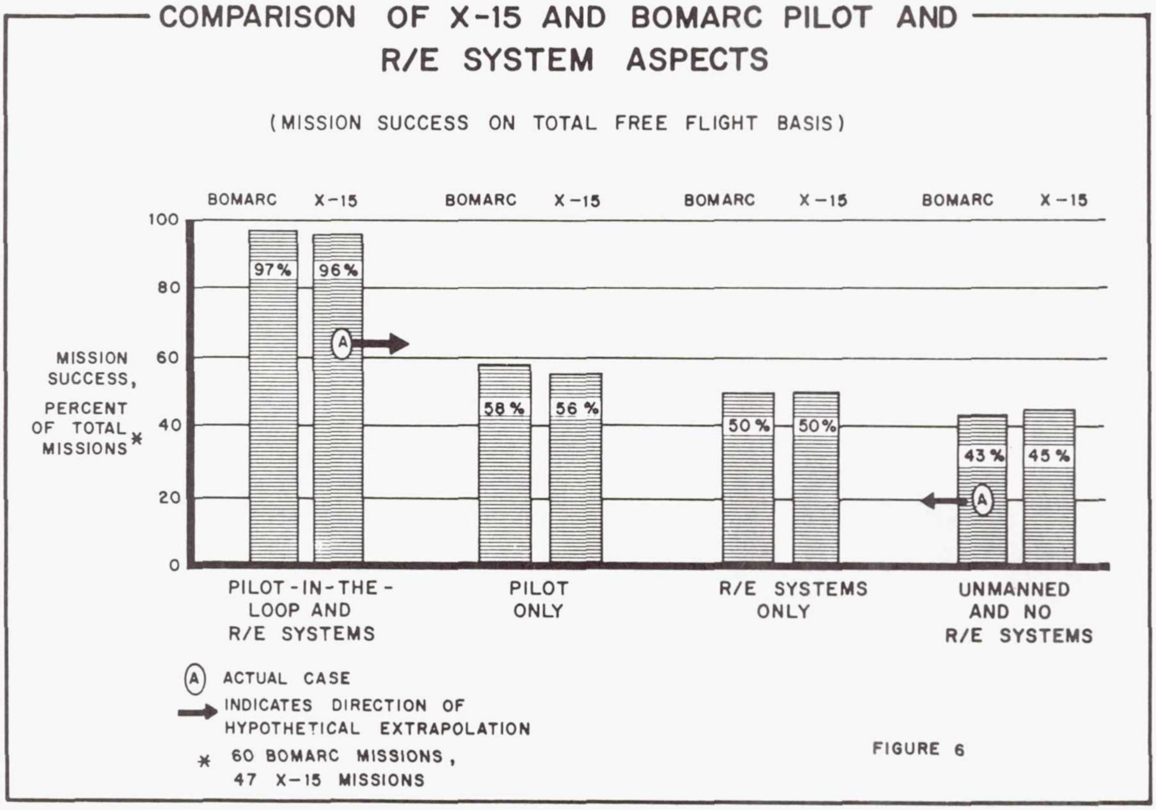


Figure 5. Comparison of X-15 and BOMARC pilot and R/E system aspects.

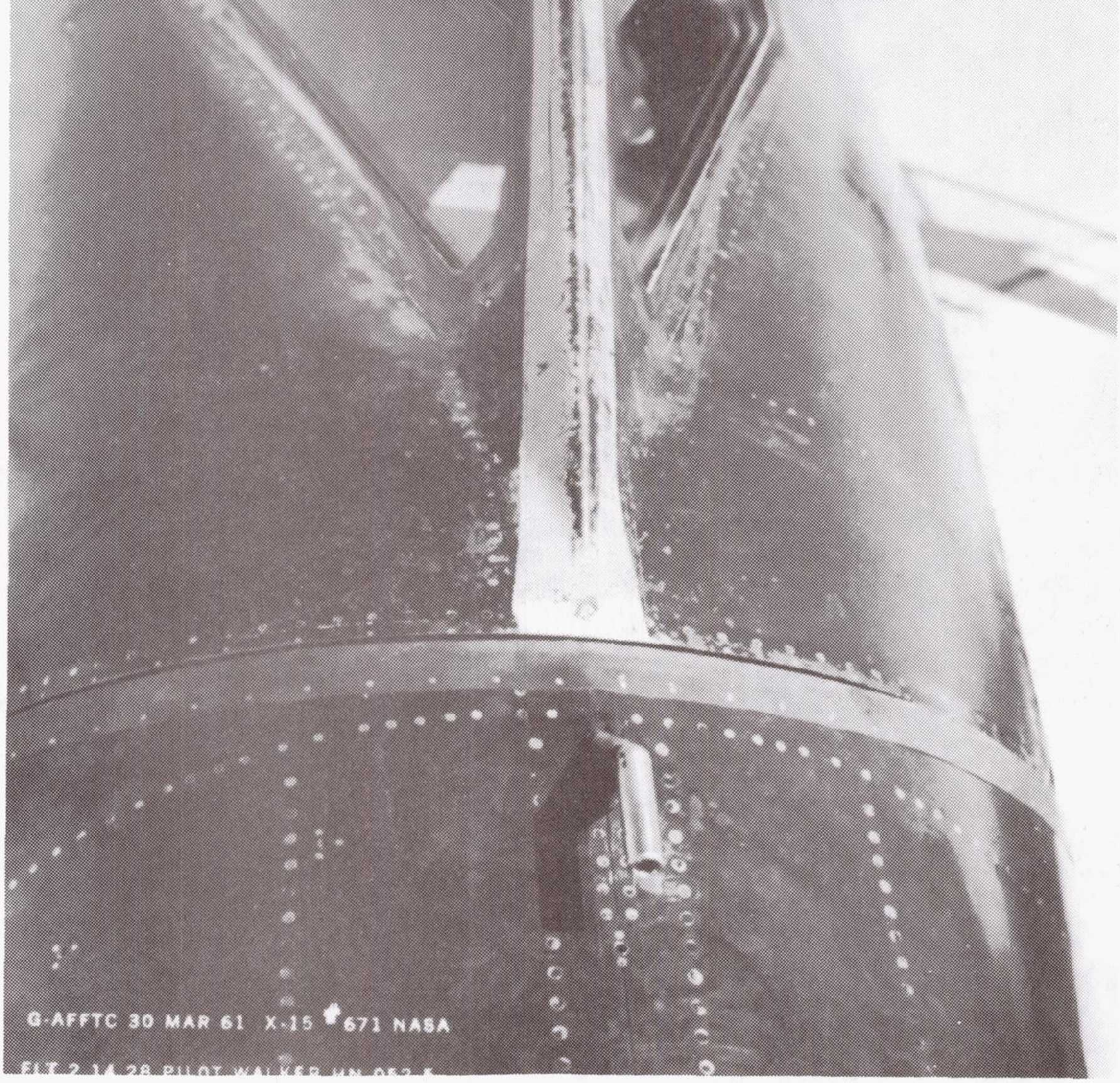


Figure 6. Inconel deflector strip riveted forward of the canopy joint.

Figure 7. Small spanwise buckles and local scorching observed in X-15's skin.

Figure 8. Heat damage to the X-15's aluminum tubing.

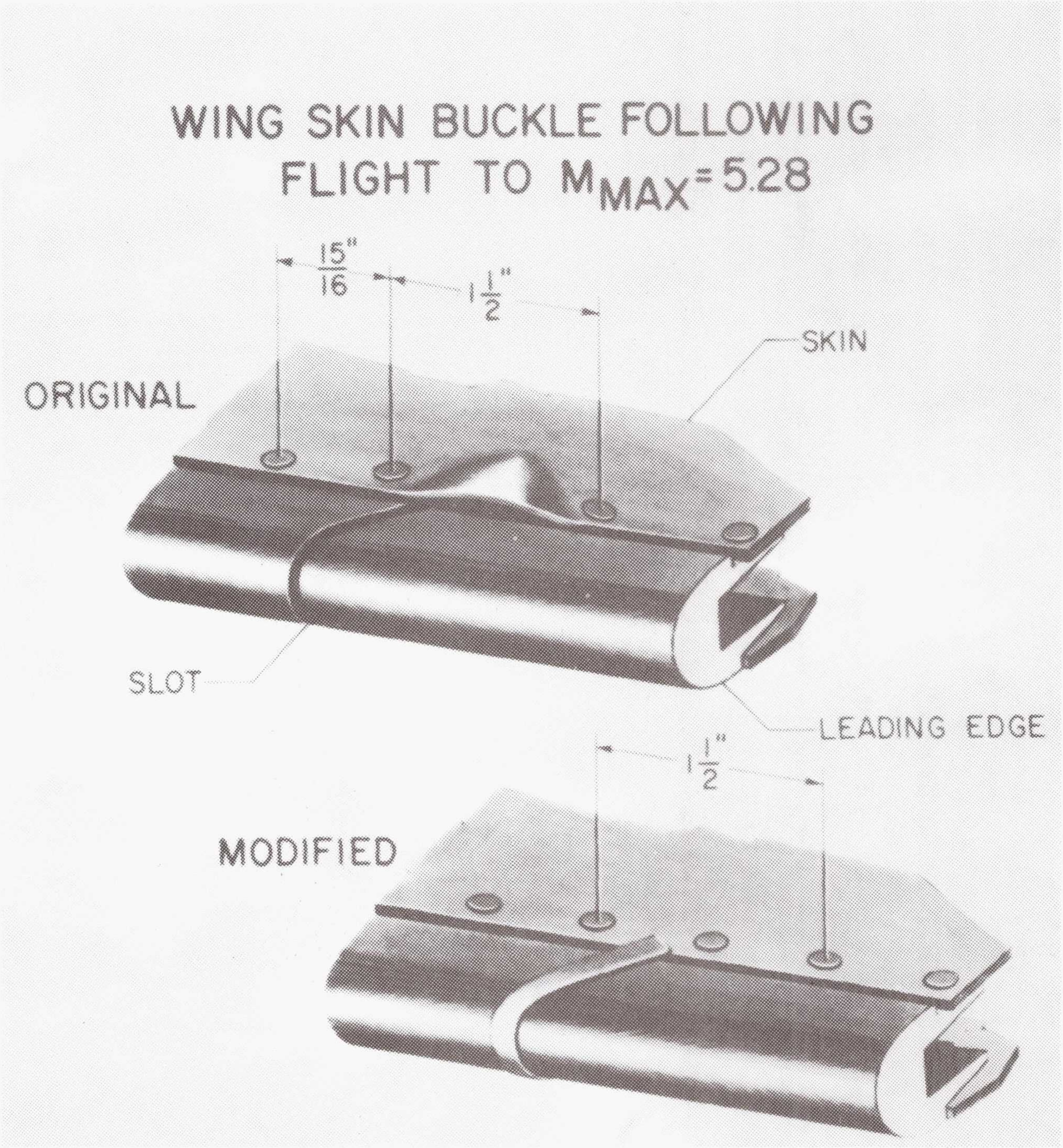


Figure 9. Wing skin buckle following flight to M_{max} = 5.28.

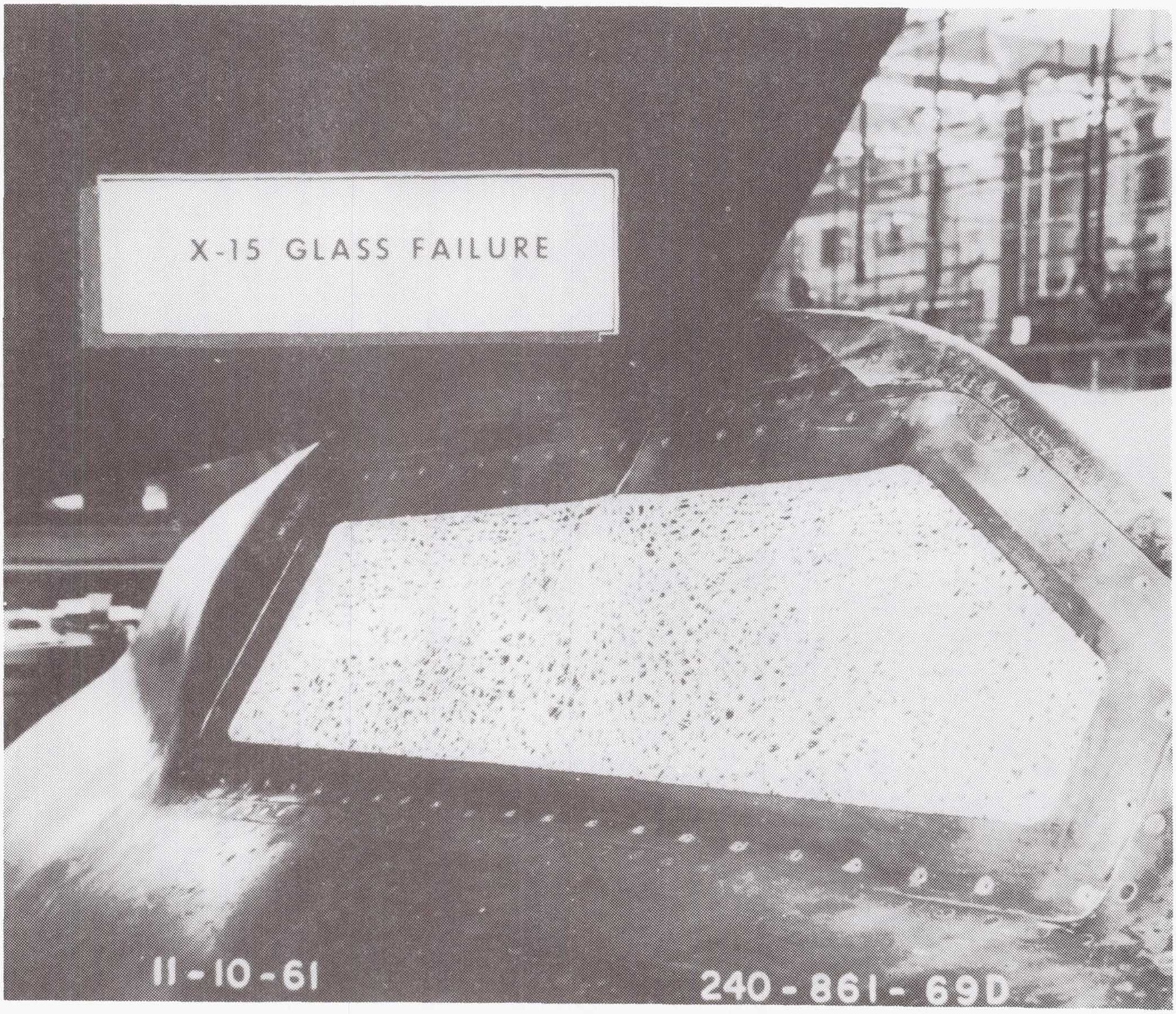


Figure 10. X-15 glass failure.

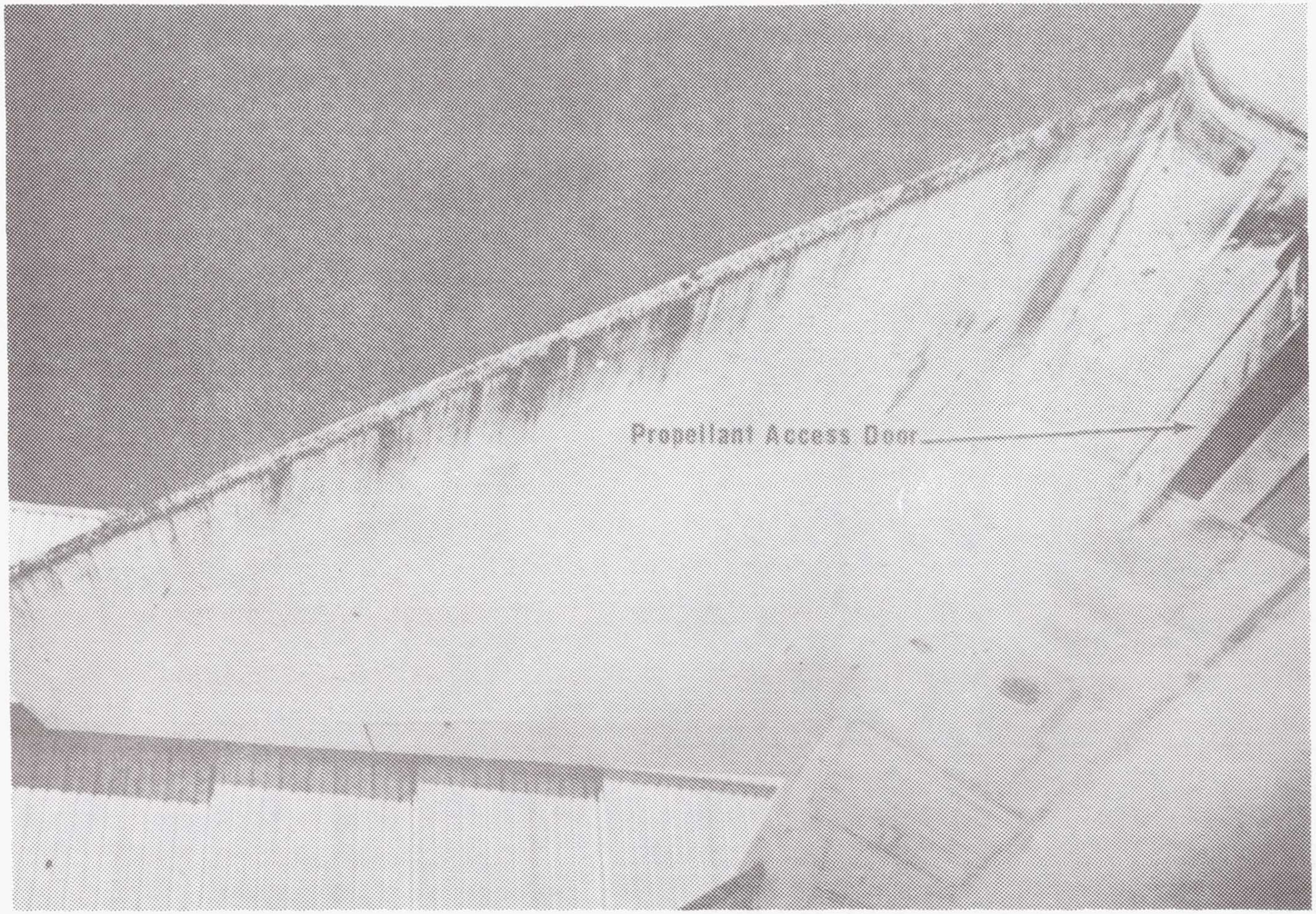


Figure 11. Ablative wear lower fuselage and wing.

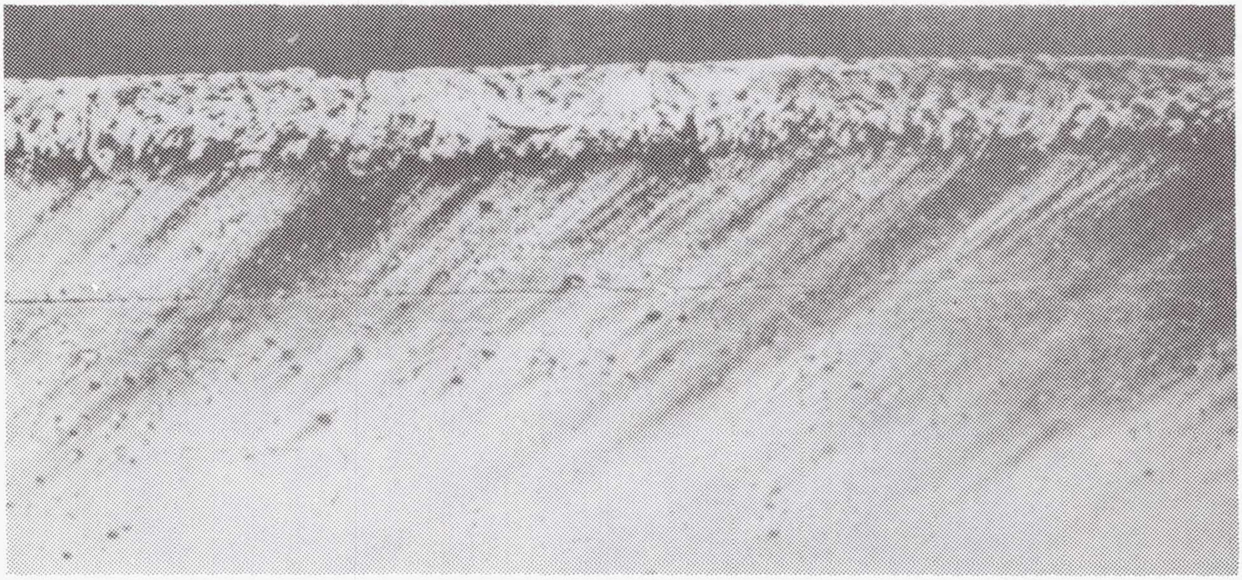


Figure 12. Ablative wear wing leading edge.

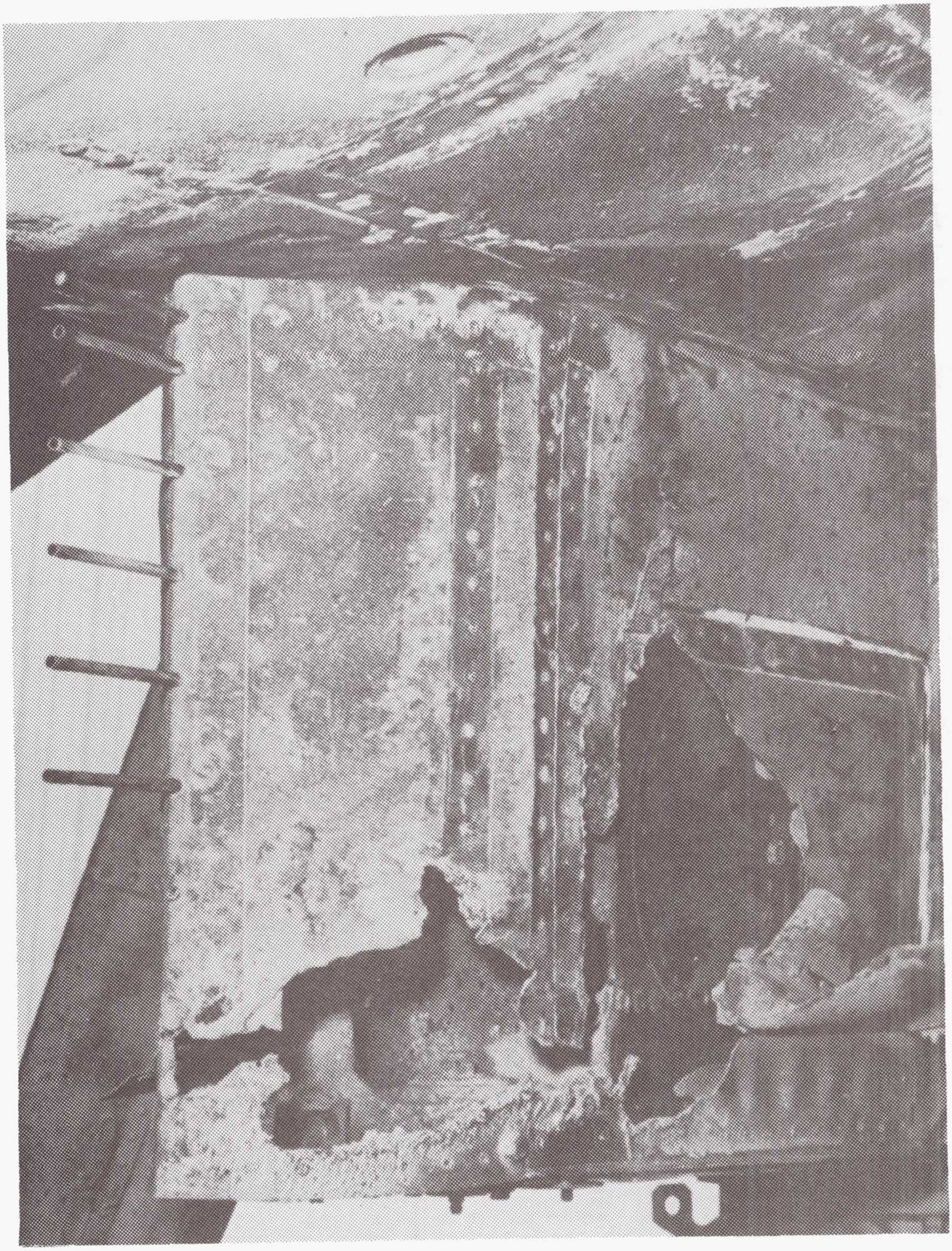
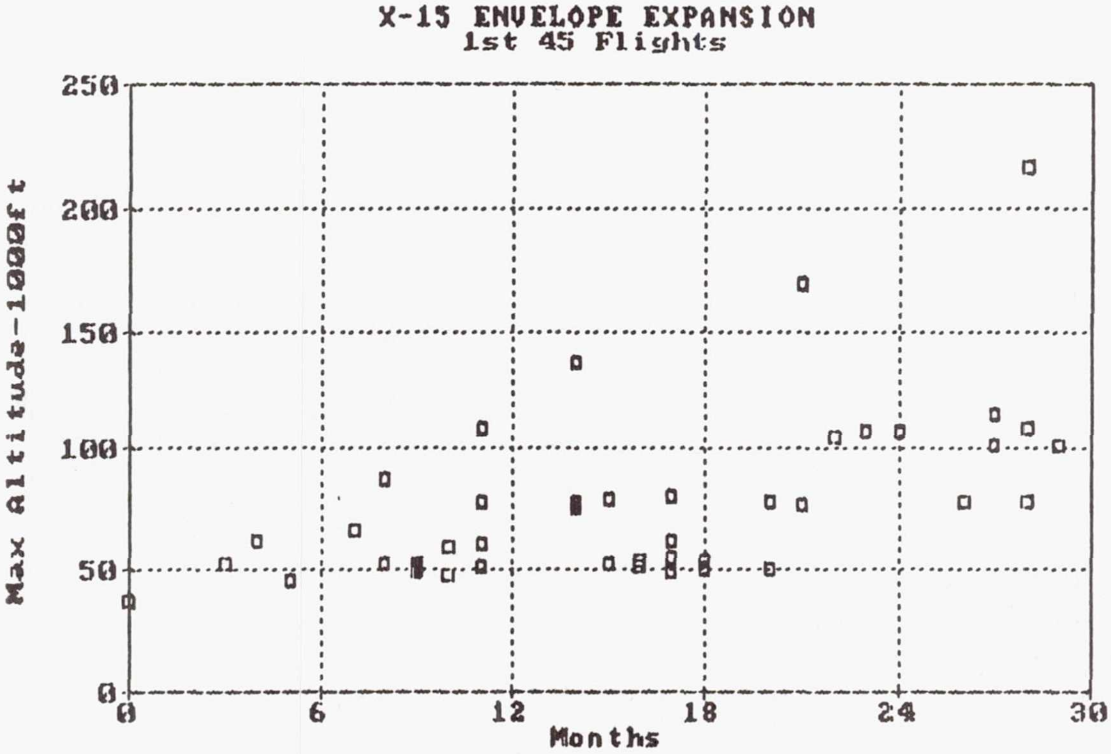
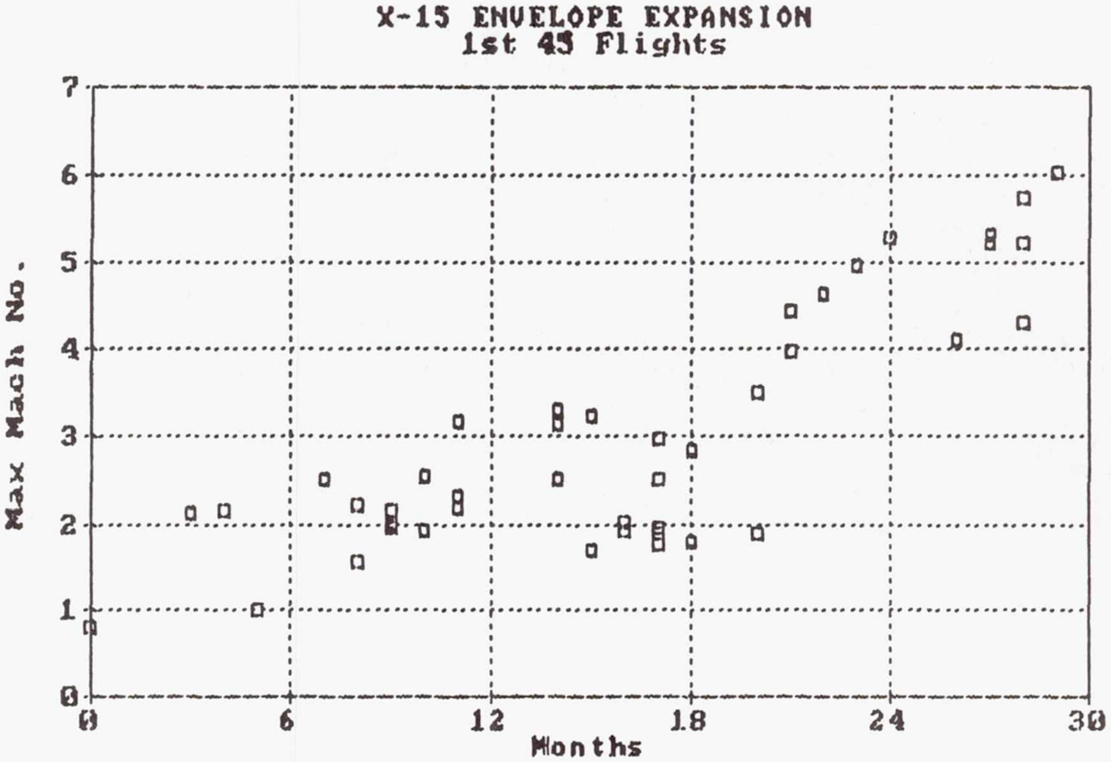


Figure 13. Pylon heat damage, left side.



(a) Maximum altitude history.



(b) Maximum Mach number history.

Figure 14. X-15 envelope expansion for first 45 flights.

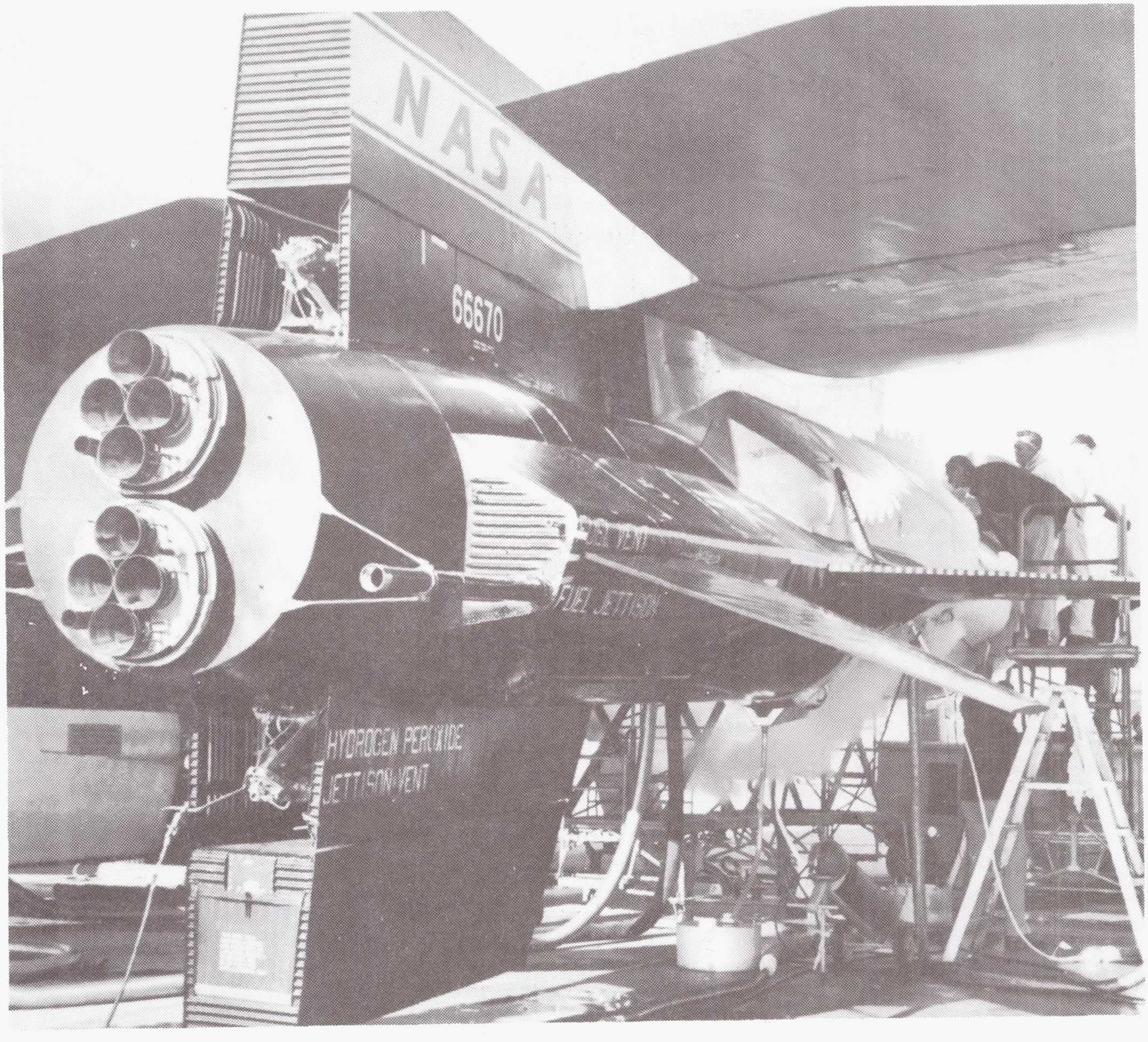


Figure 15. Simultaneous development of a new airframe and a new propulsion system.