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REVIEW OF THE X-15 PROGRAM

Compiled by Joseph Weil

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SUMMARY

A review of the X-15 project from its inception in 1954 through 1961 is presented. Some of the more important historical aspects of the program are noted, but major emphasis is placed on the significant research results.

It is shown that the X-15 program has contributed significantly in a number of broad research fields such as aerodynamics and structural heating, structural dynamics, supersonic and hypersonic aerodynamics, and stability and control. The program has kept in proper perspective the role of the pilot in future projects of this nature. It has pointed the way to simplified operational concepts which should provide a high degree of redundancy and increased chance of success in future space missions. But, perhaps most important, is the fact that a sizable segment of industry and government engineers and scientists has had to face up to problems of designing and building hardware and making it work. This has provided invaluable experience for the future aeronautical and space endeavors of this country.

INTRODUCTION

The X-15, which is the latest of a long series of research airplanes that began with the historic X-1, is the nation's first piloted reentry vehicle. The pilot is in complete control of the vehicle from launch to landing, thus making it possible to accomplish extensive research on the proper role of man in future space ventures.

Numerous articles and several books describe the development of the X-15 airplane and early flight test results; therefore, only brief mention is made herein of some of the more important historical aspects of the X-15. Although the flight test phase of the X-15 program is not yet complete, many tangible results have been achieved. Major emphasis in this paper is placed on these research results and, when pertinent, their relation to the original objectives. In this manner, the true value of the X-15 as a research tool may be assessed.

Because of the broad scope of the X-15 research program, discussion of some phases is necessarily abbreviated. Reference sources which present more detailed presentations are included in a bibliography.

SYMBOLS

a_l longitudinal acceleration, g units

a_n normal acceleration, g units

C_m pitching-moment coefficient, $\dfrac{\text{Pitching moment}}{q S \bar{c}}$

$\bar{c}$ mean aerodynamic chord, ft

C_N normal-force coefficient, $\dfrac{\text{Normal force}}{q S}$

$C_{N_\alpha} = \dfrac{\partial C_N}{\partial \alpha}$

F_t horizontal-tail aerodynamic load, lb

g acceleration due to gravity, ft/sec^2

L lifting force, lb

L/D lift-drag ratio

M Mach number

q dynamic pressure, lb/sq ft

S wing area, sq ft

V_{v_0} airplane sinking speed at initial touchdown, ft/sec

W airplane landing weight, lb

α angle of attack

α_0 initial angle of attack at touchdown, deg

δ_a total aileron deflection

θ pitch angle

$\Delta\phi$ peak-to-peak amplitude of limit cycle in roll

Subscript:

max   maximum

HISTORY OF PROJECT

Inception

During the spring of 1952, a resolution was passed by the NACA Committee on Aerodynamics and ratified by the NACA Executive Committee directing the Laboratories to initiate studies of the problems likely to be encountered in space flight and of the methods of exploring them. Laboratory techniques, missiles, and manned airplanes were considered. By the spring of 1954, an NACA team was studying the characteristics and technical feasibility of designing and building an airplane suitable for exploratory flight studies of the aerodynamic heating, stability, control, and physiological problems of hypersonic and space flight. This work led to an NACA proposal for the construction of an airplane capable of a speed of 6,600 feet per second and an altitude of 250,000 feet, not necessarily to be attained simultaneously. The NACA studies also indicated that a heat-sink type of structure of Inconel X would require the least development and would give a reasonable factor of safety, when the assumptions that had to be made in the light of the knowledge then available were considered.

On July 9, 1954, NACA representatives met with members of the Air Force and Bureau of Aeronautics research and development groups to present the proposal as an extension of the cooperative research airplane program. The Air Force Scientific Advisory Board had made similar proposals to the Air Force Headquarters; also, the Office of Naval Research had an active contract to determine the feasibility of constructing a manned aircraft capable of climbing to an altitude of 1,000,000 feet. These independent actions made possible the early acceptance of the NACA proposals for a joint effort and eventually led to the X-15 project.

Design Development

The design requirements specified for this airplane were that it should achieve a maximum velocity of 6,600 feet per second, be capable

of flying to an altitude of at least 250,000 feet, have representative areas of the primary structure experience temperatures of 1,200° F, and have some portions of these representative structures achieve heating rates of 30 Btu per square foot per second. The airplane was specifically designed to have satisfactory aerodynamics and structural characteristics relative to flight profiles, resulting in attainment of the specified performance and heating requirements.

In December 1954, invitations were issued to contractors with experience in the design of high-speed, high-altitude aircraft to participate in the design competition. Proposals resulting from the invitation were received and evaluated during the summer and fall of 1955. A contract was awarded North American Aviation for construction of three "X-15" aircraft in June 1956, and a contract was given to Reaction Motors for development of a suitable rocket engine.

An extensive wind-tunnel and structural-component testing program was initiated in 1956. By September 1957, enough data had been collected so that construction of the first X-15 could be started. Much had been learned in these tests about hypersonic design considerations. This knowledge was reflected in numerous design changes instituted to accomplish the design requirements. The final X-15 configuration is illustrated in figure 1.

The X-15 propulsion system includes a 1,000-gallon liquid-oxygen tank, a 1,400-gallon anhydrous-ammonia fuel tank, and an XLR99 rocket engine. This engine is throttleable from 50- to 100-percent thrust and can be shut down and restarted in flight. An important feature of the engine is the idle capability which allows about 85 percent of the engine starting cycle to be completed prior to launch.

To withstand the temperature environment expected, all external surfaces on the X-15 airplane are Inconel X, and the internal structure is a composite of Inconel X, titanium, and some aluminum, depending on the expected local temperature environment. Cooling for areas such as the flow-direction sensor on the nose, the cockpit, and electronic bay is supplied by liquid nitrogen.

Aerodynamic control is provided by a conventional horizontal stabilizer for pitch, differential deflection of the horizontal tail for roll, and upper and lower movable vertical-tail sections for directional control. The vertical tail is a 10°-wedge section, and the lower movable section is jettisoned (and recovered) for landing clearance. Attitude control at low dynamic pressures is provided by rockets in the nose and wings. The stability augmentation is essentially a conventional damper system. The landing-gear system incorporates a nose gear and unique main-gear skids located well to the rear on the fuselage.

Flight Tests

The various studies and experiments required during the development phase of advanced-aircraft programs provide solutions to many problems. Generally, however, verification of these answers must await the flight-test phase of the program.

Configurations.- The external configuration of the X-15 as it has been flown in the research program is similar to that shown in figure 1. During the flight program, however, some specific external configuration modifications were made, including those illustrated in figure 2.

The interim LR11 engine installation (lower right, fig. 2) was used initially in the program because of delays in the development of the design engine. This engine, which was a combination of two of the engines designed for the X-1 airplane, consisted of eight rocket cylinders, produced a total thrust of approximately 16,000 pounds, and used alcohol and water as fuel. The X-15 XLR99 ammonia-burning-engine installation, shown in the upper portion of the figure, produces approximately 57,000 pounds of thrust at an altitude of 45,000 feet and is throttleable to 28,000 pounds. All flights except one have been flown with the lower rudder on (shaded area), except, of course, for landing. One flight to a Mach number of 4.3 and to an altitude of 78,000 feet was made with the lower rudder off. As the program progressed to the higher temperature conditions, the familiar nose boom (lower left) with flow-direction-sensing vanes and static- and total-pressure sensors was replaced with a nitrogen-cooled, null-seeking ball, which provided airplane angles of attack and sideslip to the pilot and to the recording equipment.

Mode of operation.- The mode of operation for the X-15 flight program is illustrated in figure 3. Two B-52 airplanes have been converted as carrier airplanes. The X-15 is launched from a location between the B-52 fuselage and inboard engine nacelles of the right wing.

The research flights were planned to be conducted along the instrumented range extending approximately 420 nautical miles northeast of Edwards, Calif., to Wendover, Utah. Only two of the three instrumented stations along the range, Edwards and Beatty, have been required thus far in the program. Future flights, which may attain altitudes above 250,000 feet with correspondingly higher speeds, may require the use of the Ely station and a greater length of the range.

Flight progress.- The conduct of the X-15 flight program can be described best as simply a series of progressive steps to higher speeds and higher altitudes. Some deviations from this approach were made to investigate higher structural heating rates and stability and control at high angles of attack in order to insure a reasonable level of flight safety.

Figure 4 presents a summary of the flight progress for each of the three X-15 airplanes, including some of the events that affected the program progress. The first glide flight was made in June 1959 by the contractor with the number 1 airplane (X-15-1); a powered flight with the number 2 airplane (X-15-2) was made in September 1959. In all, eleven contractor flights were made with the interim LR11 engine during 1959 and 1960 to evaluate the airplane and the various systems. During this period, the X-15-2 airplane was damaged during an emergency landing after a fire developed in the engine compartment during flight.

The government received the X-15-1 airplane with the interim engine and performed the first flight in March 1960. This airplane was tested until February 1961, and the maximum speed and altitude for the interim engine were achieved. Six pilots of the Air Force, Navy, and NASA participated in this phase of the program.

The X-15-2 airplane was the first of the aircraft to be converted to the XLR99 engine and was flown three times by the contractor during November and December of 1960 to demonstrate engine throttling and engine restart capability.

The government first flew the X-15-2 with the XLR99 engine in March 1961 and continued the research program that had been started with the X-15-1 airplane. After engine conversion, the X-15-1 airplane was returned to the government and was flown again in August. Since then, the X-15-1 and X-15-2 airplanes have been used interchangeably in support of the flight program.

The X-15-3 airplane, which suffered major damage in June 1960 during a ground run of the XLR99 rocket engine, has been rebuilt and modified to accommodate an advanced control system. The first flight of this airplane was made in December 1961.

Performance.- Since the X-15 airplane is now heavier than originally designed, maximum velocity will be somewhat less than the original design goal; however, this weight penalty does not impair the capability of reaching the design altitude.

A summary of the predicted and accomplished performance of the X-15 airplanes is presented in figure 5. The solid curves show the design envelopes of altitude and velocity predicted for the LR11 and XLR99 engines. The shaded area shows the accomplished performance: a maximum altitude of 217,000 feet and a maximum velocity of 6,005 feet per second.

RESEARCH OBJECTIVES AND ACCOMPLISHMENTS

It was recognized early in the X-15 project planning that an important benefit would be derived from focusing the research required to support manned flight in the hypersonic speed ranges within and outside the earth's atmosphere. The following major research areas are discussed from the standpoint of objectives and accomplishments:

Aerodynamic and structural heating
Structural dynamics
Supersonic and hypersonic aerodynamics
Piloting aspects
Bioastronautics
Mission planning and simulation
Operational experience

From the time the program was conceived, the first five areas have been recognized as being of primary importance. The usefulness of the X-15 in providing information in the last two fields was not fully anticipated originally, but became more obvious as the potential of the aircraft was considered in greater detail.

Aerodynamic Heating and Structural Temperatures

Aerodynamic heating.- In the initial design phase, surface temperatures of the X-15 were calculated by means of heat-transfer theories in general use at the time. The theories assumed full turbulent flow on the fuselage and a transition Reynolds number of 100,000 on the wing and tail surfaces. Subsequently, extensive wind-tunnel tests were conducted in the Langley Unitary Plan wind tunnel and at the Arnold Engineering Development Center at Tullahoma, Tenn. The wind-tunnel tests provided heat-transfer coefficients which were higher than the theoretical values, particularly on the lower surface of the fuselage. Because of these results, factors were introduced which modified the theoretical calculations of skin temperature, and the X-15 was designed to withstand the temperatures predicted by the modified theory. However, measurements made in X-15 flights indicate that the skin temperatures of the primary structural areas of the fuselage, main wing box, and tail surfaces are several hundred degrees less than values predicted by the modified theory and even below predictions using the original theory.

An example of the different temperature values obtained from flight data, theoretical calculations, and theoretical calculations modified for wind-tunnel factors is shown in figure 6. Although the true nature of the discrepancies between wind tunnel, theory, and test data is not

yet known, these results show graphically that extrapolation of heat-transfer model test data to actual airplane flight conditions may give inaccurate results. Even though analysis of the X-15 flight test data is not complete, sufficient data have been gathered to suggest that modification of standard thermodynamic techniques of design will be required in the prediction of hypersonic flight structural temperatures. This conservatism in structural temperature prediction, however, does not necessarily imply a structural design conservatism throughout the aircraft, inasmuch as thermal gradients in some areas may be critical.

Wing leading-edge problem.- Although surface temperatures have in general been somewhat lower than predicted, in some specific locations temperatures have been higher. As shown in figure 7, the wing leading edge is fabricated from an Inconel X bar which serves as a heat sink to absorb heat generated at the stagnation point. Principal loads are carried by the main wing box immediately to the rear of the secondary structure leading-edge box. In order to minimize attachment stresses between the bar and the wing skin, as a result of unequal thermal expansion, the bar was segmented into five pieces with expansion joints or slots each about 0.08-inch wide between the segments. Patterns obtained from temperature-sensitive paint applied to the wing (fig. 8) defined the temperature distributions resulting from the turbulence generated by these leading-edge slots. The magnitude and profile of the temperatures resulting from this turbulent flow and the stresses induced locally on the wing skin were not predicted. This condition contributed to the local permanent buckling as shown in figure 9. In an effort to minimize this buckling problem, three design changes have been made. Two of the changes are shown in the lower sketch. An 0.008-inch thick Inconel tab welded along one edge was installed over each slot to eliminate or at least minimize the local hot spots. A fastener was added at the slot to decrease the fastener spacing and to increase the skin buckling allowable. To reduce the load that the skin splice must carry at each slot, the third change added expansion slots with cover tabs in three of the outboard segments of the leading edge. In addition to the design changes, shear ties have been added at the new slots to prevent relative displacement of the leading-edge segments.

Windshield damage.- Aerodynamic heating of the outer panel of the double-paneled windshield provides another area of interest. The original analysis for selection of outer windshield glass was based on theoretical heat-transfer data and the then-known thermal properties of the glass selected. The analysis indicated that soda-lime glass would be adequate for conditions imposed by the X-15 flight program. Temperature data obtained during early flight testing of the airplane pointed toward a higher surface temperature and greater temperature gradient through the glass than had been predicted originally. A subsequent reevaluation of the wind-tunnel data showed that these data actually correlated well with the flight temperatures. A sample of the outer

windshield soda-lime glass was then subjected to the surface temperature and temperature gradient extrapolated for a high-temperature flight; the glass failed.

Meanwhile, alumino-silicate glass, developed under contract to the U. S. Air Force, had been qualified for aircraft glazing. This material, which has greater heat capacity, higher thermal conductivity, a lower coefficient of expansion, and greater strength at high temperatures than the soda-lime glass, was subjected to the same thermal test and did not fail. The alumino-silicate sample was then successfully subjected to surface temperatures and gradients from outer to inner surface of approximately 150 percent of the maximum predicted. Since these thermal conditions were believed to be considerably more severe than would be required by any X-15 mission, it was planned to replace the soda-lime outer windshields with alumino-silicate glass on all three airplanes.

Failures of the outer panel were encountered in two flights in 1961. The first failure (fig. 10) occurred in a soda-lime panel. The second failure (fig. 11), however, did involve the alumino-silicate panel. Common to both failures was the similar location of the initial point of failure, even though the second instance involved the right-hand outer panel. In both cases, the failure originated at a point approximately 1/2 inch down from the upper edge of the glass, nearly coincident with the trim line of the retainer, and at approximately the midpoint fore and aft. Since this location was near the rear edge of a buckle in the retainer, it was concluded that the failure occurred as a result of thermal stresses produced by excessive local temperature gradients caused by the retainer buckle. It is noteworthy that the buckle was much more severe during the second failure and would contribute to the higher local temperatures. The material for the retainer has been changed from Inconel X to titanium, since the reduced coefficient of expansion of titanium compensates better for the differential expansion associated with the cooler Inconel X substructure frame. The thickness of the frame has also been increased.

Structural Dynamics

The X-15 is the first airplane in which extensive use of high-temperature materials was necessary in order to withstand the flight environment. The design, manufacture, and flight testing of the X-15 have added impetus to wind-tunnel and analytical studies that have advanced the state of the art in several fields of structural dynamics.

Noise.- Estimates of the noise environment of the X-15 led to some concern for fatigue of the structure. The most severe noise appeared to be that produced by the engines of the B-52 carrier airplane during

take-offs and by the X-15 rocket engine during ground runs. Tests were made in a Boeing test facility up to noise levels of 158 decibels, which approximated the maximum level predicted. These tests indicated that modifications to the X-15 horizontal and vertical tails would be required. Flight tests, however, were already underway with the unmodified surfaces and, after three captive flights, fatigue failures were detected in the upper vertical tail. The failures consisted of separation of the skin panel from the corrugated web. Subsequent flight measurements and wind-tunnel tests indicated that the cause of the failures was turbulence in captive flight created by the pylon ahead of the vertical tail and the large cutout in the trailing edge of the B-52 wing (fig. 12). A vertical tail with modified construction was installed, and the climb schedule of the B-52 was changed to reduce the free-stream dynamic pressures encountered. These solutions have been completely satisfactory.

Buffeting.- Another area in which the B-52/X-15 combination was of concern was the effect of the X-15 airplane on the buffet characteristics of the B-52 airplane. Wind-tunnel tests indicated that the buffet characteristics of the B-52 airplane would be essentially unaffected by the addition of the X-15 airplane; therefore, buffeting would not be a problem. Flight experience has verified this prediction. The launch conditions are just below the flight-determined buffet boundary for the B-52/X-15 combination, and no problems due to buffeting have been encountered even though the buffet boundary has been penetrated slightly with the X-15 airplane aboard.

The buffet characteristics of the X-15 airplane in free flight at subsonic and transonic speeds are similar to those of other low-aspect-ratio, thin-winged airplanes. The X-15 airplane usually penetrates the buffet boundary slightly during round-out after launch before accelerating to supersonic speed and usually encounters some mild buffet again during deceleration after completing the supersonic portion of the flight. However, buffeting has not been a problem in the X-15 flights.

Flutter.- Classical-flutter considerations influenced the design of the X-15 horizontal and vertical tails and landing flaps, shown as shaded areas in figure 13. Adequate wind-tunnel tests were made on the various components to provide proof tests to 30 percent above the design dynamic pressure of 2,500 lb/sq ft. No indication of classical flutter has been experienced in flight.

Panel flutter was considered in the design of the X-15 using criteria then available and was not believed to pose a problem. Nevertheless, panel flutter has occurred in flight and has required modification of extensive areas of the fuselage side fairing and vertical tails, which are shown as shaded areas in figure 14. The side-fairing

panels consisted of flat sheet stiffened by transverse corrugations attached to the inner face of the skin. In flight, vibration was detected by accelerometers in the fuselage, by strain gages in the wing, and by the pilot. Strain gages were then added to the side-fairing panels and their responses were measured. Panel flutter was definitely indicated (fig. 15) by abrupt increases (fanning out) in strain-gage traces at a dynamic pressure of about 650 lb/sq ft and a Mach number of approximately 2.4. Wind-tunnel tests of an X-15 panel were conducted, and the flight experience was duplicated. In addition, cracks were found originating at drain holes in the corrugations and extending outward to the base of the corrugation. Careful inspection of the airplane revealed several panels which had a similar type of fatigue crack. A modification now incorporated on the X-15 consists of hat-section stiffeners riveted to the corrugations extending forward and rearward. Vibration levels were found to be greatly reduced by the addition of these stiffeners, as shown in figure 15.

Panel flutter of the vertical tail was also experienced in wind-tunnel tests and in flight. Modifications to the vertical-tail structure were incorporated after proof tests of the proposed modification were successfully conducted in the Langley 9- by 6-foot thermal structures tunnel.

During the remaining flights of the X-15, in which dynamic pressures as high as 1,600 lb/sq ft have been achieved, no further panel-flutter problems have been encountered.

Landing-loads dynamics.- One of the major problems that must be considered in the design of glide reentry vehicles is the provision for a safe landing on return. Landing-gear systems for these vehicles must meet all the usual requirements and, in addition, must be exceptionally light and able to withstand the temperatures resulting from reentry. The X-15 marks the beginning of a class of reentry vehicles with a landing gear designed to meet these requirements.

The X-15 landing-gear system consists of a main gear with steel skids placed well back on the fuselage, along with a conventional, nonsteerable nose gear placed well forward. Serious consideration was given to the landing dynamics associated with the X-15 landing-gear configuration several years before the first flight tests, and experiments and analyses indicated that acceptable landing characteristics would be provided. Landing experience with the X-15 airplane, however, has shown that the landing-gear system as originally designed was not adequate.

Subsequent to the first flight, when the main-gear cylinder bottomed and the gear was damaged, additional energy-absorption capacity was added to the main gear. Later, a still greater capacity was

provided by increasing the cylinder stroke and allowing even higher
peak loads by strengthening the gear and backup structure.

The nose-gear loads were known to be extremely responsive to
airplane angle of attack as well as to airplane weight. The nose-gear
energy-absorption capacity was believed to be adequate, even though
the landing weights and touchdown angles during the first three landings
were exceeding design values. However, during the fourth landing--a
hard emergency landing on Rosamond Dry Lake following an in-flight
engine explosion--the nose-gear wheels were bent and the fuselage was
broken immediately behind the cockpit area.

The post-accident investigation revealed that the principal
problem existed in the nose-gear arresting system. In order to con-
serve space when the nose gear was retracted, the gear was stowed in
a nearly compressed position. Upon rapid gear extension, the nitrogen
gas which had been entrapped by the oil under high pressure was re-
leased and produced a gas-oil foam within the cylinder. Approximately
the first one-third of the cylinder stroke was rendered ineffective by
this foam; consequently, the loads built up to excessive values during
the remainder of the stroke. A permanent solution was achieved by
redesigning the internal mechanism of the strut to incorporate a
floating piston which keeps the gas and oil separated at all times.

As noted previously, the X-15 landing experience with the skid
gear represented the first opportunity to study a system of this type.
Much state-of-the-art information was obtained, inasmuch as the airplane
has been instrumented to measure gear loads, gear travel, and acceler-
ations. Figure 16 shows the main-gear shock-strut force and travel
measured on a typical landing. The upper curve is the strut travel and
the lower curve is the strut force measured from time after main-gear
touchdown. At touchdown, the angle of attack was 8°, the sinking speed
was 3 feet per second, and the landing weight was 14,500 pounds. The
sketches at the top of this figure aid in identifying the landing
sequence. It is important to note that both the shock-strut force and
travel are appreciably higher during the second reaction on the main
gear following the nose-gear touchdown than during the initial portion
of the landing. Extensive study has shown that these high values
result from several factors, primarily the main-gear location well back
of the airplane center of gravity, but also the pronounced aerodynamic
down load on the tail, the negative wing lift during this portion of
the landing, and the airplane inertia loads. The increasing down load
on the tail is brought about by two sizable increases in angle of
attack: the rotation of the airplane onto the nose gear, and a change
in the wind-flow direction to nearly horizontal. Experience with the
X-15 has shown that the horizontal-tail angle, and, hence, the tail
loads, are also increased by the action of the stability augmentation
system as the airplane pitches down.

Supersonic and Hypersonic Aerodynamics

Performance.- Considerable uncertainty has existed regarding prediction of the range potential of future supersonic transports and reentry vehicles from wind-tunnel tests and theory. Complete dependence upon wind-tunnel data exposes the designer to the hazards of incompatible boundary-layer conditions and extrapolation of drag data to Reynolds numbers at least 10 times greater than for the model tests. The X-15 program provides the first detailed full-scale drag data at Mach numbers above 2, and eventually, of course, will relate wind-tunnel and full-scale lift and drag results throughout the Mach number range to approximately 6. The primary objective of the performance study is to evaluate the various components of drag in a way that will serve as a guide to designers of future aircraft.

An analysis of the X-15 performance data indicates that in the low angle-of-attack range, wind-tunnel trimmed lift and drag-due-to-lift obtained on models show excellent agreement with flight results. Furthermore, flight data indicate that reasonable values of the full-scale minimum drag can be obtained from extrapolations of wind-tunnel results to flight Reynolds numbers. To achieve this, the condition of the boundary layer must be known and a representative wind-tunnel model must be tested, even to the extent of including all the protuberances found on the full-scale airplane. These protuberances include such items as the landing skids, camera fairings, and antennas. Existing theoretical methods were adequate for estimating the X-15 minimum drag; these theories, however, underestimated the drag-due-to-lift and overestimated the maximum lift-drag ratio (fig. 17). This result was attributed primarily to the inability of the theories to predict the control-surface deflections for trim. It was also found that two-dimensional theory, which has been known to predict the base pressures on relatively thin wings with blunt trailing edges, also predicts satisfactorily the base pressures behind the extremely blunt vertical surface of the X-15. This information will have direct applications to winged reentry vehicles.

Stability and control derivatives.- From the many wind-tunnel and theoretical studies performed in developing the final X-15 configuration, an extensive compilation of derivative characteristics was made available for preflight evaluation of the vehicle's performance, stability, and control. To reveal any possible differences that may arise from such factors as scale effects, wind-tunnel techniques, and theoretical assumptions, a fairly comprehensive flight evaluation of the derivative characteristics is also required, particularly during the expansion of the flight envelope to its ultimate limits.

The X-15 flight program has established fairly well-defined derivative trends for Mach numbers approaching the design limit. In

general, these trends have agreed well with wind-tunnel predictions.
(See, for example, fig. 18.) Also, many of the basic stability and
control design parameters have been confirmed in a substantial portion
of the overall flight envelope. The gradual development of these basic
trends from flight-to-flight has generated a high level of confidence
in proceeding to the more critical flight areas during the development
program, particularly since the pilots were able to correlate X-15
flight control trends on the fixed-base simulator. No serious flight-
control problems have been encountered in the longitudinal mode; however,
one serious deficiency in the lateral-directional mode has been observed
in the form of an adverse dihedral effect at high Mach numbers and
angles of attack. This is discussed in more detail in the following
section. Further studies and tests are planned for the high Mach
number and angle-of-attack ranges to reveal any further flight-control
problems that may exist in these more critical areas and, at the same
time, provide more data for correlation with wind-tunnel tests and
theory.

Piloting Aspects

One of the primary research goals of the X-15 was to make possible
studies that would provide much-needed information on the handling
qualities of future aircraft and space vehicles. Although useful data
can be obtained from speed missions, the greatest research return is
realized during performance of high-altitude trajectories. During such
missions the pilot is exposed to relatively high longitudinal acceler-
ation in the rocket-powered phase during exit and could experience
large transients during burnout. This is followed by a period of
weightlessness, often several minutes long, in the thin upper atmos-
phere. During this time, the conventional aerodynamic controls are
useless and the pilot must resort to the small reaction rockets located
in the nose of the aircraft and at an outboard wing location. Perhaps
the most demanding control region occurs during reentry into the earth's
atmosphere. At this time the pilot is required to control the aircraft
at high angle of attack while experiencing the combined effects of high
normal acceleration and large longitudinal deceleration. It should be
mentioned that many of the X-15 trajectories are more demanding from
the piloting standpoint than those contemplated, for example, for the
Dyna-Soar vehicle, in that many of the controlling aerodynamic and
environmental characteristics change much more rapidly with the X-15.

Display and control description.- In order to perform the complex
tasks required, special attention was given by the project pilots to
the evolution of the X-15 display. The display (fig. 19) is conven-
tional in that it shows in standard fashion the status of many of the
aircraft and engine systems. The flight phase is monitored chiefly
from the inertial system which provides readouts in altitude, velocity,

and aircraft attitude. Signals from the ball-nose position pointers and cross bars afford the pilot a reading of angle of attack and vernier indications of angle of attack and sideslip. Prime reliance is placed on the attitude indicator in three axes, inasmuch as the earth's horizon is quickly lost as an outside reference during the high-pitch-angle climb experienced on all flights.

Simplicity is the key to the X-15 display. Many small changes requested by the pilots are being made continually to provide a readable display for the rapid cross checks that a pilot makes in a fast-moving situation.

Aerodynamic control is provided by a conventional center stick or by an interconnected side stick positioned to allow pilot control without inadvertent or adverse inputs from acceleration forces. Reaction rockets for attitude control at low dynamic pressure are activated by a simple controller on the left side of the cockpit that allows inputs in roll, pitch, and yaw.

Typical altitude mission.- Figure 20 presents the details of a typical altitude mission to 217,000 feet on which many comments may be made pertinent to X-15 flight control characteristics. The X-15 launch is characterized by two prominent features: first, a sudden departure from the B-52 pylon, yielding a zero-g peak normal acceleration; second, a tendency to roll abruptly to the right. The pilot usually partially compensates for the rolling tendency by initially holding the stick slightly to the left so that the maximum roll angle at launch rarely exceeds 10° to 15°. The release, after the first experience, is of no concern to the pilot inasmuch as normal 1 g flight is regained within 2 seconds. The roll-off at launch stops as the X-15 emerges from the B-52 flow field.

Immediately after launch the engine is fired and the climbout begins. The handling qualities at an altitude of 45,000 feet, a Mach number of 0.8, and at maximum weight are considered excellent. Supersonic speed is reached very quickly after engine light-off. Following initial rotation at an angle of attack of 10°, a constant pitch angle of 32° is established and maintained to burnout where the acceleration along the longitudinal axis reaches 3.6g. From engine shutdown until reentry, the aircraft follows a ballistic trajectory. Two unique features are experienced: about 2 minutes of weightlessness and the necessity of using reaction controls. This portion of the flight is followed by the reentry maneuver, which terminates when the aircraft rotates to level flight after experiencing, as in this flight, a normal acceleration of 3.8g, longitudinal acceleration of -2.2g, and peak dynamic pressure in excess of 1,400 lb/sq ft.

The portion of the profile during exit is characterized by very good handling qualities, since the airplane is stable and the damping

appears to be adequate, even with roll and yaw dampers inoperative. The increase in acceleration along the longitudinal axis during the thrust period reaches a maximum of 3.6g at burnout. The acceleration level, although obvious to the pilot, has not been high enough to impair in any way the pilot's ability to perform essential tasks. Thrust termination during flight occurs when the pilot stops the engine or when burnout results from propellant exhaustion. No transient aircraft motions have been experienced, and thrust misalinement has not been of concern. The stabilizer is trimmed to maintain an angle of attack of 0°. This change in trim is complete at approximately 145,000 feet, where dynamic pressure has decreased to 26 lb/sq ft. At this point, a decay in response to aerodynamic control is easily noted by the pilot, and reaction controls are employed. The reaction controls have proved to be very effective, aircraft response to inputs in roll and yaw is good, and the response in pitch is more than desired, causing some difficulty in damping the pitch oscillations.

Zero g has had no noticeable effect on the pilot performance during the approximate 2-minute weightless state.

The X-15 reentry is perhaps the most interesting maneuver from the pilot's standpoint, since it is flown at relatively higher angles of attack and under the rapidly changing conditions of dynamic pressure, temperature, and velocity, with the associated changes in aircraft stability and responses. The maneuver actually begins as the aircraft passes through an altitude of 180,000 feet and the reaction controls are used to establish the reentry angle of attack.

With the stabilizer constant and the angle-of-attack raised to 10°, the normal acceleration a_n increases to approximately 2g as the dynamic pressure increases. The stabilizer is repositioned to maintain the reentry normal acceleration at a maximum of about 4g until level flight is regained at just above 60,000 feet. It is of interest to note that static simulations and the centrifuge program at the Naval Air Development Center, Johnsville, Pa., provided good training for these conditions so that the actual reentry did not result in a completely new or unexpected flight experience.

General comments.- In all X-15 flights the speed brakes have been used effectively in many areas throughout the speed and altitude range for flight-path control. During brake extension there is a mild trim change, but no other undesirable aircraft motions. No reports of buffet caused by speed-brake deflection have been made.

Lateral control of the X-15 is provided by differential deflection of the horizontal stabilizer, or "rolling tail." This method of control has provided excellent results on the X-15. The pilot is not aware of the specific type of lateral control that produces the roll motion; he is concerned only with obtaining the aircraft response he needs.

The X-15 stability augmentation system, which provides rate damping about all axes, has had significant effect on pilot opinion. During early flights below a Mach number of 3.5, moderate gains were used and were found to be acceptable. Above a Mach number of 3.5, pilots expressed a desire for greater damping, particularly in pitch and roll. Thus, higher damper gains were incorporated. In general, pilot opinion of the augmented handling qualities in the Mach number range from 2.5 to 6.0 has been favorable. However, at an angle of attack of 8° and above with low damper gain and particularly with the roll damper off or with roll and yaw dampers off, the pilot has great difficulty controlling the lateral and directional motions to prevent divergence at Mach numbers above 2.3. This condition corresponds to the potential emergency situation created by a stability-augmentation-system failure.

Considerable effort has been expended in investigating the control problem which might follow a roll-damper failure. Investigations have utilized fixed and airborne simulators, closed-loop theoretical analysis, and actual flight tests of the X-15 airplane. The problem stems primarily from the negative-dihedral contribution of the lower rudder and was not revealed until the inputs of the pilot were used along with airplane stability to determine closed-loop stability. Subsequent analysis has shown that the use of a transfer function which represents the inputs of a pilot performing a lateral-control task permits calculation of the degree of pilot-airplane instability. Special control techniques have not completely alleviated the problem, but have provided sufficient improvement when the side stick is utilized to allow flight in the fringes of the uncontrollable region. Removal of the lower rudder, with consequent improvement in dihedral effect, is another means of lessening the instability, although some new problems are introduced. Dualization of certain components in the stability augmentation system will reduce the probability of encountering the control problem.

As experience using the side-located controller was gained and modifications were attempted to make each factor fully acceptable to the pilot, most features included in the initial design were found to be satisfactory. All pilots agree on the desirability of using the side stick at high acceleration; however, the location of the control in relation to the pilot's arm position proved most critical. A modification allowed the selection of five different positions, which provided for adjustment of the control stick, forward or backward prior to flight, to satisfy an individual pilot's desire. The trim control remains controversial, and further evaluations will seek the best compromise between a wheel or button control and the best location for it on the stick. In general, the side-located controller has been preferred on many occasions and has been used entirely on some flights from launch to landing.

Approach and landing.- The approach and landing phase of the X-15 mission received much concern and attention in the first flights. Now, however, based on the experience, procedures, and techniques developed, it has become a routine operation.

Landing simulations using the F-104 airplane were made prior to the X-15 flight program and have been continued during the program. With predetermined settings of the lift and drag devices and the engine thrust, the lift-drag ratio of the F-104 is established to match that of the X-15. This experience allows the pilots to establish geographic checkpoints and key altitudes around the landing pattern, thus becoming familiar with the position and timing required in the pattern by the X-15 low lift-drag ratio. At present, prior to each X-15 flight, the pilot devotes one or more F-104 flights to making approaches and landings at each possible X-15 landing site in what is considered satisfactory preparation and practice for the landing maneuver.

Figure 21 illustrates the wide range of conditions in altitude at the high key and lateral dispersion from the touchdown point that can be used in space-positioning the X-15 for the landing pattern. This figure indicates the flexibility allowed the pilot in maneuvering to a designated touchdown point. This flexibility is attributed primarily to several factors. The pattern is normally flown at an indicated airspeed of 300 knots, and the handling qualities, including the control-system use and the airplane responses, are considered excellent. If less sink rate is desired, the aircraft can be flown at an indicated airspeed of 240 knots for the best lift-drag ratio, and, if necessary, excess altitude can be lost at constant airspeed by use of the speed brakes. Although rates of sink average 250 feet per second and have been as high as 475 feet per second in the approach, none of the pilots has considered these values to be a limiting factor in the pattern. The average vertical velocity at the flare initiation is between 100 and 180 feet per second. Aside from airspeed control, the cues that the pilot uses are external. After a landing point is selected, a flare point is determined from which the remaining energy will carry the aircraft to the intended touchdown spot. The flare altitude, generally less than 1,000 feet, is not selected solely from the altimeter, but from the pilot's estimate of the height necessary to reduce the sink rate and arrive level in proximity to the ground. It is significant that as flight experience was obtained, the flare-initiation speeds increased, not to seek better handling qualities (which are good throughout), but to gain more time after the flare to make configuration changes, correct trim changes, then execute the landing at acceptable values of angle of attack, sink rate, and proximity to the intended landing point.

Most landings have been accomplished with vertical velocities of less than -5 feet per second at angles of attack between $6°$ and $8°$.

In each of the last 24 landings a specific spot has been used for the intended touchdown point. As shown in figure 22, all but six landings have been grouped within ±1,200 feet of this spot. This degree of precision is considered to be very good. The landing summary shown reveals an average slideout distance from touchdown of 5,000 feet to 6,000 feet. The shortest distance can be achieved by using full-back longitudinal control and flap retraction to place the greatest load on the skids, and full deflection with speed brakes for added drag. In addition to the good inherent directional characteristics of the X-15 on the ground, the pilot has used lateral-control inputs to provide a greater load on one skid and thus achieve some measure of directional control.

In summary, it should be noted that a pilot, provided an aircraft with good control and handling qualities as represented in the X-15 in the landing pattern, can intercept the landing pattern at any one of its key positions, make adjustments based on his experience, judgment, and reactions to the many cues available, and complete a satisfactory landing in proximity to a designated landing spot with power off. Experience with the X-15 has included landings with various dampers inoperative, a few landings using only the side-located controller, and one landing with one windshield outer panel shattered to opaqueness, with an attendant compromise in the pilot's visibility and the landing task. These landings have all been satisfactory and are included with the data presented in figure 22.

Bioastronautics

The ability of a pilot to successfully perform during the varied and sometimes extreme flight environment afforded by the X-15 has been of interest since the beginning of the project. In addition, it was considered highly desirable to detect unsafe conditions by monitoring the pilot's environmental system during flight by means of telemetry, thus establishing physiological baselines on which to base aeromedical decisions during future space flights.

To accomplish these objectives, electrocardiogram, oxygen flow, skin temperature, cockpit temperature, suit/cockpit pressure differential, and suit/helmet pressure differential are measured, and the pressure differentials are telemetered to aid ground personnel in detecting unsafe conditions in the pressurization system.

Early X-15 flight results indicated that certain preconceived physiological baselines should be changed. Some typical key physiological quantities measured are shown in figure 23. Heart rates of over 140 beats a minute and respiration rates of over 30 breaths a minute were the general trend rather then the exception. The data have

been useful primarily in establishing new physiological baselines for
pilots of high-performance vehicles and will be useful in connection
with future manned programs. The pilot's response to changing dynamic
flight conditions is under study.

Future flights to extreme altitudes should provide an interesting
source of additional X-15 physiological data. In these flights it is
planned to incorporate additional physiological instrumentation to
measure blood pressure. In addition, the F-100C variable-stability
airplane is being fitted with physiological instrumentation to supple-
ment X-15 data. These programs should provide answers on the possible
correlation of controllability and the physiological status of the
pilot.

Simulation and Mission Planning

The philosophy of the X-15 flight-test program has been to expand
the flight envelope to the maximum speed and design altitude as rapidly
as practical and, simultaneously, to obtain as much detailed research
data on the hypersonic environment 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, thus permitting a reasonable extrap-
olation of flight-test data from flight-to-flight and also building a
backlog of pilot experience. In the X-15 program, pilot training and
careful mission planning have been extremely important.

Training procedures.- The prime tool in planning X-15 missions is
a six-degree-of-freedom analog simulator. This simulator was con-
structed by North American Aviation, Inc., during the design and
development of the X-15 and was subsequently transferred to the NASA
Flight Research Center, Edwards, Calif., for use during the flight-test
program. The simulator includes actual hydraulic and control-system
hardware. Another primary pilot-training tool has been the F-104 air-
plane which is used by the pilots to practice low-lift-drag-ratio
landings. Digital computers have been of value in performing temperature-
prediction calculations prior to each flight. Variable-stability air-
planes have also been available during the test program. Some of the
more significant simulators used in the X-15 program are shown in the
drawings of figure 24.

Prior to each flight, the six-degree-of-freedom analog simulator
is used to acquaint both the pilot and the ground controller with the
required piloting technique and general timing of the proposed flight.
The normal flight profile is generally flown several times on the
simulator, and changes suggested by the pilot are incorporated into the
flight plan. After the pilot is familiar with the normal mission,

off-design missions are flown to acquaint him with the overall effect
of variations in the critical control parameters (fig. 25). Variations
in engine thrust or engine shutdown time are simulated, as well as
possible changes in critical stability derivatives.

Next, the pilot practices simulated failure of the engine, inertial
platform, flow-direction sensor, radar or radio, or both, and stability
augmentation system. Simulated failures of the inertial-platform
presentation are also practiced, and alternate techniques for either
completing the normal mission or for safely returning the vehicle and
pilot are devised.

In addition to these preparation procedures, which are performed
prior to each flight, additional training procedures have been used.
A centrifuge program was performed in June 1958 which verified that the
pilot could successfully control the airplane under the predicted
acceleration environment. Also, variable-stability airplanes have been
used to simulate the handling qualities of the X-15 airplane at various
flight conditions to provide more realistic motion cues to the pilot.

Ground-monitor functions.- Although the pilot is undeniably in
complete control of the flight, the ground monitoring station performs
an important function in the support of X-15 flight operations. It is
equipped with displays of the radar data and selected channels of
telemetered data. The primary functions of the ground-control station
are to:

> Monitor the subsystems operation during the flight
> and to advise the pilot of any discrepancies noted.
> Position the B-52 airplane over the desired launch
> point at the desired time by advising the B-52
> pilot of course corrections and countdown time
> corrections prior to launch.
> Time the engine operation as a backup for the on-
> board timing device and advise the X-15 pilot of
> heading corrections, radar altitudes, and position
> during the flight.
> Monitor and evaluate stability and control parameters.
> Monitor the pilot's physiological environment.
> Provide the X-15 pilot with energy-management assist-
> ance in the event of a premature engine shutdown
> or other off-design condition.
> Direct emergency air search and rescue operations.

Normally, all important information in the control room is passed
on to the pilot through the ground controller; however, other ground-
control personnel can transmit directly to the pilot in an extreme
emergency when insufficient time is available to relay the information.

In order to supply energy-management advice to the pilot as rapidly as possible, special techniques and equipment are being incorporated for ground monitoring. The analog simulator was used to define the optimum piloting techniques required to obtain the maximum forward and reverse range from various flight conditions. A computer has been mechanized to store the precomputed maximum range capabilities as a function of forward velocity, vertical velocity, and altitude. Radar values of these parameters are fed into the system, and the resulting range footprint to a high key altitude of 20,000 feet is displayed on a scope-type map presentation (fig. 26).

Flight experience.- The adequacy of mission planning and pilot training procedures can be assessed from flight results. Figures 27 and 28 compare, respectively, predicted and actual speed and altitude profiles with the XLR99 engine. The overshoot in flight velocity and altitude (fig. 28) is the result of a 2-second delay in shutting down the engine. It should be pointed out that the cockpit timer did not function on this flight and that at this point in the trajectory the airplane was accelerating at approximately 100 ft/sec^2. The pilot was, therefore, relying on a ground time callout to shut down the engine. The resulting delay was responsible for the discrepancy.

After each flight, a performance "match" is simulated on the analog computer with the actual angles of attack and thrust values which were experienced on the flight. Analog-computer matches of the speed and altitude missions (figs. 27 and 28) show good correlation. The only changes made to the simulator as a result of flight-test data have been weight- and burning-time alterations. No alterations to the predicted performance and stability derivatives have been required.

Several anticipated problems have occurred during the test program, such as failures of the stability augmentation system and engine, and malfunctions of the stop watch, inertial system, radar, and radio. The anticipated controllability problems have also been verified in flight. The value of the analog simulator in defining techniques and training the pilots to allow completion of the missions under these adverse conditions is undeniable.

Operational Aspects

System development procedures and problems and the value of the pilot in the overall operation are considered in the following sections.

System development.- The importance of careful system-development programs prior to flight testing has been dramatically illustrated by the X-15 program. The development requirements for some systems such as the inertial-data system were grossly underestimated and, as a

result, the program was well advanced by the time reasonably dependable performance was achieved. In another instance, insufficient analysis was conducted prior to a ground engine run. As a result, the X-15-3 airplane was severely damaged by an explosion.

Cause of ground explosion: Figure 29 gives an indication of the extent of the explosion damage. Investigation disclosed the initial cause to be overpressurization of the ammonia tank. This resulted from a malfunction of the relief valve and pressurizing gas regulator while the engine was operating on the ground with the ammonia tank vented through the vapor-disposal system (fig. 30). Because of the toxic nature of ammonia fumes, the vapor-disposal system had been incorporated into the facility at Edwards Air Force Base to dispose of ammonia fumes from the airplane tankage. At the time of the explosion, the ammonia-tank pressurizing gas regulator probably froze or stuck in an open position while the vent valve was operating erratically or modulating only partially open. This condition had been considered as a failure possibility in the airplane; however, these malfunctions in conjunction with the back pressure associated with the vapor-disposal system combined to cause ammonia-tank pressures high enough to fail the tank. As a result of the explosion, the pressurizing gas regulator was redesigned to reduce maximum flow through an inoperable regulator, the regulator was redesigned to provide additional closing forces in the event of freezing and relocated to minimize the possibility of moisture entrance and subsequent freezing, and the relief valve and relief-system plumbing were redesigned.

This costly lesson pointed out the need for more complete system analyses or testing, or both, under not only design conditions, but also under operational and test conditions, since analytical evaluation of such involved systems is extremely difficult and not completely reliable.

The optimum approach to system development, then, would include not only conventional test-stand testing of the various systems and ground testing of the completed airplane, but specific "fail safe" tests including utilization of any ground support equipment or facility equipment, or both, which become integrated with the airplane system at any time. In fail-safe tests, critical components are intentionally failed to insure that no single failure can cause damage to the airplane.

Stability-augmentation-system development: In some instances serious system problems can arise even after a thoroughly planned development program. Prior to installation on the X-15 airplane, the stability augmentation system underwent extensive and exhaustive testing in the laboratory for proof of performance and service-life determination. In these tests, all system components were operated in

environmental test chambers which duplicated predicted X-15 mission
environment. These tests resulted in electrical and mechanical modifi-
cations. Subsequently, the system was installed on the control-system
mock-up which was incorporated into the analog flight simulator shown
in the lower-right sketch of figure 24. Operation of the stability
augmentation system on the simulator revealed the need for additional
modifications to eliminate residual oscillations prior to installation
in the X-15.

In general, the procedure used for development of the stability
augmentation system was adequate. The functional aspects of the system
were fixed on the basis of comprehensive preliminary simulator tests.
The hardware was operated in a realistic environment and, finally, the
complete system was checked in a simulator and in the airplane with the
pilot "closing the loop." However, maintenance and checkout procedures
were inadequate and, if an operational system had been essential for
flight safety, trouble would have been experienced during some early
flights.

In spite of the extensive simulation, during reentry from a high-
altitude mission the X-15 vibrated severely. The pilot reported the
shaking to be the most extreme that he had ever encountered. Figure 31
illustrates the mechanics of the phenomenon. The lightly damped
horizontal-stabilizer surfaces, represented by the flexible beams with
masses, were excited at their natural frequency (13 cps) by the pilot
inputs to the control system. The inertial reaction of the fuselage
to this vibration was picked up by the gyro so that the augmentation
system was able to sustain the vibration with inputs to the control
surfaces. Fortunately, the amplitude of the shaking was limited by
rate limiting of the control-surface actuators; otherwise, the aircraft
may have been destroyed. Steps have been taken to eliminate the problem.
More important, however, is the fact that the problem was not encoun-
tered on the elaborate ground simulator because the particular phenom-
enon was unknown at the time. Thus, even the most sophisticated
electronic computers are no better than the knowledge of the scientists
who guide them.

Operating experience.- In more than 45 powered flights, the X-15
flight envelope has been enlarged considerably beyond that of any
other aircraft. This has been accomplished without the loss of any
aircraft and with no system failures after launch that were not readily
managed by the pilot. However, partly because of the increased number
and complexity of systems and partly because of other problems that are
discussed subsequently, many unsuccessful flight attempts and countless
schedule delays have been experienced.

Although the post-launch reliability of the X-15 has been impres-
sive, the reliability of major systems drops noticeably when based on

all airborne experience and drastically when based on all operational experience, both on the ground and in the air. An increasingly large amount of ground time has been spent and many cancellations have occurred because of parts failures or hard-to-analyze system malfunctions. As a result, the high mission success has been obtained at a great cost in parts, materials, and technical and engineering man hours. The same amount of preparation and testing is required for a cancelled flight as for a successful one.

As the X-15 program has progressed, the failure rate of most major systems has decreased. For example, figure 32 shows failure experience for the auxiliary power unit (APU) and ballistic control rocket (BCR) system in which the number of failures is plotted against airborne operations. In this figure a failure is defined as a system malfunction considered unsafe for flight. Since very few major failures have occurred in free flight, each point represents a malfunction which resulted in schedule delay, flight cancellation, or airborne abort. Most of these malfunctions occurred very early in the program.

Causes of operating problems.- Four causes of the systems problems encountered on the X-15 are unexpected environmental conditions, failure of qualification tests to duplicate true conditions, contamination sensitivity, and human error.

Unexpected environmental conditions: Since the beginning of actual flight operations, a variety of last-minute problems, including poor weather conditions, has necessitated extended waiting periods prior to take-off. In most of these instances, the airplane had already been serviced with liquid nitrogen, oxygen, and chilled gases. As a result, both structure and components have been cold-soaked to extremely low temperatures. Since most parts and systems were designed for elevated temperatures, such cold-soak conditions have been one of the most aggravating sources of trouble.

Even though all components of the system met rigid specifications, they were built to operate under conditions not considered in their original design.

Inadequate qualification tests: Specifications covering procurement of a part include a series of tests designed to assure that the part will withstand the conditions under which it must operate. It is impossible, however, to duplicate with such tests all circumstances that will occur in service. For example, the X-15 auxiliary power unit and fuel system were tested for many hours on an exact replica of the aircraft installation. Yet this system has been the cause of more schedule delays and cancellations than any other system. As an example of a component failure, a critical pressure switch in the auxiliary power unit, although thoroughly qualified by the vendor, has been

replaced numerous times and, even with improvements, still constitutes a problem.

Contamination sensitivity: The major sources of contamination sensitivity are residual or built-in debris, oxidation, wear, corrosion, deterioration, decomposition, and airborne particles (silica and dust).

Many parts and systems are constructed and tested under extremely clean conditions with exact tolerances. Qualification tests are conducted in rapid series with special equipment to check the particular component or system. In the actual aircraft, periods of system activity are followed by long inactive periods with stagnant fluid in lines. Systems are opened and closed many times and at many points. Actual aircraft configurations may contain dead ends or deposit points that did not exist in test setups. In any case, much more particle contamination is evident in actual X-15 systems than is found in controlled test equipment. This is apparent from the large number of repeat component failures due to contamination. If such contamination were considered in the original design and testing of parts and systems, considerable time and effort would be saved during actual use.

Human error: Some factors that contribute to human error are misinterpretation of procedures, faulty problem diagnosis, use of standard but improper test methods on standard parts, insufficient quality control, and breakage or damage.

Human error plays an important role in parts and system failures. The well-known "Murphy's Law" dictates that human errors are a function of the design and procedures employed; thus, if a system presents an opportunity for a mistake, a mistake will be made.

This is not to say that all possibilities of error can be eliminated through proper design. Actually, most of the errors can be detected only during actual field operations. Many problems could be prevented, however, by "idiot proofing" procedures and designing systems with practical service and operating conditions in mind.

Value of human pilot and redundant systems.- The value of the human pilot and redundant systems is a matter of great controversy in the preliminary design of space vehicles. Unfortunately, quantitative results with previous aerospace systems have not been properly documented to enable a direct assessment of either the pilot or redundancy aspects. Thus, much has been based upon intuitive projections and purely qualitative appraisals. Because of the currency and many similiarities of the X-15 program to the next generation of aerospace vehicles, data have been obtained that lend realism and validity to considerations of manned, as opposed to unmanned, vehicles and redundancy, as opposed to nonredundancy, in systems design, particularly

for a vehicle developmental phase. ("Redundancy" is defined broadly to include dualized systems, emergency backup provisions, and fail-safe devices.)

The basic approach to the X-15 pilot-in-the-loop and redundancy evaluation was to perform a flight-by-flight detailed engineering analysis of each problem or failure which occurred for all X-15 launch and aborted flights. Each problem or failure was completely described, and corrective action by the pilot or redundancy was analyzed. The effect and value of the pilot and redundancy were assessed with regard to the impact on mission success and vehicle recovery. The hypothetical cases of an unmanned and/or nonredundant "X-15" were then studied to confirm the previous assessment of the pilot and redundancy aspects of each in-flight problem or failure.

A comprehensive evaluation shows that the X-15 flights have benefitted greatly from inclusion of a pilot in the control loops and from redundant systems. These benefits have been accrued both in terms of mission success and safe recovery of the airplane. Figure 33 illustrates that all but one of the first 44 X-15 free flights actually resulted in mission success. However, the evaluation shows that with neither a pilot in the loop nor redundant systems, less than one-half of those same 44 missions would have been successful to even a small degree. Similarly, there have been no losses of X-15 airplanes. But, for a hypothetically unmanned, nonredundant "X-15," it was found that the airplane would have crashed on almost one-third of the flights.

The X-15 flights have demonstrated resounding net benefits of the pilot in the loop and redundant systems in terms of mission success, safe aircraft recovery, and the very continuance of the X-15 program. Even though the assessment was conservative, 24 of the first 44 X-15 free flights were found to require pilot in the loop and redundant systems in order to culminate in successful missions. Only 6 of the first 76 flights of the X-15 were aborted because of overall pilot and redundancy detriments. Most of the 24 other aborted flights were benefitted by both the pilot and redundancy in deferring abort, allowing safe continuance of a captive flight after call for abort, or preventing launch in the presence of an otherwise undetected and unsafe condition. The pilot and redundancy were instrumental in safely handling most of the multiple failures and compounded problems which have been prevalent in the X-15 flight program.

The most important pilot and redundancy benefit to the X-15 program is graphically demonstrated in figure 34. The upper curve is a time plot of the first 44 X-15 free flights. The lower curve plots hypothetical aircraft recovery for the unmanned, nonredundant vehicle. The shaded area between the two curves represents 13 losses of aircraft in the absence of a human pilot and system redundancy. These

quantitative results and results similarly derived from other current
aerospace programs should offer a firm basis for making preliminary
design decisions on the value of the pilot-in-the-loop and redundancy
functions in future space vehicles.

FUTURE PLANS FOR THE X-15

Basic Program

The X-15 program in the spring of 1962 will be oriented toward
continuing research investigations in the primary areas of aerodynamic
heating, reaction controls, including rate damping, adaptive control
system, performance, and displays and energy management.

Aerodynamic-heating information has been of great interest thus
far in the program. Future flights will be directed toward obtaining
additional data under more stabilized test conditions, as well as
extending the results to higher angles of attack.

Although much has been learned about the flight control character-
istics of a representative winged reentry vehicle, the most interesting
X-15 research phase should be attained in the projected flights to and
beyond an altitude of 250,000 feet scheduled for the spring and summer
of 1962. In these tests much information should be obtained pertinent
to control requirements prior to and during high-angle-of-attack atmos-
pheric reentry. Reaction-control research data are now becoming avail-
able from the flight program. An important feature of future flights
will be the incorporation of rate damping in the reaction control
system.

In addition to studies with the basic, rather conventional control
system, flights are being conducted with a more advanced "self-adaptive"
flight control system. Comparisons and overall experience with the
adaptive approach and the more conventional control approach will enable
designers to make more intelligent assessments of the logical trade
between simplicity, reliability, and available control precision. In
addition, the X-15 self-adaptive experience will be directly applicable
to an advanced reentry vehicle now under construction.

Data will also be obtained to more completely define the lift and
drag characteristics of the X-15 configuration.

Work on displays and energy management will be continued toward
the goal of providing a working onboard display for the use of the
pilot in selecting his landing site.

Follow-On Programs

As the basic X-15 programs are completed, follow-on programs will explore, with new instrumentation, areas already partially investigated, such as display, boundary-layer noise, skin friction at high Reynolds numbers, and structural panel tests. Numerous space experiments have been proposed which make use of the X-15 as a test bed to obtain heights greater than those obtained by balloons, but lower than satellite altitudes. These experiments capitalize on the ability of the X-15 to provide on-the-spot pilot input in the conduct of the experiment and the return of the experiment to the ground for detailed evaluation and adjustment or correction of deficiencies. Included in the many experiments being prepared for the follow-on program are ultraviolet stellar photography, infrared exhaust signature, letdown computer, detachable high-temperature leading edges, and horizon definition.

Many other proposed experiments are being evaluated. Some will ride "free" in piggy-back fashion; others may be grouped to share the cost of operation. Some proposals require extensive modifications and are expensive in both time and money. For example, figure 35 shows a stellar photographic experiment which will involve a stabilized platform extended through clamshell doors from a modified instrument bay.

The future X-15 program will be flexible and will be modified, extended, or terminated on the basis of timely reviews by the Research Airplane Committee.

EVALUATION OF THE X-15 PROGRAM

It appears that the research goals established for the X-15 project were generally sound and logical. More ambitious design goals might have introduced substantial additional time delays with little additional return from the research aspect.

The level of turbulent heat transfer and structural temperatures predicted by theories in general use overestimated the temperatures experienced on the X-15, except in local areas of high heat transfer. The use of wind-tunnel data resulted in still further conservatism in temperature estimates in primary structural areas on the X-15. However, the occurrence of local areas of high turbulent mixing in the boundary layer can be generated in areas that would otherwise be laminar as a result of disturbances from leading-edge slots, production joints, and protuberances. This suggests the advisability of continuing to use conservative methods in heat-transfer predictions.

Local thermal problems such as that which produced buckling at the X-15 wing leading edge have been encountered. Such occurrences could

have been dangerous; however, they were experienced in noncritical environments as a result of the rational step-by-step philosophy used to expand the X-15 flight envelope. In any event, sources of local thermal problems should be evaluated in great detail in design stages, particularly when deformed structures due to aerothermodynamic stresses are being investigated.

The design, manufacture, and flight testing of the X-15 have given impetus to studies that have advanced the state of the art in several fields of structural dynamics. The X-15 program has provided a unique opportunity to document panel flutter in a severe flight environment and, as such, has generated theoretical and experimental research that will have a significant effect on the design requirements of advanced vehicles. The X-15 program has also provided much-needed experience pertinent to the understanding of skid landing-gear design and has demonstrated the feasibility of this type of system for space-vehicle recovery.

In general, the lift and drag data and stability and control derivatives extracted from X-15 flight-test data have confirmed the estimated derivatives obtained from wind-tunnel tests and thereby provided increased confidence in wind-tunnel evaluations at hypersonic speeds.

Pilots have generally considered the X-15 handling qualities to be very good.

Exits have been made to a high degree of precision under environmental conditions approximating those expected with some future vehicles.

Although only limited flight experience has been gained with the reaction control system, its basic design appears to be adequate. Pilot transition from aerodynamic controls to reaction controls has been accomplished without difficulty. There is no evidence of any unexpected increase in piloting problems associated with the reentry maneuver.

As a result of preliminary flight test on research test beds and actual flight experience with the low-lift-drag-ratio X-15 glider, approach and landing techniques have been developed that convert a possibly hazardous undertaking to a routine operation. Most touchdowns are made within ±1,200 feet of a predetermined point.

The vital need for providing damper augmentation for hypersonic vehicles has been verified. The simple stability augmentation system of the X-15 airplane has proved to be a good technical design, and the operating experience obtained is being compared to the more sophisticated adaptive control system being tested in one of the X-15 airplanes.

The techniques developed for mission planning and pilot training have worked out well in practice. All predictions of stability, performance, and flight trajectories have been within expected accuracies. The use of the analog simulator to establish pilot cues and timing and to allow the pilot to practice until the techniques become routine has considerably eased the total piloting task. The pilot's ability to obtain more precise flight data in the time available has thereby been improved. Predictable emergency conditions or off-design missions have been encountered during the program. In each instance, simulator training has contributed greatly to the pilot's ability to complete the mission. The two most valuable training devices have been the fixed-base six-degree-of-freedom analog simulator and the F-104 in-flight landing-pattern simulator. Other training devices, such as the centrifuge and variable-stability airplane, have contributed to the overall pilot experience level, but are not considered necessary for continuous use on a flight-by-flight basis. Unexpected problems have been encountered; however, neither pilot nor flight vehicle safety has been compromised, by virtue of the incremental-performance philosophy of envelope-expansion testing.

Consider the implication of the X-15 experience in terms of the development of future systems. The use of available and proven systems and components in these systems would be desirable; however, future requirements may dictate radical and new concepts. The development of systems and techniques cannot be relied on during a long and carefully planned build-up flight test program in a prototype vehicle as in the X-15, because the tight scheduling and prohibitive cost of future programs are increasingly incompatible with this logic. In the development of new systems, it would appear that the best procedure is to carefully plan a coordinated program of ground simulator tests and supplementary flight demonstrations. Flight tests would be conducted using operational military aircraft and special test beds, and would be restricted to demonstration of systems or techniques, or both, for which ground tests cannot provide the proper environment. At least limited flight tests in the final vehicle--with some buildup to critical conditions, as in Project Mercury--are highly desirable. The absence of such planning virtually guarantees repeated program slippage, or worse, critical in-flight systems malfunctions.

Finally, the X-15 program has kept in proper perspective the role of the pilot in future programs of this nature. It has pointed the way to simplified operational concepts which should provide a high degree of redundancy and increased chance of success in future space missions. But, perhaps most important, is the fact that a sizable segment of industry and government engineers and scientists has had to face up to problems of designing and building hardware and making it

work. This has provided invaluable experience for the future aero-
nautical and space endeavors of this country.

Flight Research Center,
    National Aeronautics and Space Administration,
        Edwards, Calif., April 6, 1962.

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  Directional Control Characteristics of the X-15 Airplane. NASA
  TM X-726, 1962.
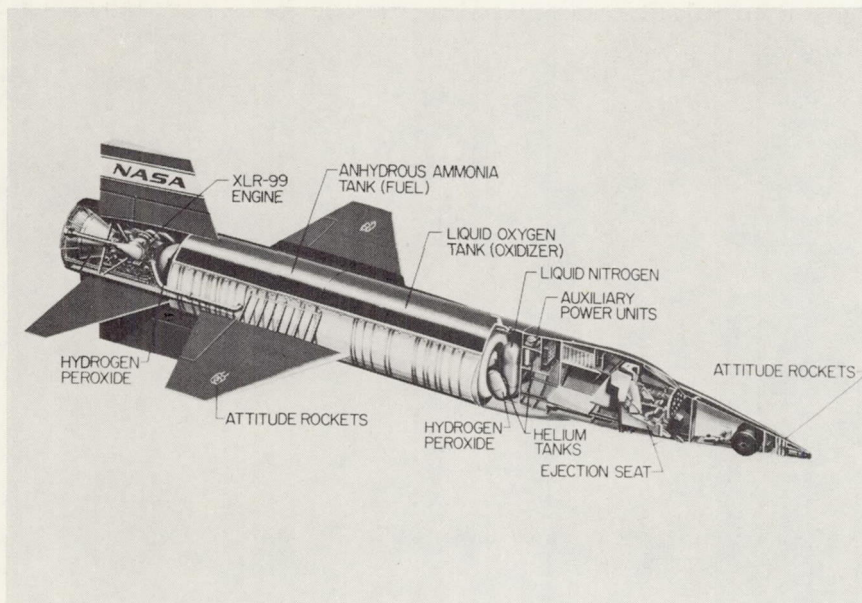
X-15 AIRPLANE

Figure 1

X-15 AIRPLANE CONFIGURATIONS
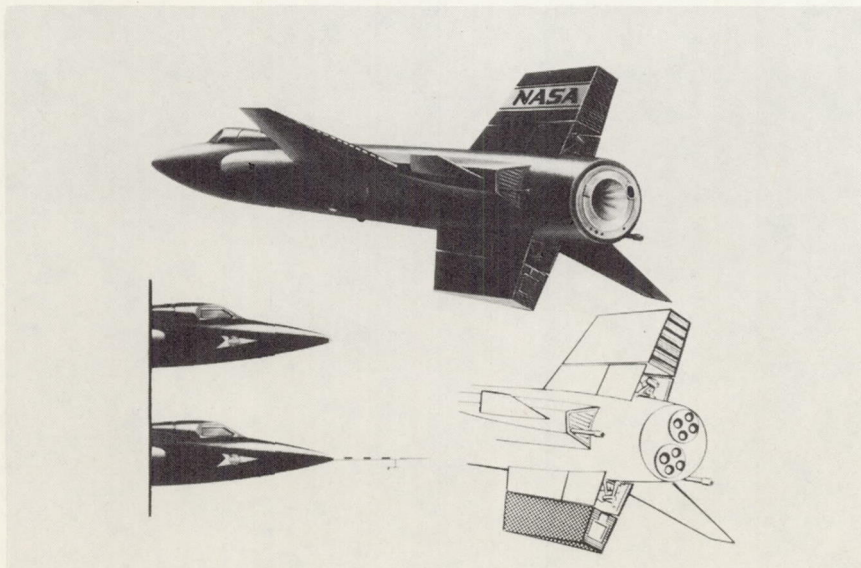
Figure 2

X-15 RESEARCH MISSION
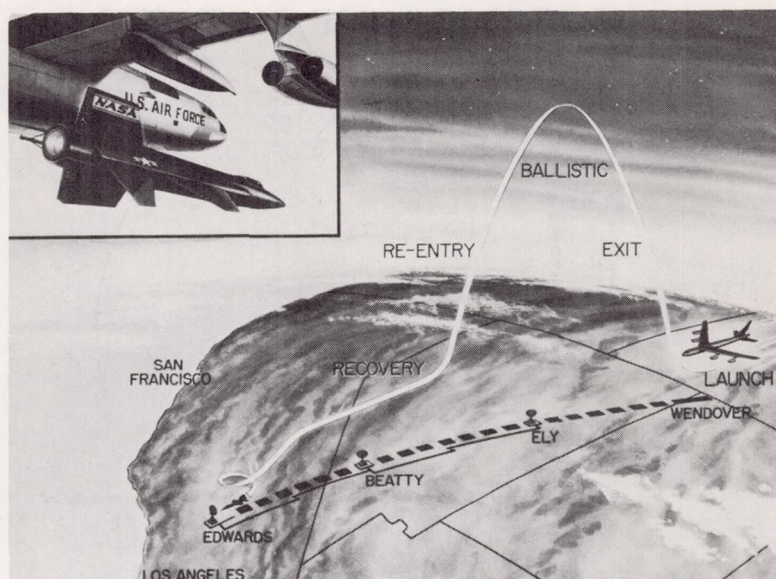
Figure 3

X-I5 FLIGHT PROGRESS
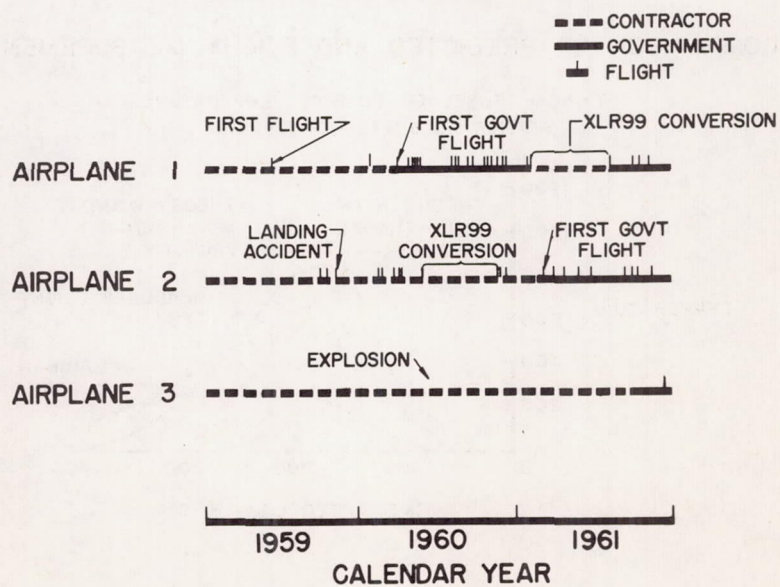
Figure 4

X-15 PERFORMANCE ENVELOPE
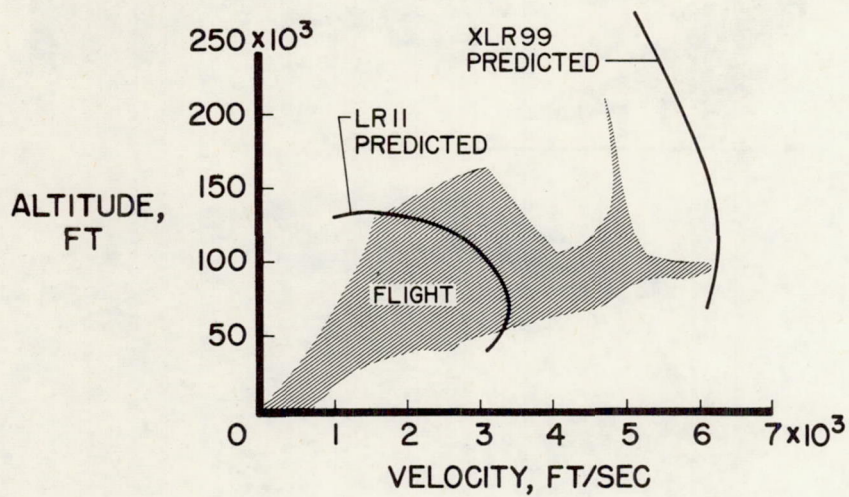
Figure 5

COMPARISON OF PREDICTED AND FLIGHT MEASUREMENTS

TYPICAL FUSELAGE SURFACE TEMPERATURE
STATION 26 BOTTOM CENTERLINE
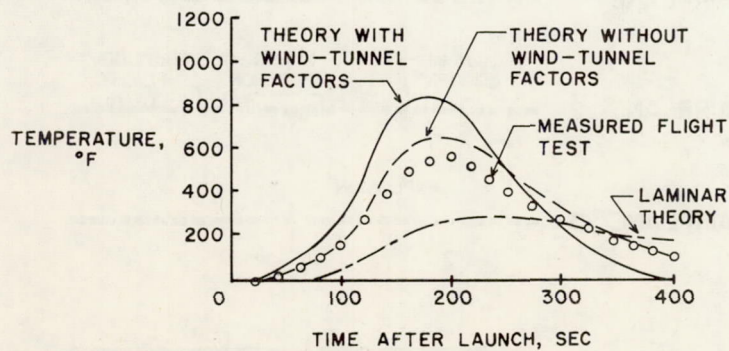
Figure 6

TYPICAL WING STRUCTURE
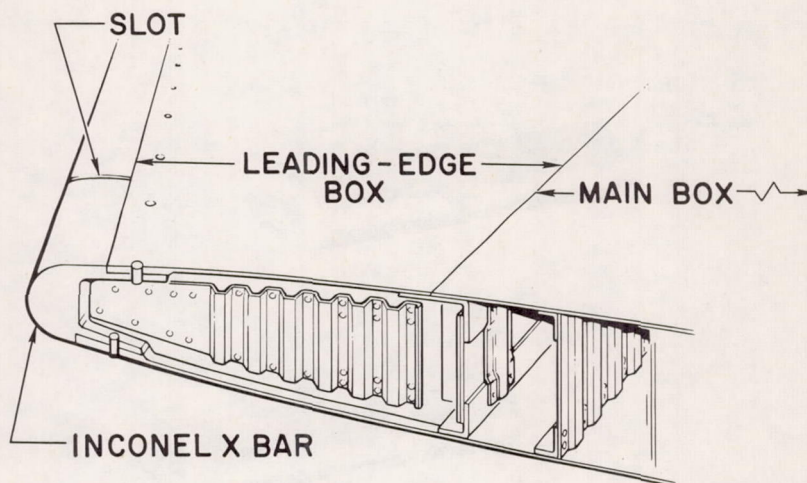
Figure 7

TEMPERATURE DISTRIBUTION REARWARD OF
LEADING-EDGE EXPANSION SLOT

Figure 8

WING SKIN BUCKLE FOLLOWING
FLIGHT TO M$_{MAX}$=5.28

ORIGINAL

$\frac{15}{16}$" 1$\frac{1}{2}$"

SKIN

SLOT

LEADING EDGE

MODIFIED

1$\frac{1}{2}$"
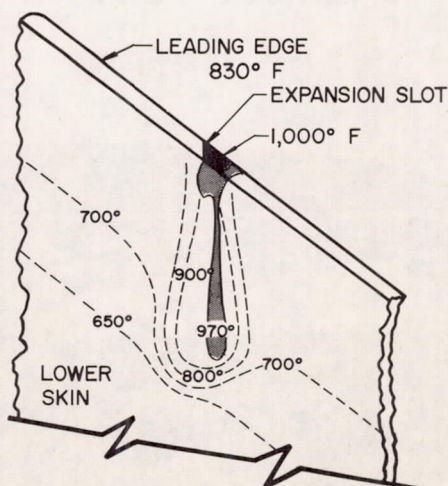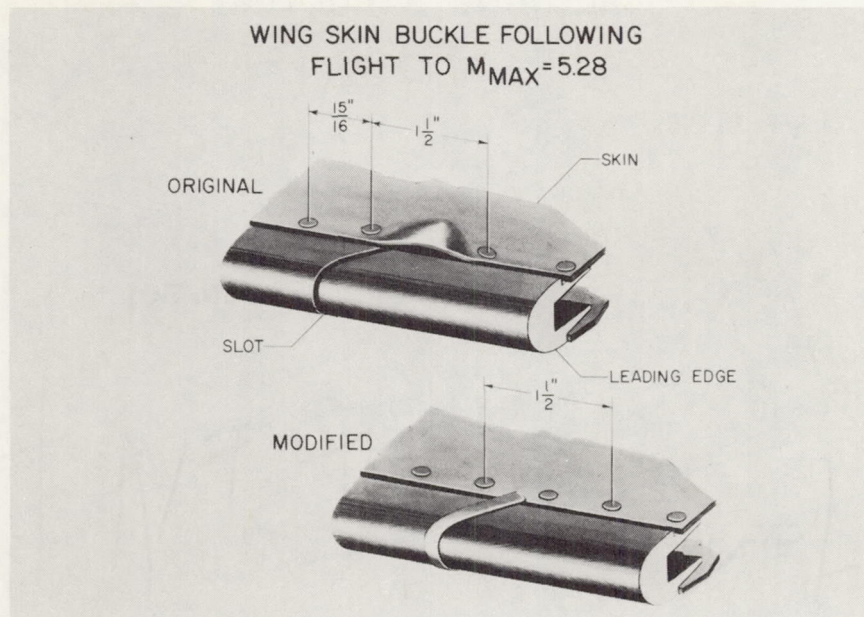
Figure 9

DAMAGED WINDSHIELD GLASS FOLLOWING
FLIGHT TO 217,000 FEET ALTITUDE
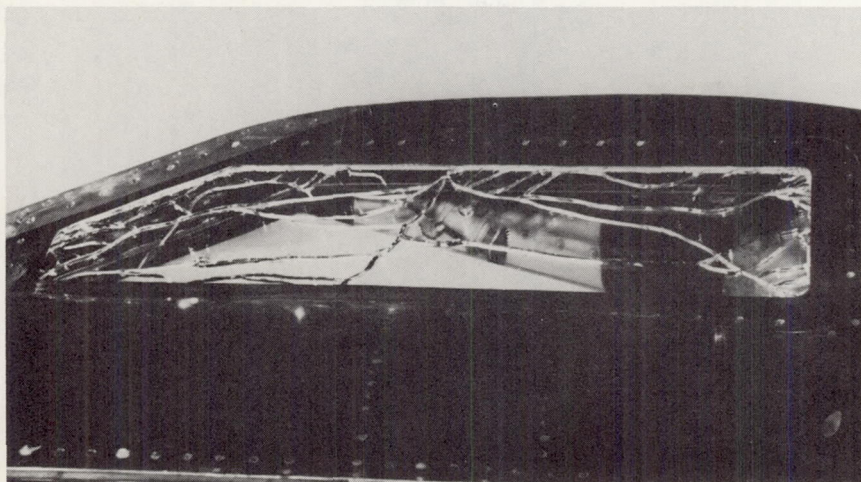
Figure 10

DAMAGED WINDSHIELD GLASS FOLLOWING
FLIGHT TO M_{MAX} = 6.04
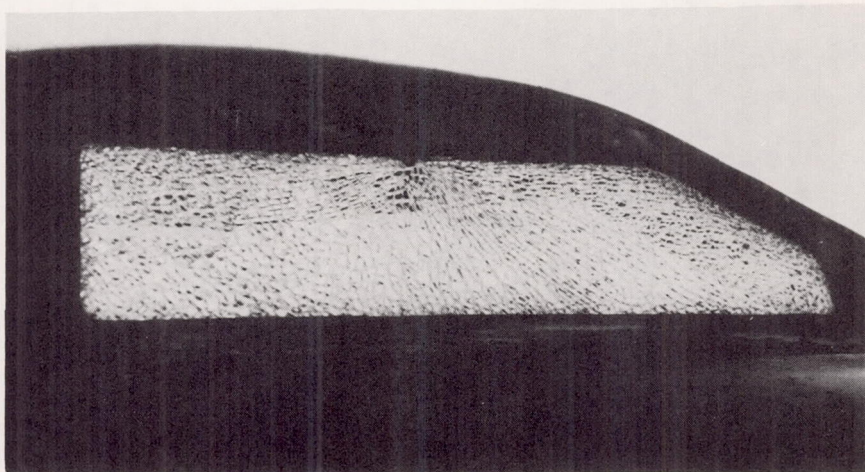
Figure 11

VERTICAL TAIL IN B-52 WING
CUTOUT
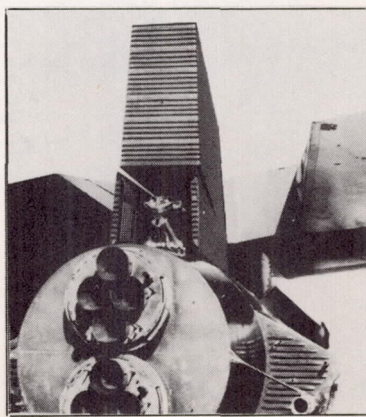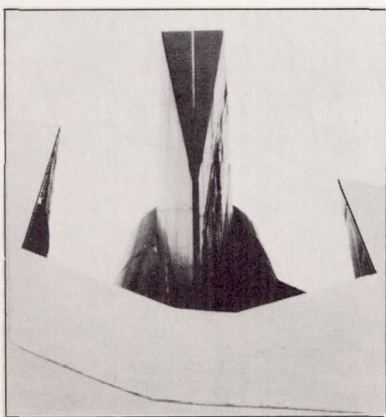
Figure 12

COMPONENTS DESIGNED BY FLUTTER CONSIDERATIONS
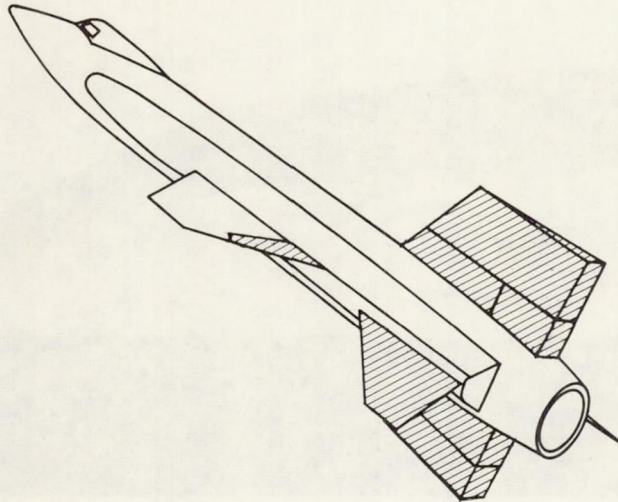
Figure 13

AREAS AFFECTED BY PANEL FLUTTER
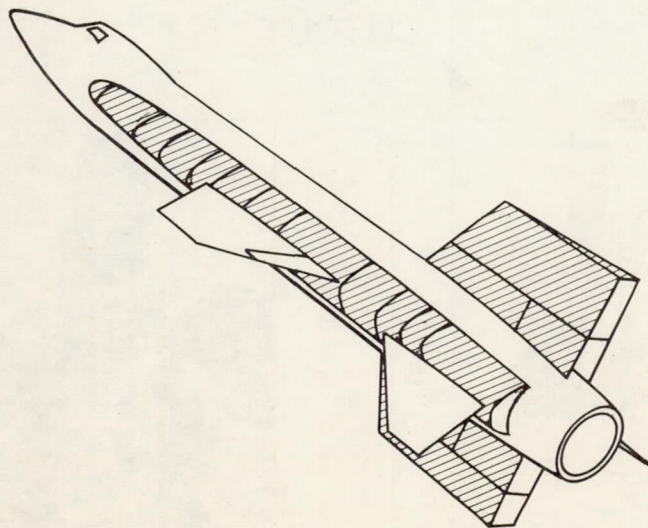
Figure 14

X-15 PANEL RESPONSE
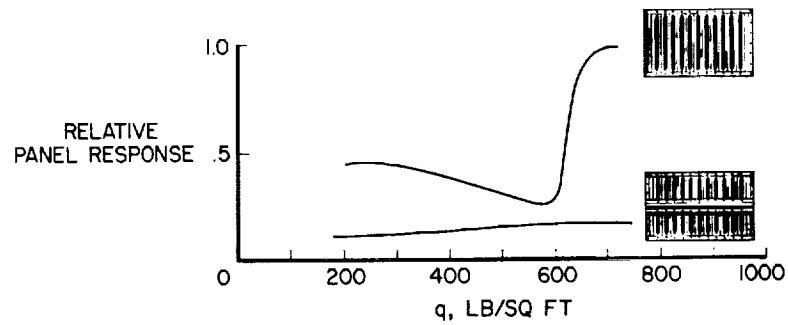
Figure 15

MAIN-GEAR SHOCK-STRUT FORCE AND TRAVEL
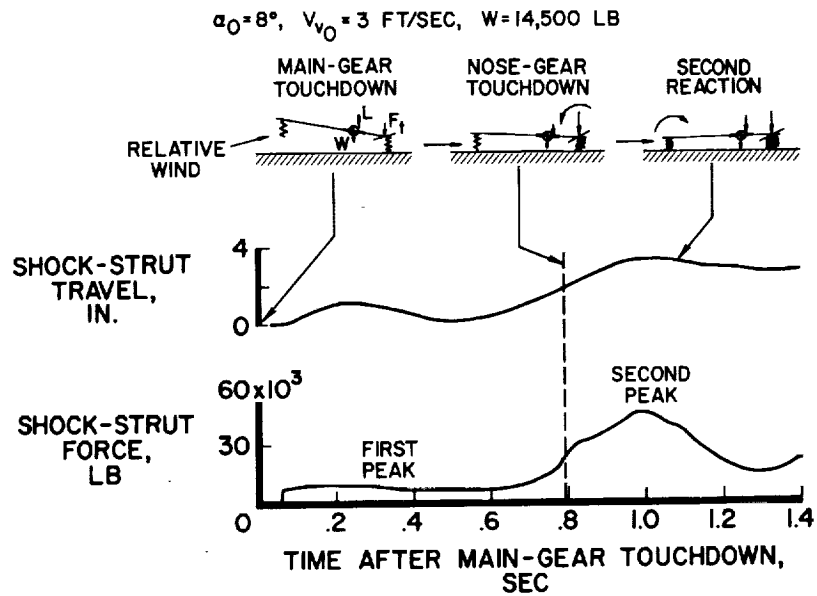
Figure 16

EFFECT OF MACH NUMBER ON THE TRIMMED
MAXIMUM LIFT-TO-DRAG RATIO
POWER OFF
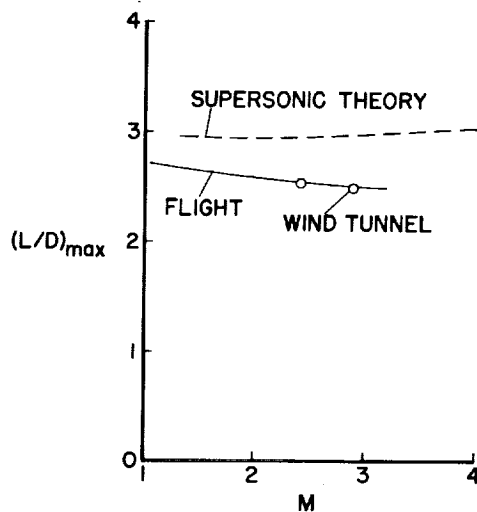
Figure 17

SUMMARY OF LONGITUDINAL STABILITY

o FLIGHT
— WIND TUNNEL
--- THEORY
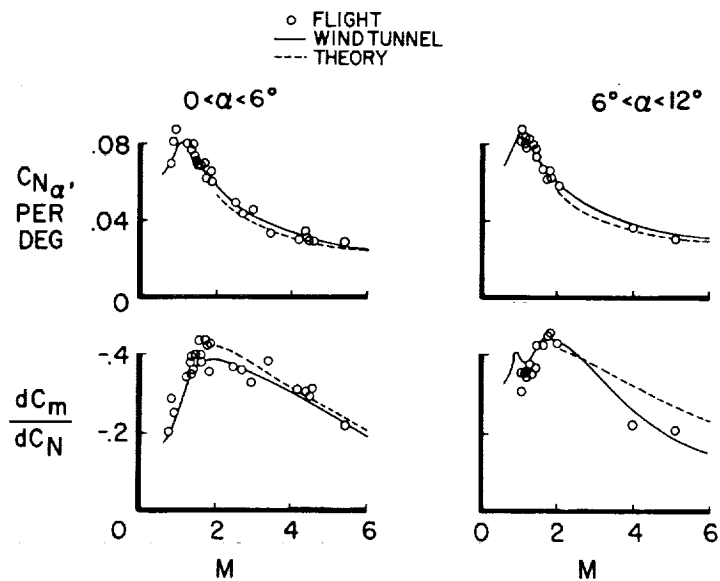
Figure 18

X-15 COCKPIT
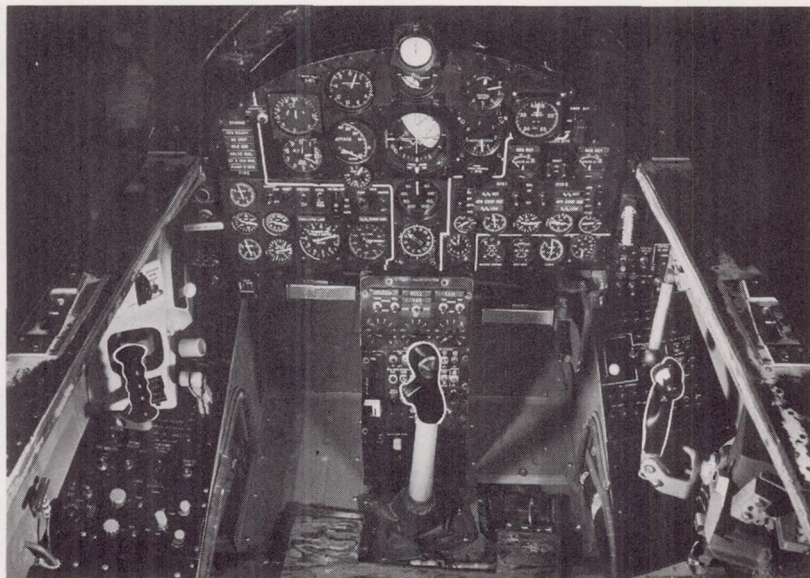
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REPRESENTATIVE ALTITUDE MISSION
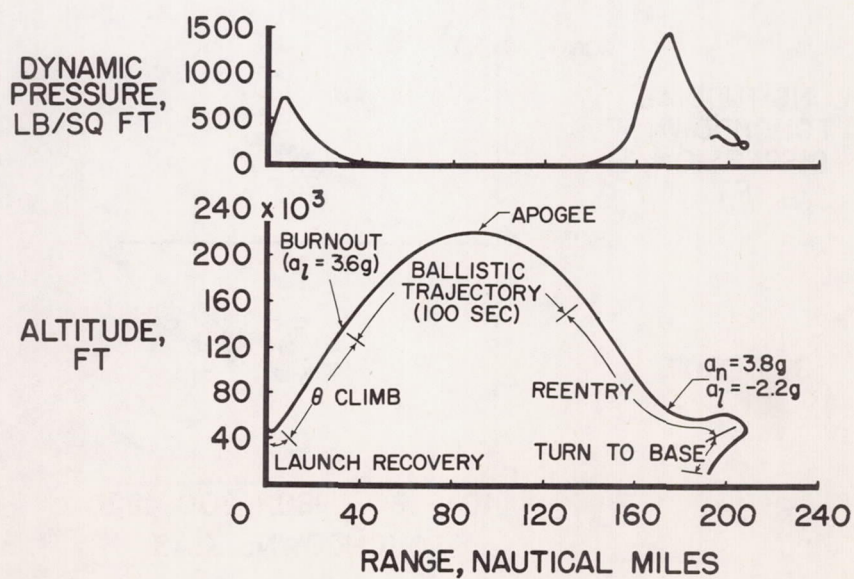
Figure 20

SUMMARY OF X-15 LANDING PATTERN

LATERAL DISTANCE
FROM TOUCHDOWN,
FT

TYPICAL APPROACH

RANGE OF FLIGHT DATA

ALTITUDE,
FT

LONGITUDINAL DISTANCE
FROM TOUCHDOWN, FT
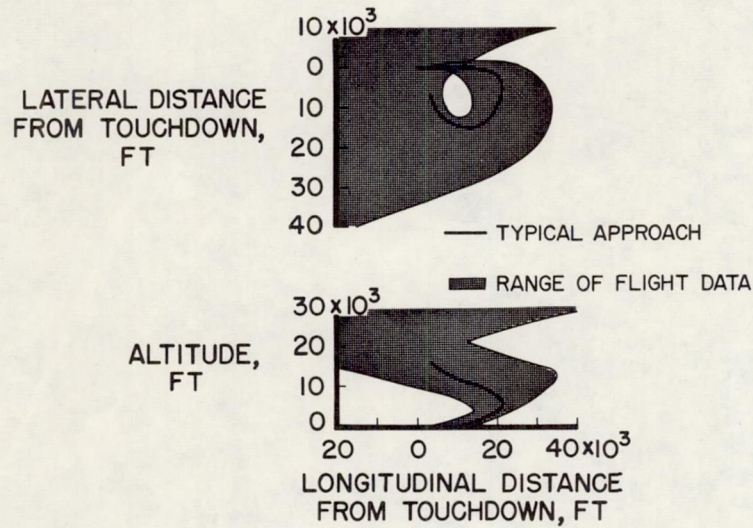
Figure 21

X-15 TOUCHDOWN AND SLIDEOUT DISTANCES

LONGITUDINAL
TOUCHDOWN
DISPERSION,
FT

LONG

SHORT

SLIDEOUT,
FT

TOUCHDOWN, KIAS
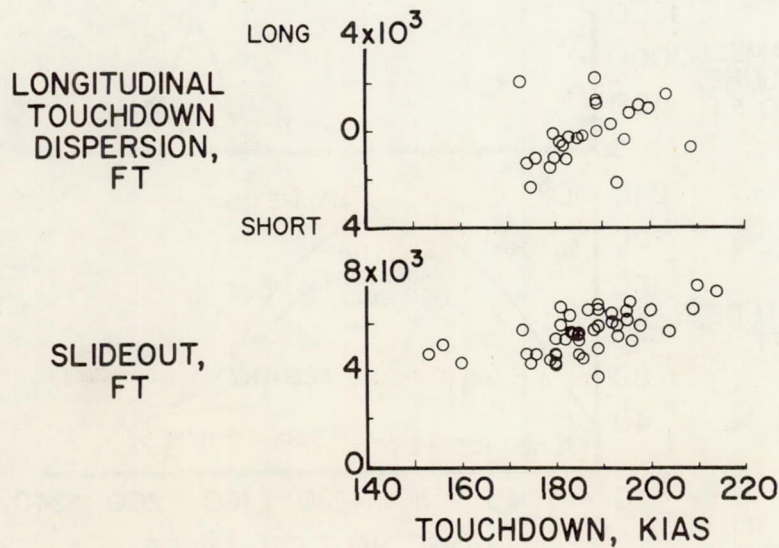
Figure 22

BASELINE HUMAN ENGINEERING DATA
AVERAGE FROM 8 X-15 FLIGHTS
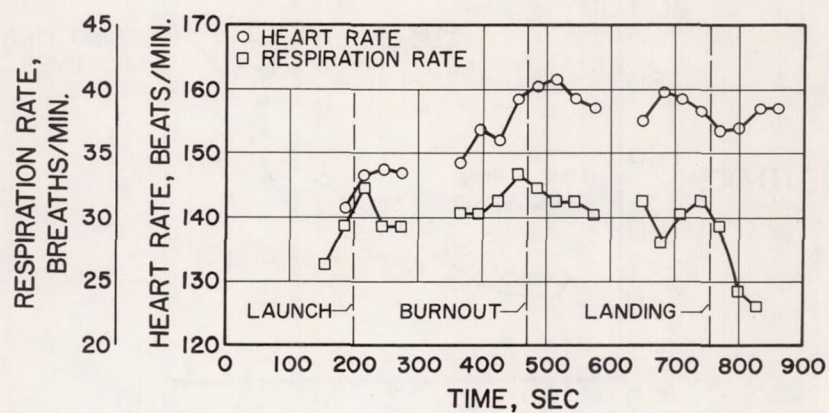
Figure 23

X-15 SIMULATION

Figure 24

48
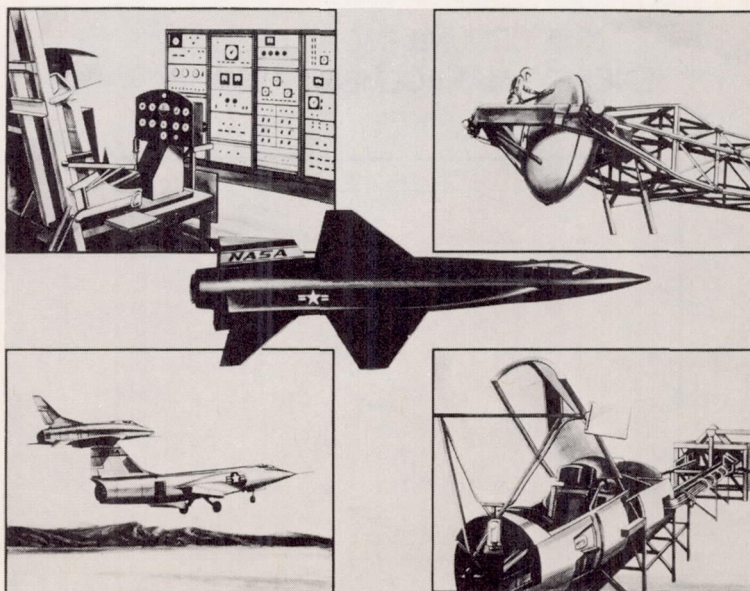
XLR99 ALTITUDE-MISSION PROFILE
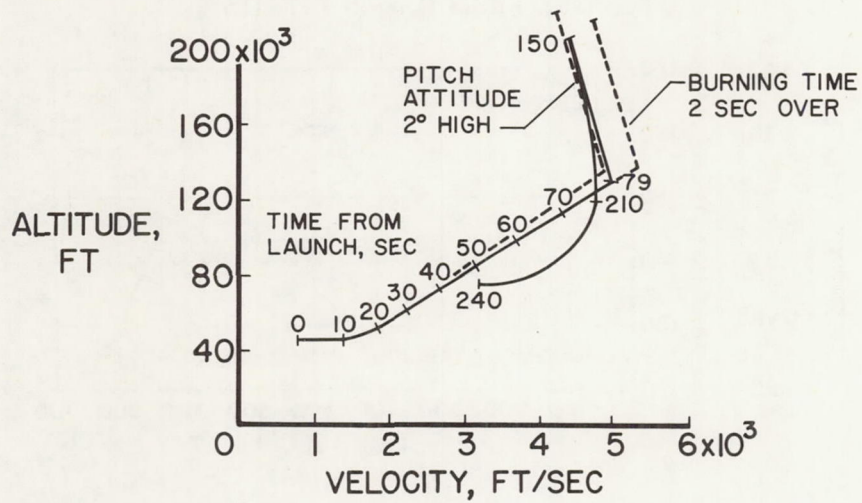
Figure 25

X-15 GROUND-MONITORED
ENERGY-MANAGEMENT DISPLAY
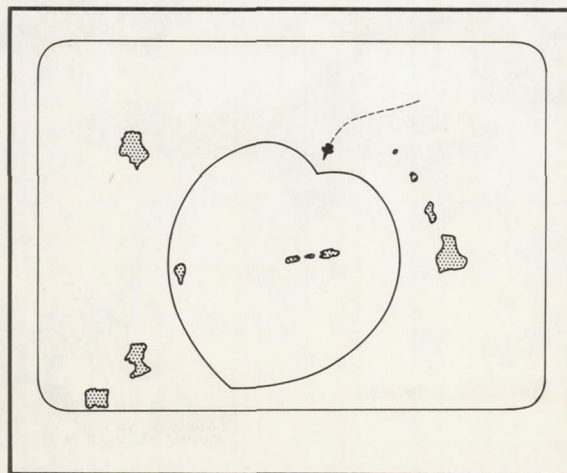
Figure 26

SPEED – FLIGHT PERFORMANCE COMPARISON
XLR99 ENGINE
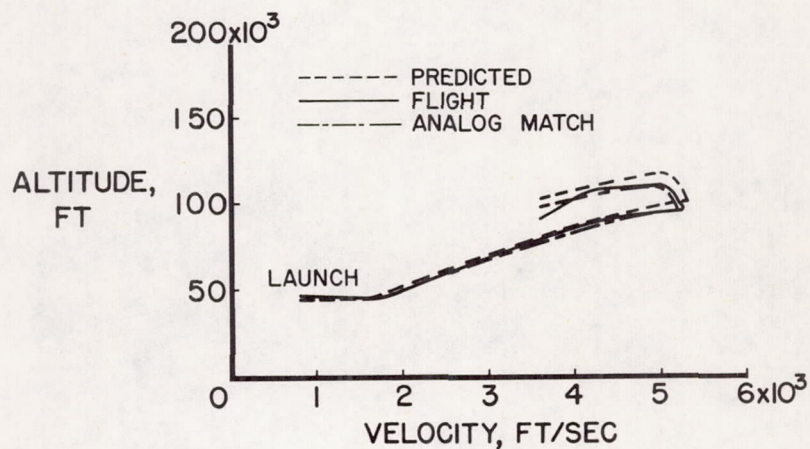
Figure 27

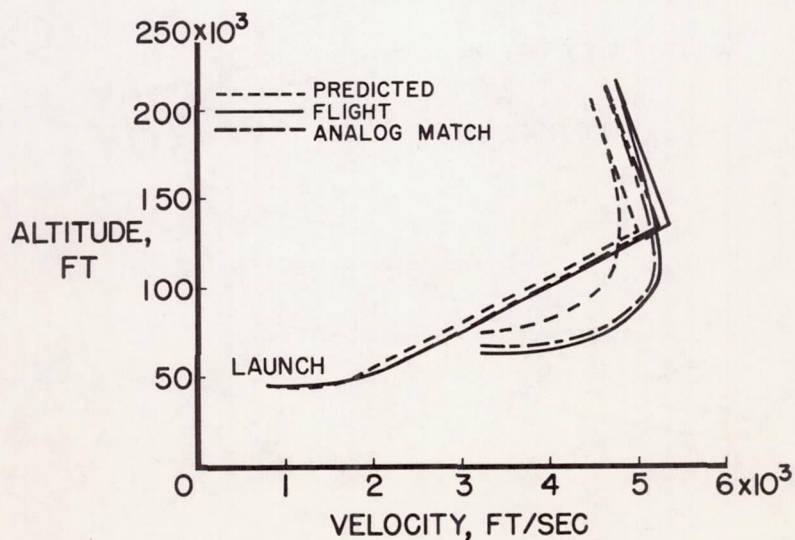## ALTITUDE – FLIGHT PERFORMANCE COMPARISON
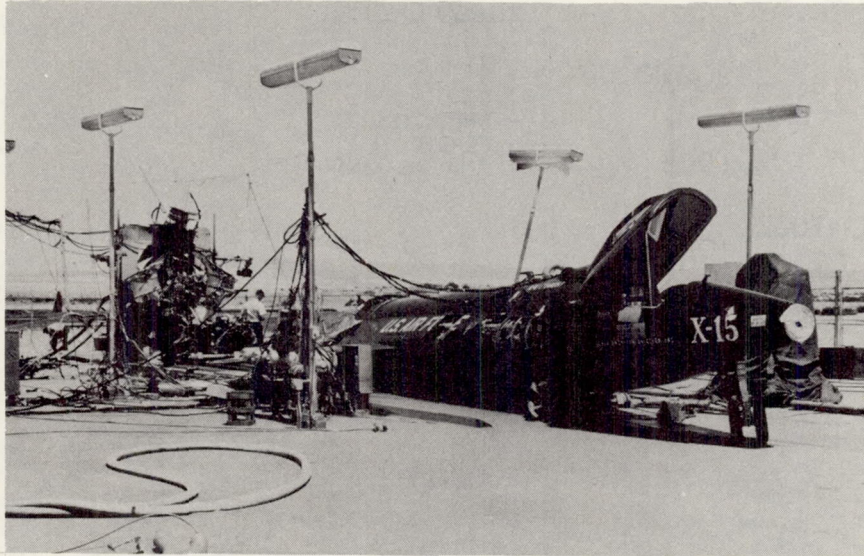### XLR99 ENGINE

Figure 28

X-15 EXPLOSION SCENE

Figure 29

AIRPLANE TEST-SITE
ENGINE RUN

WATER 4 FT DEEP
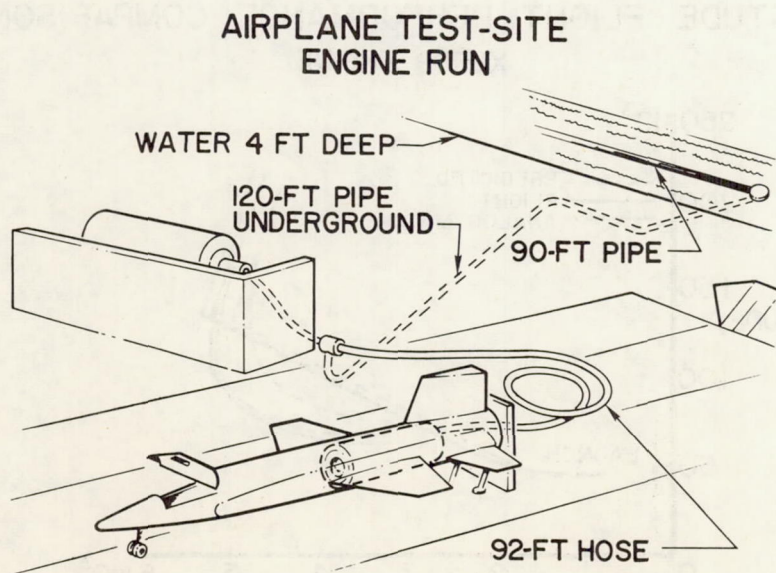
120-FT PIPE
UNDERGROUND

90-FT PIPE

92-FT HOSE

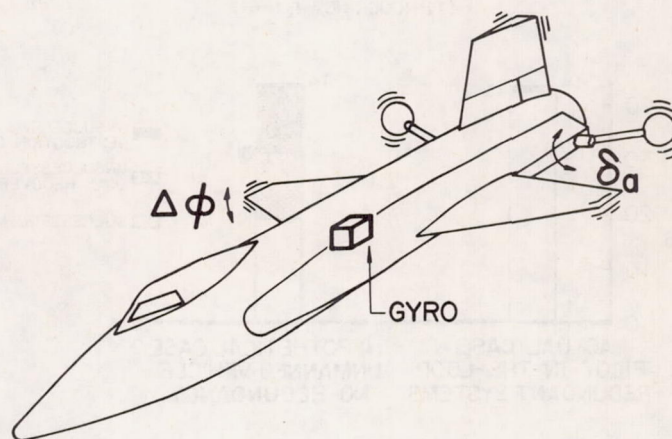Figure 30

MECHANISM OF VIBRATION

Figure 31
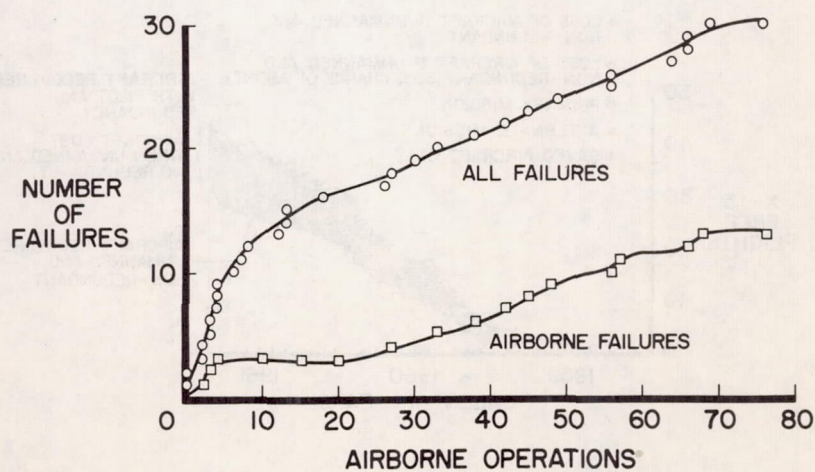
APU/BCR SYSTEM EXPERIENCE
vs
AIRBORNE OPERATIONS

Figure 32

OVERALL PILOT–IN–THE–LOOP AND REDUNDANCY BENEFITS
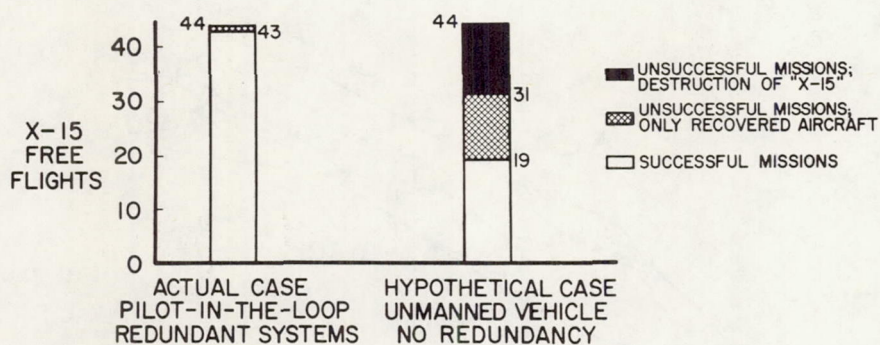
PRE–LAUNCH + POST–LAUNCH

(THROUGH NOV. 1, 1961)

ACTUAL CASE
PILOT–IN–THE–LOOP
REDUNDANT SYSTEMS

HYPOTHETICAL CASE
UNMANNED VEHICLE
NO REDUNDANCY

UNSUCCESSFUL MISSIONS;
DESTRUCTION OF "X–15"

UNSUCCESSFUL MISSIONS;
ONLY RECOVERED AIRCRAFT

SUCCESSFUL MISSIONS

Figure 33

X-15 FREE-FLIGHT RECORD OF SAFE AIRCRAFT RECOVERY

(PRE–LAUNCH + POST–LAUNCH)

◆ LOSS OF AIRCRAFT IF UNMANNED AND
NON–REDUNDANT

◇ LOSS OF AIRCRAFT IF UNMANNED AND
NON–REDUNDANT (50% CHANCE OF ABORT)

○ PRIMARY MISSION

● ALTERNATE MISSION

▲ SAVED AIRCRAFT ONLY

AIRCRAFT RECOVERED
WITH PILOT AND
REDUNDANCY

AIRCRAFT LOST
WHEN UNMANNED AND
NO REDUNDANCY

AIRCRAFT RECOVERED
UNMANNED AND
NON–REDUNDANT
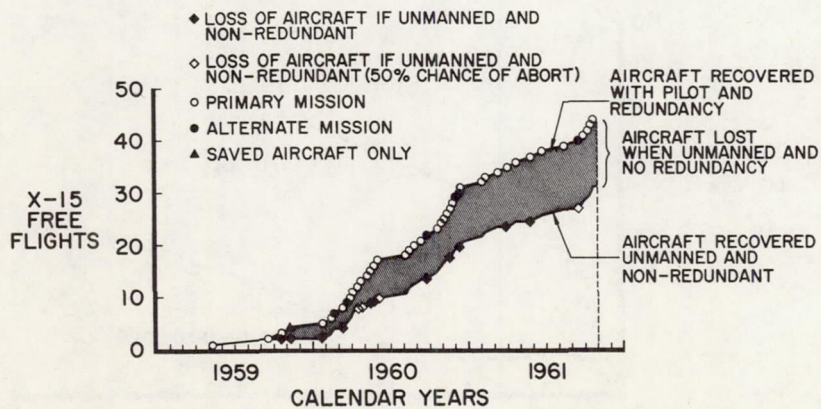
X–15
FREE
FLIGHTS

CALENDAR YEARS

Figure 34

X-15 INSTRUMENT-COMPARTMENT MODIFICATION
("SKYLIGHT")

Figure 35