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THE X-15 RESEARCH AIRCRAFT - [illegible]
RESEARCH ACCOMPLISHED AND PLANNED

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INTRODUCTION

The X-15 is often referred to as the most successful member of the series of research airplanes, beginning with the X-1--which was the first airplane to penetrate the so-called sonic barrier. Results of the X-15 research program have been far-reaching, and, after almost 5 years of flight testing, useful data continue to be produced and challenging extensions to the program are planned. Continuation of the flight research program at a time when major military and commercial airplane programs have been separated by years of low developmental activity undoubtedly has been an important factor in sustaining interest and in provoking ideas on the value and future of manned flight.

This paper is addressed to the implementation of X-15 flight tests, to the research results, and to the total value of the program. It can be considered as a sequel to the story of the conception and background of the X-15 project, prepared by John V. Becker of the NASA Langley Research Center and published in the previous issue of Astronautics and Aerospace Engineering.

Both the general public and members of the professional aerospace community have been generously provided with information on the progress of X-15 flight tests. Public news media have reported on many of the highlights, such as maximum speeds, velocities, and temperatures, methods for conducting flight operations, accidents and delays in the program, and on the pilot's comments following flights. A larger number of detailed technical papers on the

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relationships with many of the users of the information in the aerospace industry, government agencies, and universities.

DEVELOPMENT OF THE FLIGHT PROGRAM

The benefits of a research airplane program begin with the research performed to establish feasibility and preliminary design, and continue as a result of problems brought to light in the course of detailed design and fabrication. With regard to the latter items, the significance of the manufacturer's contribution (in this case, that of North American Aviation, Inc.) to the general technology cannot be stressed too highly. Unfortunately, space limitations do not permit a detailed treatment of this phase of the X-15 program in the present article.

Soon after a firm go-ahead had been established for the X-15 program, the team of research pilots destined to fly the aircraft was selected. Since the program was to be a joint venture between NASA, the manufacturer, the Air Force, and the Navy, pilot representatives of each of the organizations were named. NASA selected Joe Walker, Jack McKay, and Neil Armstrong, all experienced research pilots from its Flight Research Center staff. A. Scott Crossfield, who had earned wide recognition for his accomplishments in piloting the early rocket-powered research airplanes at the Flight Research Center, joined the staff of North American Aviation and was assigned as Company pilot for demonstration flights. Capt. (now Major) Robert White and Capt. (now Major) Robert Rushworth--succeeding Capt. Iven Kincheloe--were assigned by the Air Force, and Lt. Comdr. (now Commander) Forrest Petersen was assigned by the Navy. Figure 1 is an early photograph of the team of government pilots and the X-15 airplane.

All of the assigned pilots participated actively in the development phase of the program. They were called upon to evaluate various operational systems

From the beginning, plans called for approaching the design speed and altitude through a carefully monitored incremental-performance-buildup program. Because of the greater relative significance and cost of each flight in the program compared with tests of previous research vehicles, and in order to optimize each flight mission as much as possible, the six-degree-of-freedom X-15 fixed-base simulator has been used for flight planning and pilot training, as well as for development and checkout of selected hardware and concepts, throughout the flight program. The research instrumentation, in addition to providing information of general interest, has been used in connection with flight safety analyses. Originally, about 17 flights, aside from pilot checkout flights, were expected to be required to reach design conditions. The expected number of buildup flights was not far from the actual number used; however, intermediate progress deviated considerably from the plan, since, in the course of the program, observations sometimes indicated the need for extreme caution and at other times permitted larger increments than planned. In general, the philosophy of the flight planning has been to evaluate the characteristics of the vehicle and components in a noncritical environment prior to penetrating a possibly critical regime. The performance buildup afforded by this approach is shown by the summary of flight-by-flight progress, in terms of speed and altitude, provided in figure 3. The maximum speed achieved (4,104 mph or Mach 6.06) is about equal to the design value when adjusted for the airplane weight increase that occurred during development. The maximum altitude (354,200 ft) so far obtained is more than 100,000 feet higher than the design value. Though not shown in figure 3, it is of interest to note that skin temperatures as high as 1,323° F have been measured, whereas, the airplane was designed to withstand 1,200° F.

Measurements of stability and control parameters and of structural temperatures were especially pertinent to establishing flight safety during

1. Verification of predicted hypersonic aerodynamics, including heating rates.
2. Study of airplane structures in high-heating and loading environment.
3. Investigation of stability and control problems encountered while leaving and reentering the earth's atmosphere.
4. Investigation of problems associated with weightlessness.

The great quantity of engineering data that has resulted from the program and is applicable to the above objectives is not easily appreciated except by persons close to the program. Only a very brief summary can be included herein.

The Airplane

In the area of aerodynamics, problems resulting from the heat generated by high-speed flight were of most concern to designers at the time of the X-15 feasibility studies. Some concern also was expressed regarding the adequacy of wind-tunnel facilities and theoretical techniques for predicting hypersonic aerodynamic parameters, particularly at high angles of attack or in nonlinear ranges. Although previous research had established quite reliable aerodynamic-load design procedures for the low supersonic regime, it remained for the X-15 to verify the suggested techniques for the higher speed range. In general, such verification has been provided by the flight results, which show essential agreement of aerodynamic stability and control parameters, loads, and load distribution with the predicted characteristics. In the case of aerodynamic heating, however, the various proposed calculation procedures were not in good agreement, and wind-tunnel techniques had not been developed to the point that a preference for a given method could be clearly established. Since permissible structural weights required to withstand given thermodynamic conditions in the hypersonic range depend critically on heat transfer, it was clear that design. The flight results show, on the other hand, measured temperatures even slightly below the lower boundary. The rather large discrepancy between predicted and measured temperatures under turbulent-flow conditions has not yet been fully explained. The situation is under serious consideration however by heat transfer specialists, and basic research has been started in order to obtain clarification. The research consists of wind tunnel and analytical work, as well as additional flight experiments with the X-15. On the basis of the results shown in figure 4, the X-15 design would appear to be very conservative, and it might be supposed that the structural weight was much higher than necessary. Before arriving at such a conclusion, however, we should consider what has been learned of the reaction of the X-15 structure to its environment.

Maximum structural temperatures have been experienced during X-15 operation at high speeds and comparatively low altitudes, with accompanying normal-acceleration values which are much lower than those experienced during recovery from high altitudes. In the course of an altitude flight, the structure normally radiates a portion of its stored heat while in the very thin air at the top of the trajectory; consequently, although as much as 5g may be pulled during the reentry, the peak temperatures attained are somewhat lower than those encountered in speed missions. The combined heating and aerodynamic-loading environment so far imposed on the aircraft have caused no failures of primary structural components during flight. Also, as far as can be determined from the available internal instrumentation and from post-flight inspections using X-ray and other techniques, there is no evidence of excessive local stresses or incipient failures. Many types of failures that are considered to be of a superficial nature have occurred due to conditions of high local heating or dynamic pressure. These occurrences are illustrated in figure 5.

between the surfaces of the tanks, which contain very-low-temperature fuel and liquid oxygen, and the edges of the fairings, where the low thermal capacity permits the attainment of very high temperatures. A modification of the design of the side-fairing panels to allow for greater expansion of the material has greatly alleviated this problem. New skin buckles continue to appear, however, as the service life of the aircraft is extended. Although these occurrences do not present any particular hazard to the X-15, they deserve serious consideration by potential designers of high-performance service aircraft that may experience thousands of thermal cycles during their lifetime.

Skin buckling also has occurred near the wing leading edge in the vicinity of open expansion joints provided in the Inconel X leading-edge block. The buckling resulted in part from the fact that the expansion joints were not distributed with sufficient frequency along the span of the leading edge and also from the fact that the wing skin behind the open expansion joints was subjected to excessive local temperatures due to turbulence generated by the discontinuities at the leading edge. The problem was corrected by increasing the number of joints and by adding protective shields to avoid generation of vortex turbulence at the joints.

By way of assessment of the failures experienced, there appear to have been no cases in which the structure deteriorated to such a degree as to seriously endanger the integrity of the airplane. It is entirely probable, however, that had a less conservative design been followed the problems noted might have resulted in greater deterioration with more serious consequences. Certainly the flight results obtained have important applications in future aircraft in that they demonstrate the importance of looking critically at small details of the design to avoid unexpected local problems. When adequate of some concern initially; however, they have not been associated with any detectable physical deterioration or loss of ability to perform precise piloting tasks, at least over the short periods of time required for an X-15 flight. Though the measurements so far performed have been elementary, they have been timely in that they have been available for consideration in connection with the manned space program. A considerably more sophisticated biomedical instrumentation system is now under development by NASA and will be used in a later phase of the X-15 program.

As in other manned flight programs, X-15 experience again has shown that the man aboard serves as an extremely valuable sensor and recorder. Countless occurrences that could not possibly have been expected have been noted by the pilots and related to others in detail that could never have been matched by instrumentation. For example, repeated observation of faint wisps of smoke in the cockpit eventually revealed charring of electrical insulation due to slight leakage of hot boundary-layer air to the interior of the airplane. The notation of loud "oil canning" bangs has provided a valuable note to the reaction of the structure to rapidly changing thermal conditions. The pilot continues to prove his value as a system capable of adapting to unusual circumstances. Many flights have been performed during which some failure has been encountered in auxiliary systems or in the sensors required for the display of flight information. Thanks to the pilot's training and past experience, he has been able to assess the situation quickly and select alternate means for completing his mission safely.

It is true that at times the pilot responds incorrectly to the information provided, or he may be diverted from his task by an apparent problem. Also, it is clear that there are limitations to the amount of information he can assess simultaneously and to his time response. Thus, it is likely that

The damper-out controllability situation, as indicated by the studies, is summarized in figure 6. Combinations of angle of attack and Mach number falling in the shaded regions were expected to be accompanied by controllability problems ranging from difficult to impossible with the damping system failed. The conditions encountered in a typical reentry are shown by the curved lines on each part of the figure. It is evident that removal of the lower rudder results in essential elimination of the problem. Fortunately, this expedient proved entirely practical, since it was shown quite early in the flight program that thrust misalinement is negligible, and, therefore, no transients at engine shutdown have occurred. During the latter part of the program, all flights have been made with the lower rudder removed. The possibility of directional divergence due to low directional stability with lower rudder off is avoided by partial opening of the speed brakes at the higher Mach numbers.

In the course of the flight program, one of the three X-15 airplanes has been equipped with an adaptive control system, representing a substantial advance in the state of the art over the simple damping system used in the other airplanes. One of the many special features is a blending of aerodynamic and reaction controls into a single pilot's controller. Other features include the use of hold modes for automatically holding selected attitude angles and angles of attack, a g-limiting capability, and automatic force trimming. A comparison of the performance of the two systems during recoveries from two generally similar altitude flights is shown in figure 7. An improvement in controllability with the adaptive system is indicated by the fact that airplane motions are of smaller amplitude and are less erratic than for the older simple damper system. Pilots generally favor the adaptive system, and, consequently, the adaptive-control airplane has been used in all recent extreme-altitude missions.

Although the behavior of the X-15 airplanes during landing is considerably different from previous airplanes, because of low values of lift-drag ratio and an unconventional landing-gear design, the pilots have achieved a record for precise landings that is considered to be remarkable. During most operations, engine thrust is available for less than one-third of the total flight distance, with the remaining two-thirds of the distance, or up to 200 miles, accomplished in a power-off glide. Differences in details of the operation result in considerable variations in the energy and direction of the aircraft while approaching the landing field. Nevertheless, pilots have achieved touchdown points surprisingly close to a target provided on the lakebed. During the past 2 years, approximately 70 percent of the landings have been within 1,000 feet of a smoke marker provided as a touchdown target point.

Vertical velocities at touchdown also are maintained consistently at about the same levels expected in routine military operations. Figure 9, which presents the vertical velocities and gear loads experienced at X-15 touchdown, shows an average sink rate of approximately 4 fps occurring at an average airspeed of about 188 knots. No significant effect of pilot experience with the X-15 is evident in these results--probably because of the satisfactory X-15 landing simulation provided in F-104 aircraft prior to each X-15 flight. Inasmuch as main-gear loads have approached the ultimate limit during several landings, methods recently have been devised to alleviate this condition. By automatically disengaging the stability augmentation system at the instant of main-gear touchdown and by reducing pilot inputs after main-gear touchdown, horizontal-tail deflections have been reduced, thereby reducing tail downloads which are transferred to the gear. The resultant decrease in main-gear loads associated with the use of these methods is apparent from the levels of the solid square symbols in figure 9.

An illustration of the use of the aircraft to perform the ultraviolet stellar-photography experiment, which will supplement the NASA astronomy program, is shown as figure 10. Doors located at the top of the instrument compartment are opened at high altitude to expose a cluster of telescopic cameras. The cameras are directed on a selected area of the sky and are controlled within required limits by means of a gyro-stabilized platform located beneath the cameras. The pilot is required to maintain the attitude of the airplane within angular displacements of about 5° for each of the three axes. As the airplane falls back into the denser air, the compartment doors are again closed. Experiments of the type listed in the table, though generally performed only incidentally to other mission objectives, constitute an important addition to the basic program. It is likely that such work will continue to be performed as long as X-15 airplanes are flown.

ASSESSMENT AND FUTURE PLANS

The contributions of the X-15 program to the technology of flight are in some respects specific and tangible; however, in other respects the contributions are of such breadth that they are not easily described. Certainly, the results obtained in hypersonic aerodynamics, structures, and handling qualities already are being applied and have been valuable in establishing the confidence with which future designs can be carried out. Also, at a time when the usefulness of the man in high-performance flight vehicles was being questioned, the X-15 program effectively demonstrated the value, not only of having a man onboard, but also of using him as an active participant in the flight mission. Lessons also were learned about the design of control systems and of other piloting aids provided to derive the most benefit from the pilot's unique capabilities. Repeated successful operations of a vehicle capable of encountering many of the critical conditions expected during boost and recovery of propulsion systems. In-flight techniques probably will have to be relied upon in the development of full-scale hypersonic air-breathing engines because of practical problems of providing adequate ground test facilities.

Plans are underway to extend the scope of the program in several areas. For example, a series of boundary-layer experiments is planned to study conditions resulting in transition from laminar to turbulent flow and to measure the skin-friction coefficient. Smooth, rough, and wavy surfaces will be studied over wide ranges of Mach number, dynamic pressure, and heat transfer. Tests of various ablative materials to maintain relatively low skin and structural temperatures in regions of high heating also are planned.

Preparations are being made to perform tests of advanced structural panels at the locations shown in figure 12. The airplane now being modified will have provision for detaching a portion of one wing tip so that instrumentation can be provided to study in detail the reaction of the tip structure to its environment. Also, alternate tips, using different materials as well as construction methods, will be investigated. Studies of various leading-edge concepts and of the dynamic response of structural panels will be conducted on the jettisonable lower rudder.

Other studies are planned of advanced pilot displays and guidance concepts, for use in specific flight regimes, such as the boost-climb or reentry, during complete trajectory missions, and for general research into the optimum techniques for control of a hypersonic vehicle to specific predetermined conditions. Investigations also are planned in the area of hypersonic handling characteristics in order to obtain an improved understanding of the various parameters affecting the flight behavior.

In consideration of present thoughts on future aeronautical developments, a continuing desire to increase the speed of transportation in the air is anticipated. Consequently, flight research in environmental conditions beyond

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X-15 AND ASSIGNED GOVERNMENT PILOTS

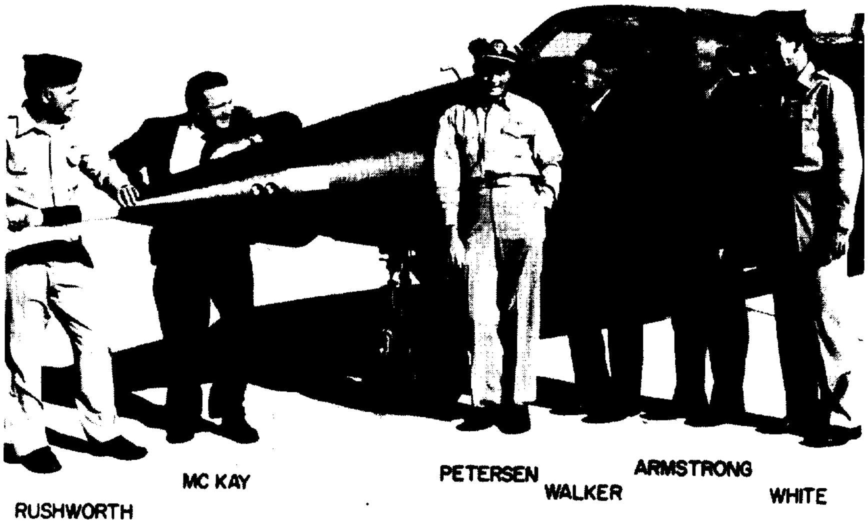


Figure 1

X-15 RESEARCH AND SYSTEMS SENSORS

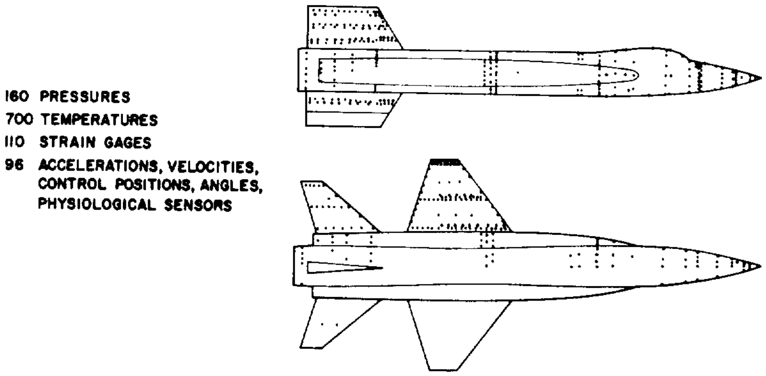


Figure 2

X-15 STRUCTURAL PROBLEMS

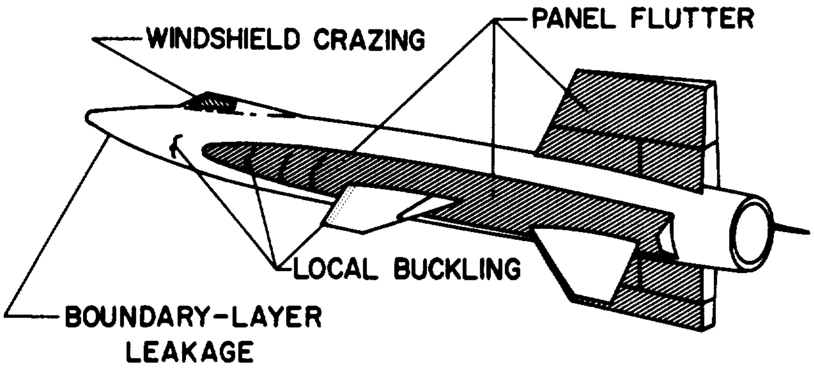
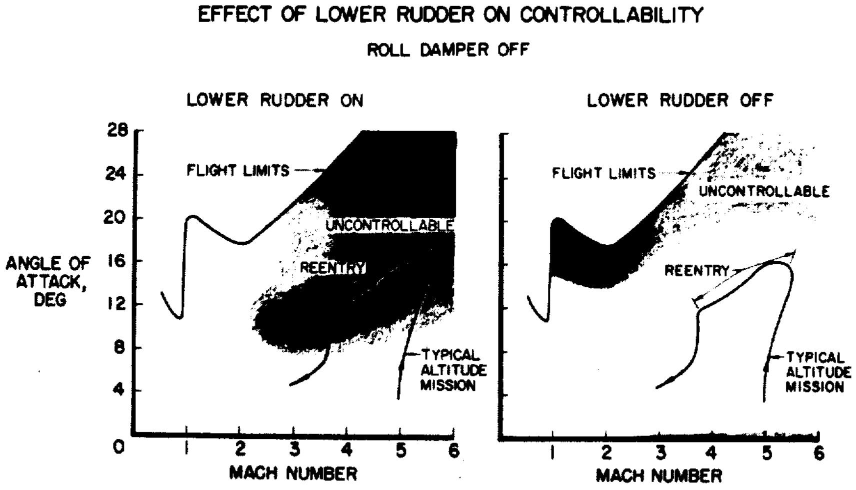


Figure 5


EFFECT OF LOWER RUDDER ON CONTROLLABILITY

ROLL DAMPER OFF

LOWER RUDDER ON

LOWER RUDDER OFF

Figure 6

TOUCHDOWN CHARACTERISTICS

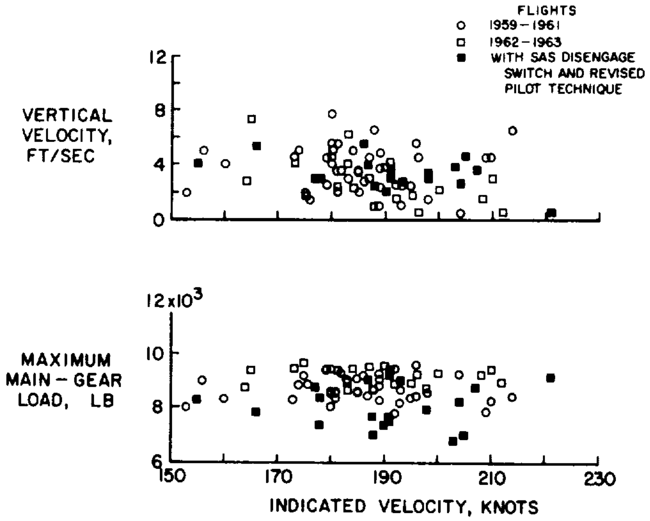


Figure 9

STELLAR-PHOTOGRAPHY EXPERIMENT

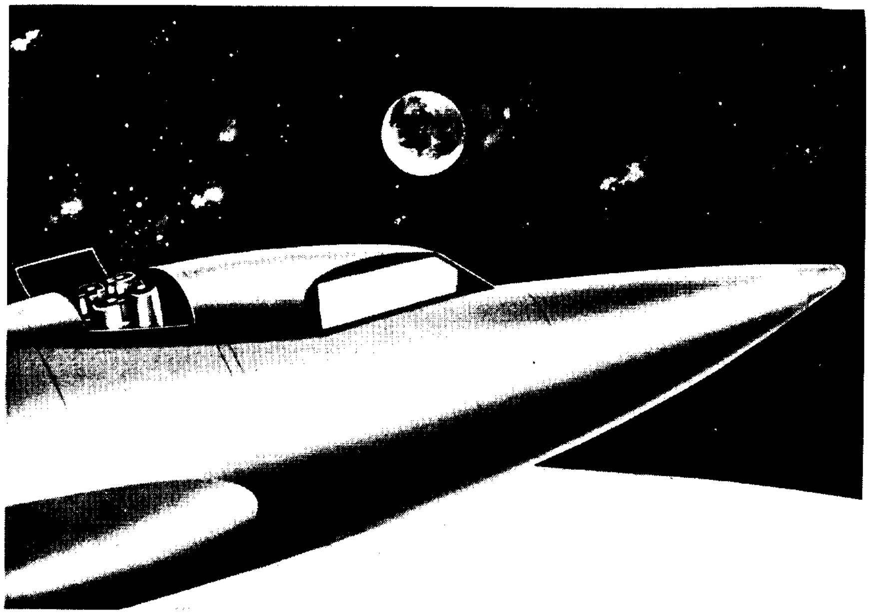


Figure 10