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MISSION PLANNING AND OPERATIONAL PROCEDURES FOR THE

X-15 AIRPLANE

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SUMMARY

The expansion of the X-15 flight envelope is being accomplished according to a planned program. All predictions of stability, perform-ance, and flight trajectories have been within expected accuracies. General piloting techniques, pilot-training procedures, and emergency procedures which were developed primarily through the use of an analog simulator have proven to be satisfactory. Ground-monitor functions have been of value in assisting the B-52 and X-15 pilots in the safe conduct of flights. Unexpected problem areas have been encountered; however, neither pilot nor vehicle safety has been compromised because of the incremental-performance philosophy of envelope-expansion testing.

INTRODUCTION

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 one flight to the next and also building a backlog of pilot experience.

The mission planning and operational procedures associated with the program are discussed in this paper. The effect on flight planning of systems reliability, stability limitations, and ranging considerations are also discussed. General piloting techniques and pilot training are described.

SYMBOLS

g acceleration due to gravity, ft/sec^2

n_z normal-load factor, g

R range potential to high key

t time, sec

x distance along High Range centerline, nautical miles

y distance perpendicular to High Range centerline, nautical miles

α angle of attack, deg

β angle of sideslip, deg

δ_h horizontal-stabilizer position, deg

θ angle of pitch, deg

ψ airplane heading angle, deg

A dot over a symbol represents the derivative of the quantity with respect to time.

DISCUSSION

Preliminary Studies

Many tools are used to perform the flight-planning and pilot-training task for the X-15 program. The prime tool is a six-degree-of-freedom analog simulator shown in figure 1. This simulator was constructed by North American Aviation, Inc., during the design and development stage of the X-15 program and was subsequently transferred to the NASA Flight Research Center, Edwards, Calif., for use during the flight-test program. This simulator is relatively complete, including actual hydraulic and control-system hardware. Another primary pilot-training tool has been the F-104 airplane 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 airplanes have also been available during the test program.

One factor which had a significant effect on flight planning was the development status and demonstrated reliability of the subsystems on the X-15 airplane. Lack of duality in the stability-augmentation system required that flights be performed in such a manner as to provide

for the safe return of the pilot and the aircraft in the event of a
stability-augmentation malfunction. Inasmuch as the flow-direction
sensor, reaction control system, and inertial-platform system were
newly developed for the X-15 airplane, they could not be used as primary
flight instruments until reliability had been demonstrated.

Two flight-envelope-expansion programs, one with the LR11 engines
and the other with the XLR99 engine, were to be performed. The
predicted flight envelope for the two configurations is shown in
figure 2. A maximum velocity of about 3,300 ft/sec and a maximum
altitude of 133,000 feet were predicted for the LR11 powered configuration.
A maximum velocity of slightly over 6,000 ft/sec was predicted for the
XLR99 powered configuration. Although the performance capability exceeds
the design altitude of 250,000 feet, this altitude was chosen as an
objective for completing the envelope-expansion program.

Prior to the delivery of the X-15 airplane, a general handling-
qualities study was performed on the X-15 analog simulator. The
results of this study are summarized in figure 3. The crosshatching
represents areas of instability. Flight in these areas was predicted
to be uncontrollable with or without the stability-augmentation system.
The shaded area represents a region of predicted uncontrollability with
the stability-augmentation system (SAS) off. This controllability
problem is discussed in detail in references 1 and 2. Considerable
flight-planning effort was expended to insure that these areas could
be avoided or investigated under controlled conditions on all flights.

Before the first cross-country flight of the X-15 airplane could be
attempted, it was recognized that intermediate emergency lakes must be
provided so that the pilot was always within gliding range of a landing
site. A study was then performed, again on the analog simulator, to
determine the overall range capabilities of the airplane. A simultaneous
survey was conducted to locate all of the usable dry lakes in the area
north and east of Edwards Air Force Base along the High Range, which
consists of three radar sites distributed over a 400-nautical-mile course.
A summary of this study for the XLR99 powered configuration is shown in
figure 4. Burning time is plotted against distance from the launch
point. The solid curve represents the position of the airplane at any
time during the powered portion of the flight. The dashed curve on the
right represents the maximum forward-range potential of the airplane at
any instant to a high-key altitude of 20,000 feet. The dashed curve on
the left represents the maximum rearward-range capability after a 180°
turn is performed, again to an altitude of 20,000 feet. For example,
for a premature shutdown at 55 seconds the airplane is at the point
shown in the example plan view and can perform a turn to arrive at a
point 30 miles from launch or can glide straight ahead to a point
160 miles from launch; however, the airplane cannot land at the lake
over which it is flying at that instant. The usable emergency dry lakes

were then spotted along the abscissa, and lakes were selected which provided overlap throughout the entire flight. The general shape of these curves changes somewhat depending on the type of flight profile flown; however, the general spacing of the emergency lakes is not greatly affected. For the LR11 powered configuration the range potential increases much more slowly than for the XLR99 powered configuration, and closer spacing of emergency lakes was required. The launch lakes selected and intermediate emergency sites are shown in figure 5. All flights with the LR11 engine could be made either in the local area around Rogers Dry Lake or from the Silver Lake launch site. Envelope-expansion flights with the XLR99 engine could be flown from Silver, Hidden Hills, and Mud dry lakes. After the lakes had been selected, the right to use the lakes was acquired, and runway outlines were marked on the surface of each lakebed.

Piloting Techniques

Once the predicted performance, ranging, and handling qualities of the airplane were well understood, the task of defining the piloting techniques required to reach the performance objectives was undertaken. The intent was to make the best possible use of the pilot's presentation and to depend heavily on the most reliable information in the cockpit, using the less dependable indications for cross checks during the flight or as backup information in the event of failure of a prime system. The analog simulator was invaluable in determining optimum piloting techniques. During most of the program with the LR11 engine, the airplane was equipped with a standard nose boom which provided accurate values of angle of attack, airspeed, and pressure altitude to the pilot. Piloting techniques were based on these parameters, and the resulting flight profiles were much like those of previous research airplanes, such as the X-2. The flow-direction sensor was installed for the XLR99 powered flights, and the sole source of velocity and altitude information to the pilot was then from the inertial platform. It was believed that the reliability of these indications from the inertial platform had not been adequately demonstrated to allow them to be used as prime instruments. Therefore, engine burning time was reverted to as the prime reference during the powered portion of the flights with the XLR99 engine.

A typical XLR99 altitude mission is shown in figure 6. The technique and pilot cues which have been devised to accomplish this mission are discussed in this section. Immediately after launch the pilot rotates to an angle of attack of 10°, lights the engine, and throttles immediately to 100-percent thrust. The angle-of-attack indicator as shown in figure 7 is the primary instrument used during this roundout; however, a successful roundout can also be accomplished by using either the accelerometer or the stabilizer-position indicator

on the trim knob. The angle of attack of 10° is maintained until the desired exit pitch angle θ of the airplane is reached (32° for the flight shown). This occurs approximately 28 seconds after engine start. A pitch null vernier on the three-axis attitude ball allows the pilot to preselect the desired pitch angle and fly it precisely during the exit phase. The pilot then maintains a constant pitch attitude until the engine-shutdown time is reached.

At the extreme pitch angles required the pilot cannot see the horizon and, therefore, must rely on the attitude indicator to maintain proper heading and to keep wings level, as well as to maintain the desired exit pitch angle. A stop watch has been installed in the cockpit which is actuated by the main propellant valves to indicate engine burning time to the pilot and is used to initiate the engine shutdown. Obviously, a constant throttle setting must be used with this technique. The inertial-platform-system indications of velocity and altitude provide additional cues to the pilot during the powered portion of the flight, as do radar altitude and time communications from the ground. The engine shutdown time and exit pitch angle are the two performance items over which the pilot has the most effective control during powered flight. These two parameters are adjusted during the planning phase to attain the desired peak altitude yet still complete the entry within a nominal range which corresponds to one of the launch and emergency lake complexes (fig. 5). After engine shutdown the stabilizer is trimmed to zero and the reaction control system is used to control the vehicle over the top. The prime cues used by the pilot during this portion of the flight are the attitudes from the three-axis ball and the angle-of-attack α and angle-of-sideslip β cross pointers which are displayed on the same indicator. The entry conditions are established by trimming the stabilizer position to the desired value as indicated on the trim knob and then by using the reaction control system to set up the desired angle of attack on the angle-of-attack gage. This angle of attack is maintained until the normal acceleration n_z reaches 4.0g, and the remainder of the pull-up to level flight is performed at 4.0g with the accelerometer as the prime indicator.

A typical speed flight is shown by the dashed curves of figure 6. The initial rotation and climb is performed in the same manner as the altitude profile. After 39 seconds of burning, the pilot pushes over to 0g and maintains 0g until the shutdown time is reached. After engine shutdown a rudder pulse is usually performed at low angle of attack followed by subsequent data maneuvers at increasing angles of attack in order to obtain stability and control data for the complete envelope. The angle-of-attack indicator is generally used to establish the trim conditions for these data maneuvers; however, the stabilizer-position indicator can also be used. All speed-buildup flights have been flown along the same general powered flight profile, with higher peak velocities being obtained by either extending the engine burning time

slightly or extending the speed brakes prior to shutdown. This greatly simplifies the temperature-prediction technique, since direct extrapolation of flight-test data is possible from one flight to the next.

The pressure instruments (pressure-altitude, airspeed, and Mach number indicators) are used only after the airplane is subsonic to perform the landing pattern and the landing.

Pilot Training

Before each X-15 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, 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. 8). Variations in engine thrust or engine-shutdown time are simulated. For example, an error in total impulse of 120,000 lb-sec, which can result from either a 2-second error in burning time or a 1,500-pound error in average thrust, will result in a difference in peak altitude of approximately 10,000 feet. An error in pitch angle of 2° during the exit phase will result in a peak altitude difference of approximately 12,000 feet. A reduction in angle of attack of 1° or 2° during the roundout increases the average dynamic pressure during powered flight and, therefore, reduces the overall performance significantly.

Several simulated emergency conditions are practiced next by the pilot, including variation in stability levels, and failures of the engine, inertial platform, flow-direction sensor, radar and/or radio, and stability-augmentation system. For flights into critical stability areas, simulated missions are performed, with the stability of the analog altered to reflect the most pessimistic combination of errors which might exist in the predicted stability derivatives. Premature engine shutdowns are performed at the critical points in the flight to acquaint the pilot with the optimum technique required to either return to a lake behind him or to fly to an alternate lake ahead of him. Simulated failures of the inertial-platform presentation are practiced and alternate techniques for either completing the normal mission or, at least, for safely returning the vehicle and pilot are devised. Normally, failure of the velocity or altitude readout does not affect the flight; however, in the event of an attitude-presentation failure, an immediate push-over must be initiated to a pitch angle of approximately 18° where the pilot again has the horizon in sight. Simulated flights with the flow-direction sensor inoperative are also practiced. In general, all missions can be completed without the angle-of-attack or sideslip indications by using

normal-acceleration, attitudes, and stabilizer-position indications; however, the pilot does not have as precise control of the flight conditions. Radar and communications failures are also practiced to assure that the flight can be accomplished with only the information available in the cockpit.

Single- and multiple-channel failures of the stability-augmentation system are examined to determine the ground rules to be used for each flight. In most cases, a single failure of the pitch or yaw channel can be tolerated and the mission can be completed in a normal manner. Failure of the roll damper, however, could create a critical situation, especially for high-altitude flights where an entry must be performed. This single item has caused, by far, the most concern during the X-15 flight-test program. Previous controllability studies (refs. 1 and 2, for example) predicted that the airplane could not be controlled above an angle of attack of approximately $7°$ with the roll damper inoperative. For any altitude above 200,000 feet, an angle of attack greater than $7°$ is required during the entry to avoid exceeding the maximum dynamic-pressure limits of the airplane. Three possibilities have been examined for successfully accomplishing an entry with the roll, or roll and yaw damper inoperable. The first possibility is to jettison the lower vertical fin which improves the handling qualities appreciably at high angles of attack but at the expense of degraded handling qualities near zero angle of attack. The second possibility is the use of the $\overset{\circ}{\beta}$ technique discussed in reference 1. Although all X-15 pilots have mastered this special control technique on simulators, it is not considered a final answer to the problem. The third possibility is the dualization of the roll damper which is presently being undertaken but requires appreciable time to accomplish. Pilot practice is, therefore, concentrated in the first two areas. The $\overset{\circ}{\beta}$ technique is practiced during entries with the stability-augmentation system off, and entries with the lower vertical fin off are performed on the simulator. For flights to altitudes below 200,000 feet, entries at an angle of attack of $7°$ with the stability-augmentation system off are also practiced.

An important pilot-training device for the landing phase of X-15 flights is the F-104 airplane. The use of the airplane in preparing for X-15 flights is discussed in reference 3.

In addition to these preparation procedures which are performed prior to each X-15 flight, other training procedures have also 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. Prior to his first flight in the airplane, each pilot went through a ground dry run with the X-15 airplane mated to, or in the vicinity of, the B-52 airplane. The purpose of this dry run was to permit the pilot to become familiar with the complete prelaunch check list and cockpit procedures. Engine runs on the

propulsion system test stand were also performed by each pilot prior to his first X-15 flight. 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:

(1) Monitor the subsystems operation during the flight and advise the pilot of any discrepancies noted
(2) 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
(3) Time the engine operation as a backup for the cockpit stop watch and advise the X-15 pilot of heading corrections, radar altitudes, and position during the flight
(4) Monitor and evaluate stability and control parameters
(5) Monitor the pilot's physiological environment
(6) Provide the X-15 pilot with energy-management assistance in the event of a premature engine shutdown or other off-design condition
(7) Direct air search and rescue operations in the event of an emergency

Normally, all important information in the control room is passed on to the pilot through the ground controller; however, other ground control personnel have the capability of transmitting directly to the pilot in the event of extreme emergency where insufficient time is available to relay the information.

Ground-Monitored Energy-Management System

In order to supply energy-management advice to the pilot as rapidly as possible, special techniques and equipment are being incorporated. The analog simulator was used to define the optimum piloting techniques required to obtain the maximum forward, reverse, and cross range from various flight conditions. These techniques are fairly well standardized and understood by the X-15 pilots. A small analog 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. 9). The ground controller can see at a glance which lakes are within the range capability at any particular instant. Three modes of operation are used. The normal mode shows the total attainable ground-area footprint which is essentially a cardioid. The other two modes indicate the instantaneous airplane position or heading by a single dot or line.

The sequence of cardioid size and position during a normal altitude flight is illustrated in figure 10. At launch (t = 0 sec) the size of the cardioid is relatively small and represents the total range capability for pure gliding flight from the B-52 launch conditions. Obviously, the launch lake must be within or on the edge of the cardioid at launch to allow the pilot to land safely if the engine fails to light. The cardioid grows in size after engine ignition as the airplane accelerates. As the flight-path angle increases during the exit, the cardioid begins to move ahead of the airplane position (t = 50 sec). The airplane attains its maximum total energy at burnout; the size of the cardioid is, therefore, at its largest value (t = 82 sec). After burnout, the airplane is committed to several minutes of pure ballistic flight at constant energy and the cardioid remains fixed in size and position (t = 82 to 220 sec). During the entry, the cardioid shrinks rapidly, with one point on the perimeter remaining fixed geographically. The location of this point is a function of the bank angle used during the entry (t = 260 sec). After the entry, the cardioid continues to shrink slowly as the pilot maneuvers for the landing.

A simplified system using the same basic principle but with a family of curves drawn on the map instead of the scope presentation has been in use on all X-15 flights.

Flight Results

Some flight results are examined to evaluate the effectiveness of flight planning and pilot training. Figures 11 and 12 show, respectively, a comparison between the predicted maximum-altitude and maximum-speed profiles and the profiles actually flown with the LR11 engine. The comparison is considered to be good and near optimum, especially since maximum performance for both flights was obtained on each pilot's first attempt and on his fourth flight in the X-15. Figures 13 and 14 show, respectively, comparisons between predicted altitude and speed profiles with the XLR99 engine and the actual flight profiles. The overshoot in actual velocity for the altitude flight is a result of a 2-second delay in shutting down the engine. It should be noted that the cockpit stop watch did not function properly on this particular 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, and the resulting delay
was responsible for the discrepancy. In general, it has been found
that the control of flight profile is not as precise with the XLR99
engine as with the LR11 engine, primarily as a result of the larger
accelerations. After each flight a performance "match" is simulated
on the analog computer using the actual angles of attack and thrust
values which were experienced on the flight. Analog-computer matches
of these two flights are also presented in figures 13 and 14. The
overall performance of the simulator is shown to be close to that of
the airplane. The only changes which have been made to the simulator
as a result of flight-test data have been weight- and burning-time
modifications. No changes in the predicted performance and stability
derivatives have been required.

Several anticipated malfunctions have occurred during the test
program, such as failures of the stability-augmentation system, engine,
stop watch, inertial system, and radar and/or radio. The value of the
analog simulator in defining techniques and training the pilots so that
they are able to complete the missions under these adverse conditions
is undeniable.

Several unexpected incidents have also occurred during the program
which have justified the decision to perform an incremental-performance
envelope-expansion program. On the maximum-speed flight with the LR11
engine at a Mach number of 3.3, the cockpit seal was burned slightly
when the canopy lifted and allowed hot stagnation air to reach the rubber
seal. On the first flight with the XLR99 engine to a Mach number of 4.2,
side-panel buckling was encountered as a result of differential heating.
Wing leading-edge-skin buckling was also encountered as a result of
local aerodynamic heating at a Mach number of about 5.0. A poor aero-
dynamic seal around the nose-gear door resulted in some minor internal
damage due to aerodynamic heating at a Mach number of 5.3. A severe
airplane vibration induced by the stability-augmentation system was
experienced on an interim altitude flight at a Mach number of 3.8.
Inasmuch as all of these items were discovered on lower velocity flights
under less critical conditions, they have been corrected without signif-
icantly affecting the test program. Any of these incidents could have
resulted in major damage to the airplane if maximum speed or altitude
had been attempted on the first flight and could possibly have resulted
in loss of the airplane.

CONCLUDING REMARKS

The expansion of the X-15 flight envelope is being performed
according to the planned program. All predictions of stability, perform-
ance, and flight trajectories have been within expected accuracies.

General piloting techniques developed on the analog simulator have proven to be satisfactory in flight. Ground-monitor functions have proven to be of value in assisting the B-52 and X-15 pilots. Pilot-training procedures have proven to be adequate for a program of this type. 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, thereby improving his ability to obtain more precise flight data in the time available.

Predictable emergency conditions or off-design missions have been encountered during the program, and in each case simulator training has contributed greatly to the pilots' 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 airplanes, have contributed to the overall pilot experience level, but are not considered necessary for continuous use on a flight-by-flight basis.

Unexpected problems, primarily in the area of aerodynamic heating, have also been encountered; however, neither pilot nor flight vehicle safety has been compromised due to the incremental-performance philosophy of envelope-expansion testing.

Flight Research Center
    National Aeronautics and Space Administration
        Edwards, Calif., November 20, 1961

REFERENCES

1. Petersen, Forrest S., Rediess, Herman A., and Weil, Joseph: Lateral-Directional Control Characteristics of the X-15 Airplane. NASA TM X-726, 1962.

2. Taylor, Lawrence W., Jr.: Analysis of a Pilot-Airplane Lateral Instability Experienced With the X-15 Airplane. NASA TN D-1059, 1961.

3. White, Robert M., Robinson, Glenn H., and Matranga, Gene J.: Résumé of Handling Qualities of the X-15 Airplane. NASA TM X-715, 1962.
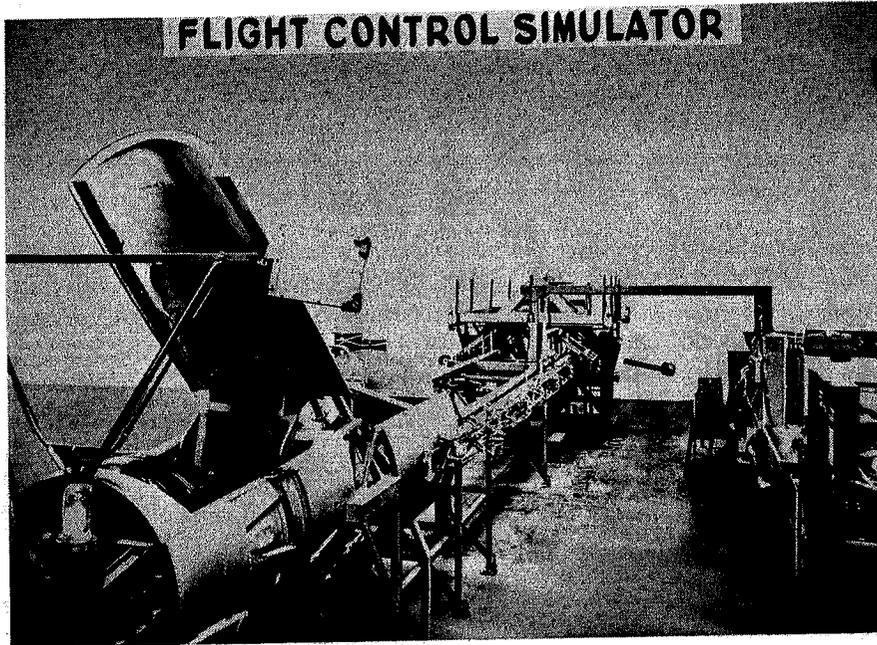
Figure 1
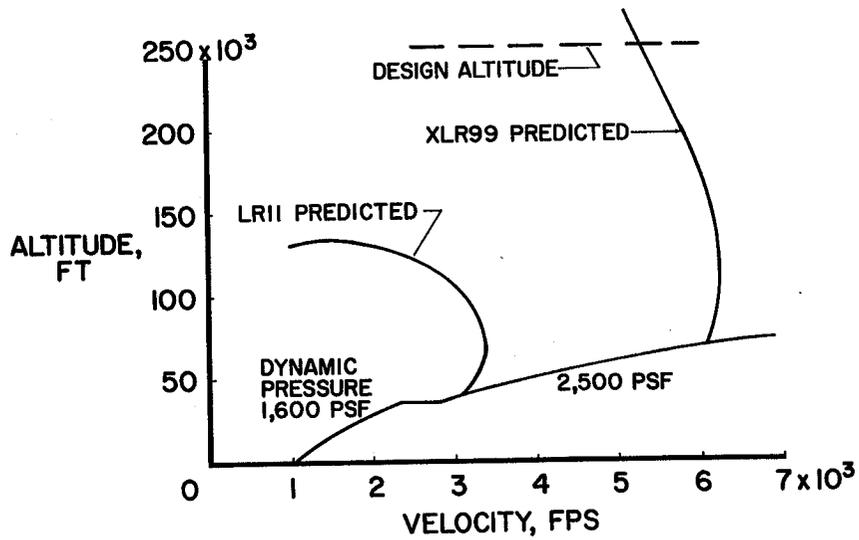
Figure 2

SUMMARY OF PREDICTED STABILITY AND CONTROL
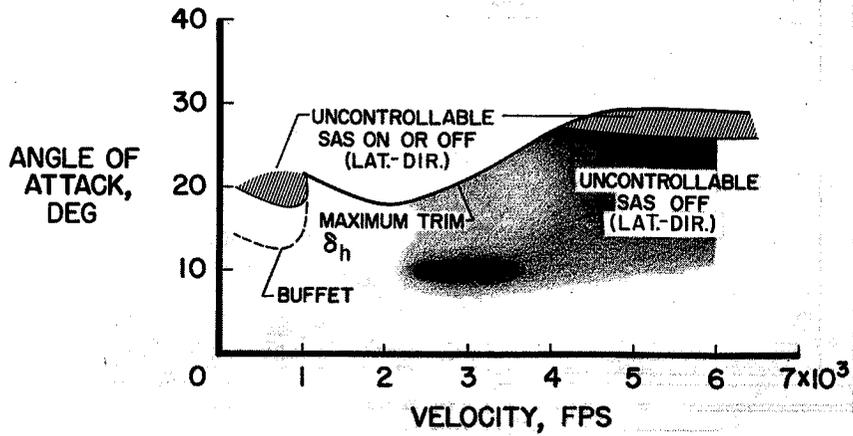
Figure 3

XLR99 RANGING
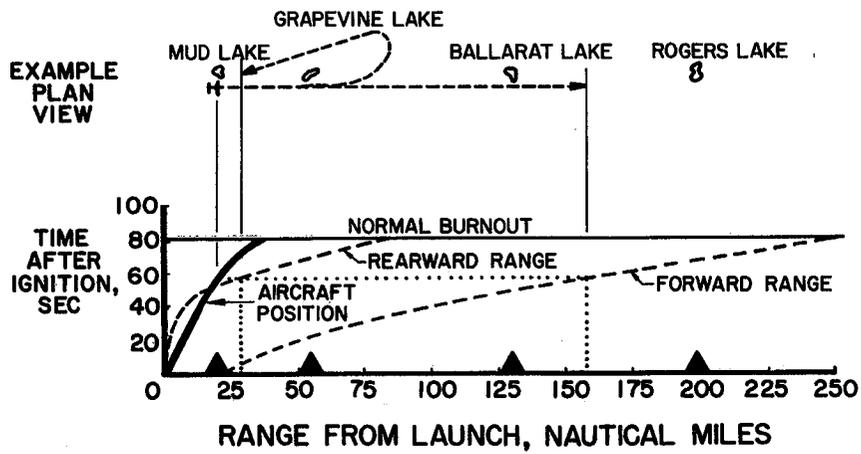
Figure 4

LAUNCH AND EMERGENCY LAKE COMPLEX
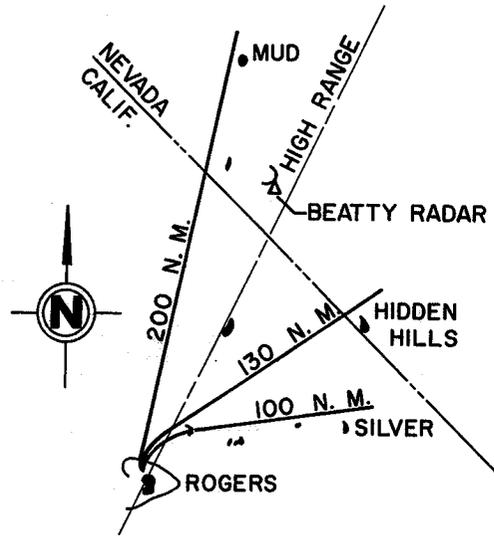
Figure 5

XLR99 ALTITUDE MISSION

SPECIFIED PROFILE
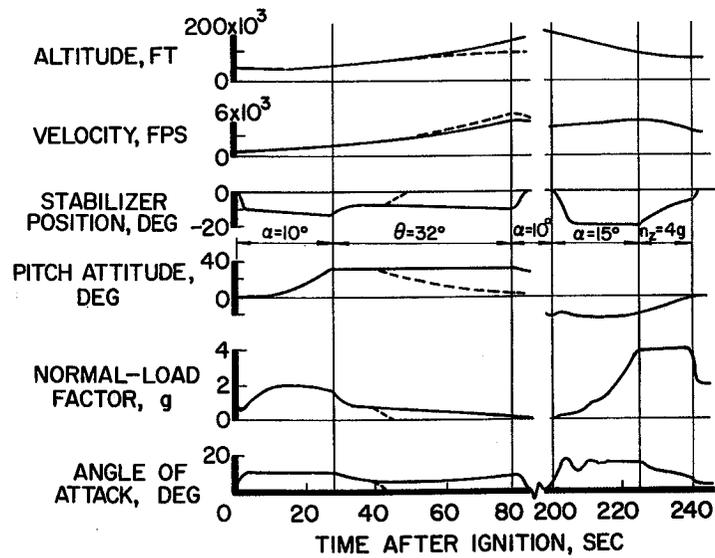
Figure 6
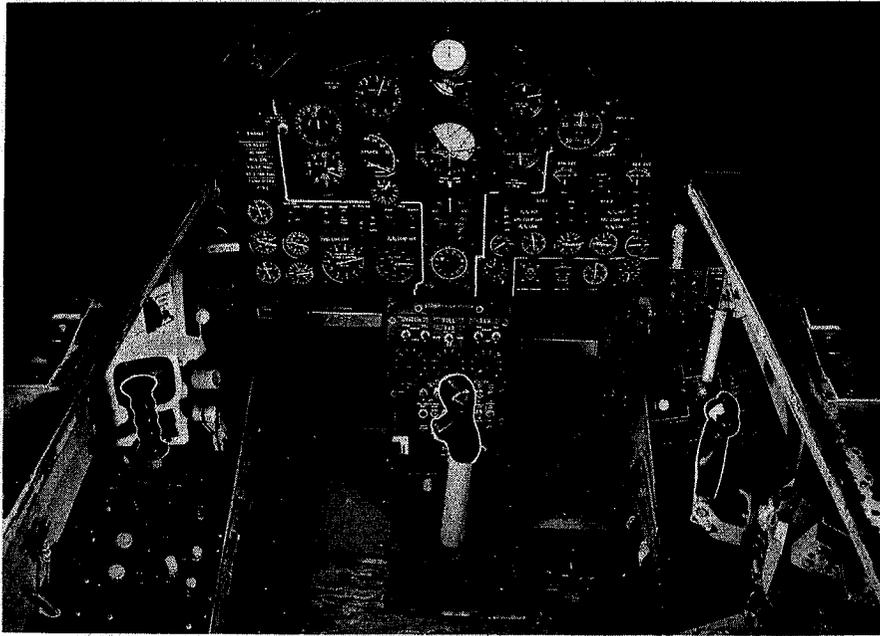
Figure 7

XLR99 ALTITUDE – MISSION PROFILE
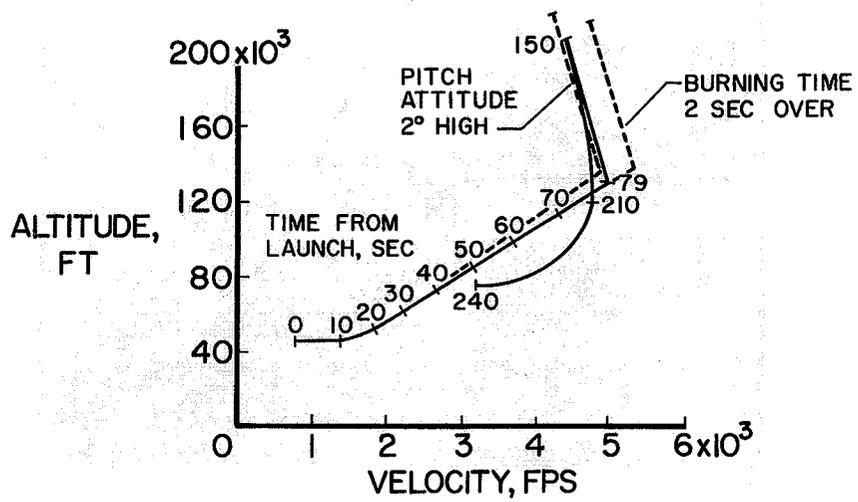
Figure 8

X-15 GROUND-MONITORED
ENERGY-MANAGEMENT DISPLAY
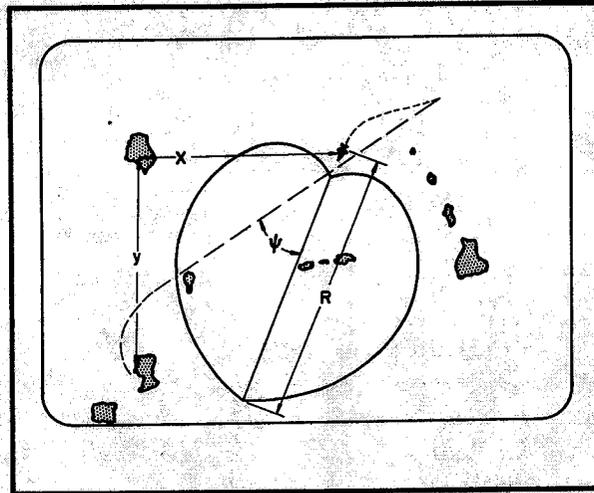
Figure 9

VARIATION OF RANGE CAPABILITY
DURING A TYPICAL X-15 FLIGHT
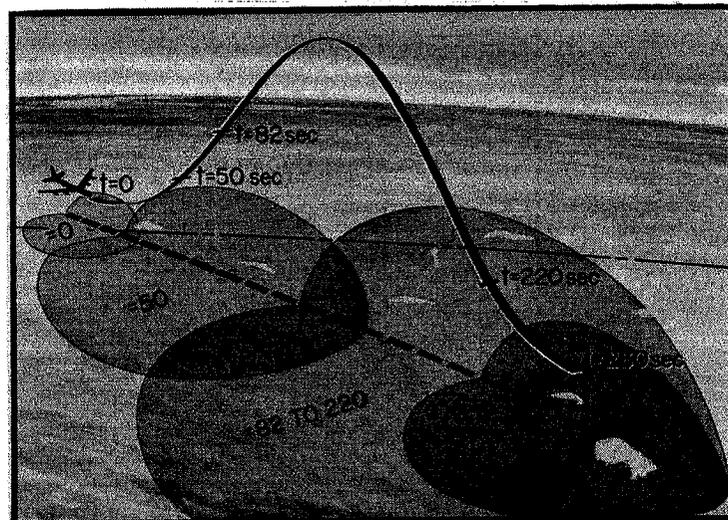
Figure 10

XLR11 PERFORMANCE COMPARISON
MAXIMUM ALTITUDE
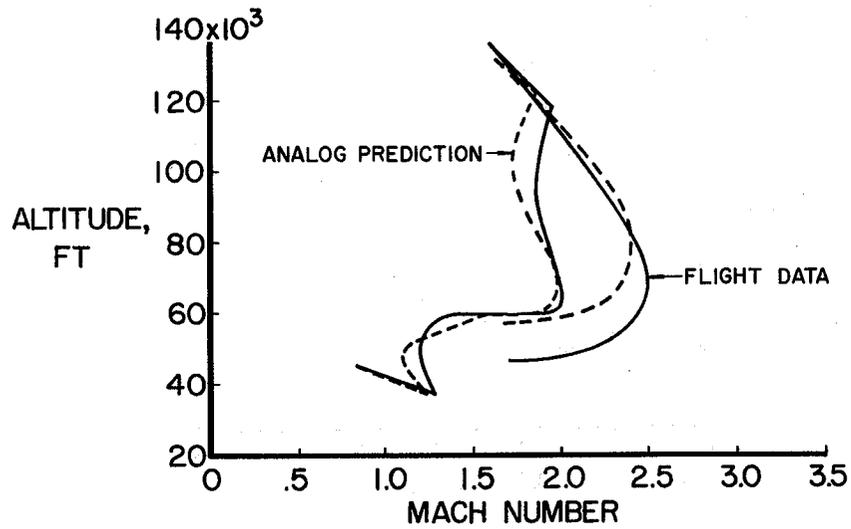
Figure 11

XLR11 PERFORMANCE COMPARISON
MAXIMUM SPEED
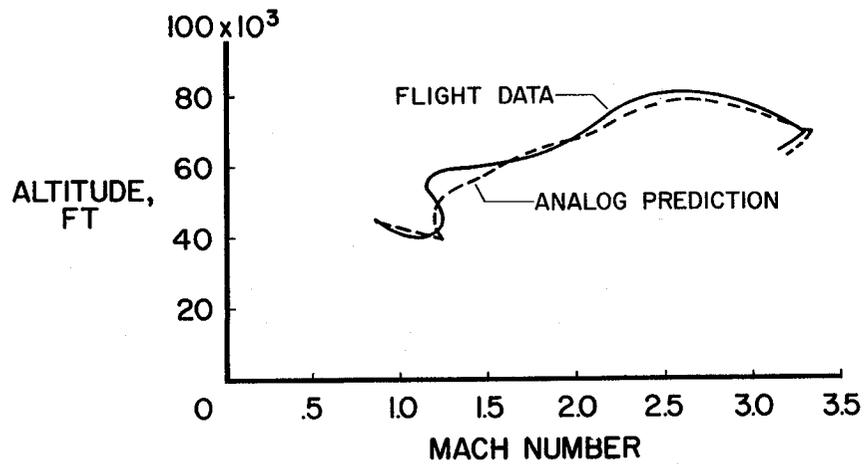
Figure 12

ALTITUDE - FLIGHT PERFORMANCE COMPARISON
XLR99 ENGINE
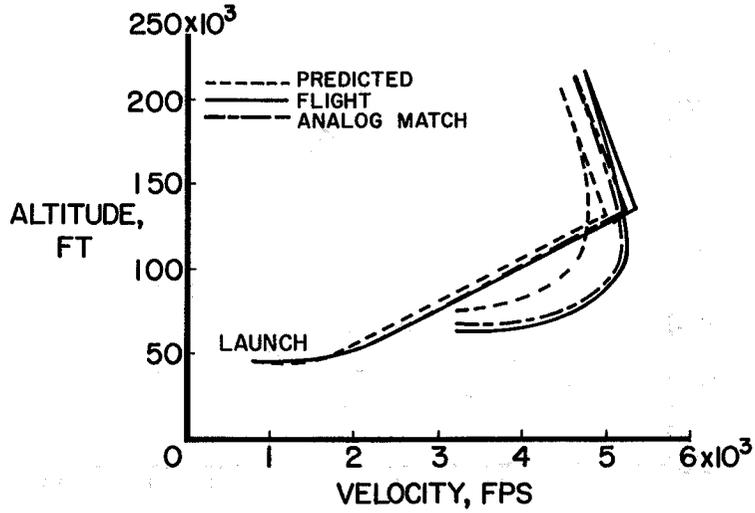
Figure 13

SPEED - FLIGHT PERFORMANCE COMPARISON
XLR99 ENGINE

Figure 14