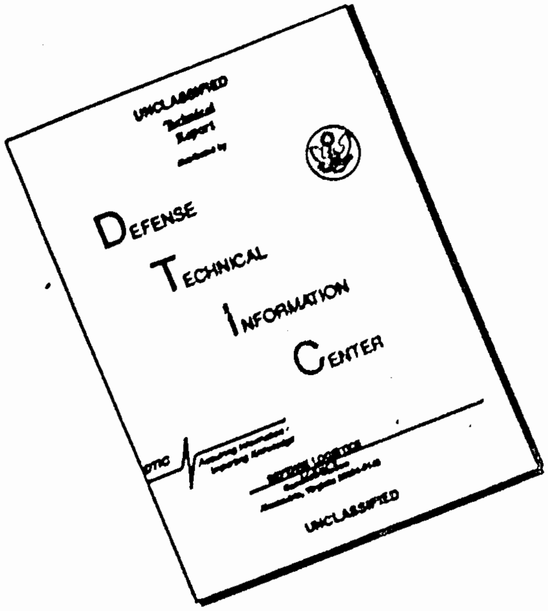
AD NUMBER
ADB029224
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; DEC 1977. Other requests shall be referred to Air Force Flight Dynamics Lab., Attn: AFFDL/FXS, Wright-Patterson AFB, OH 45433.**
AUTHORITY
AFWAL ltr dtd 12 Dec 1986

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

AFFTC-TR-76-11

AFFTC

FLIGHT PLANNING AND CONDUCT OF THE X-24B RESEARCH AIRCRAFT FLIGHT TEST PROGRAM

JOHNNY G. ARMSTRONG
X-24B Project Manager

December 1977
Final Report

Distribution limited to U.S. Government agencies only (Test and Evaluation), [redacted]er 1977. Other requests for this document must be referred to AFFDL/FXS, Wright-Patterson AFB, OH 45433.

Controlling Office:

AFFDL/FXS
Wright-Patterson AFB, OH 45433

AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

This technical report was submitted under Job Order Number 1366AO by the Deputy Commander for Operations of the Air Force Flight Test Center, Edwards AFB, California 93523.

Foreign announcement and dissemination by the Defense Documentation Center are not authorized because of technology restrictions of the U.S. Export Control Acts as implemented by AFR 400-10.

This report has been reviewed and is approved for publication: March 1978

Prepared by:

Johnny G. Armstrong

JOHNNY G. ARMSTRONG
X-24B Project Manager

William T. Twinting

WILLIAM T. TWINTING
Colonel, USAF
Commander 6510 Test Wing

Philip J. Conley Jr.

PHILIP J. CONLEY, JR.
Brigadier General, USAF
Commander

Qualified requesters may obtain copies of this report from the Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314. Department of Defense contractors must be established for DDC services, or have "need to know" certified by cognizant military agency of their project or contract.

DDC release to NTIS is not authorized

When U.S. Government drawings, specifications, or other data are used for any purpose other than a definitely related government procurement operation, the government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or any other data is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

Do not return this copy; retain or destroy

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFFTC-TR-76-11

2. GOVT ACCESSION NO.:

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): Flight Planning and Conduct of the X-24B Research Aircraft Flight Test Program

5. TYPE OF REPORT & PERIOD COVERED: Final Report, 1 Aug 73 to 26 Nov 75

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): Johnny G. Armstrong, X-24B Project Manager

8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Deputy Commander for Operations
Air Force Flight Test Center
Edwards Air Force Base, CA 93523

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:

11. CONTROLLING OFFICE NAME AND ADDRESS:
AFFDL/FXS
Wright-Patterson AFB, OH 45433

12. REPORT DATE: Dece[redacted]77

13. NUMBER OF PAGES: 108

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report):
Distribution limited to U.S. Government agencies only (Test and Evaluation), December 1977. Other requests for this document must be referred to AFFDL/FXS, Wright-Patterson AFB, OH 45433.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):

18. SUPPLEMENTARY NOTES:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

X-24B	reentry vehicle
research aircraft	air launched
unpowered landing	captive flight
rocket powered	plume effects
glide flight	hypersonic

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

This report presents an overall summary of the conduct and results of the X-24B research aircraft flight test program. The program objective to obtain flight test verification of this efficient hypersonic aerodynamic shape was accomplished in 36 flights over a 26 month time period. The X-24B was air launched from a NB-52B, accelerated to test conditions by rocket power and glided to an unpowered landing. Research data and flight verification were obtained to a maximum Mach number of 1.76. The handling qualities

at subsonic speeds and during landing were excellent. Accuracy landing tests demonstrated touchdown accuracy within $\pm$500 feet providing confidence to allow the first landing of a low L/D aircraft on a conventional concrete runway. The longitudinal stability was less than predicted by small scale wind tunnel tests. Directional stability was found to be significantly less than predicted above 1.3 Mach number resulting in a marked loss of usable L/D capability. Rocket engine exhaust degraded directional stability at transonic and supersonic conditions. Subsonic gliding performance was close to predictions.

PREFACE

This report is one of four technical reports prepared by the Air Force Flight Test Center (AFFTC) to provide final documentation of the X-24B flight test program. Early reporting requirements were satisfied with the publication of preliminary flight reports after each flight. Free flight tests of the X-24B were conducted between 1 August 1973 and 26 November 1975. The flight test program was a joint effort between the Air Force Flight Test Center and NASA Dryden Flight Research Center (DFRC). AFFTC participation was authorized by Project Directive 73-87 and was accomplished under Job Order Number 1366AO.

The author wishes to acknowledge the individuals of AFFTC, DFRC and the Air Force Flight Dynamics Laboratory (AFFDL) that constituted the X-24B test team and whose efforts are represented by the contents of this report. Special acknowledgement is made to Mr William P. Zima, project manager at AFFDL who, in addition to providing overall program management, coordinated special studies and ground tests at Wright-Patterson AFB (WPAFB) during the preparation for and conduct of the X-24B flight test program.

The X-24B is the last of the joint USAF NASA X-series, air launched, rocket powered, research aircraft. Some of the subject matter of this report is outside the scope of a typical AFFTC technical report, but is an attempt to document, by tracing one program from initial procurement through the final flight, the cumulative experience at Edwards AFB in conducting programs of this type.

TABLE OF CONTENTS

Page No.

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

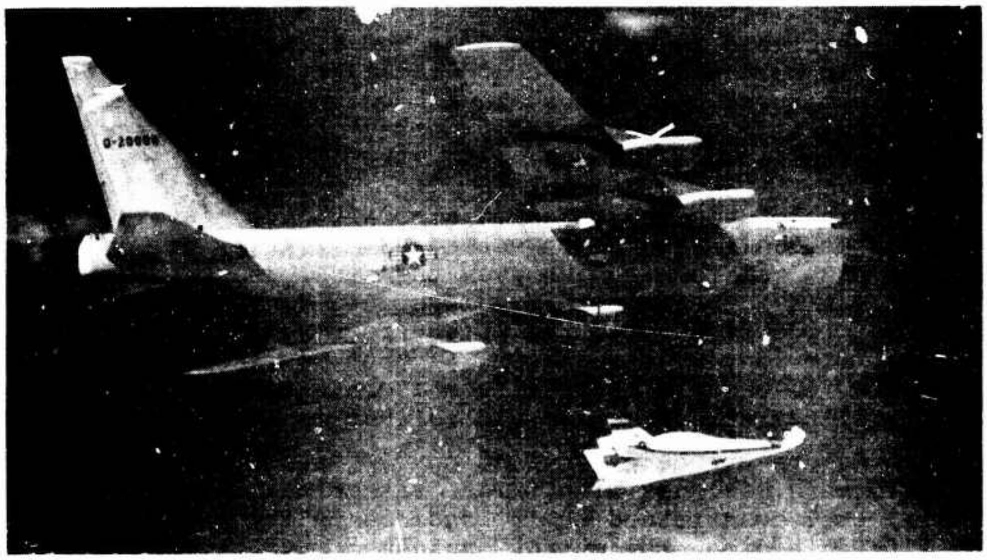
GENERAL

The X-24B was a research aircraft representative of an aerodynamic configuration that was predicted to have a high lift-to-drag ratio (L/D) at hypersonic speeds. The configuration included design features that considered aerodynamic heating factors for reentry from earth orbit. The predicted hypersonic L/D of 2.5 for this configuration could provide a considerable increase in cross range maneuvering capability during re-entry over the lifting body vehicles (M2, HL-10, X-24A) which were predicted to have maximum hypersonic L/D's of approximately 1.2 to 1.4. The purpose of the X-24B program was to obtain flight test verification of this efficient, hypersonic, aerodynamic design in the low supersonic, transonic, and subsonic flight regimes as well as in the landing mode with respect to the following areas:

- Handling qualities
- Correlation of flight test and wind tunnel data
- Control surface loads
- Surface measurements (pressure, acoustic, vibration)
- Landing gear loads validation

The total X-24B flight test program consisted of 36 air launched flights over a 26 month time period. The total flight time was 3 hours, 46 minutes and 43.6 seconds. The basic research flight program was completed in 30 flights (six glide, 24 powered) in 24 months by three pilots. A six-flight pilot check-out program was accomplished in two months by three research test pilots after completion of the basic research program. Figure 1 presents a chronological summary of the flight operations with emphasis on the maximum Mach numbers achieved on each free flight. The envelope expansion program to maximum Mach number was accomplished within 15 months from first flight. This was noticeably less than the X-24A envelope expansion which required almost 24 months to achieve maximum Mach number. The success of the X-24B envelope expansion program was attributed to the use of the proven X-24A systems and the experienced X-24A test team in addition to the generally good flying qualities of the X-24B.

The results discussed in this report will primarily emphasize those factors that were significant to the orderly conduct of the research flight program and/or were unique to the X-24B, i.e., not previously documented in other reports. No attempt will be made to duplicate the extensive discussion of the aircraft's performance, handling qualities



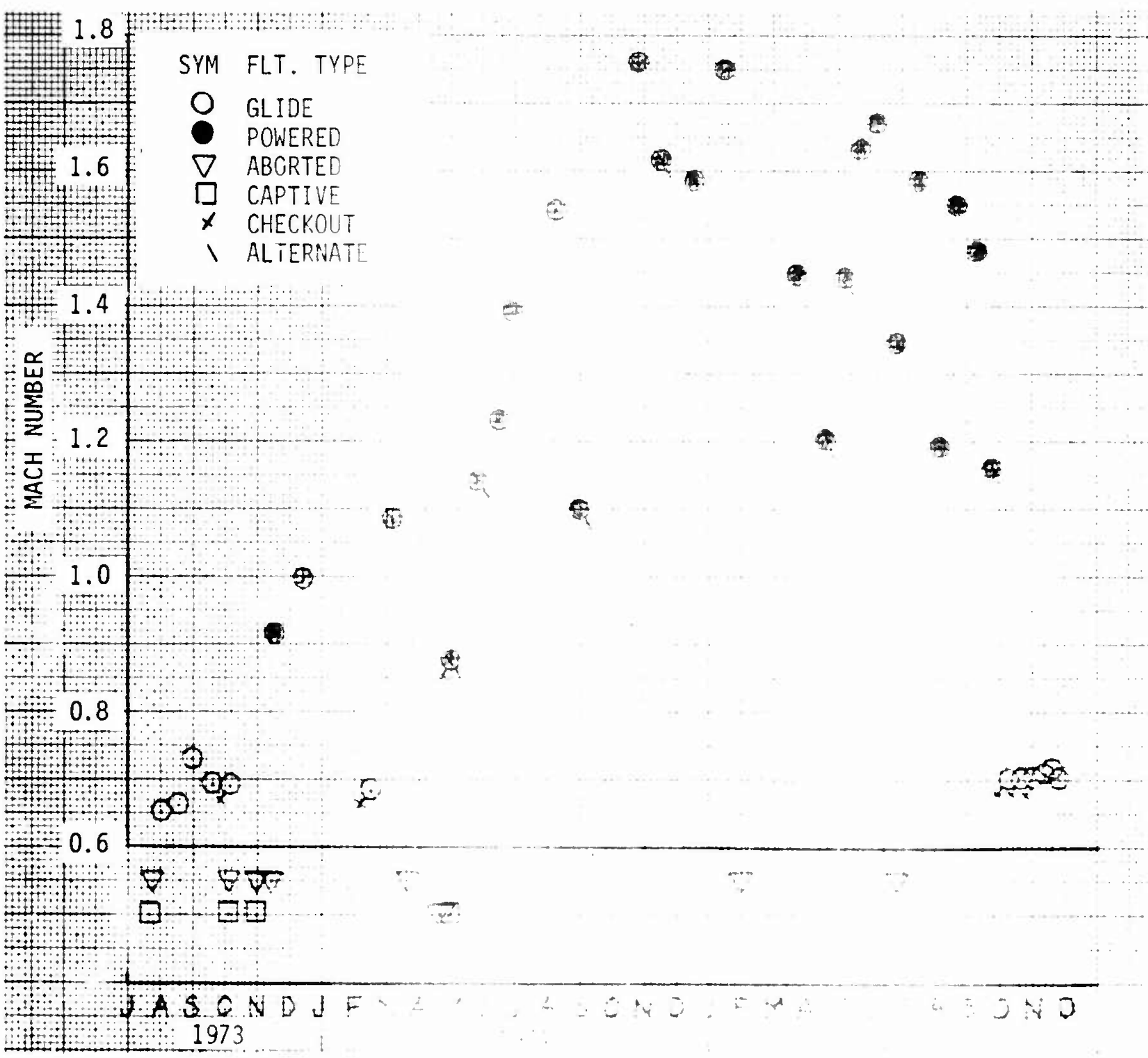


FIGURE 1 [illegible] PROGRAM MACH [illegible] and landing characteristics presented in References 1,[1] 2,[2] and 3[3] respectively. The operational philosophy and procedures for the conduct of the X-24B flights were basically the same as used in the X-24A program as described in Reference [4]. These include the elements of pilot training in both ground based a.. inflight performance simulators (T-38/F-104), prelaunch operations, launch ground rules, emergency lake requirements, real time ground control, energy management, and ad hoc committee reviews of milestone flights.

The rocket-powered research aircraft have historically been landed on dry lakebeds in the Southwestern US primarily on Rogers Dry Lake at Edwards AFB, California. However the first rocket research aircraft program, the X-1, began with landings on a conventional runway in 1946 with ten glide flights t. the 10,000 foot runway at Pinecastle Field, Orlando, Florida. These initial flights demonstrated the inadequacy of attempting to operate the X-1 from a conventional airfield and thus the X-1 flight operations were moved to what is now Edwards AFB, CA to utilize Rogers Dry Lake for landing (Reference 5).[5] The X-2 and later the X-15 were designed with skids, rather than main landing gear with wheels, that constrained their landings to dry lakebeds. Similar to the lifting bodies, the energy management and gliding capability of the X-24B required the use of the dry lakebeds in the local Edwards AFB (EAFB) area to cover potential emergency landings. Glide flights were launched in the immediate vicinity of Rogers Dry Lake. Short range powered flights were launched near Rosamond Dry Lake (approximately 15 miles west of EAFB) and high speed, longer range flights were launched near Cuddeback Dry Lake (approximately 30 miles northeast of EAFB). All flights were planned for a normal recovery at EAFB, either on Rogers Dry Lake or the main runway. A more detailed description of the flight planning considerations for emergency landings is included in Reference 4.

---

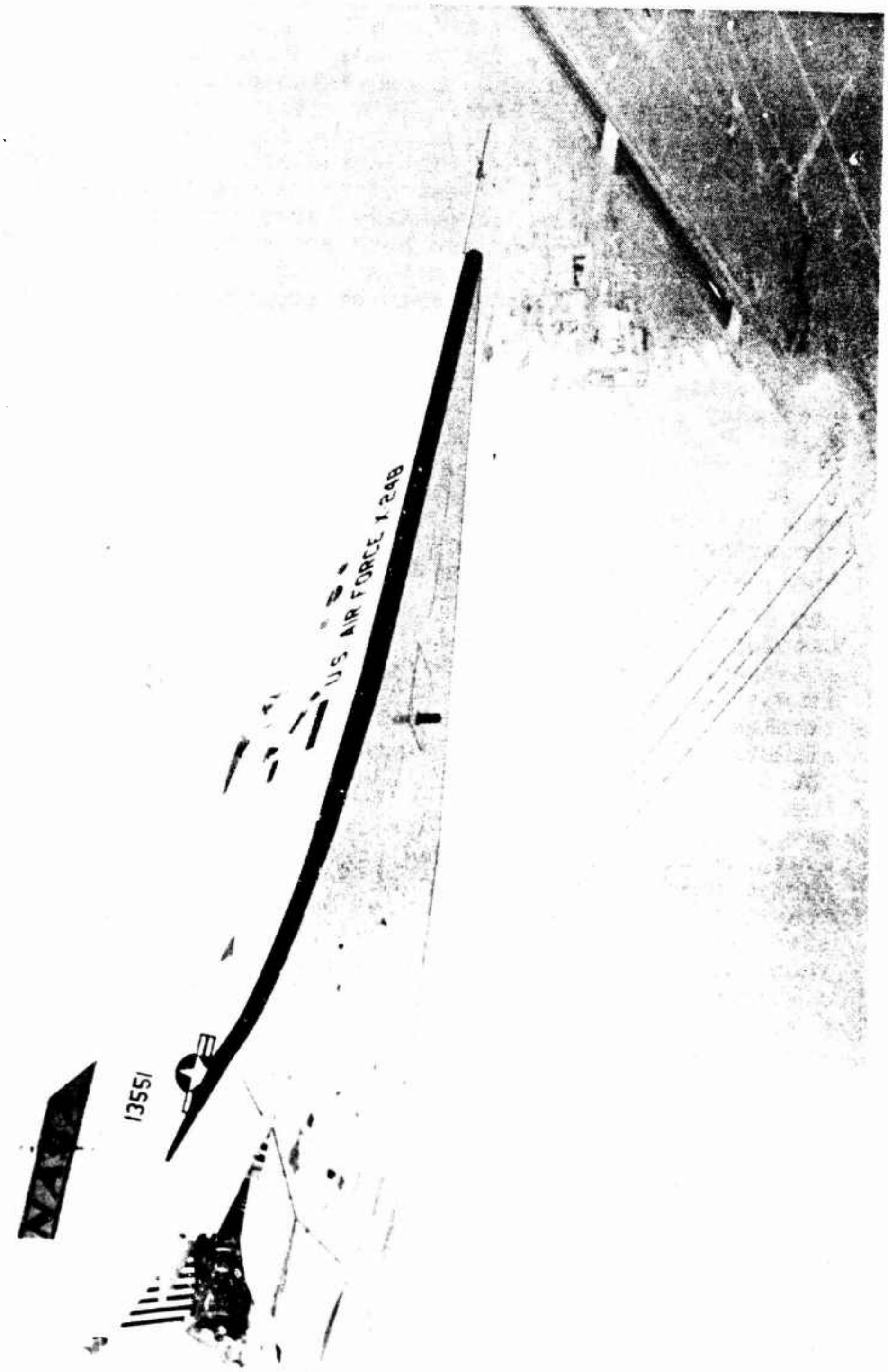
[1]Nagy, Christopher J. and Kirsten, Paul W., Handling Qualities and Stability Derivatives of the X-24B Research Aircraft, AFFTC-TR-76-8, Air Force Flight Test Center, Edwards AFB, California, March 1976

[2]Richardson, David F., Comparison of Flight Test and Wind Tunnel Performance Characteristics of the X-24B Research Aircraft, AFFTC-TR-76-10, Air Force Flight Test Center, Edwards AFB, California, April 1976

[3]Stuart, John L., Captain, USAF, Analysis of the Approach, Flare, and Landing Characteristics of the X-24B Research Aircraft, AFFTC-TR-76-9, Air Force Flight Test Center, Edwards AFB, California, November 1977

[4]Armstrong, Johnny G., Flight Planning and Conduct of the X-24A Lifting Body Flight Test Program, FTC-TD-71-10, Air Force Flight Test Center, Edwards AFB, California, August 1972

[5]Hallion, Richard P., Supersonic Flight, The Macmillian Company, 1972


US AIR FORCE X-24B
13551

HISTORY

For many years the AFFDL had pursued the development of aerodynamic configurations that would provide increased capability during orbital reentry and/or hypersonic maneuvering over the first generation lifting bodies (M2, HL-10, X-24A). This effort centered around analytical and wind tunnel studies of highly swept blended body aerodynamic shapes that were identified as FDL-5, FDL-6 and FDL-7 configurations. Those shapes evolved considering the desired requirement to attain high L/D ($\approx$2.5) at hypersonic speeds, to possess large internal volume and to be amenable to the solution of the hypersonic aerodynamic heating problems. These configurations were all similar in forebody design but varied considerably in aft body features such as location and number of vertical fins.

During the construction of the X-24A airframe, the contractor, as a company funded venture, built the basic structure for two jet powered versions of the X-24A called the SV-5J. As a result of predicted marginal performance using available jet engines these aircraft were never flown. The initial catalyst for the X-24B program came in late 1968 when the Commander of the Air Force Systems Command (AFSC) requested recommendations for the use of the partially complete SV-5J vehicles that could be available on loan from the contractor. In January 1969 the AFFDL published a Development Plan (Reference 6)[6] for an Advanced Development Program to modify and flight test an SV-5J reconfigured into a shape similar to the FDL-7. In order to minimize modification costs it was conceived that the SV-5J aft body and fin locations would be retained, with "add on" structure being applied for the forebody and aft strake wing panels. This resulting configuration was called the FDL-8. Analytical and wind tunnel studies were accomplished to validate the resulting aerodynamic configuration. The proposed FDL-8 aircraft was to be jet powered and air launched from the NB-52B mothership. However, as the studies matured, the advantages resulting from the use of rocket propulsion rather than jet engines led to the selection of the XLR-11 rocket engine. Once the decision was made to use rocket propulsion, the selection of the X-24A as the vehicle to be modified rather than the SV-5J became the obvious next step. The selection of the X-24A airframe permitted the use of the existing proven systems and reduced the overall modification and subsystem buildup costs. Figure 2 presents a photo comparison of the X-24A and X-24B.

A memorandum prepared by AFFDL delineating the development and flight test of the FDL-8 configuration using the X-24A was provided to interested parties in August of 1970. Letters indicating concurrence in the proposal were received by AFFDL from the Director of DFRC (28 Aug 70) and from the Commander of AFFTC (1 Sep 70). The memorandum was then sent to the AFSC Director of Laboratories along with a request

[6] Anonymous, Development Plan - Advanced Development Program - FDL-8 with Advanced Reusable Spacecraft Technology and Applications Study, 1632, Air Force Flight Dynamics Laboratory, AFSC, 23 Jan 69

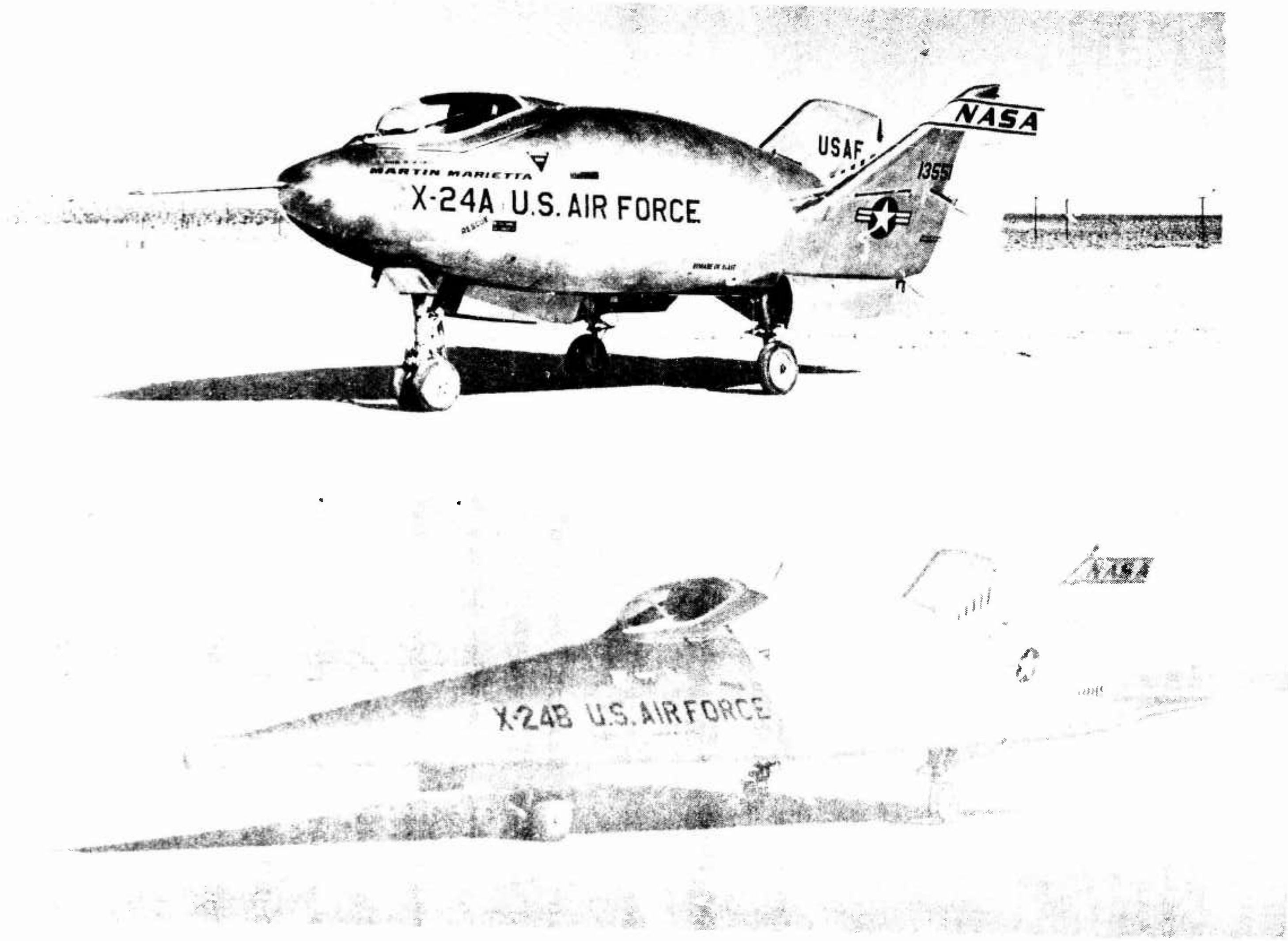


FIGURE 2 COMPARISON OF X-24A AND X-24B

for program approval. A firm step toward program approval occurred on 11 March 1971 when NASA-DFRC transferred $550,000 to the Aeronautical Systems Division (ASD) for aircraft acquisition. AFFDL was directed to proceed with the program on 21 April 1971 by the AFSC Director of Laboratories. The AFFDL provided the additional $550,000 required for the fabrication contract which was awarded in January 1972.

The aircraft structural modification was accomplished by the Martin Marietta Company in Denver, Colorado (Figure 3). The elapsed time between delivery of the X-24A shell to the contractor and return of the modified aircraft to EAFB was just over ten months. The first flight was accomplished approximately nine months later following aircraft system buildup and extensive preflight tests. The major program milestones are summarized in Table I.

TABLE I

X-24B PROGRAM MILESTONES

Late 1968	AFSC Commander requested recommendations on use of Martin owned SV-5J aircraft
23 Jan 1969	AFFDL published Advanced Development Plan to modify SV-5J into an air launched jet powered FDL-8 aircraft
4 Sep 1970	AFFDL submitted program plan to AFSC Director of Laboratories to modify the X-24A to the FDL-8 configuration
11 Mar 1971	NASA-DFRC transferred $550,000 to USAF to initiate aircraft acquisition
21 Apr 1971	Program "Go Ahead" from AFSC Director of Laboratories (1 Nov 1970)[7]
4 Jun 1971	Last X-24A Flight (28 flights)
15 Dec 1971	X-24A Airframe Delivered to Contractor (15 May 1971)
Jan 1972	Fabrication Contract Awarded (1 Jan 1971)
7 Apr 1972	X-24A Mounted in Manufacturing Fixture
11 Oct 1972	Rollout Ceremony
24 Oct 1972	X-24B Shell Delivered to EAFB (15 Sep 1971)
1 Aug 1973	First Flight (Glide) (1 Feb 1972)
15 Nov 1973	First Powered Flight
23 Sep 1975	Last Powered Research Flight
26 Nov 1975	Last Flight

[7] Dates in parentheses are the scheduled milestone dates specified in the program plan of 4 Sep 1970

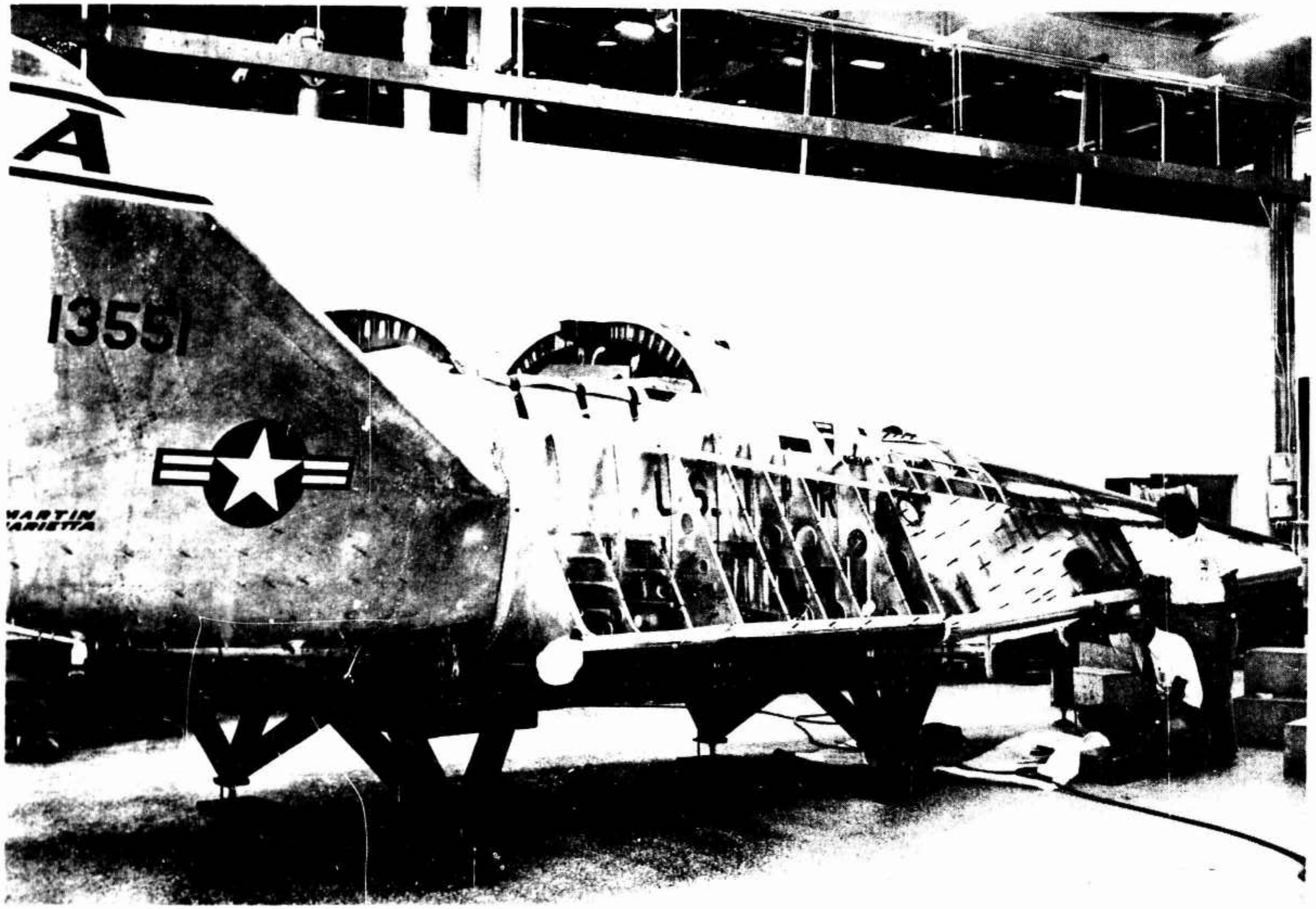


FIGURE 3 PHOTO OF X-24A TO X-24B MODIFICATION

AIRCRAFT DESCRIPTION

The aerodynamic design features of the X-24B are illustrated in Figure 4. The flat bottom and high sweep angle contributed to the high hypersonic L/D while the three degree nose ramp provided the proper hypersonic trim conditions. The three-inch leading edge radius and 60-degree side body angle were the result of aerodynamic reentry heating considerations. Flared out upper and lower flaps provided stability necessary at high speed. Boattailing these surfaces toward the faired position increased the subsonic L/D for acceptable landing performance. The double delta planform was necessary for the X-24B application in order to move the center of pressure aft. This was required because of the aft center of gravity (cg) resulting from the location of the test aircraft systems - rocket engine, propellant tanks, propellant, existing main landing gear position, etc.

In reviewing the following description of the various aspects of the aircraft the reader should refer to the photos in Figures 5 to 7, to the inboard three view shown in Figure 8, and to the control surface designations in Figure 9. Table II presents the physical characteristics of the aircraft.

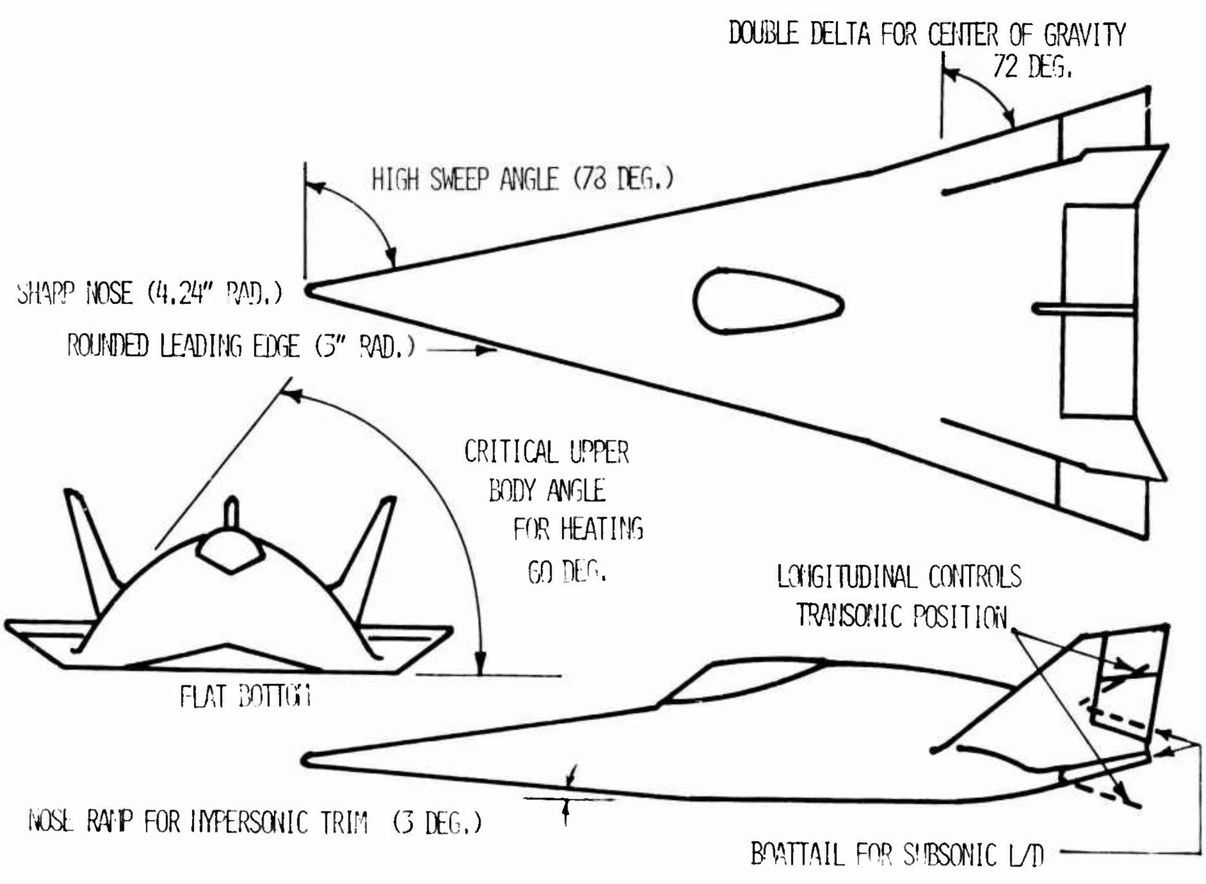


FIGURE 4 X-24B AERODYNAMIC DESIGN FEATURES

FIGURE 5 X-24B PHOTO - SIDE VIEW

FIGURE 6 X-24B PHOTO - FRONT VIEW

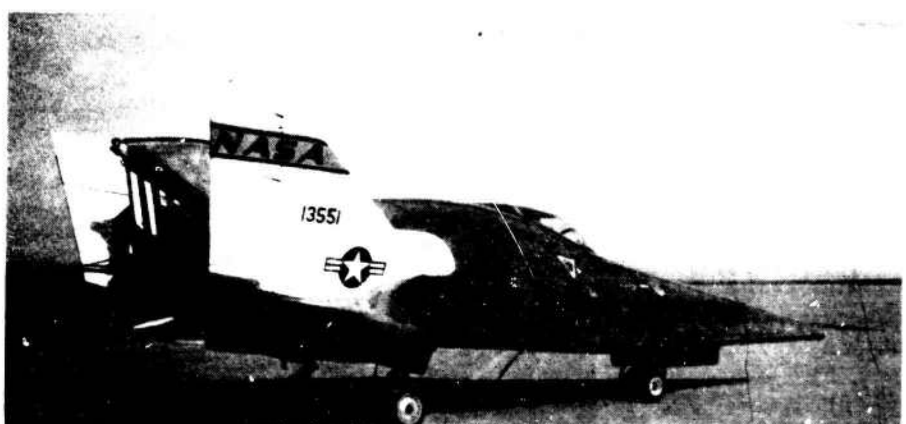


FIGURE 7 X-24B [illegible]

TABLE II

PHYSICAL CHARACTERISTICS OF X-24B RESEARCH AIRCRAFT

Body -	
Reference planform area, ft^2	330.50
Reference longitudinal length, ft	37.50
Reference span, ft	19.00
Forebody - Leading edge sweep, deg	78
Aftbody - Leading edge sweep, deg	72
Center fin -	
Area, ft^2	14.70
Root chord, ft	6.16
Tip chord, ft	3.17
Span, ft	3.23
Leading edge sweep, deg	55
Outboard vertical fins, each -	
Area, ft^2	25.90
Root chord, ft	8.46
Tip chord, ft	3.46
Span, ft	4.18
Leading edge sweep, deg	55
Upper rudders, each -	
Area, ft^2	4.99
Chord, ft	2.47
Span, ft	2.02
Bias deflection, deg	±10
Deflection from bias position, deg	±15
Lower rudders, each -	
Area, ft^2	6.67
Chord, ft	2.47
Span, ft	2.70
Bias deflection, deg	±10
Upper flaps, each -	
Area, ft^2	10.82
Chord, ft	2.84
Span, ft	3.81
Deflection, deg	0 to -40
Lower flaps, each -	
Area, ft^2	13.99
Chord, ft	3.74
Span, ft	3.74
Deflection, deg	0 to 40

TABLE II (Cont.)

Ailerons, each -

Area, ft^2	14.74
Chord, ft	3.98
Span, ft	4.16
Bias deflection, deg	3 to 11
Deflection from bias position, deg	± 5

TYPICAL MASS CHARACTERISTICS

(Powered Flight)

	Launch	Landing
Weight, lbs	13,800	8500
Center of gravity		
Longitudinal, percent MAC	66	64
Lateral, inches from BL=0	-.7	-.5
Vertical, inches from WL=0	28.3	22.5
Moments of Inertias, slugs-ft^2		
I_x	3200	2650
I_y	24900	23500
I_z	25600	23850
I_{xz}	830	660

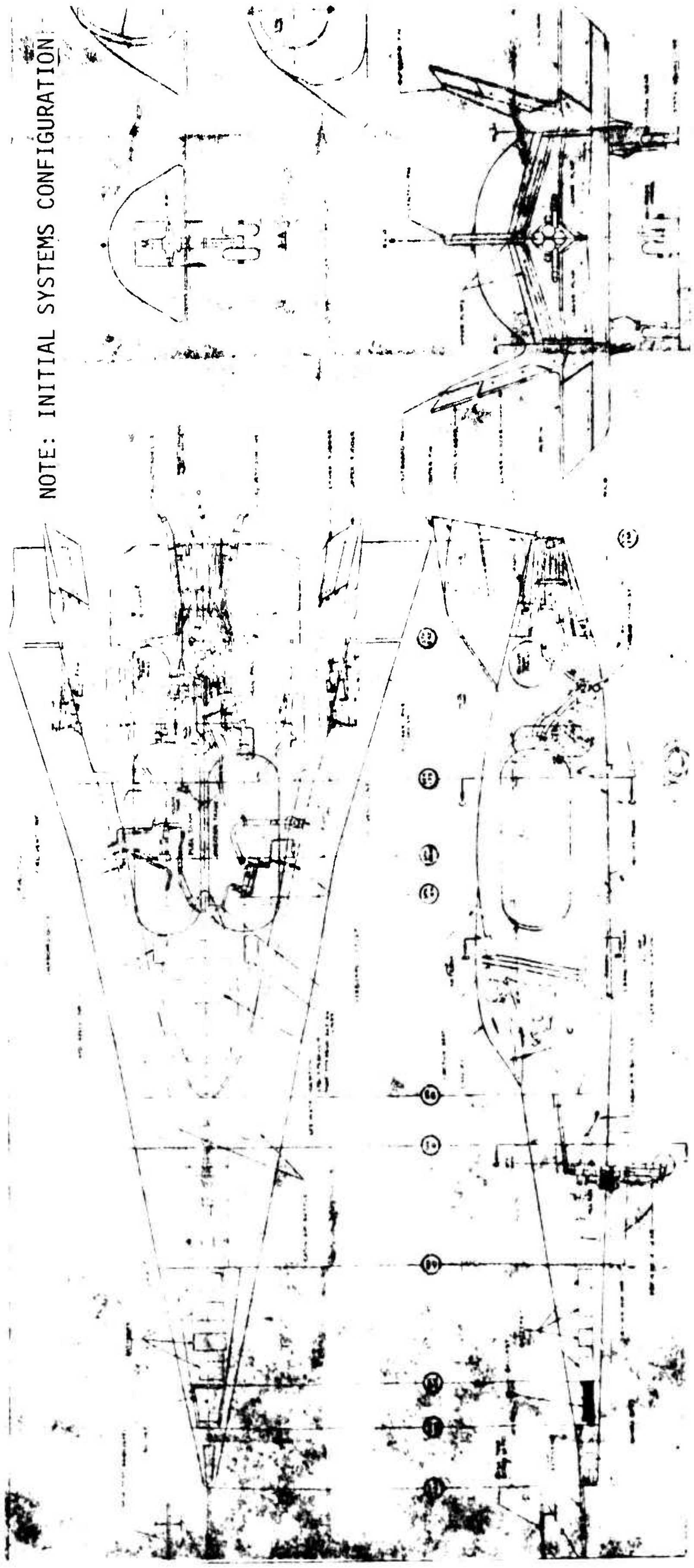


FIGURE 8 X-24B INBOARD THREE VIEW DRAWING

The flight controls for the X-24B consisted of ten movable control surfaces located on the aft body. Pitch control was derived from symmetrical deflection of the lower or upper flaps. The lower flaps were used the most during each flight, however when aft stick deflections resulted in the lower flaps fully closing (zero deflection), control was automatically transferred through a mechanical clapper mechanism to the upper flaps. Associated with this crossover region was a pitch deadband of approximately two degrees of control surface or a half of an inch of stick deflection. (This transfer usually was encountered only at low airspeed just prior to touchdown.) Yaw control was provided through rudder pedals to upper rudders only. Roll control was accomplished by differential deflection of the ailerons, located outboard of the vertical fins. In addition, an aileron-to-rudder interconnect (KRA) was used to minimize adverse sideslip during aileron inputs. The amount of KRA was automatically programmed as a function of angle of attack. There were two KRA/angle of attack schedules selectable by the pilot; one high gain schedule for transonic/supersonic conditions and a lower gain schedule for control at subsonic speeds. A manual KRA mode was also available to the pilot for use as backup to the automatic scheduling or for special test maneuvers.

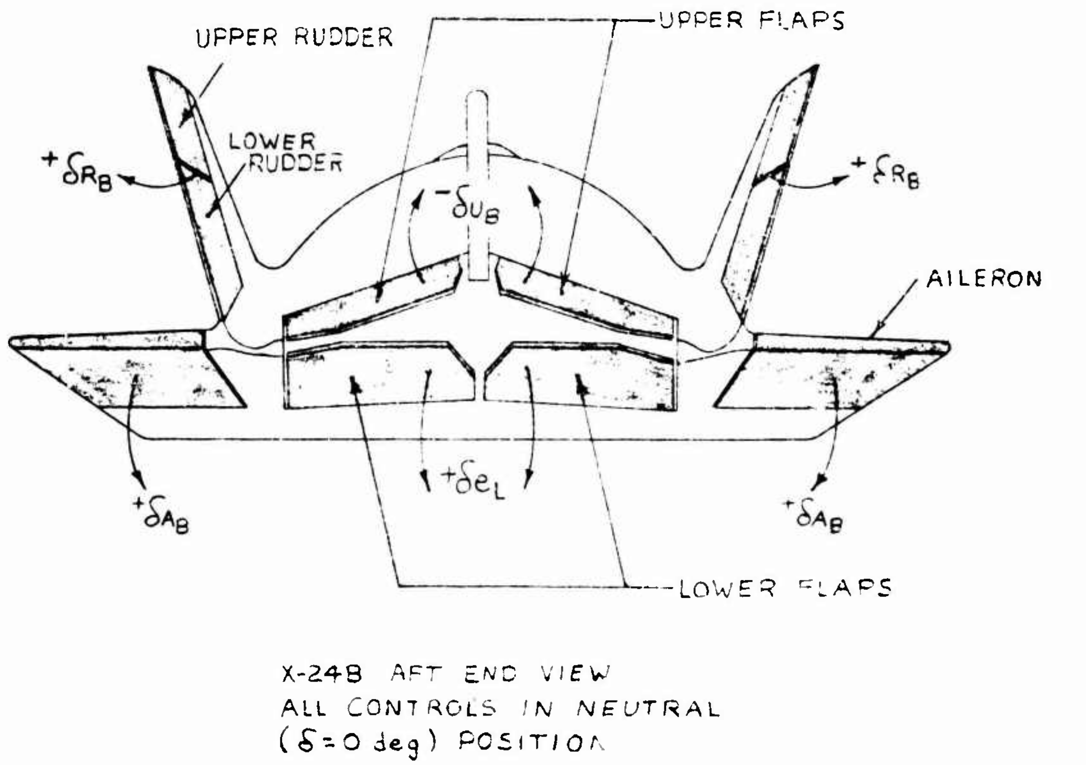


FIGURE 9 X-24B CONTROL SURFACE AND BIAS DESIGNATIONS

The control surfaces were movable by bias features. The biasing of the upper/lower flaps and upper/lower rudders provided the aerodynamic configurations necessary for satisfactory stability, longitudinal trim and gliding performance throughout the flight envelope. The pilot selected the desired position of the upper flap by a "beeper" switch located on the landing rocket throttle handle. The lower flaps were extended by a non-linear mechanical linkage as the upper flaps were extended. Both pairs of upper and lower rudders were biased automatically as a function of sensed upper flap bias position. The rudder bias could also be biased independent of the upper flaps for special test maneuvers. Figure 10 presents the control laws for the upper flap schedule versus lower flap and auto rudder bias. Electrical stops were set at -40 degrees and -20 degrees upper flap bias for most flights. Also shown are upper/lower flap deflections as a function of stick position. The ailerons could be symmetrically biased (in pitch) by the pilot for data collection purposes. Figures 11 and 12 show the positions of the control surfaces for the two primary configurations flown. The transonic/supersonic configuration consisted of -40 degrees upper flap bias and zero degrees rudder bias (faired). This "wedged open" configuration was required for stability considerations. To improve L/D characteristics for landing, the upper flap bias was set to -20 degrees and the rudders "toed in" to -10 degrees. (Landing patterns were also flown with upper flap bias settings of -24 and -28 degrees.) This change in configuration was normally accomplished as the aircraft decelerated below .6 Mach number at approximately 30,000 feet MSL (mean sea level). The standard aileron bias setting for both configurations was seven degrees. The intermediate deflections of the upper flaps between -20 and -40 degrees served as the speedbrake for energy management in the landing pattern.

The control system included a triply-redundant, three axis (pitch, roll, and yaw rate) stability augmentation system (SAS). Pilot selection of the system feedback gain was via a seven-position rotary switch in each axis. The SAS mode switches included a position for selection of zero gain to allow test maneuvers without SAS inputs. Late in the flight program a lateral acceleration feedback (a_y feedback) was added to the yaw SAS to reduce undesirable sideslip excursions.

Pilot control of the primary control surfaces was by an irreversible dual hydraulic system with artificial feel. The hydraulic system consisted of two independent systems. Hydraulic pressure for each system was supplied by a low pressure (2,750 psi) and a high pressure (3,000 psi) electrically driven hydraulic pump.

A detailed description of the flight control system characteristics and control system performance is presented in Reference 1.

All subsystem power for the X-24B during free flight was from high-rate silver zinc batteries located in a forward nose compartment. At the beginning of the program the battery system consisted of four batteries: two 79 amp hour (Ah) for the hydraulic system pumps, one 62.5 Ah for the equipment bus and one 52.5 Ah for instrumentation which was also used as a backup emergency battery. At the end of the program the battery system consisted of five 100 Ah batteries which included one that was added to serve as a backup emergency battery. Operationally,

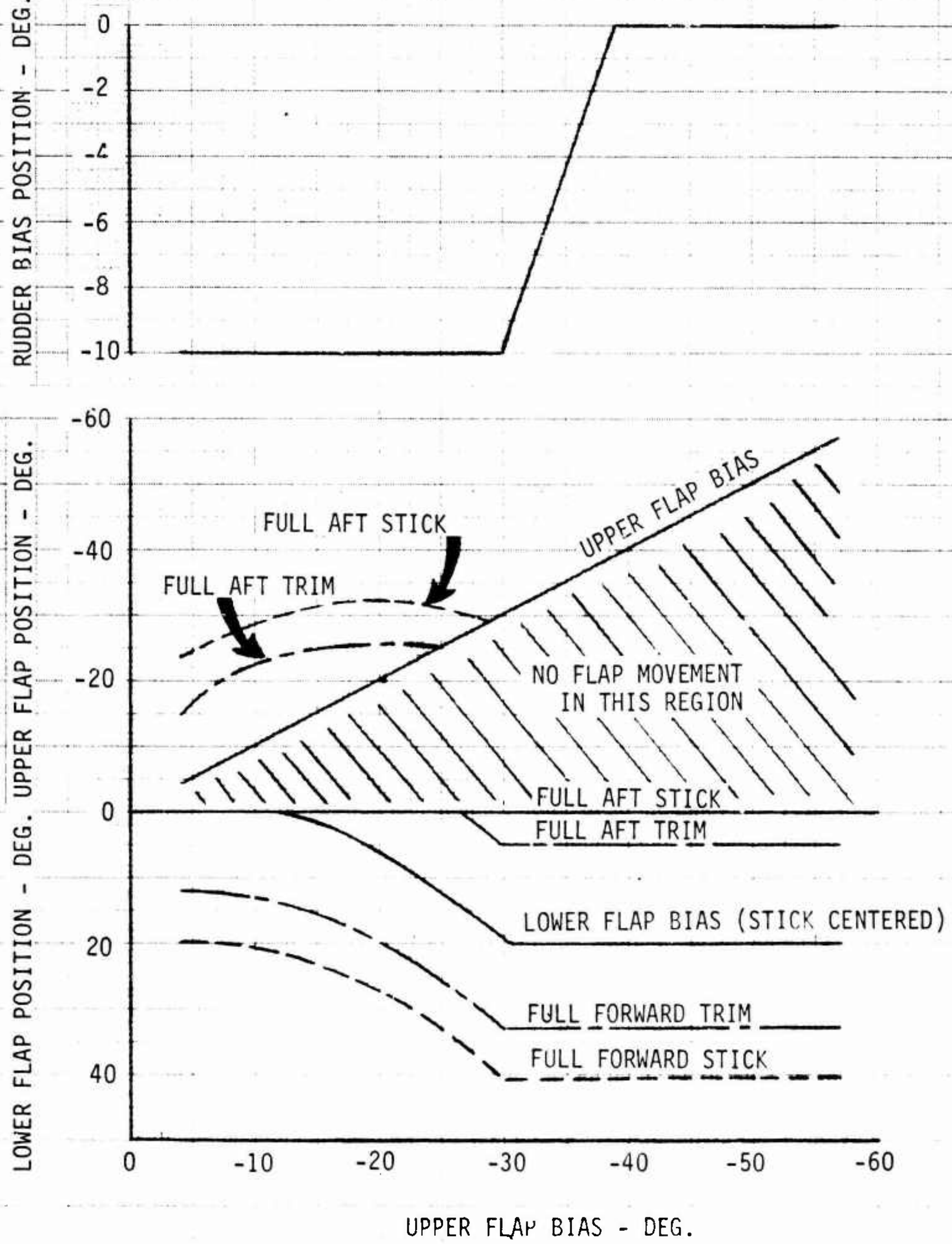


FIGURE 10 X-24B CONTROL LAWS

the batteries were used only once prior to being removed and recharged. During captive flight, power to the X-24B was obtained from the NB-52B (except instrumentation) until the five-minute-to-launch point when the pilot selected internal battery power.

The primary propulsion system for the X-24B was basically the same as used in the X-24A. The XLR-11[8] rocket engine had a nominal rating of 8480 pounds of vacuum thrust, at 265 psia chamber pressure. For the X-24B application a feature was added that allowed the engine to be operated at 300 psia chamber pressure, producing approximately 9800 pounds of vacuum thrust. However, because of start transient considerations, the engine was always started at the lower thrust level and the higher thrust was selected after the engine stabilized. The engine consisted of four regeneratively-cooled thrust chambers that could be operated individually. The propellants, liquid oxygen (LOX) and water alcohol (WALC), were forced into the combustion chambers by turbopumps driven by a gas turbine. The turbopump gas turbine was driven by decomposed hydrogen peroxide. A two compartment fuel tank contained 2510 pounds of water alcohol. The LOX tank was topped off from the NB-52B as LOX boiled off during pre-takeoff and captive flight. This tank contained approximately 2760 pounds of LOX when full. The aircraft was also equipped with two 500-pound thrust hydrogen peroxide rocket engines to be used to increase the effective L/D of the aircraft during landing, if necessary. Two hundred pounds of hydrogen peroxide for the engine turbopump and landing rockets were contained in a cylindrical tank aft of the main propellant tanks.

The existing T-38 main landing gear were retained in the modification of the X-24A airframe into the X-24B configuration. The X-24A nose gear was removed and a modified Grumman F11F-1F nose gear installed. This combination resulted in an unusual landing gear arrangement in that the main gear was significantly aft of the landing cg and the three point attitude was nose low. The landing gear was a quick-acting (approximately 1.5 second) pneumatically deployed system. The main gear deployed forward and the nose gear deployed aft minimizing the cg movement with gear deployment and consequently minimizing the longitudinal trim change. Pilot actuation from the cockpit was to the down position only.

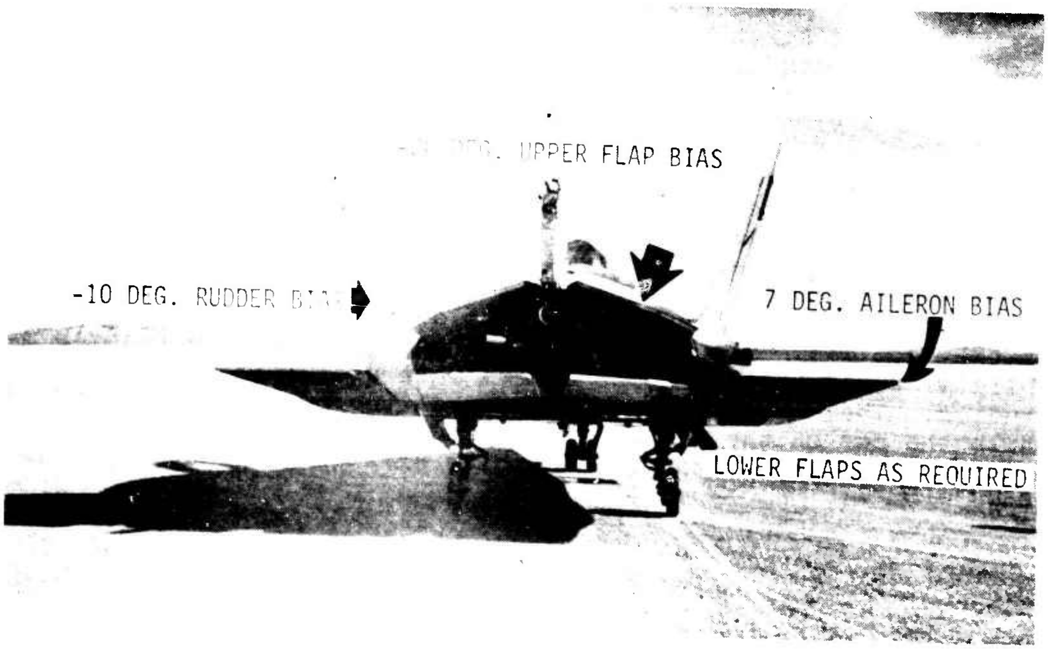
Cockpit controls and instruments were basically the same as the X-24A as described in Reference 4. Unique to the X-24B was the inclusion of an F-104 stick shaker. The shaker was set to actuate at 16 degrees indicated angle of attack to warn the pilot he was approaching an area of reduced pitch stability. Later in the program an audio sideslip warning system was added to provide the pilot with additional sideslip monitoring capability.

The primary X-24B instrumentation system consisted of a pulse code modulation (PCM) telemetry (TM) system, a set of four cameras, and a 14-channel on-board tape recorder. The X-24B data were collected from

---

[8]Similar to the engine used by the Bell X-1 in 1947

FIGURE 11 [illegible]IC/SUPERSONIC CONFIGURATION



[illegible] CONFIGURATION

on-board sensors and transducers, scaled to proper voltage levels through signal conditioning boxes, and then pulse code modulated by the PCM system. The data were then telemetered to the ground station where they were recorded on magnetic tape and displayed in real time. The CT-77B PCM system as used in the X-24B, was a nine bit-per-word, 80 word-per-frame, 200 frame-per-second system, resolved to one part in 512 with an accuracy of 0.5 percent. Initially only one CT-77B was installed in the aircraft; a second system was added later to increase the data return on each flight. Of the available 80 channels in PCM System 1, 45 were main-comm channels providing 200 samples/second data. Connected to the main commutator were parameters such as hinge moments, fin loads, accelerations and angular rates. Ten channels were used for digital on-off functions. At nine bits per channel and one parameter per bit, 90 on-off functions could be represented, 80 of which were used on the X-24B. Digital parameters included SAS and KRA status, SAS comparators, direction of movement of control surface bias, and engine functions. Twenty main-comm channels were subcommutated to provide 79 sub-comm channels with a reduced sampling rate of 50 samples/second. Such parameters as control surface positions, propulsion system pressures and temperatures, battery voltages and currents, and other miscellaneous items were represented on these channels. Two other main-comm channels were used in a second subcommutation to provide 79 sub-comm channels with a sampling rate of five samples/second. Data from the surface pressure transducers located at two locations fore and aft in the aircraft were accommodated by this second subcommutator, and by a similar subcommutator in System 2. There were a total of 251 pressure taps that shared the 156 sub-comm channels on a flight-by-flight basis. The taps were placed into four groups: fin-rudder, flap-aileron, aft-body, and fore-body with partial aft-body. Only two of these groups of pressure taps were recorded on any particular flight. PCM System 2 main-comm had, primarily, landing gear data such as gear loads, strut positions, and strut pressures. Two channels were used for a five sample/second sub-comm for the pressure survey. The on-board recorder was a fourteen-track, Astro-Science tape recorder capable of fifteen minutes data time. The "Dynamic Instrumentation" parameters required for Air Force Flight Dynamics Laboratory (AFFDL) experiments were recorded on this tape recorder. Correlatio between the on-board tape system and the telemetered system was accomplished by means of a time code generator, synchronized with time of day. On two tracks of the tape recorder, System 1 and System 2 PCM outputs were recorded as back-up to the telemetered data. The X-24B utilized four cameras located in the cockpit, in the nose, on the tip of the center fin and on the tip of the left fin. The cockpit camera photographed the pilot's panel, while pictures from the nose camera were useful in approach and landing studies. The camera on the left fin photographed tufts on the forebody while the one on the center fin photographed tufts on the upper flap and inside rudder surface, the engine exhaust plume and fuel jettison flow.

PREFLIGHT PROGRAM PREPARATION

SIMULATOR STUDIES

Early in the development of the X-24B (1971) the AFFTC mechanized a five-degree-of-freedom simulator to study handling qualities and to define the control system requirements. The results of these simulator studies were utilized to establish the design criteria for the ailerons including surface authority, surface rates and hinge moment requirements. Also defined was the lower flap pitch control gearing (Reference 1).

After the completion of the five-degree-of-freedom studies the mechanization of the six-degree-of-freedom full-mission simulator was accomplished. This simulator was initially used to define/optimize the variable features of the control system including the configuration change control law, control surface trim authorities, SAS gains and KRA schedules.

In preparation for the flight test program, parametric studies were accomplished to attain an understanding of the handling qualities and performance characteristics of the aircraft both with power on and during gliding flight including landing. Predicted controllability boundaries were defined over the anticipated flight envelope. The handling qualities were also evaluated with variations applied to the wind tunnel predicted derivatives to account for potential errors. (The simulation was "up-dated" throughout the course of the program as significant deviations between actual and wind tunnel derivatives were identified.)

These studies generally indicated that the aircraft was not very sensitive to derivative variations, which is usually an indication of good basic stability. The SAS-on handling qualities were generally expected to be good during power-off flight. Some potential problems were noted at the edges of the expected flight envelope. Based on X-24A flight experience a degradation in lateral-directional stability with the engine operating was expected, particularly at Mach numbers greater than one. The simulator indicated the aircraft might be PIO (pilot-induced-oscillation) sensitive in the lateral-directional axis at some conditions with the SAS off. A pitchup ($C_{m_\alpha} \geq 0$) at high angle of attack was predicted over the entire Mach number range. Although it was not abrupt, loss of control was possible if the pilot's attention was diverted. Since the pitchup was predicted to occur at α's above that required for normal flight control, it was felt that the pitchup condition could be avoided. The approach and landing characteristics were predicted to be improved over the X-24A. Low dihedral effect was expected to improve the lateral-directional response to turbulence during final approach. Flight characteristics in proximity to the ground were expected to be improved over the X-24A because of reduced longitudinal trim change due to landing gear deployment and a lower drag with the gear down.

The boost performance of the X-24B was reduced over that of the lifting bodies due to an increase in weight of approximately 1800 pounds. Because of the relatively low thrust to weight ratio, the angle of attack had to be maintained near maximum allowable during climb to the required altitude. Some improvement was predicted by increasing the XLR-11 chamber pressure from 265 to 300 psia. The maximum Mach number was expected to be slightly less than 1.6 at the higher chamber pressure.

CARRY ANGLE DETERMINATION

Early in the program definition phase a decision was made not to accomplish small scale wind tunnel tests of the X-24B in the presence of the NB-52B. These tests to evaluate separation characteristics were not considered necessary because of the considerable experience obtained from launching the X-15 and lifting bodies from the same general location on the NB-52B. In addition, the wind tunnel results generally did not predict the launch dynamics accurately on the other aircraft. The X-24B carry angle ($\alpha_{X-24B} - \alpha_{B-52}$) was established by comparing the launch characteristics of the lifting bodies. The X-24A and M2 launches were similar in that the normal acceleration immediately after launch ranged between -0.1 and -0.25 g's. It was decided that the X-24B carry angle would be based on a similar normal load factor at launch. The launches were also similar in that the difference between the carry angle and the free stream zero-lift angle of attack was the same (0.9 degrees). Based on this and knowing the predicted X-24B free stream zero-lift angle of attack of 2.6 degrees, the X-24B carry angle was established to be 3.5 degrees. Desired pylon hook loads were equal to or slightly greater than the weight of the aircraft to obtain the desired 0 to -.2 Δq at launch. Prior to the first launch the desired pylon hook loads were verified (at launch conditions) during the first captive flight.

AIRCRAFT BUILDUP

Prior to the delivery of the X-24A airframe to the contractor for the structural modification, all of the major systems and subsystems had been removed. Upon receipt of the X-24B airframe on 24 October 1972, the X-24B ground crew began the installation of existing and new systems. These included control system components, propulsion system, electrical system, cockpit panels and the flight test instrumentation. This task was accomplished in approximately three and a half months, and by mid-February 1973 the aircraft was ready for the series of ground tests that followed.

CONTROL SYSTEM GROUND TESTS

The control system was one of the first systems to be subjected to ground tests. Past experience with other aircraft had proven that the designed control system very often required modifications in terms of filters and/or lead-lag circuits in the stability augmentation system (SAS) to eliminate undesirable characteristics. The control system was rigged, calibrations performed, and the results were found to be as expected. SAS limit cycle tests were accomplished and adequate margins existed with the planned flight SAS gains to preclude an in-flight SAS limit cycle. During structural resonance tests, an unacceptable resonance was found in the ailerons. Once excited, neither the removal of the input signal nor disengagement of the roll SAS would stop the aileron resonance. It was determined that it was a purely mechanical resonance, sustained solely by the actuator and its associated linkage. The problem was eliminated by the addition of a mechanical damper to the actuator servo valve. Additional details on the conduct of the control system tests and the results may be found in Reference 1.

AIRCRAFT GROUND VIBRATION TESTS

Ground Vibration Tests (GVT) were conducted on the right hand strake/aileron and fin/rudder to determine actual vibration modes of these structural components. These results were found to be significantly different from the predicted math model used by the contractor in his flutter analysis. The flutter analysis was reaccomplished using the experimentally determined modal data, and adequate flutter margins still existed. Although no in-flight flutter tests per se were performed on the aircraft, strain gages on these surfaces were monitored during captive flight. Reference 7[9] presents the details of the conduct and results of these ground vibration tests.

STRUCTURAL LOADS CALIBRATION

Load calibration tests were accomplished on all ten movable control surfaces plus the left fin and strake to obtain relationships between applied loads and strain gage responses. The left fin and strake assembly were removed from the aircraft and mounted in a calibration structure. A 4000 pound compression load (approximately 51 percent of limit load) was applied to the strake/aileron from the bottom surface in an upward direction. The fin was loaded in tension through a whiffle tree and glue-on-pad system representing 17 different centers of pressure on the fin. The strain gage outputs were measured and the appropriate load equations were derived to allow interpretation of flight results.

WEIGHT, BALANCE AND INERTIA MEASUREMENTS

The aircraft weight, longitudinal, and lateral centers of gravity were determined by the conventional three-point weighing method on the AFFTC Weight and Balance Facility. The vertical cg was determined experimentally by two methods. The first method consisted of measuring the gear reactions at various nose up and nose down attitudes on the adjustable weight tables (Figure 13). The second method entailed suspending the aircraft at a single point and placing known weights at specific locations and measuring the resulting attitude change of the aircraft (Figure 14). The two results were in excellent agreement.

The pitch and roll inertias were determined experimentally by the "rocking table" technique (Figure 15). Experimental procedures for these tests are described in Reference 8.[10] The yaw inertia and the

---

[9] Reference 7: Long, James A., 1st Lt/USAF and Berry, Robert L., Sgt/USAF, X-24B Ground Vibration Test (Strake/Aileron, Fin/Rudder), AFFTC TR-73-23, Air Force Flight Test Center, Edwards AFB, California, June 1973

[10] Woodfield, A.A., Measurement of the Yawing Moment and Product of Inertia of an Aircraft by the Single Point Suspension Method: Theory and Rig Design, Royal Aircraft Establishment TR 68044, February 1968

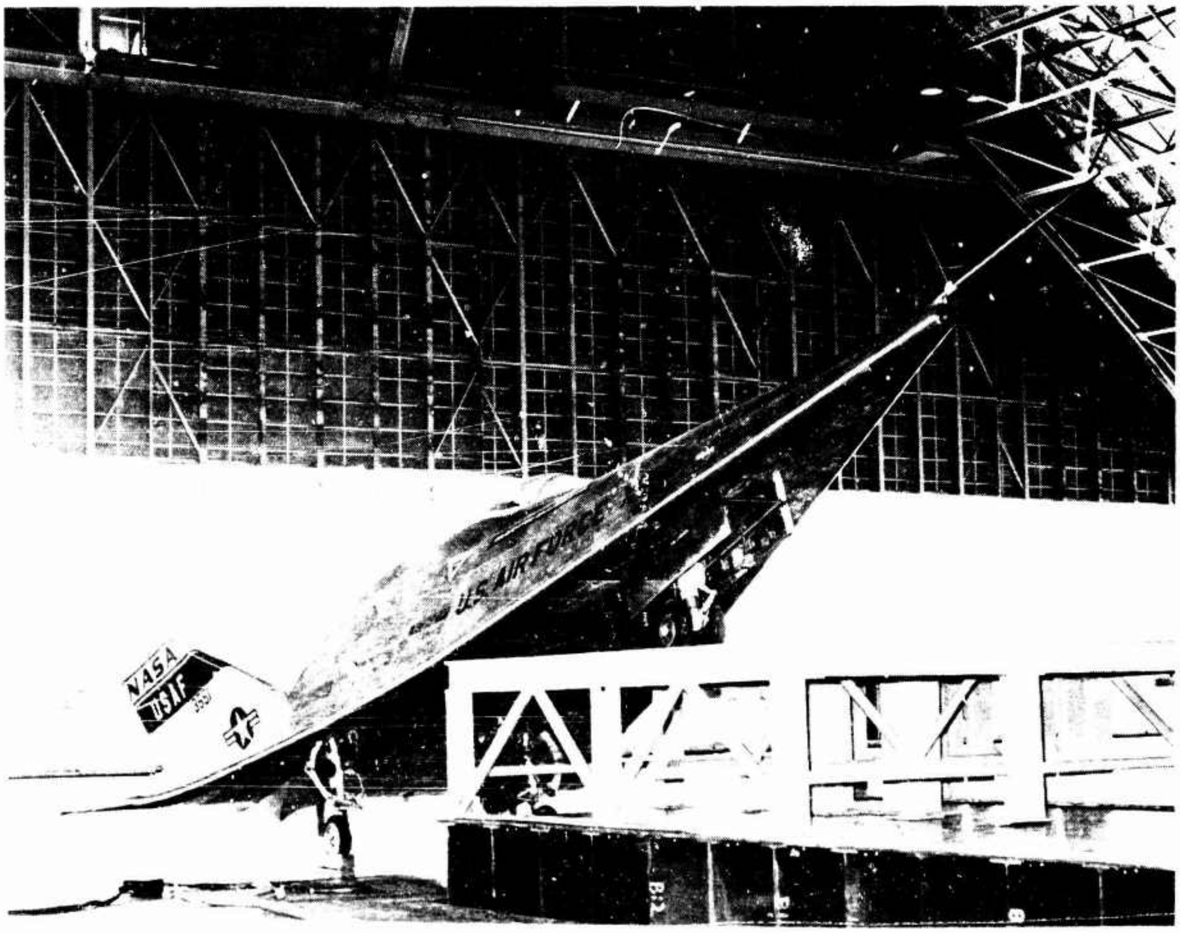


FIGURE 13 X-24B VERTICAL CG TEST - GEAR REACTION TECHNIQUE

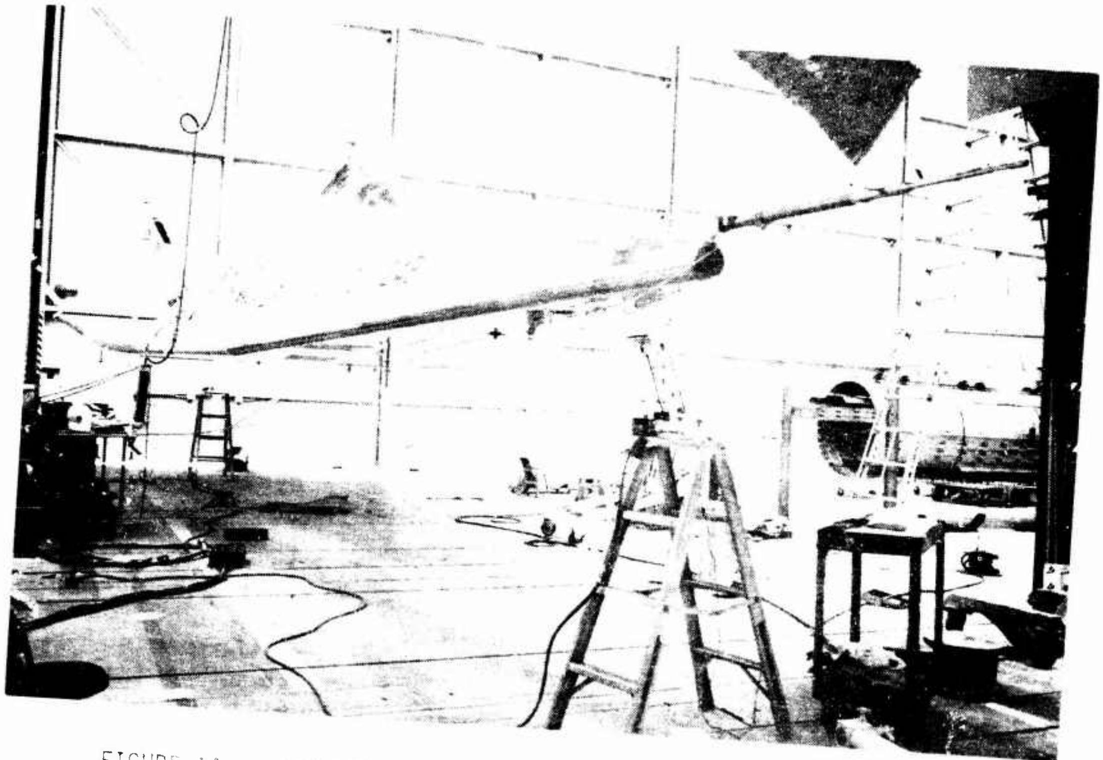


FIGURE 1[illegible] [illegible] VERTICAL CG TEST [illegible]

[illegible]

product of inertia (I_{xz}) were determined by suspending the aircraft by a single cable and restraining the aircraft with springs at both ends. This technique is described in detail in Reference 9.[11] Typical mass characteristics for a powered flight are presented in Table II.

MAIN GEAR TIRE TESTS

The X-24B landing loads were predicted to be significantly higher than experienced on the X-24A. The increased landing loads were primarily due to the addition of air loads immediately after touchdown as the aircraft pitched over to a negative lift attitude. (Because of the unusually forward cg relative to the main gear location, the X-24B nose could not be held off with aerodynamic controls after touchdown.) In addition, it was desired that the landing gear system be capable of withstanding the higher loads that would result from a heavy weight landing if the propellants could not be jettisoned after an engine failure after launch. To provide additional tire capability 12-ply T-38 tires were selected rather than the 10-ply tires used on the X-24A. Dynamic load tests were performed on the tires at WPAFB. At the anticipated loading the tread of the tires repeatedly separated from the casing. Later tests revealed that shaving the tread from the tire (thru the first ply) resulted in satisfactory tire performance. Thus it was decided that a new set of shaved tires would be used for each X-24B flight.

MAIN GEAR DRAG LOAD TESTS

Drag load tests were accomplished on the main gear to verify that the downlock would hold as the drag loads approached design values and to verify the strength of the gear backup structure. (Laboratory tests on a spare landing gear system at AFFDL showed a tendency for the downlock to unlock under load.) This test consisted of incrementally applying a 2500 pound gear drag load while measuring the tendency of the gear over-center lock to open. During the initial tests the left gear performed satisfactorily; however, the right gear exhibited a tendency to unlock. The tests were terminated and the gear inspected. The right main gear actuator was reworked by shimming the locking device to allow a slight amount of free play in the actuator in the locked condition. The tests were repeated and the measured deflections were small and in the proper direction to maintain the overcenter lock condition.

NOSE GEAR TESTS

Drop tests were performed by a contractor on the modified F11F-1F nose gear used on the X-24B. The tests were accomplished to determine

[11] Reference 9: Retelle, John P., Jr., Captain, USAF, Measured Weight, Balance, and Moments of Inertia of the X-24A Lifting Body, FTC-TD-71-6, Air Force Flight Test Center, Edwards AFB, California, November 1971

the metering pin configuration required to provide the needed load/ stroke characteristics. The tests were also accomplished to calibrate the installed strain gages in order to obtain meaningful landing load data during the flight program.

Nose gear "slap down" tests were performed to verify the strength of the new backup structure and to verify the energy absorbing capability of the nose gear and new metering pins in the actual aircraft installation. The drop tests were conducted by elevating the nose of the aircraft with the main tires restrained and releasing the aircraft from increasing heights (Figure 16). To produce appropriate nose gear drag loads the nose tires were rotated with a spinup device prior to release. The structure and nose gear performance were determined to be satisfactory.

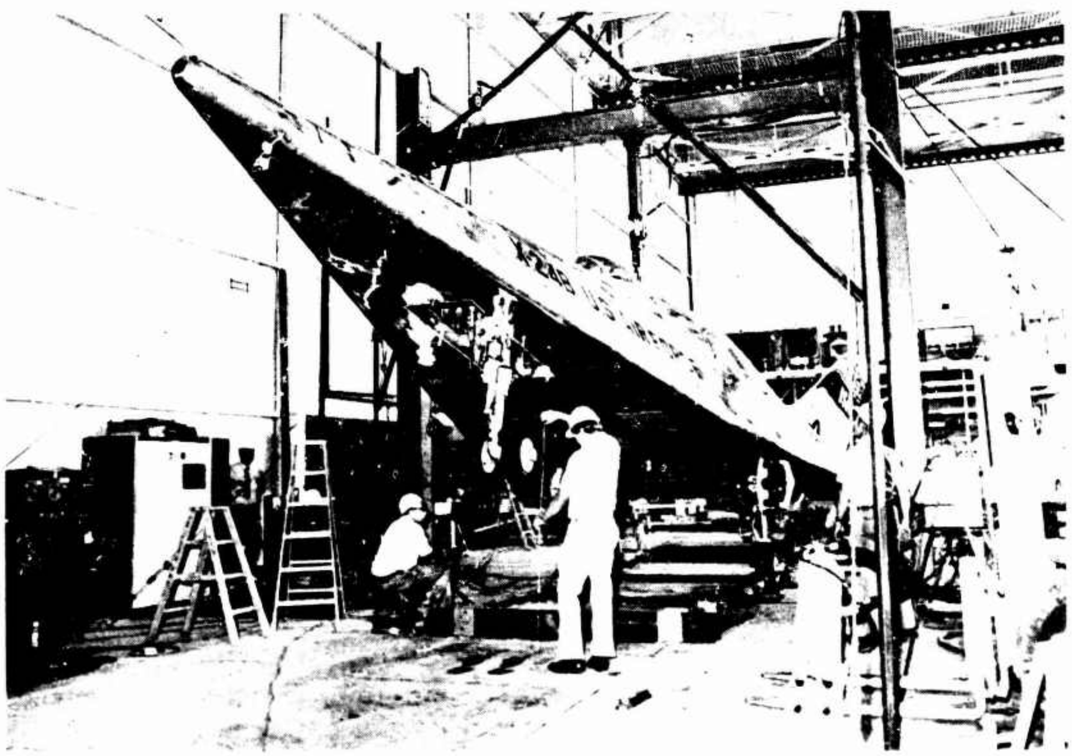


FIGURE 16 X-24B NOSE GEAR SLAPDOWN TEST

MATED GROUND VIBRATION TESTS

The X-24A pylon adapter was structurally modified to accept the X-24B configuration prior to modification of the aircraft. In order to obtain early verification of the adapter structure, mated ground vibration tests were accomplished with the X-24A[12] mated to the NB-52B. The natural frequencies of the mated combination were determined to investigate potential coupling with NB-52B wing modes. Extrapolation of the test results indicated that the lateral bending frequency of the X-24B at maximum gross weight would be approximately 2.7 Hertz. This was below the minimum of three Hertz which had been previously established for the lifting body vehicles. The original selection of this minimum value was based on the fact that there were several NB-52B wing modes in the frequency range of 2.5 - 2.8 Hertz. It was felt that by keeping all structural modes above those frequencies, flutter margins would be assured without performing a detailed flutter analysis or wind tunnel tests. With this early identification of a potential problem with the lateral bending mode (using the X-24A), adequate lead time existed to contract for a flutter analysis of the X-24B/NB-52B combination.

The mated GVT were reaccomplished after the X-24B was delivered. During the initial tests with the X-24B empty, the pylon pitch frequency could not be isolated from other NB-52 modes. The lightweight tests were repeated during the heavyweight tests a month later. The pylon pitch frequency was finally isolated by testing with and without X-24B nose ballast. The removal of the ballast changed the pylon frequency but did not significantly affect the wing frequencies, thus permitting the pylon mode to be identified. Tests of the heavyweight configuration were accomplished by filling the propellant tanks with water and liquid nitrogen to simulate the water-alcohol and LOX propellants.

The resulting frequencies are shown below:

	Lightweight	Heavyweight
Pitch	3.55 Hz	3.57 Hz
Side bending	2.97 Hz	2.38 Hz
Yaw	4.60 Hz	4.37 Hz

The frequencies determined for the lightweight condition were considered adequate in relation to the original lifting body criteria of 3.0 Hertz. Clearance for heavyweight operation was not obtained until the completion of the flutter analysis. For both cases the pylon damping was determined incrementally at increasing airspeeds during captive flight.

[12] Prior to shipment of the X-24A to the contractor for modification

TAXI TESTS

Taxi tests of the X-24B were performed to check for nose gear shimmy, to evaluate nose gear steering and to assess overall ground handling characteristics. The primary concern was that if severe nose gear shimmy was experienced at touchdown on the first flight the additional dynamic load, when added to the already high landing loads expected, might result in failure of the nose gear or back-up structure. Thus an incremental speed buildup taxi test program was conducted.

The first phase consisted of low speed taxi tests using the two 500-pound hydrogen peroxide rockets. Five test runs were accomplished on a concrete taxiway to speeds between 40 and 48 KTS (max attainable with available H_2O_2). The pilot felt that the nose gear steering was too sensitive on the first run, so the gearing was changed from ± 15 degrees to ± 7.5 degrees for full rudder deflection. The latter setting proved to be satisfactory and was used for the remainder of the tests and the remainder of the program. A mild nose gear shimmy was observed (by ground observer) at approximately 30 KTS during the runs on the taxiway. A run was then made on the lakebed to 30 KTS and no nose gear shimmy was observed.

The second phase of the taxi tests was performed on lakebed runway 36 using the XLR-11 rocket engine. In an incremental buildup test three runs were made to 80, 125, and 150 KIAS. The first run to 80 KTS was accomplished using only one chamber of the XLR-11 for acceleration. In order to maintain the aircraft weight as close as practical to the "no-propellant" landing weight only that amount of propellants necessary for the planned engine operation was serviced. However, because of the difference in design of the LOX and fuel tank feed systems, significantly more LOX (in excess of 1000 lbs) was required than fuel. Since the LOX and fuel tanks were located on opposite sides of the aircraft (left and right respectively) the lateral cg was approximately two inches further left than normal. This left cg offset relative to the thrust line and differential gear loading was expected to result in a tendency for the aircraft to track to the left during acceleration. The pilot confirmed that this nose-left moment was significant and had to be countered with intermittent right braking. The 125- and 150-KIAS runs were performed with two XLR-11 chambers. The nose gear steering (even at 150 KIAS) and ground handling characteristics were found to be satisfactory. No nose gear shimmy was experienced during the tests.

Because of the extra long ground roll during high-speed tests (acceleration and deceleration); tire performance, particularly the resulting tire temperature, was of concern. A taxi test was performed with a T-38 aircraft to 150 KTS to obtain baseline data on tire temperature and to establish operational procedures. Using temperature sensitive paint it was found that tire temperatures between 200 and 250 degrees F could be expected. Safe operating limit for this class of tire was considered to be 250 degrees F. During the actual X-24B taxi tests, maximum tire temperatures between 200 degrees and 250 degrees F were recorded.

MATED TAXI TESTS

As a final check of X-24B/pylon/NB-52B wing dynamics, a mated taxi test to approximately 80 knots was performed on the main runway. Because of known interference in telemetry reception between the main runway and the control room, a TM van was positioned next to the runway to record and evaluate aircraft accelerometer measurements. No dynamic problems were observed and the X-24B pilot reported that the "ride" was smooth and compared favorably with the lifting bodies.

CAPTIVE FLIGHT

Prior to the first free flight attempt, a planned captive flight was flown with the following objectives:

1. Determination of NB-52B/pylon/X-24B dynamic response
2. Confirmation of captive airloads and carry angle
3. Landing gear extension after cold soak
4. X-24B systems checkout
5. Pre-launch checklist confirmation

The flight was conducted under the philosophy that; (1) the X-24B and its pilot were ready for flight and, (2) the mothership would stay within X-24B gliding distance of a dry lake runway in case an emergency launch became necessary. During takeoff and initial climb the X-24B was configured in a "ready-to-launch" status: hydraulic pumps on and control surfaces set to launch settings. This was necessary because the pilot could not eject while the X-24B was mated.[13] The emergency procedure would have been to launch, and then eject from the aircraft if a landing was not feasible. After takeoff the NB-52B airspeed was maintained at less than 200 KIAS during the climb to 30,000 feet MSL. At that altitude the pylon dynamics were evaluated by exciting the system thru NB-52B rudder pulses. These were accomplished during an incremental speed buildup to 250 KIAS in order to clear the mated pair to fly at the desired NB-52B climb speed of 240 KIAS. The pylon dynamics for this lightweight configuration (no propellants) were found to be acceptable. During this speed buildup sequence, the X-24B control surfaces were checked for structural resonance by exciting the control surfaces thru the SAS gyro-torque test system. No resonance was found. Upon completion of the test at 30,000 feet MSL, the NB-52B climb was resumed to 40,000 feet MSL to verify countdown checklist functions to a simulated launch. Pylon load measurements verified the adequacy of the selected X-24B carry angle on the pylon to produce the proper incremental load factor for separation.

---

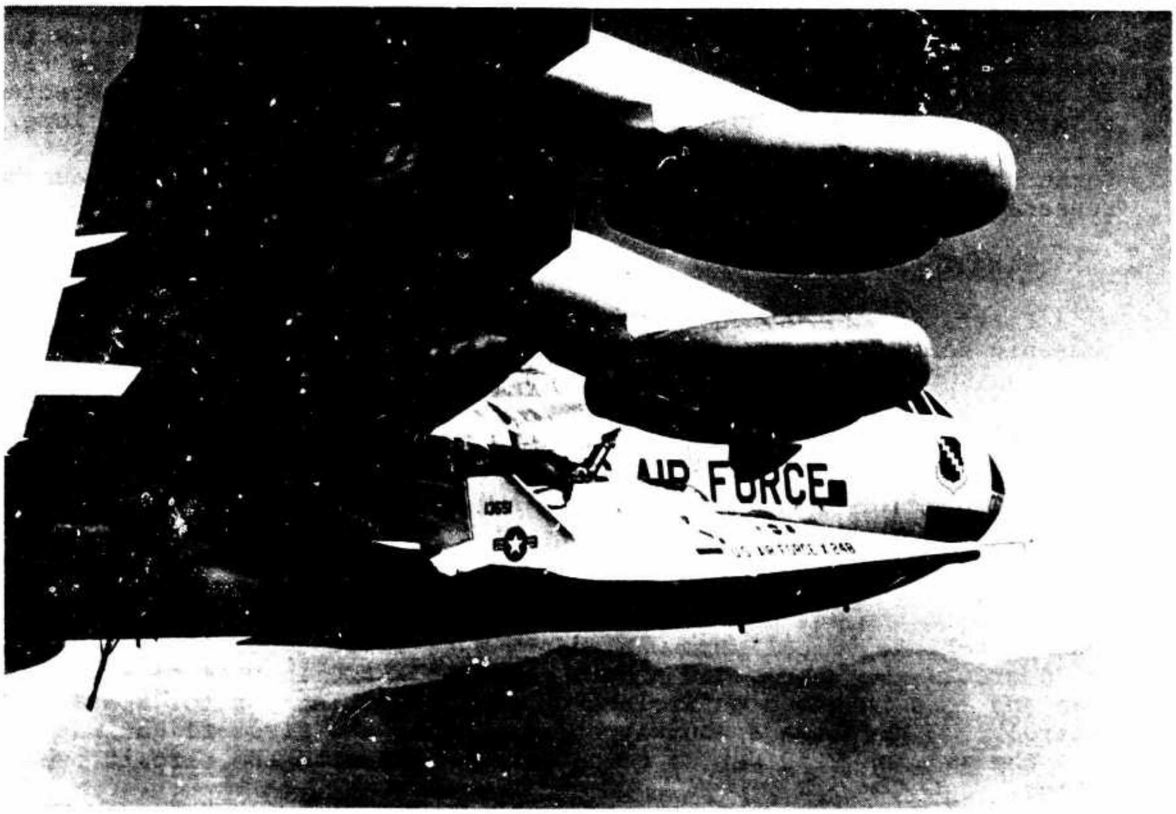
[13] The X-24B was the first aircraft from which the pilot could not eject while mated to the NB-52B. To obtain acceptable loads on the forward hook of the existing X-15 pylon, the X-24B adapter was located further aft under the X-15 pylon than the lifting bodies. This design compromise was allowed based on the proven safe operation of the X-24A propulsion system, the successful operating record of the mothership and the redundancy of the launch system.

After the simulated launch point was reached, a rapid descent was performed to check for possible X-24B windshield fogging and to allow a minimum elapsed time prior to landing. The latter condition allowed the NB-52B to arrive at the aircraft mating pit to test X-24B gear deployment after the altitude-cold-soak cycle. Inadequate main gear ground clearance while mated precluded this test from being performed during mated flight.

The X-24B PCM data system was found to be too noisy using NB-52B power, so power was transferred to the X-24B battery to complete the flight. As a result the X-24B instrumentation battery was changed from a 52 amp-hour battery to a 100 amp-hour battery and all subsequent flight operations were performed using the X-24B battery for instrumentation beginning at NB-52B taxi.

XLR-11 ENGINE TESTS

The X-24B propulsion system (tankage plus engine) remained basically the same as used in the X-24A with only minor modifications. The ignition system was modified to utilize the YLR-99 rocket engine (X-15 engine) spark plugs for improved ignition performance and reliability. This modification also included a new ignition unit which used DC power rather than an AC power source. Modifications were also made to allow the engine to operate at increased thrust level corresponding to a chamber pressure increase from 265 psi to 300 psia. The modifications/component changes were ground tested on the X-24B propulsion system test stand (PSTS). The PSTS was a duplicate of the X-24B propulsion system used initially during the X-24A test program.



GLIDE FLIGHT PROGRAM

GENERAL

The X-24B Glide Flight Program consisted of six glide flights, two of which were to provide flight experience for the Air Force test pilot who had no previous experience in this type of aircraft. The first powered flight was made after only five glide flights in three and a half months, whereas the X-24A required nine glide flights and eleven months. This timely completion of the glide phase of the X-24B program was possible because of the excellent handling qualities of the aircraft in the subsonic Mach range, the relatively trouble-free performance of the aircraft subsystems and the experience level of the test team.

The main purpose of the glide program was to determine the aircraft's low Mach number flight characteristics thru flight verification of the wind tunnel-predicted aerodynamic coefficients and thru pilot evaluation of the flight characteristics in comparison to the six-degree-of-freedom simulation. Also of prime interest was the performance of the modified control system, particular the ailerons. Due to the anticipated high landing gear loads of this particular configuration, determination of the loads was an important result obtained from each landing. In order to preclude the reoccurence of "afterfire" during jettison of the residual WALC experienced with the X-24A, a relocated jettison line was evaluated during the glide program.

FIRST FLIGHT CONDUCT

The first flight of the X-24B was planned to fulfill two main objectives: (1) to provide the pilot with adequate evaluation tasks and experience to accomplish a safe landing; and, (2) to obtain sufficient verification of predicted flight characteristics and data to allow the second flight to be planned with fewer unknowns. In planning the flight to accomplish these objectives, benign flight conditions were selected to minimize the risk and exposure to extremes of the flight envelope. The elements of the first flight will be discussed in detail to set forth the rationale and technique for a first flight of an air launched research aircraft of this type.

Flight Planning Considerations:

First, it was decided that the flight would be accomplished in the subsonic configuration (-20 degrees δU_B). This permitted the entire flight to be directed toward evaluating the basic configuration to be used for landing and allowed a limit to be placed on the maximum deflection of the upper flaps. Simulator studies had shown that a flare and landing at the low L/D associated with the -40 degree upper flap configuration would be an extremely demanding piloting task to safely accomplish. Although the basic flap bias system was the same proven system used in the X-24A, many electrical wiring changes had been made in the aircraft and it was considered advisable to guard against a runaway flap to the -40 degree position. Therefore the upper flap bias microswitch electrical stop was adjusted to limit upper flap travel to -32 degrees. This provided a more reasonable L/D in case of a runaway flap and also retained sufficient upper flap deflection for speed brake control. To preclude a runaway aileron bias, the first flight was flown with the aileron bias set to seven degrees and with the circuit breaker pulled.

The cg range for a powered flight varied from 66 percent at launch to 64 percent after propellant consumption and therefore most landings were normally at 64 percent. For the first flight the cg was moved aft from the normal emptyweight cg of 64 percent to 65 percent (by removing nose ballast). This resulted in a slight decrease in longitudinal stability but was intended to avoid flight within the crossover deadband between the lower and upper flaps and the resulting possibility of degraded handling qualities during the landing. The simulator was altered and all pilot training was accomplished at a cg of 65 percent.

At the time the flight plan was developed for the first flight, wind tunnel data for the -20 degree upper flap configuration was limited to .7 Mach number and below. It was known from X-24A results and early FDL-8 configuration wind tunnel data that the lateral-directional stability could be degraded at Mach numbers above 0.7 in the -20 degree upper flap configuration. Thus, it was decided to limit the Mach number on the first flight to .7 and below. It was found during simulator studies that the Mach number could be kept below .7 Mach number if the aircraft was launched from 40,000 feet MSL rather than the normal NB-52B capability of 45,000 feet MSL. Thus, 40,000 feet MSL was selected for the first launch.

Flight Conduct:

The primary longitudinal control parameter from launch to low key was angle of attack. The pilot maintained an angle of attack schedule determined on the simulator as a function of either altitude or airspeed. Small variations to the planned angle of attack schedule were performed occasionally, based on ground control calls to maintain the planned altitude versus range profile within acceptable limits.

The first 8,000 feet of altitude loss after launch was flown at 10 degrees angle of attack while performing the required data maneuvers. During this period the pilot correctly detected lower longitudinal stability than he had observed on the simulator. A roll maneuver was performed to ±30 degrees bank angle to evaluate the aileron control. The pilot felt that the roll response and stick harmony was "as good as, if not better than the simulator". Next the pilot performed a rudder and aileron doublet set from which lateral-directional stability and control derivatives were later extracted. Post flight analysis found that there were no major discrepancies in the predicted lateral-directional derivatives. (Had the lateral-directional control been deficient in this area the pilot was prepared to extend the upper flaps to increase the stability.) A pitch pulse was then performed which allowed the longitudinal derivatives to be determined. The C_{m_α} determined from the maneuver was significantly lower than wind tunnel prediction confirming the pilot observation of lower pitch stability (Reference 1).

One of the key pilot evaluation maneuvers of the first flight was the execution of a practice approach and flare. This provided the pilot the opportunity to evaluate the aircraft's flight characteristics at high altitude (30K to 24K) prior to the actual landing approach and flare. Exposure of the aircraft to high dynamic pressure during the practice approach presented the opportunity for anomalies (control system limit cycle, structural resonance, etc.) to occur early where proper corrective action could have been taken prior to the landing pattern. For the selected 300 KIAS final approach the resulting Mach number would be approximately 0.5. However, altitude effects on Mach number during the practice approach at high altitude dictated that the airspeed be limited to 270 KIAS to keep the Mach number below 0.7. The practice approach was accomplished as planned and no unusual high $\bar{q}$ characteristics were encountered. During the five degree angle of attack acceleration to 270 KIAS the pilot evaluated the aircraft's handling qualities and was "very pleased how it handled", particularly in roll. The flare characteristics were close to those observed on the simulator in terms of altitude and airspeed lost during the maneuver. During the practice flare the pilot closely evaluated the roll control looking for potential PIO tendencies. There was "absolutely no trace" of any PIO and the pilot remarked that the aircraft responded "beautifully in roll".

The next data maneuver performed was a pushover-pullup (POPU). This consisted of a slow sweep in angle of attack over a relatively large range to determine lift and drag characteristics, including maximum L/D. This maneuver also allowed definition of longitudinal trim characteristics (angle of attack versus lower flap deflection). The telemetered values of these two parameters were monitored in real time on an X-Y plotter in the control room. As the maneuver was performed, a comparison was made to the expected α vs δe_L variation. Had the slope of α vs δe_L been such that the angle of attack for landing required close to zero lower flap deflection, then the pilot would have been advised to extend the upper flap bias from -20 degrees to -25 degrees. Because the lower flaps program mechanically as a function of upper flap bias this action would have extended the lower flaps and insured that crossover between the lower and upper flaps would not occur during landing. This action was not required. In fact, there was more margin than expected for the lower flap deflection at touchdown due to the lower-than-predicted pitch stability.

After the completion of the pushover-pullup maneuver, in only two minutes elapsed time from launch, all required data maneuvers had been accomplished and the pilot had satisfied himself that the aircraft's handling qualities and performance would be satisfactory for landing. To this point the pilot had flown "head-in-the-cockpit" making corrections to the planned ground track between data maneuvers based only on calls from ground control. The pilot visually checked his position, arrived at the low key point at 22,000 feet, and began the 180 degree turn to final approach. (Figure 17 presents an illustration of a typical X-24B landing pattern.) Approaching the ninety degree point in the pattern the pilot detected that he was too high and extended the upper flaps (speed brakes) to -32 degrees. The pilot was very pleased with the energy management control provided by the speed brakes, remarking, "it was just gorgeous the way the airplane changed L/D". Passing 7,000 feet the pilot retracted the upper flaps to -20 degrees and rolled out on final. The maximum airspeed on final approach was 290 KIAS and the handling qualities were good with no unusual characteristics being experienced. The aircraft responded nicely during the flare maneuver. The landing gear were extended passing thru 240 KIAS and the pilot could not detect any significant trim change. Touchdown occurred at 164 KIAS and the pilot commented that "I had beautiful control of the airplane above the runway, no PIO tendency either in pitch or roll. It was one of the most pleasant flying airplanes right above the runway that I've flown."

From this successful beginning, the glide flight program proceeded rapidly with the expansion of the Mach/angle of attack flight envelope and the testing of systems required for powered flights.

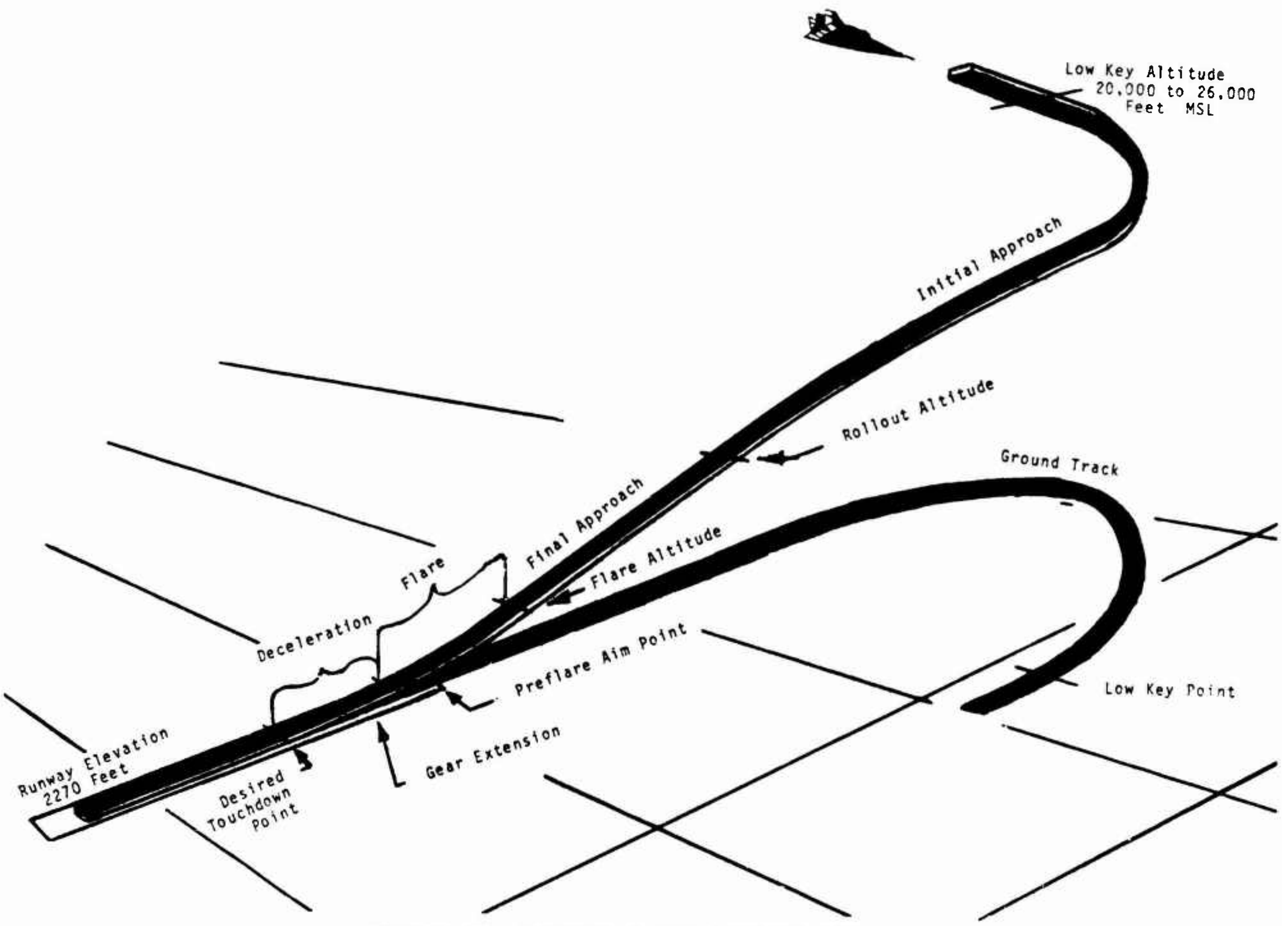
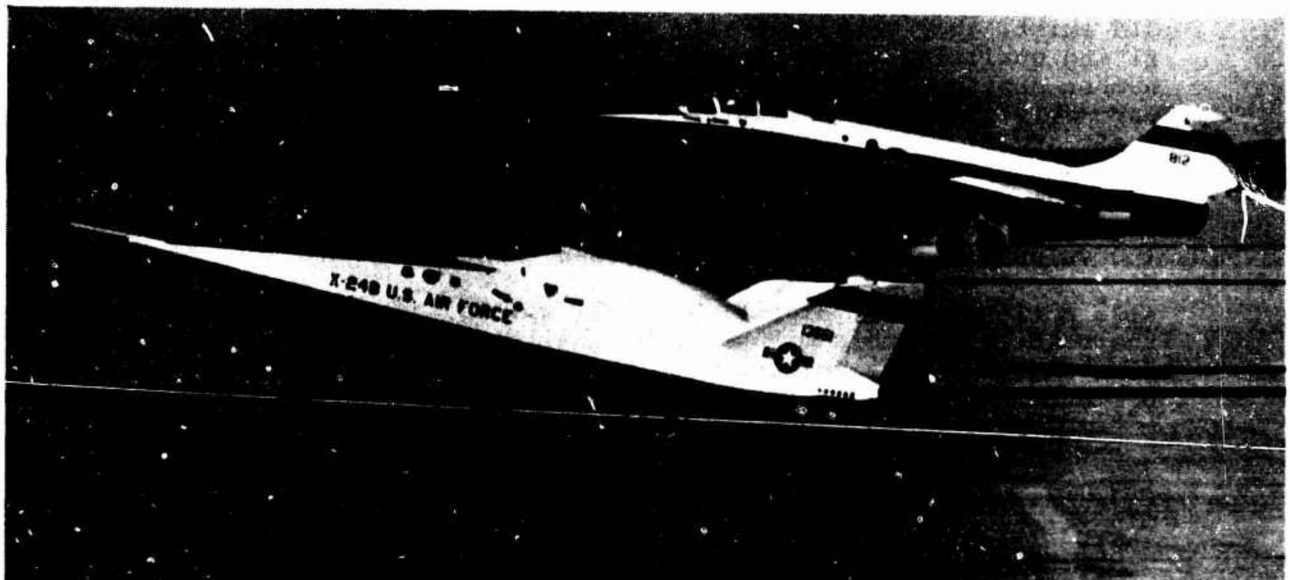


FIGURE 17 TYPICAL X-24B LANDING PATTERN



GLIDE FLIGHT RESULTS

Glide Flight Envelopes:

The envelopes of Mach number vs altitude and Mach number vs angle of attack covered during the first four glide flights are presented in Figures 18 and 19. Upon completion of the fourth glide flight adequate data had been obtained to proceed with the first powered flight. However the fifth flight was also a glide flight to check out a new pilot and therefore was flown within these envelopes. The maximum Mach number obtained during the glide flight program was 0.73. Data obtained within these envelopes were mainly in the -40 degree and -20 degree upper flap configurations with one test at -13 degrees upper flap bias, which allowed evaluation of the flight characteristics using the upper flaps for longitudinal control. All but one glide flight was flown at a mid-range cg of 65 percent. One glide flight was flown at 64 percent to duplicate a typical landing after a powered flight.

Performance and Handling Qualities:

The L/D variation with angle of attack was close to wind tunnel predictions, and no significant variations from predicted glide performance were apparent during the conduct of the flights. Although the pitch stability was less than predicted, the overall longitudinal handling qualities of the aircraft during the glide flights were considered good. In an attempt to account for the lower-than-predicted longitudinal stability the aircraft and wind tunnel model mold lines were remeasured, and the aircraft cg was verified. No significant discrepancies were found. Detailed analysis of the surface pressures after the program indicated lower suction pressures on the aft upper surface of the aircraft than the wind tunnel data (Reference 10).[14] This would result in a forward shift of the center-of-pressure on the aircraft with a corresponding reduction in stability. The lateral-directional handling qualities was also considered very good. The lateral-directional stability derivatives were close to predictions, and, where variations did exist, they were generally in a direction to further enhance the flying qualities. The overall handling characteristics below .5 Mach number during final approach and landing were excellent. The pilots favorably compared the handling characteristics to fighter type aircraft (T-38, F-104). The handling and riding qualities in turbulence during the landing approach were greatly improved over the lifting bodies. The high diehedral effect of the lifting bodies led to disconcerting roll upsets due to sideslips in turbulence. The X-24B, with low values of negative C_{ℓ_β}, rode thru turbulence with more of a side-to-side motion without significant roll upsets and was more acceptable to the pilots. Dampers-off handling qualities in the landing pattern were also found to be excellent with the pilots commenting that they couldn't believe the dampers were really off.

---

[14] Reference 10: Selegan, David R., and Norris, Richard B., Comparison of X-24B Flight and Wind Tunnel Pressure Distributions, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, to be published

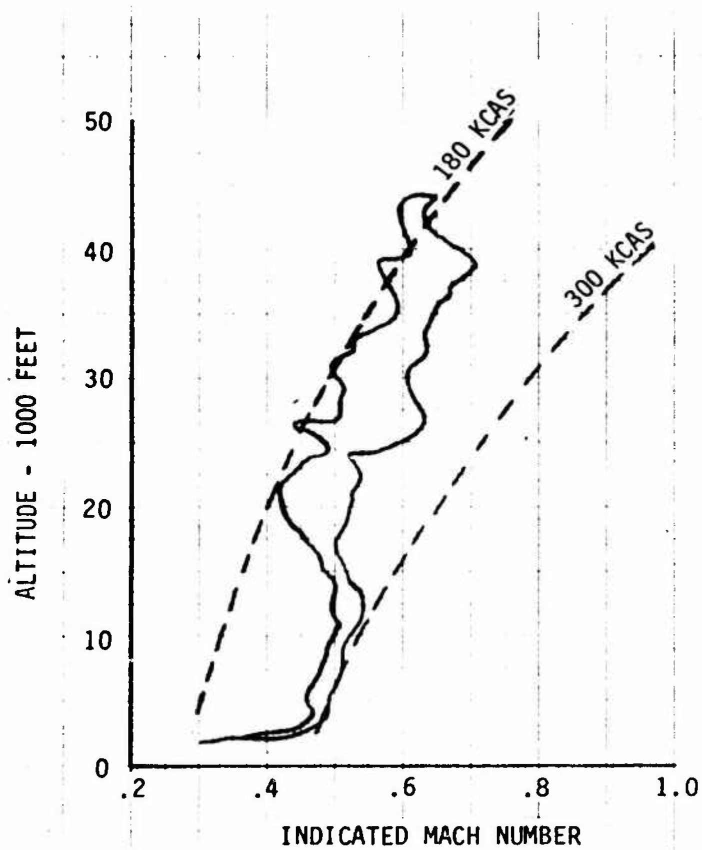


FIGURE 18 X-24B GLIDE FLIGHT ENVELOPE MACH NUMBER VS ALTITUDE

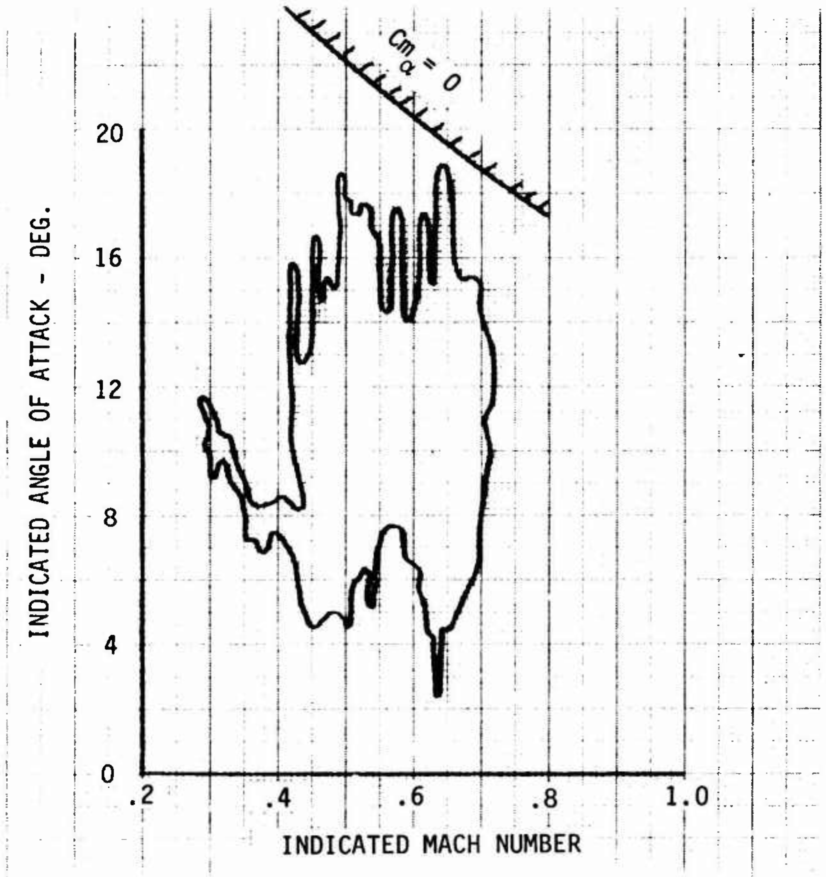


FIGURE 19 X-24B GLIDE FLIGHT ENVELOPE MACH NUMBER VS ANGLE OF ATTACK

During the design of the aircraft and control laws, attention was given to minimizing longitudinal trim changes. The payoff was very favorable pilot comments with respect to trim changes due to configuration change, speedbrake actuation and landing gear extension.

Control System:

The initial attempt to fly the first flight was aborted prior to launch when the SAS failed to pass a gyro test. Post-flight troubleshooting and teardown inspection by the manufacturer failed to conclusively reveal the cause of the malfunction (Reference 1). All SAS gyros were replaced prior to the next flight attempt and the problem never reoccurred during the flight program.

The first two glide flights were flown with all four hydraulic pumps operating throughout the flight. On the third glide flight the lower pressure pumps (2750 psi) were intentionally left off until low key to evaluate the feasibility of routinely operating on two hydraulic pumps (except for the landing pattern), thus reducing battery power consumption. (This technique had proven satisfactory on the X-24A.) The control system performance was not found to be degraded thus clearing the way to operate with only two hydraulic pumps on the longer duration powered flights.

The overall control system performance during the glide flights was satisfactory and no undesirable characteristics (limit cycle, resonance, etc.) occurred.

Inflight Fuel Jettison Tests:

Both the X-24A and M2 lifting bodies experienced in-flight damage as a result of ignition of the water-alcohol (WALC) during jettison of the unused propellants after engine operation (Reference 4). It was determined that the ignition source was a residual afterfire of the water alcohol that remained in the XLR-11 rocket chambers after shutdown. With the WALC jettison lines located near the engine in the blunt rear of the lifting bodies, turbulent flow allowed the jettisoned WALC to mix with the air contacting the engine chamber, resulting in ignition. It was found that the afterfire in the chambers could exist for long durations so it was not practical to delay jettison expecting the afterfire to extinguish. The proposed solution was to move the WALC jettison line to a location of streamline flow away from the base area.

The AFFDL conducted flow visualization wind tunnel tests to determine an acceptable location for the WALC jettison line. It was found that locating the jettison line in the cove area between the fin and the strake would provide the desired results.

In implementing this concept on the aircraft the WALC jettison line was rerouted so that it exited in the cove area at approximately a 45 degree angle near the mid chord of the right aileron (Figure 20) such that the thrust produced by the jettison mass flow would act approximately through the cg. This modification was checked out in flight on the third glide flight. A small amount of WALC (approx 350 lbs) was serviced in the tank and a short jettison cycle was performed during free flight. The chase pilot reported that there was no recirculation of the fuel into the base area near the engine. However a significant right rolling moment was produced which required the pilot to use seventy percent of the available aileron deflection to counteract for the four seconds jettison duration. In retrospect, it was not difficult to realize that an aerodynamic interference could have resulted from the WALC flowing outboard over the upper aileron surface.

After the flight the jettison line was further modified (Figure 21) so the WALC exited aft of the aileron and parallel to the longitudinal axis of the aircraft. The in-flight tests were repeated on the fourth glide flight and there were no significant trim changes noted. The jettison flow still appeared satisfactory and without recirculation in the base area. (No in-flight jettison fires occurred during the powered flights.)

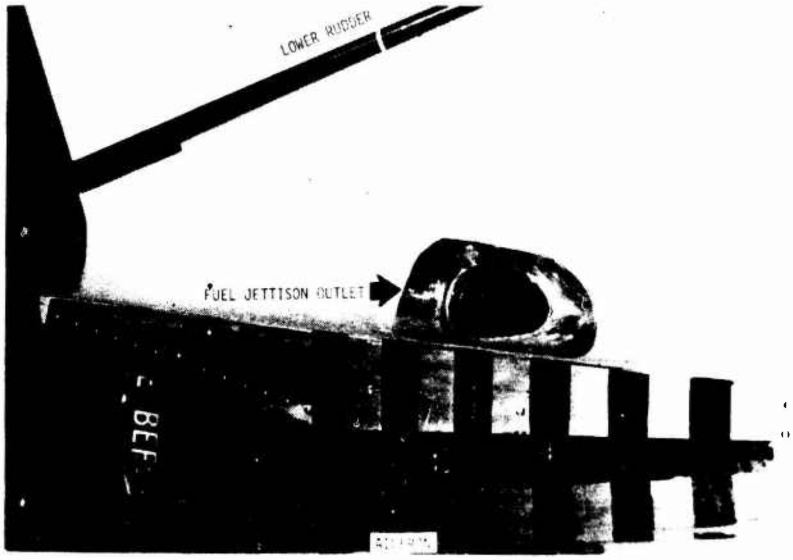


FIGURE 20 X-24B FUEL JETTISON OUTLET - INITIAL MODIFICATION

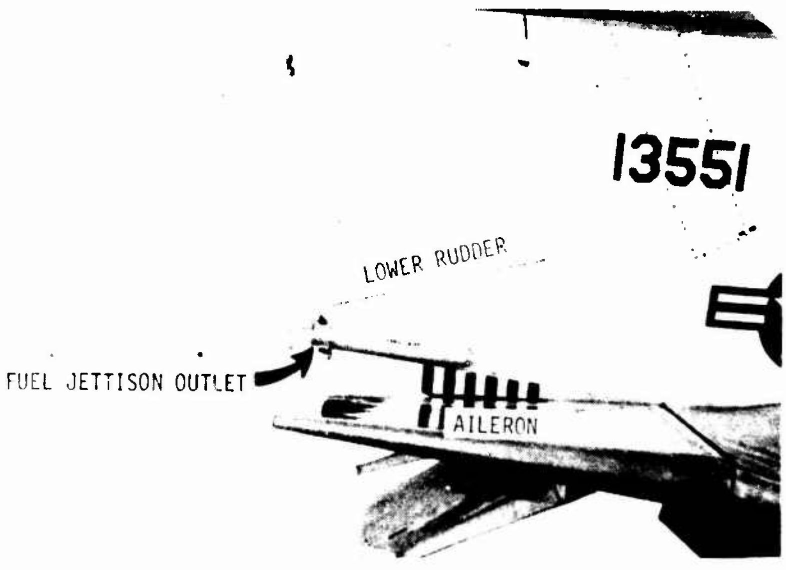


FIGURE 21 X-24B FUEL JETTISON OUTLET - FINAL CONFIGURATION

GENERAL

Twenty-four powered flights were flown during the flight program by three pilots. The Mach number envelope expansion to 1.76 was accomplished in ten powered flights. In the following 14 powered flights the angle of attack envelope was expanded and the remaining research data collected. There were five flights where the primary research data maneuvers at high Mach number were not obtained as a result of propulsion system problems. On four occasions one of the XLR-11 chambers failed to light after launch and three-chamber alternate missions were flown. On one flight the engine shut down prematurely as a result of a crack in the bulkhead between the fore and aft WALC tank compartments.

A typical X-24B powered flight generally consisted of three piloting phases during the boost: (1) a rotation after launch at constant angle of attack to achieve a positive climb rate; (2) a climb at either a constant pitch attitude or angle of attack to a predetermined pushover altitude; and, (3) an acceleration at low angle of attack (low induced drag) to the desired maximum Mach number. During the envelope expansion flights the key stability and control data maneuvers were performed immediately before and after engine shutdown. Power-on and -off data at similar conditions (M and α) were obtained to evaluate suspected power effects on stability and control derivatives first observed on the X-24A. After engine shutdown a variety of test maneuvers were performed during gliding flight down to the low key point at which time the pilot began the pattern for the power-off landing. The powered portion of all flights was flown with -40 degrees upper flap bias because of stability and control considerations. The change to the approach and landing configuration (-20, -24, or -28 degrees) was normally accomplished between 25,000 and 35,000 feet MSL in a Mach number range between .5 and .6. Table III presents a summary of the range of flight conditions experienced during the powered flights.

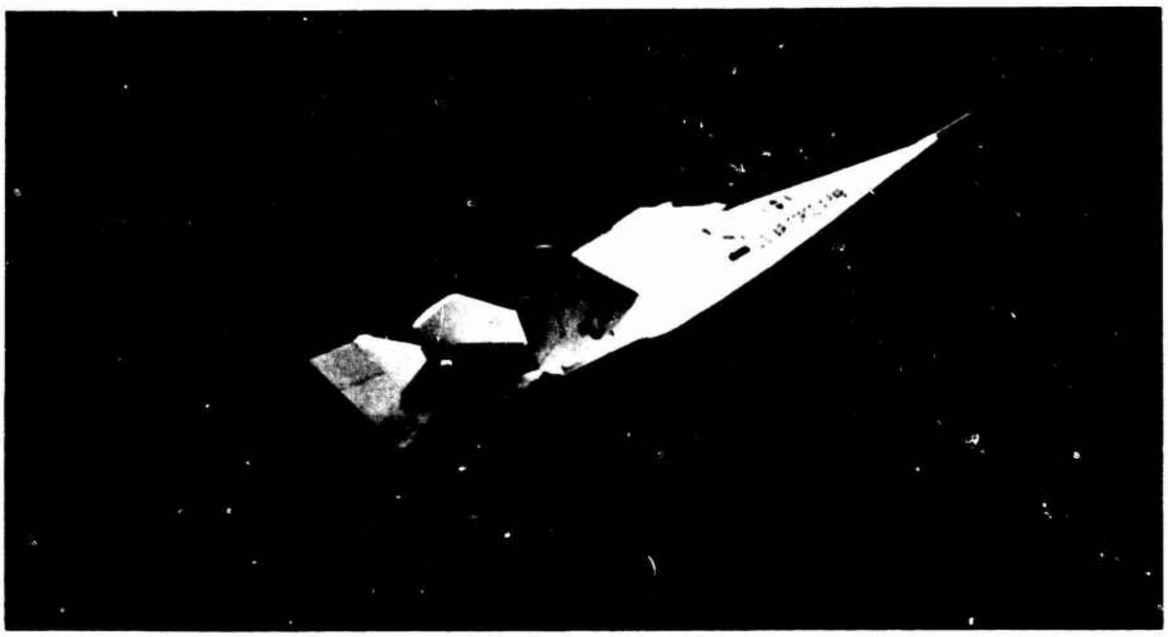


TABLE III

RANGE OF FLIGHT CONDITIONS FOR X-24B POWERED FLIGHTS

	Min	Max
Flight Time - min:sec	6:35.8	7:57.5
Engine Burntime - sec	106	156
Maximum Mach Number	.876	1.76
Maximum Altitude - ft MSL	52040	74130
Dynamic Pressure (during powered flight) - PSF	52	218
Calibrated Airspeed (during powered flight) - KTS	135	314

At this point the reader should be reminded that the aerodynamic configuration of the X-24B was optimized for a gliding reentry mission from orbit and not necessarily for the flight conditions experienced during the X-24B powered trajectories. From this standpoint, the powered phase of the X-24B flight could be considered as only a means to achieve the desired conditions to adequately evaluate the characteristics associated with gliding flight. Hence, some of the deficiencies and operational problems discussed herein would not necessarily have impacted a reentry mission. However, these power-on factors and findings are of technical interest because of the possibility that future powered hypersonic vehicles could possess features similar to the X-24B.

FIRST POWERED FLIGHT

Preparation for Powered Flights:

Since the propulsion system had been activated prior to the first glide flight in order to accomplish the high speed taxi test, no major modifications were required to prepare the aircraft for the first powered flight. A new adjustable engine thrust mount was installed and the thrust vector aligned to the desired point. The engine was then ground tested in preparation for flight.

A captive flight was flown with the X-24B serviced with propellants to verify the adequacy of the NB-52B/pylon/X-24B dynamic response at heavy gross weight, to partially check out the propulsion system after cold soak at 40,000 feet MSL, and to exercise the prelaunch checklist. Due to a malfunction of the X-24B cabin pressure system the maximum altitude of the captive flight was limited to 25,000 feet MSL rather than the planned 40,000 feet MSL. The pylon damping was determined to be satisfactory and the prelaunch checklist timing was also verified.

Conduct of the First Powered Flight:

One of the major considerations in planning the first powered flight was to minimize the change in flight conditions (M, α, $\bar{q}$) to be experienced during the rotation after launch over those already experienced during the glide flights. In order to arrest the sink rate after launch and to prevent excessive buildup in Mach number and dynamic pressure during the rotation, a high angle of attack had to be maintained. Tests during the third glide flight verified both the longitudinal and lateral-directional flight characteristics at .7 Mach number and 14 degrees angle of attack. Simulator studies had shown that a Mach number of approximately .87 could be expected during a rotation at 14 degrees α after a launch from 45,000 feet MSL with all four rocket chambers operating. In order to reduce this Mach increment the first flight was flown from 40,000 feet MSL with only three chambers operating. This resulted in a maximum Mach number during the rotation of .75 which was reasonably close to that experienced on the glide flight. The key data maneuvers that were performed later during the flight were longitudinal and lateral-directional maneuvers to determine derivatives near .85 Mach number to allow an increase in allowable rotation conditions on subsequent flights.

The handling qualities of the aircraft during the first powered flight were found to be satisfactory except for a small amplitude, lightly damped PIO-type oscillation in the lateral-directional axis that occurred shortly after launch. The primary cause of the oscillation was concluded to be the result of a small deadband in the left-hand aileron (0.6 degrees peak to peak). At the roll SAS gain used for this flight, the magnitude of the roll rate excursions experienced produced commands to the aileron that were within this deadband so no surface movement occurred. Thus the effective roll SAS gain was only half the desired value. For subsequent flights the roll SAS gain was increased and the oscillation never reoccurred. However the aileron deadband continued to occur despite extensive rework of the system between flights. The cause of the aileron deadband was later discovered to be excessive cold soak of the aileron linkage compartment as a result of LOX overflow from the LOX vent tube located upstream of the aileron linkage compartment (to be discussed later).

The performance during rocket engine boost of the first powered flight was significantly higher than planned on the simulator (without a correction to base drag). The aircraft achieved .917 Mach number in 150 seconds at engine shutdown (pilot actuated) as compared to the simulator prediction of .85 Mach number in 164 seconds. In addition the maximum altitude achieved was higher than planned; 52,760 feet MSL actual vs 48,000 feet MSL planned. The higher-than-planned peak altitude was determined to be the result of the pilot's pitch attitude vernier display being in error by two degrees. On this flight the pilot maintained a constant pitch attitude (θ) during the climb and as a result of the error in displayed θ, he climbed at 22 degrees rather than the planned 20 degrees. To assess the discrepancy in boost performance (time to climb and accelerate) a post-flight simulator match was performed. This was accomplished by reflying the flight on the simulator as closely as possible to the technique used by the pilot during the actual flight. To account for the effect of upper altitude winds on the performance, the winds measured by a rawinsonde on flight day were included in the simulation. Performance sensitive parameters were varied and the resulting effects observed on a plot of Mach number versus altitude (including times from engine light). Parameters varied included thrust, normal force, chord force, and weight. An acceptable match of the performance could only be obtained with a reduction in chord force coefficient of .005. (This corresponds to a 5.5 percent reduction in zero-lift chord force coefficient.) From other data obtained in gliding flight it was known that this reduction in chord force coefficient did not exist with the rocket engine off. The same magnitude reduction in base drag with the rocket operating had also been found necessary to match simulator and flight performance on the X-24A. This apparent increase in base pressure with the engine operating could have been associated with the fact that the engine nozzles were optimized for 37,000 feet MSL and were underexpanded at higher altitudes resulting in a higher pressure in the base area. This change to the chord force coefficient proved to be appropriate and remained a permanent change to the simulation for the remainder of the program.

POWERED FLIGHT PROGRAM RESULTS

Launch Characteristics:

Separation clearance during launch was evaluated from airborne cameras located in the NB-52B and on the pylon adapter. The launch transient was mild and clearance between the NB-52B/pylon and the X-24B was satisfactory. The lower flap was normally set so that the aircraft would trim at the desired angle of attack (nominally 10 degrees) after the initial nose down pitch. A left roll off was normally experienced to bank angles less than 10 degrees. The range of the key parameters associated with the X-24B launches are shown in Table IV for both the heavy and light weight conditions.

TABLE IV

RANGE OF PARAMETERS DURING X-24B LAUNCHES

Parameter	Glide Flight		Powered Flight	
	Min	Max	Min	Max
Altitude ~ ft/1000 MSL	40	45	40	46.5
Airspeed - KIAS	175	185	184	200
Mach Number	.60	.70	.63	.76
Pitch Rate ~ Deg/Sec	-3	-7	-6	-9
Roll Rate ~ Deg/Sec	-16	-22	-12	-20
Yaw Rate ~ Deg/Sec	0.5	2.0	1.0	3.0
Normal Acceleration ~ g	-0.11	-0.42	-0.18	-0.48
Longitudinal Acceleration ~ g	-0.20	-0.35	-0.20	-0.32

Handling Qualities:

The envelope expansion of the X-24B was governed by the determination of the adequacy of the aircraft's stability and handling qualities. The Mach number expansion was completed in ten consecutive powered flights in Mach number increments of .1 to .22. Of these ten flights, two did not achieve the planned Mach number as a result of propulsion system problems and one was a planned subsonic pilot checkout flight. Thus it could be considered that the Mach envelope was effectively expanded in seven "successful" consecutive powered flights. A composite of the Mach numbers and angles of attack experienced during the flights is presented in Figures 22 and 23 for both power on and power off, respectively. Also shown are the handling qualities boundaries established in Reference 1.

The lateral-directional handling qualities received the most attention during the envelope expansion primarily due to uncommanded sideslip excursions and early indications of lower-than-predicted values of C_{n_β}. Although the amplitude was small (less than four degrees β) considerable analysis was devoted to the explanation of the cause of uncommanded sideslip excursions because they appeared to indicate a lack of directional stability at the conditions encountered. The two areas where the uncommanded sideslips occurred were both with the rocket engine operating; one at approximately .9 Mach number above 10 degrees α and the the other at Mach numbers greater than 1.3 at seven degrees α and above. As Figure 22 shows, although the aircraft was not directionally unstable in these areas, C_{n_β} was indeed close to zero. The forcing functions that caused the sideslip excursions in these areas of low directional stability were determined to be upsets caused by climbing rapidly through wind shears and a misalignment of the thrust vector of the rocket engine, (Reference 1). The impact of this characteristic on flight planning was a self-imposed temporary limitation of usable angle of attack (α < 12 degrees at .9 Mach and α < 8 degrees above 1.3 Mach) during boost in the areas of low directional stability. After the first occurence of the steady sideslip above 1.3 Mach number at 7 degrees α on flight 18 (and prior to the discovery of the thrust misalignment) action was taken to: (1) temporarily limit α to 5 degrees above 1.3 Mach number, (2) install an audio β warning signal (set at 3.5 degrees β) for the pilot, and (3) develop a control system modification to reduce the sideslip.

Since the rudder effectiveness was still high in these areas it was felt that the addition of lateral-acceleration (a_y) feedback in the yaw damper would reduce the steady sideslip encountered above 1.3 Mach number. Little improvement was expected in the uncommanded sideslip encountered at .9 Mach number because the dynamic pressure was low. After the a_y system was fully checked out and the proper gain established, flights at 7 degrees α above 1.3 Mach number were accomplished (flights 23 and 24) and some reduction in steady sideslip was realized. However the most significant "fix" resulted when the engine thrust vector was realigned prior to flight 26. Prior to the first powered flight, the engine was aligned 0.313 degrees to the left to point the thrust vector through the laterally offset cg of -.75 inches at station 130. After flight 24 the engine alignment was remeasured and determined to be 0.66 degrees left. This amount of misalignment was sufficient to produce the sideslip observed. No explanation for the engine alignment discrepancy was determined.

The foregoing discussion of deficient handling qualities was applicable only during the boost with the rocket engine operating. The handling qualities at the same flight conditions with the engine off were significantly better due to increased directional stability. The improvement is indicated in a comparison of Figures 22 and 23, where $C_{n_\beta} = 0$ with the power off was found to occur at a higher angle of attack. (Post program analysis of surface pressure data indicated less sideforce on the fins with the engine operating than when the engine was off, Reference 10.) The handling qualities with the power off at supersonic and transonic conditions were found to be satisfactory. However it should be noted that the angle of attack for zero C_{n_β} above 1.3 Mach number was significantly lower than predicted and would likely limit the gliding performance of a reentry vehicle (to be discussed later).

The longitudinal handling qualities were found to be acceptable throughout the flight envelope even though the pitch stability was determined to be lower than predicted, particularly at subsonic speeds. The only area of concern for longitudinal control was during the rotation after launch when the pilot was required to fly at high angle of attack at the aft cg location near the $C_{m_\alpha} = 0$ boundary (Figure 22). It was primarily for this flight condition that a stick shaker was added to warn the pilot when the aircraft approached the "pitchup" boundary. This was considered necessary because of the high pilot work load after launch in maintaining precise control of α while igniting the four rocket chambers. The rotations were normally accomplished at 15 degrees α and the stick shaker was set to activate at 16 degrees α in order to avoid the $C_{m_\alpha} = 0$ condition at approximately 18 degrees α.

It was determined that the maximum obtainable angle of attack for full aft stick was lower than predicted above 1.4 Mach number. While this limitation would be undesirable for a reentry vehicle it provided a useful feature to the research aircraft in that it automatically provided a degree of avoidance for the flight conditions where directional stability was marginal (Figures 22 and 23).

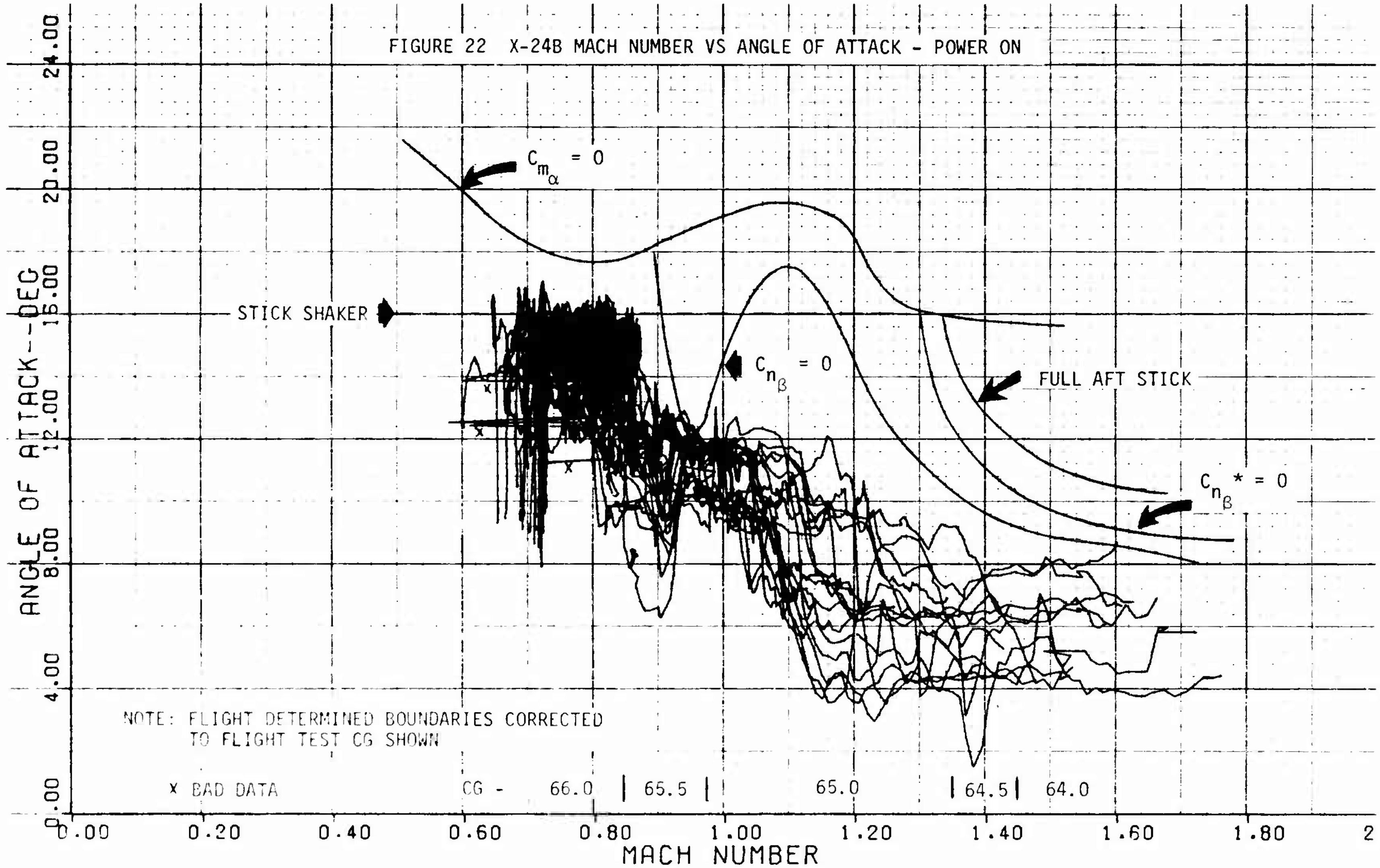


FIGURE 22 X-24B MACH NUMBER VS ANGLE OF ATTACK - POWER ON
$C_{m_\alpha} = 0$
STICK SHAKER
$C_{n_\beta} = 0$
FULL AFT STICK
$C_{n_\beta}{}^* = 0$
NOTE: FLIGHT DETERMINED BOUNDARIES CORRECTED TO FLIGHT TEST CG SHOWN
x BAD DATA
CG - 66.0 | 65.5 | 65.0 | 64.5 | 64.0
ANGLE OF ATTACK--DEG
0.00
4.00
8.00
12.00
16.00
20.00
24.00
MACH NUMBER
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2

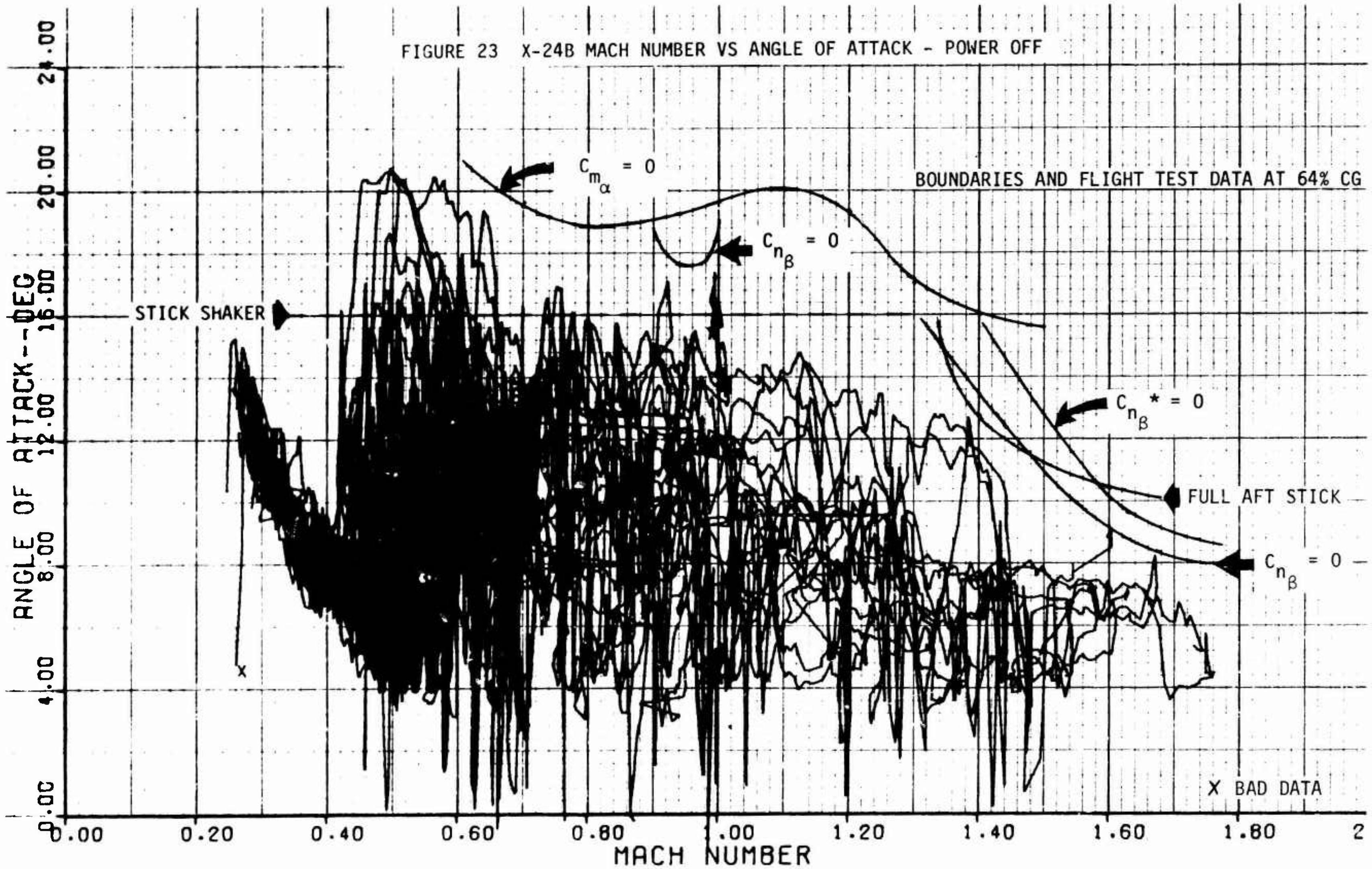


FIGURE 23 X-24B MACH NUMBER VS ANGLE OF ATTACK - POWER OFF

Performance and Trajectory Control:

As mentioned previously, during the initial flights special attention was given to an incremental build-up of Mach number during the rotation after launch. The approach was to minimize the Mach number during the rotation, then later during the flight (at high altitude) obtain stability and control data that would allow the next rotation to be performed with increased confidence at a higher Mach number. Figure 24 presents the performance factors relative to this rotation buildup. Shown are data from an early simulator study accomplished nine months prior to the first flight along with data from the simulator that was updated prior to planning the powered flights. Readily apparent is the extreme sensitivity of the resulting Mach number and airspeed during the rotation to the angle of attack maintained during the rotation. One concern was how close the pilot could maintain the planned angle of attack at a condition of low pitch stability. Note that the rotation on the first and second flight was accomplished at 14 degrees α because of the unknowns associated with the predicted $C_{m_\alpha} = 0$ and $C_{n_\beta} = 0$ boundaries. Shown also is the stick shaker actuation at 16 degrees α. This was to warn the pilot that the aircraft was approaching the boundary if his attention was taken momentarily from the α meter while performing other tasks such as lighting the rocket engine chambers. Advantage was taken of two ways to reduce the rotation Mach number - a lower thrust level during the rotation and a lower launch altitude. The flight sequence started with a 40,000-foot launch using three rocket chambers, followed by an increase in launch altitude to 45,000 feet MSL using three chambers, then finally the standard 45,000 feet/four chamber launch/rotation. Note however that the rotation angle of attack was increased to 15 degrees, which became the standard rotation α for the remainder of the flights. Using this sequence the Mach number buildup during the rotations was .756, .833, and .871.

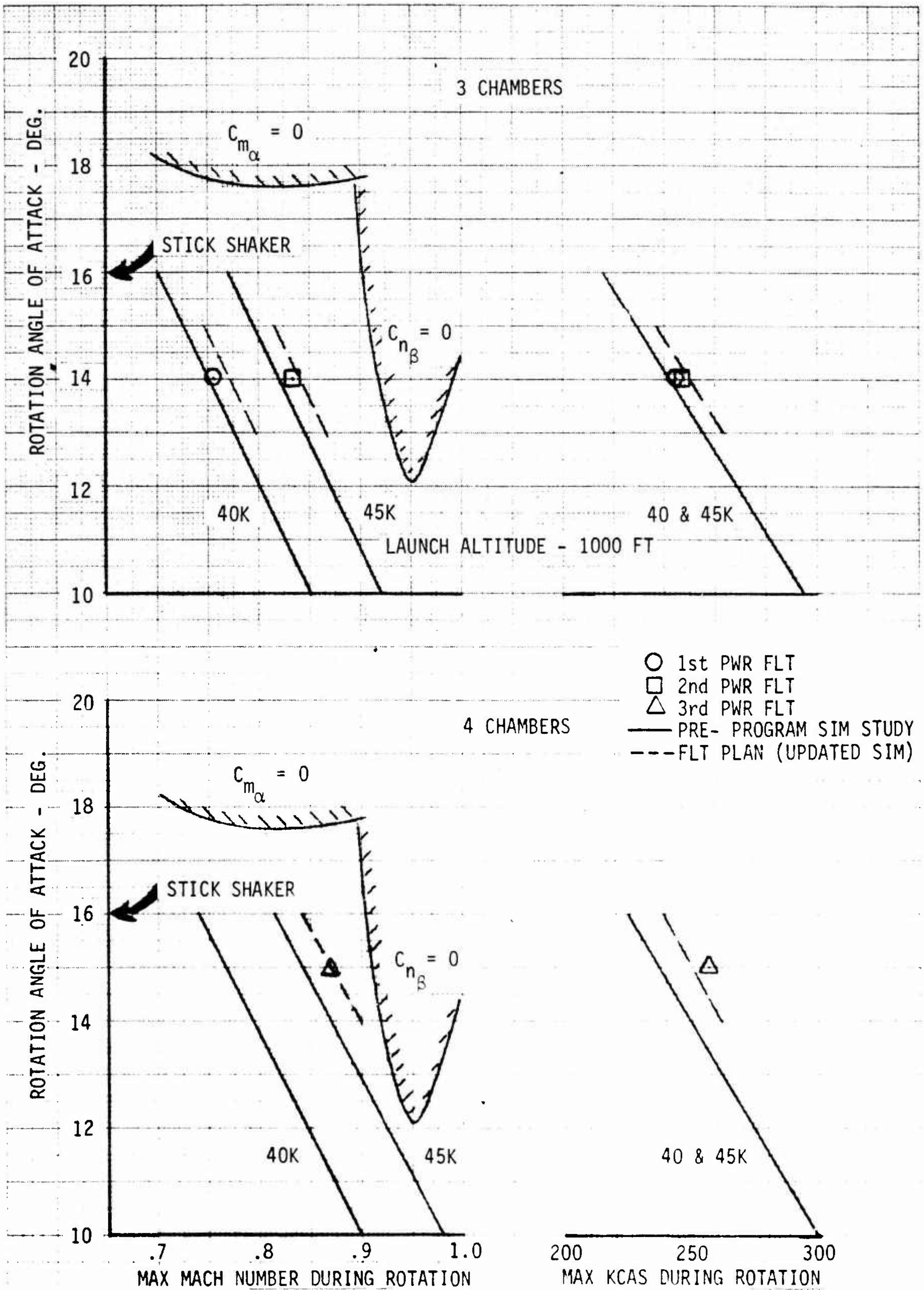


FIGURE 24 X-24B ROTATION CONDITIONS

In order to provide final documentation of additional factors associated with a typical X-24B powered flight a time history of the maximum Mach number flight (Flight 16) is presented in Figure 25. Chronologically after launch, the engine chambers were ignited in opposing pairs and the angle of attack was increased to 15 degrees. The thrust level was increased from 265 psia to 300 psia chamber pressure 30 seconds after launch when the rotation was completed. (Selection of the higher thrust prior to 30 seconds would have resulted in higher values of Mach number and airspeed during the rotation.) The maximum normal acceleration during the rotation was 1.5 g. The climb was also accomplished at 15 degrees α and was maintained within ± 1 degree. In order to verify the desired trajectory control, the pilot crosschecked pitch angle, altitude, and Mach number versus time based on that expected from simulator training. The maximum pitch angle during the climb was 45 degrees. A pushover from 15 degrees to 10 degrees angle of attack occurred at .87 Mach number to avoid the area of low directional stability above .9 Mach number and 12 degrees angle of attack discussed previously. The airspeed was at its minimum value (150 KCAS) during the boost at this condition, resulting in reduced aerodynamic restoring moments. The pushover to five degrees angle of attack was accomplished by the pilot after reaching 1.05 Mach number. Shortly after pushing over to five degrees angle of attack the aircraft achieved the maximum altitude and the remainder of the acceleration was accomplished in a descent, such that at engine burnout the aircraft was at a nose down pitch angle of -12 degrees. The engine burntime (to LOX feedline unport) was 135 seconds. This final acceleration was characterized by a rapidly increasing airspeed (dynamic pressure). The structural dynamic pressure limit (300 psf) was also a flight planning constraint to the final acceleration. The maximum Mach number achieved on this flight was 1.76.

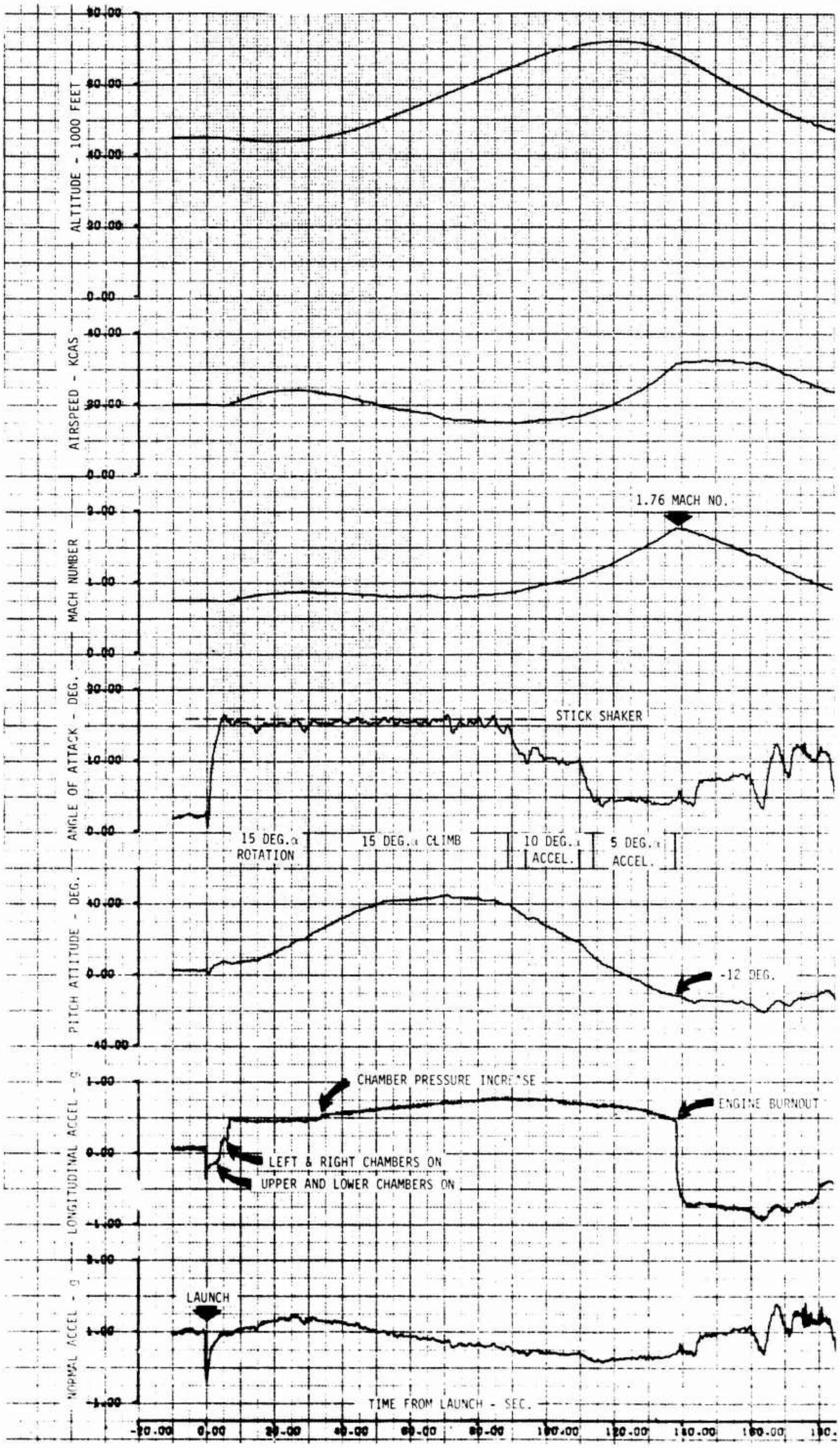
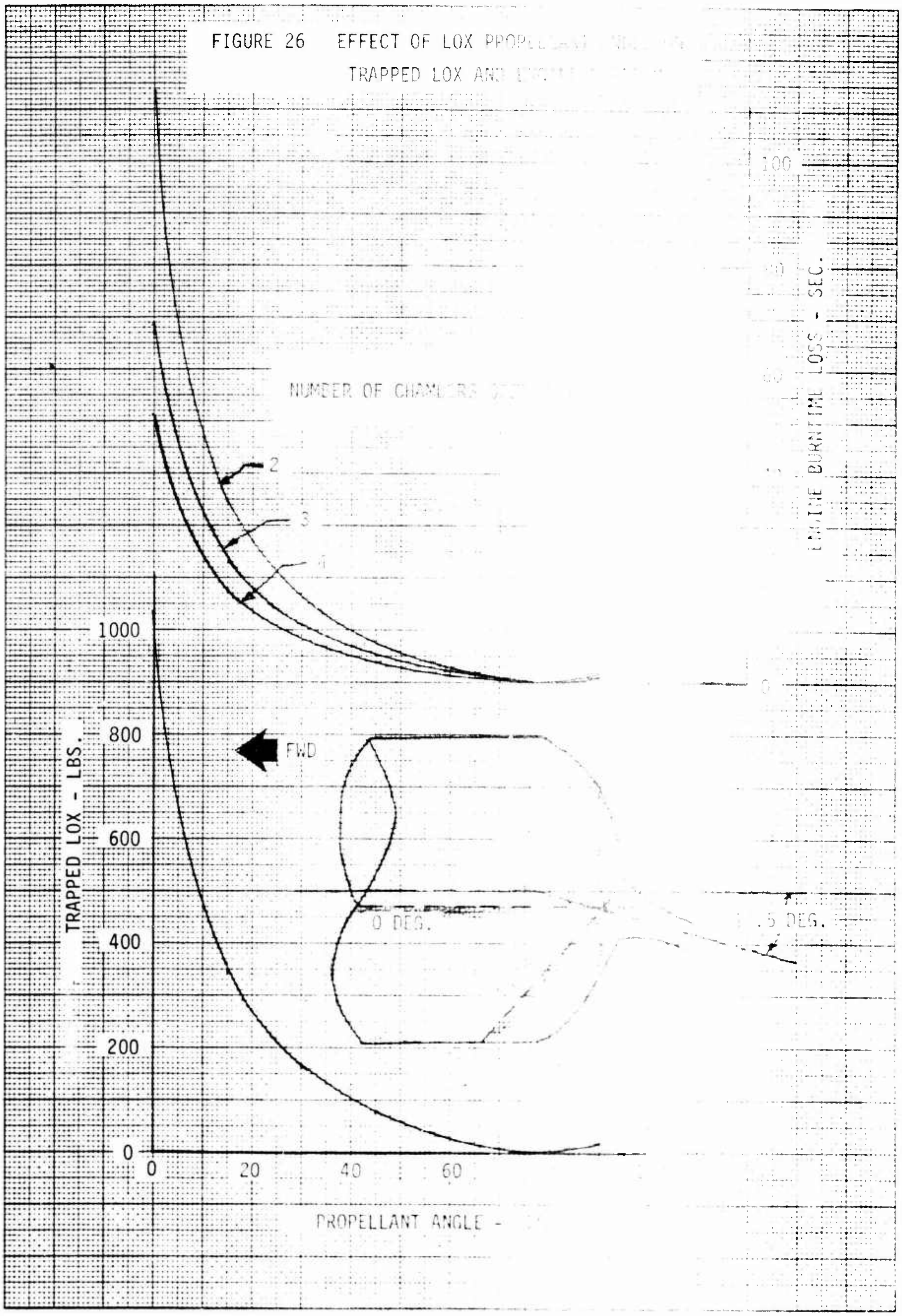


FIGURE 25 TIME HISTORY OF X-24B MAXIMUM MACH NUMBER FLIGHT

An important consideration for the X-24B flight planning was the inclusion of a mathematical representation of the LOX tank outlet characteristics in the simulation. The location of the outlet from the uncompartmented LOX tank and the propellant angle of the LOX resulting from the body axis forces acting on the aircraft near propellant depletion affected the engine burn time availble as illustrated in Figure 26.[15] Note that with the feedline outlet from the tank located 13.5 degrees below the centerline, the optimum propellant angle for minimum trapped LOX was 76.5 degrees. No attempt was made during the program to achieve this optimum tank propellant angle at burnout. Rather, the achievement of test conditions required for data purposes at burnout was the driving consideration. As in the case of the maximum Mach number flight shown in Figure 25, five degrees angle of attack was selected as the required test condition, and the flight plan was tailored to achieve as much burntime as possible by other flight planning techniques such as duration at climb angle of attack and pushover altitude. This, in effect, controlled the dynamic pressure that would result at burnout and thereby the propellant angle (thru resulting longitudinal and normal accelerations). The propellant angle at burnout for the flight shown was 50 degrees which resulted in a loss of only about three seconds of burntime. During flight planning the simulation showed that pushing over to five degrees α at lower altitudes resulted in increased dynamic pressure at burnout, decreasing the propellant angle and burntime. Consideration of unavailable LOX due to propellant angle was also an important factor in flight planning for the alternate profiles. For instance, the burnout propellant angle for the three chamber alternate profile was only about 12 degrees which resulted in a significant, thirty second loss in burntime. Had this thirty second loss not been accounted for in flight planning a very awkward energy management situation could have occurred as a result of an unexpected premature engine shutdown.

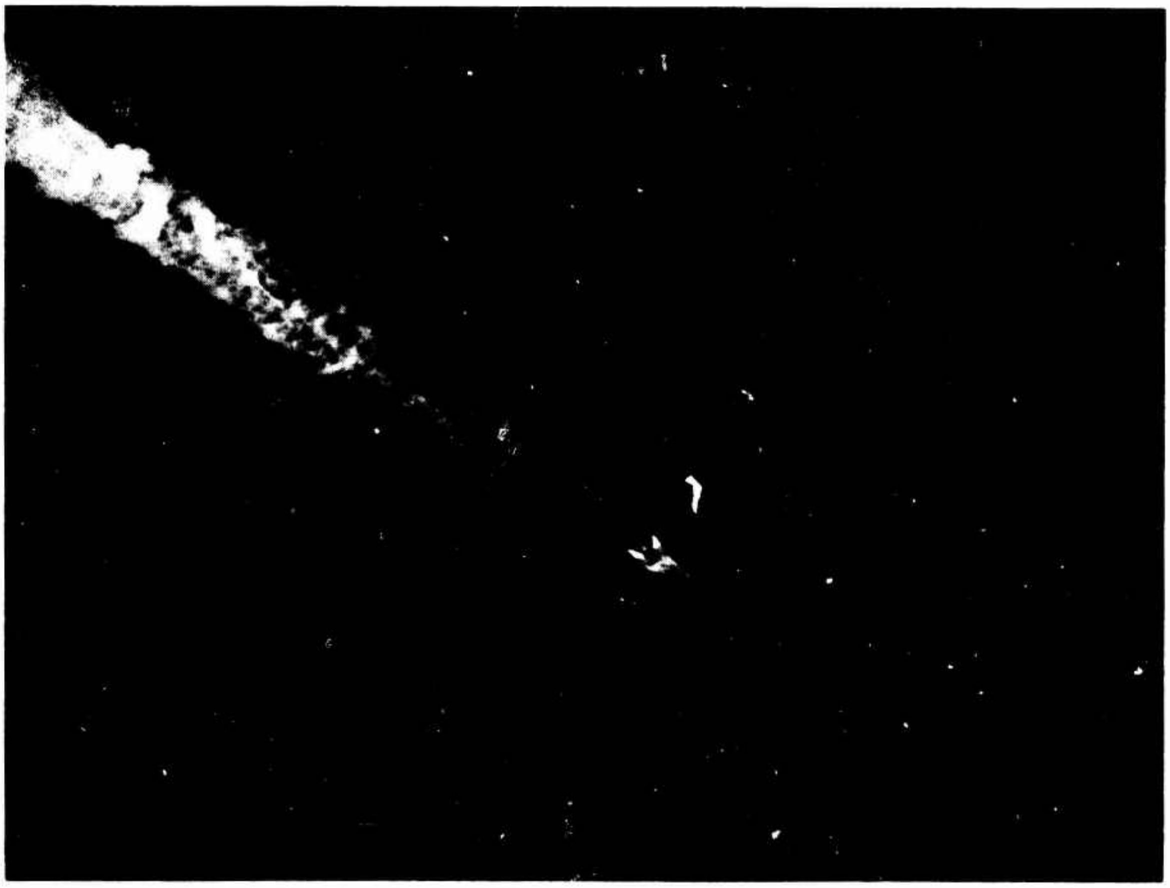
[15] Data were obtained from a combination of analytical calculations and actual altitude tests performed on the PSTS LOX tank.

FIGURE 26 EFFECT OF LOX PROP... TRAPPED LOX AND ...



The attainment of exact preplanned shutdown (or burnout) conditions of airspeed and altitude was not considered as a measure of success for each flight. Instead the aim was the attainment of the appropriate conditions, Mach number and angle of attack for the prime data maneuvers near engine shutdown. However, an assessment of the degree of accomplishment of the planned conditions does provide an insight into the man-machine relationship as the pilot attempted to obtain the required data. Figure 27 presents a comparison of the planned vs actual shutdown (or burnout) conditions for the 24 powered flights of the X-24B. Mach number (the more important parameter for data purposes) was attained within ±.08 whereas shutdown altitude showed a variation of ±4000 feet. This accuracy in attaining the desired Mach number is impressive considering the fact that the maximum speed region was an area of high pilot workload since critical envelope expansion data maneuvers were performed on most flights prior to and immediately after shutdown. Shown also is the deviation from planned conditions that occurred as a result of alternate profiles flown when system failures occurred.

A composite summary of the variation of significant parameters relative to aircraft design and flight limits are presented in Figures 28 thru 34 and are useful in that not only do they indicate the range of conditions covered but also the frequency (by darkened areas) that similar conditions were experienced. The figures are self explanatory and will be left for the reader's inspection.



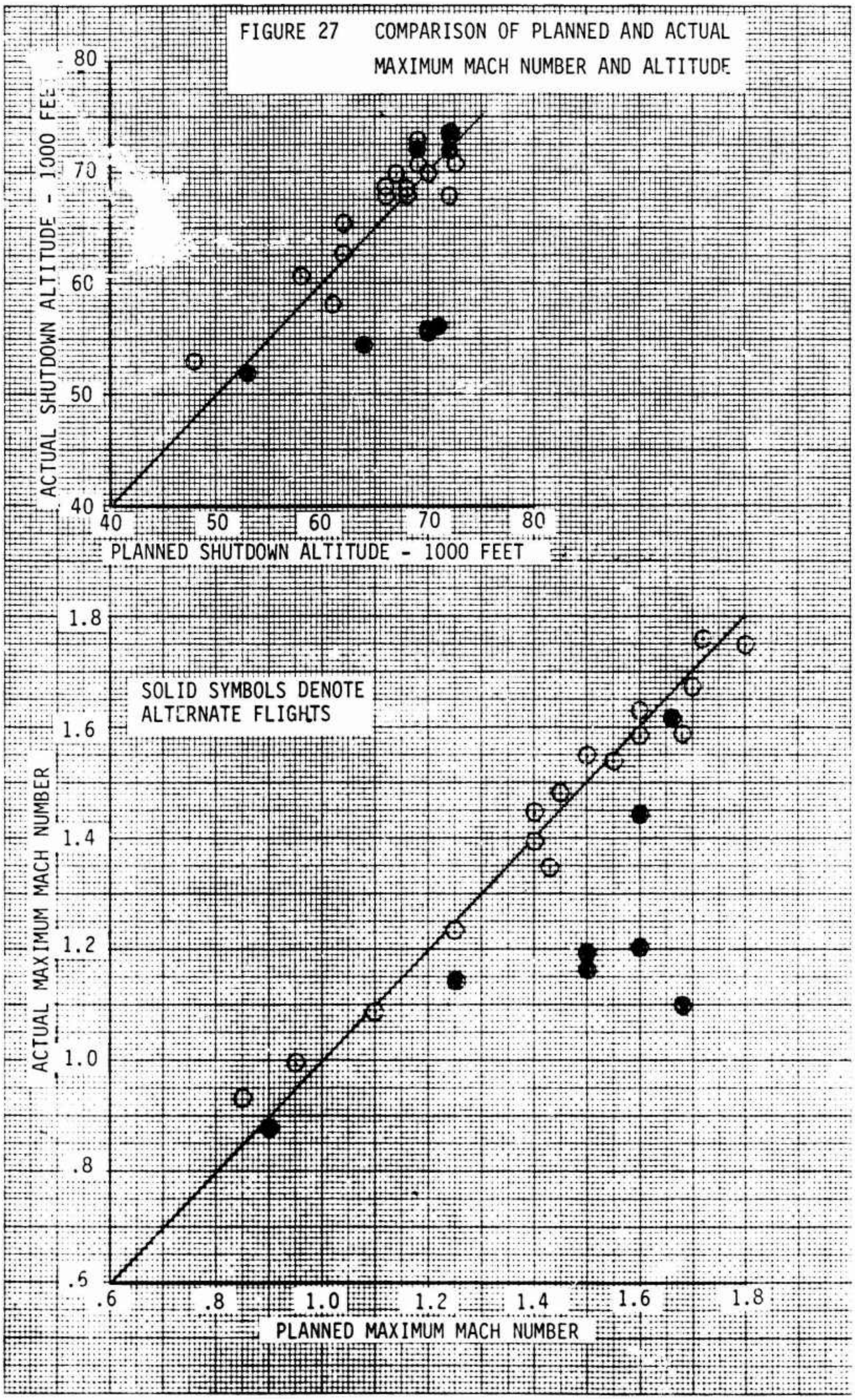


FIGURE 27 COMPARISON OF PLANNED AND ACTUAL MAXIMUM MACH NUMBER AND ALTITUDE
ACTUAL SHUTDOWN ALTITUDE - 1000 FEET
80
70
60
50
40
40
50
60
70
80
PLANNED SHUTDOWN ALTITUDE - 1000 FEET
SOLID SYMBOLS DENOTE ALTERNATE FLIGHTS
ACTUAL MAXIMUM MACH NUMBER
1.8
1.6
1.4
1.2
1.0
.8
.6
.6
.8
1.0
1.2
1.4
1.6
1.8
PLANNED MAXIMUM MACH NUMBER

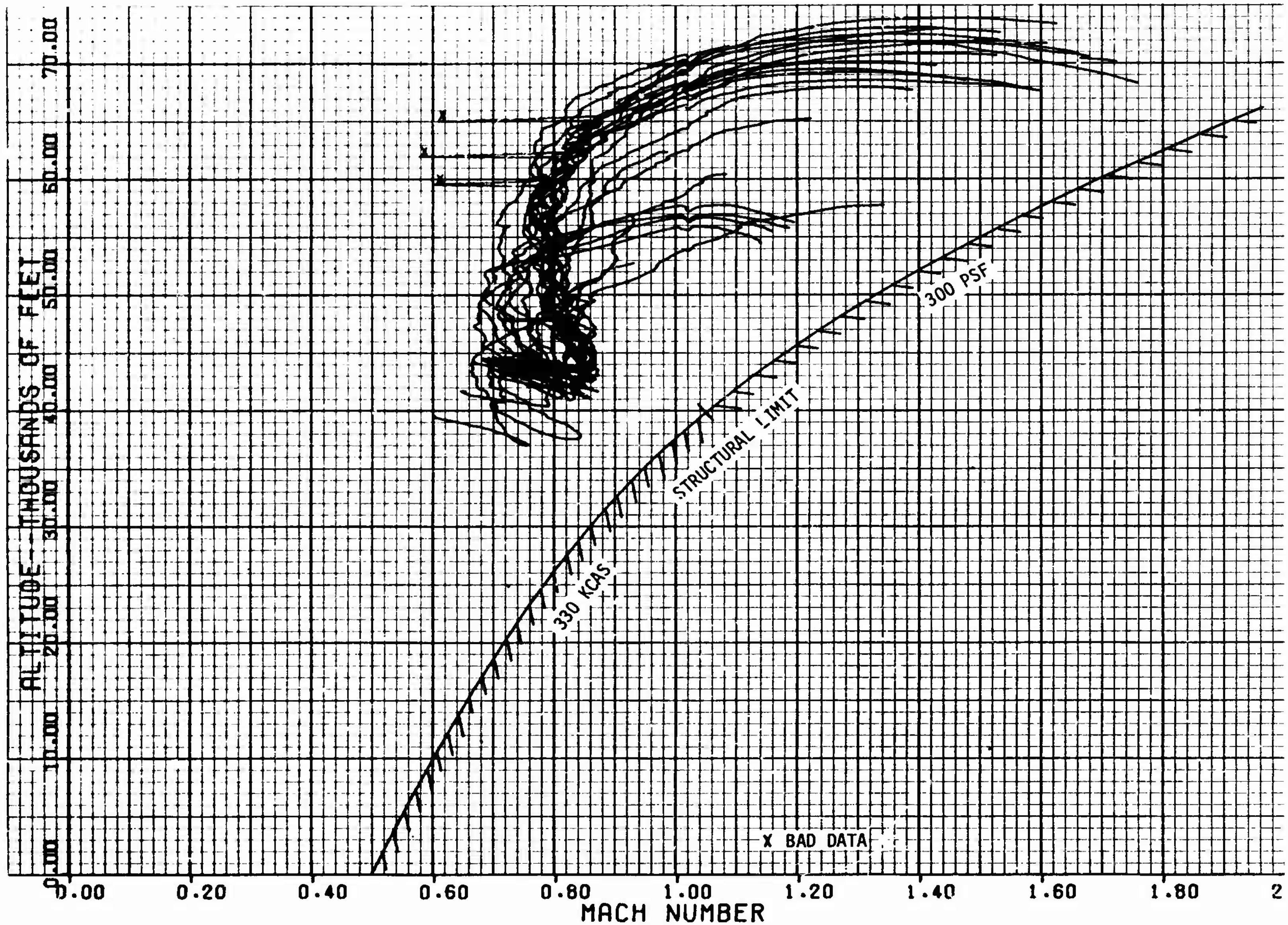


FIGURE 28 X-24B MACH NUMBER VS ALTITUDE - POWER ON

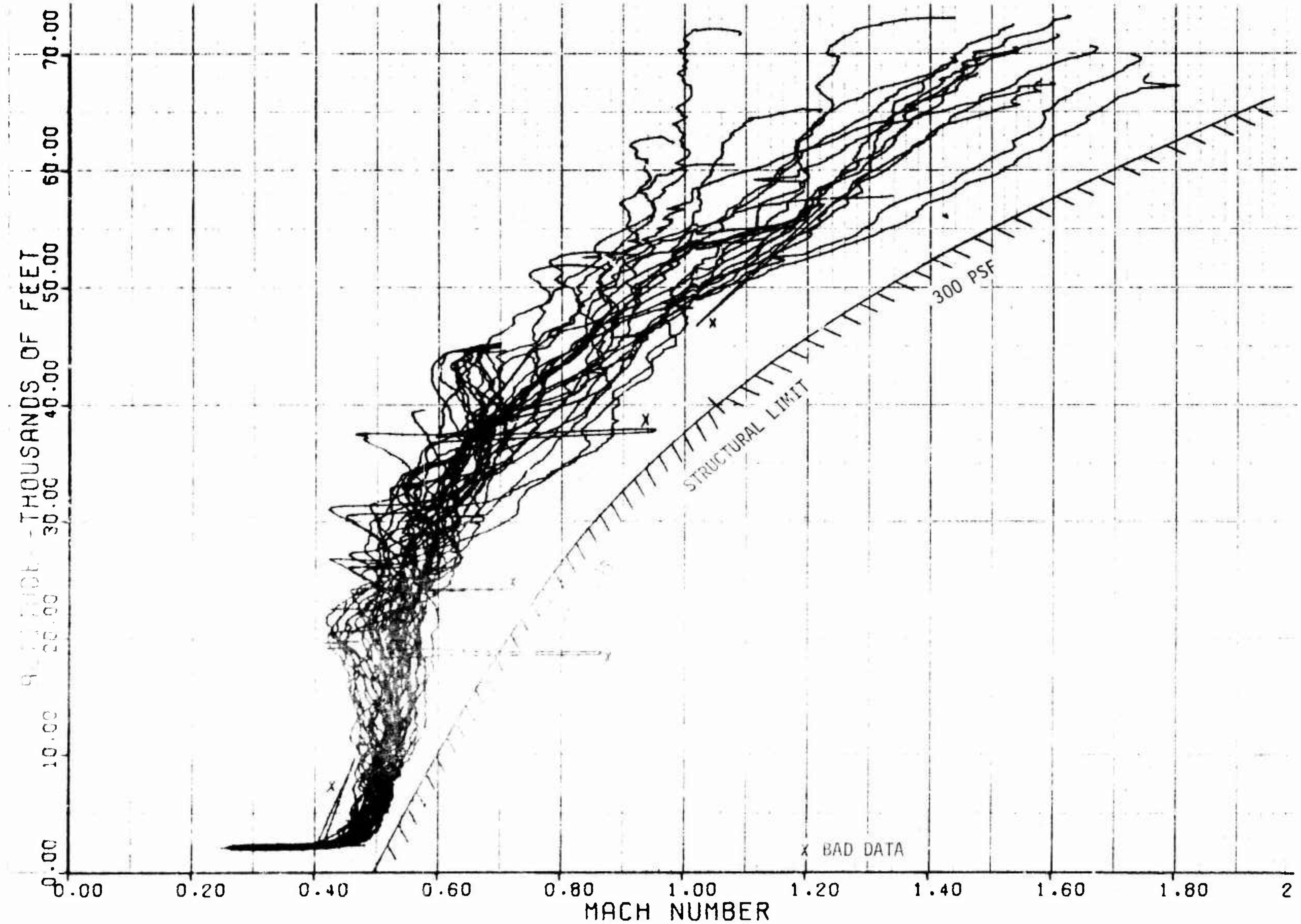


FIGURE 29 X-24B MACH NUMBER VS ALTITUDE - POWER OFF

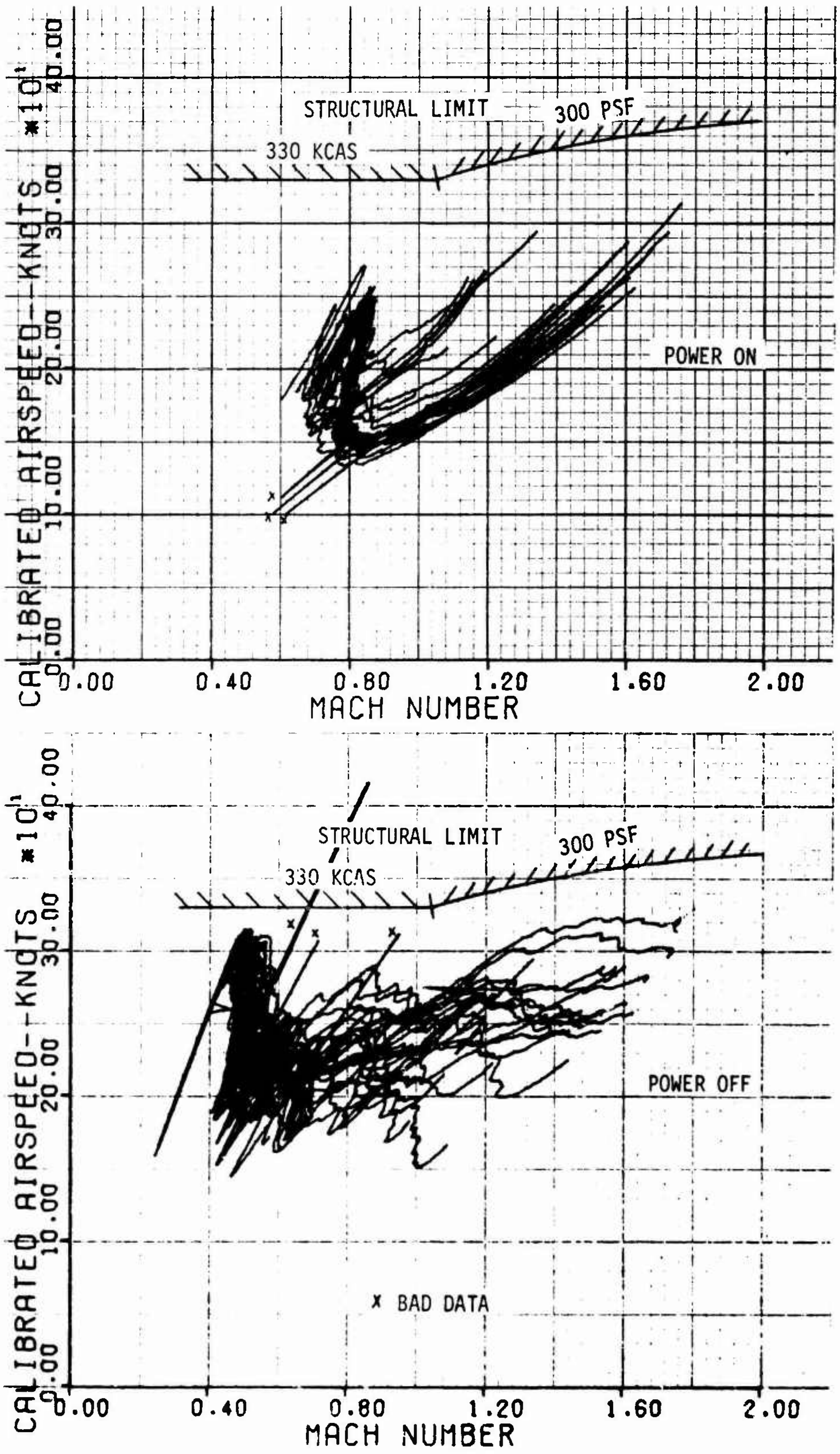


FIGURE 30 X-24B MACH NUMBER VS KCAS

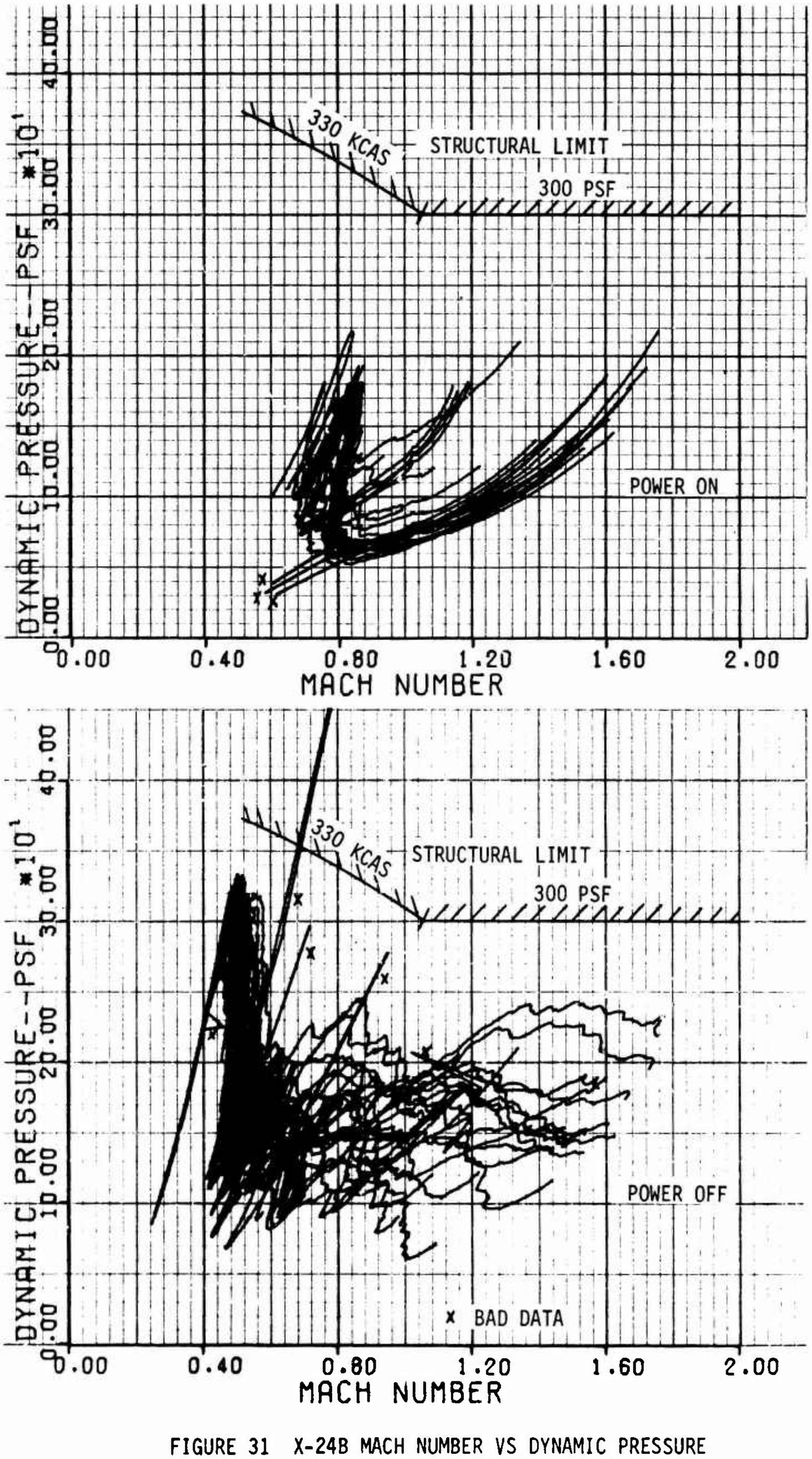


FIGURE 31 X-24B MACH NUMBER VS DYNAMIC PRESSURE

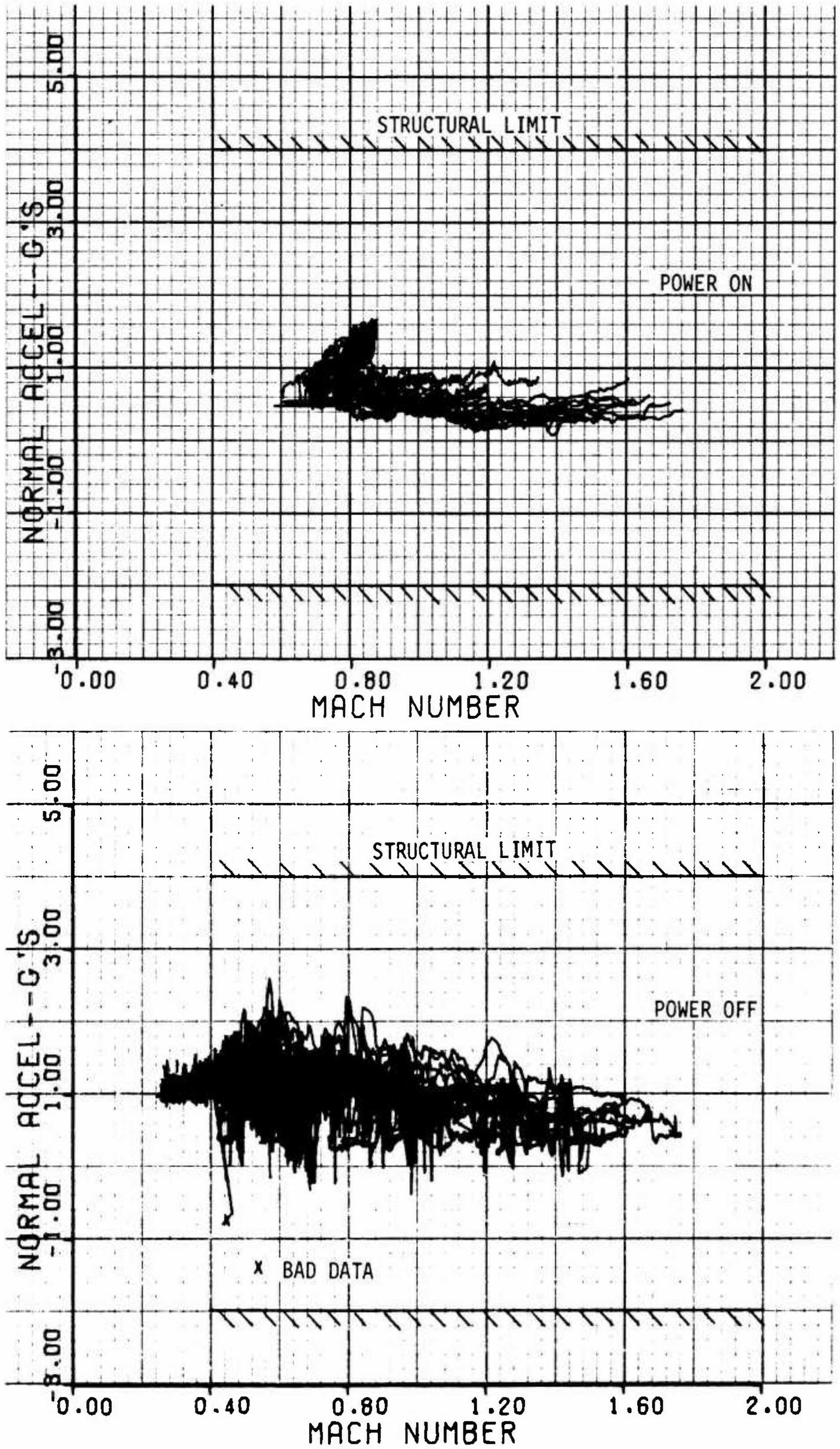


FIGURE 32 X-24B MACH NUMBER VS NORMAL ACCELERATION

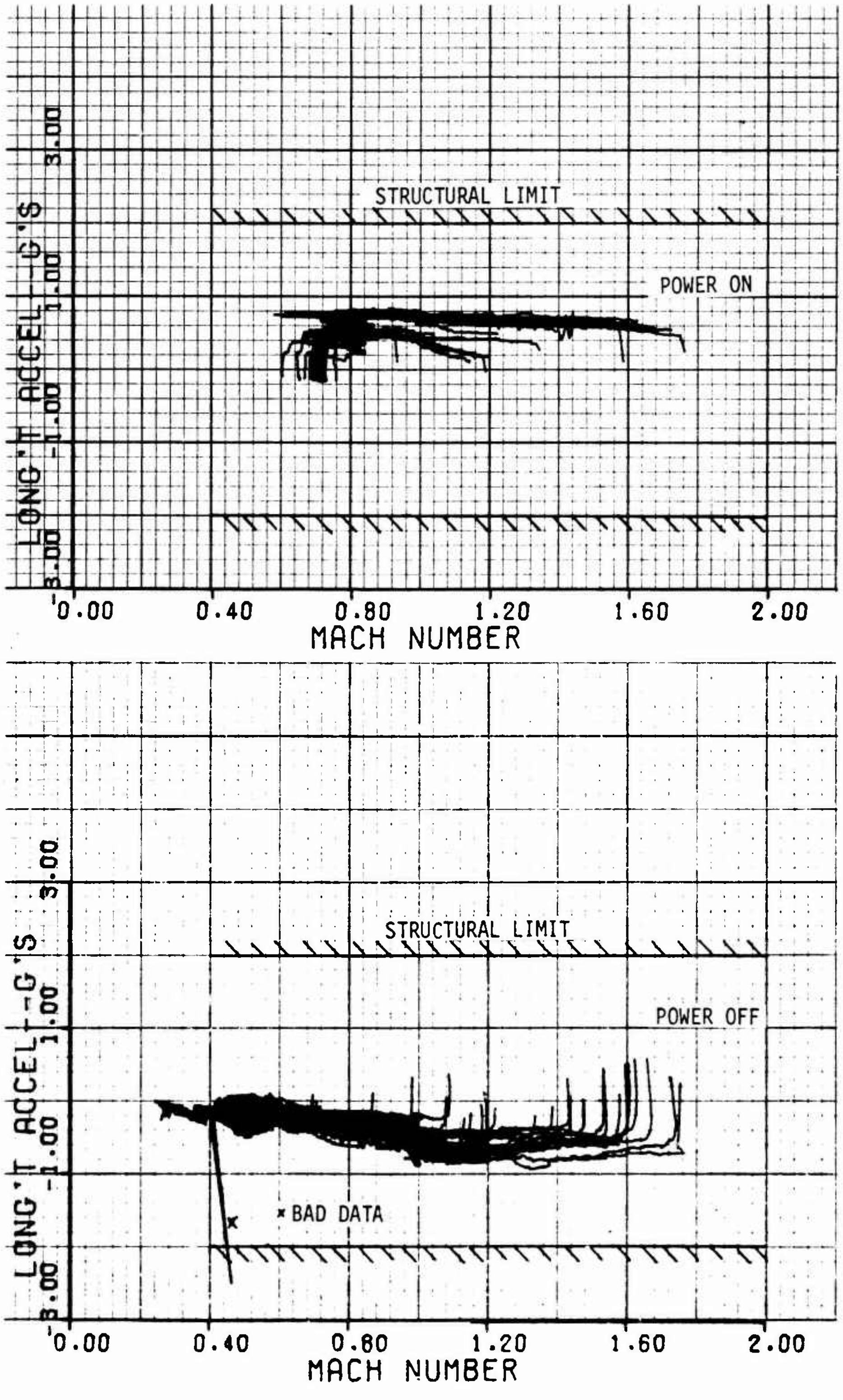
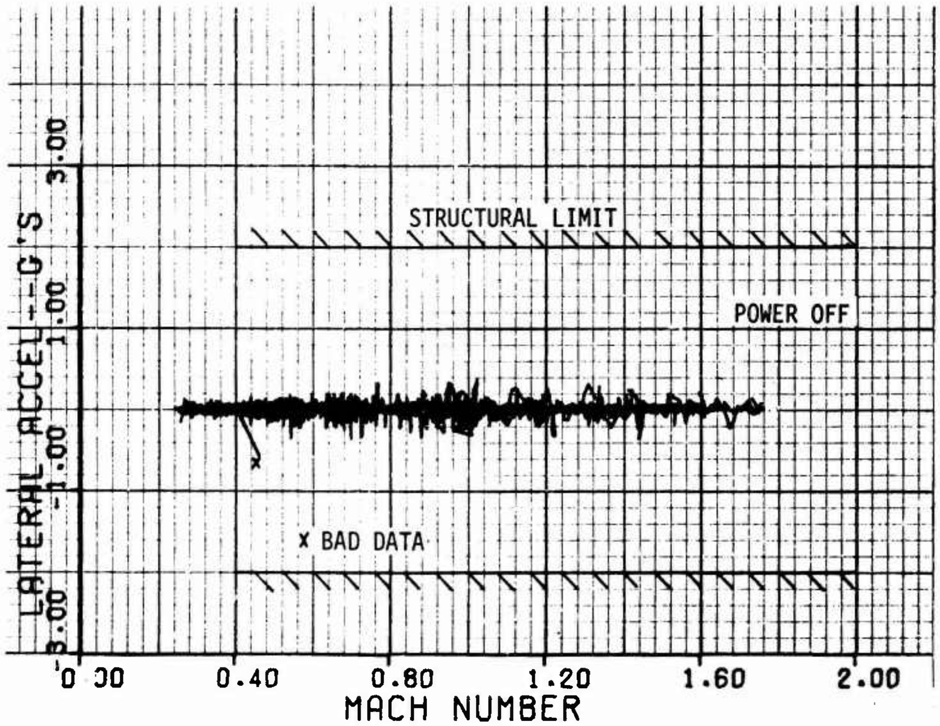


FIGURE 33 X-24B MACH NUMBER VS LONGITUDINAL ACCELERATION



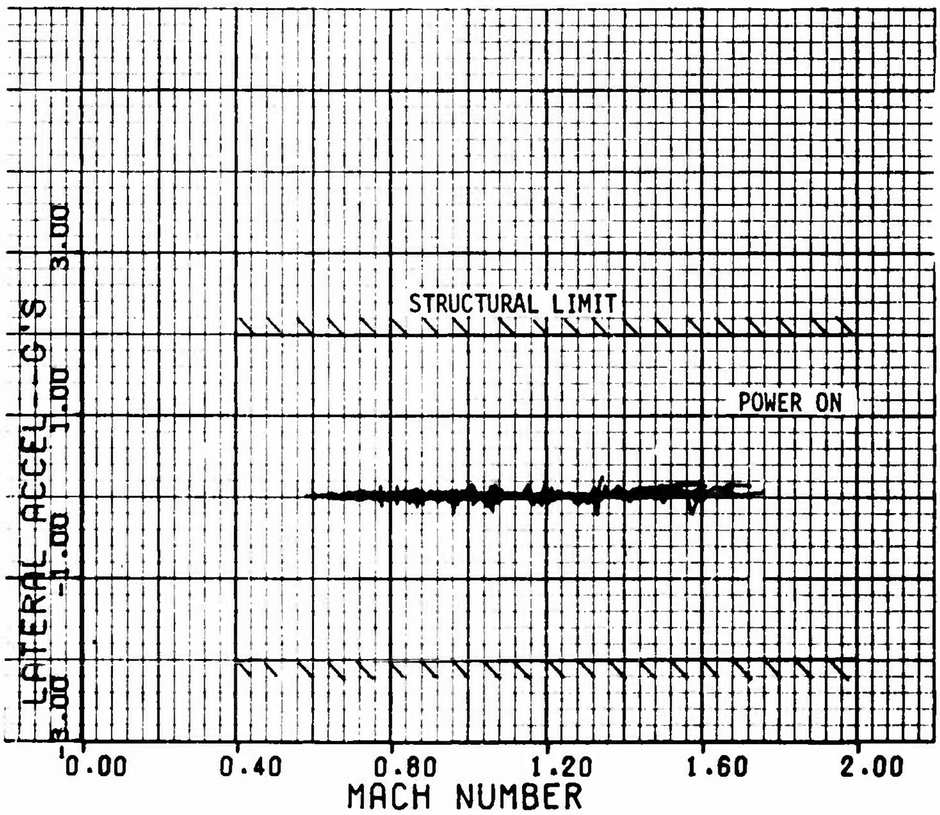


FIGURE 34 X-24B MACH NUMBER VS LATERAL ACCELERATION

The aircraft's gliding performance is summarized in Figure 35 in terms of a comparison of maximum L/D. At Mach numbers less than one the flight test determined maximum L/D was seven percent lower than predicted by small scale wind tunnel tests (Reference 2). Lift and drag data up to maximum L/D were not obtained at supersonic speeds. However, when the previously discussed stability and control factors above 1.3 Mach number are considered, a significant deficiency becomes apparent relative to a reentry mission. If the angle of attack for $C_{n_\beta} = 0$ and $C_{n_\beta}{}^* $ from Figure 23 is selected as a limiting value for usable angle of attack, the resulting loss in max L/D capability is significant. In addition, the full aft stick limit was also in this general angle of attack range.

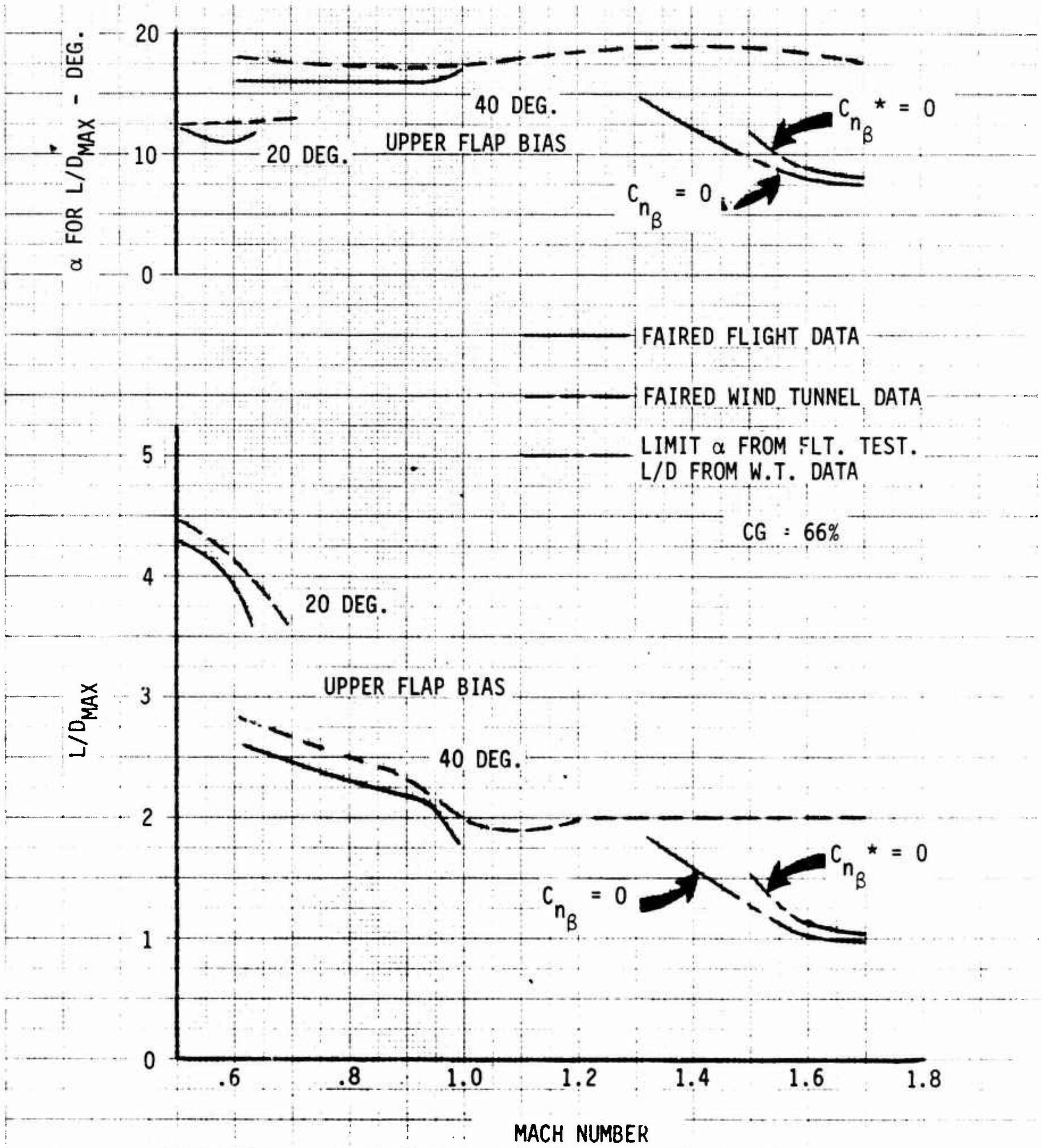


FIGURE 35 X-24B MAXIMUM L/D SUMMARY

Alternate Profiles:

Contingency planning represented a significant portion of pilot and ground control preflight training activity for each flight. Flights that required different piloting techniques than the primary mission were termed "alternate profiles". Of the 24 powered flights, eight (33 percent) alternate profiles were flown; six (25 percent) were due to XLR-11 rocket engine malfunctions.

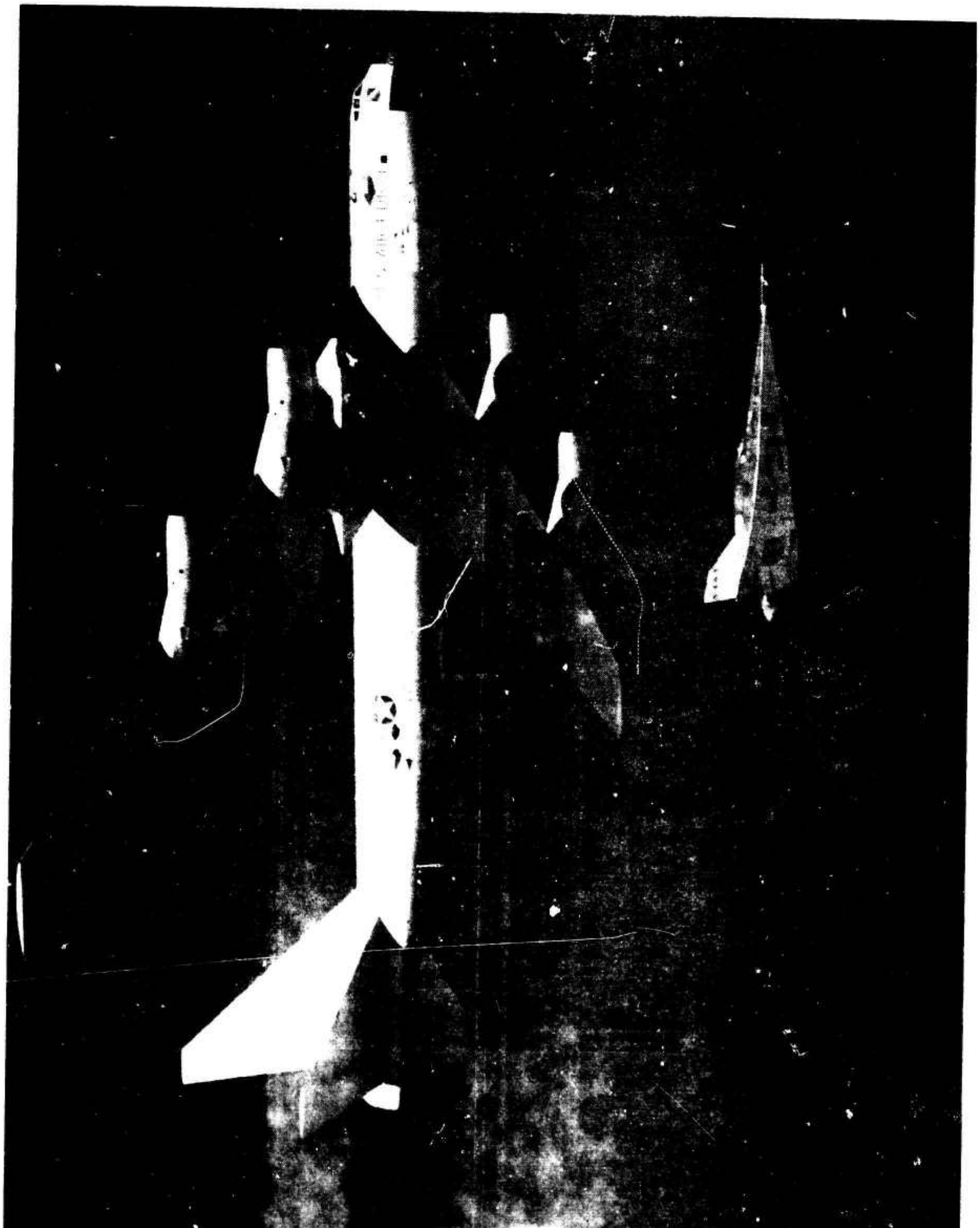
Three-chamber alternate profiles were flown on four occasions when one of the rocket chambers failed to light after launch. With only three chambers operating the aircraft achieved maximum Mach numbers between 1.1 and 1.2, and maximum altitudes between 56,000 and 58,000 feet MSL. With this performance capability, some data maneuvers were always accomplished and energy management was close to nominal, allowing the landing to be

On two flights the engine failed to start on the first attempt after launch, requiring the pilot to recycle the engine start sequence with corresponding delays in thrust onset of 10 and 14 seconds. The resulting altitude losses during the rotation on these flights were 4000 and 5500 feet compared to 2500 to 3000 feet for a normal flight. Only minor changes in piloting technique were required in order to achieve the desired conditions at engine shutdown and the required flight objectives were accomplished. (Although the number one chamber failed to light on the first attempt on flight 29, the second attempt was successful in a timely manner so that it did not effect the planned flight and was therefore not considered as an alternate profile.)

During the captive portion of one flight an engine of the NB-52B experienced an overtemperature condition and had to be shutdown. As a result the NB-52B could only achieve 42,000 feet MSL rather than the planned 45,000 feet MSL. A real time decision was made to proceed with the flight at a launch altitude of 42,000 feet MSL and fly the flight like a "delayed light" alternate profile. The flight was successfully accomplished but achieved 1.5 Mach number at engine burnout as expected rather than the planned 1.6 due to the energy loss during the low altitude rotation.

A premature engine shutdown was experienced at 109 seconds at 1.1 Mach number on a flight planned for 131 seconds, and a maximum Mach number of 1.68. At the time of engine shutdown sufficient energy (and ground position) had been obtained to allow the pilot to accomplish the planned pattern to the prime runway. The remainder of the flight became a coordination task between the pilot and ground control to adequately manage the energy to reach the landing pattern. Upon inspection of the fuel tank a two-inch crack in a weld joint was found on the bulkhead between the two compartments in the tank. It was concluded that this crack prevented complete transfer of the fuel from the aft compartment to the forward compartment thus causing the fuel-starvation shutdown.

Other contingencies that were routinely considered during flight preparation may be seen in the flight plan in Appendix D.



XLR-11 Rocket Engine Operation:

By modern standards the operational reliability of the aged XLR-11 rocket engine used in the X-24B would be considered poor. However, there are two important facts that, in retrospect, must be recognized in judging the overall system performance of the engine in the X-24B. First, the engine did in fact allow the accomplishment of the powered flight program objectives consistent with the program constraint of low cost. Secondly, the malfunctions that did occur were (by design) of a fail-safe nature and never caused damage to the aircraft or harm to the pilots.

One of the prime factors associated with the relatively low reliability of the engine was the environment that the engine was required to operate in. With the engine mounted externally, (Figure 11), it was exposed to low ambient temperature (-65 degrees F) and pressure during the approximate 50-minute mated flight to the launch point. This required that heater blankets be used to warm the engine control box which contained the temperature-sensitive control pressure switches. In addition, the engine light occurred in the presence of varing "g" forces after the X-24B was launched.

Prior to the first powered flight several changes were made to the engine in an attempt to improve system reliability. These included:

1. Igniter modification to utilize the YLR-99 rocket engine spark ignition system. This provided an increased flammability envelope over the existing ignition system.

2. The substitution of silicon "O" rings in the control box pressure switches in an attempt to improve pressure switch operation at low temperature (-40 degrees F).

3. The addition of an accumulator in the LOX manifold pressure sensing line to eliminate an undesirable pressure surge during the start sequence that could unnecessarily signal an engine shutdown.

Although there were six flight engines (and one ground test engine) available for the X-24B flight program, the same engine (S/N 8) was used throughout the powered flight program. A summary of the inflight malfunctions of this engine is presented in Table V.

TABLE V

XLR-11 MALFUNCTION SUMMARY

Flight	Malfunction/Cause
B-3C-10	Pre-launch igniter test failure - chamber #3
B-A-11	Flight aborted due to pre-launch igniter test failure - chamber #3 and #4
	Repeated igniter test later - #4 worked but #3 did not
B-A-12	#3 igniter failed pre-launch test (aborted due to clouds)
B-6-13	#3 igniter failed pre-launch test, flight flown successfully (ground rule required only three good igniters to launch)
Cause:	Ground tests of the engine in an environmental chamber revealed that all the igniter oxygen valves leaked excessively when subjected to -65 degrees F for 15 minutes and the #3 valve would not actuate. New valve "O" rings were installed to correct the deficiency
B-10-21	Engine did not start on first attempt after launch due to fuel pump cavitation
Cause:	Inconclusive - assumed plugged bleed hole in fuel line
B-11-22	#1 chamber failed to light after launch
Cause:	Concluded that frozen moisture in 65 psi pressure switch prevented its operation
B-17-28	Engine did not start on first attempt after launch due to LOX pump cavitation
Cause:	Inconclusive - assumed "hot" LOX
B-21-33	#3 chamber failed to start
Cause:	Inadequate spark due to internal arcing in the spark plug ignition lead connector
B-27-40	#3 chamber failed to start
Cause:	Inconclusive, changed ignition components
B-29-42	#1 chamber igniter failed to light on first attempt but functioned properly on second try
Cause:	Inconclusive, replaced igniter oxygen check valve
B-30-43	#1 chamber failed to light
Cause:	Inconclusive, suspected ignition system

Aileron Deadband:

The deadband that occurred in the left hand aileron on the first powered flight continued to randomly occur (with varying amplitudes) on other flights. Although this subject is thoroughly discussed in Reference 1, a brief summary/background discussion is included here from an operational "lessons learned" standpoint.

During mated flight to the launch point the LOX lost from the X-24B due to "boil-off" was replenished (topped-off) from LOX tanks located in the bomb bay of the NB-52B. As the X-24B tank became full, the overflow of LOX exited the tank thru a LOX vent line located on the bottom of the aircraft. When the aircraft was delivered the LOX vent outlet was located just forward of the left hand main landing gear compartment. With the knowledge that a similar location on one of the lifting bodies had caused a slow gear extension due to the low temperature of LOX venting over the gear compartment, an ad hoc committee, independently reviewing the flight readiness for the first powered flight, recommended that the LOX vent be relocated. The vent was moved outboard away from the gear well but upstream of the aileron compartment (Figure 36). Reference 1 presents the details of the sequence of events in attempting to identify the cause of the aileron deadband, which included replacement of components, instrumenting the aileron linkage and compartment temperature, and environmental ground tests of components. With the results for the above checks it was confirmed that the aileron deadband was caused by excessively low temperature of the hydraulic system components resulting from the LOX vent overflow. Figure 37 presents a summary of the time that the skin temperature of the aileron compartment was colder than -100 degrees F (limit of measurement) as a result of LOX (~-300 degrees F) flowing over the area during top-off. During powered flights thru flight eleven, a single top-off of approximately 30 to 35 minutes duration was used. For flights 12 through 17, two short duration top-off cycles were used with a corresponding reduction in cold soak time and without the occurrence of the aileron deadband. On flights 18 and 19 the initial top-off cycle was again to long resulting in excessive cold-soak and aileron deadband. After flight 19 the top-off procedure was changed to include three top-off periods of short duration with each top-off cycle being terminated when the LOX vent temperature indicated liquid LOX was exiting the vent. With this procedural change the aileron deadband never reoccurred. However the real lesson here is not the importance of proper top-off procedures but rather that careful consideration must be given to the location of LOX vent lines during design.

FIGURE 36 X-24B LOX VENT

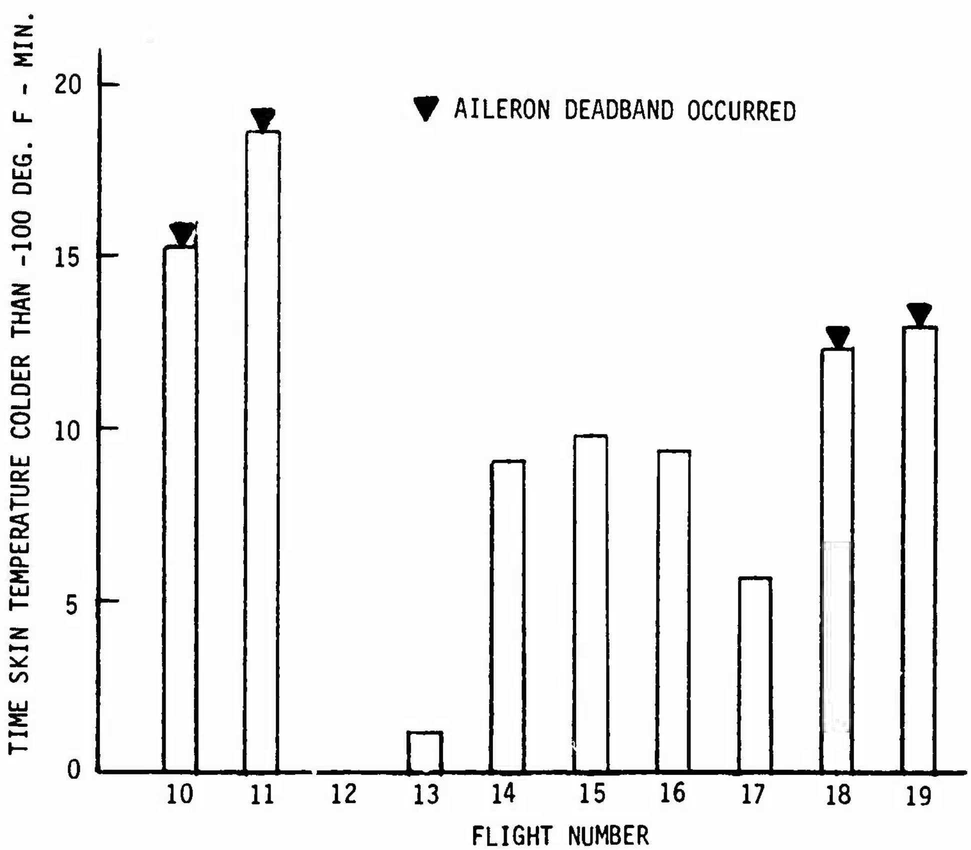


FIGURE 37 X-24B AILERON COMPARTMENT SKIN TEMPERATURE

Landing Dynamics and Main Gear Performance:

One of the research objectives of the program was the evaluation of landing dynamics of the X-24B in comparison to a prediction program developed by the AFFDL. Hence the landing gear system was heavily instrumented to provide loads, strut stokes, wheel speed, etc. The X-24B landing dynamics were unique in that the nose gear could not be "held off" after the main gear touched down due to the extreme forward position of the cg relative to the main gear location. As a result, several factors contributed to unusually high landing gear loads of the X-24B. These included the additive effects of:

1. Aerodynamic download due to increased upper flap deflection as the pilot and SAS responded to the abrupt pitch down following main gear contact.

2. Aerodynamic download at high speed (immediately after touchdown) due to the negative angle of attack at ground attitude.

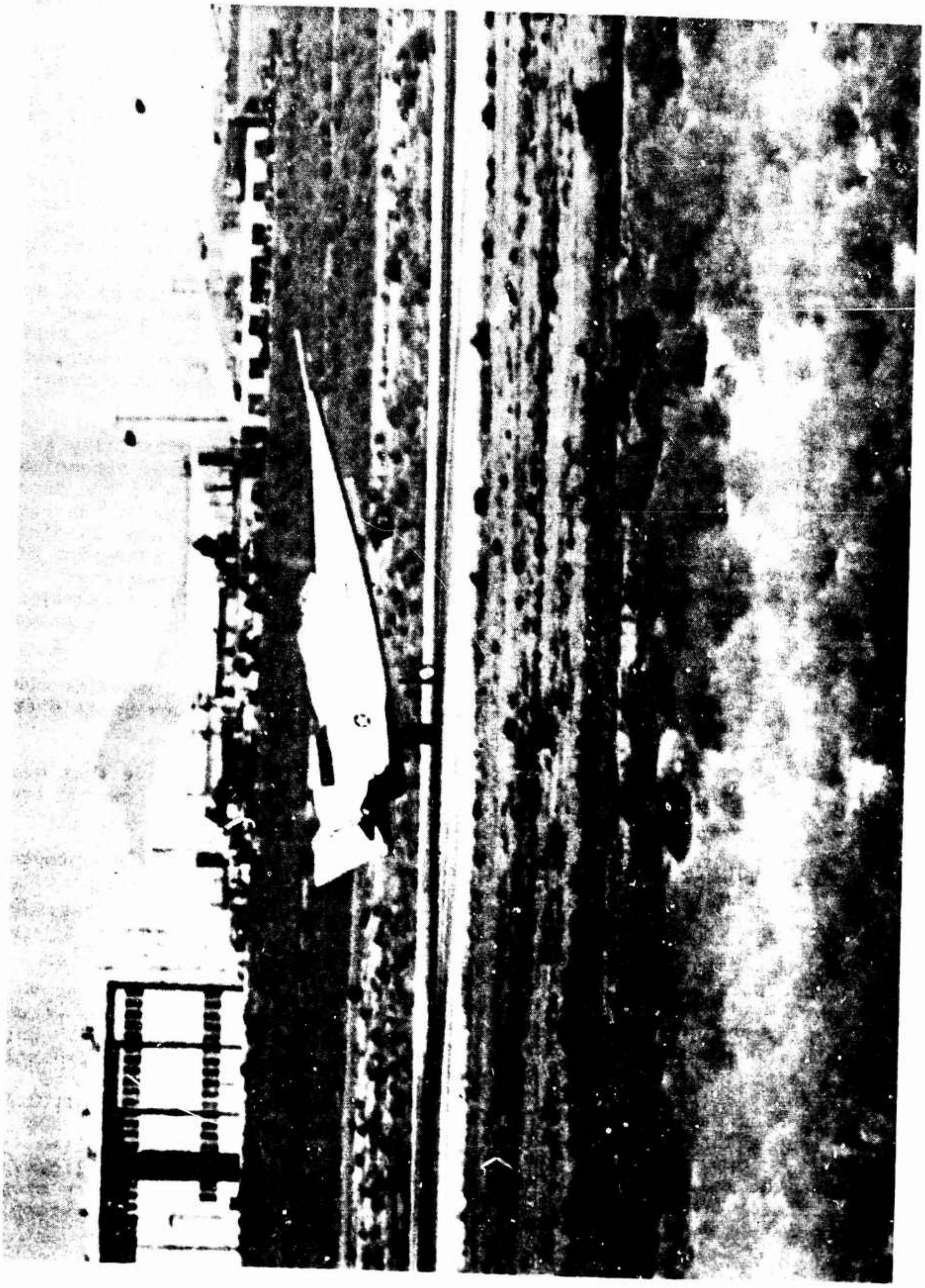
The maximum main gear loads occurred approximately at nose gear touchdown (one to one-and-a-half seconds after main gear touchdown) with the maximum vertical load (per gear) ranging between 7500 and 12,500 pounds. The main gear tires with the tread removed performance satisfactorily on all landings.

Operational difficulties were experienced with the main gear when, early in the powered flight program, bottoming (full stroke) of the gear oleos occurred (flights 9 and 10). Initially it was felt that the cause of the strut bottoming was due to a loss of oil in the strut (based on post-flight reservicing of the struts). However it was not until much later in the program after sufficient data had been collected that it became apparent that the air service pressure in the struts was significantly below standard aircraft service pressures and provided too little stroking margin for the X-24B application. Table VI provides a summary of main gear servicing and stroking margins during landings. Note that with air service pressures initially recommended by the program office of 100-125 psia less than one half an inch stroke margin existed on the first 20 flights. Bottoming of the gear resulted in both detailed inspection of the gear backup structure for potential damage and tear down inspection of the gear itself. No damage was ever found. After flight 20 it was recognized that the basic deficiency was inadequate strut air pressure. When the pressure was increased to 210 psig, adequate stroking margin existed (nominally 1.8 inches) and no further bottoming occurred.

TABLE VI

X-24B MAIN GEAR STRUT PERFORMANCE

Flt Nos	Air Service Pressure PSIG	Range of Stroke Remaining-Inches	Comments
1-17	100	0.7 to 0	Left hand gear bottomed on Flights 9 and 10
18-20	125	0.7 to 0	Right hand gear bottomed on Flight 20
21-36	210	2.4 to 1.4	No bottoming



Concrete Runway Landing:

The three lifting bodies were aerodynamically configured by requirements for lifting/maneuvering reentry from earth orbit to a power-off horizontal landing. One of the key objectives of these programs was to evaluate the power-off landing characteristics of these configurations. All three lifting body vehicles (M2, HL-10, X-24A) were equipped with conventional landing gear with wheels, none featured usable nose gear steering systems and all landings were made on dry lakebeds. Although the lateral displacement during landing rollout of most of the lifting body landings would have been within conventional runway widths there were several occasions that the vehicles could not have been maintained within allowable lateral deviations. Lacking nose gear steering; differential braking was inadequate to maintain satisfactory ground direction control during landings with crosswind components near planned limits (10 to 15 knots). The unanimous conclusions from both the X-15 and lifting body programs was that the touchdown accuracy of power-off landing of low-L/D vehicles is sufficient to allow landing on conventional runways.

Although demonstration of a runway landing was not officially an original objective of the X-24B flight test program, special attention was given to the nose gear steering system during design with the thought of a potential runway landing in mind. After a few flights of the aircraft it was recognized that the X-24B had excellent approach, landing and ground handling characteristics which would allow consideration of a runway landing. In January 1974 the X-24B Research Subcommittee accepted the proposed objective to land the X-24B on the main runway near the end of the scheduled flight program. The reasons for a runway landing were:

1. To substantiate previously stated opinions that normal recovery of unpowered low L/D aircraft on conventional runways is operationally feasible.

2. To determine the changes in philosophy and technique that evolve as one progresses from talking about performing unpowered low L/D landings on conventional runways to actually doing it.

3. The X-24B was the first low L/D research aircraft with proven capability to safely perform a runway landing (excellent flight and ground handling qualities, and nose gear steering).

In preparation for the runway landings a series of "accuracy" landings were performed on the marked lakebed runways beginning on flight 17 with emphasis being placed on touchdown accuracy, stopping distance, and ground directional control. Touchdown dispersions were within ±500 feet of the planned location with only one exception. Data obtained on stopping distance during the accuracy landings are presented in Figure 38. Pilot technique during the rollout on these landings included extending the upper flaps to full deflection once the aircraft attained a three point attitude (for increased aerodynamic drag) and immediate application of the brakes. The amount of braking applied during the roll-out was categorized correctly by the pilots as light, moderate or heavy. Good correlation may be seen in the resulting stopping distances in the figure. With the use of "heavy" braking, stopping

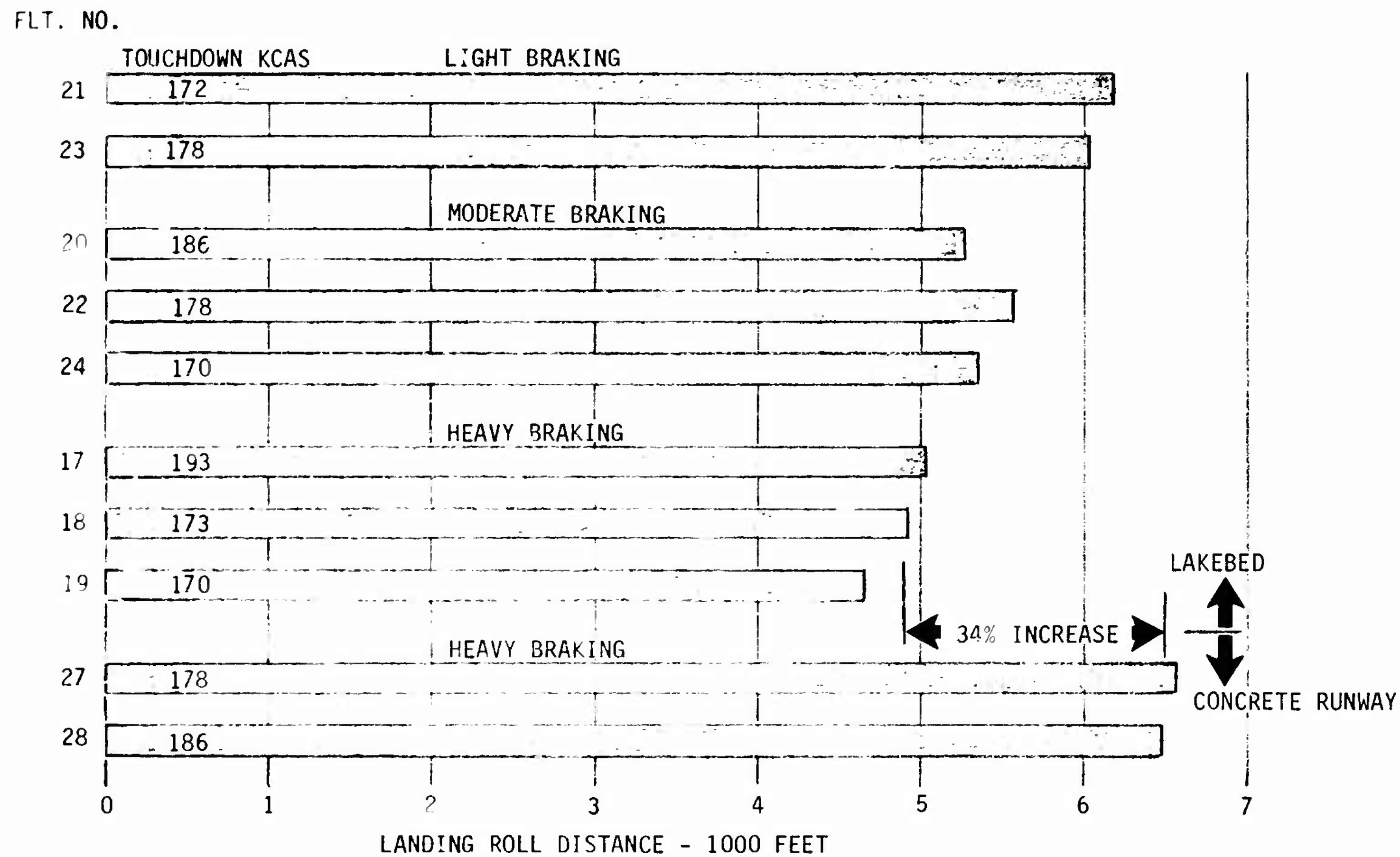


FIGURE 38 X-24B LANDING ROLL DISTANCE

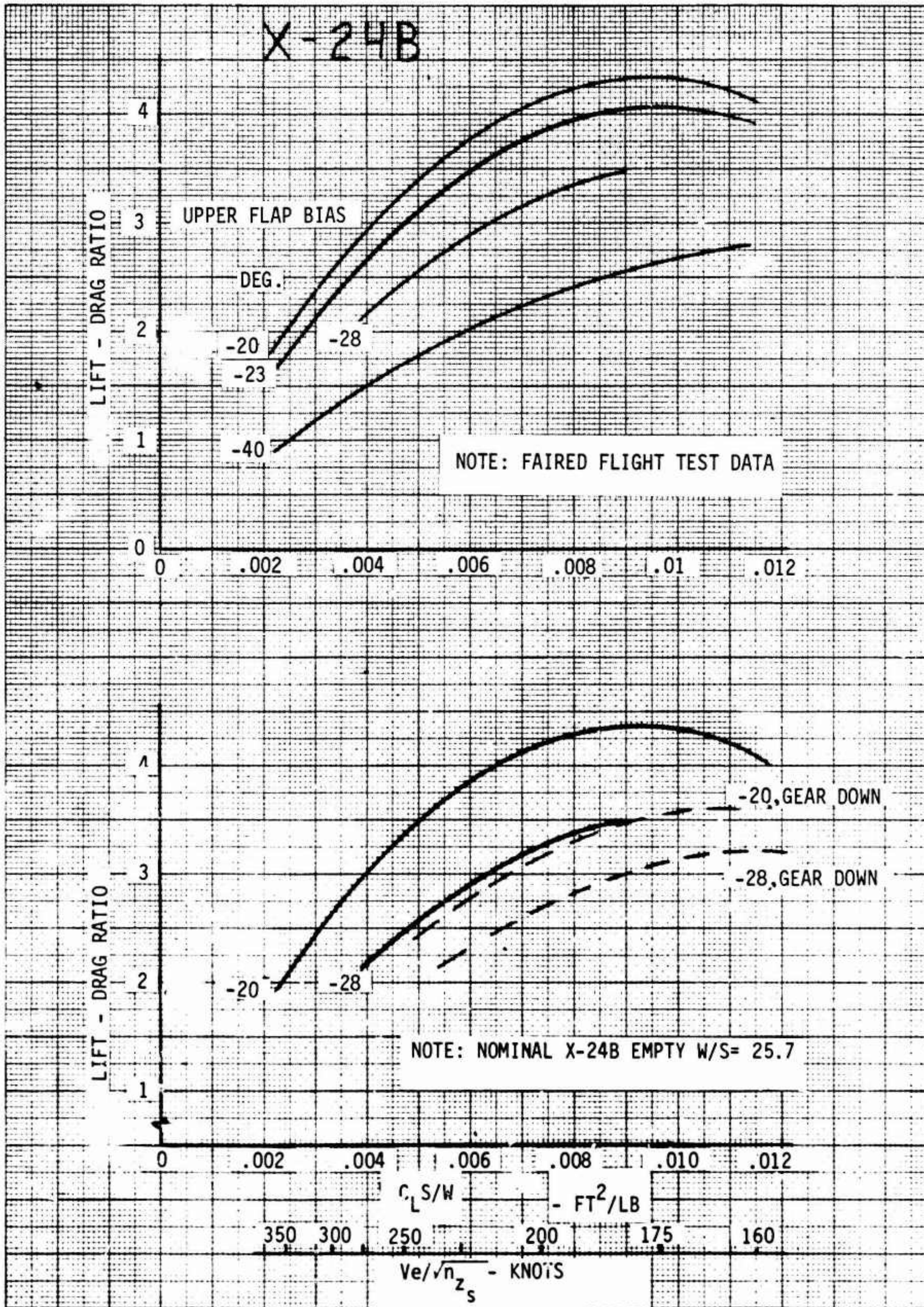


FIGURE 39 X-24B SUBSONIC L/D CHARACTERISTICS

distances between 4600 and 5020 feet were obtained on the lakebed runways. As the X-24B tires rolled on the lakebed a shallow trench was created which resulted in a higher rolling/braking coefficient than would have existed on the concrete runway. It was estimated that this would result in a 10 to 30 percent increase in rollout distance on the concrete runway as compared to the lakebed. As Figure 38 shows, the rollout distance on the concrete runway was approximately 34 percent greater than that realized on the lakebed for similar braking. Also shown are the corresponding touchdown airspeeds for the accuracy landings which ranged from 170 to 193 KCAS.

Ground directional control with both nose gear steering and differential braking was evaluated during the lakebed runway landings with the conclusion that the aircraft had sufficient steering capability to provide the required control on the concrete runway for a "normal" landing. In addition, analytical studies by the AFFDL also indicated that adequate control existed to maintain the aircraft on the 300 foot wide runway in the event of a main gear tire blowout. On both concrete runway landings the aircraft tracked straight down the runway and the pilots did not utilize nose gear steering. (However, it should be pointed out that crosswind was not a factor during these landings.)

The planned landing point on the 15,000-foot-long concrete runway was a five-foot-white line across the width of the runway at the 10,000-foot-remaining marker. On the first landing, the left hand main gear touched down 18 feet short of the line followed by a touchdown of the right hand gear on the other side of the line. This demonstrated spot landing accuracy attests to the fact that techniques and training for low L/D, power-off landings had evolved to a significant level. Some of the improved techniques that contributed to the accuracy attained include:

1. The determination of the appropriate geometric distance between the pre-flare aim point and the planned touchdown point for the performance characteristics of the X-24B. This distance (nominally 1.48 miles) was established by a combination of ground-based simulation, in-flight simulation in low L/D aircraft (F-104/T-38), and analysis of the accuracy landings accomplished on the lakebed.

2. Improved control of the trajectory to the preflare aim point by the use of partial speedbrakes as the nominal configuration to allow the pilot to both increase and decrease L/D as required during the pattern. The pattern geometry for the accuracy landings was based on the performance with -24 degrees upper flaps rather than the minimum deflection (-20 degrees) used previously. Figure 39 reproduced from Reference 3, presents a summary of the flight test measured L/D characteristics of the aircraft at various upper flap bias settings. The amount of L/D modulation available to the pilot via upper flap bias changes is readily apparent. Speedbrake deflections of -32 degrees (δU_B) were routinely used in the pattern. Most of the speedbrake usage in the pattern was during the final approach (Reference 3).

3. Another significant contributor to the touchdown accuracy was the extensive training and technical insight obtained by the pilots during simulated low L/D approaches in F-104 and T-38 aircraft. Of particular importance was the experienced gained by the pilots in flying the planned pattern in various upper altitude wind conditions that occurred during the two weeks prior to the flight. The training flight on the morning of the X-24B flight provided the pilot with first hand experience in wind conditions that would be encountered on the actual flight a few hours later.

4. During the last week of preparation for the first concrete runway landing the pilot changed the flare technique as a result of his observations on practice flights to the main runway in the F-104. The technique that evolved consisted of establishing a constant glide slope descent from a point 75 to 100 feet above the runway and 4000 feet from the intended touchdown point toward a point on the runway 1000 feet short of the intended touchdown point. (This represents a glide slope of approximately one and a half degrees.) The intent was to drive the aircraft toward this point, then hold the aircraft off until the touchdown point was reached. This technique differed from the lakebed landings in that the deceleration phase prior to touchdown was more of a tangential trajectory just off the lakebed runway for a longer distance which precluded judging the touchdown point accurately.[16] Using this technique the pilot was taking advantage of all the references and cues that had not previously been available on the lakebed landings. After his runway landing the one pilot remarked, "I found that all the references around the runway really make it easier to be accurate than it is on the lakebed because you've got all kinds of geographical references. Not just the runway markers but roads and taxiways and a better feel for the length of the runway."

After the first runway landing the pilot was asked to assess the piloting task he experienced in accomplishing the touchdown with such precise accuracy. In doing so, he was asked to assign a workload factor based on a scale of one to ten similar to a Cooper-Harper rating for handling qualities. The pilot's response was as follows: "The pilot workload rating here was rated on a scale of zero to ten with ten being the max available workload (combined mental and physical).... I rated it the other day as a seven on a scale of ten; thinking about it more I would think you were closer to eight. In other words we're pretty high on workload." The author agrees with this assessment and further submits that pilot gain was higher than normal due to the test being a "first" with high visibility and an intense desire to strive for perfection - which he accomplished. (Additional pilot discussions relative to the accuracy landings and runway landings may be found in Appendix B of Reference 3.)

---

[16] Altitude calls were routinely made during lakebed landings by chase aircraft pilots flying along side the X-24B to touchdown. Safety considerations precluded chase aircraft from descending below 50 feet AGL on the runway landings.

OTHER TEST RESULTS

In addition to the results already discussed that were of prime importance to the actual flight-by-flight conduct of the test program, there were several other areas of research that were products of the program. These will only be discussed briefly and when possible references identified where additional information may be found.

FIN AND CONTROL SURFACE LOADS

Flight loads were determined on the left fin and control surfaces from both surface pressure measurements and strain gages. These results are presented and analyzed with respect to wind tunnel predictions in Reference 11.[17]

PRESSURE DISTRIBUTION CORRELATIONS

Surface pressure measurements were obtained from 251 locations on the left side of the aircraft as follows: 104 body, 87 fin and rudder, 32 aileron, 14 upper flaps, and 14 lower flaps. These data are analyzed and compared to wind tunnel predictions in Reference 10.

BOUNDARY LAYER NOISE

Accelerometers and microphones were located on the left rudders, lower flaps, upper flaps and the aft body forward of the upper flaps to obtain data on boundary layer pressure fluctuation. Meaningful data were obtained and are presented in Reference 12.[18]

VIBRATION AND ACOUSTIC MEASUREMENTS

Six pairs of flush mounted crystal microphones and accelerometers were located along the body (top) from the nose to the rudder hinge line to obtain acoustic and vibration measurements. The intent was to utilize the data to formulate an empirical vibration prediction technique for this type of aircraft. It was found that the dynamic pressures encountered by the X-24B induced insufficient acoustic levels to provide meaningful data.

---

[17] Reference 11: Tang, Ming H., et al, Flight-Measured X-24B Fin Loads and Control Surface Hinge Moments and Correlation with Wind Tunnel Predictions, NASA TM X-56042, January 1977

[18] Reference 12: Miller, V.R., Boundary Layer Pressure Fluctuations on the X-24B Research Vehicle, AFFDL TM 77-70-FBE, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, September 1977

THERMAL PROTECTION SYSTEM QUALIFICATION TESTS

The purpose of this task was to expose candidate X-24C[19] thermal protection systems (TPS) to environmental conditions associated with X-24B flight operations. These included aerodynamic shears, pressures, and vibrations encountered during both mated and free flight. Two different TPS materials were flown on sep te flights on an access panel located on the lower surface of the ai .aft. Test results are documented in Reference 13.[20]

PILOT CHECKOUT PROGRAM

After the basic research program was completed a six-flight-checkout program was accomplished. Three test pilots (two NASA, one USAF) flew two glide flights each. The purpose of the checkout flights was two-fold: (1) to increase the experience level of the pilots for future programs, and (2) to increase the data base of handling qualities information on the X-24B.

The training aspects of the checkout flights were not only those resulting from flying a one-of-a-kind-aircraft but, equally important, was the first hand experience resulting from participation in all operational aspects of the program including flight preparation in a fixed base simulator, inflight training in F-104/T-38 low L/D approaches, captive flight operations, ground control, etc.

In general, the pilot comments substantiated the previous findings of the other pilots of the excellent handling qualities of the aircraft at the conditions flown. A detailed listing of the pilot ratings obtained during the evaluation tasks during the ckeckout flights is presented in Reference 1.

[19] The X-24C was a proposed Mach 6 research aircraft similar to the X-24B configuration

[20] Reference 13: Kirlin, R.L., Evaluation of Bond-on Insulation TPS Material for X-24C - Vol I, AFFDL TR 76-25, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, 31 March 1976

CONCLUSIONS

The X-24B flight test program demonstrated and documented the flight characteristics of the FDL-8 generic hypersonic configuration from 1.76 Mach number through power-off landing. The concept of making major airframe modifications to an existing research aircraft (X-24A) to obtain flight test results on a significantly different aerodynamic configuration (X-24B) proved to be efficient and cost effective. The timely completion of the X-24B envelope expansion was attributed to the use of the proven X-24A systems, to generally good flying qualities of the aircraft and to the experience/continuity of the X-24A/B test team. In addition, extensive ground tests both enhanced the quality of the flight test data and allowed identification of potential problems prior to the first flight. Ground based and inflight performance simulators (T-38, F-104) once again proved their value in the safe planning and conduct of a research program of the type represented by the X-24B.

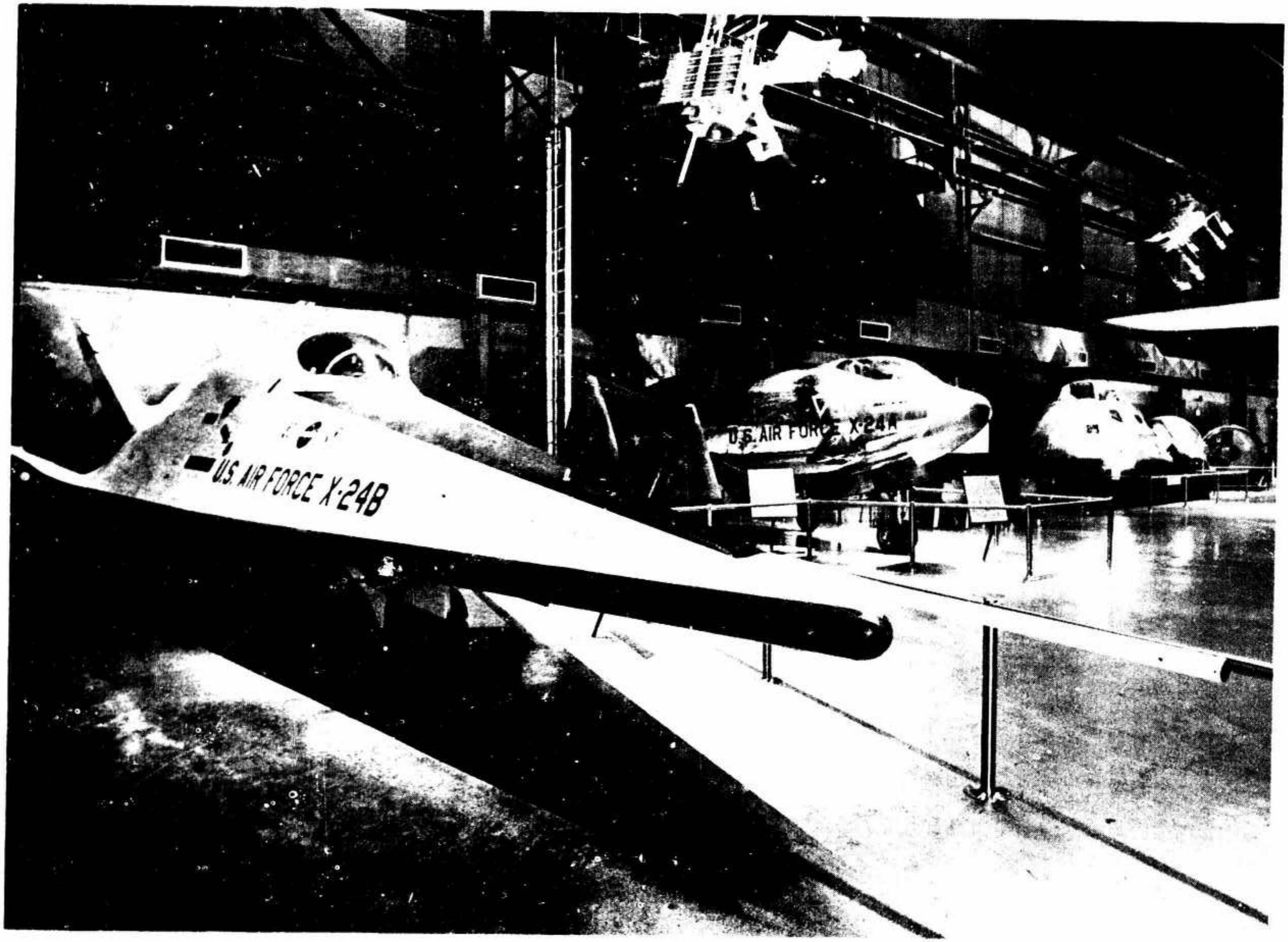
The X-24B handling qualities below .5 Mach number and during landing were excellent. The aircraft rode through turbulence during final approach very well and was improved over the X-24A because of the lower level of dihedral effect of the X-24B. The longitudinal stability was determined to be less than wind tunnel predictions particularly at subsonic speeds. Directional stability (C_{n_β}) was significantly lower than predicted above 1.3 Mach number. A reduction in C_{n_β} due to the rocket engine exhaust was identified based on X-24A flight test results and was substantiated on the X-24B. At some flight conditions, this reduction in directional stability with power on allowed uncommanded sideslip excursions to occur. The forcing functions of the sideslip was concluded to be thrust misalignment and wind shears.

The gliding performance was found to be close to predictions at the conditions flown. At Mach numbers less than one the maximum L/D was seven percent lower than wind tunnel data. A serious loss in supersonic performance (L/D capability) resulted when the angle of attack for zero C_{n_β} was considered as a limit. As with the X-24A, it was determined that a reduction in chord force coefficient of .005 was necessary to duplicate the power-on flight test performance with the simulator

Landing accuracy tests demonstrated a touchdown accuracy within ± 500 feet, providing sufficient confidence to allow two landings on the main concrete runway. The landing rollout on the concrete runway was found to be 34 percent longer than on the lakebed surface for similar braking.

Wind tunnel flow visualization tests successfully defined a location for the fuel jettison line to provide streamline flow of the fuel away from the base of the aircraft thereby precluding "jettison afterfire" that were experienced on the X-24A.

LOX venting from a location forward of the left aileron compartment resulted in a cool-down of the aileron actuator components that caused an undesirable aileron deadband on some flights.

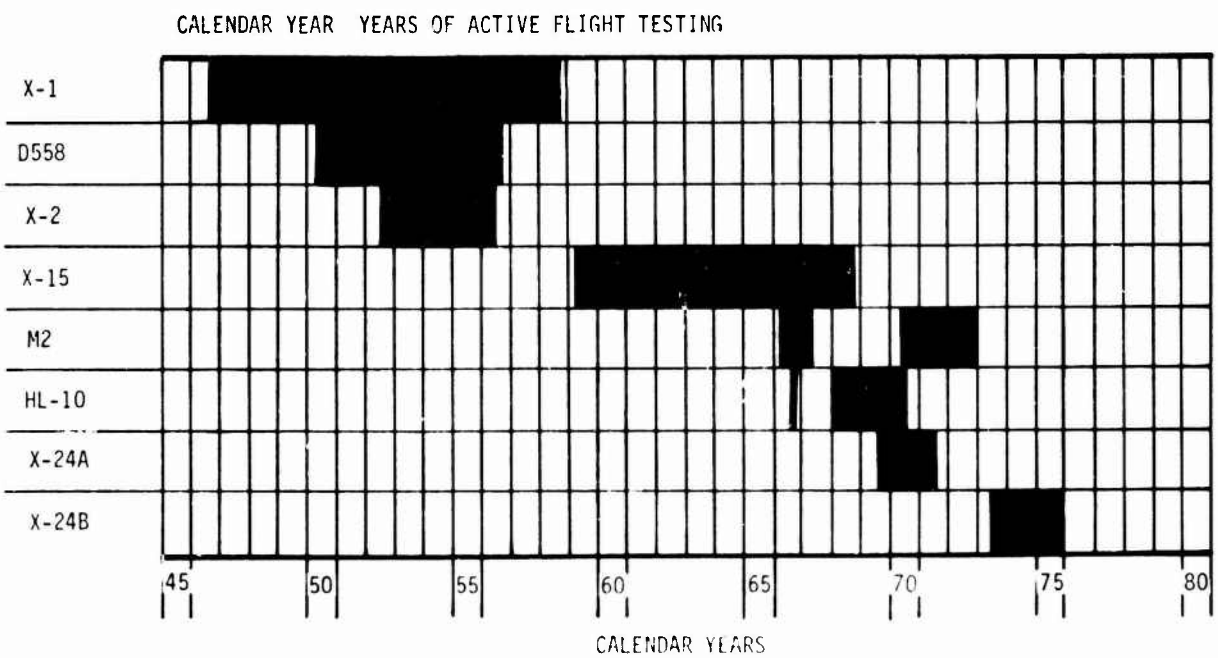

U.S. AIR FORCE X-24B
U.S. AIR FORCE X-24A

EPILOGUE

The X-24B departed Edwards AFB by Pregnant Guppy aircraft on 26 May 1976 for Kennedy Space Center, Florida where it was on display during the Nation's Bicentennial Celebration. The aircraft was then delivered to the Air Force Museum at Wright-Patterson AFB, Ohio on 19 November 1976 where it is displayed next to other historical lifting reentry vehicles - a replica of the X-24A (one of the SV-5J aircraft), PRIME (same shape as the X-24A), and ASSET vehicles.

The accompanying chart places the X-24B in its proper historical prospective as the last of the continuous series of air launched rocket powered research aircraft that began with the Bell X-1 in 1946. These unique research aircraft all had a common goal - that of pursuing the technology of high speed flight - the X-1, D558, X-2, and X-15 by direct exploration, being the first to exceed Mach numbers of one, two, three, and six, respectively. The others, including the X-24B, indirectly contributed to high speed technology by verifying proof of concept (at speeds less than Mach 2) of aerodynamic configurations that were developed for hypersonic flight or orbital reentry.

CHRONOLOGY OF AIR LAUNCH ROCKET RESEARCH AIRCRAFT PROGRAMS



REFERENCES

1. Nagy, Christopher J. and Kirsten, Paul W., Handling Qualities and Stability Derivatives of the X-24B Research Aircraft, AFFTC-TR-76-8, Air Force Flight Test Center, Edwards AFB, California, March 1976

2. Richardson, David F., Comparison of Flight Test and Wind Tunnel Performance Characteristics of the X-24B Research Aircraft, AFFTC-TR-76-10, Air Force Flight Test Center, Edwards AFB, California, April 1976

3. Stuart, John L., Captain, USAF, Analysis of the Approach, Flare and Landing Characteristics of the X-24B Research Aircraft, AFFTC-TR-76-9, Air Force Flight Test Center, Edwards AFB, California, November 1977

4. Armstrong, Johnny G., Flight Planning and Conduct of the X-24A Lifting Body Flight Test Program, FTC-TD-71-10, Air Force Flight Test Center, Edwards AFB, California, August 1972

5. Hallion, Richard P., Supersonic Flight, The Macmillian Company, 1972

6. Anonymous, Development Plan - Advanced Development Program - FDL-8 with Advanced Reusable Spacecraft Technology and Applications Study, 68FD-1632, Air Force Flight Dynamics Laboratory, AFSC, 23 Jan 69

7. Long, James A., 1st Lt/USAF and Berry, Robert L., Sgt/USAF, X-24B Ground Vibration Test (Strake/Aileron, Fin/Rudder), AFFTC-TR-73-23, Air Force Flight Test Center, Edwards AFB, California, June 1973

8. Woodfield, A.A., Measurement of the Yawing Moment and Product of Inertia of an Aircraft by the Single Point Suspension Method: Theory and Rig Design, Royal Aircraft Establishment, TR 68-44, February 1968

9. Retelle, John P., Jr., Captain, USAF, Measured Weight, Balance, and Moments of Inertia of the X-24A Lifting Body, FTC-TD-71-6, Air Force Flight Test Center, Edwards AFB, California, November 1971

10. Selegan, David R., and Norris, Richard B., Comparison of X-24B Flight and Wind Tunnel Pressure Distributions, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, to be published

11. Tang, Ming H., et al, Flight-Measured X-24B Fin Loads and Control Surface Hinge Moments and Correlation with Wind Tunnel Predictions, NASA TM X-56042, January 1977

12. Miller, V.R., Boundary Layer Pressure Fluctuations on the X-24B Research Vehicle, AFFDL TM 77-70-FBE, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, September 1977

13. Kirlin, R.L., Evaluation of Bond-on Insulation TPS Material for X-24C - Vol I, AFFDL TR 76-25, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, 31 March 1976

APPENDIX A - X-24B FLIGHT LOG SUMMARY

X-24B FLIGHT LOG SUMMARY

TOTAL NUMBER OF FLIGHTS	36
Glide Flights	12
Powered Flights	24
Flight Time	3 Hrs 46 Min 43.6 Sec
BASIC RESEARCH PROGRAM FLIGHTS	30
Glide Flights	6
Powered Flights	24
Flight Time	3 Hrs 21 Min 33.8 Sec
PILOT CHECKOUT PROGRAM FLIGHTS (Glide Only)	6
Flight Time	25 Min 9.8 Sec
NUMBER OF FLIGHT ABORTS	7
Aborts due to Weather	4
Aborts due to SAS	1
Aborts due to Engine	1
Aborts due to Preflight Closeout	1
NUMBER OF PLANNED CAPTIVE FLIGHTS	4
NUMBER OF CAPTIVE ABORTS	2
Aborts due to B-52 TV Fire	1
Aborts due to B-52 LOX Top off	1
NUMBER OF FLIGHT DAY CANCELLATIONS	9
Cancellations due to Weather	5
Cancellations due to Wet Lakebed	1
Cancellations due to Radar	1
Cancellations due to B-52 Maintenance	1
Cancellations due to SAS	1
NUMBER OF ALTERNATE PROFILES	8
Three Chamber Profiles	4
Delayed Engine Lights	2
Premature Engine Shutdown	1
Lower Altitude Launch (B-52 Engine Problem)	1
FLIGHTS BY JOHN A. MANKE (4 Glide, 12 Powered)	16
Flight Time	1 Hr 46 Min 47.3 Sec

FLIGHTS BY LT COL MICHAEL V. LOVE (2 Glide, 10 Powered)	12
Flight Time	1 Hr 20 Min 13.6 Sec
FLIGHTS BY WILLIAM H. DANA (Powered Only)	2
Flight Time	14 Min 32.9 Sec
FLIGHTS BY EINAR ENEVOLDSON (Glide Only)	2
Flight Time	8 Min 12.9 Sec
FLIGHTS BY CAPT FRANCIS R. SCOBEE (Glide Only)	2
Flight Time	8 Min 24.4 Sec
FLIGHTS BY THOMAS C. McMURTRY (Glide Only)	2
Flight Time	8 Min 32.5 Sec

APPENDIX B - X-24B FLIGHT LOG

X-24B FLIGHT LOG

DATE	Flight Number	Pilot	Launch ALT/A/S	Launch Area	MAX MACH	MAX True A/S KTS	MAX ALT Feet	Flight Time Min:Sec	Burn Time Sec	Land Runway	REMARKS
2 Jul 73											-11 Engine run, 6 taxi runs with L/D rockets
5 Jul 73											2 taxi runs with -11 engine
6 Jul 73											1 taxi run with -11 engine
10 Jul 73											Mated taxi test
19 Jul 73	B-1C-1	Manke									Systems check, Pylon damping
24 Jul 73	B-A-2	Manke									Abort due to failed SAS Gyros
1 Aug 73	B-1-3	Manke	40/175	S. Rogers	.652	400	40000	4:11.5	Glide	18	20° Upper Flaps
17 Aug 73	B-2-4	Manke	45/175	S. Rogers	.661	390	45000	4:27.3	Glide	18	
31 Aug 73	B-3-5	Manke	45/180	S. Rogers	.730	416	45000	4:37.8	Glide	18	Fuel jettison test
18 Sep 73	B-4-6	Manke	45/1[illegible]5	S. Rogers	.691	391	45000	4:30.8	Glide	18	Fuel jettison test
3 Oct 73	B-2C-7	Love									Pilot training
4 Oct 73	B-A-8	Love									Abort due to Rudder CALB Fixture
4 Oct 73	B-5-9	Love	45/185	S. Rogers	.689	395	45000	4:39.0	Glide	18	Pilot checkout
30 Oct 73	B-3C-10	Manke									Prop systems, Pylon damping
31 Oct 73	B-A-11	Manke									Abort due to Igniter failure
13 Nov 73	B-A-12	Manke									Abort due to clouds
15 Nov 73	B-6-13	Manke	40/185	Rosamond	.917	519	52764	6:44.7	150	18	First powered flight
12 Dec 73	B-7-14	Manke	45/185	Rosamond	.993	560	62604	7:14.8	131	18	
15 Feb 74	B-8-15	Love	45/185	S. Rogers	.683	391	45000	5:07.7	Glide	15	
5 Mar 74	B-9-16	Manke	45/184	Cuddeback	1.086	615	60334	7:17.2	116	36	
19 Mar 74	B-A-17	Love									Abort due to clouds
22 Apr 74	B-4CA-18	Love									Abort due to T V Monitor fire in B-52
23 Apr 74	B-4CA-19	Love									Abort due to B-52 Lox Top Off System
25 Apr 74	B-4C-20	Love									Aileron Deab Band investigation
30 Apr 74	B-10-21	Love	45/190	Rosamond	.876	502	52040	6:59.1	139	18	Delayed lite profile
24 May 74	B-11-22	Manke	45/190	Rosamond	1.14	654	55979	7:28.9	156	18	# 1 didn't lite, 3 chamber alternate
14 Jun 74	B-12-23	Love	45/190	Rosamond	1.23	704	65512	6:45.4	106	18	
28 Jun 74	B-13-24	Manke	45/190	Rosamond	1.39	799	68150	7:07.6	117	18	
8 Aug 74	B-14-25	Love	45/190	Rosamond	1.54	888	73380	6:35.8	130	18	Engine POGO due to H_2O_2 UNPORT
29 Aug 74	B-15-26	Manke	45/200	Rosamond	1.097	632	72440	7:47.6	109	18	Premature shutdown, crack in fuel tank
25 Oct 74	B-16-27	Love	45/200	Rosamond	1.76	1011	72150	6:57.1	135	15	Planned MAX Mach Flight
15 Nov 74	B-17-28	Manke	45/200	Rosamond	1.015	930	72060	8:1.9	138	18	Delayed light, 1st Performance Landing
17 Dec 74	B-18-29	Love	45/200	Cuddeback	1.585	900	68780	7:00.7	133	33	Instrumentation total pressure inoperative
14 Jan 75	B-19-30	Manke	46/200	Rosamond	1.748	1005	72787	7:57.5	135	15	
31 Jan 75	B-A-31	Love									Abort at one min due to clouds over Rosamond
20 Mar 75	B-20-32	Love	45/200	Rosamond	1.443	830	70373	6:49.8	118	15	X-wir : landing, Main gear bottomed
18 Apr 75	B-21-33	Manke	45/200	Rosamond	1.20	690	57900	7:29.6	153	18	#3 chamber didn't light, 3 chamber alternate
6 May 75	B-22-34	Love	42/190	Rosamond	1.44	832	73370	7:31.3	135	18	42klaunch, B-52 engine problem
22 May 75	B-23-35	Manke	45/195	Rosamond	1.63	942	74130	7:40.9	134.5	18	
6 Jun 75	B-24-36	Love	45/200	Rosamond	1.67	965	72140	7:53.6	134.5	18	
24 Jun 75	B-A-37	Manke									Abort due to surface winds
25 Jun 75	B-25-38	Manke	45/198	Cuddeback	1.343	770	57999	7:07.2	124	36	High $\bar{q}$ flt for pwr effects
15 July 75	B-26-39	Love	45/195	Cuddeback	1.585	910	69486	6:54.0	132	36	
5 Aug 75	B-27-40	Manke	45/199	Cuddeback	1.19	683	57050	7:02.0	153.8	04	First landing on main runway; 3 ch alternate
20 Aug 75	B-28-41	Love	45/192	Cuddeback	1.548	891	71076	7:00.1	133	04	Second landing on main runway
9 Sep 75	B-29-42	Dana	45/190	Rosamond	1.48	852	69734	7:15.0	126	18	
23 Sep 75	B-30-43	Dana	45/197	Rosamond	1.16	664	56830	7:17.9	151	18	3 Chamber Alternate, Last Rocket Flt.
			End of Basic Research Program								
9 Oct 75	B-31-44	Einar*	45/185	S. Rogers	.700	402	45000	4:11.2	Glide	18	Pilot Checkout
21 Oct 75	B-32-45	Scobee	45/185	S. Rogers	.700	402	45000	4:15.0	Glide	18	Pilot Checkout
3 Nov 75	B-33-46	Tom	45/185	S. Rogers	.700	402	45000	4:07.4	Glide	18	Pilot Checkout
12 Nov 75	B-34-47	Einar*	45/185	S. Rogers	.708	406	45000	4:01.7	Glide	18	
19 Nov 75	B-35-48	Scobee	45/185	S. Rogers	.714	409	45000	4:09.4	Glide	18	
26 Nov 75	B-36-49	Tom**	45/185	S. Rogers	.700	402	45000	4:25.1	Glide	18	Last Flight

*Einar Enevoldson ** Tom McMurtry

APPENDIX C - X-24B OPERATIONS LOG

X-24B OPERATIONS LOG

DATE	OPERATION
1973	
2Jul	XLR-11 Engine Run, Six Taxi Runs with L/D Rockets
5Jul	Two Taxi Runs with XLR-11 Engine
6Jul	One Taxi Run with XLR-11 Engine
10Jul	B-52/X-24B Mated Taxi Tests
19Jul	B-1C-1 First Captive Flight (System Checkout)
20Jul	Flight B-1-2 Scheduled - Cancelled on 19 July due to Lack of Batteries
24Jul	B-A-2 Abort due to SAS Gyro Failures
1Aug	B-1-3 Flown
17Aug	B-2-4 Flown
31Aug	B-3-5 Flown
18Sep	B-4-6 Flown
3Oct	B-2C-7 Captive Flown (Pilot X-Out)
4Oct	B-A-8 Abort due to Rudder Calibration
4Oct	B-5-9 Flown
30Oct	B-3C-10 Captive Flown (Propulsion System and Pylon Checks)
31Oct	B-A-11 Abort at 10 Sec due to Igniter Failure
2Nov	Flight 6 Cancelled yesterday at 1530 due to Igniter Relay Problem, A/C Demated, Engine Removed
13Nov	B-A-12 Abort at 7 Minute Point due to High Surface Winds
15Nov	B-6-13 First Powered Flight Flown
11Dec	Flight B-7-14 Cancelled at 1130 due to Clouds
12Dec	B-7-14 Flown (30 Minute Delay for Clouds)
	(Holidays, Control System Adjustments to Reduce Aileron Dead Band, Instrumentation Calibrations)
1974	
15Feb	B-8-15 Flown

DATE	OPERATION
5Mar	B-9-16 Flown
19Mar	B-A-17 Abort due to Clouds, Aileron Deadband not Acceptance, A/C Demated
	(Installed Aileron Instrumentation, B-52 Engine Problems)
22Apr	B-4CA-18 Captive Flight Aborted due to Fire in TV Monitor in B-52
23Apr	B-4CA-19 Captive Flight Aborted due to B-52 LOX Top Off System Problem
24Apr	Captive Cancelled due to "Red X" on B-52 Hydraulic Packs
25Apr	B-4C-20 Captive Flown (Aileron Deadband Check)
26Apr	Flight 10 Cancelled at 0730 due to Yaw SAS Problems
30Apr	B-10-21 Flown (Delayed 2½ Hours due to Yaw SAS Problems)
	(Major Rework of SAS System)
24May	B-11-22 Flown
14Jun	B-12-23 Flown
28Jun	B-13-24 Flown
8Aug	B-14-25 Flown
	(B-52 Inspection)
29Aug	B-15-26 Flown
	(Fuel Tank Bulkhead Repair)
25Oct	B-17-27 Flown
15Nov	B-17-28 Flown
17Dec	B-18-29 Flown in Afternoon due to Winds in Morning
1975	
14Jan	B-19-30 Flown
30Jan	Flight 20 Cancelled due to Clouds
31Jan	B-A-31 Aborted at One Minute due to Clouds Over Rosamond Dry Lake
	(Wet Lakebed and B-52 Phase Maintenance)
20Mar	B-20-32 Flown

DATE	OPERATION
8Apr	Flight 21 Cancelled due to Clouds
18Apr	B-21-33 Flown
6May	B-22-34 Flown
22May	B-23-35 Flown
6Jun	B-24-36 Flown
19Jun	Flight 25 Cancelled due to Space Shuttle Facility Construction Accident Cut Radar Cable
24Jun	B-A-37 Aborted at Two Minute Point due to High Surface Winds
25Jun	B-25-38 Flown
15Jul	B-26-39 Flown
3Aug	B-27-40 Flown
19Aug	Flight 28 Cancelled due to Surface Winds
20Aug	B-28-41 Flown
9Sep	B-29-42 Flown
23Sep	B-30-43 Flown (Last Rocket Flight)
7Oct	Flight 31 Cancelled due to Winds and Clouds
9Oct	B-31-44 Flown
21Oct	B-32-45 Flown
31Oct	Flight 33 Cancelled due to Wet Lakebed
3Nov	B-33-46 Flown
12Nov	B-34-47 Flown
19Nov	B-35-48 Flown
26Nov	B-36-49 Flown (Last Flight)

APPENDIX D - X-24B FLIGHT REQUEST

X-24B Flight Request

24 July 1975

Flight No: B-27-40

Scheduled Date: 5 August 1975

Pilot: John Manke

Purpose:
1. Landing on concrete runway.
2. Body pressure survey (Group 2).
3. Lefthand fin tuft study.
4. TPS qualification test.
5. Stability and Control with aileron bias at 3 degrees.

Launch: Cuddeback, Mag Heading 209 degrees + cross wind correction angle. 45,000 feet, 200 KIAS. Flap bias "Manual", upper flaps= -40 degrees, lower flaps= 27 degrees, rudder bias mode "AUTO", rudder bias = 0 degrees. Rudder trim = 1 degree left. Aileron bias = +7 degrees, SAS gains 6, 5, 3. Mach repeater "Manual" = 1.0, KRA "AUTO". Hydraulic Pumps 2 and 4 on. Ay "OFF"

Landing: Main base runway 04.

B-52 Track: X-24B track #3 (R2502, R2524, SPIN AREA I)

ITEM	TIME	ALT	A/S	α	M_T	EVENT
1	0	45	200	5	.74	Launch, light 4 chambers, trim to and maintain 15° α
2	30	45	225	15	.83	At 30 sec., turn overdrive on. Turn Ay feedback on.
3	78	61	150	15	.80	At 61K pushover to 12° α.
4	90	66	155	12	.90	At .83 M_i perform rudder and aileron doublets (±4° δ_r)
5	103	70	170	12	1.05	At 1.05 $Mach_i$ pushover to 5° α.

ITEM	TIME	ALT	A/S	α	M_T	EVENT
6	112	71	190	5	1.15	At 1.15 M_i, perform steady sideslip (±3°β).
7	126	70	260	5	1.50	Shutdown the engine. Turn Ay feedback off. Move the aileron bias to 3°.
8	139	66	265	5	1.40	At 1.43 M_i perform rudder and aileron doublets. Trim to 7° α, move aileron bias to 7° and trim to 5° α.
9	159	53	295	5	1.22	At 1.25 M_i perform steady side-slip (±3°β). Trim to 8 α.
10	171	45	290	8	1.0	At 1.05 $Mach_i$ perform steady sideslip (±3°β).
11	179	42	280	8	.95	At .95 M_i perform steady side-slip (±3°β). Trim to 10° α. Set SAS gains to 4,3,2. Jettison propellants. Begin systems checks.
12	218	31	215	10	.58	At .60 M_i change configuration to 20° upper flap.
13	227	29	220	10	.57	Commit point. Complete systems checks. NASA I ok to proceed.
14	265	24	220	10	.51	Low Key. #1 and #3 hydraulic pumps ON. Open upper flap to 24°.
15						Change Mach repeater to 0.3 during final. Change upper flap to 20° prior to the flare.
16						Gear down, and land RW 04 (Planned touchdown = 5000Ft.)

NOTES:

1. Nose Ballast = 120 lbs (+ five 93 lb batteries)

2.

	Weight-lbs	cg-%	
Launch	13686	66.13	
Shutdown	8925	64.00	
Landing	8520	64.1	(gear down)

3. Engine S.N 8 (new #1 chamber), Pump S/N 8A

	NORMAL	OVERDRIVE
Thrust - lbs/chamber	2150	2450
LOX flow rate - lb/sec/chamber	4.32	4.92
WALC flow rate -lb/sec/chamber	4.18	4.76

4. Power on base drag reduction C_C = -.005

5. Pitch attitude null at 46 degrees

6. Ay feedback gain = 1.0 deg/ft/sec^2

Ground Rules for NO LAUNCH:

1. Radio, radar, PCM failure
2. Electrical or SAS malfunction
3. A/S, altitude, Machmeter failure
4. Angle of attack or sideslip malfunction
5. Any control system malfunction
6. Loss of cabin pressure
7. Turbulence below 10K in excess of moderate
8. Surface winds greater than 20 kts, crosswind greater than 5 kts or tail wind greater than 10 kts.
9. Failure of engine control box heater
10. Failure of stick shaker
11. Launch altitude less than 42,000 feet
12. Support equipment and aircraft not in position
13. Runway 04 is wet
14. Control zone and runway 04 not closed

(In addition to standard ground rules published in Lifting Body Joint Operations Plan)

Alternate Situations After Launch:

	FAILURE	ACTION
1.	Radar, PCM	Proceed as planned at pilots discretion
2.	Radio	X-24B radio receiver: At or prior to the commit point, proceed as planned

	FAILURE	ACTION
2.	Radio	except land on Rogers lakebed runway 36. After the commit point, proceed as planned. X-24B radio transmitter: Proceed as planned. NASA I radio: Proceed as planned except all commit point checks are performed by the X-24B pilot.
3.	Only one chamber operates	Vector for RW 01 Cuddeback, shutdown chamber, jettison, change configuration.
4.	Only two chambers operate	Turn Overdrive ON, turn Ay "ON" and maintain 15α. Shutdown on NASA I call. At shutdown pushover to 10°α turn Ay "OFF" and proceed as planned with the SAS gain change.
5.	Only three chambers operate	Turn overdrive ON, turn Ay "ON" and maintain 15α. At .85 M_i (55K) pushover 12°α. At 1.05 Mach pushover to 8°α. At engine burnout (155 sec, 1.16 $Mach_T$) turn Ay off and proceed with the Mach 1.0 steady β.
6.	Delayed engine light	Proceed as planned, but limit θ to 50°.
7.	Overdrive failure	Maintain 15°α. At .85M_i (61K) pushover to 12°α. at 1.05M_i pushover to 10°α and at 1.2 M_i pushover to 6°α (do not do the steady β). Burnout at 142 sec, 1.48 $Mach_T$, 310 knots. Pushover to 5°α, turn Ay "OFF" and proceed as planned with the doublet set at 1.43 M_i with 3°δ_{A_B}.
8.	Total damper failure any axis	Fly 2 chamber profile, leave overdrive ON. Maintain 15°α (13°α for a pitch damper failure). Roll or Yaw failure set KRA to "MAN" 0% and turn Ay "OFF". If roll failure, turn Yaw gain to zero. Shutdown at pilot's discretion, but Limit Mach to .9. Pitch failure, close up to -24°δ_u at low key. Do not Land on runway 04.

FAILURE	ACTION
9. KRA "AUTO" failure	Set to maual 10% and proceed as planned. If "MANUAL" mode inoperative - switch to "EMER" position and set to above value.
10. Angle of attack (Indicator only)	Proceed as planned using backup angle of attack gage. KRA "MANUAL" 10%, stick shaker OFF.
11. Total Angle of attack	0 to 30 seconds; fly two chamber profile, no overdrive; use 200 kts instead of 15°α. To rotate set the lower flap at 25 ° until 230 KIAS then fly 200 KIAS. (KRA manual 10%, stick shaker OFF). 30 to 60 seconds; fly three chamber profile, overdrive stays on, se: the lower flap at 25°, shutdown on NASA I Call. (RW 15 energy). At shutdown turn Ay "OFF". Fly 250 KIAS until Mach = .85, then fly 200 KIAS (KRA MAN 10%, stick shaker OFF). 60 seconds and up; shutdown, turn Ay "OFF" fly 250 KIAS until Mach = .85 then fly 200 KIAS. (KRA MAN 10%, stick shaker OFF).
12. A/S, altitude, Mach	Proceed as planned using α, Θ and time for profile control. Closeup to -20° δ_u on NASA I Call at 30K. Land on Rogers lakebed runway 36 for α/c failure
13. Attitude system	Proceed as planned using backup attitude indicator.
14. Rudder bias "AUTO" failure	Switch to "MANUAL" mode and toe-in to -10°. If "MANUAL" fails closeup to -24° upper flap.
15. Upper flaps fail to close	Cycle emergency flap switch to closeup to -20° upper flaps. If emergency flap switch fails, move δ_{A_B} to 11° and land on Rogers lakebed runway 36.

FAILURE	ACTION
16. Aileron bias "NORMAL" failure	Switch to "BACKUP" and move the aileron bias to 7°. If "BACKUP" fails, pull the C/B's. If the aileron bias is stuck at less than 7° proceed as planned. If the aileron bias is greater than 7° close-up to 24° δ_u.
17. Ay feedback failure	For normal or delay engine light proceed as planned except pushover at 64K to 10°α and at 1.05 M_i pushover to 5°α. Shutdown the engine at 1.50 M_i. In all cases do not do the .83 M_i doublet set. For all other failures, proceed as planned with the appropriate alternate action for that failure.
18. Launch at 42,000 feet, 190 KIAS	Proceed as planned but limit Θ to 50°.

19. Premature engine shutdown

0 - 40 Sec RW 01 Cuddeback
40 - 77 Sec RW 15 Rogers
77 - up Sec RW 36/04 Rogers

Commit Point Checks:

Must have the following systems and checks to land on runway 04. If not, proceed with the appropriate alternate action for the failure and land on Rogers lakebed runway 36.

1. (a) System checks by pilot
   Airspeed indicator, and radio receiver

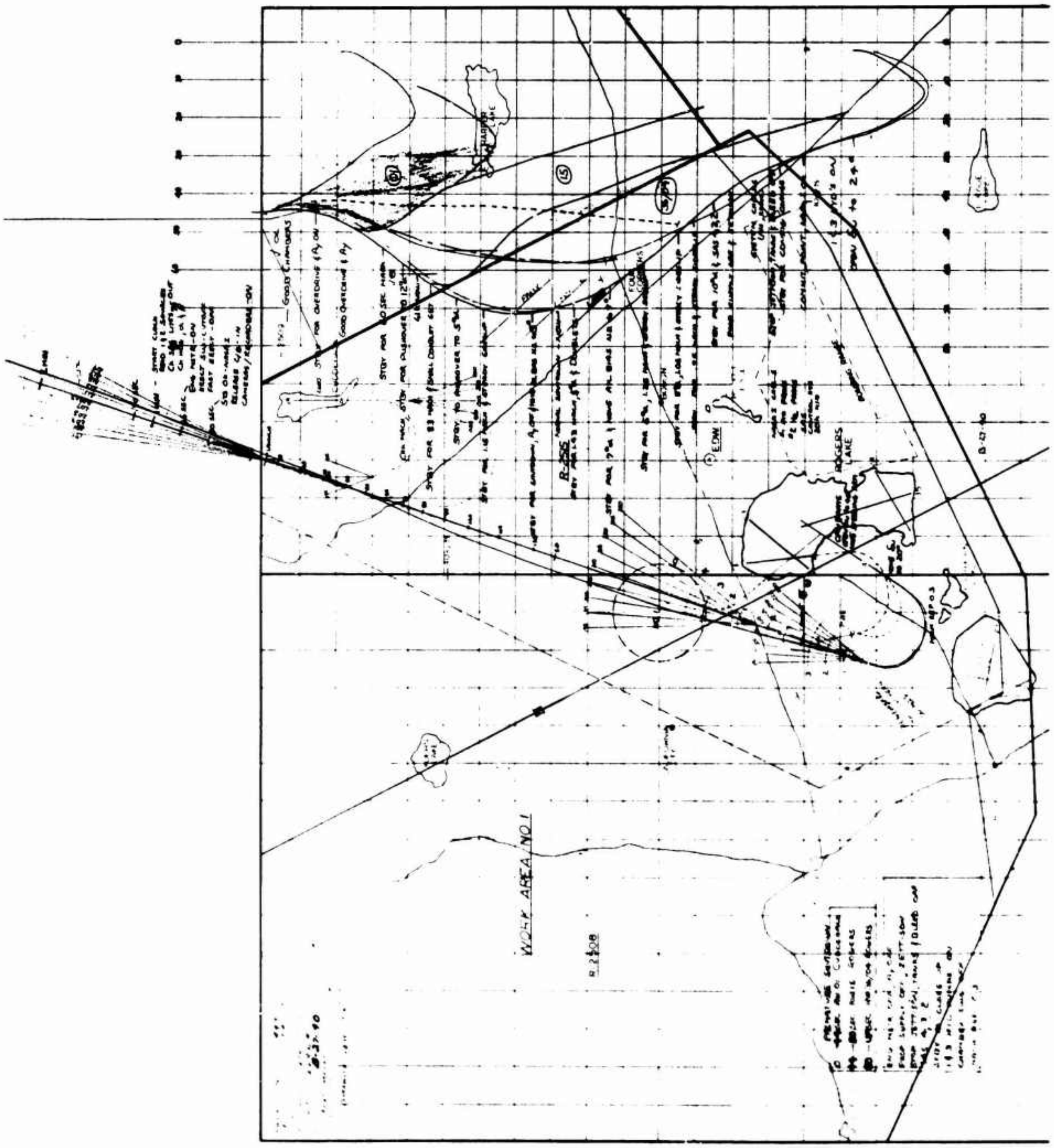
   (b) System checks in control room
   #1 hydraulic system pressure, #2 helium pressure, or gear pressure
   total SAS and control system

2. Upper flap operational check (movement to at least 35°)

3. Altitude greater than or equal to 20,000 feet

JOHNNY G. ARMSTRONG

JACK L. KOLF


WORK AREA NO 1
ROGERS LAKE
EDW

LIST OF ABBREVIATIONS AND SYMBOLS

SYMBOL	DESCRIPTION	UNITS
AFFDL	Air Force Flight Dynamics Laboratory	---
AFFTC	Air Force Flight Test Center	---
ASD	Aeronautical Systems Division	---
a_y	Lateral Acceleration	g's
$\bar{c}$	Reference chord (37.5)	ft
cg	Center of gravity (reference 66 percent)	percent $\bar{c}$
C_L	Lift coefficient	dimensionless
C_{ℓ_β}	Rolling moment coefficient due to sideslip	per degree
C_{m_α}	Pitching moment coefficient due to α	per degree
C_{n_β}	Yawing moment coefficient due to sideslip	per degree
$C_{n_\beta}{}^*$	Dynamic C_{n_β}	per degree
DFRC	Dryden Flight Research Center	---
EAFB	Edwards AFB (CA)	---
g	Acceleration of gravity (32.17405)	ft/sec^2
GVT	Ground Vibration Test	---
I_x	Rolling moment inertia	slug-ft^2
I_{xz}	Product of inertia	slug-ft^2
I_y	Pitching moment inertia	slug-ft^2
I_z	Yawing moment inertia	slug-ft^2
KCAS	Knots calibrated airspeed	---
KIAS	Knots indicated airspeed	---
KRA	Aileron to rudder interconnect	deg/deg
KTS	Knots	---

SYMBOL	DESCRIPTION	UNITS
LOX	Liquid oxygen	---
M	Mach number	dimensionless
MSL	Mean Sea Level	---
NASA	National Aeronautics and Space Administration	---
n_{z_s}	Load factor opposite to the stability z-axis	dimensionless
PCM	Pulse Code Modulation	---
PIO	Pilot Induced Oscillation	---
PSTS	Propulsion System Test Stand	---
$\bar{q}$	Dynamic pressure	lb/ft^2
S	Reference area (330.5)	ft^2
SAS	Stability augmentation system	---
TM	Telemetry	---
TPS	Thermal Protection System	---
Ve	Equivalent airspeed	knots
W	Weight	lb
WALC	Water-Alcohol	---
WPAFB	Wright-Patterson AFB (Ohio)	---
α	Angle of Attack	degrees
β	Angle of Sideslip	degrees
Δ	Prefix indicating increment	---
δA_B	Aileron bias position	degrees
δa	Aileron position	degrees
δe_L	Lower flap position	degrees
δe_U	Upper flap position	degrees
δR_B	Rudder bias position	degrees
δr	Rudder position	degrees
δU_E	Upper flap bias position	degrees
θ	Pitch angle	degrees


END OF AN ERA
SEPT. 23 1975
LAST ROCKET FLIGHT