PAT Projects was Dissolved June 30, 2002

Curent Contacts:
Robert G. Hoey, Author
e-mail: "Bob Hoey" <bobh@antelecom.net>

Wayne Ottinger, Former Managing Director, PAT Projects
e-mail: wottinger@aletro.org
875 Roxwood LN #B Boulder, CO 80303

The image above is a reproduction of the mural commissioned by NASA Dryden and created by Robert T. McCall ©, 1977, which is part of the visitor's lobby at the NASA Dryden Research Center, Edwards, CA.

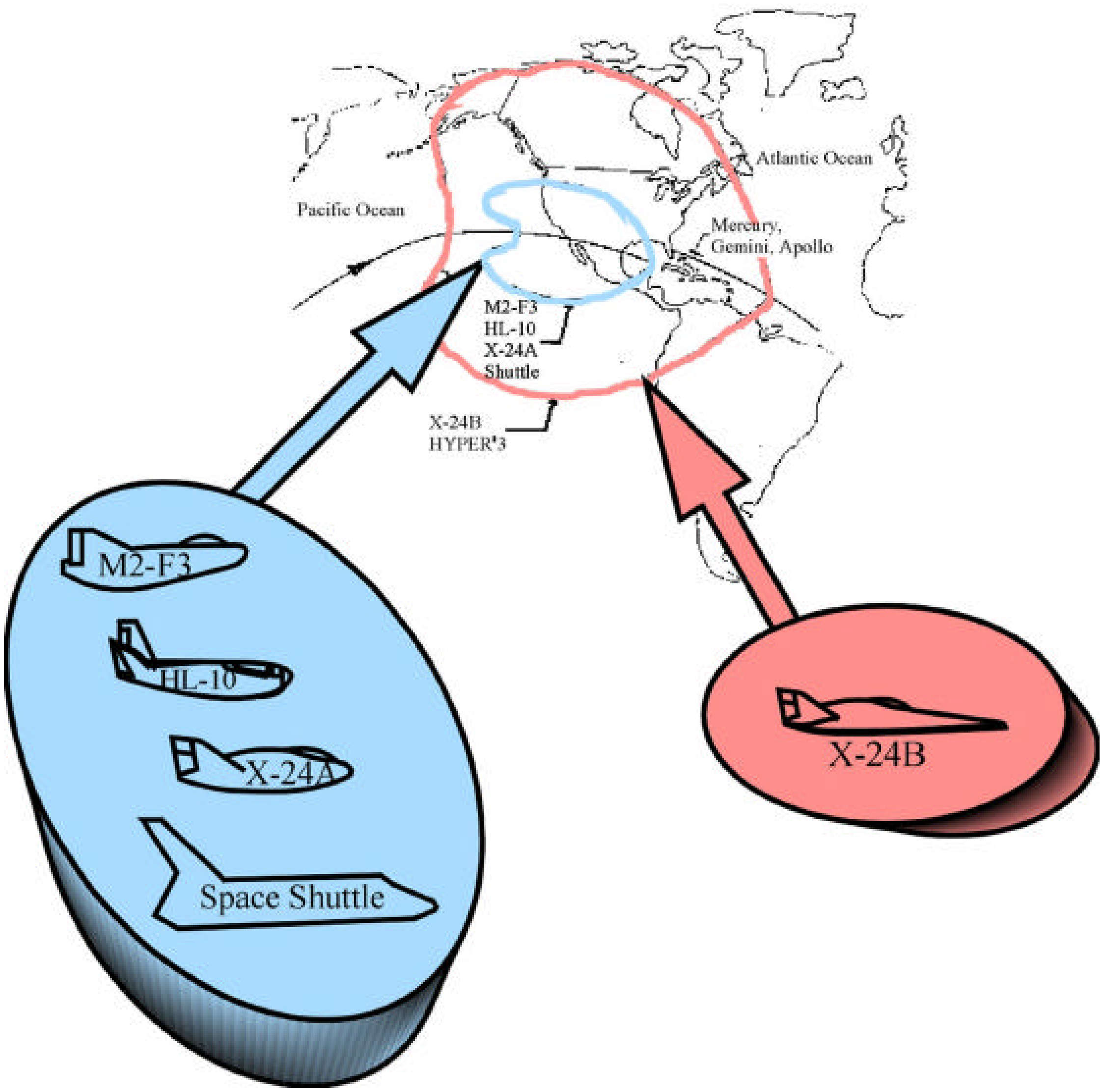
Testing Lifting Bodies at Edwards

By

Robert G. Hoey

~~A *PAT* Projects, Inc., Publication~~

Air Force/NASA Lifting Body Legacy History Project



PAT Projects, Inc.
September 1994

418 Bogie Street
Palmdale, CA 93551

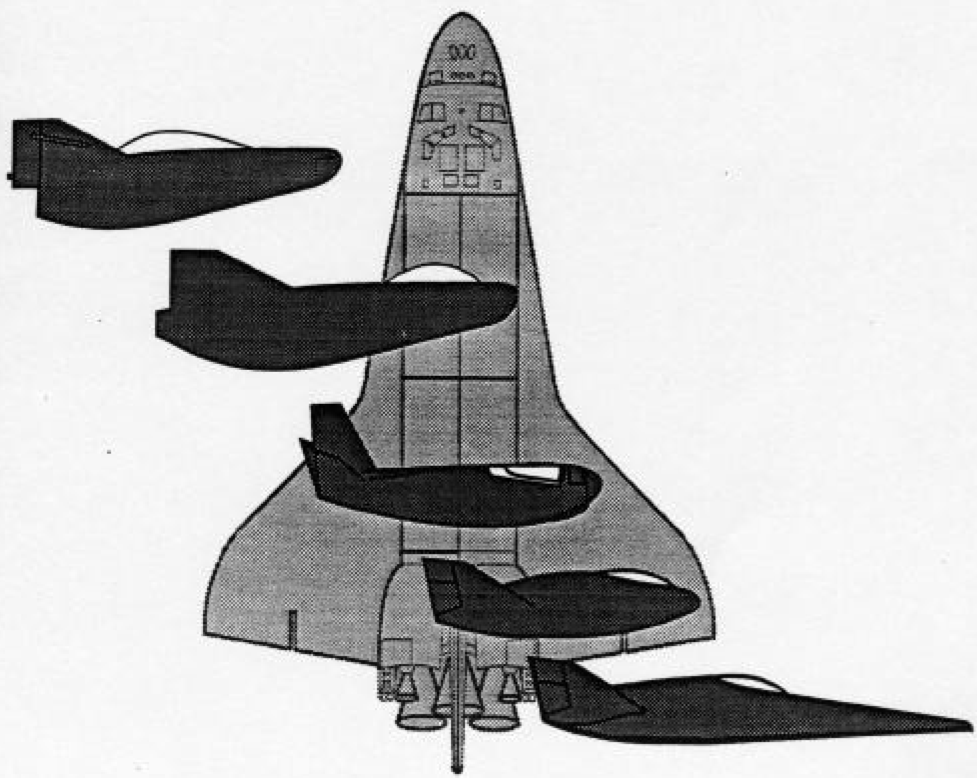
(805) 947-9440
Fax (805) 947-9402
e-mail: ......wayne@patprojects.org
WWW: http://www.patprojects.org

AIR FORCE MATERIEL COMMAND

AD INEXPLORATA

LEGACY OF THE LIFTING BODIES

VOLUME II




M2-F1
M2-F2


USAF
U.S. AIR FORCE X-24A
X-24A
M2-F3
HL-10


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

PDF Version for Adobe Acrobat®

The conversion of the HTML publication to PDF has been designed to accomodate a hard copy print of this document for single sided page printing layout. the key conversion items are:

1. Elimination of all HTML navigation tools and links.
2. Use of images sized for page layout in lieu of "thumbnails" linked to larger size images.

Material	**PDF File**	**PDF File Size**
Contents and Illustrations	coil.pdf	64k
Entire Publication (all of the above files integrated into one)	lbbook.pdf	10,183k
Front Matter (all materials preceding Chapter 1)	fm.pdf	734k
Chapter 1: Returning From Space	ch1.pdf	181k
Chapter 2:Lifting Entry With Horizontal Landing: The Quest Begins	ch2.pdf	312k
Lifting Bodies: A NASA Perspective	nasap.pdf	8k
Chapter 3: The M2-F1 Program	ch3.pdf	637k
Chapter 4: The M2-F2 and M2-F3 Program	ch4.pdf	2,467k
Chapter 5: The HL-10 Program	ch5.pdf	858k
Chapter 6: The X-24A Program	ch6.pdf	1,393k
Chapter 7: The X-24B Program	ch7.pdf	1,168k
Chapter 8: Epilogue	ch8.pdf	336k
Back Matter (all materials following chapter 8)	bm.pdf	2,106k

Sponsorship

World Wide Web Publication

NASA Dryden Flight Research Center
NASA Contract # I-2102D to PAT Projects, Inc.
July 31, 1997

Original Works

Air Force Flight Test Center
Subcontract No. CS4-00012
Prime Contract No. FO 4611-92-C-0045 (USAF)
LOTD 17P3D0011: NASA Lifting Bodies and Cold War Jets Study
21 September 1994

In 1993 the Legacy Resources Management Program provided funding to the Air Force for a study of AF/NASA Lifting Body Program. The Air Force tasked Computer Sciences Corporation (CSC) to undertake a historical, cultural, and technological study of the Lifting Body Program. CSC subcontracted with PAT Projects, Inc., to produce a general and technical narrative history of the Lifting Body Program

Foreword

At long last the point has been reached where Space Shuttle flights have lost their novelty and become nearly routine matters to the aerospace community. After Columbia's first two-day test mission in April 1981, the initial flush of enthusiasm about the new space era began a steady evolution into a proud but casual acceptance of its technological marvels. Even the Challenger tragedy proved to be only a temporary setback, and now each successful Shuttle mission is seen as a completely normal occurrence. These days an Orbiter falling out of the sky onto a runway at the Kennedy Space Center or Edwards Air Force Base merits little more than a brief segment on the evening news programs.

This is, in the main, a desirable state of affairs. NASA's long-term goal has been to make space activities routine, systematically transforming the adventure and drama of the new space medium into a practical exploitation. Yet this very predictability also minimizes the critical problems involved in each space flight and habituates us to the extraordinary applications of technology which are necessary to overcome them.

Not least of these are the numerous problems involved in returning a Shuttle safely to the ground. Several possibilities were considered during the early design phase of the project. The one ultimately selected--reentering the atmosphere without power and landing--seemed "natural" and unexceptional to the layman, but its simplicity was deceptive. Data from the X-15 studies suggested that a craft with minimal wing area could consistently make successful dead-stick landings. Proving the concept, however, necessitated an elaborate and inherently fascinating effort by AFFTC, NASA and the industry. In the end the two programs--X-15 and Lifting Body--converged to validate the concept which has now been successfully used for the last decade-and-a-half.

Oddly enough, though, the very success of the Lifting Body Program seems to have helped insure its relative obscurity. With the Shuttle Orbiters now in routine operation and no similar space ventures in sight, the lifting body technology has been fully absorbed by the aerospace community but allowed to become dated. At the same time, the Lifting Body Program and its unique aircraft have received singularly little attention from the public, even from the hardy breed of aviation buffs. The muted attention to the subject even extends to the printed page, where very little more than professional papers have seen public print.

In view of this, Robert Hoey has done a commendable service in presenting this long-overdue study of the entire Lifting Body Program. More importantly, although he presents the story from the viewpoint of the engineers and test pilots, he has made it accessible to the layperson who is interested in space activities. Likewise, his associates have explored other program ramifications which are usually neglected in basic engineering studies.

Preserving aerospace technology, and especially the means and processes by which it has been developed, is the central mission of PAT Projects, Inc., which proposed and managed this work. Technology does not exist in a vacuum, and having only the final data of a successful program tells little about how that accomplishment might be replicated. It is apparent that researching the story of the lifting body effort was a singularly worthwhile venture for this group.

Raymond L. Puffer, Ph.D.
AFFTC History Office
Edwards Air Force Base

Introduction

This document attempts to bridge the communication gaps between the technical/scientific community, the history and archival disciplines, and the non-professional aviation enthusiast. It describes the events of the Lifting Body Program with as much objectivity and detail as possible so as to provide an accurate history of the program. At the same time, the technical aspects of the program are discussed in sufficient detail to assure that the engineering community will benefit from the new technology that was derived from these tests. Chapter 1 presents a brief, simplified introduction to the subject of atmospheric entry so that the non-technical reader may also read and understand the lifting body story. Hopefully all readers will sense the excitement, the pioneering spirit, the camaraderie, the "can-do" attitude that prevailed within the small team of engineers and pilots who were privileged to participate in the lifting body flight test program at Edwards.

Preface

This historical document portrays the Lifting Body Program as seen by the engineers and pilots who actively participated in the development and testing of these unique vehicles. You may notice a lack of reference to political policies and decisions, or media events and labels (for example, International Geophysical Year, Cold War, creation of NASA, Sputnik, Space Race, etc.). Such events or labels are commonly used in historical documents to indicate changes in direction or an altered public perception of advances in technology. In actuality, these events or labels had little, if any, effect in the near term on the Lifting Body Program. They were almost transparent to those actually working in the technical field.

Advancement in science and technology is a continuing process. Advances usually occur through a series of small steps in theory and/or laboratory demonstrations. Often technological "breakthroughs" occur in almost simultaneous, but unrelated demonstrations in different parts of the world. It is occasionally necessary for the scientists to pause in a line of investigation, and allow the engineers to construct a complete operating device to validate their findings and demonstrate practical applications. Periodic demonstration of current technology is important to validate the ability to construct real hardware, and to boost and update the industrial base.

Frequent hardware demonstrations reduce the technical risk for each step. When the cost and complexity of a hardware demonstration becomes very high (such as in most space travel ventures) the decision to build hardware may be deferred for political or economic reasons. This results in fewer demonstrations and therefore higher risks for each step. Engineers then begin looking for low cost, partial demonstrations that will sustain the technological advance but reduce the risk for the next big hardware demonstration step.

The Lifting Body Program falls into the category of a low cost, partial technology demonstration to reduce the high technical risk that was emerging from the Dyna Soar program (discussed in Chapter 2). Notice that the Lifting Body Program was created PRIOR to cancellation of Dyna Soar, and was NOT a result of that cancellation. The ASSET program, discussed in Appendix A, section 4.4, falls into the same category further highlighting the recognition within the technical community of the high technical risk of Dyna Soar. Other similar technology advances and partial demonstrations were continuing in other fields such as the development of new thermal protection materials, power sources and flight control systems. All of these partial technology demonstrations were intended to reduce the risk for whatever larger and more costly demonstration of controlled, manned entry would eventually follow. What follows is the lifting body story told from the perspective of engineers and pilots.

Acknowledgements

The author wishes to acknowledge the assistance of Johnny Armstrong from the AFFTC Research Projects Office in locating, and making available, various documents and photos that were used in the preparation of this report. Jack Kolf of NASA FRC graciously allowed the use of the heavy-weight Lifting Body Flight Logs which he had assembled earlier from other NASA FRC documents. The Photo Department at NASA FRC were also very helpful in locating and printing copies of various photos which were used in the document. I also appreciate the help of the NASA DFRC Library and AFFTC History Office for personal assistance and access to historical resources.

In a quick-reaction peer review, the draft report benefited from comments of the following individuals who actually participated in the various activities described in this document;

Jack Wesesky	Dyna Soar and X-15
Jack Paulson	HL-10 configuration definition
Clarence Syvertson	M2 configuration definition
A. J. Evans	NASA Headquarters
Fred Stoliker	AFFTC Technical Director
David Richardson	X-24A, X-24B Performance Engineer
Dale Reed	M2-F1, Program Manager
Jack Kolf	X-24B Program Manager for NASA
Johnny Armstrong	X-24A, X-24B Program Manager for AFFTC

I offer a special thanks to Ray Puffer of the AFFTC History Office who reviewed the manuscript and wrote the Foreword.
Contract supervision came from John Terreo, Computer Sciences Corporation, and Richard Norwood, AFFTC Historic Preservation Office.

The author also wishes to thank the following members and consultants of PAT Projects, Inc., for their direct contributions to sections of this document, as well as their review of the final manuscript: Betty Love, for gathering photos and preparing the M2-F1 flight log in Appendix C; Bruce Peterson and John Manke for the pilot comments in Appendix B; John McTigue for information about the M2-F2 and HL-10 procurement from Northrop; Lyle Schofield for his assistance in preparing the discussion on aerodynamic heating and low L/D approaches; Anne Millbrooke for her insightful review and her help in reformatting the text for historical validity; Chris Licciardi for computer graphics and production support; and Wayne Ottinger for his overall assistance and management of the effort.

World Wide Web (WWW) Publication

Some minor corrections and additions were made to the original works for the WWW publication. Book Two, The Cold War Context, and most of Book Three, Lifting Bodies As Cultural Resources, were not included in the WWW publication. The author, Robert G. Hoey, and Betty Love provided the minor corrections and additions. With NASA's assistance, the color photographs available were selected as substitutions for the black and white photos original used. Wayne Ottinger, of PAT Projects, Inc., produced the WWW version in both HTML and PDF configurations with the assistance of Carla Thomas (Adobe® Photoshop® 4.0) and Denise Pregenzer (Corel Corporation CorelDRAW™ 7), both under a consulting services order from PAT Projects, Inc. The HTML version was produced with Microsoft® FrontPage 97™ and the PDF version was produced using both Microsoft® Word 97 SR-1 and Adobe® Acrobat 3.0®.

NASA Removed this publication from their website when the Lifting Book authored by Dale Reed (Wingless Flight: The Lifting Body Story) was published.

Contents

Book One of Original Air Force Publication

TESTING THE LIFTING BODIES AT EDWARDS

Illustrations

All photos and old artwork images were scanned originally at 300 dpi and in 'True Color or 256 gray scale as appropriate. All images were processed with DEBABELIZER® PRO at 75% on the "quality" scale to reduce file sizes.

For 1280 X 1024 pixel size images from the NASA Dryden photo server, go to: http://www.dfrc.nasa.gov/gallery/photo/index.html
There, is an index at that site to retrieve the larger image files for images listed on this table.

X-15s and Lifting Body Research Aircraft in Main NASA Hanger, 1966

Chapter 1

Returning From Space

1.1 The Capability: Exiting the Atmosphere

Exiting the atmosphere into space is an exercise in "brute force." The rocket engines must have thrust that exceeds the weight of the entire vehicle (including propellants) before it can lift off from the launch pad. An exit trajectory is usually very steep (nearly straight up) so the vehicle is well above the dense atmosphere before it accelerates to high speed. Exiting the atmosphere for the express purpose of placing a warhead in a precise location several thousand miles away requires not only "brute force," but also a sophisticated control and guidance system. Exiting the atmosphere to achieve a permanent circular orbit requires the same technology as the warhead delivery. It was only natural that the first orbital flight of a man-made object would be a direct application of missile technology.

To return an object from space is a more challenging task. Friction with the atmosphere creates very high heating at the surface of an object. Shooting stars or meteors are demonstrations of the extreme environment associated with atmospheric entry. [1]Some type of thermal protection is required for objects entering the earth's atmosphere.

1.2 The Challenge: Atmospheric Entry

The term "Lifting Body Program" usually refers to a flight test program conducted between 1963 and 1975 at Edwards, California on a strange looking family of wingless aircraft. The reason for these unusual configurations is found in the challenge to design a manned vehicle which would survive entry into the earth's atmosphere. Three factors would affect the design of a manned entry device:

---

[1] The terms "entry" and "reentry" are often used interchangeably in the industry. In this document the term "reentry" refers to a suborbital maneuver where the path and environment back through the atmosphere are dictated by the launch trajectory; the flight from launch to landing can be viewed as a single maneuver. The term "entry" refers to a maneuver which is initiated from orbital or super-orbital conditions where the path and environment back through the atmosphere are created independently from the launch trajectory.

(1) Intense heat generated by friction with the earth's atmosphere,
(2) High accelerations, and resulting "g" loads [2] associated with the rapid loss of speed during entry,
(3) Selection and control of the initial entry angle (relative to the horizontal) which would dictate the heat and g loads (Figure 1-1).

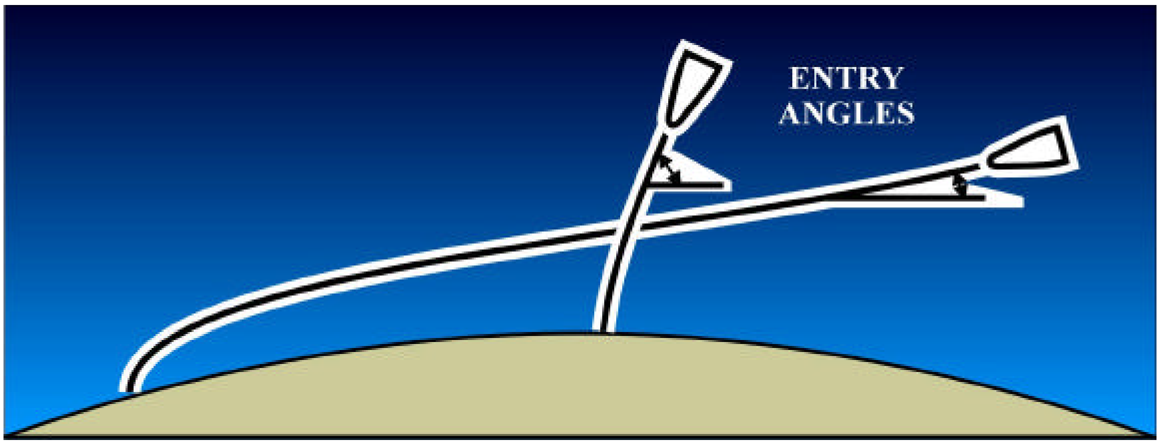


Figure 1-1: Entry Angle

These three factors are related to each other and they offered the early entry vehicle designers some trade-offs. Steep entry angles were known to produce very high g loads. The time of entry would be very short, however, and, although temperatures were expected to be extremely high, there were known methods for handling the short heat pulse. This entry method was appropriate for ballistic missile warheads but g loads were far too high for human survival (100 "g" or more). Shallow entries could be tailored to produce lower g loads but would result in a longer entry time. Peak temperatures were expected to be lower but the longer duration heat pulse was an additional design challenge. There was a very narrow range of entry angles which would provide acceptable g loads for human survival, and these required very careful trajectory control at the beginning of the entry. Thus there was reason to believe that a ballistic entry could be tailored to allow a manned vehicle to survive entry through the atmosphere.

---

[2] .."g" loads are those forces affecting the vehicle and its occupants resulting from rapid changes in speed (accelerations or decelerations). The normal measure of "g" load is the "load factor" or "g" which is the ratio of the force experienced under acceleration to the force that would exist if the object was at rest on the surface of the earth.

1.3 Ballistic Entry

A ballistic entry is one in which the force created is always parallel to the line of flight, that is, a "drag" force. The trajectory is always in the form of a parabola and represents the balance of forward speed with the earth's gravity. Baseballs, arrows, bullets and artillery shells follow ballistic trajectories but their velocities are too low to induce significant atmospheric friction. The primary design parameter for ballistic entry is the Ballistic Coefficient;

Ballistic Coefficient = Weight/(Drag Coefficient x Area)

Heating and deceleration are less intense for a low Ballistic Coefficient (low weight and/or high drag and large frontal area) than for a high value since the entry occurs high in the atmosphere where the air is less dense (Figure 1-2).

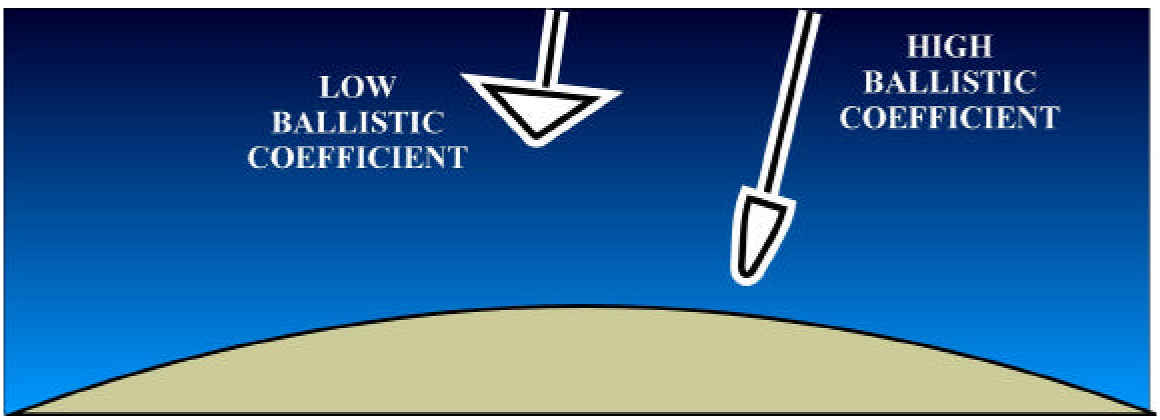


Figure 1-2: Ballistic Coefficient

Early Inter-Continental Ballistic Missiles (ICBM's) utilized this reentry method. Thermal protection for these early warheads was a massive metallic heat shield which merely provided a "heat sink" for the short heating pulse. It was soon discovered that delivery accuracy could be improved by increasing the values of the Ballistic Coefficient thus increasing the impact velocity so that the final descent phase was less affected by winds. Thermal protection was provided by allowing the material at the surface of the heat shield to melt or vaporize thus transferring much of the heat back into the atmosphere. This method of thermal protection is referred to as "ablation," and the material that is applied to the vehicle's outer surface is called an "ablator."

The development of missile warheads was the primary technological goal of the fifties, and significant progress in the development of ablators was accomplished as a result. Early designs for manned entry vehicles took maximum advantage of the missile warhead technology. By using low Ballistic Coefficients and shallow entry trajectories the g load could be maintained within the human tolerance level. This resulted in a longer time for a manned entry, however, and thus required a thick layer of ablation material on the outer surface.

The initial entry angle (determined by the capsule attitude at retrofire) was quite critical and, at best, the g loads were almost incapacitating to the crew (approximately 8 "g" for about a minute and a half). Centrifuge studies had shown that the human tolerance to long periods of high g loads was greatest if the subject was in a reclining position and the force was applied from front to back (that is, "eyeballs-in"). Manned ballistic entry capsules were therefore designed to position the crew member(s) lying on their backs facing away from the direction of flight (Figure 1-3).

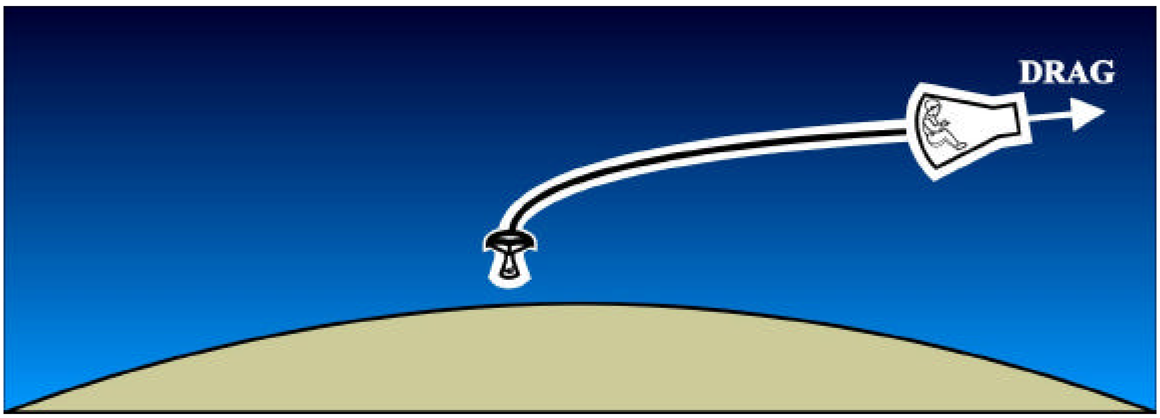


Figure 1-3: Ballistic Entry

During the final phase of a manned, ballistic entry some type of auxiliary device was necessary to slow the vehicle to a very low sink rate at the moment of impact with the earth (parachute, rotor, landing rocket, etc.). This entry vehicle concept was commonly referred to as the "Decoupled Mode" since the aerodynamic features necessary for the atmospheric entry were different (or "decoupled") from those necessary for final landing. The Mercury program was the only U.S. manned entry program to utilize a pure ballistic entry trajectory. A parachute was used for the final landing (Figure 1-3). Even before the first Mercury flight it was recognized that the pure ballistic entry was too critical for an "operational" (that is, routine and low cost) manned entry system. In addition to the g load and heating criticality of the entry, the poor predictability of the final impact point led to the selection of ocean landing areas requiring a rather large contingent of ships and helicopters for recovery as evidenced by the Mercury program.

Some improvement in the recovery accuracy was possible by adding maneuverability to the second, decoupled phase. A maneuverable parachute concept (Rogallo wing) was explored as a potential improvement for decoupled mode entries, but it has never been incorporated in any U.S. manned system. The concept, however, has continued to evolve. Recently, successful low speed demonstrations of parachute recoveries of small, unmanned entry shapes have been made using high-lift parachutes.

1.4 Semi-Ballistic Entry

By providing a small amount of "lift" during entry, that is, an aerodynamic force perpendicular to the flight path, the severity of the entry could be reduced substantially and the recovery accuracy could also be improved. Lift was created by offsetting the center of gravity of the entry vehicle slightly so that the blunt face of the heat shield was inclined at an angle to the flight path (Figure 1-4).

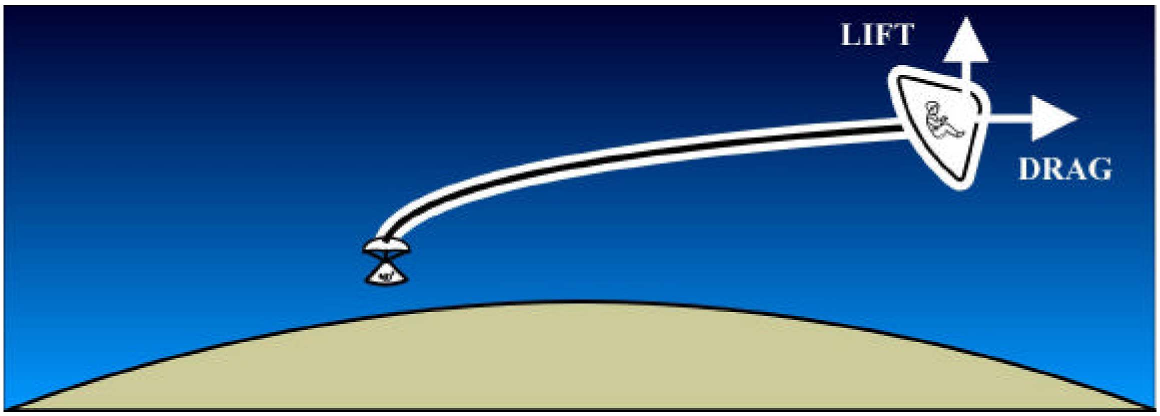


Figure 1-4: Semi-Ballistic Entry

By controlling the bank angle during entry, the lift could be directed to control the flight path. Initially the lift could be directed upward to maintain a small flight path angle as long as possible. Once the vehicle passed the high speed heating pulse, it could be banked to turn toward the desired recovery point. After achieving the heading to the target recovery point, a continuous roll could be introduced to cancel the lift effects and thereby simulate a pure ballistic trajectory for the remainder of the entry.

The resulting semi-ballistic entries were of longer duration than a pure ballistic entry, but produced somewhat lower g loads and lower peak temperatures. The design of the ablator heat shield was more complex since the heating was not symmetrical on the heat shield and the duration of high heating was somewhat longer. A modified ablator, called a "non-receding, charring ablator," evolved. At high temperature the material burned and released hot gases, but the char stayed in place and maintained the outer contours of the surface. In this way the aerodynamic and lifting capabilities of the shape were retained. The material was molded into a honeycomb grid during construction to help control the shape of the char. When the ablator was used in sufficient thickness the combination of char and virgin ablator material provided an effective insulation blanket during entry and thus allowed the use of common materials for the sub-structure (steel, titanium or even aluminum). The semi-ballistic entry gave the entry vehicle designer more latitude for design trade- offs. The trajectory could be continuously adjusted throughout the entry for control of both heating and recovery location. The g loads on the human crew were no longer a limiting factor; however, the semi-ballistic entry still required the reclined, aft-facing crew position and a parachute or some other type of "decoupled mode" recovery device.

The Gemini and Apollo capsules employed semi-ballistic entry designs using non-receding, charring ablators, and both used non-maneuverable parachutes and water recovery for the final de-coupled phase. Of course all of the ballistic and semi-ballistic concepts discussed thus far were designed to survive a single entry. Although technically feasible, major refurbishment would have been required to refly any of the vehicles.

1.5 Lifting Entry

A lifting entry is one in which the primary force being generated is perpendicular to the flight path, that is, a "lift" force. Although drag is present throughout the entry, the resulting flight path can be adjusted continuously to change both vertical motion and flight direction while the velocity is slowing. The gliding flight of a sailplane is an example of "lifting" entry without high velocities and heating. The primary design parameter for lifting entry is the Lift to Drag Ratio, or L/D;

L/D = Lift/Drag

Low values of L/D produce moderate g loads, moderate heating levels and low maneuverability with moderate entry duration's (essentially the same as the semi-ballistic entry). High values of L/D produce very low g loads, but entries are of very long duration and have continuous heating. Although the peak temperatures of a lifting entry are below the peak temperature of a ballistic entry, the total heat load that must be absorbed over the duration of the entry is higher. Lateral maneuverability during entry (commonly referred to as "cross-range capability") is dramatically increased as the L/D increases.

A secondary, but important, parameter for lifting entry is the Wing Loading ;

Wing Loading = Weight/Projected Area

The Wing Loading for a lifting entry is comparable to the Ballistic Coefficient for a ballistic entry with a similar effect. Low Wing Loadings (low weight and/or large projected area) cause the deceleration and heating to occur high in the atmosphere. Heating and deceleration are less intense for a low Wing Loading (similar to low Ballistic Coefficients).

The lifting entry promised improved conditions for crew members during entry. The g loads of a lifting entry were expected to be so low (approximately 1.5 "g") that the crew members could be seated in a normal aircraft-like fashion facing the direction of flight. It was also expected that the crew could function normally throughout the entry without concern for even a temporary loss of consciousness (Figure 1-5).

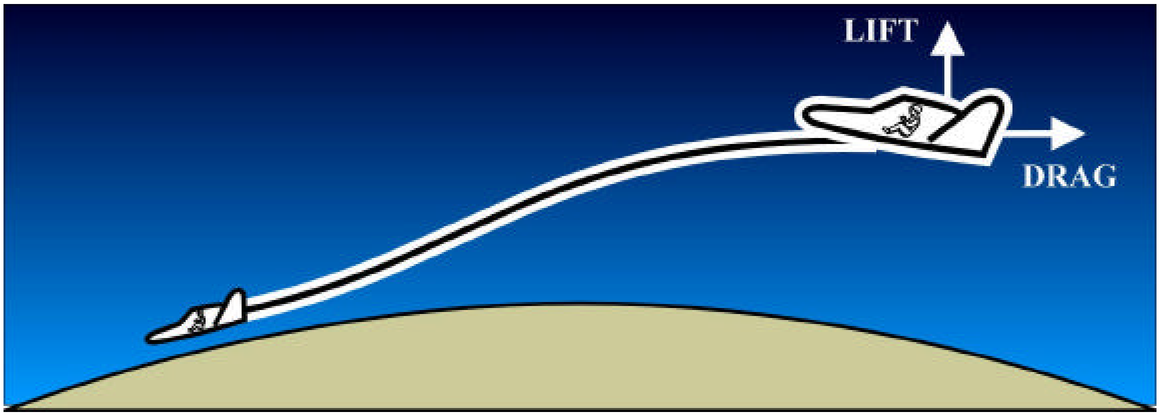


Figure 1-5: Lifting Entry

One of the advantages foreseen for a lifting entry vehicle was the high probability that the vehicle could be landed like a normal glider after completing the entry. This would eliminate the need for parachutes or other "decoupled mode" recovery concepts. Theoretical and wind tunnel studies, however, showed that the aerodynamic configurations which produced the highest L/D at very high Mach number during entry did not necessarily produce "high" L/D at landing speeds. The highest L/D's during entry were produced by long slender cones or wedges without wings. The highest L/D for landing was, of course, obtained with a long, glider-like wing. Compromises were soon found in the form of delta-wing configurations (triangular wing planforms) with moderately high L/D during entry yet also with the capability to land on a normal runway. Wing loading also had an effect on the land-ability; low wing loadings resulted in slow landing speeds and high wing loadings resulted in high landing speeds.

Thermal protection concepts for lifting entry were more challenging than the ballistic and semi-ballistic methods due to the longer entry time. Early thermal protection methods (of the late 1950's) revolved around two basic concepts: (1) "Active cooling" concepts which circulated fluid through the hot area, then through a radiator, much like the engine cooling system for an automobile; and (2) "Passive or Radiative cooling" concepts which used thin, high-temperature materials that reached an equilibrium temperature by radiating the heat away from the surface, much like the heating element of a stove. The ceramic tiles or fire brick then available were brittle and far too heavy to be seriously considered. Both active and passive thermal protection methods could be reusable with little if any refurbishment required, but both were complex and dependent on the successful development of high temperature materials.

The lifting entry concept gave the entry vehicle designer even more latitude for design trade-offs than ballistic or semi-ballistic entry concepts. A reusable entry vehicle capable of landing on a normal aircraft runway was seen as a key to increasing manned access to space at a reasonable cost.

1.6 Emergence of the Lifting Body

The entry concepts described thus far have been portrayed in a sequence that shows an increase in complexity (from pure ballistic to lifting), and a parallel increase in capability or utility. The knowledge of these different interactions and trade-offs did NOT emerge gradually as different vehicles were built and tested. All of these factors and trade-offs were well known by the late 1950's as a result of pioneers in the field, such as Alfred J. Eggers and H. Julian Allen of the National Advisory Committee for Aeronautics (NACA) Ames Research Center (ARC) (Reference Syvertson, 1968). The technology required to implement the more complex (but more useful) lifting entry methods, however, was not yet fully developed or proven.

The application of available "ablator" technology appeared to provide a means for near-term manned space flight. The question that arose was:

Could a low L/D lifting entry vehicle be developed that would use the available thermal protection methods of the non-receding charring ablators, yet still have sufficient low speed L/D so it could land safely?

The use of ablator technology would limit the allowable time for entry and thus the maximum useful entry L/D to a value of about 1.0. The use of ablators would also constrain the value of the entry L/D to a relatively narrow range around the nominal value of 1.0. This entry L/D was easily achievable by a variety of blunt-nosed, wingless entry shapes. The answer to the second part of the question was less obvious. Designers proposed modifications to several of these entry configuration shapes which would hopefully allow them to perform horizontal landings (Figure 1-6).

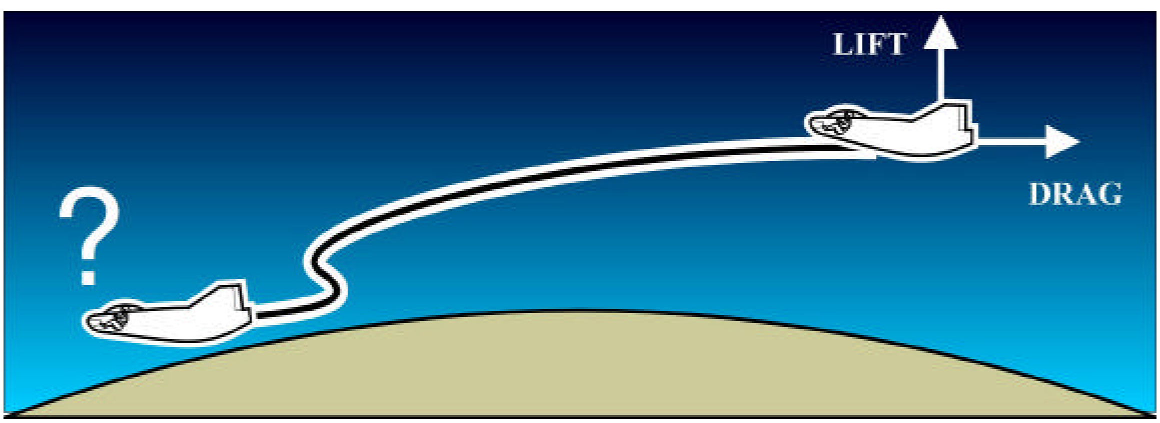


Figure 1-6: Lifting Body Entry

A brief flight test program was conducted on an F-104 by the National Aeronautics and Space Administration (NASA) Flight Research Center (FRC) in 1959 (Reference Matranga, 1959) to explore low L/D landing methods. If landings were feasible, a lifting body vehicle could be used in the near term to demonstrate the primary advantages of lifting entry without being dependent upon the development of the exotic materials or systems necessary for a high L/D entry vehicle.

The "Lifting Body Program" was conceived to answer the land-ability question regarding these proposed entry configurations. The program called for the construction of low cost, all-aluminum airframes that would not include thermal protection systems, or other subsystems, necessary for an actual entry. The program addressed concerns not only for the low speed L/D and land-ability, but also for the transonic stability and control of these blunt shapes as they decelerated through the critical transonic speed regime.

1.7 Glider Landing Techniques

Lifting entry vehicle designers gave serious consideration to including a propulsion system for landing. Although landing engines would allow a vehicle to land like a normal airplane, the powered approach was not an attractive alternative due to the added weight and complexity. Before beginning a discussion of the individual projects, it is, therefore, appropriate to describe simply the techniques used to land unpowered airplanes.

All gliders, whether they are sailplanes (L/D’s from 25 to 50) or lifting bodies (L/D’s from 2.8 to 5.0), use the same general strategy to perform safe and accurate horizontal landings. The energy possessed by an airplane is of two forms: potential energy (altitude above the ground) and kinetic energy (forward velocity relative to the ground). Unlike a powered airplane which can add energy or maintain a constant energy level, a glider is constantly losing energy. Potential and kinetic energy can be traded with each other. A constant-speed glide loses only potential energy while a slow-down at constant altitude loses only kinetic energy. The pilot must control the loss of energy so that he arrives at the desired landing point at zero altitude and at the proper landing speed. There are three primary methods used to control energy: speed, landing pattern geometry, and drag-producing devices (speed brakes). The usual philosophy for performing a safe glider landing is to give up potential energy for an increase in kinetic energy as the glider gets closer to the ground; that is, increase speed by allowing the approach angle to steepen. Since speed can be quickly dissipated near the ground by drag devices, this excess speed allows for last minute pattern corrections for winds or other anomalies. Although the general technique for landing a lifting body is similar to that of a sailplane, there is an enormous difference in the levels of energy involved. The development and perfection of this energy exchange to achieve a controlled, accurate landing were primary objectives of the Lifting Body Program.

X-24A, M2-F3, and HL-10 Lifting Bodies

Chapter 2

Lifting Entry With Horizontal Landing; The Quest Begins

Many concepts for accomplishing a lifting entry followed by a horizontal landing were proposed in the late 1950's. There were inflatable vehicles with very low wing loading, delta-winged flat-on-top shapes, delta-winged flat-on-bottom shapes, semi-ballistic shapes with extendable wings, and several lifting bodies. Some of these configurations received considerable attention and were tested extensively in wind tunnels. None were committed to hardware, however until about 1957 when the Air Force initiated a design competition for the X-20 "Dyna Soar" program. It was to be a continuation of the Air Forces "X-plane" research on manned, high speed flight, and was to be conducted in a fashion similar to the X-15 program. The vehicle would be designed and constructed by industry, then turned over to a joint Air Force/NACA team who would conduct the research flight testing.

An overall schedule for projects that were actually committed to hardware between 1957 and 1982 is shown in Figure 2-1. The various programs discussed in this document are related to each other, and to parallel programs by this figure.

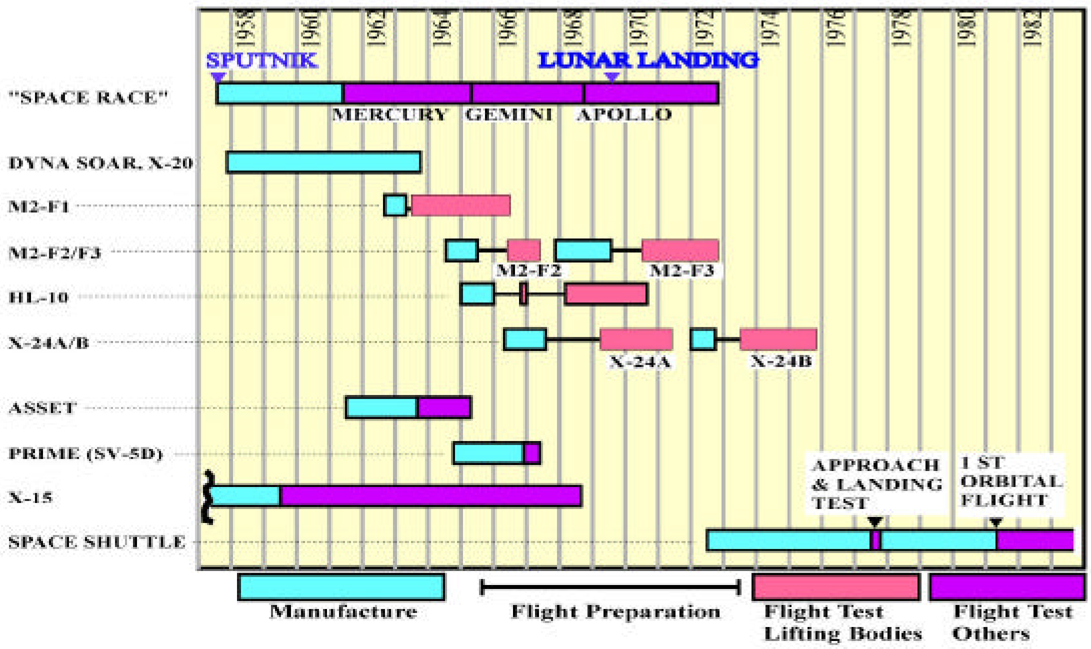


Figure 2-1: Entry-Related Testing 1957-1982

2.1 High L/D, or Low L/D?

The lifting body concept for manned entry vehicles was first introduced during the competition for the X-20 Dyna Soar contract in the mid fifties. The configuration that was finally selected for the Dyna Soar was NOT a lifting body, but was a high L/D, delta-winged glider that would use the "lifting" entry concept described in Chapter 1. The X-20 was never completed and never flew, nevertheless, it represents the first serious attempt to design and build a vehicle which would perform a lifting entry from orbit followed by a horizontal landing. The program was cancelled in December, 1963 while the first flight vehicle was under construction. A more complete description of the X-20 program is included in Appendix A.

2.2 From X-15 to X-20

The Dyna Soar program grew out of concepts first proposed by Eugen Sänger, a German scientist, in the 1930's (Reference Geiger as quoted in Hallion, Vol. I, 1987). Sänger envisioned a winged aircraft boosted to near-orbital speeds above the earth's atmosphere by a rocket engine. It would then skip along the outer reaches of the atmosphere like a flat stone on water until it slowed to a normal glide speed for landing. The term "boost-glide vehicle" was born. The range of the aircraft would be greatly extended by the skipping action, as would the maneuverability. Sänger coined the term "dynamic soaring" to describe the concept. This terminology was shortened to "Dyna Soar" as the name for the program even though the reentry was envisioned as a long, controlled glide without "skipping."

The Dyna Soar program evolved from the aircraft community rather than the missile community, which was the primary source of entry technology for the Mercury program. The Dyna Soar glider was seen as a natural progression of the successful X-series high speed rocket-powered aircraft. At the time of the first design competition in the mid fifties the X-15 was under construction. The X-15 was expected to advance the frontiers of manned flight to Mach 6.6 and to 250,000 feet altitude. It was recognized that the next step upward in speed and altitude beyond the X-15 could probably not be achieved by air-launching or by using a self-contained propulsion system. Some large, unique air-launching platforms were studied and proposed but none were built. Existing ICBM's had the capability to boost small payloads (approximately 5,000 lbs.) to orbit, but could also boost a 9,000-pound research aircraft to a speed of about 17,000 ft per second (about Mach 20) and well into the reentry heating regime. Considering the anticipated future increase in booster capability, the Dyna Soar was proposed as a research glider that would be designed for entry from orbit, but would be initially tested and developed in sub-orbital flight. The program married the ICBM booster technology and high speed research airplane technology. For launch, the glider would be mounted on the top of a modified ICBM booster. The booster trajectory would be altered to place the glider in a nearly horizontal trajectory at burnout, as envisioned by Sänger, rather than the typical steep and high ballistic trajectory of an ICBM.

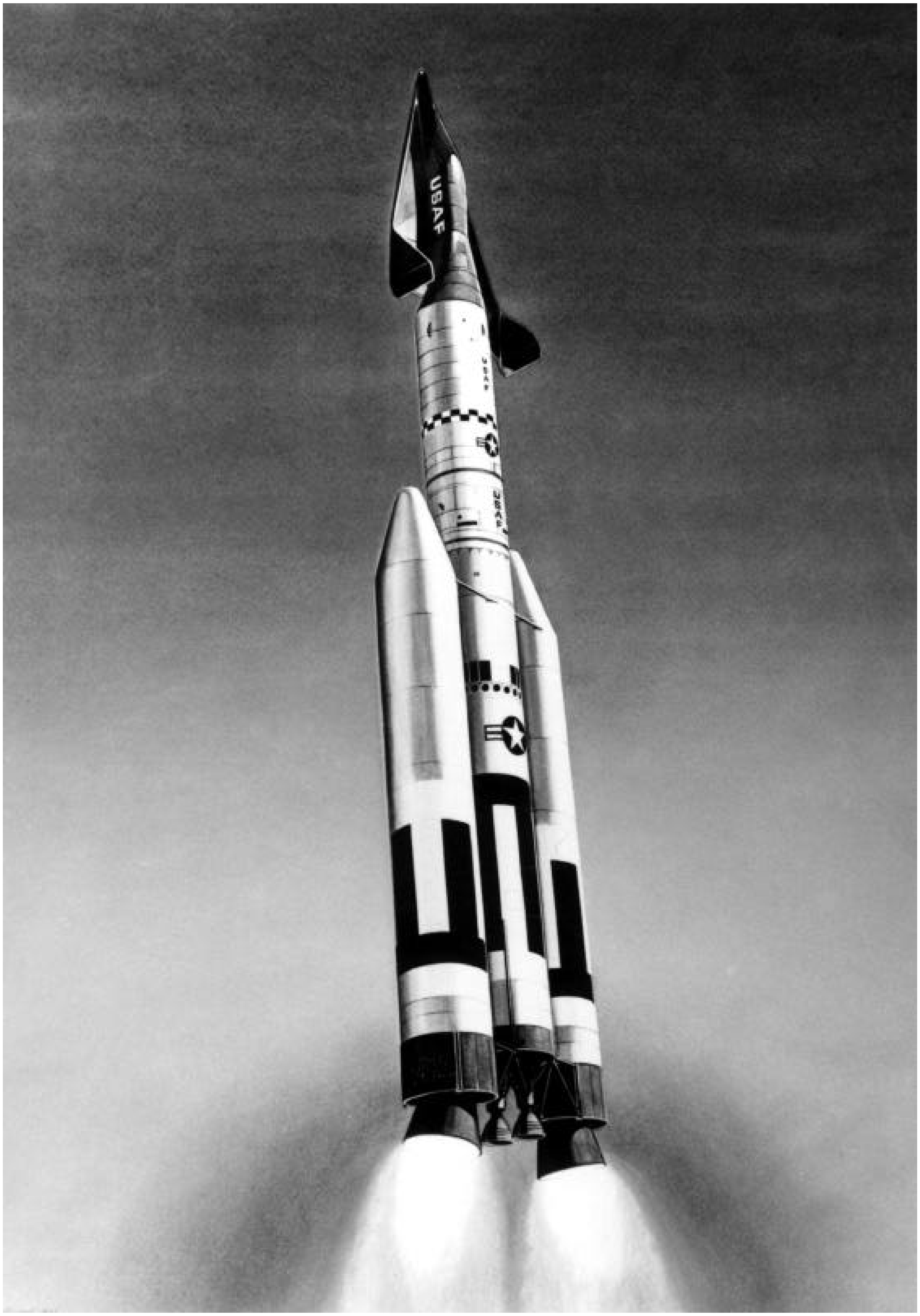


Figure 2-2: Dyna Soar Glider on Titan III Booster

2.3 Legacies of Dyna Soar

After program cancellation, several of the systems that were under development for the X-20 program found a place in the continued technology advance of the early 1960's and provided the cornerstones for the continuation of lifting entry research. Some of these systems and concepts are outlined below.

(1) The ASSET Program - The ASSET vehicle was designed to validate the "hot structure" concept of the Dyna Soar glider. The structure and shape of the vehicle represented the forward 4 feet of the X-20 in most respects. Six vehicles were built and successfully flown between 1963 and 1965 (mostly after the cancellation of the X-20) along gliding reentry trajectories . Although this program received little attention at the time, its success validated the X-20 "hot structure" thermal protection concept (Reference Hallion, Vol. I, 1987).

(2) The self-adaptive, fly-by-wire flight control system designed for the X-20 was adapted to the X-15 mission and was installed in the #3 X- 15 . The features of the system, including the autopilot and the merging of aerodynamic and reaction controls, were demonstrated on many successful X-15 flights.

(3) The first Pulse Code Modulation (PCM) airborne instrumentation system was initiated for the X-20 program. The NASA FRC at Edwards recognized the potential value of this system and continued support of its development (known as the CT-77 Instrumentation System). It was used successfully on all of the lifting body programs.

(4) The Inertial Guidance System that was developed for the X-20 program also found its way into the X-15 program, where it provided a major improvement in accuracy for the later high-altitude flights.

(5) Special simulation computer hardware and software (hybrid digital/analog) were procured to provide an accurate, real-time simulation of the X-20 lifting entry for mission planning and crew training. An accurate lifting entry simulation was established at Edwards AFB, and the new equipment was used to support the lifting body programs at Edwards as well as the Space Shuttle program.

(6) The X-20 laid much of the ground work for the crew escape philosophy which is used in the Space Shuttle today. The X-20 glider design team recognized that it was not practical to provide an escape mode for all aspects of a space flight. In case of an emergency, the entry vehicle itself was considered the primary method for returning the crew to subsonic speeds. Design safety features, usually in the form of system redundancy, were incorporated in the entry vehicle to insure that it could function following most high-probability space emergencies.

(7) The booster man-rating concept was first addressed during the X-20 program. Available ICBM boosters were designed to deliver an unmanned payload one time, consequently they lacked any redundancy for emergencies. The escape towers and escape rockets used on the early manned flights of these boosters were designed to fly the manned vehicle away from the booster in the event of a fire or explosion. Although the X-20 also planned to use an abort rocket, the program highlighted the need to merge the airplane and booster man-rating philosophies for any reusable manned entry vehicle.

2.4 Death of the Dyna Soar

By December of 1963, when the Dyna Soar program was cancelled, many of the perceived barriers to lifting entry and horizontal landing had been laid to rest by the perseverance of the X-20 team. Lifting entry and horizontal landing were still viewed as the most cost-effective way to return astronauts from orbit. The stage was set for a different approach; one with less technical risk than the X-20.

Lifting Bodies: A NASA Perspective

Robert G. Hoey's study, "Testing Lifting Bodies at Edwards," provides a valuable history of the lifting body program conducted jointly by the NASA Flight Research Center (now NASA's Hugh L. Dryden Flight Research Center) and the Air Force Flight Test Center at Edwards Air Force Base, California. It does so, however, from the perspective of an Air Force civil servant who worked on both the Dyna-Soar and the lifting body programs.

While this perspective is not blatant or entirely one-sided, it comes through significantly in Chapter 2, which is devoted exclusively to the X-20 Dyna-Soar and which might lead an unsuspecting reader to infer a greater influence of the X-20 on the lifting body program than Hoey specifically implies. In Chapter 2, Hoey states explicitly that Dyna-Soar "was NOT a lifting body," but a winged glider designed to test lifting reentry. Despite this disclaimer and Hoey's careful and very limited claims for Dyna-Soar's contributions to the lifting body program, the fact that there is an entire chapter devoted to a non-lifting body that never flew in a study that devotes a single chapter to the M2-F2 *and* the M2-F3 and one each to the other lifting bodies, all of which did fly, gives undue prominence to Dyna-Soar. Hoey's study, after all, is explicitly about lifting bodies and not about lifting reentry and other programs to which the X-20 made significant contributions.

From a NASA perspective, at least, the lifting body program had its beginnings--as Hoey briefly relates--in the studies of H. J. "Harvey" Allen, Alfred J. Eggers and others at the National Advisory Committee for Aeronautics' Ames Aeronautical Laboratory in the early to mid-1950s into the blunt body reentry principle and the concept of lifting reentry from space. This predated Dyna-Soar. And it was these studies, plus roughly contemporary ones at the NACA Langley Aeronautical Laboratory on wingless lifting shapes, that led R. Dale Reed, a young engineer at the Flight Research Center, to advocate a flight research program involving lifting bodies. In turn, it was Reed's efforts, seconded by research pilot Milton O. Thompson and supported by FRC Director Paul Bikle, that really inaugurated the lifting body flight research program.

In the course of time, as Hoey relates, Langley's studies led to the HL-10, one of the lifting body configurations. Later studies by the Martin Company under contract to the Air Force resulted in the SV-5 configuration that became the X-24A, later modified to the X-24B--two other lifting body configurations flown at Edwards.

In view of these developments and the chronology discussed above, it is misleading from the NASA perspective to devote an entire second chapter in a study of lifting bodies to the Dyna-Soar, even though it did make contributions to lifting bodies **in** the development of the Pulse Code Modulation data system used in the lifting body program. This is not to denigrate Dyna-Soar's overall contributions to lifting reentry technology. Even though the X-20 never flew, the research and wind-tunnel testing for the program contributed significantly to many hypersonic and reentry programs, especially the Space Shuttle.

The point of this brief essay is rather one of focus. The intent here is not to disagree with Hoey's facts but simply to present a different perspective on what was and was not critical in the development of the lifting body program. The reader can then make a more informed decision as to which perspective is more valid. This issue aside, the Hoey study is a valuable contribution to an important story. For that reason, it is made available on the NASA Dryden website.

Reference: For further reading, consult *From Max Valier to Project Prime*, vol. 1 of *The Hypersonic Revolution*, edited by Richard P. Hallion (Wright-Patterson Air Force Base, Ohio: Aeronautical Systems Division, 1987), esp. Clarence J. Geiger, "Strangled Infant: The Boeing X-20A Dyna-Soar," pp. 185-377, and John V. Becker, "The Development of Winged Reentry Vehicles: An Essay from the NACA-NASA Perspective, 1952-1963," 379-447.

M2-F1 Under Tow

M2-F1 Glide Flight

Chapter 3

The M2-F1 Program

The first attempt to actually fly and land an entry-configured lifting body occurred in April 1963. The flight occurred at NASA FRC at Edwards AFB. The vehicle was a small, light weight shape designated the M2-F1.

3.1 Theoretical Development

The M2 Lifting Body configuration was developed by Alfred J. Eggers, C.A. Syvertson, George Edwards, and George Kenyon at the NASA Ames Research Center (ARC). The approximate evolution of the design is shown in Figure 3-1.

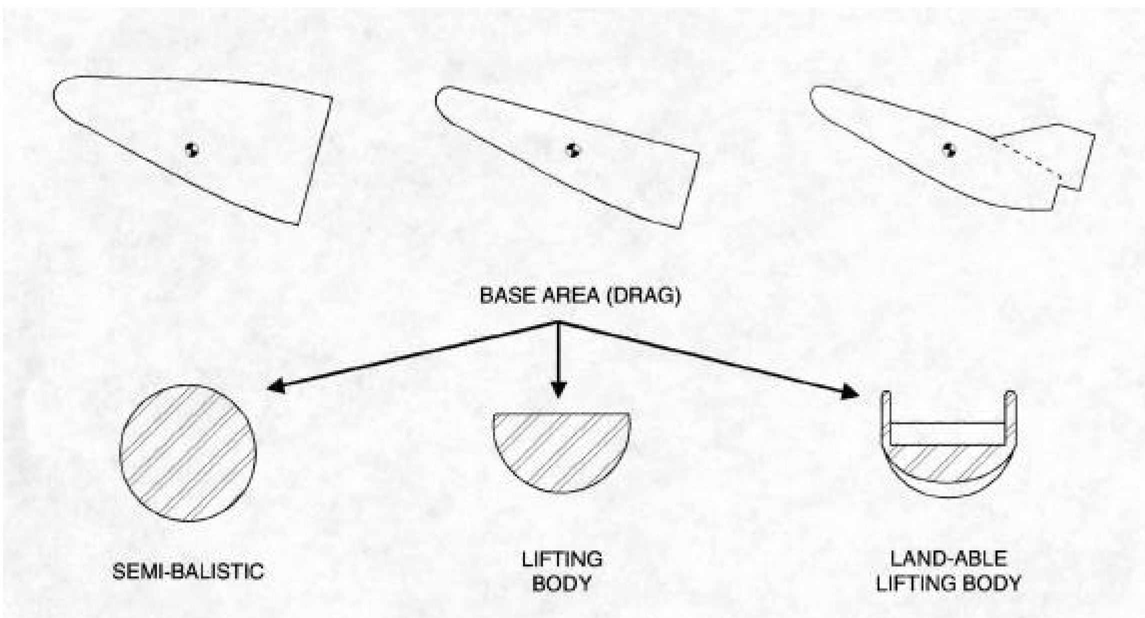


Figure 3-1: Evolution of M2 Lifting Body Design

The design started with a blunted, 26-degree nose cone. With a vertically offset center of gravity to establish an angle of attack, a nose cone such as this could perform a semi-ballistic entry. The top half of the cone was flattened to provide additional lift and to reduce the base area and thus reduce drag. The base area was reduced even more by boat-tailing both the upper and lower surfaces of the half cone. The boat-tailing simultaneously improved the entry trim capability. Fins were added to provide directional stability and to add lift at low speed (Reference Syvertson, 1968). Preliminary low-speed wind tunnel tests indicated that this configuration should have a maximum L/D of about 3.5 and would probably be land-able if an adequate control system could be developed.

Robert D. "Dale" Reed was a research engineer at the NASA FRC (now Dryden Flight Research Center) at Edwards. He had been following the development of the lifting body shapes at Ames and Langley with some interest and wanted to develop a low-cost approach to assessing the land-ability of these shapes. Reed and Eggers began to develop an M2 configuration that would be suitable for a piloted experiment. They added small horizontal control surfaces or elevons outboard of the vertical fins (referred to as "elephant ears") to provide lateral control and lateral damping. A cockpit and windows in the nose provided visibility for the pilot during landing. This configuration was designated the M2-F1 (Figure 3-2).

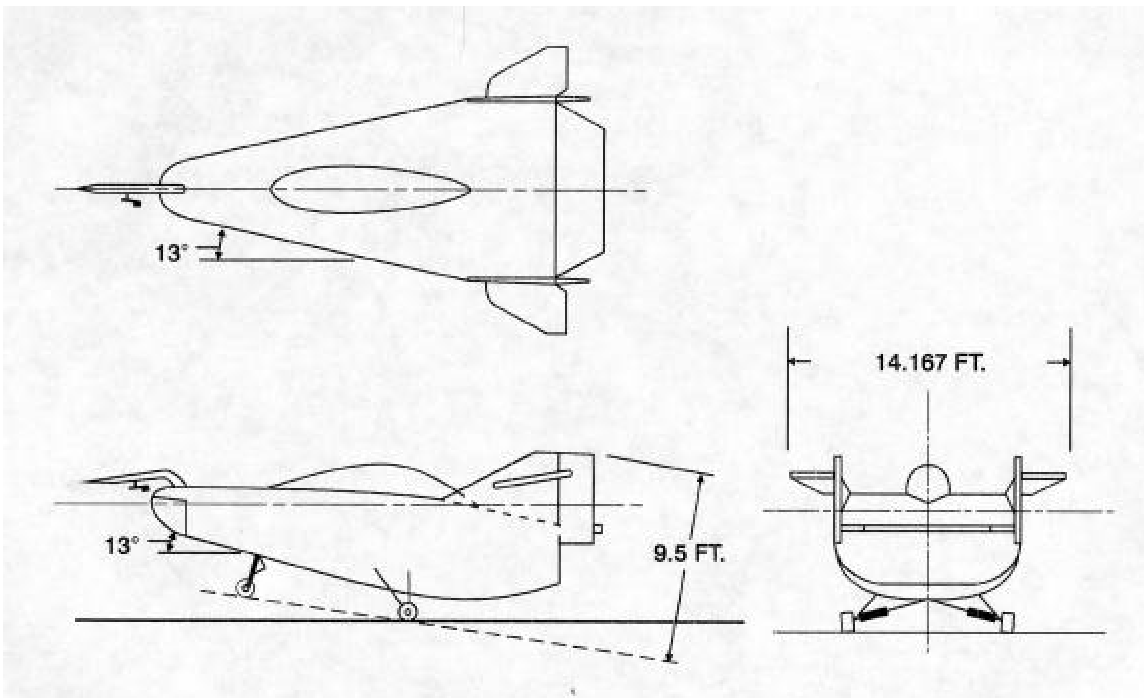


Figure 3-2: Three-View Drawing, M2-F1

3.2 Technical and Physical Development

Reed constructed a 24-inch radio-controlled model of the M2-F1 shape and towed it behind a larger radio-controlled model. He showed movies of these flights to NASA FRC Director Paul Bikle, and presented him a proposal to build a piloted, light-weight, low-cost version of the M2-F1. Reed envisioned a pathfinder program that would establish the feasibility of landing an entire class of lifting body vehicles. Both Reed and Bikle were active sailplane pilots (Bikle was an internationally known competition pilot), and thus both were familiar with glider landing techniques and also launching techniques. Bikle decided to proceed in September 1962. He appointed Reed to head a small team of research engineers (approximately six people). They designed a light weight vehicle that could be built in two segments: (1) an internal structure including the landing gear, flight controls, seat, and primary load carrying structure (Figure 3-3), and (2) a light-weight external shell in the shape of the M2-F1. Close and continuous coordination with personnel from NASA ARC continued throughout the design of the vehicle.

Figure 3-3: Internal Structure of the M2-F1

The control system was simple with designed-in flexibility for experimentation during the early flights. The pilot's control stick was connected to a "swash-plate" at the rear of the aircraft. There were four horizontally-hinged control surfaces (left and right elevons inboard of the fins, and left and right elevons outboard of the fins) and two vertically-hinged surfaces (left and right rudders on each fin). These surfaces could be connected to the "swash-plate" in several ways. This allowed various control surface combinations and stick gearing values for pitch and roll control to be tested by simply changing the connections at the "swash-plate." There was no stability augmentation in the M2-F1.

NASA FRC created an internal organization that was composed of Reed, the design engineering team of Richard Klein and Richard Eldredge, and eight skilled craftsmen in the NASA FRC shops (four machinists and four sheet metal workers), as well as test pilots and operations engineers from FRC's Flight Operations. The intent was to keep the contracted cost low so as to not incur the delays associated with high-level review and approval. Bikle thought that the M2-F1 shell should be constructed by someone familiar with glider construction methods. The contract for construction avoided reference to government specifications and documentation and thereby greatly reduced the cost. This cost-effective, hands-on approach maximized the use of skilled, in-house personnel and minimized the complexity of contracts and work statements for outside work. This modus operandi was used through the entire Lifting Body program.

3.3 Construction

The size of the M2-F1 was dictated by the desire to achieve a fairly light wing loading (approximately 9 lbs. per sq. ft.). This produced a vehicle that was 20 feet long with a base width (or span) of 9.5 feet. Under the direction of Dale Reed and his small team of design engineers, the NASA FRC shop personnel manufactured the internal structure. Simultaneously the construction of the external shell was contracted to Gus Briegleb, a sailplane designer who was operating a glider operation at nearby El Mirage airport at Adelanto, California. The shell was constructed at his shop by a team of about five workers including his two sons, Ross and Ken. The M2-F1 shell was constructed of plywood using methods typical of glider construction at that time. NASA gave Briegleb the necessary loft lines for the M2-F1 shape and also identified the shell attach-point dimensions and expected loads. The total contracted cost for the M2-F1 shell was approximately $10,000. The shell was completed and delivered to NASA FRC. The final assembly of the shell and internal structure was completed at NASA FRC only four months after the go-ahead from Bikle.

Following ground checkout of the control system, the M2-F1 vehicle was trucked to the NASA Ames Research Facility at Moffett Field, California, where it was installed in the 40x80-foot full-scale wind tunnel (Figure 3-4).

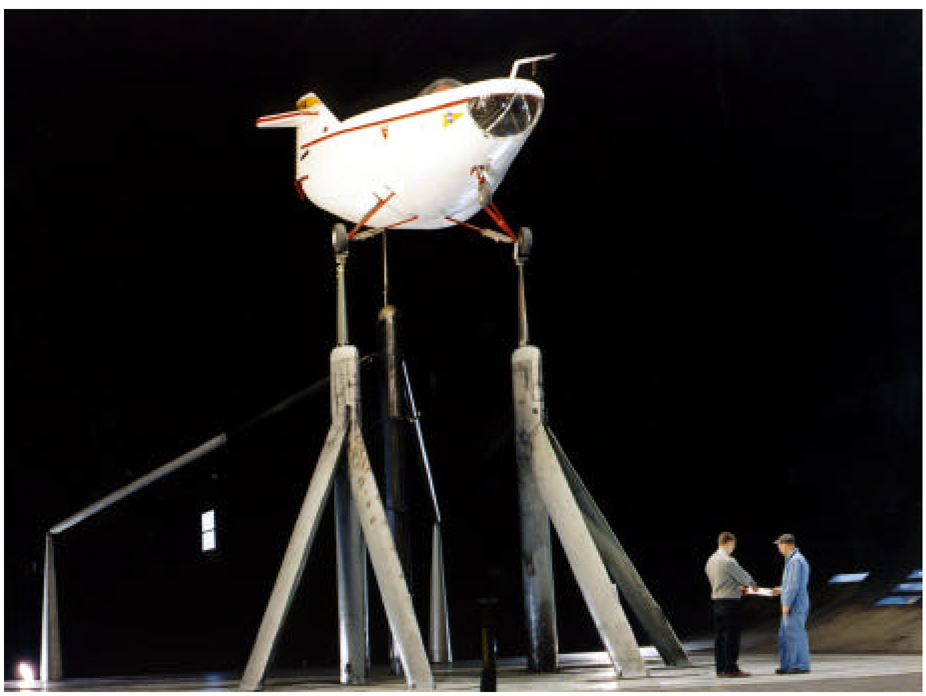


Figure 3-4: M2-F1 in Ames 40 X 80 Wind Tunnel

A complete low-speed wind tunnel test series was performed. On many of the wind tunnel runs the assigned test pilot, Milt Thompson, was seated in the M2-F1 operating the controls while data measurements were being taken. Because of the low wing loading of the M2-F1 (9 psf), the airspeeds obtained in the wind tunnel were about the same as those expected in flight. The success of these tests was crucial to the continuation of the program. A removable, triangular center fin had been constructed in anticipation of low directional stability, and tests were run with and without the fin. The results showed that the directional stability was adequate without the fin. Overall the wind tunnel results supported the potential flyability and land-ability of the vehicle. It was returned to Edwards to be prepared for flight (Reference Horton, 1965). A small solid landing rocket, referred to as the "instant L/D rocket," was installed in the rear base of the M2-F1. This rocket, which could be ignited by the pilot, provided about 250 pounds of thrust for about 10 seconds. The rocket could be used to extend the flight time near landing if needed.

Two standard methods for launching sailplanes are the car-tow and the air-tow. The NASA test team intended to use both methods for launching the M2-F1. Recognizing that the drag of the lifting body would be considerably higher than that of a sleek sailplane, NASA FRC procured a high performance Pontiac convertible and proceeded to have it modified to "race car" status in order to have the speed and power needed for the car tows. The convertible body style allowed engineers to observe the M2-F1 flights from aft-facing seats (Figure 3-5). Walter Whiteside, Assistant to the Chief of Operations at NASA FRC, became the crew chief and "tow-driver" of the Pontiac. Ralph Sparks maintained the car's high performance capability throughout the program.

Figure 3-5: Pontiac Convertible Tow Vehicle

Air-tows were accomplished behind a C-47 "Gooney Bird" cargo airplane, which NASA FRC maintained as a utility aircraft. A tow hook (of the type used during World War II for towing troop gliders) had been found in a junk yard and installed on the tow plane. A 1000-foot towline was used.

3.4 Flight Testing

The M2-F1 flight test program ran from the early car tows in April 1963 to the last flights in August 1966. Seven pilots flew the vehicle.

3.4.1 Car Tows

Flight testing began with car tows on the smooth surface of Rogers dry lakebed at Edwards on 5 April 1963. NASA's Milt Thompson was at the controls of the M2-F1. The Pontiac towed the vehicle until it was airborne, then the pilot assessed the handling qualities of a particular control combination. Among the combinations tried were connecting the rudder to the lateral stick deflection and the pedals to the elevons. Differential upper flap deflections had been found to have low roll effectiveness in the full-scale tunnel so the left and right body flaps were linked together for pitch control only, then left that way for the entire test program. The most suitable system was a standard hookup with the lateral stick deflection moving the elevons, the rudder pedals operating the rudders, and the longitudinal stick moving both the body flap and pitch movement of the two elevons. When acceptable control was established, the tow speeds were increased until the vehicle could lift off and fly for several minutes behind the tow car, then release and land (Figure 3-6). Since the full-scale tunnel tests did not show any improvement in lateral stability or handling qualities with the center fin installed, the fin was never tried in actual flight. The small landing rocket was tested during taxi tests and was also operated while airborne during car tows.

About 93 car tows were performed before the first air tow was attempted. The car-tow technique was used throughout the program to evaluate any changes that were made to the vehicle or the control system and to check out new pilots. Nearly 400 car tows were accomplished during the course of the program.

3.4.2 Air Tows

Prior to the first air tow, an T-37 ejection seat replaced the simple, light-weight pilot seat that was used in the test vehicle for car tows. This gave the pilot a capability to eject safely from the M2-F1 from any portion of a flight including a zero-altitude, zero-speed condition. Thompson flew the first air tow on 16 August 1963. The flight was quite successful. It was followed by a series of test flights to determine the actual performance and stability characteristics of this unique aircraft (Figure 3-7).

Taking off from Rogers dry lakebed, the M2-F1 pilots maneuvered into a high tow position above the wake of the tow plane. The flights circled the edge of the lakebed during the climb to insure that the M2-F1 could reach a lakebed runway in the event of a rope break. When the tow plane reached an altitude between 8,000 and 11,000 feet above the lakebed, and was approximately over the intended landing site on the lakebed, the M2-F1 pilot would release from the tow plane and begin a steep gliding turn. He would initiate the landing flare about 300 feet above the ground and at a speed of about 110 knots. Because of the light wing loading, the M2-F1 lost speed very quickly. Only 8 seconds elapsed between the start of flare and touchdown at approximately 75 knots (Figure 3-8).

Figure 3-6: M2-F1 Low Speed Car Tow

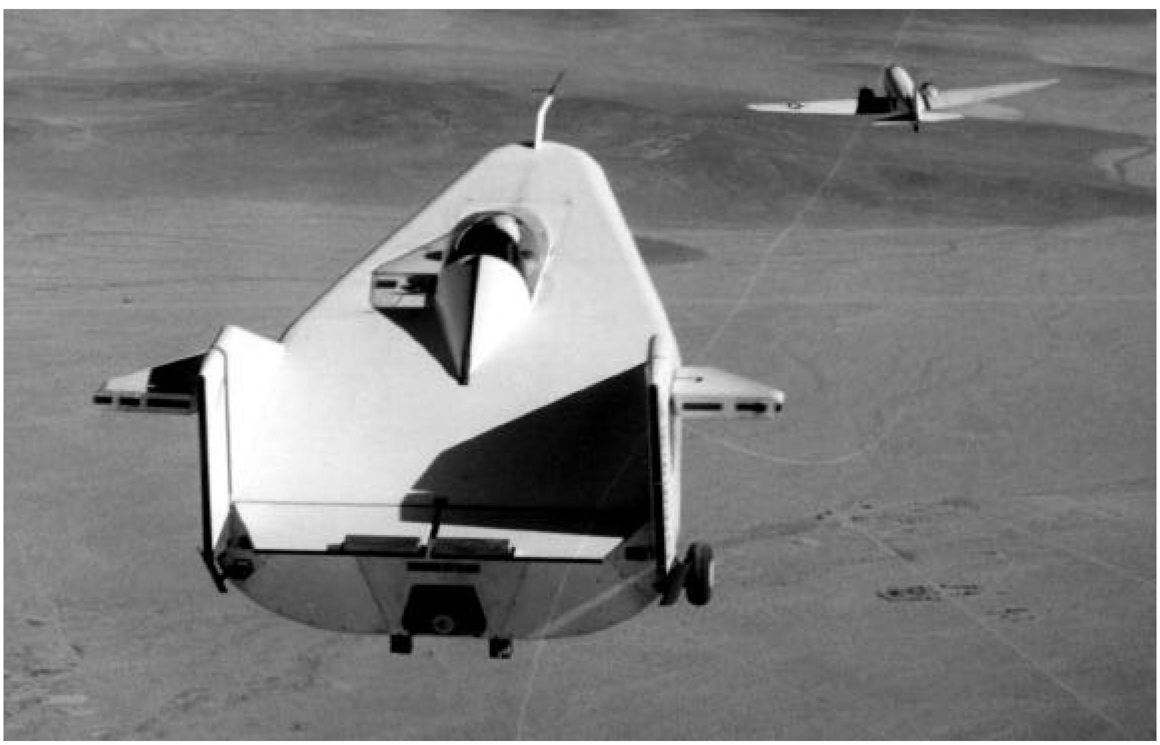


Figure 3-7: M2-F1 Air Tow Behind C-47

Figure 3-8: M2-F1 in Free Flight using "Instant L/D Rocket"

3.4.3 Handling Qualities

The M2-F1 in free flight had fairly good handling characteristics. Pitch control was positive and well damped. Steady state sideslips could be accomplished smoothly, although they required high pilot concentration.

The M2-F1 exhibited one unusual characteristic that required some learning and adapting by the pilots. It was brought about by the combination of sideslip produced by deflection of the ailerons, and of very high dihedral effect (a tendency to roll sharply when a small amount of sideslip is present). When the vehicle was commanded to roll, there was a slight hesitation brought about by a small sideslip. The vehicle would then begin to roll as originally commanded. [3] This characteristic was of little consequence during free flight of the M2-F1 when there was little requirement for quick response or for precise bank angle control. While on tow, however, the pilot's visibility was hampered by the small nose window. The poor visibility, coupled with a requirement to stay in position behind the tow plane, created a need for quick roll response. The use of a small amount of rudder for coordination was used by most pilots, however excessive rudder resulted in a tendency toward Pilot Induced Oscillation (PIO). Some pilots had difficulty adapting to this characteristic (See Paragraph 3.5.1).

During the flare maneuver just before landing, the wide upper deck of the M2-F1 and the extreme nose-high attitude of the vehicle caused the pilot to lose his view through the canopy of the ground and the horizon. He was forced to transfer his viewing to the small nose window. This hampered his depth perception and thus his ability to accurately control the landing sink rate. All M2-F1 pilots eventually learned to compensate for this difficulty. Other handling quality comments are contained in Appendix B.

[3] This characteristic is commonly referred to as "adverse yaw" in the aircraft community. It is a feature which designers strive to eliminate or minimize by altering the shape of the wings or ailerons.

3.4.4 Schedule and Pilots

In the early 1960's the lifting body concepts were viewed as adversarial to the winged-entry concepts such as the X-15 and X-20. In fact, the lifting body supporters were at least partly responsible for the cancellation of the Dyna Soar program. They advocated the use of existing ablation technology rather than supporting the development of the exotic high-temperature materials required by the Dyna Soar. It was with some chagrin, therefore, that the winged-entry advocates viewed the M2-F1 vehicle flight test program growing out of the airplane community rather than the missile community, which had previously been their prime adversary. Test pilot Milt Thompson simultaneously supported the X-20 program while flying the early flights on the M2-F1. Flight research was viewed as advancing the technology of flight in any direction that seemed fruitful. This philosophy was typical of Bikle and others at NASA FRC at that time.

Colonel Chuck Yeager flew 33 car tows and five air tows in the M2-F1. At the time he was the Commandant of the Air Force Test Pilot School at Edwards AFB. Bikle had a high degree of respect for Yeager's abilities as an aviator and for his accurate reporting abilities as a test pilot. Bikle invited him to fly the M2-F1 to get his opinion as to the practicality of the concept. On 10 Dec 1963, shortly after his first successful air tow in the M2-F1, Yeager ejected from a rocket-assisted NF-104A and received severe facial burns. The M2-F1 was the first aircraft that Yeager flew following his month-and-a-half hospital recuperation (likened by some to a long stay in orbit). After his successful flights in the M2-F1 Yeager enthusiastically supported the lifting body venture.

In all, ten pilots flew approximately 395 M2-F1 car tows. Seven of the ten pilots flew an additional 77 air tows. (The M2-F1 schedule relative to the other lifting bodies is shown in Figure 2-1. A summary log of flights and pilots is included in Appendix C.)

Pilot	Number of Car Tows	Air Tows
Milt Thompson	Unknown	46
Bruce Peterson	49	17
Major Don Sorlie	33	5
Captain Jerry Gentry	Unknown	2
Colonel Chuck Yeager	33	5
Don Mallick	32	2
Bill Dana	Unknown	1
Captain Joe Engle	3	0
Fred Haise	3	0
Major Jim Wood	10	0

3.5 Technology Lessons Learned

The M2-F1 flight test program generated technical knowledge from accidents and lesser incidents as well as through improvements and problem resolutions. Some problems remained unresolved at the end of the program.

3.5.1 Accidents/Incidents

The M2-F1 landing gear was equipped with automotive shock struts serviced with heavy-weight oil. The system worked well during the early flights which were in warm weather. On a very cold morning in December 1963, pilot Bruce Peterson made a rather hard landing following an air tow. Both wheel axles failed due to the combination of the hard landing and shock struts stiffened by the cold temperature. Luckily both axles failed simultaneously so the vehicle settled abruptly onto the gear legs, but tracked straight ahead to a stop. The shock struts were subsequently replaced with elastic "bungee" cords and no further incidents of gear failure occurred.

The M2-F1 was still flying when the M2-F2 and HL-10 were delivered to NASA FRC (Figure 2-1). Near the end of the M2-F1 flight program the AF assigned test pilot Captain Jerauld Gentry to the Joint AF/NASA Lifting Body program in anticipation of delivery of the heavy weight vehicles. NASA agreed to a checkout flight for Gentry in the M2-F1. Shortly after takeoff behind the C-47 tow plane, and at an altitude of a mere 400 feet above the lakebed, the M2-F1 began to roll violently from side to side. The oscillations increased in magnitude until the vehicle was inverted. At this point, Gentry released from the tow line and completed the roll back to an upright position. He used the landing rocket after recovering from the roll to give him more time to accomplish the landing and he landed safely straight ahead on the lakebed. After a limited discussion and analysis it was concluded that the vehicle had been upset by the tow plane slipstream. After receiving some additional tow training in a sailplane, Gentry again tried an M2-F1 air tow. An identical incident occurred on the second attempt. It was generally concluded that the combination of poor forward visibility on tow (Gentry was shorter than the other M2-F1 pilots), known lag in the lateral responsiveness, and aggressive pilot actions had caused a classical pilot-induced oscillation (PIO) to occur. At this point Bikle grounded the M2-F1. Its primary mission accomplished, it was retired from further flight activity on 18 August 1966.

3.5.2 Validations

The M2-F1 program demonstrated the feasibility of the lifting body concept for horizontal landings of atmospheric entry vehicles. It also demonstrated a procurement and management concept for prototype flight test vehicles that produced rapid results at VERY low cost (approximately $40,000 excluding salaries of Government employees assigned to the project).

In-flight measurements of Lift-to-Drag ratio were 10 percent higher than those measured on the same vehicle in the full-scale wind tunnel. The measured free-flight value of maximum L/D was 2.8 (Figure 3-9). Notice that both the full-scale tunnel results and the flight test results for L/D were considerably less than the value of 3.5 predicted with earlier and smaller wind tunnel models. The reason for the discrepancy was that the M2-F1 had a fixed landing gear and some canopy differences as well as some of the normal manufacturing joints and other protrusions associated with real flight vehicles.

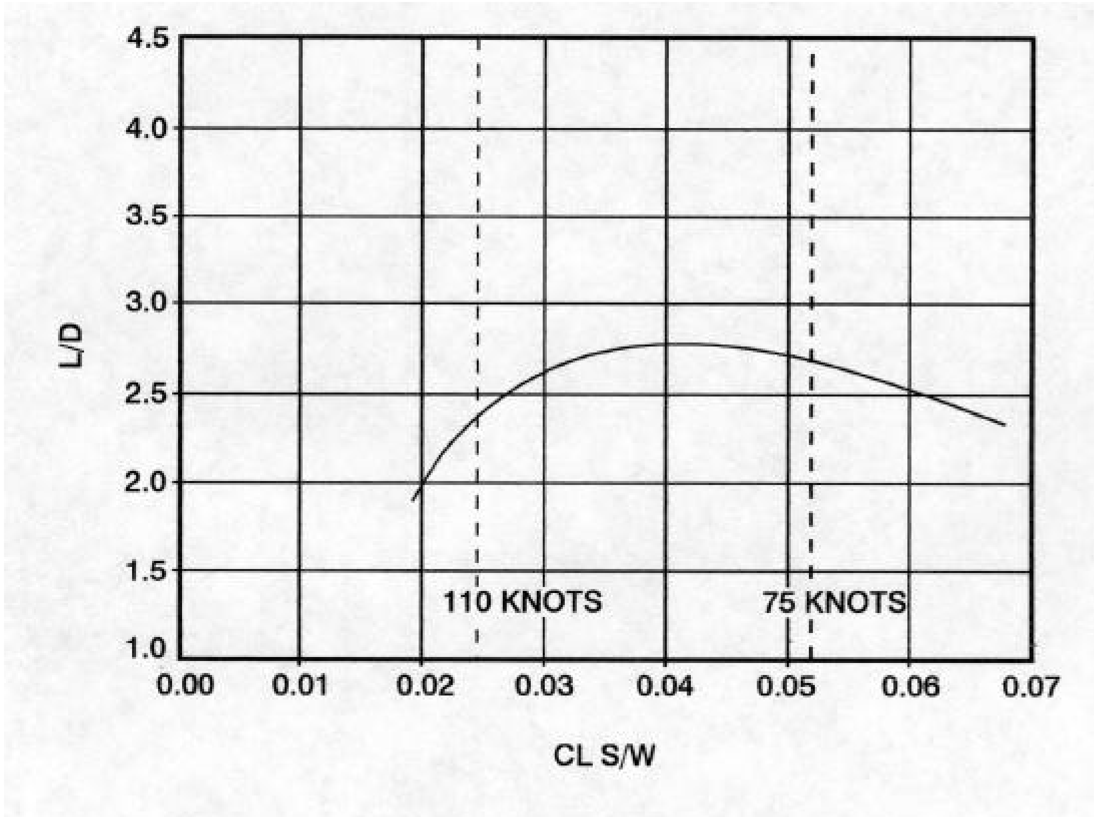


Figure 3-9: M2-F1 Trimmed Lift/Drag Ratio

3.5.3 Problems Resolved

An acceptable (but not optimized) flight control system was developed during the early car tows and was used throughout the M2-F1 program. Even though this system was a simple mechanical control system, it produced acceptable handling qualities over most of the flight envelope. It demonstrated that an acceptable and practical control system for a lifting body vehicle was possible.

3.5.4 Unresolved Problems

In a foreboding of things to come, the M2-F1 exhibited some peculiar roll response characteristics resulting from adverse yaw and the very high roll-to- sideslip ratio of the highly swept conical shape.

Although successful landings were performed at very low values of L/D (less than 3.0), the wing loading of the M2-F1 was considerably lower than that of any of the proposed lifting body entry vehicles. The ability to land at the higher mission weight and resulting higher approach and landing speeds had yet to be demonstrated.

Forward visibility was considered to be marginal during air tows and was barely adequate during the actual landing at high angle of attack. This was in spite of a window placed in the nose area specifically for the landing maneuver. The requirement for a thick ablator on the nose of an actual entry vehicle would preclude the use of ANY forward window in this location for pilot visibility at landing. Periscopes or blow-off panels were being considered to solve this problem for future lifting body vehicles.

3.6 Test Sites

All flights of the M2-F1 lifting body were conducted over, and landed on, Rogers dry lakebed at Edwards AFB, California. After the full-scale wind tunnel tests at Ames, the vehicle remained at NASA FRC and maintenance was accomplished in the Calibration Hangar (now building Number 4801). Tests of the solid rocket "instant L/D" motor were conducted on the ramp as well as on the lakebed during early taxi tests.

3.7 Current Status of Aircraft

The M2-F1 vehicle remained at NASA FRC after its last flight in August 1966. It was displayed in an informal museum area in front of the main building for several years. The fabric and plywood structure deteriorated from the sun and weather. The vehicle was eventually donated to the Smithsonian Institution. In February 1994 a contract was let through NASA FRC to Dick Fischer (a former NASA FRC employee) for $100,000 to begin restoration of the M2-F1. He has subcontracted much of the work to other NASA retirees who actually worked on the airplane during its construction and flight testing days. The restoration is expected to be completed in 1997. The location and method of final display of the M2-F1 has not yet been decided, but it is expected to remain at Edwards.

The Pontiac tow vehicle was turned over to the NASA Langley Research Center (LaRC), which used it to tow test devices for measuring tire/runway friction.

M2-F2 and F-104 Chase

Chapter 4

The M2-F2 and M2-F3 Program

The M2-F2 and M2-F3 were the same vehicle, initially configured and tested as the M2-F2. Following a crash, NASA had the vehicle rebuilt as the M2-F3 and continued the flight test program.

4.1 Theoretical Development

The M2-F2 and M2-F3 retained the same basic M2 shape described in Chapter 3. Theoretical analysis of both the aerodynamics and thermodynamics of the M2 shape had continued at NASA ARC while the M2-F1 was being flown at NASA FRC. ARC's goal was to minimize entry heating problems and to improve on the subsonic L/D. The M2-F2 configuration resulted from these analyses.

4.2 Technical and Physical Development

Retaining the same basic configuration as the M2-F1, the M2-F2 was also the same size. The width or span (the diameter at the base of the original cone) was found to be about the same as the diameter of the upper stage of a Titan II or Titan III launch vehicle. It was hoped that by constraining the outer size of the glide vehicle to the mold lines of the booster the destabilizing influence of a lifting shape on the nose of the booster could be minimized. Of course neither the M2-F1 nor the M2-F2 was designed to perform an actual entry. The ARC/FRC design team, however, thought that a successful demonstration of a safe landing by a vehicle of this dimension would be of value to the space program.

There were some differences between the M2-F1 and M2-F2 that resulted from the continuing evolution of the M2 as an entry configuration (Figure 4-1):

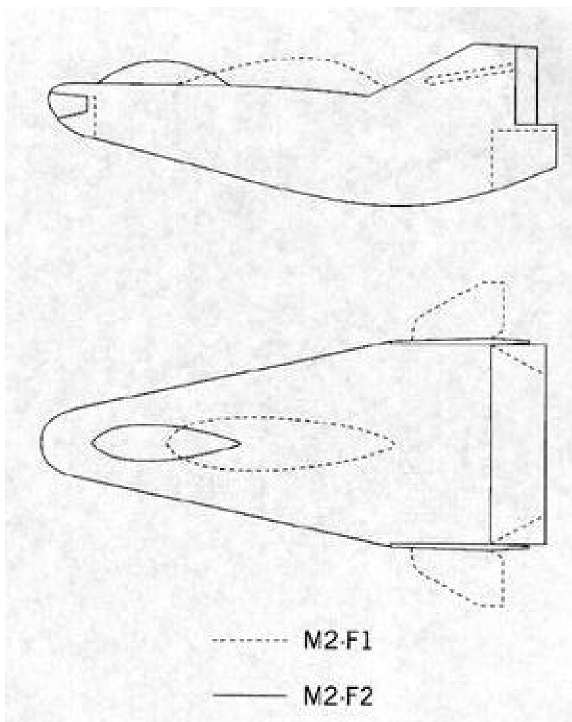


Figure 4-1: Comparison of M2-F1 and M2-F2 Configurations

(1) Pilot location - The M2-F2 cockpit was moved forward to allow the propellant tanks to be located on the center of gravity. This would minimize the trim change as fuel was being used. It would also provide an "over-the-wing" ejection capability while the vehicle was still mated to the B-52 and improve the forward visibility for the pilot. The nose window was retained, however, to provide depth perception at landing.

(2) Outboard elevons - Further analysis and high speed wind tunnel tests at Ames indicated that thermal protection for the outboard elevons would be extremely difficult. The M2-F2 thus returned to the split, upper body-flap for roll control that was discarded during early M2-F1 wind tunnel tests.

(3) Aft fuselage - The boat-tailed region of the aft fuselage was extended so that the rear end of the fuselage corresponded with the rear end of the pitch flap. This space later contained the XLR-11 rocket engine.

(4) Lower Body Flap - An additional pitch flap was installed on the aft lower surface of the fuselage.

(5) Landing Gear - Unlike the fixed landing gear of the M2-F1, the landing gear of the M2-F2 was flown in a retracted position and was extended for landing.

The M2-F2 was controlled with 5 control surfaces: a single flap on the lower aft fuselage, left and right flaps inboard of the fins on the upper aft fuselage, and left and right rudders on each fin which moved outboard only (Figure 4-2). The single lower flap was used exclusively for pitch control. The upper flaps were deflected differentially for roll control (ailerons). They could also be moved symmetrically by the pilot through a trim wheel in the cockpit. Differential deflections of the inboard upper flaps were known (from wind tunnel tests) to have low roll effectiveness. To enhance the roll control, the M2-F2 was equipped with a roll-yaw interconnect. This system mechanically linked aileron commands to the rudder through a ratio changer that was controlled by the pilot. The pilot could vary the amount of rudder created by an aileron command from 0 to 100 percent (that is, from no rudder, to equal amounts of rudder and aileron). The interconnect ratio was referred to as the "KRA" setting. The rudders could also be operated by the pilot's rudder pedals.

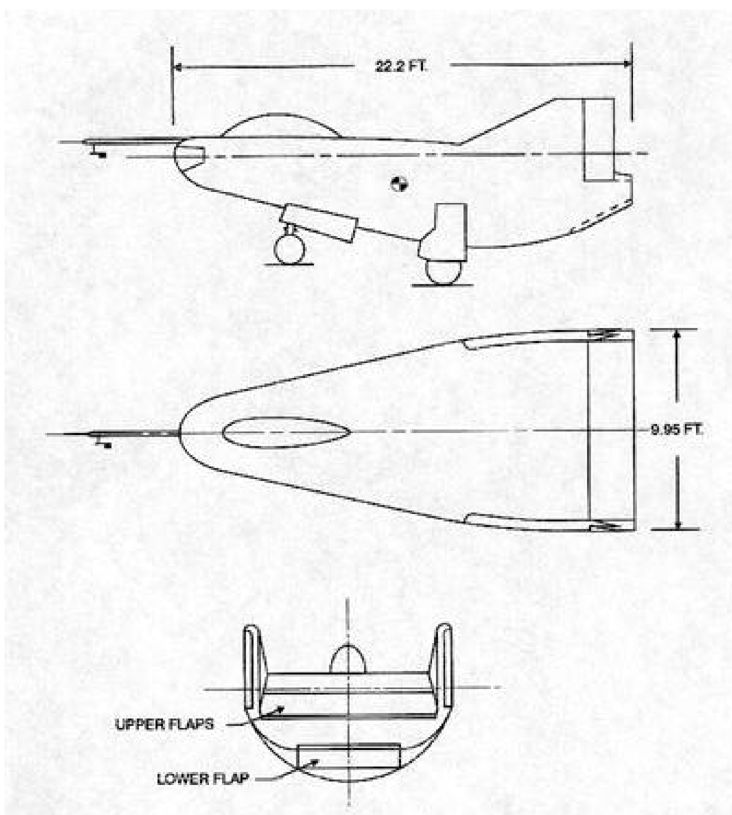


Figure 4-2: Three-View Drawing of M2-F2

The M2-F2 was equipped with a three-axis stability augmentation system which consisted of rotational rate dampers. The damper signals were mechanically added to the pilots stick and rudder commands. The M2-F2 did not have a speed brake capability.

Because of the conical shape of the M2-F2 and M2-F3, the landing gear design was somewhat of a challenge. In the final design the extension of the landing gear was expected to result in a significant increase in drag as well as a loss of lift. Main landing gear doors would open to expose vary large holes in the lifting lower surface. The landing gear was also expected to cause a significant nose-down trim change upon extension. The high drag and predicted trim change from the landing gear were known by the pilots and engineers from the beginning of the program. Recognizing the research nature of the program, they felt that the vehicle could be landed safely with appropriate training and anticipation. A rapid, pneumatic, blow-down feature was added which would extend all three gear in less than one second. By delaying the landing gear extension until after flare completion, the pilots expected to be able to successfully land the airplane in the same manner as the X-15. (The blow-down feature was added to the landing gear of all lifting bodies.)

4.2.1 Funding and Procurement Philosophy

After the success of the M2-F1, Ames Research Center was supportive of the construction and testing of a heavy-weight version of their vehicle. Bikle and other pragmatists at NASA FRC felt that a high risk flight test venture of this type would be best served by the construction of two test articles, a primary and backup vehicle.

Eugene Love, Bob Rainey, Jack Paulson and others at the Langley Research Center had developed their own version of a Lifting Body, the HL-10 (Horizontal Landing, model 10). The HL-10 (discussed in detail in Chapter 5) represented a different approach to accomplishing a lifting entry. Although conceptually different from the half-nose-cone concept of the M2, it was predicted to have similar landing characteristics. NASA FRC proposed the construction of one each of these vehicles rather than two M2-F2 vehicles. The generic similarity between the two vehicles allowed either one to serve as the research backup for the other. Both Ames and Langley agreed to support the development of their respective vehicles. By capitalizing on the rivalry between these two NASA agencies, Bikle was able not only to gain their support at NASA Headquarters for funding of the program, but also to obtain their in-house support for theoretical and wind tunnel studies that would otherwise have been very difficult to obtain.

Hubert Drake, one of the research engineers involved in the conception of the X-15 program, prepared a single request for proposal for construction of both the M2-F2 and HL-10 vehicles. Reed, the instigator of the lifting body flight test concept and manager of the M2-F1 program, oversaw the initial evaluation of the proposals. Bikle recognized that overseeing this relatively large procurement activity would be a totally different task for Reed and proposed that his creativity might be better utilized by allowing him to conceive and develop new ideas and other projects. Reed agreed. Bikle then selected John McTigue, a NASA FRC Operations Engineer with a reputation of getting things done, to manage the Lifting Body program for NASA FRC. Reed subsequently explored several other innovative ideas on entry vehicle design and demonstration, including the HYPER III project which was based on the Air Force's FDL-7 entry shape.

McTigue and a small team of engineers and technicians evaluated the proposals for the manufacture of the two different NASA lifting bodies. The primary competition was between North American Aviation (now Rockwell) and Northrop. Northrop's proposal identified (by names of individuals) a small but experienced team who had been working on the F5 fighter program development. Bikle and McTigue wanted to use a small government/contractor team, similar to the concept used successfully on the M2-F1 vehicle, so Northrop's small-team concept was consistent with FRC's approach to the Lifting Body effort. Northrop was (and is) a non-union shop which was another key factor in its selection. Closed union shops of most large aircraft manufacturers prevent government personnel from assisting in the actual construction or instrumentation installation. The proposed joint government/contractor team posed no problem for Northrop.

The work statement to the contractor was very brief, estimated by McTigue at one tenth the size of a similar government work statement for normal aircraft procurement. It avoided most references to common aircraft design specifications. It was rightly assumed that Northrop (or any other aircraft manufacturer) would use common military or civil aircraft design specifications whether or not they were named in the contract. The cost of documenting and ground testing to these specifications was avoided by requesting that the contractor abide by the "intent" of various specifications but not necessarily the "letter" of the documents. A contract for construction of two vehicles, the M2-F2 and the HL-10 was signed on 2 June 1964 The cost was $2.4 million dollars. NASA directed Northrop to make maximum use of off-the-shelf hardware and existing proven technology. This approach would minimize both cost and program risk, and concentrate attention on the aerodynamic and piloting objectives. The M2-F2 was to be constructed first. The total contract time was 19 1/2 months (Reference Northrop, 1966). The delivered vehicles were to be gliders equipped with water ballast tanks for adjusting weight and center of gravity. Approval from NASA headquarters for inclusion of the XLR-11 rocket engine occurred later. The contract was then modified to incorporate the necessary rocket engine substructure, and to build the water/alcohol fuel tank and liquid oxygen tank that would replace the ballast tanks.

Included in the contract was a requirement to build a pylon adapter for each vehicle which would mount to the existing X-15 pylons on the two B-52's. The lifting body would then mount to the adapter and all electrical and LOX topoff lines, as well as the launch mechanism, would be transferred through the adapter to the lifting body.

4.3 Construction

Design and construction of the M2-F2 began in June 1964, immediately after NASA awarded the contract. The vehicle was delivered to NASA FRC a year later in June 1965.

4.3.1 Management and Organizational Structure

Northrop assigned Ralph Hakes to be the company's Program Manager for the Lifting Body program. Hakes assembled a small team of about 30 highly experienced engineers and craftsmen. They set up shop in a small corner of the plant at Hawthorne, California. The engineers and their drafting tables were in the same room as the sheet metal workers and machine tools. Hakes proudly proclaimed that the average experience level of his "skunk works" team was over 20 years.

NASA FRC assigned Meryl DeGeer to be the Operations Engineer for the M2-F2 program. He was responsible for configuration control, maintenance scheduling and vehicle flight preparation. Several NASA FRC inspectors, instrumentation technicians, and engineers were assigned to stay on-site at Northrop throughout the construction. Instrumentation sensors, attachment brackets, holes in bulkheads for wiring, etc ., could then be accommodated or installed on the spot as the vehicle was manufactured.

4.3.2 Government-Provided Instrumentation and Subsystems

Most of the subsystems for the M2-F2 and HL-10 were off-the-shelf items from other programs - landing gear, ejection seats, control surface actuators, hydraulic pumps, etc. (Figure 4-3). These components were procured through either AF, NASA, or Northrop supply channels as appropriate. Flight-test-unique subsystems, such as cockpit instruments, research instrumentation, rocket engines and associated support hardware, were supplied directly from Government stock at NASA FRC or AFFTC. Although most of the space and provisions in the vehicles for government-supplied hardware (such as instrumentation boxes) were included in the manufacturing process, the final installation of these components was to take place after delivery to NASA.

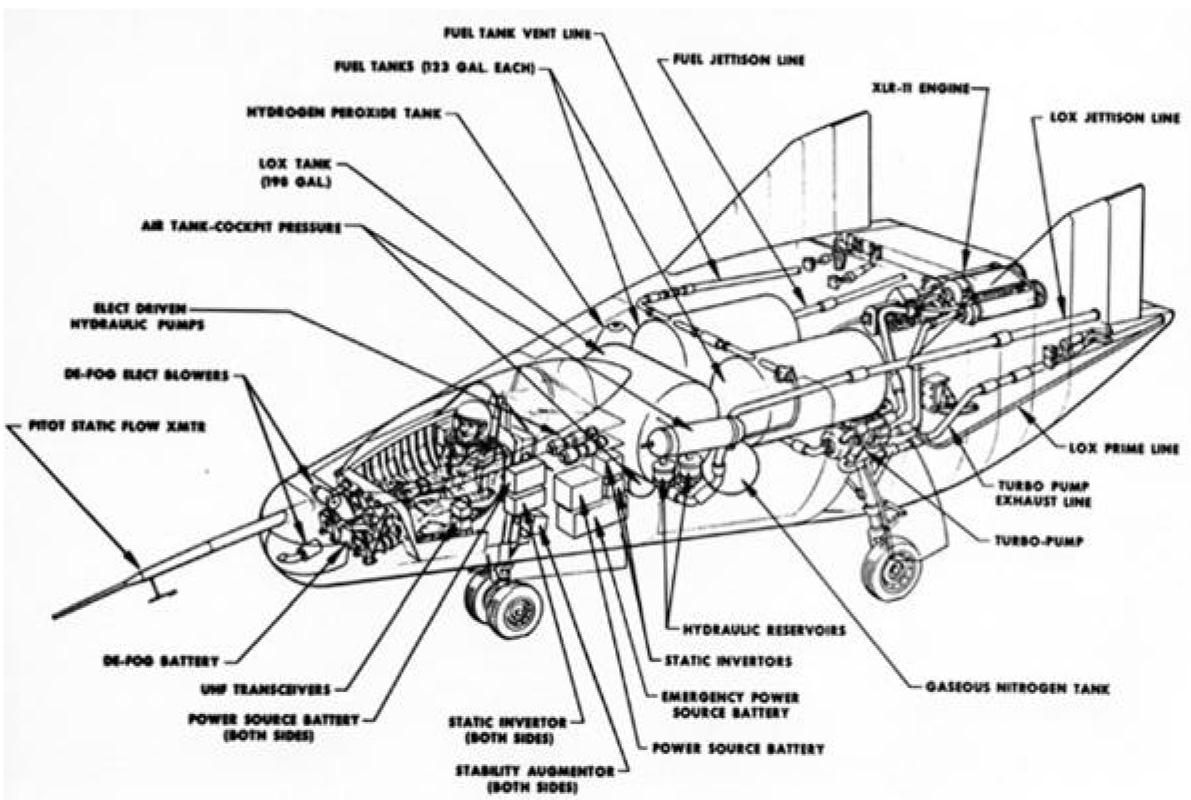


Figure 4-3: M2-F2 Cutaway Drawing

4.3.3 Rocket Engine Procurement and Refurbishment

While the vehicles were being constructed at Northrop, McTigue began a search for the remaining Reaction Motors XLR-11 rocket engines (Figure 4-4). These engines had been used first in the X-1 research aircraft (first to achieve supersonic speed in 1947), but were also used in the Douglas D-558-II Skyrocket and early flights of the X-15. McTigue found most of the engines and spare parts either in museums, dusty warehouses at Edwards or in airplanes on outside display pedestals. Some thrust chambers had been chrome plated for museum display and were discarded. The Air Force Rocket Engine Shop at AFFTC would normally have been responsible for refurbishment, assembly and ground testing of these engines. The X-15 program was in full swing however, and the AF Rocket Shop was very busy keeping the larger and newer XLR-99 engines in operation to support three X-15 airplanes. The XLR-11 engines and parts which McTigue found were turned over to Jack Russell, the rocket shop supervisor at NASA FRC. Russell and a small team of NASA mechanics who had worked on the earlier rocket airplanes completely disassembled and refurbished the engines. The engines were then turned over to the AF Rocket Shop which supported the XLR-11's, concurrently with the XLR-99's, at the Rocket Engine Test Facility (RETF) for the remainder of the X-15 and Lifting Body program (Figure 4-5).

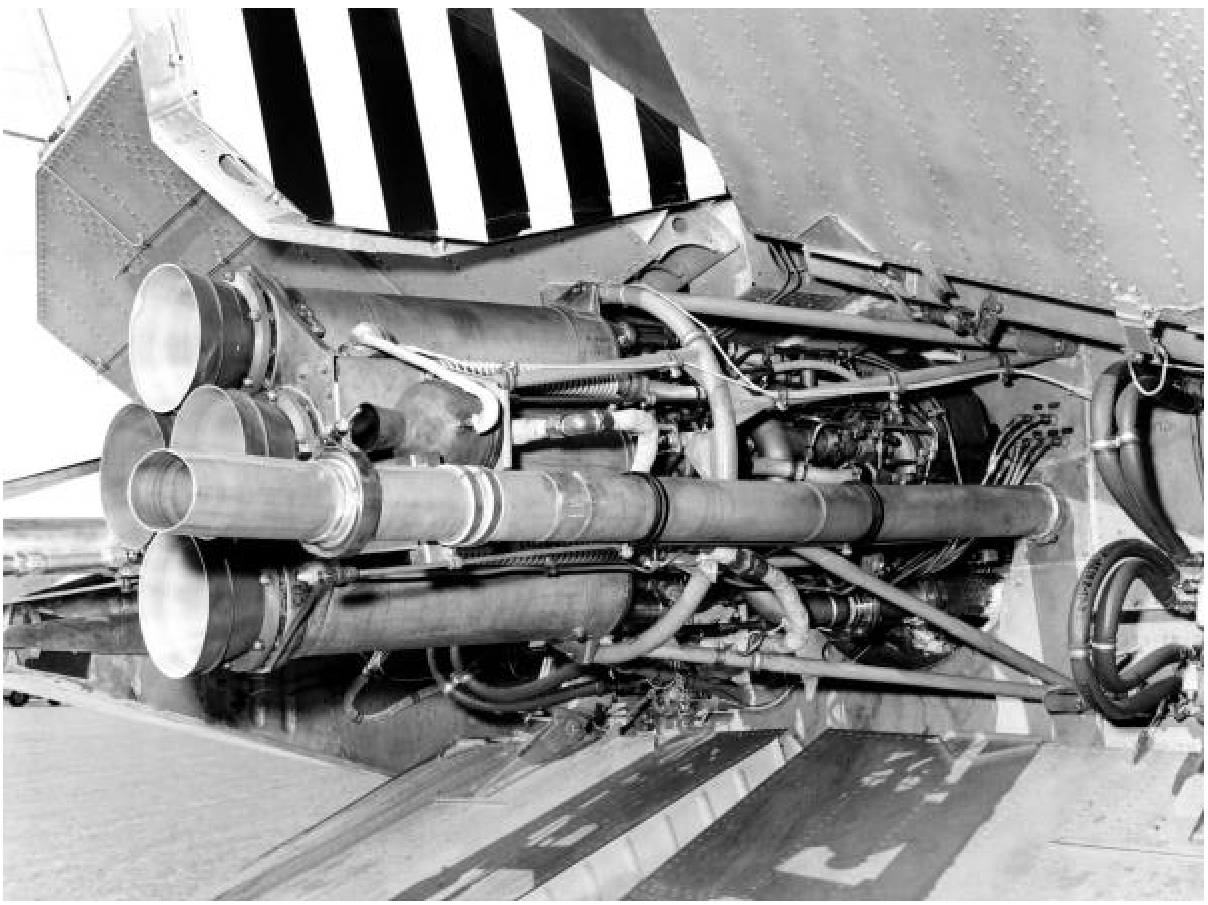


Figure 4-4: XLR-11 Rocket Engine

Figure 4-5: Air Force Rocket Engine Test Facility (RETF)

The test team decided that an emergency landing rocket, similar to that installed on the M2-F1, was also a necessary provision on the heavy-weight vehicles. A higher thrust level was required for the M2-F2 due to the heavier weight, so the team selected the hydrogen peroxide rockets from the Lunar Landing Research Vehicle (LLRV). Each rocket produced a thrust of 500 pounds. Four of these rockets were installed in the M2-F2. For glide flights a relatively large peroxide tank was used. These four rockets could produce a total thrust of 2000 pounds for about 35 seconds.

4.3.4 Schedule and Delivery

The manufacturing schedule for construction of the M2-F2 is shown in Figure 4-6. The vehicle was delivered to NASA FRC on 15 June 1965 (Figure 4-7), and the installation of the remaining government-supplied instrumentation and other subsystems started immediately.

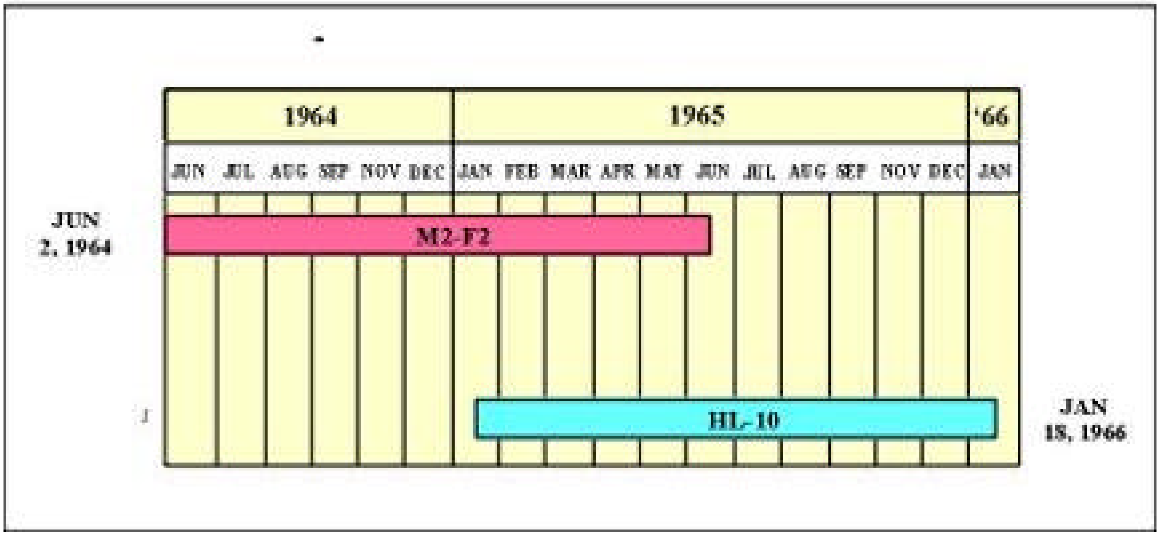


Figure 4-6: M2-F2 and HL-10 Manufacturing Schedule

Figure 4-7: M2-F1 and M2-F2 Lifting Bodies

4.3.5 Wind Tunnel Tests

Two necessary wind tunnel tests preceded the first glide flight in the M2-F2. A test program was conducted in the Langley 7X10-foot High Speed wind tunnel to define the launch transients produced by the flow field of the B-52 mother ship and to define the proper carry angle for the pylon adapter. These tests predicted that an abrupt but controllable right roll would occur at launch. The second required test was the full-scale wind tunnel test of the actual M2-F2 vehicle in the Ames 40x80-foot wind tunnel (Figure 4-8). Data from these tests were analyzed in detail and the results showed that the performance and stability were adequate to begin flight testing.

Figure 4-8: M2-F2 in Full Scale Wind Tunnel

4.3.6 Ground Tests

After installation of all systems necessary for the glide flights, the M2-F2 was mounted on a steel cradle in the NASA FRC hangar. The cradle was suspended on knife edges and supported by springs. This structure was used to measure the moments of inertia of the vehicle. Analysis of stability and control data requires accurate values for moments of inertia.

Flight control system checks on the ground showed several discrepancies. Modifications were required to avoid structural vibrations which were triggered by the flight control system. Taxi tests were performed in February 1966 using the landing rockets to test for braking and steering capability. There was no nose gear steering system, and the castering nose wheel provided excellent directional stability on the ground. The only available directional steering was through differential braking. When one brake was applied, the vehicle would initially turn slightly toward the braked wheel, but would then return to the original heading. This was apparently a result of the increased weight applied to the tire on the outside of the desired turn. The "bias-ply" tires were replaced with "radial-ply" tires and a small, but acceptable, steering capability was achieved. The HL-10 and X-24A were subsequently equipped with "radial-ply" tires.

4.4 Flight Testing of the M2-F2

NASA and the AF conducted flight tests of the M2-F2 at Edwards from 1966 to 1967. The testing of the M2-F2 ended on the sixteenth flight with a crash on the lakebed.

4.4.1 AFFTC/NASA-FRC Test Team

The effort by NASA to construct and flight test two lifting body shapes did not go unnoticed by the Air Force who also had some lifting body shapes under study. The contract to build the X-24A (discussed in detail in Chapter 6) was under serious consideration at the time the Northrop contract began.

When construction of the M2-F2 and HL-10 vehicles started, the X-15 rocket research aircraft flight test program was under way at Edwards by a joint AF/NASA team. Both local organizations - AFFTC and NASA FRC - were contributing capabilities that were specialized within their individual organizations, but complementary to each other for this type of test program. NASA FRC had a unique, in-house capability to operate and maintain one-of-a-kind research airplanes, to install and operate research instrumentation systems, and to conduct and control research test missions. The AFFTC had a capability to operate and maintain bomber aircraft (B-52 mothership), to maintain and test rocket engines, and to provide fire, crash and rescue capability for local and up-range operations. Facilities and equipment required to sustain these capabilities within both agencies were institutionally funded, so only direct time and manpower costs were charged to a project.

Both organizations had an excellent and experienced staff of flight test engineers and test pilots to draw from, so those responsibilities were shared. The chase pilots and chase aircraft were also shared responsibilities. Bikle and Brig. Gen. Irving "Twig" Branch (Commander of the Air Force Flight Test Center at Edwards) decided to create an AF/NASA Lifting Body Joint Operating Committee along the same lines as the existing AF/NASA X-15 Joint Operating Committee. The Lifting Body Joint Operating Committee would oversee the conduct of tests on the M2-F2 and HL-10 vehicles. Everyone understood that if, and when, the X-24A was funded by the Air Force, it would be added to the fleet. Robert Hoey directed the AFFTC engineering team supporting both the X-15 and the Lifting Body test programs. John McTigue directed the NASA FRC participation.

(The Memorandum of Agreement between the AFFTC and NASA FRC is shown in Appendix D.)

4.4.2 Fixed Base and Airborne Simulators

The X-15 program had reinforced the need for fixed base simulators to support the conduct of research flight testing. All flight planning and pilot training for the first M2-F2 flight, and for the first 15 glide flights were performed on the AFFTC Hybrid Analog/Digital simulator (Figure 4-9). This AF simulation facility was being used to support several programs including the X-15A-2. The AFFTC agreed to support the initial M2-F2 flights on an interim basis using a modified X-15 cockpit, while NASA FRC was installing new computers and an M2-F2 cockpit at their facility. Both simulators incorporated all of the available wind tunnel data, including the Ames full-scale tunnel results.

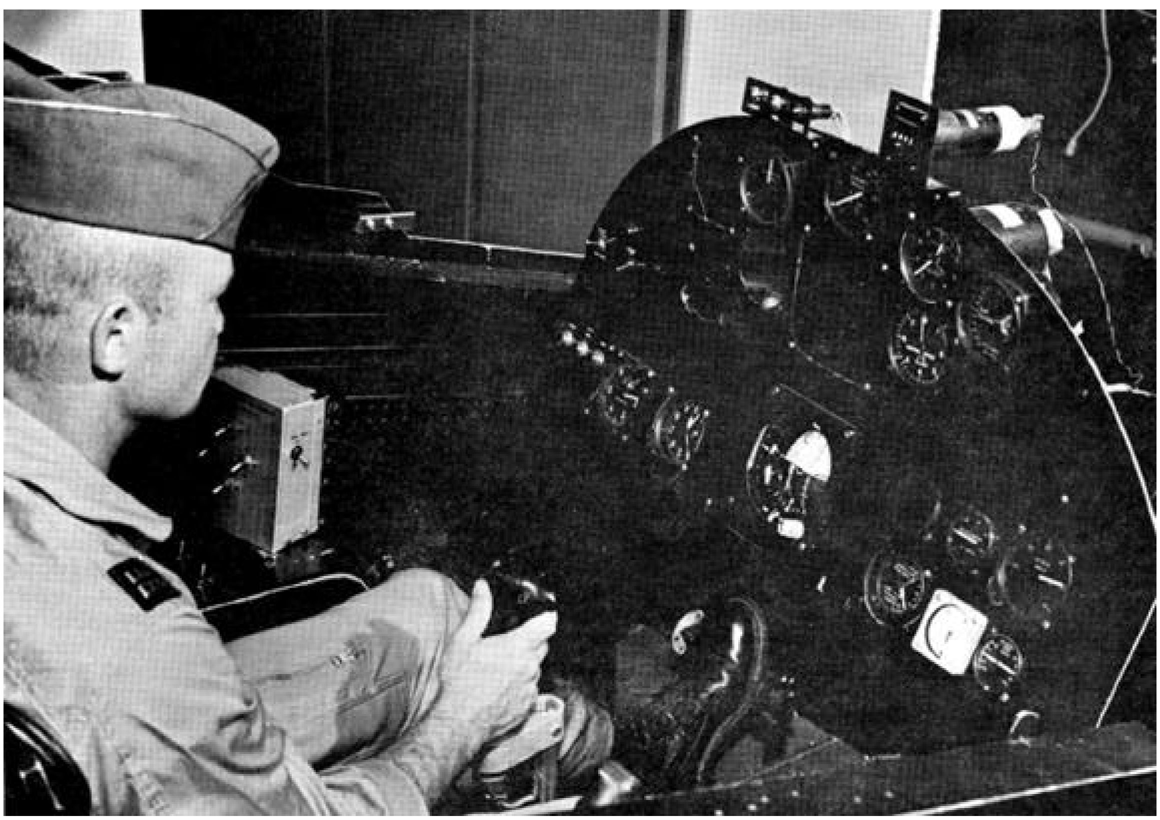


Figure 4-9: Air Force Hybrid Simulation of M2-F2

Flight planning engineers used the simulators to plan the trajectories, establish the proper launch points, study the effects of prediction uncertainties and high-altitude winds, and establish the appropriate control system settings (Reference Durrett, 1967). The test pilots used the simulators to develop and practice the individual flight plans, and to develop and practice emergency procedures for various system malfunctions. All glide and powered flight plans were developed using the fixed base simulators either at FRC or AFFTC. Alternate flight plans were developed which would return valuable data even if one or two of the XLR-11 rocket chambers failed to start. (This technique of using simulators for test planning and conduct was later infused into the more conventional flight testing done at AFFTC). The NASA simulation was used to support preparation for the 16th flight of M2-F2 and all flights of the M2-F3.

The Air Force NT-33 Variable Stability Airplane, operated by the Cornell Aeronautical Laboratory in New York, was used to simulate the handling qualities of the M2-F2 in flight. The tendency toward a lateral pilot-induced-oscillation (PIO), similar to that seen on ground fixed-base simulations, was observed during these tests. The violence of the maneuver quickly overloaded the variable-stability equipment on the NT-33 and tripped the simulation off-line, so the seriousness of the situation was not readily apparent to the pilots. The NASA C-140 "Jetstar" Variable Stability Airplane was also used to simulate the handling qualities of the M2-F2 vehicle.

The test pilots felt that they needed some type of in-flight training device, in addition to the fixed base simulator, to practice the steep approaches that would be required with a lifting body. A similar need within the X-15 program had prompted a series of tests on the F-104 fighter that identified a configuration which would reproduce the unpowered landing approach of the X-15. Accordingly, specific tests conducted on both the F-104 and F5D fighter aircraft established aircraft configurations (some combination of flap, speed brake, landing gear and power) that best matched the predicted performance of the M2-F2. AF and NASA pilots then made repeated practice approaches and landings using these in-flight simulations. On the morning of an actual launch they usually flew a training flight to experience the effects of current upper altitude winds. These same aircraft and configurations were used to provide close chase and photo chase during the actual approaches and landings of the M2-F2 and M2-F3. Chase pilots called out wheel height during the final few seconds before touchdown, a valuable help to the lifting body pilot.

Flight experience in the M2-F1, simulator studies, and training flights in the F-104's were all used to develop a baseline landing procedure for unpowered lifting bodies. The ground track for a typical glide and powered flight is shown in Figure 4-10. The geometry of a typical final approach, flare and landing are depicted from a side view in Figure 4-11. Only the aim point locations and final approach flight path angles were different for each vehicle.

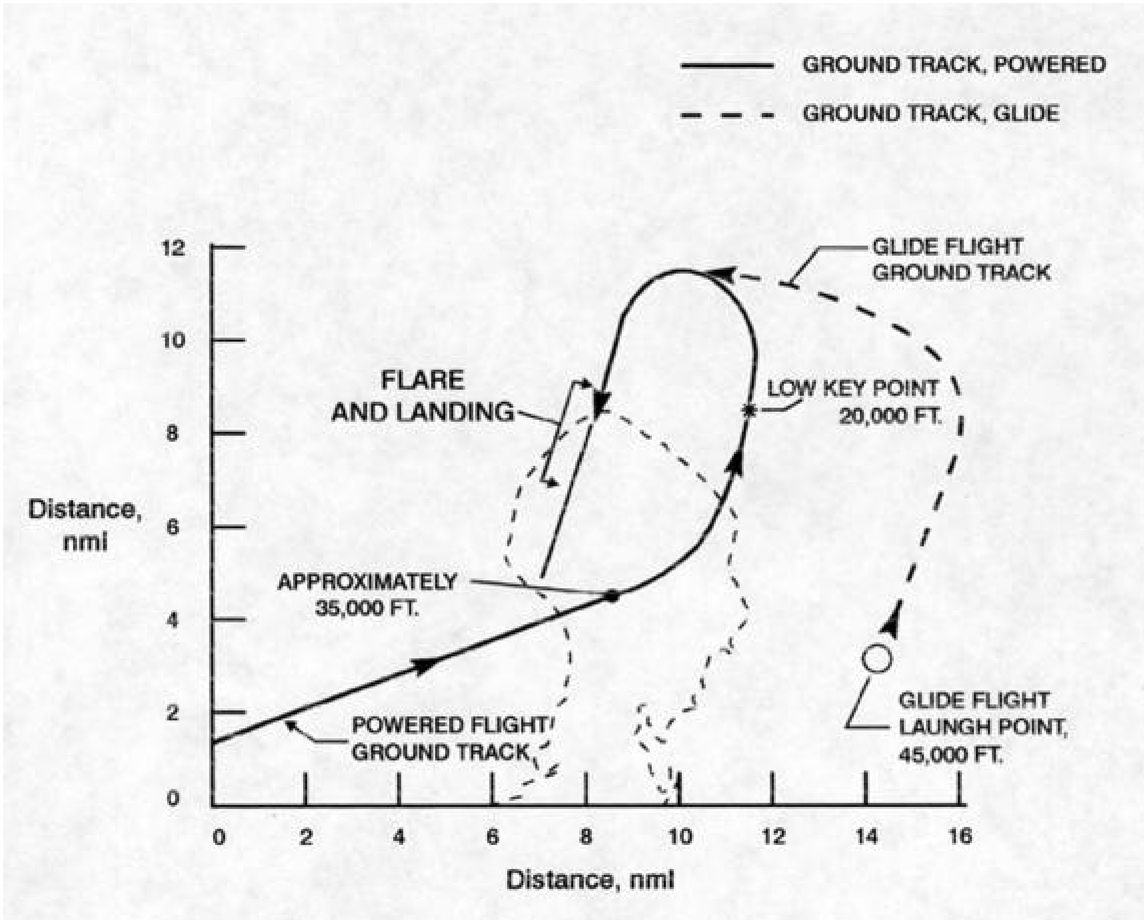


Figure 4-10: Typical Lifting Body Ground Track

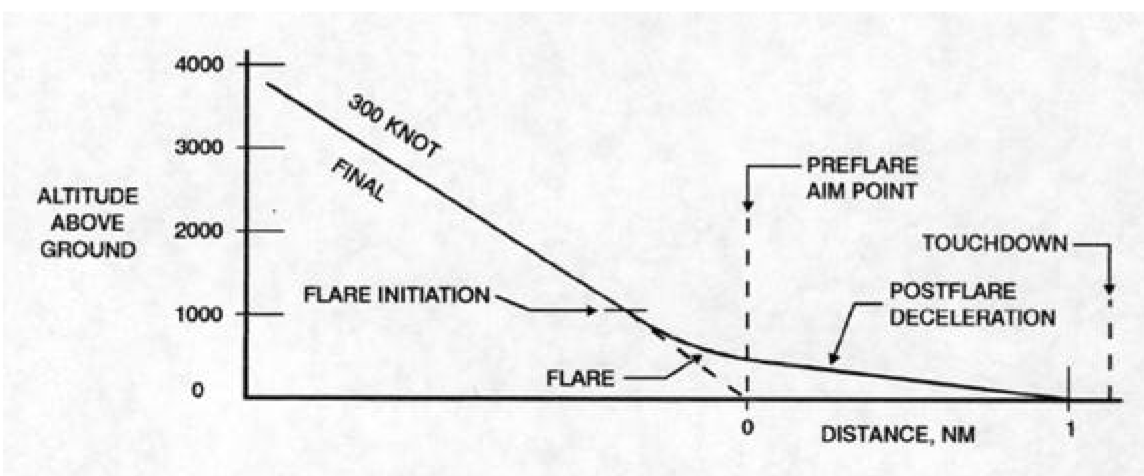


Figure 4-11: Typical Lifting Body Approach, Flare and Landing

4.4.3 Glide-Flight Program

Two B-52 motherships were available at the beginning of the Lifting Body program. Both were being used in their primary role as launch aircraft for the X-15, and both were maintained and flown by the Air Force. A lifting body glide flight operation began the day before a scheduled flight. One of the B-52 mother ships would be towed to the NASA FRC ramp area (Figure 4-12) and the appropriate pylon adapter would be installed on the X-15 wing pylon. The lifting body was towed into position and mated to the adapter using hoists and special mating fixtures. The lifting body was then serviced with breathing oxygen, pressurization gases, hydrogen peroxide (for the landing rockets) and other servicing fluids (Figure 4-13).

Figure 4-12: NASA FRC Circa 1966

Figure 4-13: Mating of M2-F2 with B-52 at NASA Hanger

Prior to the first glide flight, six planned captive flights, wherein the M2-F2 remained attached to the B-52, were performed (Figure 4-14). The first of these was a short, straight-ahead lift-off and landing on the long lakebed runway to validate the structural integrity of the pylon adapter. During this test there was no pilot in the M2-F2. A pilot flew in the M2-F2 during the remaining five planned captive flights, which tested whether the systems on the aircraft would operate satisfactorily in the high-altitude environment, and whether the battery power system had sufficient capacity to safely complete a flight with plenty of margin.

Figure 4-14: M2-F2 in Captive Flight

NASA test pilot Milt Thompson flew the first glide flight of the M2-F2 on 12 July 1966 (Figure 4-15). The roll-off at launch was less severe than predicted. Lift and drag measurements were found to be close to predictions, as were stability and control characteristics. Early flights showed that the prediction of a lateral instability at low angle of attack (high airspeed) was correct, and some controlled tests were conducted to try to establish the boundary for this instability.

Figure 4-15: M2-F2 Lifting Body with F-104 Chase

Following the fourteenth glide flight, the XLR-11 engine was installed in the vehicle in preparation for the first powered flight. Space and weight limitations resulted in a reduction in the tankage for the peroxide landing rockets as well as a reduction in the number of rockets from four to two. The potential run time of the two landing rockets was about 10 seconds. A conical fairing was added to the lower flap of the vehicle to provide adequate clearance for the engine. Glide flights number 15 and 16 were conducted to insure that the handling qualities were not degraded by these changes.

4.4.3.1 Handling Qualities: Simulator studies showed that the gliding handling qualities of the M2-F2 would not be as good as the M2-F1, primarily due to the reliance on the inboard elevons and rudders for lateral control. Flight tests confirmed the simulator predictions. Longitudinally the vehicle was stable and easy to fly. The vehicle was highly sensitive to the aileron/rudder interconnect setting in the lateral axis and pilots often commented that they felt uncomfortably close to a lateral instability during the high speed portion of the final approach. Other handling quality comments are contained in Paragraph 4.5.2 and in Appendix B.

4.4.3.2 Schedule and Pilots: Four pilots flew sixteen glide flights in the M2-F2 between 12 July 1966 and 10 May 1967. (The schedule relative to the other lifting bodies is shown in Figure 2-1. A complete log of flights and pilots is included in Appendix C.)

Pilot	Glide Flights
Milt Thompson	5
Bruce Peterson	3
Major Don Sorlie	3
Captain Jerry Gentry	5

4.5 M2-F2 Landing Accident

The most famous event of the Lifting Body program in terms of public awareness, was the spectacular crash landing of the M2-F2 on flight 16. Bruce Peterson was the pilot.

4.5.1 Events

On 10 May 1967 the M2-F2 was launched on its 16th flight, the last planned glide flight before beginning the powered flight phase. This was Bruce Peterson's third flight in the M2-F2. As he was completing his turn to line up with the runway and was accelerating to pre-flare speed, the vehicle began a series of violent rolling motions. Peterson recovered control of the vehicle, but he was no longer lined up with the marked runway on the lakebed and he was too low to make a correction. The vehicle was now aimed toward a rescue helicopter that was hovering near the runway. He was concerned that it was in the way. Peterson successfully completed the flare, lit the landing rocket, and he had just pulled the landing gear deployment handle when the vehicle touched the lakebed. Contact with the ground prevented completion of the landing gear extension cycle. The vehicle rolled and tumbled several times before coming to rest upside down on the lakebed (Figure 4-16). Peterson was severely injured and was immediately flown to the hospital at Edwards AFB. He made an excellent recovery although he lost the use of one eye.

Figure 4-16: M2-F2 After Crash on Lakebed

4.5.2 Cause of the Accident

The M2-F2 used a split upper flap for roll control rather than the outboard elevons that had been used on the M2-F1. The effectiveness of this control was considerably less than that of the elevons. To augment its effectiveness, some rudder deflection was needed to assist in the roll. The aileron-to-rudder interconnect (described in Section 4.2) provided the appropriate rudder deflections. The setting for the interconnect ratio was known to be quite critical for acceptable handling qualities (Figure 4-17). If the setting was too low, there was insufficient roll power to control the vehicle at low speed just before touchdown. If the setting was too high the pilot could induce a severe pilot-induced-oscillation (PIO) during the high speed final approach phase. This high speed boundary was quite abrupt. The vehicle could change from a normal flying airplane to a violently out-of-control airplane with a change in angle of attack of less than 2 degrees. The PIO potential had been observed on three previous occasions during the glide flight testing, once inadvertently (1st flight) and twice intentionally to validate the boundary. Later theoretical analysis would show that this instability was possibly a result of a "coupled roll-spiral" mode [4] of the pilot/airplane combination (Reference Kempel, 1971).

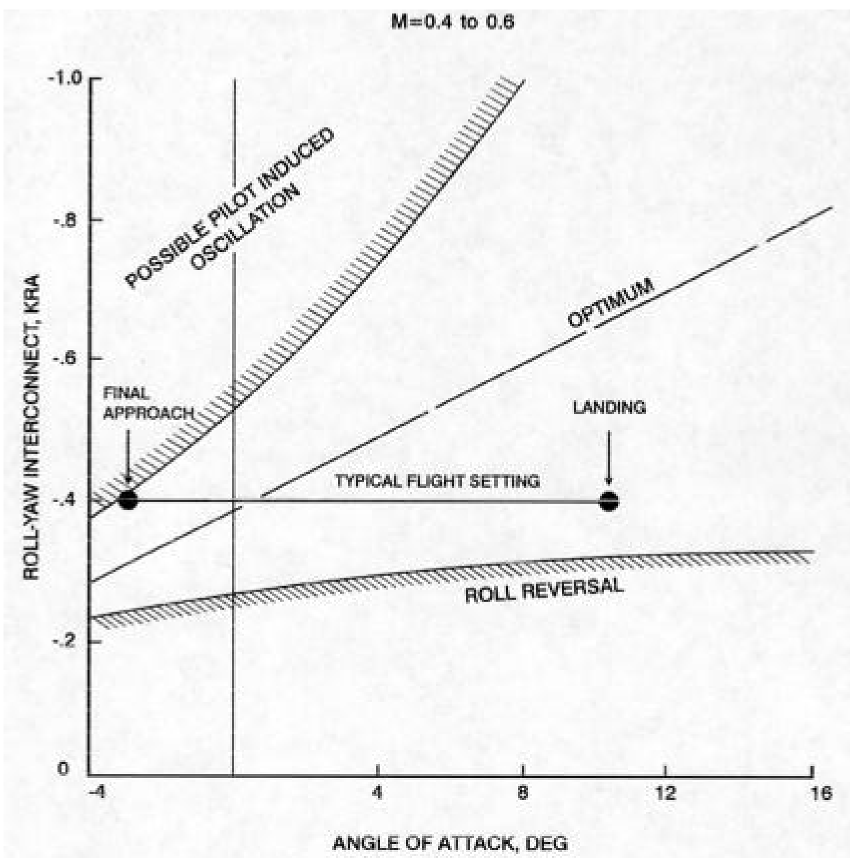


Figure 4-17: Variation of M2-F2 Roll Characteristics with Interconnect Ratio

---

[4] A "coupled roll-spiral" mode is a combining of two classical handling characteristics which are normally quite benign (roll mode and spiral mode). When the two combine into an oscillatory mode, the handling qualities can become unpredictable and potentially uncontrollable

On the day of the accident it is speculated that the pilot momentarily entered the PIO region while establishing his final approach glide slope, possibly as a result of an upset due to wind shear. After the oscillation started he reacted properly and increased the angle of attack. This action produced an immediate recovery. But the vehicle's heading was no longer aligned with the runway and its altitude was too low to complete a correction. The completion of the flare maneuver was further complicated by the lack of markings on the lakebed for depth perception.

4.5.3 Reconstruction to the M2-F3

The wreckage of the M2-F2 was transported back to the Northrop plant at Hawthorne. Northrop was given a small amount of money to "inspect" the vehicle while NASA was deciding whether to rebuild. The vehicle was reinstalled in the manufacturing jigs, and skins and structural components were systematically removed by the manufacturing team. Many of the components were magically returned to the vehicle in "good-as-new" condition and were reinstalled on the vehicle. When the approval was finally obtained from NASA Headquarters to rebuild and modify the vehicle to a new M2-F3 configuration, much of the structure had already been repaired. The cost of rebuilding and modifying the vehicle was $700,000. The M2-F3 was delivered to NASA FRC in July 1969. Gary Layton took over as the NASA FRC Lifting Body Program Manager from John McTigue.

The primary modification from the M2-F2 to the M2-F3 was the addition of a "splitter" fin on the upper aft centerline of the fuselage between the upper flaps (Figure 4-18). This fin was not for the purpose of adding directional stability, as was the earlier center fin on the M2-F1. It was for the purpose of preventing the strong yawing moment produced when the upper flaps were deflected unsymmetrically for roll control. Wind tunnel tests had shown that the splitter would significantly reduce adverse yaw and thereby eliminate most of the lateral handling quality problems which had been observed on the M2-F2. (Lateral control on the M2-F1 had used the outer elevons, thus the handling quality advantage of the center fin was not apparent.)

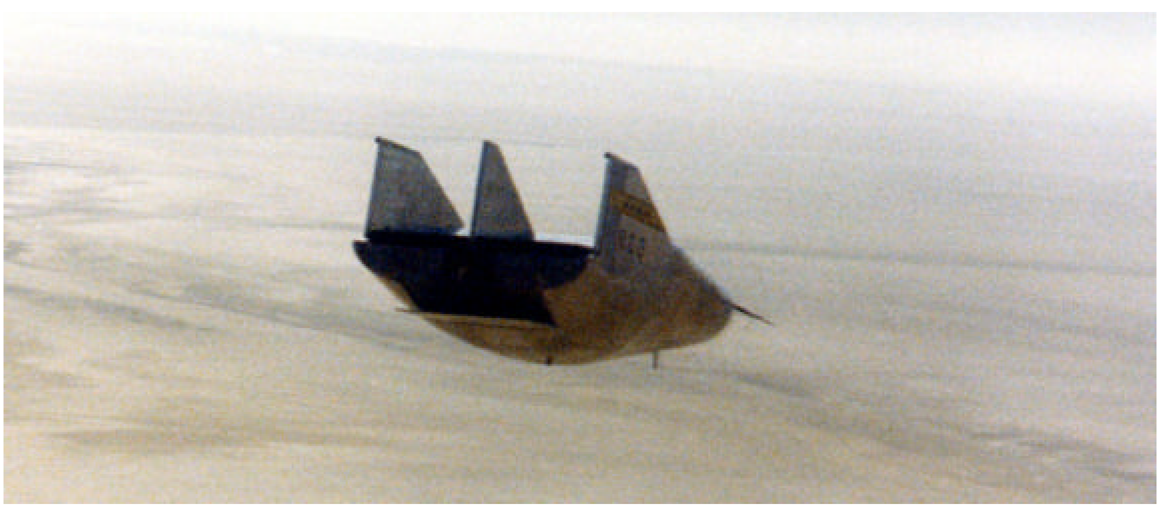


Figure 4-18: M2-F3 in Flight

M2-F3 Lifting Body

The M2-F3 was also equipped with a speed brake capability not available on the M2-F2. Even though the L/D of the M2-F2 was the lowest of the three lifting bodies, and the approach angle was the steepest, the pilots recognized the need for a speed brake to control the energy on final approach. The rudders of the M2-F3 could be simultaneously flared outboard to increase drag (similar to the speed brake system proposed for the X-20).

A structural change in the nose window region was also incorporated in the M2-F3 but the forward visibility remained essentially unchanged.

4.6 Flight Test of M2-F3

After reinstallation of the instrumentation and other internal hardware, the modified vehicle, the M2-F3, was carried aloft on 2 June 1970 for its first glide flight. Test maneuvers by NASA test pilot Bill Dana showed that the splitter fin had, in fact, solved the lateral handling qualities problems seen in the M2-F2. Although the L/D of the M2-F3 was the lowest of the original 3 heavy weight lifting bodies, the handling qualities were now considered adequate for powered flight (Figure 4-19).

Figure 4-19: M2-F3 Powered Flight

It should be noted that the first flight of the M2-F3 followed, chronologically, the successful powered flights of the HL-10 and X-24A (Figure 2-1). A rocket-powered lifting body flight required some different procedures for flight preparation. After mating of the lifting body and the B-52 mothership, the B-52 was towed to the X-15 Servicing Area where the large volumes of fuel (water-alcohol), (WALC) and liquid oxygen (LOX) were serviced (Figure 4-20). The LOX-top-off system, which was installed in the B-52 to support X-15 flights, was also serviced and was used to replace LOX that boiled off from the lifting body LOX tank while the B-52 was climbing to altitude.

Figure 4-20: Location of Lifting Body Facilities at Edwards

Full pressure suits were used by the pilots for all powered flights since the altitude was expected to exceed 50,000 feet. In preparation for a flight a special Life Support van was parked near the B-52. The lifting body pilot donned his pressure suit, and suit operation was completely checked out inside the van.

All lifting body flights used the NASA FRC Control Room (Figure 4-21). Since all flights were conducted in close proximity to Edwards, no on-board recording was provided. All data were gathered through telemetry directly to receiving stations on the ground.

Figure 4-21: NASA Mission Control Room

In the fall of 1972, when Rogers lakebed became wet while Rosamond lakebed remained dry, two M2-F3 flights were successfully flown with planned landings on Rosamond lakebed (Figure 4-22). The vehicle was towed back to the NASA hangar along Rosamond Boulevard, the normal access road to Edwards. (The schedule relative to the other lifting bodies is shown in Figure 2-1. A complete log of flights and pilots is included in Appendix C.)

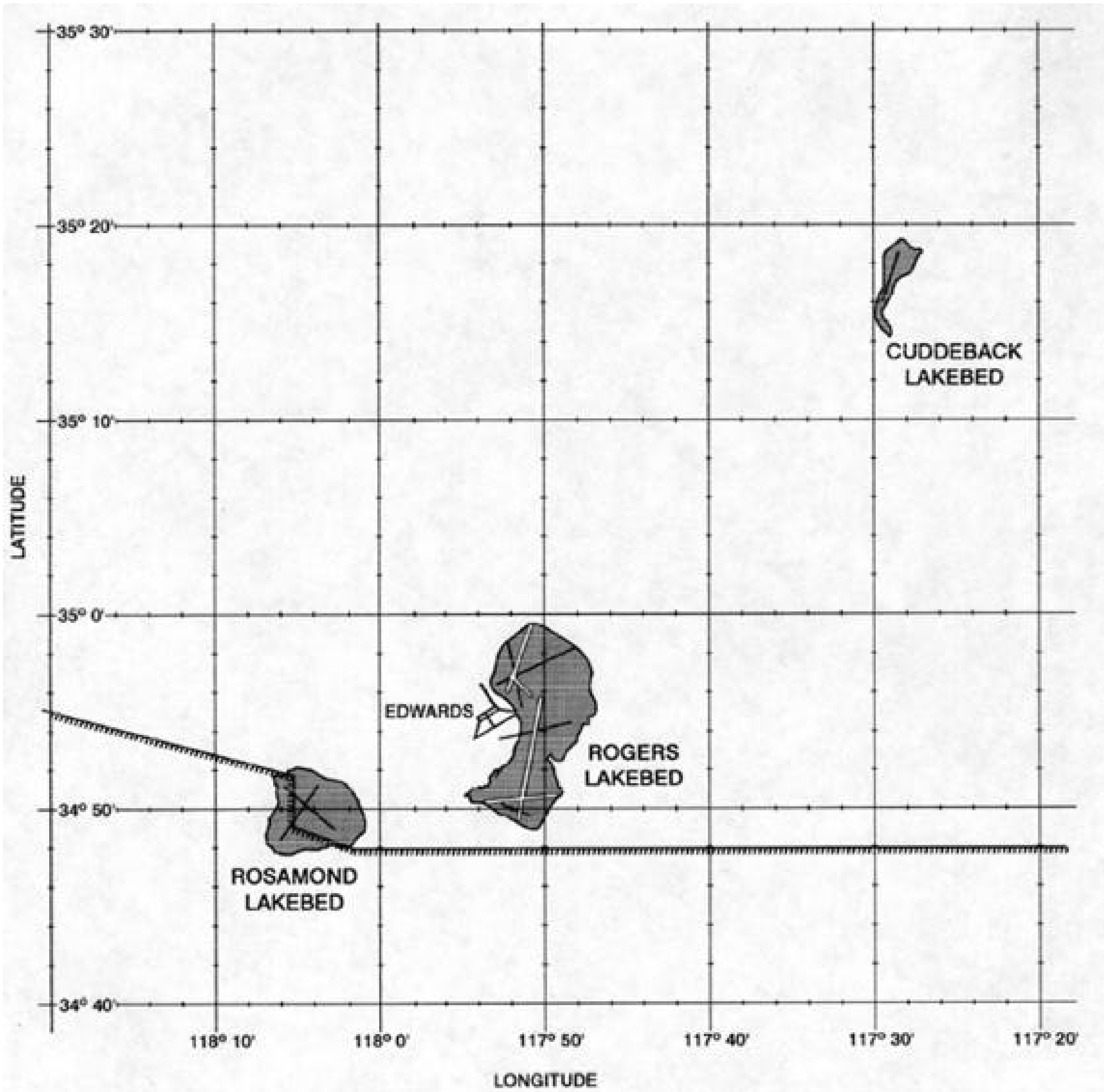


Figure 4-22: Dry Lakebeds Near Edwards AFB Used for Lifting Body Operations

4.6.1 Handling Qualities

The rebuilt vehicle with the new designation M2-F3 employed the same basic flight control system (built by Sperry) as the X-24A, rather than the Northrop system that had been used in the M2-F2. The lateral-directional characteristics were significantly improved with the center fin. The aileron-rudder interconnect, which was so critical on earlier flights, was no longer needed and the system was removed shortly after flying resumed. The first few powered flights into the transonic region revealed a longitudinal problem. The basic flight control system was incapable of either stabilizing the low level of pitch stability or suppressing the small, abrupt pitch transients that were encountered during the climb phase in the transonic speed range with the rocket engine running. This posed a significant pilot work load during powered flight. Occasional lateral disturbances, or upsets, were also observed during the climb; this characteristic was found on all lifting bodies. The improved lateral stability of the M2-F3 caused these upsets to be only a minor nuisance to the pilot. (The upsets were later determined to be caused by high altitude wind shear and is discussed in Chapter 7.)

The M2-F3 was later equipped with a Command Augmentation System (CAS) and a side-arm controller. These improved the handling qualities, and also explored the applicability of modern fly-by-wire concepts to lifting body vehicles. The CAS system included a pitch-rate-command mode and some autopilot features such as an angle-of-attack hold mode. When used during the climb, the CAS system significantly reduced the pilot work load. It also eased the piloting task during the transonic deceleration and configuration change.

A Reaction-control Augmentation System (RAS) (similar to the attitude control system used in a spacecraft) was also installed for several flights. When engaged, it provided a normal control system stability augmentation function in the pitch axis but used small reaction-control jets rather than control surfaces to pitch the vehicle. In some flight regimes this system was as effective as the aerodynamic controls, and in other regions it was somewhat less effective. These two control system modifications produced improvements in the handling qualities of the M2-F3 relative to the early control system configuration. (Additional pilot comments are found in Appendix B.)

4.6.2 Schedule and Pilots

Four pilots flew the M2-F3 on a total of 27 flights between 2 June 1970 and 20 December 1972. The vehicle reached a maximum altitude of 71,500 feet and a maximum speed of Mach 1.613. (The schedule relative to the other lifting bodies is shown in Figure 2-1. A complete log of flights and pilots is included in Appendix C.)

Pilot	Glide Flights	Powered Flights
Bill Dana	4	15
Captain Jerry Gentry	1	0
John Manke	0	4
Major Cecil Powell	0	3

4.7 Technology Lessons Learned

The M2-F2/F3 was the first of the heavy-weight, entry-configuration lifting bodies. Its successful development as a research test vehicle answered many of the generic questions about these vehicles.

4.7.1 Accidents/Incidents

The M2-F2 accident on 10 May 1967 (section 4.5.1) was the only major accident in the Lifting Body program.

One incident occurred that could have been disastrous if it had not been properly handled. After mating the M2-F3 to the B-52 in preparation for one powered flight, crew members discovered fuel (water/alcohol) flowing out of the liquid oxygen vent line. A multiple failure had occurred in one of the servicing valves. This failure allowed fuel to be inadvertently pumped into the liquid oxygen tank. The crew knew that a mixture of LOX and water alcohol was potentially explosive and highly unstable. It could be set off by the slightest movement (much like nitroglycerin). They had no way of determining the exact amount of either fuel or LOX in the tank and therefore could not determine the level of instability of the mixture. They elected to carefully open the vent valves on the LOX tank and evacuate the area until the LOX had completely vented from the tank. That took several days. The M2-F3 ground crew notified the Flight Operations Office at the AFFTC of the situation and all supersonic flights were cancelled during the interim to avoid the possibility of a sonic boom triggering an explosion. After the LOX had completely boiled off, the tank was purged, the faulty valve replaced, and the servicing restarted without incident.

4.7.2 Validations

The M2-F2 program demonstrated that lifting bodies could be successfully landed at realistic mission weights. Wind tunnel predictions of low speed stability and performance were validated. The M2-F3 also validated the wind tunnel predictions in the transonic region where confidence in wind tunnel results had been low.

As the first of the heavy-weight lifting bodies to fly, the M2-F2 demonstrated the continuing value of air-launched, rocket-powered, manned research aircraft to validate predictions of unconventional shapes or concepts.

4.7.3 Improvements

The splitter fin which was installed during the rebuild to the M2-F3 configuration provided a significant improvement to a known lateral handling quality deficiency of the M2 shape. This problem had been circumvented during early glide flights by extensive pilot training and careful flight planning. Unlike the M2-F2, the HL-10 and X-24A had center fins installed in their original configurations (based on the need to minimize adverse yaw from the upper flaps). This feature emanated from earlier and independent wind tunnel tests on these configurations and represents an example of a technical discovery occurring almost simultaneously, but independently, at Ames (on the M2), at Langley (on the HL-10), and at Martin (on the X-24A).

Improved flight control systems, which included both a Command Augmentation System (CAS) and a Reaction control Augmentation System (RAS), were successfully tested in the M2-F3 vehicle. Handling qualities were noticeably improved by the fly-by-wire features of the new control systems.

After completing one of these short and intensive lifting body flights, the pilots consistently remarked that events seemed to happen faster during the flight than they did on the simulator, and they had the feeling of being 'behind the airplane". Jack Kolf speculated that by running the simulator "faster-than-real time" he might be able to better match the the pilots comprehension of the actual flight experience. After completion of the M2-F3 flight test program the M2-F3 simulator was modified to use a variable time base. Kolf used a flight plan for a flight that had actually been flown, to experiment with the variable time base. He found that a time factor of 1.4 faster than real time produced very positive responses from the M2-F3 pilots. They commented that this time base was very close to what they perceived in flight. This time-compression concept was applied very successfully to the simulator training for an F-15 Stall/Spin program that was performed by NASA DFRC using a 3/8 scale remotely-piloted vehicle.

4.7.4 Problems Resolved

The M2-F2 control system, in its original configuration, proved inadequate and unsafe for flight. A large deadband in the rudder controls, transients in the damper system, and structural resonance (flight controls responding to structural excitation) prompted a redesign of the basic control mechanism. The deadband in the rudder control was eliminated by biasing the neutral position of each rudder so that both rudders could operate simultaneously (one inboard and one outboard) rather than separately (outboard only on one side or the other). Frequent automatic disconnects of the system were experienced even though no failure was present (these were known as nuisance trip-outs).

The transients and structural resonance were resolved by filtering some of the electrical signals. Nuisance trip-outs were avoided by eliminating the monitor channels in the yaw and roll axes and by limiting the authority of the system.

Available wind tunnel data on the M2-F2 configuration prior to the first flight was incomplete and somewhat inconsistent between different wind tunnels, especially in the transonic region. Flight testing proceeded cautiously and the resulting test data resolved those differences.

4.7.5 Unresolved Problems

As expected, the extension of the landing gear created a large drag increase and a significant nose-down pitch trim change. With the blow-down feature this trim change occurred very abruptly and required quick reaction from the pilot while he was only a few feet above the ground. The highly trained test pilots associated with the Lifting Body research program did successfully adapt to these characteristics. These problems were never seriously addressed from the viewpoint of an operational vehicle. An engineering redesign could have significantly improved the gear-down characteristics.

Although the cockpit was farther forward on the M2-F2/F3 than the M2-F1, the nose window still was needed and used by the pilots to establish the desired final sink rate and to receive depth perception cues for landing. The requirement for a thick ablation heat shield on the nose of an actual entry vehicle would preclude the use of ANY forward window in this location for pilot visibility at landing. On one flight the nose window of the M2-F3 was intentionally covered with paper so that the only forward visibility was over the sides of the fuselage. Bill Dana made a successful, but hard, landing in this configuration. He concluded that the situation was dangerous and that the experiment should not be repeated. Periscopes or blow-off panels were being considered to solve this problem.

The degradation in performance and stability due to the roughened surface of the ablative heat shield after entry was not factored into the Lifting Body flight test program. Subsequent analysis (discussed in Chapter 8) would show that this degradation was sufficient to raise serious questions as to the true land-ability of these vehicles following an actual entry.

4.8 Test and Support Sites

The AF/NASA Joint Operating Agreement specified the breakdown in responsibilities for support activities. This division of responsibilities remained the same throughout the M2-F2 and M2-F3 program.

4.8.1 NASA Facilities

Test vehicle maintenance was a NASA responsibility conducted mostly in the West Hangar at NASA FRC (now building number 4802). The vehicle mating to the B-52 occurred on the NASA FRC ramp southeast of the NASA hangar (Figure 4-12). Servicing of hazardous fluids was done in the X-15 servicing area which was about a mile southeast of NASA FRC, well away from active hangars and offices (Figure 4-20). After each flight the vehicle was towed from the lakebed back to the ramp at NASA FRC where tanks and lines were purged before returning the vehicle to the hangar.

NASA FRC purchased pressure suits from the David Clarke Company for the non-military lifting body pilots. These suits were turned over to the AFFTC Life Support Facility (Bldg. 3920) where they were maintained, as were the AF pressure suits for the military pilots, throughout the Lifting Body program.

All electrical and hydraulic power on all of the lifting bodies was provided by silver-zinc batteries. NASA FRC created a new Battery Shop in building 4801 to develop, test, and maintain these batteries. Their work significantly contributed to the success of the Lifting Body program and also to the general technology of large, high-discharge-rate batteries.

The NASA Control Room was used for all M2-F2 and M2-F3 flights (Figure 4-21). Both real-time and follow-on data reduction were provided by the NASA FRC data reduction computers and staff. Radar tracking was displayed in the control room and was provided by NASA radar, although the display of AFFTC radar was available as a backup.

4.8.2 AFFTC Facilities

Procurement of spare rocket engine parts and stockbins of parts were maintained at the Air Force Rocket Engine Test Facility. All engine maintenance, following the initial refurbishment, was performed there. The RETF was used to test-fire engines after major maintenance (Figure 4-5). For the first few installed engine runs the M2-F3 vehicle was tied down in the rocket engine test area. Later the installed engine runs and leak checks were performed at the south end of the NASA ramp.

The two B-52 mother ships (Serial Number 003 and 008) were operated by the Air Force and maintained by Air Force crews in the Maintenance & Modification (M&M) Hangar (Figure 4-20).

Fire Crash and Rescue support was provided by the AFFTC Fire Department. The fire department was often required to position fire trucks and teams at two different runways on Rogers lakebed as well as an emergency truck at Rosamond or Cuddeback lakebed.

The flight preparation, planning and pilot training for the first 15 flights of the M2-F2 were supported by the AF hybrid analog/digital simulation in building 1408 at the AFFTC (Figure 4-20).

4.9 Current Status of Aircraft

NASA donated The M2-F3 vehicle to the Smithsonian Institute in December 1973. It is currently hanging in the Air and Space Museum along with X-15 aircraft number 1 which was its hangar partner from 1965 to 1969.

HL-10 Lifting Body at the Entrance to the NASA Dryden Flight Research Center

Chapter 5
The HL-10 program

Concurrent with the development of the M2-F2/F3 vehicle was the development of the HL-10 vehicle. The HL-10 lifting body evolved from work at NASA Langley.

5.1 Theoretical Development

The HL-10 (Horizontal Lander, model number 10) entry configuration was developed at the NASA Langley Research Center (LaRC) under the general guidance of Gene Love, Bob Rainey and Jack Paulson. It was based on some studies initiated in 1957 that showed that an entry configuration with negative camber (cross section like an inverted wing airfoil) and a flat bottom would have good stability during entry and a slightly higher L/D than a blunt half-cone (Reference Kempel, 1994). Work continued at LaRC on the development of this concept and in 1962 the configuration was designated as the HL-10 . When Bikle suggested the construction of the heavy weight M2-F2 to NASA headquarters, the Langley engineers proposed that their HL-10 shape was a viable alternative and worthy of consideration. Headquarters approved the construction of both vehicles and the contract was awarded to Northrop in April 1964. The Langley engineers then concentrated on the development of a practical shape that could be safely flown in the transonic and subsonic flight regime, yet would retain the aerodynamic features necessary for successful atmospheric entry.

5.2 Technical and Physical Development

The HL-10 design team made no attempt to incorporate in their vehicle a canopy for forward visibility as was done on the M2-F2. The pilot was completely enclosed within the vehicle outer mold lines and would be totally dependent on the nose and side windows for visibility during landing.

Wind tunnel tests on the basic HL-10 continued at Langley after the contract award to Northrop. These tests showed that there were some deficiencies in directional stability around Mach 1.5 and that the subsonic L/D of the basic configuration was lower than expected. In February 1965 (10 months after contract award) Langley proposed some changes to the HL-10 configuration. The size of the center fin and tip fins was increased and additional control surfaces were added at the aft end of the vehicle to "boat-tail" the individual surfaces and reduce the base drag at low speed. Although the increased complexity of the control system was not popular with the NASA FRC team at the time, Northrop incorporated these changes during initial construction (Figure 5-1).

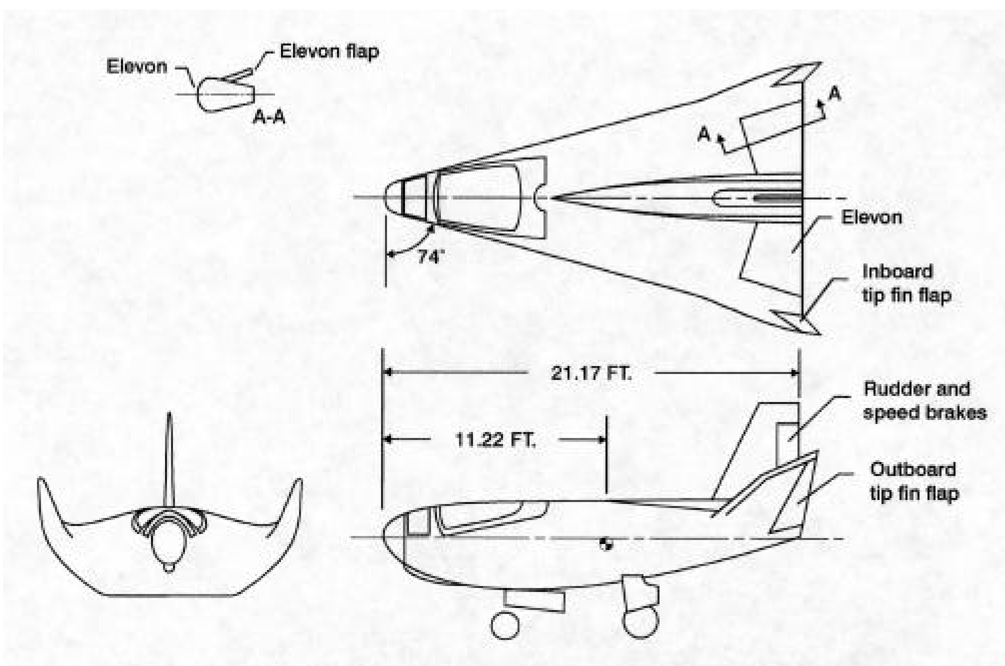


Figure 5-1: Three-View Drawing of HL-10

The HL-10 was equipped with thick elevons, left and right, at the aft edge of the body. These surfaces were deflected differentially for roll control and symmetrically for pitch control. A single, split rudder was mounted to the center vertical fin. Both sides of the rudder could be deflected together, asymmetrically for yaw control. The two sides of the rudder could be extended symmetrically to serve as a speed brake.

Secondary moveable surfaces were located on the inboard and outboard trailing edges of the tip fins and the upper surface of the elevons. These were slow moving controls designed to reduce the base area, and thus the drag, at low speed. They were also used to flare the aft end of the vehicle for added stability in the transonic region (Figure 5-2).

Figure 5-2: HL-10 Control Surface Configurations, Subsonic

Figure 5-2: HL-10 Control Surface Configurations, Transonic

Like the M2-F2, the HL-10 was equipped with a three-axis stability augmentation system which consisted of rotational rate dampers. The damper signals were mechanically added to the pilots stick and rudder commands.

The landing gear design philosophy for the HL-10 was similar to that for the M2-F2, namely, a rugged, non-optimized design with a rapid (one-second) blow-down feature. The pilots had accepted this philosophy based on the research nature of the program.

5.3 Construction

The HL-10 was procured with NASA funds under the same contract and government/contractor team philosophy as the M2-F2 (discussed in Sections 4.2.1 and 4.3). Langley was still working on the final loft lines when the contract was awarded so the HL-10 construction and delivery were to follow the M2-F2. The HL-10 construction started in January 1965 and finished in January 1966 (Figure 4-6). The construction proceeded smoothly in spite of the late configuration changes mentioned earlier. Initially George Sitterle was assigned as the NASA FRC Operations Engineer for the HL-10. He was on site at Northrop during most of the vehicle construction.

5.3.1 Wind Tunnel and Ground Tests

A test program was conducted in the Langley 7X10-foot High Speed wind tunnel to define the launch transients produced by the flow field of the B-52 mother ship and to define the proper carry angle for the pylon adapter. After delivery of the HL-10 to NASA FRC on 18 January 1966, the government-furnished equipment was installed. The vehicle was then trucked to the Ames 40X80-foot wind tunnel for final testing. Results were generally satisfactory although some momentary flow separation was noted on the tip fins at some flight conditions.

Since the landing gear and tires of the HL-10 were similar to the those on the M2-F2, lakebed taxi tests were not considered necessary. Flight control system checks showed some discrepancies. Filters were installed to suppress structural vibrations which were being triggered by the flight control system. An inertia "swing" was performed in a manner similar to the M2-F2 to measure the moments of inertia about all axes. By late 1966 the HL-10 was declared ready for flight.

5.4 Flight Testing

Flight testing began with a glide flight in December 1966. Glide and powered research tests were concluded in July 1970.

5.4.1 AFFTC/NASA FRC Test Team

The HL-10 flight test program was conducted under the auspices of the Edwards AF/NASA Lifting Body Joint Operating Committee described earlier (and in Appendix D). Most of the support functions provided by AFFTC and NASA FRC were the same as those provided to the M2-F2 program. The AF provided the B-52 maintenance and support, fire crash and rescue, and rocket engine maintenance. NASA provided the test vehicle maintenance, instrumentation, data reduction and control room operation. NASA FRC maintained flight safety responsibilities for each operation. After receipt of the HL-10 vehicle, NASA FRC assigned Herb Anderson as the Operations Engineer for the HL-10 responsible for maintaining configuration control and for overseeing maintenance and flight scheduling activities.

By the time the HL-10 was ready for flight the X-24A program had been approved and construction was under way. The AFFTC engineering team, which had been supporting the M2-F2 flight planning effort, turned to preparations for the X-24A program. The NASA engineering team therefore assumed all aspects of the HL-10 simulation and flight planning effort with minimum engineering support from the Air Force (Figure 5-3). Air Force and NASA test pilots continued to share pilot and chase responsibilities for all lifting body flights.

Figure 5-3: NASA HL-10 Simulator

5.4.2 Glide Flight Program

The test team initially planned to conduct two captive flights for the HL-10 to check out all subsystems. Only one was found necessary. Bruce Petersen flew the first glide flight on 22 December 1966 (Figure 5-4). Shortly after launch moderate vibrations were felt by the pilot and were observed via the telemetry in the control room. The pilot was advised to change some flight control switch positions to reduce damper gains. He did and the vibrations subsided. One of the planned maneuvers for the first flight of any of the lifting bodies was a practice flare at altitude. The purpose of this maneuver was to investigate whether the vehicle was controllable throughout the high speed approach (planned at 300 knots) and the subsequent deceleration to a low speed landing condition (expected to be about 180 knots). It also insured that the vehicle had sufficient L/D to complete the flare. As Peterson accelerated to the 300-knot high speed approach condition, he noticed that the vehicle was very sensitive in the pitch axis. He completed the practice flare and, as he was slowing down, noticed that the vehicle was no longer responding properly to pitch and roll commands. He lowered the nose and immediately regained control of the airplane. He decided to fly the final landing approach at a higher speed than originally planned so that he could land before slowing into the area of poor control. As he approached 340 knots on final approach, he again encountered some control vibrations and the vehicle became very sensitive. He completed the flare and made a successful landing, touching down quite fast, however, at about 280 knots (See Appendix B).

Figure 5-4: HL-10 Glide Flight

5.4.2.1 Analysis, Test and Redesign: The flight control vibrations of that first glide flight were a result of an error in the predicted elevator effectiveness and an improper filter in the rudder flight control electronics. These discrepancies, along with the overly sensitive pitch control, were quickly identified and easily rectified. The loss of control at low speed was a more difficult problem to identify. It took several weeks before the data were fully analyzed and correlated. The problem was identified as a separation of the airflow over the upper surface of the outboard fins. This flow separation caused the elevons to become ineffective (Reference Kempel, 1994).

The NASA Langley aerodynamicists returned to the wind tunnel. Soon they were able to duplicate the flow condition experienced in flight, a condition observed in earlier tests (and in the full scale tests at Ames) but dismissed as spurious scatter in the data. Langley devised several "fixes" and presented them to the NASA FRC Lifting Body team (now headed by Program Manager Gary Layton). NASA FRC selected adding an inward-cambered glove to the leading edge of the tip fins (as shown in Figure 5-5). This glove allowed the airflow to stay attached to the upper surface of the tip fins at high angles of attack (low speeds).

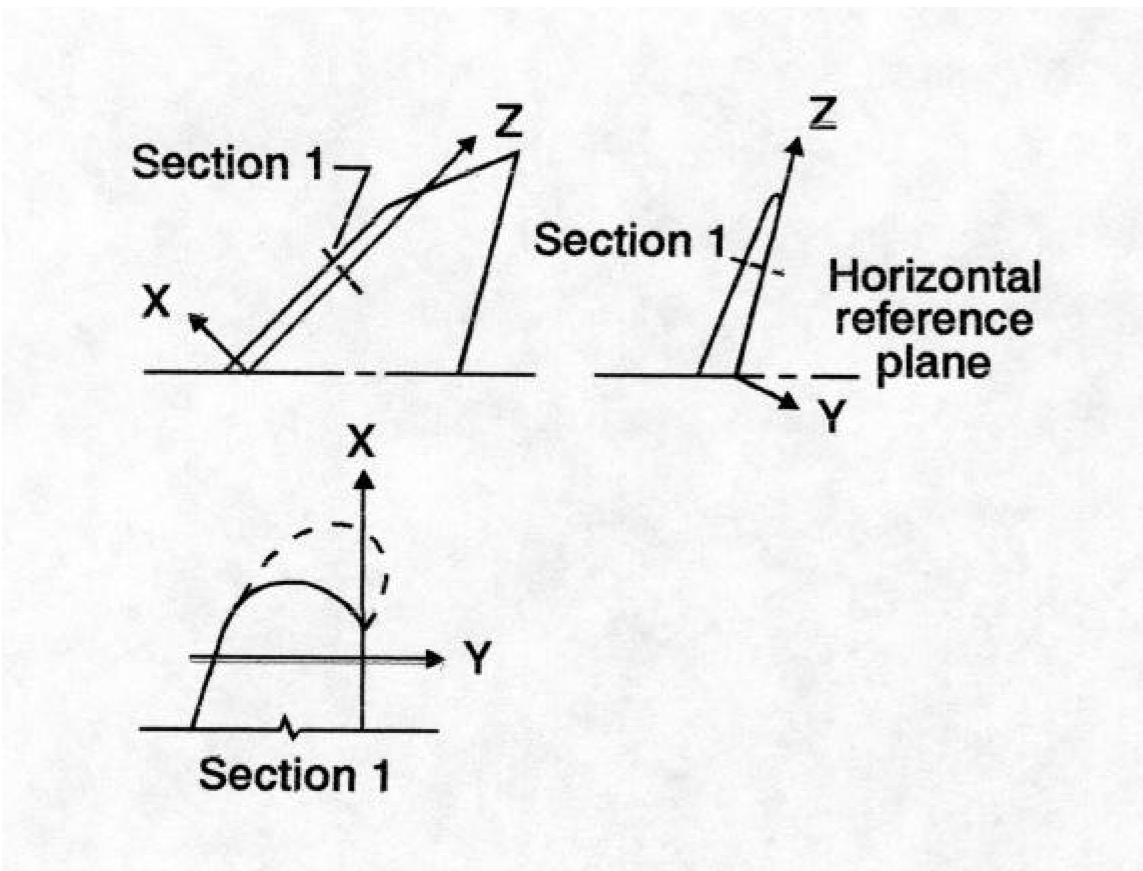


Figure 5-5: Inward-Cambered Glove Modification to HL-10 Fins

The entire process of retesting in the wind tunnels, redesigning the fins, manufacturing the gloves, installing them, and retesting the control system took over one year. Since the problem flight condition had been successfully duplicated in the small scale wind tunnels, NASA FRC decided that a return to the full-scale tunnel was unnecessary. The second glide flight occurred on 15 March 1968. It achieved a more reasonable approach speed of 300 knots and a normal touchdown speed below 200 knots. The flight was quite successful and was followed by nine more glide flights to refine the control system and prepare for powered flight.

5.4.3 Powered Flight Program

NASA FRC pilot John Manke performed the first rocket powered flight of a lifting body on 13 November 1968. The vehicle was the HL-10. An earlier attempt in the same vehicle by AF Major Gentry had failed when the rocket engine malfunctioned after launch. The flight envelope of the HL-10 was expanded gradually on successive flights by igniting two, then three, then all four of the chambers of the XLR-11 rocket engine. The first supersonic flight was accomplished on 9 May 1969, and by February 1970 the HL-10 had attained a maximum Mach number of 1.86 and a maximum altitude of 90,300 feet - - the fastest and highest of any of the lifting bodies (Reference Kempel, 1994).

The final two flights of the HL-10 explored the potential use of low thrust during the landing to produce an approach angle that was less steep, and more "airplane-like." For these tests the XLR-11 engine had been removed and had been replaced by three hydrogen peroxide emergency landing rocket engines (approximately 300 pounds of thrust each). A relatively large propellant tank was also installed. This allowed the pilot to light the rockets on final approach and thereby reduce the approach angle from about 18 degrees to only 6 degrees.

Both landings were made on the south lakebed runway number 17 which was seven miles long. The plan called for the pilot to maintain an airspeed of 280 knots while the HL-10 was on the 6-degree flight path with the rockets burning. At 200 feet altitude the pilot would shut off the rockets and lower the landing gear. He would then perform a deceleration and gentle flare to landing (Figure 5-6). Captain Pete Hoag flew both of these flights and his comments were quite negative. He reported that the shallow approach made it difficult for him to judge where the airplane would touchdown. The nose-high attitude during the entire maneuver forced the pilot to rely on the nose window, and its resulting poor depth perception, for a long time before touchdown.

Figure 5-6: HL-10 Landing

Pilot Bill Dana, the Hl-10 and the B-52 Fly-over

The largest deterrent to a low-thrust, rocket-powered landing, however, was the need to establish a safe procedure to land the airplane if the rockets did not fire. For the two tests, the pilot set up for an unpowered landing on the near end of the seven-mile runway. At some pre-determined altitude he would try the rockets. If the rockets failed to light, he would land close to the near end of the runway. If the rockets worked properly, he would establish a new aim touchdown point about four miles farther down the runway. This procedure was not very practical for a runway of normal length. The tests successfully pointed out the need for alternate-runway planning for any future entry system that required an engine to be started after entry, but before landing.

5.4.3.1 Handling Qualities: The handling qualities of the HL-10 on the second glide and all subsequent flights were quite good. The vehicle was susceptible to rather abrupt rolling motion in turbulence, as were the M2 and X-24A vehicles. It had exceptionally good inherent damping characteristics with the stability augmentation system disengaged. Even after several control system improvements, however, the HL-10 was still slightly sensitive in the pitch axis during the high speed final approach. A transonic pitch trim change occurred between 0.97 and 0.96 Mach number. The magnitude of the trim change was as expected, but the trim change was much more abrupt than predicted, apparently a result of an abrupt flow change or shock wave movement. (Additional pilot comments are included in Appendix B.)

5.4.3.2 Schedule and Pilots: A total of five pilots participated in the HL-10 program which included 13 glide flights and 24 powered flights.

Pilot	Glide Flights	Powered Flights
Bruce Peterson	1	0
Captain Jerry Gentry	7	2
John Manke	3	7
Bill Dana	1	8
Major Pete Hoag	1	7

(The schedule relative to the other lifting bodies is shown in Figure 2-1. A complete log of flights and pilots is included in Appendix C.)

5.5 Technology Lessons Learned

Some new and different lessons were learned through the successful flight testing of the HL-10. These lessons, when combined with lessons learned with the sister ship, the M2-F2/F3, provide an excellent starting point for designers of future entry vehicles.

5.5.1 Accidents/Incidents

There were no major incidents or accidents associated with the HL-10 test program beyond the rather frightening first glide flight. This safety record is a tribute to the dedicated engineers and pilots of the Lifting Body team.

5.5.2 Validations

After correction of the local tip-fin flow separation problem of the first glide flight, the flight test data validated wind tunnel predictions for stability and L/D from transonic down to landing speeds. The flat-bottom, negative-camber concept did produce a flyable and land-able vehicle which had an L/D that was 14 percent higher than the M2 half-cone concept (Reference Kempel, 1994). The additional complexity of the "boat-tail" control surfaces (added during the initial construction) proved to be a worthwhile investment and probably produced much of this difference in L/D.

The HL-10 was judged to be the best handling of the three original heavy-weight lifting bodies (M2-F2/F3, HL-10, X-24A). The HL-10 also achieved the highest speed and altitude of any of the lifting bodies.

5.5.3 Improvements

NASA FRC selected the HL-10 to explore potential advantages of powered approaches during landing because the vehicle had the best low speed handling qualities, and the smallest landing gear trim change, of the three early lifting bodies. The results of the tests were largely negative, however, and only two powered approaches were flown.

5.5.4 Problems Resolved

Although the first HL-10 glide flight was completed successfully, four serious problems were encountered. It is remarkable that, based on a single flight that lasted a mere three minutes and seven seconds, all of these problems were identified and subsequently corrected. The problems were directly or indirectly a result of misinterpretation of wind tunnel data. The tip fin stall was corrected through additional wind tunnel tests which duplicated the condition and allowed aerodynamicists to develop suitable modification options. A glove was added to the fin leading edge to improve flow over the tip fins at moderate and high angle of attack. Two different flight control vibrations were the result of errors in the predictions of both rudder and elevon effectiveness. These were suppressed by altering the flight control electronics. The high stick sensitivity was related to the error in control effectiveness and was corrected easily by altering the stick gearing. Participating engineers learned some valuable lessons on how to interpret wind tunnel data.

On one of the early captive flights a test of the propellant jettison system was planned. At the initiation of jettison a violent vibration began. Both the HL-10 pilot and the B-52 crew felt the vibration. It stopped when the HL-10 pilot turned the flight control stability augmentation off. Apparently the pulsing of the jettison had triggered a structural vibration in the B-52 wing/pylon/adapter that was sustained by the HL-10 flight control system. Subsequent captive jettisons were done with the stability augmentation off.

5.5.5 Unresolved Problems

The HL-10 program left a few problems unresolved. For example, the visibility through the nose window was distorted such that the depth perception near landing was poor (as indicated in Appendix B). Pilots adapted to this visibility restriction and landings were easily accomplished. A substantial ablation heat shield would be required over the entire nose area on a mission vehicle, however, and some other provision for pilot landing visibility would be required. This problem, which was similar for the HL-10, M2-F2/F3, was never seriously addressed during the Lifting Body program at Edwards.

The degradation in performance and stability that would be caused by the roughened surface of an ablative heat shield after entry was not factored into the Lifting Body flight test program. Subsequent analysis (discussed in Chapter 8) showed that this degradation was sufficient to raise serious questions as to the true land-ability of these vehicles following an actual entry.

5.6 Test Sites

The test sites for the HL-10 flight test program were the same as for the M2-F2/F3 program - all at AF and NASA properties at Edwards AFB. The two vehicles were stable mates in every sense of the word and used many common subsystems.

5.7 Current Status of Aircraft

Following an unfortunate handling accident - the vehicle was damaged while being repositioned for display in San Diego, California - the HL-10 was restored to display status. It was mounted on a pedestal in front of the NASA FRC building and was dedicated in a ceremony on 3 April 1990.

Photo of X-24A on B-52 Pylon

Chapter 6

The X-24A Program

Growing out of the AF's independent studies of lifting body concepts, the X-24A aircraft evolved from Martin's SV-5 configuration and other paper design studies. Both AF and NASA pilots participated in its flight testing between April 1969 and June 1971.

6.1 Theoretical Development

After the Martin Company lost the X-20 Dyna Soar competition to Boeing in 1958, the AF Space and Missile Systems Organization (SAMSO) continued to fund Martin to study some lifting body concepts that had been suggested during the Phase Alpha review. Martin engineers found that they could improve the L/D of the early conceptual lifting bodies at both hypersonic and subsonic speeds by making the body more slender and the lower surface flatter. After consulting with engineers at the AF Flight Dynamics Laboratory they introduced positive camber in the longitudinal axis (the opposite of that used on the HL-10). They also improved the L/D as well as the directional and longitudinal stability by canting the tip fins outboard slightly. A configuration named the SV-5 evolved from an earlier configuration, the A3-4, under the guidance of Hans Multhopp, a World War II German engineer (Reference Hallion, Vol. I, 1987). The X-24A was one adaptation of the SV-5 configuration.

6.2 Technical and Physical Development

John Rickey, an aerodynamicist at Martin, was assigned to refine the SV-5 configuration into a practical design that would be capable of both hypersonic entry and horizontal landing. Low speed wind tunnel tests were conducted throughout 1963. These tests led to several changes to the shape to enhance the transonic and low speed characteristics. The angle of the nose ramp was altered slightly to accommodate both high speed and low speed trim capability. Wind tunnel tests revealed the need for a center fin (splitter). The center fin would reduce adverse yaw if the upper flaps were to be used for roll control. Low speed tunnel tests also showed that extra care was required in the shaping of the airfoil for the outer tip fins in order to prevent fin stall at the higher angles of attack. As finalized in late 1963, the configuration incorporated both a center fin and a tip fin airfoil that included inward camber. (Both of these findings were to be rediscovered later during the initial M2-F2 and HL-10 test flights.)

Martin presented the final SV-5 configuration to the Air Force in December 1963 (about the time of Dyna Soar cancellation). The contractor suggested that the SV-5 was the best shape for future lifting body research.

The AF Space Division had considered the use of a maneuvering lifting body configuration, with an ablator heat shield, as a potential unmanned data-return capsule for orbital space missions. In 1964 a program called START (Spacecraft Technology and Advanced Reentry Test) was conceived to flight test the Martin SV-5 configuration.

The first phase of the START program was to boost a capsule-sized vehicle (approximately 7 feet in length) to orbital entry speeds and to demonstrate its thermal protection system and cross-range maneuvering capability. At this phase the vehicle was designated the SV-5D or PRIME (Precision Recovery Including Maneuvering Entry). The PRIME vehicle was to be recovered through deployment of a parachute, and air-snatching the chute over the ocean with a C-130 cargo airplane, which was the standard recovery mode in use at that time for ballistic data capsules (Reference Vitelli, 1967).

The second phase of the START program was to build a larger piloted vehicle (approximately 25 feet in length) and test it at transonic and landing speeds. The intent was to explore the land-ability of this same configuration (SV-5) for potential application as a space ferry vehicle for resupply missions to future military manned space stations. The larger, low speed vehicle was designated the SV-5P or PILOT (PIloted LOw speed Test). It later became the X-24A. The Air Force intended to add the PILOT vehicle to the AF/NASA Lifting Body test program at Edwards.

Martin conducted additional low speed wind tunnel tests on the SV-5 in 1964 to further optimize the configuration for a piloted vehicle. They chose to address the forward visibility problem by adding a canopy for the pilot. The initial canopy configuration was found to be destabilizing at subsonic speeds. After several iterations, a low profile canopy was developed which did not detract from stability.

A control law for the deceleration through the transonic region also evolved from these wind tunnel tests. It recognized the need for a large "wedge angle" (combined angle of the upper and lower flaps as well as an outboard flare to both rudders) to provide stability in this region. At landing speed the wedge angle needed to be reduced (boat-tailing of the rear of the vehicle) in order to increase the L/D.

The basic control system for the X-24A version of the SV-5 configuration (Figure 6-1) consisted of eight moveable surfaces located at the aft end of the vehicle. Pitch control was derived from symmetrical deflection of two upper flaps, or two lower flaps, depending on the flight condition. Differential deflection of these flaps provided the primary roll control. Pitch or roll commands that caused either lower flap to fully close resulted in control being transferred to the corresponding upper flap through a mechanical clapper mechanism. Two pairs of rudder surfaces (upper and lower) were deflected symmetrically as a bias feature with directional control being provided by asymmetrical deflection of only the upper rudder surfaces.

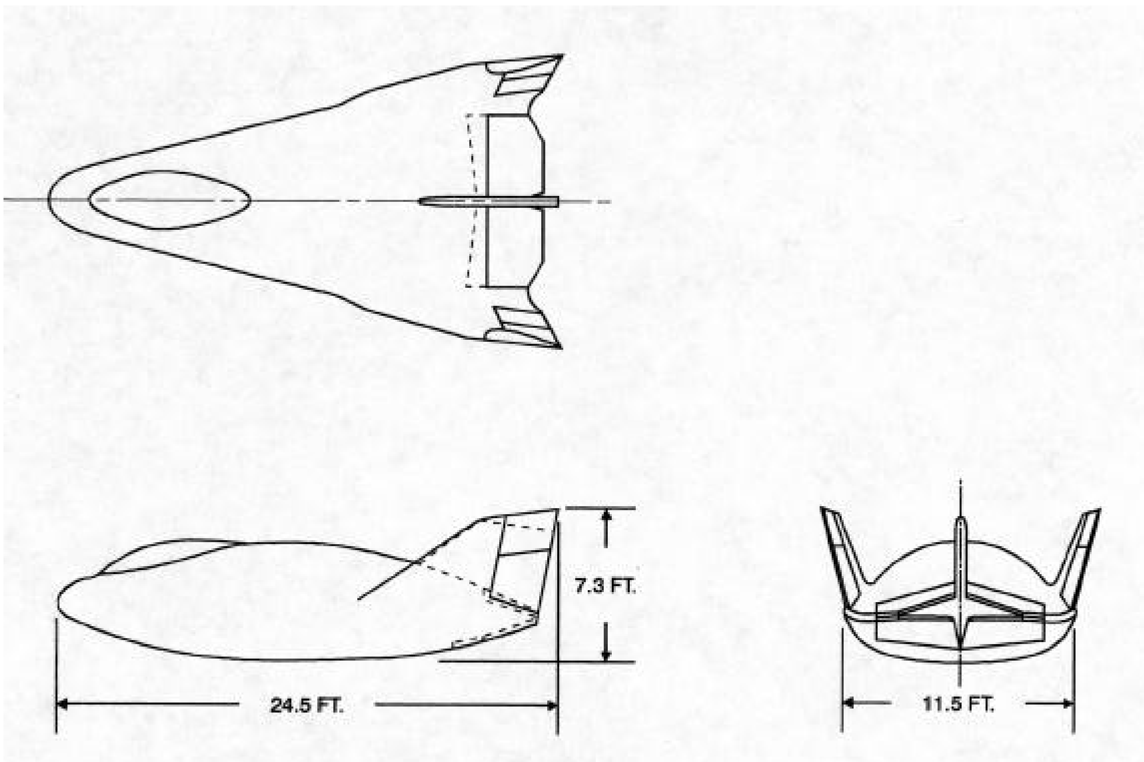


Figure 6-1: Three-View Drawing of X-24A

An automatic programming feature was designed into the vehicle to cause the "wedge angle" configuration change to occur automatically. When engaged, the upper flap position, rudder bias position, and elevator gearing were programmed to change with Mach number as the vehicle slowed through the transonic region.

As a backup to this non-redundant, automatic configuration-change feature, the X-24A was equipped with a manual "upper-flap bias" feature operated by a spring-loaded switch in the cockpit. When activated this switch symmetrically and simultaneously altered the positions of the upper and lower flaps and altered the stick gearing. The combined bias feature was designed to minimize the total trim change. This upper-flap bias feature could also create two discrete configurations - one for low speed (subsonic) and one for high speed (transonic) flight (Figure 6-2).

Figure 6-2: X-24A Control Surface Configuration, Subsonic

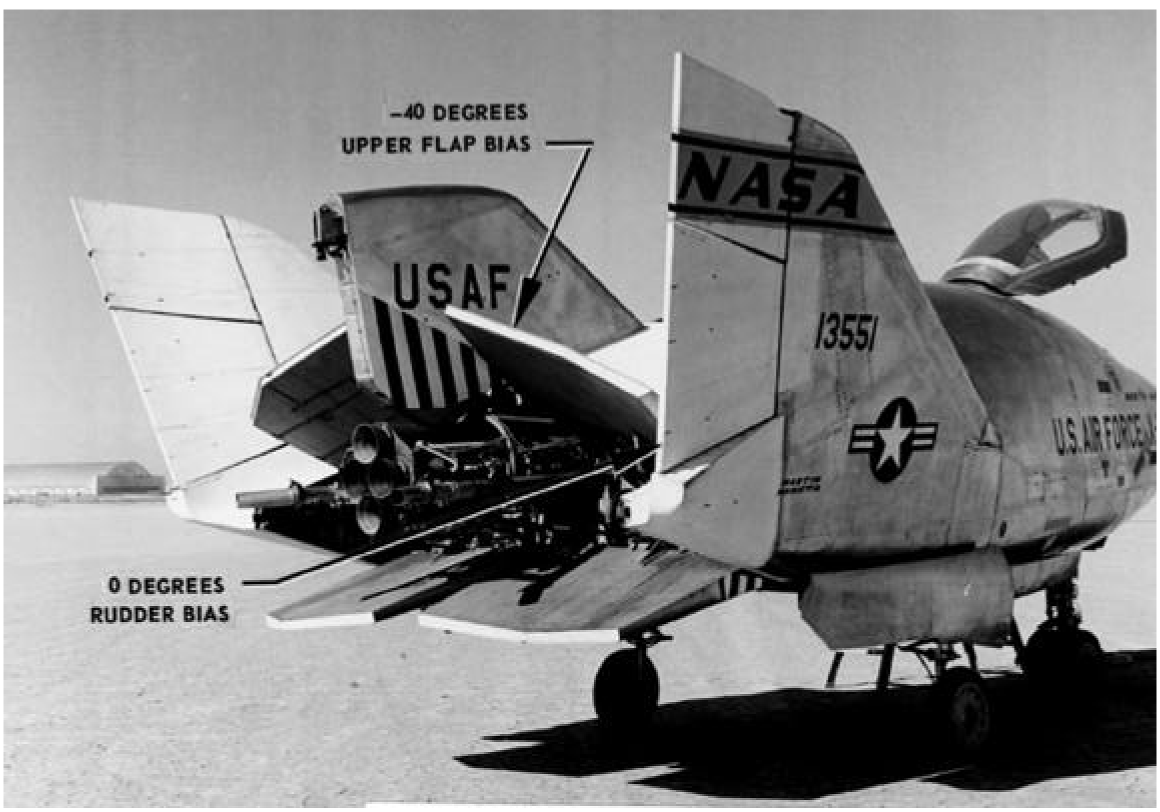


Figure 6-2: X-24A Control Surface Configuration, Transonic

Like the M2-F2, the X-24A was equipped with an aileron-to-rudder interconnect. The interconnect ratio (KRA) was automatically programmed with angle of attack and Mach number. The automatic schedule could be biased up or down by the pilot.

The X-24A used a triply redundant, three-axis, stability augmentation system. The damper signals were mechanically added to the pilots commands.

6.2.1 Funding and Procurement Philosophy

The START program was approved in November 1964 in a decision boosted by the demise of the X-20 Dyna Soar program. Work started immediately to build the PRIME vehicle and test it in the hypersonic environment. Approval to proceed with the PILOT program lagged behind. In September 1965 direction was received from the Secretary of the Air Force to procure a single rocket-powered vehicle. The same directive letter transferred management of the low-speed PILOT program from the START office within the USAF Space Division at El Segundo, CA, to the USAF Aeronautical Systems Division (ASD) at Wright Paterson AFB, OH (Reference Vitelli, 1967).

For some people at ASD this decision was a bitter pill to swallow. They had been managing the X-20 Dyna Soar program and had been strong advocates of winged, high L/D entry configurations. They had lost the winged battle to the lifting body advocates. Now they had been tasked to manage and support a lifting body flight test effort. Some key members of the AF Flight Dynamics Laboratory, such as Al Draper, had been studying a different class of lifting bodies with hypersonic L/D as good as, or better than, the winged vehicles. They viewed the SV-5P program as a foot-in-the-door to gain a practical understanding of the low speed characteristics of lifting bodies.

The program was officially transferred to ASD in October of 1965, and Bill Zima from the AFFDL was assigned as the ASD Program Manager. Northrop and Martin submitted proposals to the AF to build a single SV-5P vehicle. Martin had the aerodynamic background and wind tunnel data on the vehicle, while Northrop had recent experience building the M2-F2 and HL-10 vehicles. In March 1965 Martin was selected by the AF to build the vehicle and the designation was changed from PILOT, or SV-5P, to X-24A, an experimental designation.

6.3 Construction

Martin constructed the X-24A in its Baltimore plant between April 1966 and August 1967. The AF provided all funding for its construction.

6.3.1 Management and Organizational Structure

The Martin Company was a closed union shop. The Government/Contractor team relationship was therefore not as close during construction of the X-24A as it had been with the Northrop/NASA team during M2-F2 and HL-10 construction. The vehicle was constructed in a small shop area at the Martin facility in Baltimore, Maryland. The 2000-mile distance between the manufacturing site and the flight test site at Edwards further inhibited the formation of a close team. NASA FRC assigned Norm DeMar as the Operations Engineer for the X-24A. He would be responsible for scheduling and maintaining the vehicle after delivery. A few NASA technicians were on-site in Baltimore during the manufacturing process. They were allowed to install some wiring, but often were frustrated by their inability to make small changes that they knew would be required later. In spite of these differences, the construction of the X-24A proceeded on schedule.

All of the earlier proposals for the PILOT program had included more than one vehicle, some as many as four (two rocket-powered and two jet-powered). When contract approval specified only one rocket-powered X-24A vehicle, Martin management elected to construct two additional structural shells with company funds. These shells were configured initially for jet power and were designated SV-5J. Martin hoped to sell them either as backup vehicles for the X-24A, or as jet-powered trainers to the Air Force Test Pilot School at Edwards.

By the time the X-24A was delivered to Edwards in August 1967, the AF Lifting Body team had assembled and checked out a simulation of the vehicle. Using the simulator, the lifting body team members briefly explored the potential use of the jet-powered version (SV-5J) for either research or as a trainer. Results of this study confirmed earlier reservations about the value of the jet-powered vehicles. They would be severely underpowered and flight safety would be compromised during the ground takeoff and initial climb (for any kind of engine malfunction). Some consideration was given to air-launching the jet version, but little appeared to be gained over the planned flights of the X-24A. The AFFTC Lifting Body team recommended against AF procurement of the SV-5J vehicles except as backup to the rocket-powered X-24A.

6.3.2 Government-Provided Instrumentation and Subsystems

Like the M2-F2 and HL-10, the X-24A used off-the-shelf items, such as landing gear, ejection seats, control surface actuators, and hydraulic pumps, from other programs for most of the subsystems (Figure 6-3). These components were procured by the AF Program Office or through Martin supply channels, as appropriate, and were delivered to Baltimore for installation by Martin technicians. NASA FRC technicians prepared the flight-test-unique subsystems, such as research instrumentation, rocket engines and associated support hardware, for installation in the X-24A, but this hardware was not installed until after vehicle delivery to Edwards.

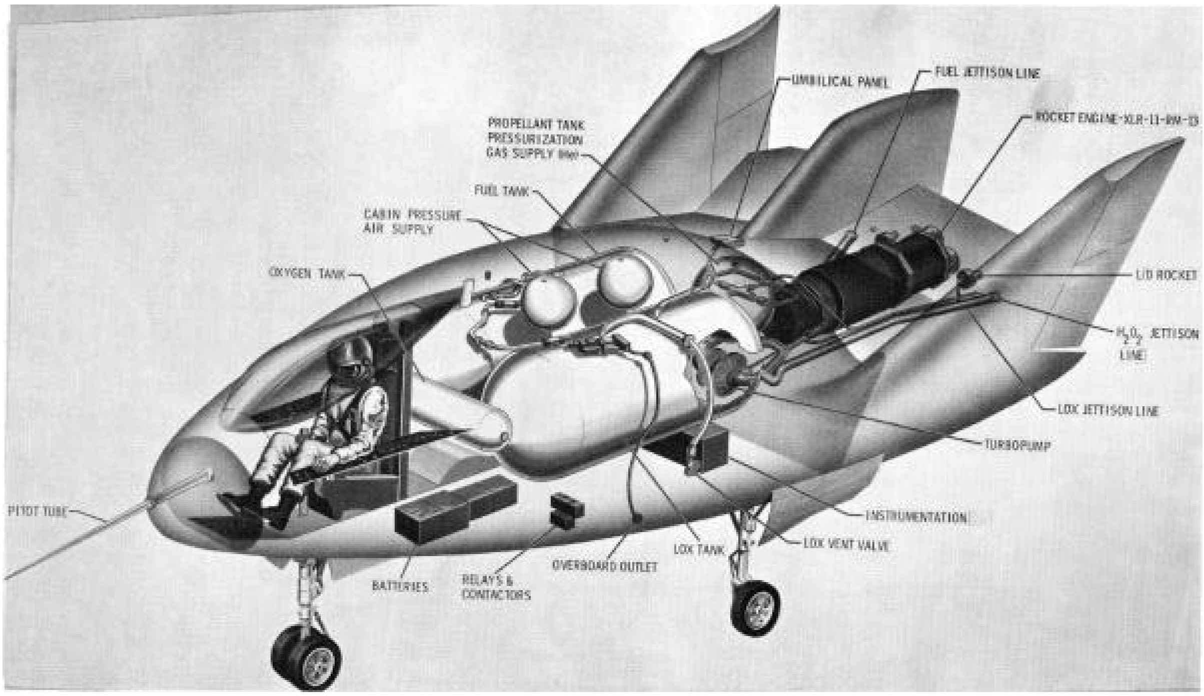


Figure 6-3: X-24A Cutaway Drawing

The primary difference between the Northrop and Martin contractual processes was the additional time required after delivery of the vehicle to NASA FRC. That time was needed for the installation and calibration of the Government-supplied flight test equipment and instrumentation. The cockpit had to be completely dismantled in order to rework the necessary flight test instrumentation and controls.

6.3.3 Propulsion System Test Stand

As part of the contract, Martin also constructed a Propulsion System Test Stand (PSTS) for the X-24A. This unit duplicated all of the tankage and propulsion system components of the X-24A on a test cart (Figure 6-4). Development of the propulsion system, including actual engine runs, could then take place in parallel with other vehicle preparations. This alleviated, to some degree, the schedule impact of the delayed instrumentation installation.

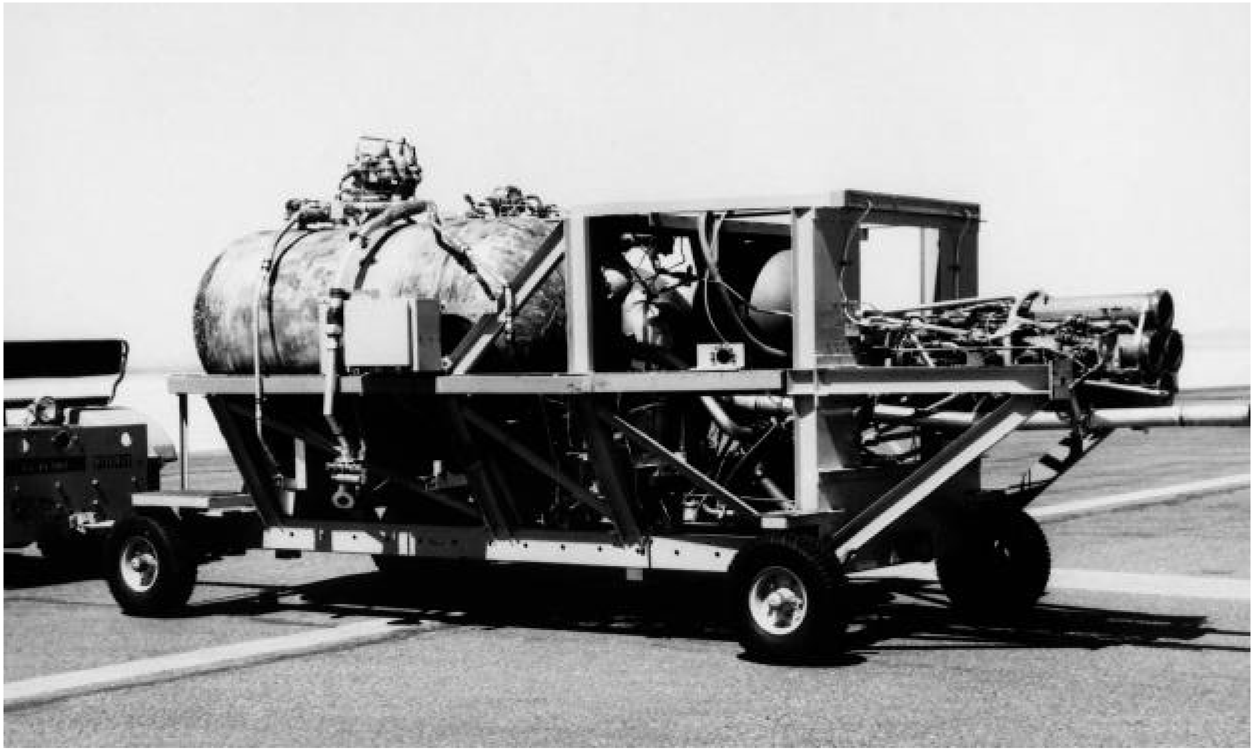


Figure 6-4: X-24A Propulsion System Test Stand

6.3.4 Schedule and Delivery

Martin had begun construction of the X-24A following an initial design review in April 1966. The AF accepted the vehicle in Baltimore on 3 August 1967. For transportation, Martin removed the tip fins and mounted the vehicle on pallets. It was flown to Edwards in an AF C-130 cargo airplane and arrived on 24 August 1967 (Reference Armstrong, 1972).

6.3.5 Wind Tunnel Tests

The launch transients produced by the B-52 flow field were tested with a small X-24A model in the Langley 7X10-foot High Speed tunnel. The pylon adapter carry angle was also established during these tests. Launch transient results were similar to the M2-F2 and HL-10 - an abrupt, but controllable right roll after launch.

The AF/NASA FRC flight test team carefully reviewed the available wind tunnel data on the X-24A in light of the flight test results from the early M2-F2 and HL-10 flights. Additional small scale wind tunnel tests were requested to fill in gaps in the data, partly in order to avoid a repeat of the HL-10 first flight experience. These tests were also conducted at the Langley 7X10 foot High Speed tunnel.

After the arrival of the X-24A at Edwards, NASA FRC mechanics and technicians reinstalled the tip fins, then began the installation of subsystems and instrumentation. By 19 February 1968 the vehicle was ready for testing in the 40X80 foot full-scale wind tunnel at Ames. Test results confirmed the stability and performance predictions from earlier scale model tests. Additional tests were performed with a simulated ablator roughness applied to the vehicle (Figure 6-5). A water-soluble glue was sprayed on the airplane, and a wire mesh screen was laid over the surface to simulate the pattern of the ablator honeycomb. A coarse sand was then sprayed over the surface. When the glue was dry the wire mesh was removed leaving a rough protruding pattern on the surface. It was hoped that these results could be correlated with the effects that were observed on the PRIME vehicle following an actual entry. The results from the full-scale tunnel tests showed a reduction in maximum L/D of 20 percent and some degradation in stability caused by surface roughness. Any thoughts of flying the vehicle with the simulated ablator roughness were quickly dismissed.

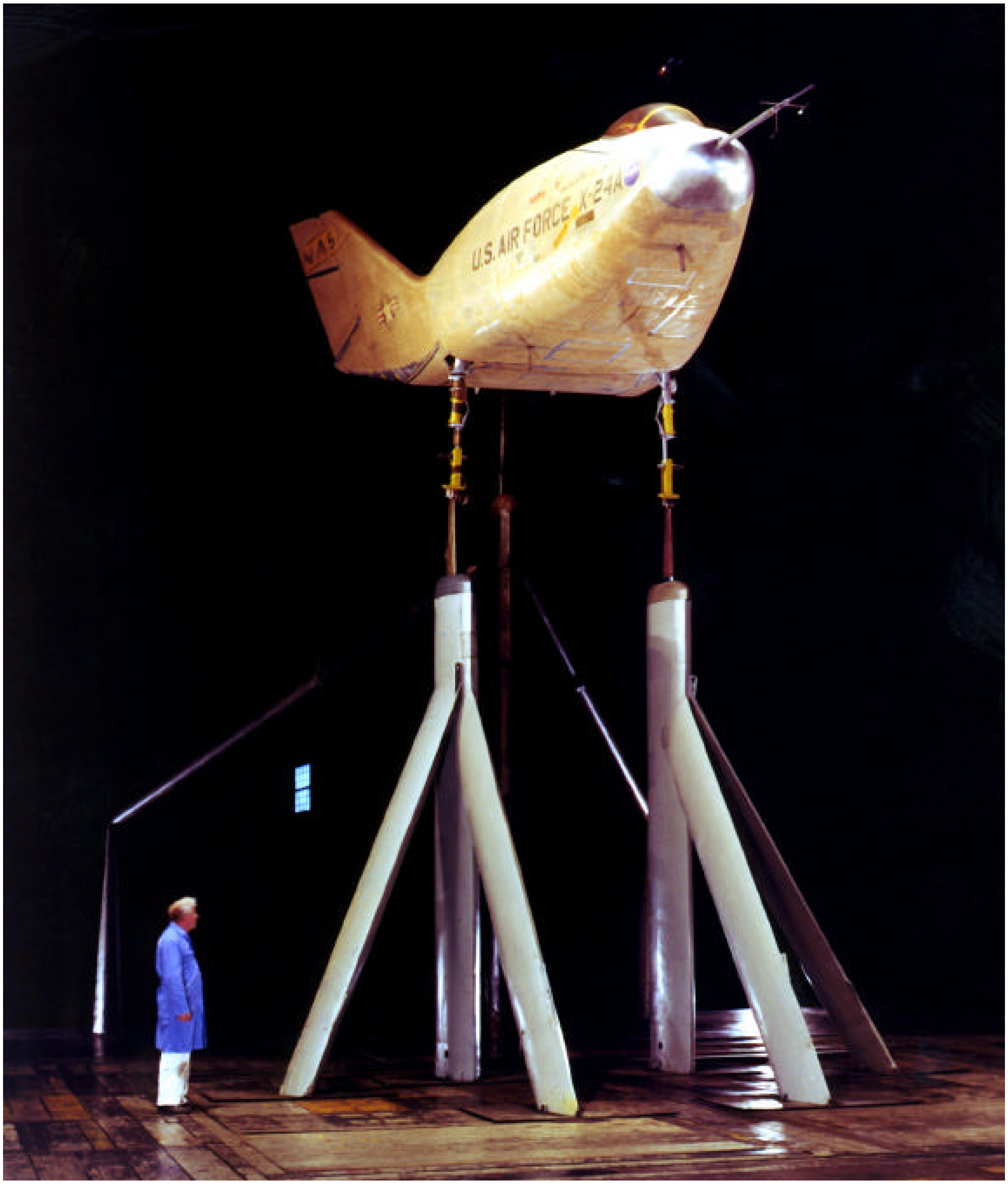


Figure 6-5: X-24A in Full Scale Tunnel with Simulated Ablative Coating

6.3.6 Ground Tests

The X-24A inertias were measured by balancing the vehicle on knife edges supported by calibrated springs (Figure 6-6) (Reference Retelle, 1971). The analysis of flight test stability and control data required these measurements.

Figure 6-6: X-24A Iyy Inertia Test Setup

Ground tests of the flight control system produced some changes to the electronics. Previous experience with the M2-F2 and HL-10 had resulted in a more seasoned test procedure and quick isolation of potential self-induced vibrations. These ground tests also isolated a rather large deadband in the pitch axis (2 degrees of flap travel) when the control was being mechanically transferred from the lower to the upper flap. The effect of this deadband on the handling qualities, especially near touchdown, was unknown. Ground tests also showed the possibility of a divergent vibration if the controls were maintained in the deadband region for more than about three seconds. This finding resulted in a reassessment of the control laws for the first flight to insure that the flaps would not be operating in the crossover region at landing (Reference Kirsten, 1972).

The X-24A was the first of the lifting bodies to be equipped with nose wheel steering. The M2-F2 and Hl-10 had castering nose gear; they used differential braking to steer on the lakebed after landing. Several low speed taxi tests of the X-24A were performed on the taxiway and also on the lakebed. These assessed the usability of the nose wheel steering system. The nose wheel steering unit on the X-24A came from a T-39 aircraft and had been originally designed for low speed taxiing. Because of the very high expected touchdown speed of the X-24A (about 200 knots ground speed), the steering was far too sensitive for use during the landing rollout. Since the system had no redundancy and a failure could have led to a roll-over accident, a decision was made to not use the nosewheel steering capability.

6.4 Flight Testing

The X-24A was tested in gliding and powered flight between April 1969 and June of 1971. Twenty eight flights were successfully completed.

6.4.1 AFFTC/Dryden Test Team

The original AFFTC/NASA FRC Memorandum of Agreement (Appendix D) only mentioned the M2-F2 and HL-10. It had been assumed from the onset that the X-24A would be treated as a third vehicle in the program when it arrived, and that the assigned responsibilities would remain the same. Shared responsibilities of piloting and engineering would also continue with the exception that the AF engineering team would concentrate on the X-24A and would hold primary responsibility for the documentation of test results on that vehicle. An addendum to the Memorandum of Agreement was signed in October 1966. It formally added the X-24A to the joint program (Appendix D).

The AF engineering team of about eight engineers of varying experience level and headed by Robert Hoey had been working jointly with the NASA FRC engineers in the planning and data analysis of the M2-F2 glide flights. The team members had, in fact, gained valuable experience while programming and utilizing the AFFTC simulation of the M2-F2 to support the first 15 glide flights. When the X-24A program was approved, they immediately began to program an engineering simulation (Figure 6-7). They also prepared to oversee the ground and flight testing of the new vehicle. When the vehicle was delivered to Edwards, Johnny Armstrong, an AF Flight Planning Engineer on the X-15 program, was reassigned as the AFFTC Program Manager for the X-24A program.

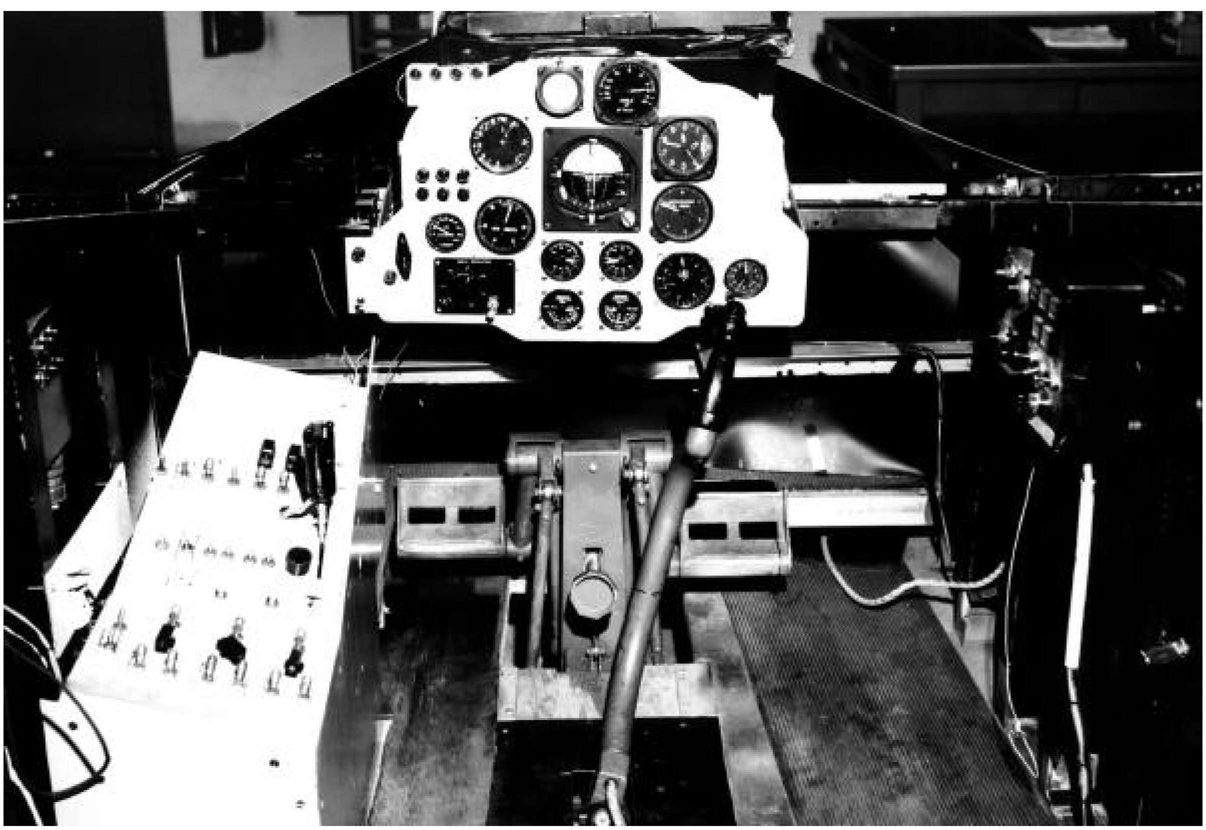


Figure 6-7: X-24A Simulator Cockpit

Throughout the X-24A/B flight test program, the AFFTC engineering team members were in an unusual position relative to their responsibilities on the program. Since NASA FRC held flight safety responsibility for all Lifting Body operations, the AFFTC management paid little attention to the day-to-day activities of these engineers. AFFTC management was far more concerned (and rightly so) with the variety of other high-risk AF flights at Edwards that required close safety monitoring and supervision. At NASA FRC, however, engineering and maintenance personnel viewed the AF engineering team as the final authority on activities relating to the X-24A, even though they were outside the NASA chain of command. This placed an unusually high sense of personal responsibility on the AF engineers. They cross checked and double checked their findings and recommendations before taking them to NASA FRC. This show of confidence by both the AF and NASA management staff created a very high morale and sense of job satisfaction within the team members. The situation permitted a much more rapid response to problems than was possible within the normal chain of command at either NASA or the AF.

6.4.2 Use of Fixed Base and Airborne Simulators

The X-24A program continued the trend toward an increased reliance on fixed base simulators for conducting tests on rocket-powered vehicles. The complex automatic control laws, proposed and designed into the vehicle by Martin, were found to be unsuitable for the initial flights. The effects of the large crossover deadband mentioned earlier was a concern, as were the lack of redundancy and an inability to accomplish an appropriate practice flare at altitude. A simpler first flight control law was devised on the simulator wherein the pilot manually changed the flap configuration. This control law was used for the low speed portion of the early X-24A flights.

The F-104 airplane was used to simulate (and chase) the X-24A landings. The M2-F2 and HL-10 flights continued to show the strong effects of upper altitude winds on the landing task, especially if a spot landing was being attempted. The X-24A test pilots made F-104 flights during the early morning hours immediately prior to each actual X-24A flight. The purpose of these flights was to allow the pilot to experience the actual upper altitude wind effects on the planned landing pattern.

6.4.3 Glide Flight Program

Captain Gentry flew the first glide flight of the X-24A on 17 April 1969 (Figure 6-8). The practice flare at altitude was performed successfully. Gentry noted some lateral sensitivity at high speed on his final approach and he related this to the uneasy feeling of the M2-F2 at the same flight condition. He elected to slow down from 300 knots to 270 knots and then fire the emergency landing rockets at the start of flare. When the landing gear was extended, a rather abrupt nose-down trim change was experienced (as expected), but a normal landing was performed.

Figure 6-8: X-24A Glide Flight

A review of the flight data showed that a malfunction had occurred in the aileron-to-rudder interconnect electronics, and this was considered as the most likely cause for the lateral sensitivity problem.

On the second flight (with the interconnect working normally) the pilot again experienced an uneasy lateral sensitivity and rolling motions on final. Again he slowed down and used the emergency landing rockets during the flare and landing.

Prior to flight three, a considerable amount of simulator investigation took place and several changes to the flight control system, both electronic and mechanical were accomplished. It appeared that there was a significant error in the wind tunnel prediction of the differential lower flap effectiveness in yaw. The AF flight test team felt that the final approach lateral handling problem was a combination of incorrect control settings due to this prediction error, and an unnatural vehicle response to light turbulence (referred to as "poor riding qualities").

At this juncture of the Lifting Body program, the M2-F2 had been damaged in a serious accident, the first HL-10 flight had been frightening, and two X-24A flights had been marginally successful. Both the AF and NASA safety organizations scrutinized the flight plans and readiness in detail. There were also cross reviews by the individual engineers within the Lifting Body program.

After several briefings and reviews Gentry was cleared to make the third glide flight in the X-24A. The launch occurred 45 seconds prematurely, which allowed the pilot to fly a normal flight, but resulted in an approach and landing to a different lakebed runway. Again the landing rocket was used at the flare. This time, however, the pilot felt more comfortable during the approach and the rocket was used more for energy management purposes than for avoiding poor stability.

The wind tunnel mis-prediction was apparently caused by flow interference between the wind tunnel model mount and the lower flaps. The riding qualities concern persisted for several flights until the pilots became accustomed to the small sharp rolling motions (due to high dihedral effect) that accompanied flight through light turbulence or wind shear. Nine glide flights were accomplished by two pilots before the X-24A was considered ready for powered flight.

6.4.4 Powered Flight Program

Powered flights for all of the Lifting Bodies were a challenge to the flight test team because the vehicles were all designed for entry (decelerating flight). During entry a moderate amount of drag can be helpful. By flaring the aft end of the vehicle, an increase in stability could be achieved (often referred to as "shuttlecock stability"). For the X-24A this drag and stability were characterized by the position of the upper flap; the larger the angle, the higher the stability and drag. During an actual entry of an SV-5 shape, the upper flap deflection was designed to gradually decrease from 55 degrees at Mach 2, to 35 degrees at Mach 1.

Rocket-powered acceleration was an unnatural mode of flight for the SV-5 shape. In order to achieve supersonic speeds, it was necessary to keep the drag as low as possible during the powered phase of flight. The trick was to trade off the desired lower drag (achievable with smaller flap deflections) with the undesired reduction in stability.

This trade off study was a perfect example of the use of engineering simulators to support flight testing. Simulator studies showed that powered flight with the upper flap held constant at 35 degrees would still retain adequate stability margins at transonic and supersonic speeds. After a couple of subsonic powered flights it was discovered that the rocket engine plume was causing an additional, and unexpected, reduction in directional stability. In order to regain the lost stability with the rocket engine running, the upper flap deflection was increased from 35 to 40 degrees. The additional drag resulted in a reduction in the expected maximum attainable speed from about Mach 1.8 to about Mach 1.7.

The first powered flight of the X-24A was flown by Gentry on 19 March 1970 (Figure 6-9). Following that flight, and the subsequent alteration to the upper flap setting, the envelope expansion program proceeded smoothly.

Figure 6-9: X-24A Powered Flight

6.4.4.1 Handling Qualities: After the flight control system settings were optimized, the handling qualities of the X-24A were quite good. It exhibited some transonic pitch trim changes similar to the HL-10, but these were easily controlled. When the rocket engine was operating, there was an unpredicted pitch trim change as well as a measurable reduction in lateral-directional stability. This was surmised to be the influence of the engine exhaust plume on the flow around the rear of the vehicle (Reference Hoey, 1973).

Pilots commented on occasional spurious and uncommanded rolling disturbances, or upsets, during the climb. These upsets were small and barely apparent in the data, but were nevertheless a concern since they were occurring in the transonic flight region (0.85 Mach number). It was suspected that these mild upsets during steep climbs were a result of passing through wind shear but they did not seem to correlate with the daily balloon wind surveys. The confirmation of wind shear as the cause did not occur until the X-24B program (discussed in Chapter 7).

The automatic programming feature of the flight control system, which was designed to gradually reduce the wedge angle as the vehicle decelerated, was engaged on one transonic flight. It functioned well but was not used extensively because the system lacked redundancy and because the programming features were not consistent with the requirement to systematically gather flight test data in fixed control configurations. Instead of allowing the automatic system to change the configuration, the transition from a high wedge angle to a low wedge angle was accomplished as a single, pilot-initiated event (referred to by the pilots as the "close-up" or "configuration change") after the vehicle was subsonic. This ability to momentarily increase or decrease the wedge angle, and thus the drag, by simultaneously increasing or decreasing the upper and lower flap deflections was used as a speed brake feature during the landing pattern.

The X-24A had a significant nose-down trim change when the landing gear was extended, similar to the M2-F2. (Additional pilot comments are included in Appendix B.)

6.4.5 Schedule and Pilots

Three pilots flew 28 flights in the X-24A between 17 April 1969 and 4 June 1971. A maximum altitude of 71,400 feet and a maximum speed of Mach 1.60 were reached.

Pilot	Glide Flights	Powered Flights
Captain Jerry Gentry	8	5
John Manke	1	11
Major Cecil Powell	1	2

(The schedule relative to the other lifting bodies is shown in Figure 2-1. A complete log of flights and pilots is included in Appendix C.)

6.5 Technology Lessons Learned

The X-24A configuration evolved from a somewhat different path than the NASA in-house process that conceived the M2 and HL-10 configurations. A new set of lessons was learned relative to lifting body reentry vehicles.

6.5.1 Accidents/Incidents

There were no serious accidents involving the X-24A. On the third glide flight, flown by Gentry, a switching error by the B-52 flight crew caused the X-24A to be launched about 45 seconds earlier than planned. Luckily all systems were operating normally at that point in the countdown. The pilot's casual comment on the radio - "I've been inadvertently launched" - caused a momentary scramble in the control room to choose the best landing runway. The flight was completed successfully. The landing occurred on an alternate runway on Rogers lakebed.

On the seventeenth powered flight only two of the four rocket chambers ignited and the pilot flew a planned alternate flight profile. The landing was normal but inspection of the vehicle showed evidence of a fire in the engine compartment. Several instrumentation wires and aluminum pressure-sensing lines were damaged by the fire. One upper flap was warped slightly and was traded with a flap from one of the SV-5J vehicles at Martin. Engineers were concerned that the fire could have tempered and embrittled the engine mount, so the engine and mount were removed from the airplane. John Cochrane, the on-site representative from Martin, owned a Piper Comanche (single-engine light aircraft). Cochrane and DeMar loaded the engine mount into the Comanche and flew it to Denver where the engine mount was annealed in one of Martin's heat-treatment ovens.

All engine instrumentation showed that the engine had performed normally during the flight so the source and cause of the fire were puzzling. Jettison lines were extended and canted outboard. No further fires occurred on the X-24A.

Subsequently, however, two similar engine fires occurred on the M2-F3. Some clever detective work isolated the cause of the three fires. The normal procedure was to jettison any remaining propellants shortly after engine shutdown to lighten the vehicle as quickly as possible and minimize any hazards (Figure 6-10). In cases leading to fires, an after-fire (slow burning of fuel remaining in the engine chambers) had sustained itself in the base area of the vehicle. Both fuel and LOX jettison lines were also located in the base area. When propellant jettison was initiated the after-fire ignited the fuel and oxidizer which were mixing in the turbulent region between the upper and lower flaps. The problem had not been seen on earlier flights since the normal engine shutdown altitude was considerably higher than that for a two-chamber flight. There was insufficient oxygen in the atmosphere to sustain the after-fire at the higher altitudes.

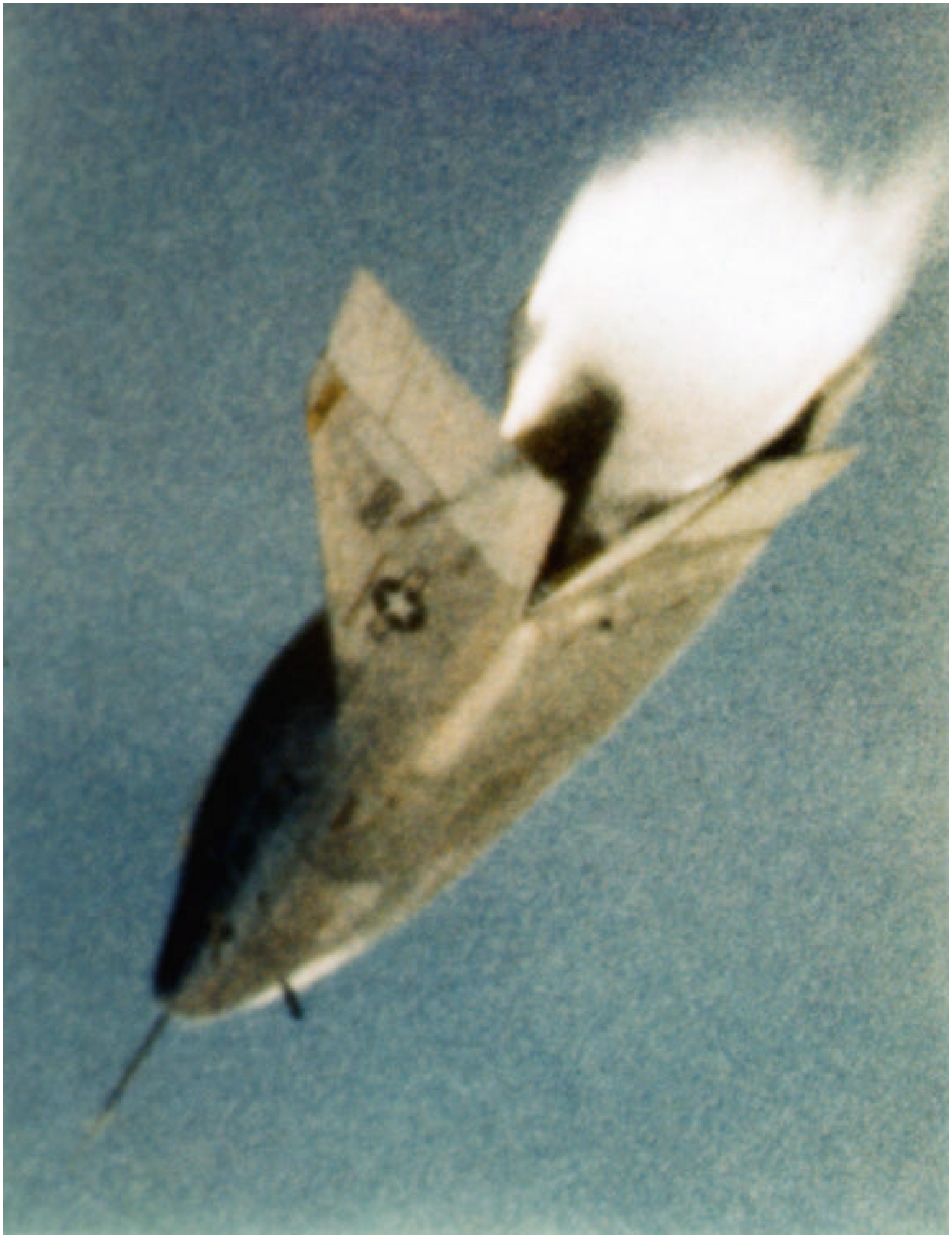


Figure 6-10: X-24A In-Flight Jettison

6.5.2 Validations

The X-24A version of the SV-5 configuration was farther along in the evolutionary process than were either the M2-F3 or HL-10 at the end of the lifting body program. The center fin requirement (M2-F2 deficiency) and the criticality of the tip fin airfoil (HL-10 deficiency) had been resolved earlier in the design phase. A cockpit configuration with suitable visibility for landing as well as practical possibilities for thermal protection during entry had also been developed, and it was used on the X-24A.

With the exception of the mis-prediction of differential lower flap effects (mentioned earlier), the wind tunnel predictions for the X-24A were very close to flight measurements. In-flight movies of flow-direction "tufts" and some intensive flight testing in the transonic region showed some small but discrete changes in stability that were related to abrupt changes in the flow on the inside of the tip fins as Mach number changed. These characteristics were generally predicted correctly by the wind tunnels, but the data had been interpreted as smooth Mach effects and not small, abrupt discontinuities as seen in the flight data.

The L/D of the X-24A in its optimized configuration was slightly above 4.0 in the low speed region. This high L/D was not realizable during landing, however. The preflare airspeed of 300 knots and 0.5 Mach number dictated a larger wedge angle for stability. By the time the vehicle had flared and slowed to a low Mach number flight condition, the landing gear had been extended, thus reducing the L/D significantly.

6.5.3 Improvements

The development of a simplified control law allowed flight test data to be gathered in a systematic manner. It also created a speed brake option which was useful to the pilot in establishing an accurate landing pattern.

Several specific tests were conducted to establish confidence in the low speed controllability using the upper flap for both lateral and pitch control. Once this confidence was established, the normal upper flap setting for landing was changed from 21 degrees to 13 degrees. This reduction in wedge angle improved the L/D during the high speed portion of the approach, but primary pitch and roll control remained on the lower flaps. When the landing gear were extended, the large, and almost instantaneous, trim change allowed a rapid crossover from the lower flap to the upper flap for control of the final landing.

The large nose-down trim change due to landing gear extension came from two sources. The nose gear door was a flat plate that pivoted forward 90 degrees at extension and thereby caused a significant interruption of the flow over the lower surface. All of the landing gear struts pivoted forward when they were extended and thus produced a significant forward movement of the center of gravity. During the test program Martin devised a modified hinge for the nose gear door that allowed it to remain at a 45-degree angle when in the open position. This produced a small reduction in the landing gear trim change.

6.5.4 Problems Resolved

The lateral sensitivity that was observed on the first two flights was corrected by relatively minor changes to the flight control system. The unusual riding qualities in turbulence were partly responsible for the sensed lateral problem. Pilots became less concerned about this effect as they gained experience in the vehicle.

A longitudinal trim change was observed to occur whenever the engine was ignited or shut down. This trim change was assumed to be a result of a change in the flow around the aft surfaces when the rocket plume was present. The effect was easily controllable and no physical changes were required to compensate for the trim change.

Small lateral disturbances were noted during the powered climb phase on some of the X-24A flights. These upsets were suspected to be a result of wind shear but could not be correlated with balloon wind surveys. The high dihedral effect was thought to cause the vehicle to respond to these upsets with small rolling motions. The correlation with atmospheric wind shear was validated later during the X-24B test program (See Chapter 7). The engine after-fire problem was solved by extending the fuel jettison lines and canting them outboard.

6.5.5 Unresolved Problems

The landing gear legs on the X-24A were quite long, resulting in the center of gravity of the vehicle being high off the ground relative to the width of the main landing gear. As a result the X-24A had poor crosswind landing characteristics. The vehicle would heel over uncomfortably during the rollout on the lakebed if the pilot tried to steer straight using differential braking and aileron. If the pilot did not attempt to steer, the vehicle would tend to drift downwind off the marked runway. The use of nosewheel steering would have provided only a small improvement to this characteristic since the problem was mostly related to the landing gear geometry.

As mentioned earlier, the nose wheel steering system was tried on early taxi tests. It was non-redundant and too sensitive and so was not developed into a workable system. It did, however, set the stage for the selection and development of a nose gear steering system for the X-24B.

The nose-down landing gear trim change on the X-24A was alleviated to some degree by the modified nose gear door hinge, but it continued to be a nuisance to the pilots. The need to minimize the landing gear trim change was not obvious during the design of the lifting bodies. The large drag penalty of the landing gear created a need for late (low altitude) and rapid (about 1 second) gear deployment. The combination magnified the effect of even a small trim change. Although there was no easy way to correct the problem on the X-24A, the lesson was applied to the X-24B design.

The latter phase of the X-24A program was affected by a series of XLR-11 engine problems that resulted in several aborted launches and flights with partial engine runs. These engine problems were never totally solved, although continual progress was being made. The decision to modify the airplane into the X-24B had already been made at the time that flight 28 was completed with another partial engine run. The AF engineering team evaluated the data benefits to be gained from attempting to repeat that flight against the ever-present risk of damage and further delay, and decided to end the X-24A flight test program.

The effect of ablator surface roughness on stability and L/D was one of the few remaining unsolved problems of this configuration.

6.6 Test Sites

Upon delivery the vehicle was taken directly to the NASA FRC Hangar (Building 4802). There it was reassembled and maintained along with the other two lifting bodies. A NASA maintenance crew chief, Charlie Russell, and an instrumentation engineer, Bill Clifton, were assigned to the X-24A, as was Operations Engineer Norm DeMar. The other NASA facilities used for the M2-F2 and HL-10 vehicles were also used to support the X-24A test program.

The X-24A Propulsion System Test Stand was unique to the X-24A and was maintained and operated by the AF Rocket Shop at the Rocket Engine Test Facility at Building 1928.

All simulation activities in support of the X-24A were conducted at the AFFTC Simulator Lab in Building 1408. In that building was the hybrid analog/digital simulator equipment ordered in June 1963 to support the X-20 Dyna Soar program. Digital computers of that period were not fast enough to do a complete real-time simulation, but the digital accuracy was needed to solve the orbital equations of motion for the Dyna Soar mission. By the time the new equipment arrived in July 1964, the Dyna Soar had been cancelled. The orbital equations of motion for Dyna Soar had already been programmed. The simulation continued to use these precise calculations for simulating the X-15A-2 and M2-F2 as well as the X-24A, X-24B and other vehicles that would follow, even though the degree of precision required for orbital calculations was no longer necessary (Reference Lyons, 1967).

6.7 Current Status of Aircraft

The X-24A was modified to become the X-24B. The vehicle resides within the X-24B currently on display at the AF Museum at WPAFB. Martin eventually donated their two SV-5J structural shells to the Air Force. Neither one was ever flown. Both were configured to simulate the X-24A (rocket-powered version). One of these, marked as the X-24A, is on display next to the X-24B in the WPAFB Museum (Figure 6-11). The other is displayed on an outdoor pedestal at the Air Force Academy in Colorado Springs, Colorado.

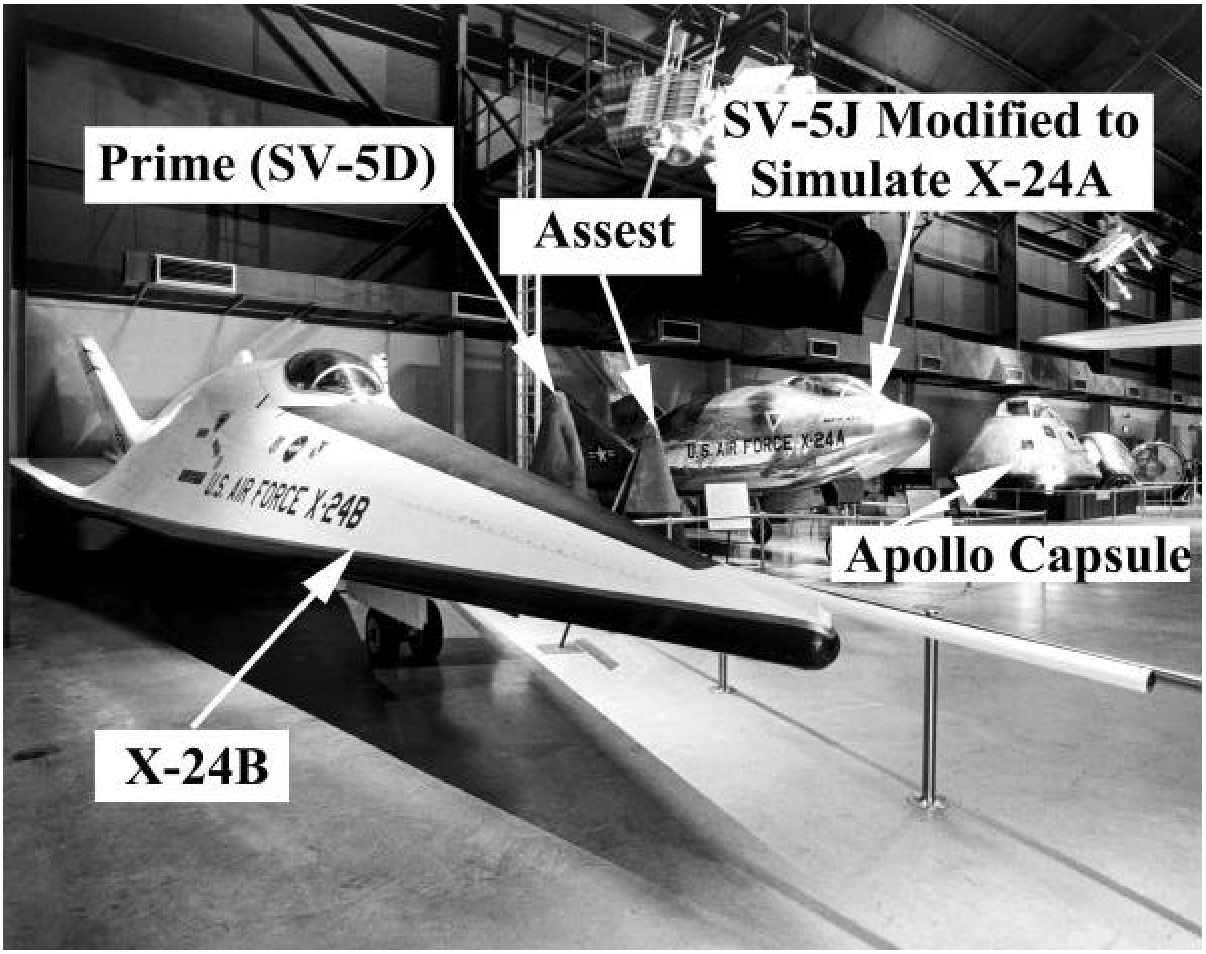


Figure 6-11: Lifting Bodies Displayed in AF Museum, WPAFB

X-24B Glide Flight

Chapter 7

The X-24B Program

The X-24B entry configuration was developed by the AF to generate higher values of entry L/D than the previous lifting body configurations. Unlike the programs discussed previously, however, the X-24B construction was funded jointly by the AF and NASA. It was flight tested between August 1973 and November 1975.

7.1 Theoretical Development

In the late 1950's, even before the X-24A program got under way, the AF Flight Dynamics Laboratory had under study a series of long slender lifting body configurations which were capable of achieving hypersonic L/D's of 2.5 or greater. The low speed L/D for some of these shapes was quite low, however, and the engineers considered switch-blade wings, or some other variable-geometry concept, to facilitate horizontal landing. (NASA FRC's HYPER III was a low speed, unmanned flight demonstration of such a vehicle.) Some of the shapes, such as the FDL-7, had aft, wing-like strakes that produced a subsonic L/D that was comparable to the other lifting bodies. In the mid 1960's, Al Draper and Bill Zima began to explore the possibility of building a gloved external shape around the existing jet-powered SV-5J vehicles that Martin had constructed. The shape which evolved was similar in many respects to their FDL-7 shape, but it had been adapted to the triple-fin upper fuselage of the SV-5. The configuration was called the FDL-8 and initial analysis showed that it had considerable promise as a land-able configuration. The original FDL-8 used a straight 78-degree-sweep planform.

Loft lines were developed to accurately merge the SV-5 configuration with the FDL-8 configuration, and a steel wind tunnel model was constructed. Several wind tunnel tests were conducted to develop the best sweep angle for the added aft strakes, the best aileron control surface size, and to gather the necessary information for design of the flight control system. These tests resulted in the final, double-delta configuration using 72 degrees of sweep for the aft strakes.

The personnel at the Flight Dynamics Lab saw this as their opportunity to perform a low cost flight demonstration on one of their configurations with a hypersonic L/D of 2.5. In contrast, the three vehicles of the existing Lifting Body program (M2-F3, HL-10, X-24A) had hypersonic L/D's of between 1.2 and 1.4. The wind tunnel results looked very promising. Al Draper proposed to add the glove modification to the X-24A rather than an SV-5J in order to reduce cost by utilizing existing subsystems and to also obtain transonic flight test data (Figure 7-1). The designation of the configuration was changed to X-24B in 1971 (Figure 7-2).

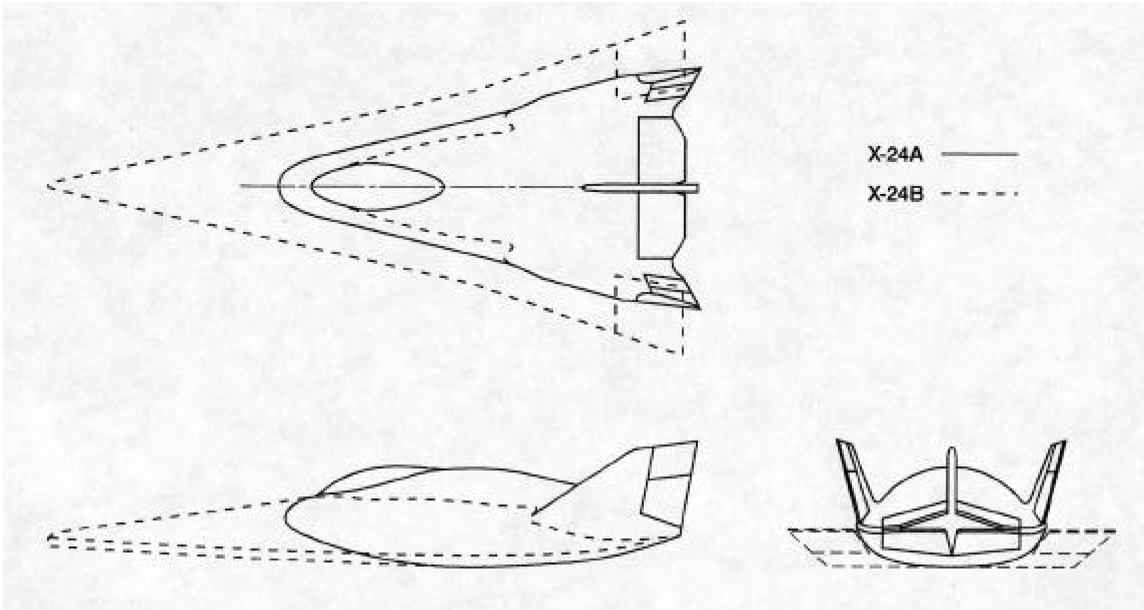


Figure 7-1: X-24B Glove Modification to X-24A

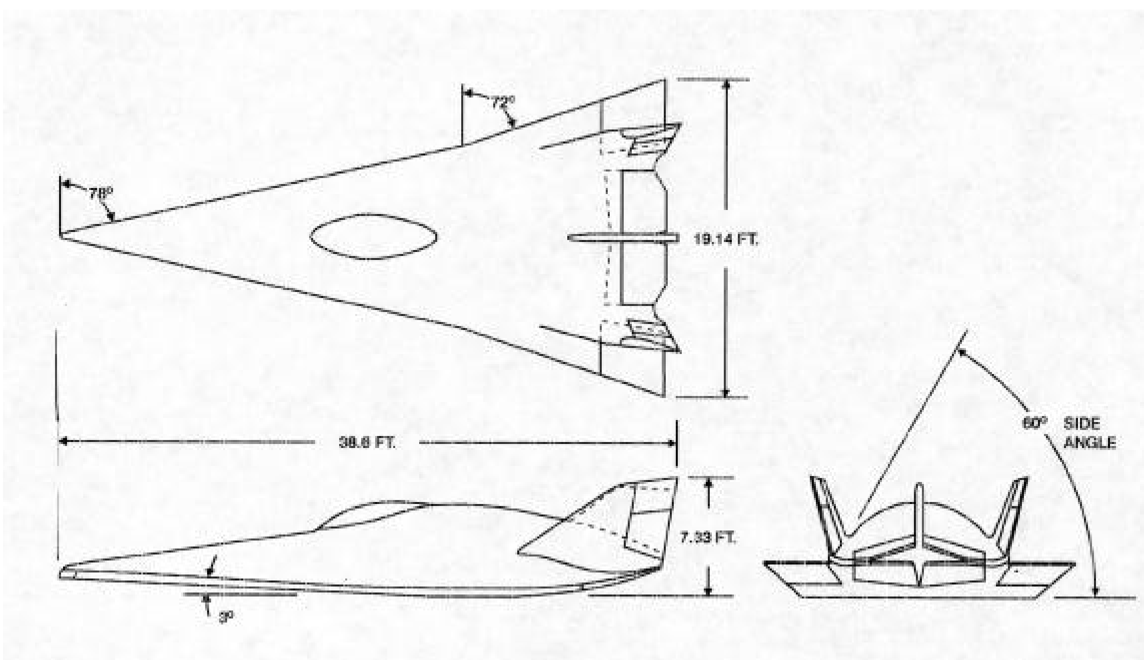


Figure 7-2: Three-View Drawing of X-24B

7.2 Technical and Physical Development

The AFFTC simulation of the X-24A had proven to be both complete and accurate in its representation of the rather complex control system and aerodynamics. In order to assess the feasibility of the proposed X-24B modification, the X-24A simulation was temporarily modified. The cockpit and all flight control features of the X-24A simulation were retained. The only changes were those associated with the modified mass characteristics and new aerodynamic data tables which had been obtained from recent wind tunnel tests on the X-24B shape. The simulation was operating within a few months of the receipt of the wind tunnel data. Pilots quickly became quite enthusiastic about the indicated handling characteristics of this X-24B configuration. Of particular significance was the effect of the triangular cross-section of the fuselage. The sloping sides of the forward fuselage tended to counteract the high dihedral effect produced by the high sweep angle (Figure 7-3). The overall dihedral effect at low speeds and the lateral handling qualities were more like a normal aircraft than the X-24A or the other lifting bodies. The aileron surfaces outboard of the tip fins on the trailing edge of the strakes were also more effective than the inboard surfaces that were employed on the X-24A. The sloping sides also provided good visibility for landing in spite of the long nose and high pitch attitude at touchdown.

Figure 7-3: X-24B Upper Body Shape

The X-24B used the same control surfaces as the X-24A plus two additional flaps at the aft end of the strakes outboard of the fins. These new strake flaps were operated differentially for roll control. There was also a bias capability which allowed the strake flaps to be trimmed symmetrically for additional pitch trim capability.

The flight control laws for the X-24B were similar to the X-24A except that the inboard upper and lower flaps were no longer commanded to move differentially, the lateral control function having been transferred completely to the strake flaps. Pitch control remained with the inboard upper and lower flaps, and rudder control was on the upper rudders. The upper-flap-bias function was retained and was used as a speed brake in the same manner as on the X-24A.

Although both NASA FRC and the AFFTC were strongly supportive of X-24B modification, there was some resistance within the higher levels of the AF. At a briefing to the joint Air Force Scientific Advisory Board and National Academy of Sciences, the general philosophy of the proposed modification was described as well as the results of the quick-response simulation studies. The review panel members enthusiastically endorsed the program as a low cost effort with a large technology pay-off (Reference Hallion, Vol. II, 1987).

The modification cost of $1.1 million was to be shared between NASA and the AF, with the AF managing the procurement. When the AF had difficulty finding their half of the money, the NASA FRC Program Manager John McTigue forced the issue by forwarding NASA's portion ($550,000) directly to the AF Flight Dynamics Laboratory. The AF produced its share of the funds, and the AFFDL engineers finally found themselves enthusiastically supporting a flight test program on one of their own configurations.

7.3 Construction

The Martin company received the contract to modify the X-24A into the X-24B. They accomplished the task at their Denver facility in 1972.

7.3.1 Management and Organizational Structure

The contract for modification was awarded to the Martin Company, which was in the process of closing its Baltimore plant where the original X-24A had been manufactured. Martin decided to perform the modification at their missile facility near Denver, Colorado. A few of the original craftsmen who built the X-24A were transferred to the Denver plant to perform the modification; these included Dick Boss, the chief of manufacturing for the project. For the third time (first the M2-F2/HL-10, then the X-24A), a small, enthusiastic group of designers, technicians and flight test engineers from the AF, NASA and industry, formed a team to accomplish a low cost, manufacturing task of a new and radical lifting body design (Figure 7-4).

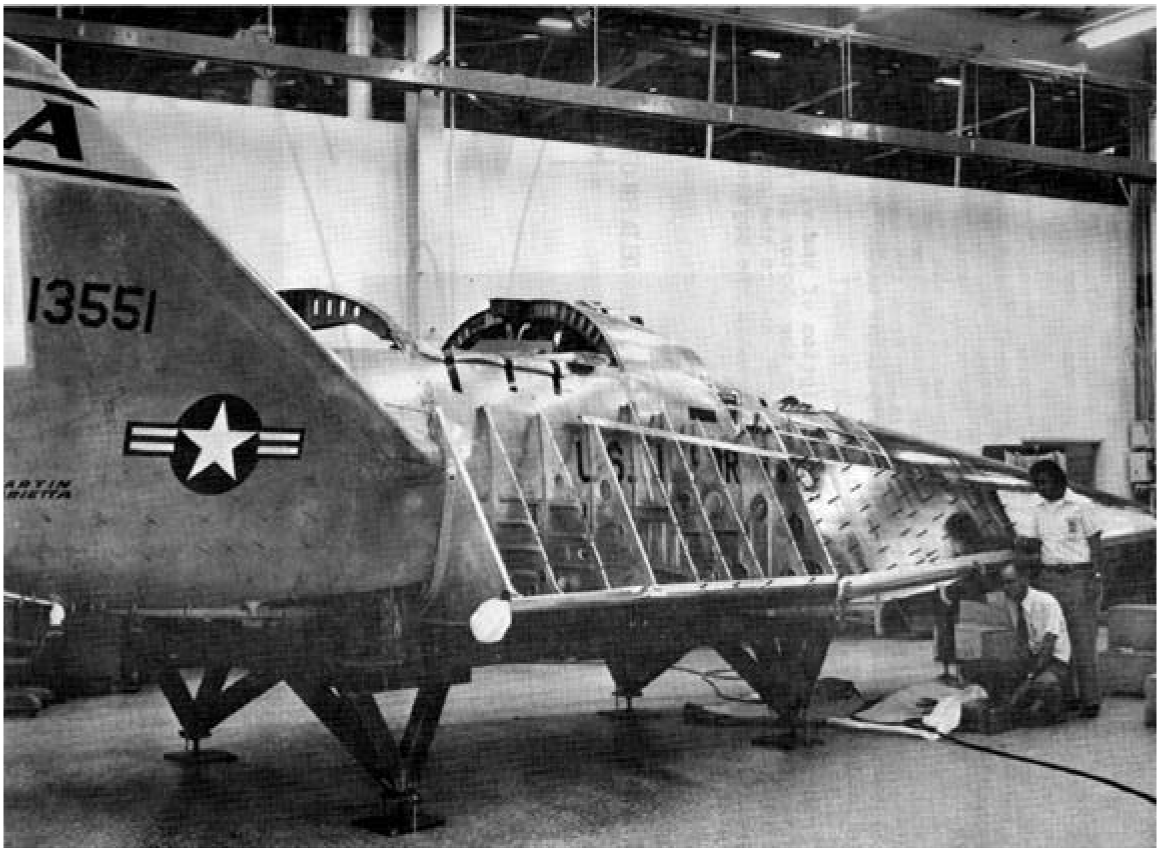


Figure 7-4: X-24A Conversion to X-24B

Following the last flight of the X-24A on 4 June 1971, all of its subsystems were removed and stored at NASA FRC. The vehicle shell was then mounted on a pallet and flown to Buckley Field (a National Guard Base south of Denver), then trucked to the Martin plant on 15 December 1971. A small corner of the plant was set aside for the construction and Dick Boss was given free reign of Martin's shops and facilities to complete the modification.

7.3.2 Government-Provided Instrumentation and Subsystems

The loft lines for the X-24B shape were provided to Martin by the AF Flight Dynamics Laboratory. The landing gear design was also a product of the FDL. The X-24B would be heavier than the X-24A, and the center of gravity would be considerably farther forward relative to the main landing gear. This would result in considerably higher loads on the landing gear. A new nose gear system with more energy absorption capability was needed. The Flight Dynamics Laboratory chose the nose gear system from the F-11F-1F (a Navy fighter) and procured a unit from the Navy. New actuators were also needed for the new aileron surfaces. X-15 rudder actuators were selected for this function and were provided to Martin by NASA FRC.

While the new vehicle structure was being designed and built, the AFFTC Lifting Body test team continued to refine the X-24B simulation. It was used to define the control laws and design loads for the new ailerons. Based on their experience with the other lifting bodies, the AF test team also provided other design suggestions to Martin. For example, it was suggested that the nose landing gear move aft during extension (to compensate the center of gravity change from the main gear moving forward), and that the gear doors open parallel to the airflow to minimize the landing gear trim change and drag. For the most part, the AFFDL (who maintained configuration control) and Martin incorporated these suggestions into the new design.

The B-52 pylon for the X-15 research aircraft had been designed to allow the X-15 pilot to eject over the wing of the B-52 in the event of an emergency on the mother ship. All three of the original lifting bodies had been mounted on the B-52 pylon using a pylon adapter. For those aircraft the adapters were designed to place the pilot's location well forward of the B-52 wing so that ejection over the wing was also possible. The canopy on the X-24B was farther aft relative to the center of gravity so it was not possible to configure the adapter to allow captive ejection - not at least without exceeding the pylon load capability. The decision was made to accept the added risk and configure the adapter so that ejection over the wing was not possible. A B-52 emergency would have required the X-24B to be launched before the pilot could have ejected.

7.3.3 Schedule and Delivery

The modification was completed in ten months, and the vehicle was returned to Edwards on a C-5 cargo airplane on 24 October 1972. NASA FRC Operations Engineer Norman DeMar oversaw the reinstallation of all subsystems by the NASA technicians.

7.3.4 Ground Tests

The good correlation of the full scale wind tunnel tests with small scale wind tunnel tests of the other lifting bodies prompted a decision to forego the full-scale tunnel tests of the X-24B vehicle. The B-52 launch experience accumulated on the X-15 and three lifting bodies, also allowed the AF/NASA FRC test team to forego the launch and separation wind tunnel tests for the X-24B. They selected an appropriate carry angle for the pylon adapter design based on data from the previous vehicles.

An "inertia swing" was performed on the X-24B. A series of drop tests to validate the new landing gear design were also performed. The vehicle was hoisted to a pre-established attitude and altitude, then released (Figure 7-5). Control system tests uncovered several structural and hydraulic problems which required both electronic and hardware changes.

Figure 7-5: X-24B Landing Gear Drop Test

Both the HL-10 and the X-24A programs had generated considerable interest in understanding the flow fields over the inboard surface of lifting body tip fins. NASA FRC sponsored an effort to install research instrumentation (pressure and strain gage measurements) on one of the X-24B tip fins. The entire tip fin structure was removed from the vehicle and mounted on a fixture. Calibration loads were applied to the fin. Pressure instrumentation was also installed along the entire length of the fuselage (left side only) for correlation with similar measurements taken in the wind tunnels (Reference Tang, 1977).

AFFDL was concerned about the possibility of nose-wheel shimmy and tire failure due to the unusually high predicted loads on the landing gear, and the fact that it was a new and untested system. The AFFDL Gear Loads Facility conducted a series of tests on the landing gear system at WPAFB. These tests showed that the tires (standard T-38 tires) could handle the combination of increased weight and high landing speed if the tires were shaved of their outer tread and replaced after every landing. These recommendations were passed on to the Lifting Body test team at Edwards.

The Edwards Lifting Body test team also wanted to develop and test the nose-wheel steering system. Initial low-speed taxi tests were performed to 30 knots on the lakebed using the emergency landing rockets. Final taxi tests were conducted to a maximum speed of 150 knots using two chambers of the XLR-11 rocket engine; these were commonly referred to as the "Bonneville Racer Tests" (Figure 7-6). The steering performed well. The tire procedures recommended by AFFDL were followed and no tire problems occurred during the program.

Figure 7-6: X-24B High Speed Taxi Test using XLR-11 Rocket Engine

7.4 Flight Testing

The flight test program began with a traditional glide flight in August 1973. The program was completed in September 1975 after 32 successful flights.

7.4.1 AFFTC/Dryden Test Team

The AFFTC test team, still under the overall guidance of engineer Robert Hoey, led the X-24B envelope expansion and mission planning effort. There was considerable interest and participation by the NASA FRC research engineers, led by NASA FRC Project Manager Jack Kolf. Johnny Armstrong continued to be the AFFTC Program Manager for the X-24B program and Norm DeMar continued as the NASA FRC Operations Engineer. The assigned test pilots were John Manke, an experienced lifting body pilot from NASA FRC, and Major Mike Love, an experienced test pilot who was newly assigned to the Lifting Body team. The Joint AF/NASA FRC Memorandum of Understanding was extended, although some of the responsibilities shifted. Maintenance of the aging B-52 mother ship was becoming difficult for the AFFTC, so the AF offered the airplane to NASA. NASA FRC assumed both maintenance and operational responsibilities for the B-52 mother ship. The AFFTC rocket shop was being reduced in size following the completion of the X-15 program in 1969. Its technicians, however, continued to support the XLR-11 engines throughout the X-24B program. The cooperation between the AF and NASA continued at all levels throughout the X-24B program.

7.4.2 Use of Fixed Base and Airborne Simulators

The same AFFTC simulation capabilities that were used for the X-24A continued to support the X-24B flight test effort. In this instance the simulator supported the design of the vehicle as well as the direct flight test activity.

About 1972 the AFFTC switched from F-104's to F4's as primary chase airplanes. The AFFTC F-104 aircraft were, therefore, no longer available to the Air Force Lifting Body test pilots. The AFFTC Lifting Body team searched for a suitable replacement vehicle for both chase and pilot training. A series of tests were performed on both the F4 and the T-38 to determine if these aircraft could be safely configured to duplicate the low L/D of the lifting bodies. A T-38 configuration came very close to the desired L/D but forced pilots to operate at, or slightly above, the limit speed for the landing gear doors. A special waiver was obtained to allow the T-38's to operate at 300 knots with the gear extended, provided that an extensive gear door inspection was accomplished after each flight. The AF X-24B pilots flew practice missions in the T-38, but also flew the NASA F-104 aircraft for final practice runs. Both AF T-38's and NASA F-104's chased the X-24B missions.

7.4.3 Glide Flight Program

NASA FRC pilot John Manke flew the first X-24B glide flight on 1 August 1973 (Figure 7-7). Although he had to fly through a small cumulus cloud that had formed along the planned flight path, the flight was quite successful.

Figure 7-7: X-24B Glide Flight (Touchdown)

As a result of the engine fire which had occurred late in the X-24A program, the Flight Dynamics Lab engineers had performed a flow visualization wind tunnel test using the X-24B model. The goal was to identify a fuel jettison location which would prevent fuel from recirculating into the engine area. The best location identified was in the cove at the base of the fin and above the aileron. To test the jettison system and insure that no recirculation was occurring, the vehicle was serviced with a small amount of fuel (water alcohol) for the third glide flight. When Manke operated the fuel jettison valve, the airplane rolled sharply to the right requiring 70 per cent of the available aileron to maintain level flight. After the jettison stopped the lateral control returned to normal. Apparently the fuel, which was exiting at high pressure, disturbed the flow over the fin and aileron creating a nearly uncontrollable roll. Subsequently the jettison line was routed directly aft to the rear of the vehicle and the problem disappeared. The fuel did not recirculate into the engine area from either location (Figure 7-8). Five more glide flights were performed by two pilots before the vehicle was declared ready for powered flight.

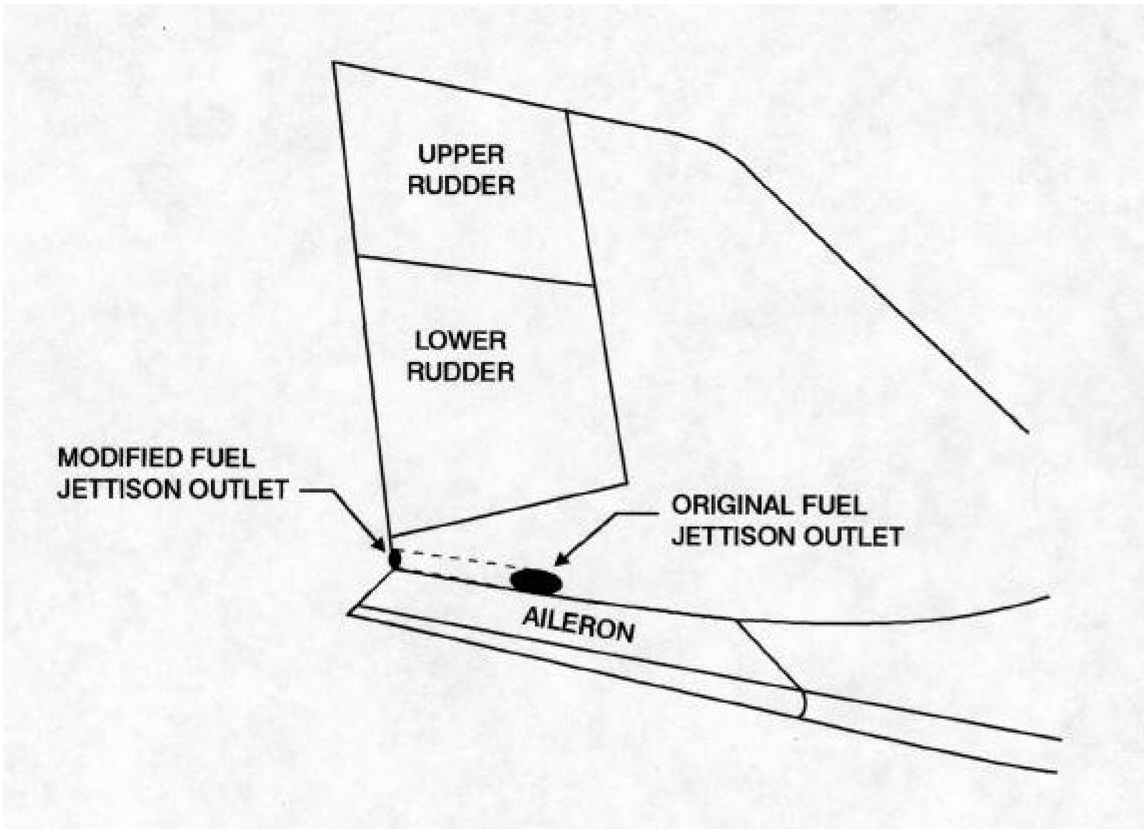


Figure 7-8: X-24B Fuel Jettison Modification

7.4.4 Powered Flight Program

Manke, who had flown the first glide flight, also flew the first powered flight of the X-24B. The flight occurred on 15 November 1973, only 3 1/2 months after the first glide flight (Figure 7-9). The expansion of the flight envelope proceeded smoothly. Manke and Major Mike Love alternated piloting duties for these flights.

Figure 7-9: X-24B Powered Flight

The X-24B was heavier than any of the other lifting bodies. Simulator tests showed that, with the same XLR-11 propulsion system used on the X-24A, it would only reach about 1.4 Mach number. Two propulsion system engineers, Jerry Brandt from the AF and Bill Arnold from the engine manufacturer (Reaction Motors/Thiokol), suggested that higher thrust could be obtained from the XLR-11 engines by increasing the chamber pressure to 300 psi. (Reference Brandt, 1969). Ground runs had confirmed the safety of the higher pressure. The only stipulation was that the initial start should be at the baseline chamber pressure of 265 psi. A switch was added in the cockpit. Commonly referred to as the "overdrive" switch, this switch produced an upward adjustment to the chamber pressure regulator. After launch, the engine was started with the switch off. When all chambers were running smoothly (about 30 seconds after launch), the pilot engaged the "overdrive" which increased the thrust of the rocket engine by almost 14 percent (from 8600 lbs. to 9800 lbs.). This capability was added after flight 10 and was used on most supersonic flights of the X-24B. It allowed the vehicle to reach a maximum Mach number of 1.76.

7.4.4.1 Handling Qualities: The X-24B handled differently than the other lifting body vehicles in two primary respects. The dihedral effect was considerably lower than for the other vehicles, and the outboard strake flaps operated like normal ailerons which the other vehicles lacked. The combination created a vehicle with excellent handling qualities as well as excellent riding qualities in turbulence. When the rocket engine was running, however, the same longitudinal trim change and reduction in directional stability that were experienced on the X-24A were also present on the X-24B. This was attributed to the influence of the exhaust plume on the flow at the rear of the vehicle (Reference Norris, 1979).

During the powered climb phase, small lateral disturbances or upsets were noted on some of the X-24B flights, as well as on other lifting body flights. These upsets were thought to be a result of the vehicle climbing at a very steep angle through wind shears (abrupt changes in wind velocity or direction with changes in altitude). The upsets did not correlate with balloon wind surveys, however, and a different series of tests was required to validate these suspicions. By using special balloons and also by photographing the vapor trail during the powered phase of flight, the abrupt wind shears were verified. It was discovered that the standard balloon wind surveys were averaging the winds over a large altitude segment thus masking the sharp wind shears that were, in fact, present in the atmosphere (Reference Armstrong, 1977). (Additional pilot comments are included in Appendix B.)

7.4.4.2 Runway Landing and Pilot Checkout Program: From the beginning of the X-24B program the team participants harbored the idea that this second-generation lifting body vehicle should be capable of demonstrating a landing within the confines of a standard concrete runway. Steering, braking and cockpit visibility were specially designed for that capability. In preparation for such a demonstration, an additional research task was added to nine of the flights (flights 16 through 24). These flights were designated as "accuracy landing" flights. After completing the high-speed research objectives of the flight, pilots attempted to land at a designated marker on the lakebed runway. These flights showed that pilots could successfully touch down within plus or minus 500 feet of the selected marker (Reference Stuart, 1977). Since the vehicle was traveling at about 320 feet per second at landing, the pilot was within the touchdown zone for only three seconds - a remarkable demonstration of energy management.

After expanding the flight envelope of the X-24B and completing the desired research testing, the project pilots (Manke and Love) proposed that the performance and handling qualities of the X-24B were good enough to attempt to land on the 15,000-foot concrete runway at Edwards. This feat had not been possible with any of the previous lifting bodies because of the lack of adequate steering after touchdown. (The X-15 was equipped with landing skids so was incapable of landing anywhere but on a dry lakebed.)

A plan to accomplish runway landings with the X-24B was presented to the FDL, NASA FRC and the AFFTC Commander (General Robert Rushworth who was an experienced X-15 pilot). Included in this briefing were results of the nine accuracy landings. When the X-24B team received approval to proceed, it triggered an extensive preparation and training buildup by Manke, Love and the entire lifting body team. Actually landing on a concrete runway was a little more difficult than merely saying that it could be done. Earlier high-speed taxi tests on the lakebed had successfully demonstrated ground steering. Many practice flights were made in the F-104 to fully assess wind effects and establish reference and aim points for the new pattern.

Following an alternate powered flight to Mach 1.18 during which only 3 of the 4 rocket chambers had ignited, Manke performed the first runway landing on 5 August 1975. The aim touchdown point was a stripe painted on the runway 5,000 feet from the approach end. Manke touched down in a very slight bank with one main wheel touching before the stripe and the other wheel after passing the stripe (Figure 7-10). Lt. Colonel Love made the second runway landing on 20 August 1975, when he touched down 400 feet beyond the stripe. Both pilots commented that the additional visual cues of roads, Joshua trees, etc., made the final phase of the landing easier than on the smooth, flat lakebed.

Figure 7-10: X-24B Runway Landing

X-24B & Chase Fly-Over

The Space Shuttle Orbiter was under construction at this time and was being designed for unpowered, runway landings, so the successful X-24B runway landing was an important demonstration. Preparation for this flight by Manke and Love resulted in the concept of a two-step flare. The two-step flare started, as before, with an initial flare (or "pre-flare") at 1000 feet altitude. The vehicle was flown to a second, shallow glide slope, however, (about 3 degrees) rather than level. Just before touchdown, a final, short flare was performed . The two-step flare concept is currently used for landings of the Space Shuttle Orbiter.

The handling and performance of the X-24B were considered excellent and very similar to contemporary fighter aircraft. Following completion of the research program on the X-24B, it was decided to perform a series of checkout flights for some of the other qualified test pilots who had not had the opportunity to fly lifting bodies. X-24B glide flights were offered to the NASA astronauts who were preparing to fly the Enterprise (the first Space Shuttle Orbiter). Although the astronauts themselves wanted to fly the X-24B, the offer was turned down for political reasons. Captain Dick Scobee, who was an AFFTC test pilot at that time, did perform two successful glide checkout flights in the X-24B. He would later become an astronaut. On his second Shuttle flight, he was the Commander of the Challenger when it exploded on 28 January 1986.

Two powered and six glide checkout flights were successfully completed by four different test pilots (beside Manke and Love), three of whom had never before flown a lifting body (Figure 7-11). The last flight of the X-24B was flown on 26 November 1975. It closed 30 years of continuous flight testing at Edwards of experimental, rocket-powered research vehicles that started with the Bell X-1. It is interesting that the first and last of these vehicles used the same rocket engines, the XLR-11 - not only the same engine model, but the same actual hardware. The final flight of the X-24B also closed the flight testing program for lifting bodies.

Figure 7-11: Test Pilots Who Flew the X-24B

7.4.5 Schedule and Pilots

Six pilots flew the X-24B between 1 August 1973 and 26 November 1975 on 12 glide and 24 powered flights. A maximum altitude of 74,130 feet and a maximum speed of Mach 1.76 were reached.

Pilot	Glide Flights	Powered Flights
John Manke	4	12
Lt. Colonel Mike Love	2	10
Bill Dana	0	2
Einer Enevoldson	2	0
Major Dick Scobee	2	0
Tom McMurtry	2	0

(The schedule relative to the other lifting bodies is shown in Figure 2-1. A complete log of flights and pilots is included in Appendix C.)

7.5 Technology Lessons Learned

The X-24B was not only a new lifting body configuration, but was also a second generation lifting body vehicle. It incorporated some design features that resulted from test flights in the three heavy-weight vehicles. New lessons were learned, some of which were applicable to the operational aspects of landing lifting entry vehicles.

7.5.1 Accidents/Incidents

Piloting the X-24B was easier than the other lifting bodies as a result of several improvements that were incorporated in the design. There were no serious accidents or incidents during the X-24B flight test program.

7.5.2 Validations

The success of the X-24B program reinserted the "winged," high L/D shapes as valid competitors in the search for an operational lifting entry configuration capable of horizontal landing.

The handling qualities of the X-24B were the best of the lifting bodies primarily due to the lower dihedral effect and due to more responsive ailerons. Landing the vehicle compared favorably with flying simulated low L/D approaches in the T-38 and F-104.

The subsonic L/D of the clean X-24B was only slightly higher than that of the X-24A, but the gear-down L/D was substantially higher. Subsonic stability was as predicted by the wind tunnels for everything except the longitudinal stability, which was lower than predicted. At transonic and supersonic speeds the stability was as predicted except for directional stability, which was also lower than predicted.

The X-24B performed the first concrete runway landings of an unpowered, low L/D vehicle. These landings confirmed earlier predictions that accurate landings and controlled rollouts could be accomplished with this class of vehicle. The task of attempting accurate landings reinforced the need for a speed brake capability. An interesting sidelight was discovered during the analysis and preparation for the runway landings. The energy condition and vehicle location at the start of a flare correlated directly with the stopping point on the runway (if the same braking technique were used). The actual point of touchdown was of secondary importance since the vehicle slowed at almost exactly the same rate after flare completion whether it was still flying or was on the ground.

The reduced friction of the concrete runway relative to the lakebed surface was also noticeable. The two runway landing rollouts were about 34 percent longer than equivalent lakebed landings for the same braking. A similar difference was noted between lakebed and runway landings of the Space Shuttle Orbiter (Reference Hoey, et al, 1985).

During the latter part of the powered flight test program one of the access panels on the lower surface was used as a test bed for the Space Shuttle thermal protection system tiles. One array of tiles was bonded to the panel and successfully flown on several flights. The primary objectives were to assess the tiles ability to withstand the aerodynamic shear forces in flight, and to investigate the susceptibility to damage during landings on the lakebed.

7.5.3 Improvements

The X-24B was the first of the low L/D glide vehicles to incorporate a useable nose gear steering system. Successful development of ground steering was a key factor in the demonstration of the concrete runway landing.

The landing gear extension trim change, which had degraded the landing handling qualities of all of the earlier lifting bodies, was effectively eliminated by careful attention to the design parameters. Although rocket engine reliability continued to be a problem, the added ability to increase engine thrust after ignition allowed the X-24B to achieve a higher speed (Mach 1.76) than was originally expected.

7.5.4 Problems Resolved

The subsonic longitudinal stability was less than that predicted by the wind tunnels. Discrepancies between different wind tunnels prior to flight test had alerted the test team to the uncertainty. Pressure measurements were made to obtain the necessary validation data. Early glide flights were planned with ample margin for error. As a result the discrepancy between the wind tunnels did not disrupt the test program even though the stability level was only half of the original prediction. The research flight test data allowed researchers to better understand the interpretation of wind tunnel data for long, slender vehicles like the X-24B.

The influence of the rocket engine plume was to significantly reduce stability. Similar effects had been observed on the X-24A. An exhaust plume is very difficult to duplicate in a wind tunnel so there were only trend predictions available prior to flight tests. Since the X-24B, and all other lifting body configurations, were intended for gliding entry, the power effects were of theoretical interest only. Subsequent studies were performed to better understand these plume effects relative to air-breathing or rocket powered research aircraft under development such as the X-24C (Reference Norris, 1979).

While jettisoning fuel from the X-24A, recirculation of the fluid back into the engine area had resulted in a small engine fire. Wind tunnel flow visualization tests were run on an X-24B model to establish the best location for the jettison line. The initial test of the X-24B jettison system produced a large lateral trim change. The entire problem was corrected by extending the line to the aft end of the vehicle.

Flight test data disclosed that one aileron actuator exhibited sluggish response during the early portion of each powered flight. It was discovered that the LOX vent line was located just forward of the aileron actuator compartment and was super-cooling the hydraulic fluid in the actuator, thus causing slow response.

7.5.5 Unresolved Problems

Among the X-24B unresolved issues was the continued need for the center fin. The center fin was needed on the X-24A as a "splitter" to reduce adverse yaw whenever the upper flaps were deflected differentially for roll control as discussed in Chapter 6. The lateral control surfaces on the X-24B were located outboard of the tip fins and the upper flaps were only used for pitch control. The "splitter" function of the fin was therefore no longer required for the X-24B, and removal of the fin was seriously considered. Early wind tunnel tests had shown low directional stability in the transonic region for the X-24B with or without the center fin, so in the interest of safety, the fin was retained, at least for envelope expansion flights. The noticeable degradation in directional stability at supersonic speeds revealed from flight test data was never totally explained so the center fin was never removed.

The low directional stability and poor longitudinal trim capability at supersonic speeds could probably have been corrected by increasing the upper flap position and flaring the rudders outboard as was originally planned for the X-24A. Since this would have significantly increased the drag, the desired test Mach numbers would not have been obtained using the XLR-11 engine so the potential improvement was never explored. Optimization of the control laws for the X-24B configuration in the supersonic flight regime (Mach 1.2 to 5.0) was never studied either in wind tunnels or on simulators.

The XLR-11 rocket engine's reliability continued to be a problem during the X-24B program. The components were old and the engine was a 1940's design. Attempts to streamline and update its capabilities often resulted in the creation of additional problems. In spite of the frustration at having to repeat some flight attempts, the fail-safe features worked well, and there were no serious explosions or hazardous flight conditions caused by engine malfunctions.

Like the X-24A, the X-24B also had poor crosswind landing characteristics, but for a different reason. Between main landing gear touch down and nose gear touchdown, the vehicle tended to roll and yaw sharply in the downwind direction. From the cockpit the nose appeared to slice uncontrollably during the rotation. After the vehicle stabilized on all three wheels the nose gear steering was adequate to control the rollout. The vehicle did not "heel over uncomfortably" as was experienced on the X-24A.

7.6 Test Sites

The test sites and facilities supporting the X-24B were identical to those supporting the X-24A (Figures 4-20 and 4-22) - all AF and NASA properties at Edwards AFB. The Propulsion System Test Stand was used to develop and validate the uprated thrust capability of the XLR-11 engine.

7.7 Current Status of Aircraft

In November 1976 the X-24B was loaded into a "Pregnant Guppy" transport aircraft and delivered to the Air Force museum at Wright Patterson AFB, Ohio. It is currently displayed next to one of the two SV5J aircraft which has been configured to look like the X-24A (Figure 6-11).

Chapter 8

Epilogue

8.1 Summary of Test Results

The initial Lifting Body research flight test program was aimed at the development of horizontal landing techniques for a class of entry configurations which would use ablation technology for thermal protection during entry (M2-F3, HL-10, X-24A). Aerodynamic refinements which produced acceptable low speed L/D's suitable for approach and landing were demonstrated . Flight control difficulties for these short-coupled and roll-prone vehicles were successfully overcome. Following flight at supersonic speeds, each of the three heavy-weight lifting bodies were successfully landed. Adequate transonic stability and controllability were thereby demonstrated. Only the X-24A had a pilot canopy configuration with suitable forward visibility at landing for a mission vehicle.

A successful and highly repeatable approach and landing technique was developed for unpowered, low L/D vehicles. The critical phases of this technique were identified. In spite of the high drag of these vehicles, some type of speed brake was required to achieve the precise, pre-flare energy conditions needed for accurate landings.

The fourth configuration - the X-24B - must be considered a second-generation lifting body. It could use either metallic or ceramic insulation for thermal protection and could accomplish considerably more maneuvering during entry than the earlier configurations. The low-speed handling qualities were improved over the earlier vehicles. Following a supersonic flight, the X-24B successfully landed on a concrete runway, and thereby demonstrated an additional aspect of operational flexibility.

While the lifting body flight test data were being gathered, the effects of ablation surface roughness on low speed drag were also being assembled. As mentioned in Chapter 6, full scale wind tunnel tests of the X-24A with a simulated rough ablator surface showed a reduction in L/D of 20 percent (Reference Pyle, 1969). Tests at WPAFB on an 8 percent model of the X-24A showed similar results (Reference Ash, Vol. II, 1972). Flight tests of the X-15A-2, which used a thin ablative coating, showed a reduction in L/D of about 15 percent after a relatively mild exposure to the aerodynamic heating environment (Ref Ash, Vol. II, 1972). Comparison tests of two PRIME vehicles, one before flight and one after flight, showed a 30 percent reduction in L/D (Reference Spisak).

These effects were also accompanied by reductions in stability which would obviously be quite detrimental to the handling qualities. It must be concluded that the first three lifting body vehicles, as originally conceived, would probably not have been land-able following an entry with a normally-ablated thermal protection system. [5]

8.2 Implications for Space Shuttle

These flight test programs represent some, but certainly not all, of the research flight testing that led to the Space Shuttle Orbiter as the first successful, manned lifting-entry vehicle. [6] The Orbiter is a winged vehicle and bears more resemblance to the X-20 than to any of the lifting bodies. Landing the Orbiter utilizes unpowered landing techniques that were originally developed for the X-15 program, and later adapted to the lifting bodies. The continued successful ability of the AF/NASA team to accurately land all of these vehicles without power caused the Space Shuttle design team to reassess their need for a landing engine. John Manke personally made over thirty flights in the NASA 2-seat F-104's or T-38's demonstrating to various astronauts, engineers, managers and politicians the simulated lifting body approach and landing patterns. The Space Shuttle design team finally accepted the unpowered landing technique which had been developed and validated by the AF/NASA flight test team at Edwards, thus saving a considerable amount of weight and complexity in the Orbiter.

The low-speed L/D's of each configuration are compared at the same airspeeds [7] in Figure 8-1. A similar comparison of the gear-down configurations is shown in Figure 8-2. The predicted L/D of the X-20 is not shown since it was never flown, but the predicted values were almost identical to those of the X-24B. Notice that the L/D of the "winged" Orbiter is closer to the L/D of the "winged" X-15 than to any of the lifting bodies.

---

[5] Further study and wind tunnel testing were required to identify the true cause of these effects. It is likely that the judicious use of smooth, high temperature materials (such as carbon-carbon) placed in critical locations on the vehicle would have substantially improved the low speed characteristics after entry.

[6] The ASSET and PRIME flight test programs have already been mentioned in the text. Several other test programs were flown using jet-powered aircraft simulating low L/D vehicles. These programs demonstrated large-airplane low L/D approaches, instrument approaches to 1000 feet altitude, night landing techniques as well as telescopes and fiber optics for reduced visibility (Reference Schofield et al, 1970).

[7] L/D is plotted against the lift coefficient (CL) divided by the wing loading (W/S). This parameter allows vehicles of different size and configuration to be compared at the same equivalent airspeed.

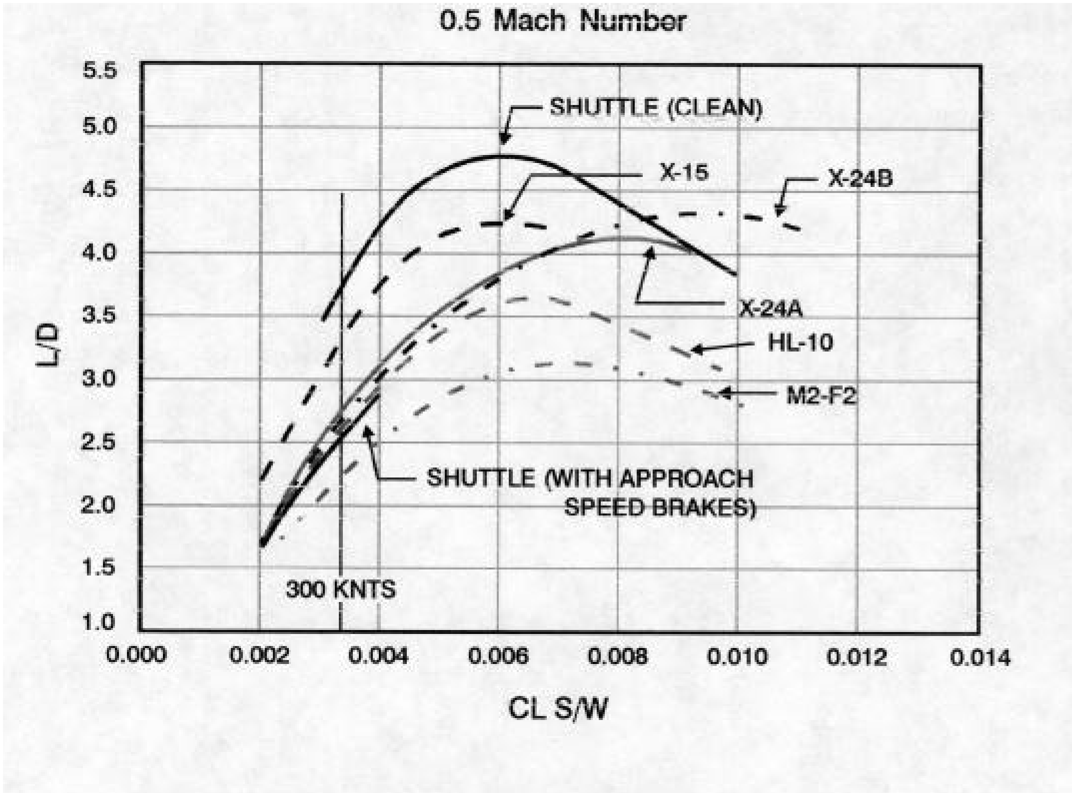


Figure 8-1: L/D Comparisons, Gear Up

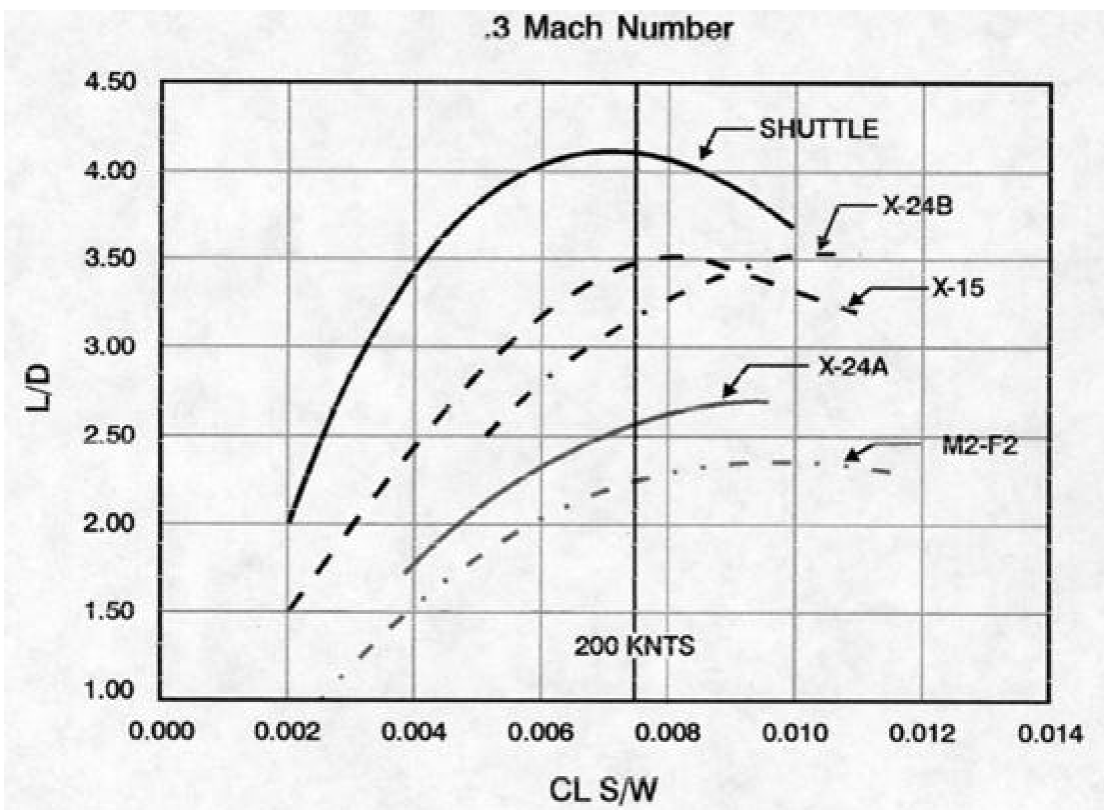


Figure 8-2: L/D Comparisons, Gear Down

The most significant technology contribution to the success of the Space Shuttle Orbiter came from the laboratory, not the Lifting Body program. Pioneered by Lockheed and fostered by NASA Ames Research Center, it was the successful development of a new thermal protection concept. The light weight ceramic tiles and the associated bonding attachment methods were truly the enabling technology for lifting entry. As John Becker stated (Reference Hallion, Vol. I, p. 444),"..the Shuttle enjoys a thermal protection system far more effective and more durable than the metallic radiative structure of Dyna Soar. In essence its light weight ceramic blocks are the ' unobtainium' that we could only dream of in the '50s and early '60s."

The Air Force originally planned to launch the Space Shuttles into polar orbit from Vandenberg AFB in California. In order to return to the launch site during a once-around-abort, the Orbiter needed a cross-range capability of 1200 nautical miles. Throughout the development of the Space Shuttle, the DOD insisted on retention of this 1200-nautical-mile cross-range capability. Although it has never been demonstrated, transient tests of the Orbiter during actual entry have shown that the thermal protection system (as currently configured) is adequate for this high cross-range entry (Reference Richardson, et al, 1983). The current Shuttle mission does not require high cross-range, and the entry L/D used by the Orbiter is about 1.0, similar to that available with the M2, HL-10 and X-24A configurations. Although the technology and hardware are now available, it is significant that a truly high L/D entry has yet to be flown with any vehicle.

8.3 The Future of Lifting Bodies

The light-weight ceramic tile technology developed for the Space Shuttle opens the door to ALL of the lifting entry concepts, including the lifting bodies described in this report. Highly maneuverable entries with over 2400 miles cross-range are possible with X-24B-like configurations. For non-military entry missions (space station return, space-rescue, etc.), where payload fraction is more important than cross-range, the entire spectrum of lifting bodies with entry L/D's of 1.0 to 1.4 are also now feasible (Figure 8-3).

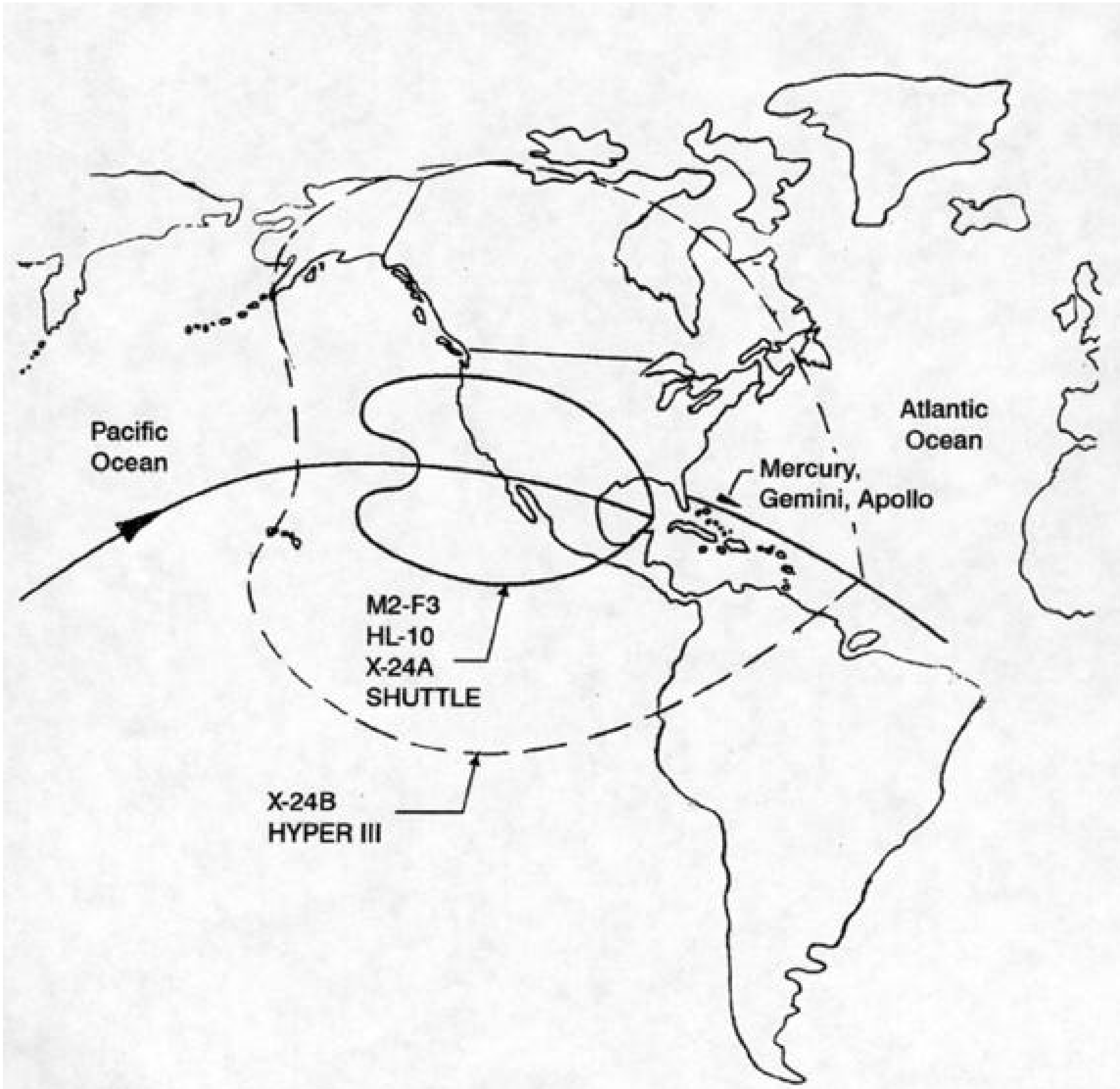


Figure 8-3: Orbital Entry Footprints for Lifting Bodies and Other Vehicles

8.4 Other Benefits

The Lifting Body program highlighted another important attribute not related to technology: the ability of a small team of dedicated individuals to achieve great accomplishments in a short time and with limited resources, provided they are not encumbered by political or bureaucratic constraints. This is especially significant when one realizes that two-thirds of this team were within the Federal Government (NASA and AF). Team members were allowed to function in a manner which was outside the typical procurement practices, and, for the most part, were allowed to make major decisions at the working level throughout the program. This highly productive environment was created by the outstanding leadership of Paul Bikle, the Director of NASA Flight Research Center with full cooperation of several AFFTC Commanders.

The rocket-powered research aircraft programs conducted by joint AF/NASA teams over the years have also made significant contributions in the area of new flight test methods. By their nature, the flights of these vehicles are very transient. Stabilized flight conditions (speed and altitude) cannot be sustained for longer than a few seconds. The flight test engineers supporting these programs developed new methods of transient testing and analysis involving short control pulses and control sweeps. The value of these new methods, in terms of data return per minute of test time, were obvious to the jet-airplane testing community, and many of these methods are now employed in the routine testing of conventional airplanes.

The value of one-of-a-kind research airplanes continues to be a controversial subject. Advocates think that the value of periodically constructing and testing new hardware at relatively low cost will lead to advancements in technology even though the particular subject of the research may not prove fruitful. Charlie Feltz, Chief Engineer for North American on the X-15 program, stated that well over 50 percent of the research value from the X-15 program occurred BEFORE the first flight. He was referring to (1) new manufacturing methods for Inconel and Titanium, (2) new subsystems designed for operation at 0 g, (3) a new man-rated rocket engine, (4) the overall systems integration task, and a host of other new design and manufacturing technologies that had to be developed before flight could even be attempted. Opponents argue that the research would be better focused on the development of true, mission-capable vehicles even though technological failure would be very costly.

Frequent low-cost testing of one-of-a-kind vehicles allows the country to retain a team of researchers who can provide continuity in technological advancement and changing operational concepts. The major development of a new mission-capable vehicle is often separated from its predecessor by 20 to 50 years and the technology transfer is often a major problem. The AF/NASA team at Edwards provided this technical continuity for over 30 years and provided a major portion of the operational concepts, technical requirements and personnel to the Space Shuttle program.

The Lifting Body program proved to be a good application of the research airplane principle: the use of low cost vehicles in a relatively high-risk environment. The success of the Lifting Body program set the stage not only for the Space Shuttle, but also for an entire family of future lifting entry vehicles.

Appendix A

The X-20 "Dyna Soar" Program

The Air Force (AF) initiated the Dyna Soar program as a continuation of its research on manned, high speed flight. Design and development continued from 1957 to 1963 when the program was cancelled before completion of the first vehicle.

1.0 Basic Concept and Design Evolution

The lifting body concept for manned entry vehicles was first introduced during the competition for the X-20 Dyna Soar contract in the mid fifties. The configuration that was finally selected for the Dyna Soar was NOT a lifting body, but was a high L/D, winged glider that would use the "lifting" entry concept described in Chapter 1. Although the X-20 never flew, the story of lifting entry in the United States begins with a discussion of this important program. An overall schedule of activity between 1957 and 1982 is shown in Figure A-1. The various programs discussed in this document are related to each other, and to parallel programs by this figure.

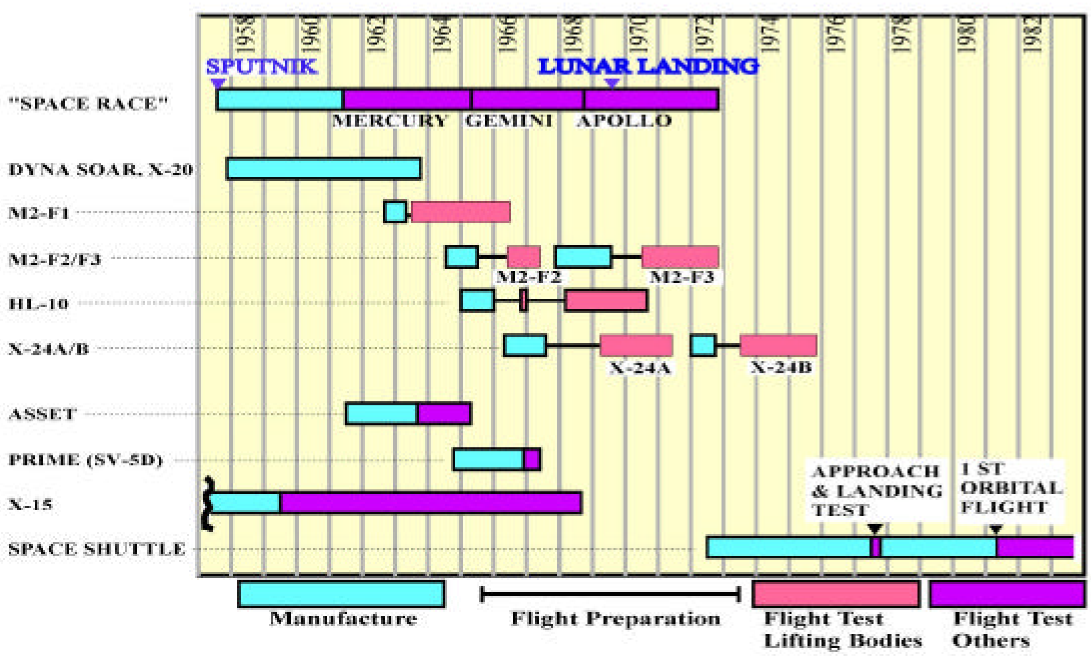


Figure A-1: Entry-Related Testing 1957-1982

1.1 From X-15 to X-20

The Dyna-Soar program grew out of concepts first proposed by Eugen Sänger, a German scientist, in the 1930's (Reference Geiger as quoted in Hallion, Vol. I, 1987). Sänger envisioned a winged aircraft boosted to near-orbital speeds above the earth's atmosphere by a rocket engine. It would then skip along the outer reaches of the atmosphere like a flat stone on water until it slowed to a normal glide speed for landing. The term "boost-glide vehicle" was born. The range of the aircraft would be greatly extended by the skipping action, as would the maneuverability. Sänger coined the term "dynamic soaring" to describe the concept. This terminology was shortened to "Dyna Soar" as the name for the program even though the reentry was envisioned as a long, controlled glide without "skipping."

The Dyna Soar program evolved from the aircraft community rather than the missile community, which was the primary source of entry technology for the Mercury program. The Dyna Soar glider was seen as a natural progression of the successful X-series high speed rocket-powered aircraft. At the time of the first design competition in the mid fifties the X-15 was under construction. The X-15 was expected to advance the frontiers of manned flight to Mach 6.6 and to 250,000 feet altitude. It was recognized that the next step upward in speed and altitude beyond the X-15 could probably not be achieved by air-launching or by using a self-contained propulsion system. Some large, unique air-launching platforms were studied and proposed but none were built. Existing ICBM's had the capability to boost small payloads (approximately 5,000 lbs.) to orbit but could also boost a 9,000-pound research aircraft to a speed of about 17,000 ft per second (about Mach 20) and well into the reentry heating regime. Considering the anticipated future increase in booster capability, the Dyna Soar was proposed as a research glider that would be designed for entry from orbit, but would be initially tested and developed in sub-orbital flight. The program married the ICBM booster technology and high speed research airplane technology. For launch, the glider would be mounted on the top of a modified ICBM booster. The booster trajectory would be altered to place the glider in a nearly horizontal trajectory at burnout, as envisioned by Sänger, rather than the typical steep and high ballistic trajectory of an ICBM.

1.2 Contractor Selection

The initial competition for the Dyna Soar contract drew bids from nine major contractors in the industry. No definitive selection resulted from the first review and the Air Force held a second competition between two teams: Martin/Bell, and Boeing/Chance Vought. The Boeing/Chance Vought glider was a flat bottom, high L/D configuration using a radiative-cooled structure (hot structure)(Figure A-2). At the time of competition Boeing/Chance Vought had selected the Atlas-Centaur as the booster. The Martin/Bell glider was a more blunt, lifting body configuration with a lower L/D than the Boeing/Chance Vought design and used some active cooling in the structure. Martin/Bell selected the Titan II booster. Another key difference between the two proposed gliders was the crew escape system. The Boeing/Chance Vought glider jettisoned the forward flat-bottom section of the vehicle as an escape capsule. The capsule then performed a low L/D lifting reentry with the pilot facing forward. The Martin glider also jettisoned the forward section of the vehicle as an escape capsule, but the capsule turned around to place a heat shield forward. The capsule then performed a ballistic reentry with the pilot facing aft. In December 1957 the Air Force declared Boeing/Chance Vought as the winner. Shortly after source selection a decision was made to switch first to the Titan I, then to the Titan II booster to launch the Boeing/Chance Vought glider. Like the X-15 program, the Dyna Soar initially received funds and management from the Air Force. A joint Air Force /National Advisory Committee for Aeronautics (NACA) flight test team would conduct the research flights.

Figure A-2: Dyna Soar

1.3 Flight Test Planning

The expansion of the flight envelope was initially planned by the research airplane community to be similar to that of other research aircraft. All flights would have a pilot on-board. A short series of air launches from a B-52 (similar to the X-15 launches) was planned at Edwards AFB to validate the landing capability. Vertical launches using the Titan II booster were to be launched to the southeast from Cape Canaveral, Florida. The first flight was planned as a low-speed, low-altitude flight (about Mach 3 and 100,000 feet) wherein the booster would be shut down early and the glider would glide to a landing on one of the Caribbean islands. On each subsequent launch the booster would use a slightly different trajectory to attain a somewhat higher speed and altitude, and the glider would travel to landing strips farther down the island chain, eventually reaching Fortaleza, Brazil (Figure A-3). If the lifting reentry research went well, and the booster capabilities proved to be consistent with the glider weight, the final flight was envisioned as a once-around, barely sub-orbital flight, from Cape Canaveral east to Edwards Air Force Base (EAFB). This flight would be intended to demonstrate a maneuverable lifting entry capability from orbit and set the stage for transition to an orbital research mode and/or military operational mode for the glider. The glider would use a more powerful, and yet-to-be developed booster. [8] .

The ICBM rocket engines (as well as guidance and other subsystems) had not been man-rated to the same standards as those in use on the research aircraft programs. There were no automatic shutdown or redundancy features. (The missile safety record was rather poor in the late fifties). The incorporation of these capabilities would have extended the cost and schedule, and also increased both the weight and complexity of the booster system. The missile community had a different perception of how the Dyna Soar test program should be conducted. They envisioned designing for only one boost trajectory which would attain a high cutoff speed and altitude. They wanted a series of unmanned launches to demonstrate the modified booster features and validate booster safety before beginning the piloted portion of the glider program.

[8] The plans for the flight test of the X-20 were never finalized. The philosophies expressed here were the viewpoints of the AF/NASA/Boeing flight test engineering personnel who would have eventually been responsible for conducting the flight test program. The flight sequence may be inconsistent with flight plans presented in some high-level X-20 documents.

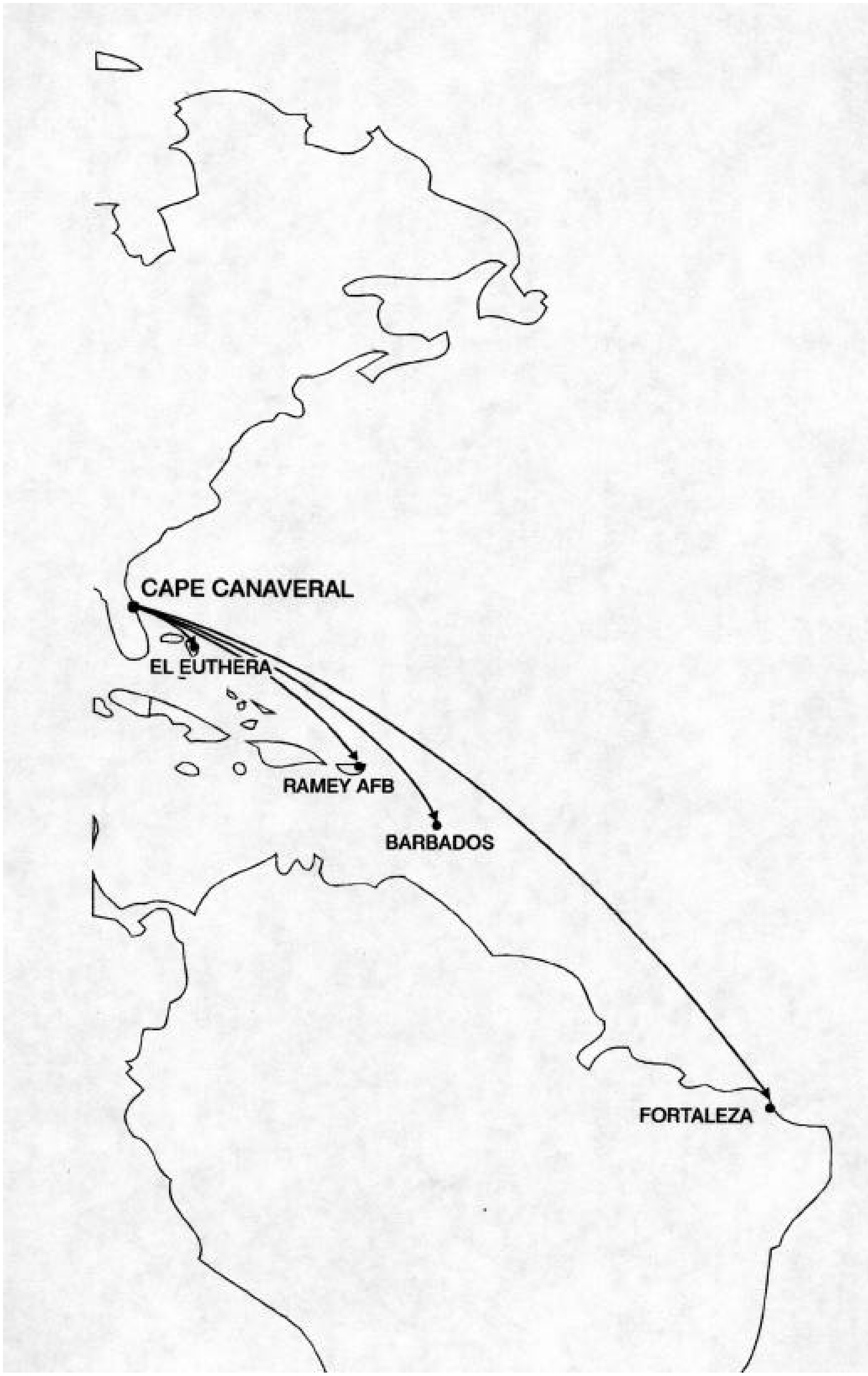


Figure A-3: Planned Dyna Soar Sub-Orbital Tests

1.4 Sub-orbital to Orbital Decision

Attempts to reach a compromise test concept between the airplane and missile community were still underway when the decision was made to switch to one of the larger, but untried, boosters (Saturn I or Titan III). These boosters were being designed to carry both manned and unmanned payloads thus alleviating some of the reliability concerns with the earlier ICBM boosters. The larger payload capability of either of these boosters (about 30,000 lbs. in low earth orbit) changed the Dyna Soar program objectives. Instead of concentrating on lifting reentry research, some broader objectives were added which included orbital research, orbital entries, and military payload evaluations (those same objectives that had been envisioned as following the suborbital glider testing). In order to emphasize the experimental nature of the Dyna Soar program, the Air Force obtained the designation X-20.

The Titan III was selected as the X-20 booster (Figure A-4) and the **first** planned X-20 launch was to be the flight that had previously been envisioned as the **last** flight of the reentry research program described earlier; that is, a once-around flight to Edwards (Figure A-5). The Titan III booster had not yet flown, and the X-20 was scheduled to be the first real Titan III payload following a few developmental launches. The first once-around flight was now scheduled to occur in 1966, which was prior to the establishment of any continuous global tracking or communications networks. The glider would have been only intermittently in contact with the ground from shortly after booster burnout until it emerged from the entry blackout region at about Mach 12 over the eastern Pacific. The risks had obviously increased significantly from the earlier suborbital research program. The X-20 test team was now faced with a difficult decision: Should the first flight be manned or unmanned? The glider design process had emphasized the utilization of the pilot as an important ingredient to the successful conduct of a flight in the same manner as other research aircraft. The pilot could correct malfunctions and select alternate courses of action for unforeseen events. Relying only upon the automatic features for the first orbital flight would significantly reduce the chances for success and place the entire program at risk should the flight end in failure. On the other hand, although the probability of mission success would have been higher with a pilot on board, the personal risk to the pilot on the first flight was extremely high and the entire U.S. manned space program would have been in jeopardy had the pilot not survived, regardless of the reason. The decision was made for an unmanned first launch with the hope that the glider could perform an automatic reentry and automatic landing on the dry lakebed at Edwards. Five subsequent piloted flights, some that were to achieve multiple orbits, were planned.

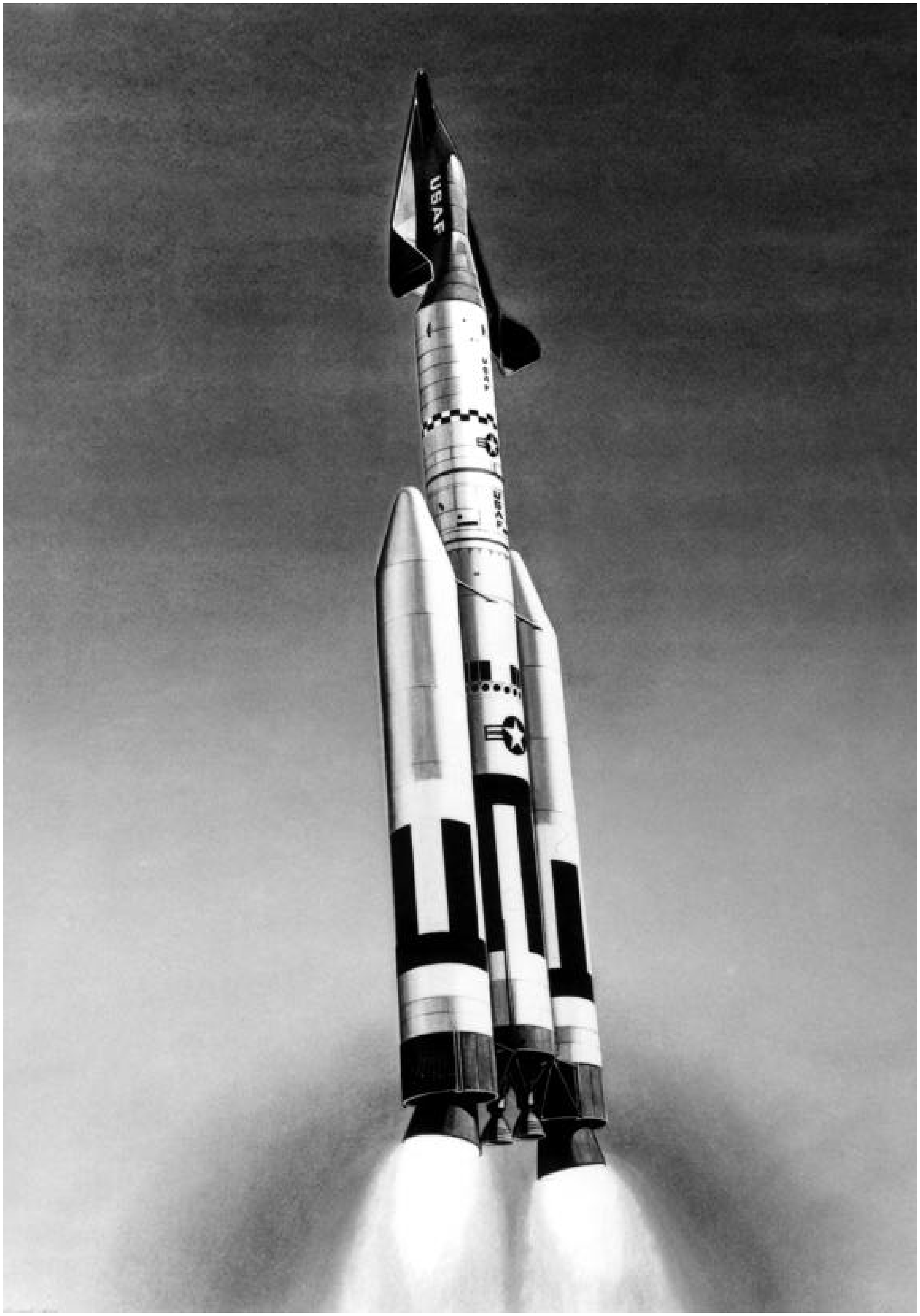


Figure A-4: Dyna Soar Glider on Titan III Booster

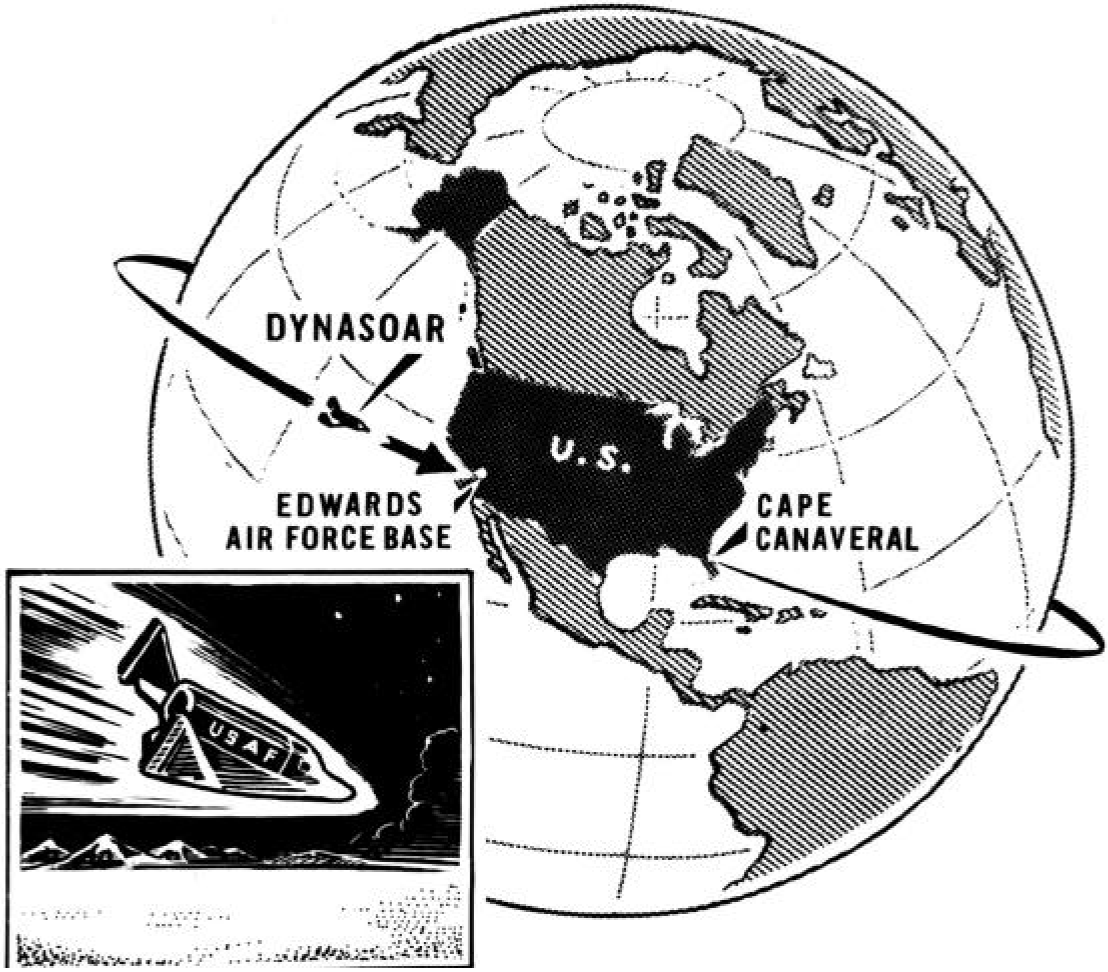


Figure A-5: Once-Around to Edwards

2.0 The X-20 Glider

The X-20 glider was a single-seat, delta-winged aircraft (Figure A-6). The design of the glider progressed normally even though the selection of a booster for the program changed frequently. The design weight of the glider was allowed to grow somewhat after the decision was made to use the Titan III booster and had reached about 13,500 lbs. at program termination. Notice that the X-20 glider was designed from the outset as a lifting reentry research aircraft. The glider was to incorporate overdesign where predictions were uncertain, and to be capable of exploring lifting reentries over a wide range of L/D's. The only payload for the research glider was a 1000-pound instrumentation package to gather the research data.

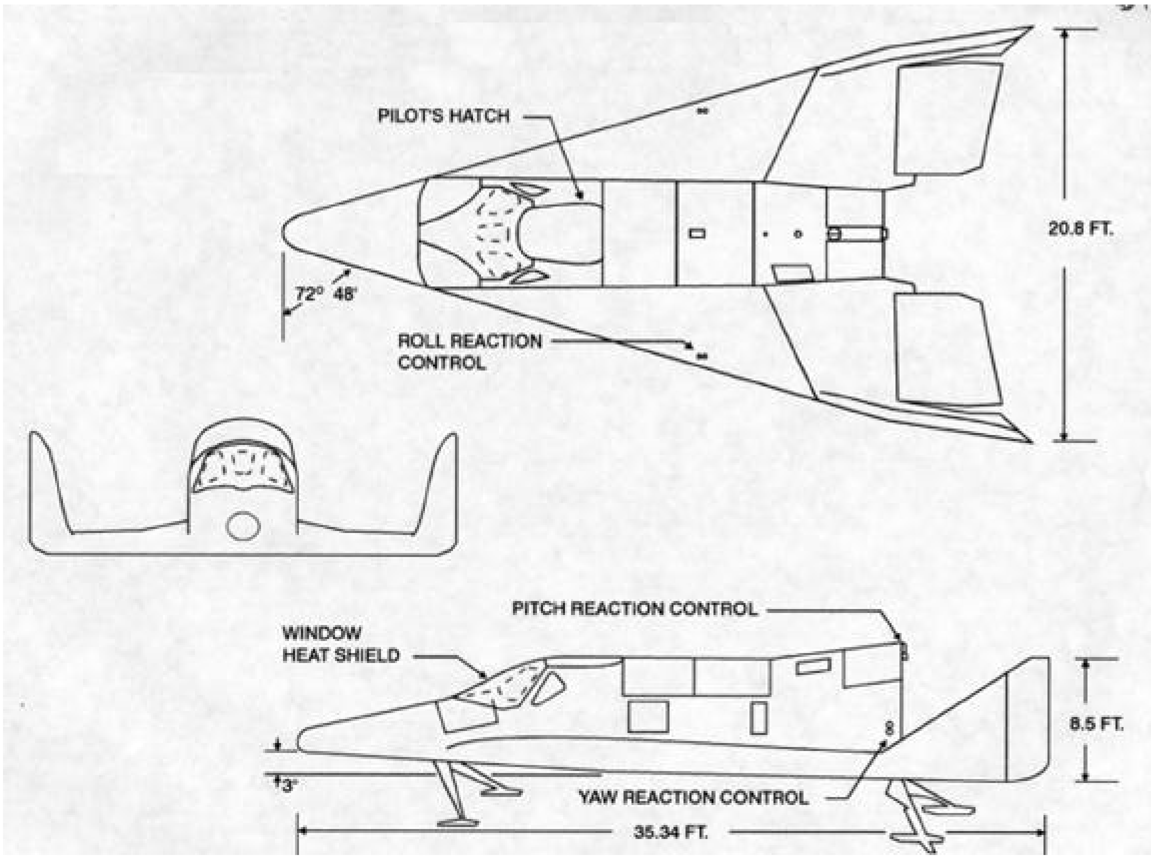


Figure A-6: Dyna Soar, X-20 Glider

2.1 Aerodynamics

The general shape of the X-20 was similar to that of a delta wing airplane such as the Navy F5D or the Air Force F-102 and the subsonic and transonic aerodynamics were similar. The predicted maximum L/D during entry (Mach 20) was 1.8, while the maximum L/D at landing was 4.25. The entry maneuver was designed to occur on the back side of the L/D curve while the approach and landing was to use the front side of the L/D curve (Figure A-7). The glider was designed to be stable and controllable over a large angle of attack range and could fly an entry at any selected L/D between 0.6 and 1.8 (corresponding to angles of attack between 55 and 18 degrees). By combining different bank angles with different L/D's, the vehicle could fly a wide variety of entry trajectories. Selecting a low L/D with zero bank would result in a very short, straight-ahead trajectory. Selecting a high L/D with a large bank angle would produce a long, turning entry and very high cross-range. The ground pattern produced when all possible entry trajectories were plotted was commonly referred to as the entry "footprint" (Figure A-8). Any landing site that was within the "footprint" at any point in time during the entry could be reached by the glider. The size of the footprint got smaller as the vehicle decelerated during the entry. The entry footprint for the X-20 at the beginning of its entry was expected to be approximately 3,000 miles wide and 8,000 miles long. The subsonic L/D of the X-20 was very similar to the X-15 airplane and the unpowered approach and landing techniques developed for the X-15 were expected to be applicable.

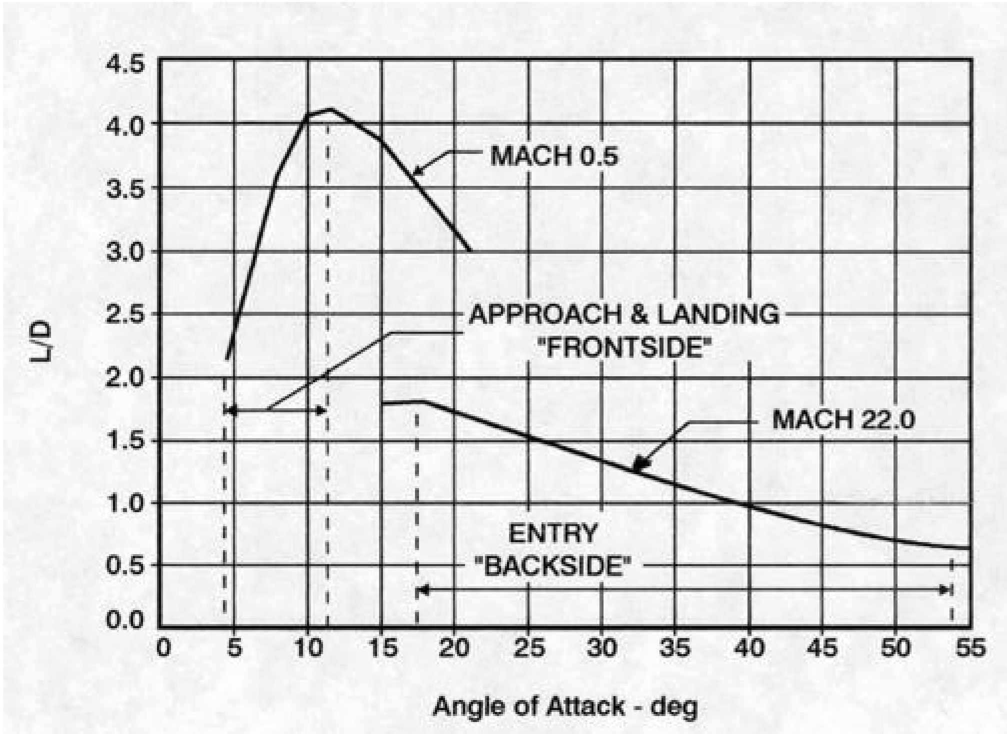


Figure A-7: X-20 L/D vs. Angle of Attack

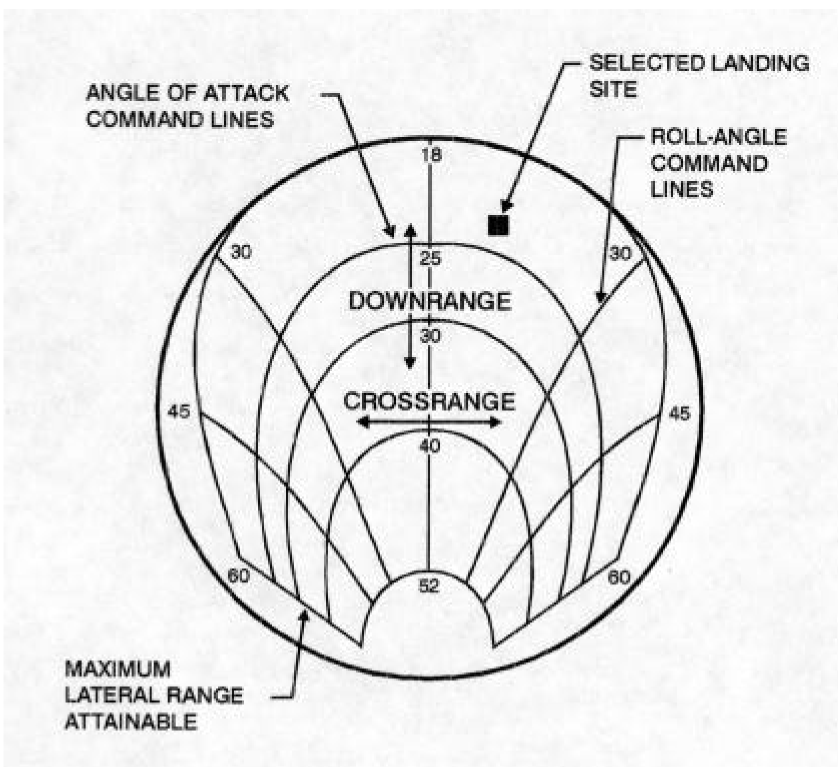


Figure A-8: Energy Management Overlay, X-20

2.2 Thermal Protection

The thermal protection system for the X-20 was a major challenge for the structural designer as well as the metallurgist. The structure was designed to achieve an equilibrium heating condition during the entry wherein the heat being generated was radiated back to space. Unlike the ablative or heat sink concepts, this design placed no time constraints on the entry. It was expected that the vehicle would be reusable with only minor refurbishment between flights. New materials were developed and tested to withstand the predicted wing leading-edge temperatures of over 3000 degrees Fahrenheit (F). Coated Molybdenum alloy panels were used on the wing leading edge and Coated Columbium alloy panels were used on the lower surface. A special nose cap composed of Zirconia rods imbedded in graphite was developed to withstand the 4200-degree F temperatures expected at the nose of the vehicle. The upper surfaces, where temperatures were expected to be about 1000 degrees F, were constructed primarily of Rene 41, a steel alloy. Each external surface panel overlapped the adjoining panel like shingles on a roof. This allowed adjacent panels that were experiencing different temperatures to expand and move relative to each other without causing buckling and possible burn-through.

The internal load carrying structure was also Rene 41. The high temperature, radiative panels on the wing leading edges and lower surfaces were backed with a ceramic wool-like insulation to reduce the heat transfer to the internal structure. There were two major concerns regarding this type of structure: (1) Could the exotic materials be produced, and then manufactured into a practical structure, and (2) Could the internal loads and deformation of the structure caused by the heat be accurately predicted?

The wide range of L/D's (and therefore wide range of angles of attack) that were being sought meant that the thermal protection system for each individual location on the glider had to be designed for the worst-case heating environment. The nose cap and wing leading edges received the highest heating at low angle of attack (high L/D) while the bottom of the wing and control surfaces received their highest heating at high angle of attack (low L/D).

2.3 Flight Control and Guidance

The X-20 flight control surfaces were standard for a delta winged airplane. The vehicle was equipped with two elevons at the wing trailing edges for pitch and roll control and two rudders at the rear of the two tip fins for yaw control. The surfaces were operated by an analog, triply-redundant, self-adaptive, fly-by-wire flight control system. Pilot inputs were accomplished by a side-arm control stick and rudder pedals similar to those used in the X-15. Although the glider was statically stable throughout the entry, the aerodynamic damping was expected to be very light, thus a complex control system was necessary. A reaction control system (small rockets used to control vehicle attitude in space) was merged with the aerodynamic controls for periods of operation in space and during the early phase of entry.

An inertial platform provided the basic information for the entry guidance system. An oscilloscope in the cockpit was used in conjunction with a mechanical film overlay system to present information to the pilot. Two display modes were available. The primary display showed the "footprint," that is, the position of the glider relative to the available landing sites, and allowed the pilot to select the best L/D and bank angle to reach the desired site. The large size of the footprint allowed the pilot to select an alternate landing site even after initiation of the entry (Figure A-8). The second display mode showed the current temperature margins for various critical external locations on the glider. The overlays changed automatically with velocity during the entry and showed the continual reduction in the size of the footprint as energy was dissipated (Figure A-9).

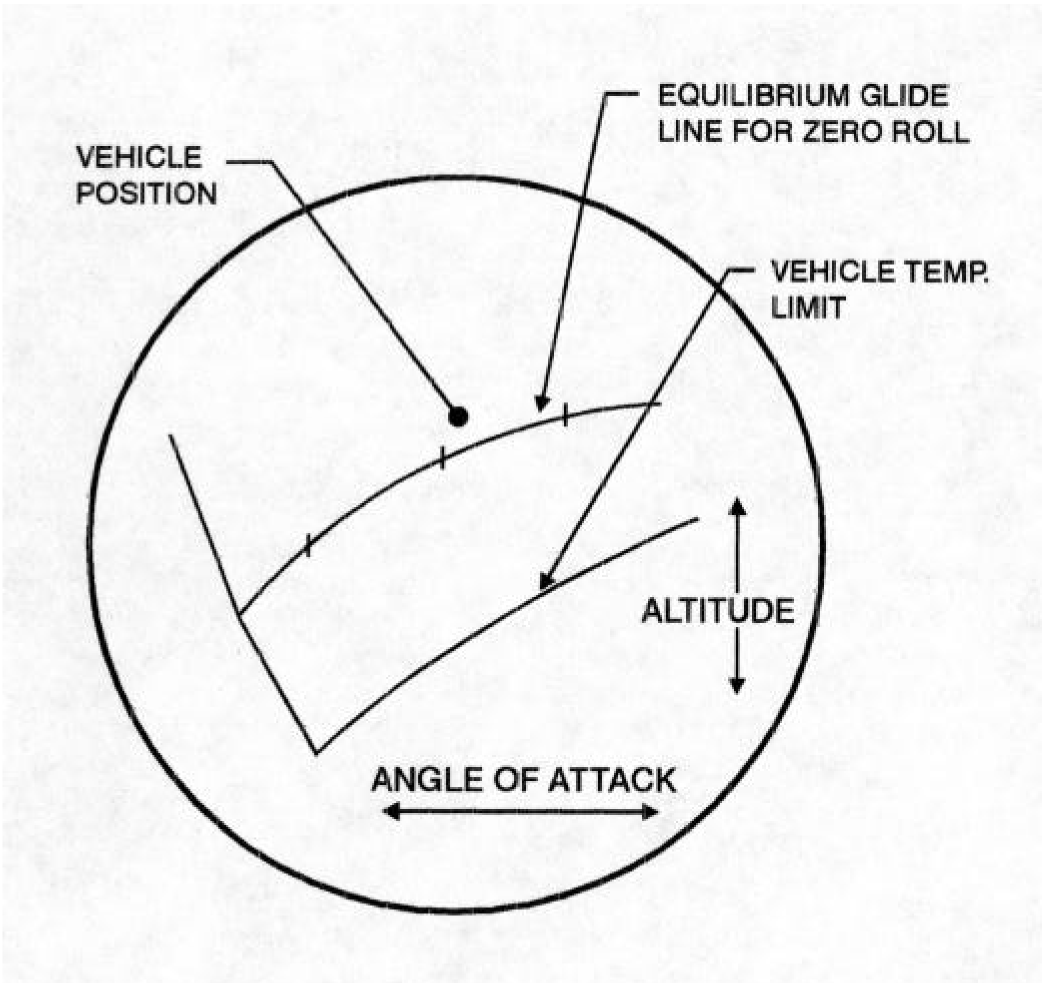


Figure A-9: Flight Integrator Overlay, X-20

The flight control and guidance concepts were tested extensively in fixed-base analog simulators, both at Edwards and at Boeing, a lesson learned from the X-15 program. (Pilot comments regarding the X-20 simulator are included in Appendix B.)

An idea that evolved during the X-20 program was the potential use of the pilot to control the Titan III booster during the ascent phase of flight. Simulator studies performed at Boeing and on the centrifuge at Johnsville, Pennsylvania, showed that the pilot could quite easily provide control inputs to the booster autopilot based on the glider guidance displays. This could have provided the necessary guidance redundancy without complicating the booster/glider interface (Reference Hoey, 1965).

2.4 Other Subsystems
Since the temperature of the external surface of the X-20 would stabilize at very high values, it was necessary to provide an internal, double-walled compartment for the cockpit, instrumentation and other operating subsystems.

The crew escape system for the X-20 went through an interesting evolution. Four solid rockets were installed directly behind the glider in the interstage structure when it was on the booster. All four rockets could be ignited instantly by the pilot at any time from before lift-off to the point of booster separation. The entire glider would then separate from, and quickly accelerate away from, the booster. The concept was similar to the escape towers used on all of the NASA manned launches prior to Space Shuttle, except that the rockets were behind the vehicle rather than on a tower above it. From the launch pad the escape rockets could boost the glider vertically to an altitude of nearly a thousand feet. There a half loop and turn could be performed to a landing on the nearby "skid strip" at Cape Canaveral. Assigned X-20 pilots at Edwards practiced these maneuvers in an F5D aircraft. They pulled up to a vertical climb from a low altitude over the lakebed, then retarded the power and completed the glider-like landing. During boosted ascent the escape rockets could separate the entire glider from an exploding or burning booster. The escape rockets were also planned to be used as primary propulsion during a B-52 air-launch program. They would boost the glider to a slightly supersonic speed in order to explore the glider's transonic flight characteristics.

For the remainder of the flight, following booster separation, the initial glider design would have used an escape capsule. This capsule consisted of the forward segment of the glider including the cockpit and some subsystems. When escape was initiated during reentry, the capsule was designed to trim itself to an acceptable angle and perform a low L/D lifting reentry to a predetermined altitude at which a parachute would deploy. As the design of the glider and capsule proceeded, the complexity and added weight of the escape system become more critical. The sharp pitch-up that accompanied the capsule separation was also expected to incapacitate the pilot for some period of time. A decision to make the reaction control system in the capsule redundant led to a counter-proposal to reduce the glider control system redundancy from three to two systems. It became obvious that the design team was attempting to create "an airplane within an airplane," and that overall safety would be enhanced by concentrating the redundancy and backup systems toward the successful recovery of the glider itself. As a result, the escape capsule was replaced with a standard ejection seat for low altitude escape only.

The X-20 carried a protective heat and glare shield over the forward window of the cockpit which was to be jettisoned at about Mach 3, after entry and before landing.

Since standard tires would have been very difficult to protect within the hot structure, the landing gear consisted of two wire-brush skids at the rear of the aircraft and a nose "dish" at the front. The landing gear were to be extended just before touchdown, a technique used successfully in the X-15 program. The X-20 had no ground steering capability. It was expected that the higher friction of the aft wire-brush skids compared to the friction at the nose "dish" would help maintain a stable and straight slide-out.

3.0 Configuration Reassessment (Phase Alpha)

A major program reassessment was initiated in late 1962. NASA and several contractors (including Martin) had conducted preliminary wind tunnel tests at high Mach number on several lifting body configurations with maximum entry L/D's of 1.0 to 1.4. There was a strong opinion that these configurations would be quicker to build than the winged X-20 because standard internal structural materials with ablative heat shields could be used. In addition, a lifting body would have more usefulness as a space supply vehicle due to its higher volumetric efficiency. Land-ability of these vehicles was still an open question. Lifting body supporters criticized the X-20 as being an inefficient entry configuration and cited the heavy thermal protection system, unnecessary wings, and low payload fraction. These comments ignored the fact that the glider design did not attempt to optimize payload fraction. The design was aimed at gathering research data from which to optimize future entry vehicle designs; a similar philosophy had been used to select the X-15 configuration. Proponents of the X-20 felt that the lifting body principle had a very limited capability for lifting entry research and that the major refurbishment of the heat shield required after each flight would greatly impact the potential operational capability. Responsible for most of the funding for the X-20, the Air Force continued to stress the requirement for high cross-range and thus argued to continue the X-20 as an entry research program.

The assessment team recognized that the winged X-20 design was more technically challenging than the more expedient approach of the lifting bodies, but also recognized that the X-20 had been under detailed design for several years whereas the lifting body detailed design had not yet begun. The decision was made to continue with the winged X-20 glider concept.

4.0 Program Cancellation

Secretary of Defense Robert S. McNamara cancelled the X-20 Dyna Soar program in December of 1963. He reasoned that the immediate need for evaluating man's usefulness in space could be accelerated by reallocating funds to the Air Force Manned Orbiting Laboratory (MOL) program, which was to use the Gemini capsule for the manned entries. Lifting entry research was to be continued using small unmanned test vehicles such as the ASSET program (Aerothermodynamic/elastic Structural Systems Environmental Tests, already underway, described in Section 4.4) and a new lifting body research effort called START (Spacecraft Technology and Advanced Reentry Test, described in section 6.2.1). In 1969 McNamara also cancelled the MOL program thus ending all Air Force attempts to identify a military role for man in space (Reference Geiger as quoted by Hallion, Vol. I, 1987).

4.1 Status at Cancellation

At the time of the X-20 program cancellation nearly all of the engineering drawings for the glider had been completed. For the first vehicle, construction of the pressurized compartment for the pilot and subsystems was essentially complete. The wing spars, vertical tail spars, and fuselage primary structure were in the final assembly jig.

A complete, fixed-base piloted simulator was operating at Boeing in Seattle, Washington. It was capable of simulating the entire mission from lift-off to landing. A pilot-in-the-loop centrifuge program simulating the boost phase had been successfully completed at the Naval Air Development Center at Johnsville, Pennsylvania. Following completion of the centrifuge program, the X-20 centrifuge cockpit was shipped to the Air Force Flight Test Center (AFFTC) Simulator Laboratory at Edwards and was used in an all-analog piloted simulation of the entry. This simulation was operating at the AFFTC where research flight test planning was under way. The AFFTC simulation capability was being expanded to become an orbital, full mission simulator.

When the X-20 was cancelled, the first developmental launch of the Titan III (without any payload) was approximately a year away. The first air-launched glide flight of the X-20 from a B-52 was about a year and a half away, and the first boosted flight of the combined Titan III and X-20 was about 2 1/2 years away.

4.2 Known Problems

Several known technical problems or expected delays were on the horizon at program termination in late 1963. None of these were considered major hurdles by the X-20 team members at the time, but their true impact will never be known.

(1) The manufacturing department at Boeing was undergoing a major learning process trying to develop methods for forming, fastening, drilling, and otherwise working with the exotic high temperature materials (Coated Columbium, Coated Molybdenum, Rene 41). This necessary learning process was causing delays in the glider assembly.

(2) Recent tests had shown that the landing gear brushes and nose plate were inadequate for landings on concrete runways due to excessive wear and inadequate tracking stability. Alternate concepts were under development.

(3) Some relatively minor structural problems existed at the interface between the glider and the booster, but a much more serious problem was related to the glider/booster aerodynamics. The winged surfaces of the glider, mounted at the forward end of the booster, created a large static instability during the early phase of boosted flight through the atmosphere. The addition of fins at the rear end of the booster would regain the static stability (as proposed on the Titan II version). Wind tunnel tests, however, uncovered some unexpected aerodynamic interference effects between the forward wing and the aft fins; this interference negated the effectiveness of the aft fins. The added weight of the fins was also undesirable. Increasing the control capability of the rocket nozzles allowed the instability to be properly controlled without the added fins. This change introduced excessive structural loads in the booster and also in the glider/booster interstage structure. At program termination, a solution was still being sought. (The lifting body concepts eliminated, or at least minimized, this destabilizing effect since the overall vehicle width would have been about the same as the diameter of the booster.)

(4) The piloted approach and landing capability of the X-20 were not in question due to the similarity to the X-15 landings. The decision had been made that the first boosted flight would be unmanned. The ability to accomplish a steep, high speed, gliding approach and flare automatically, without a pilot on board, was a new challenge. Many in the flight test community believed that the drone technology that was under development would be inadequate.

4.3 Assigned Pilots

Six test pilots had been selected for the program. They were in training and they were directly participating in the cockpit and systems design process at Boeing (Figure A-10). The designated pilots were:

Maj. James W. Wood	USAF (Chief pilot)
Maj. Henry C. Gordon	USAF
Maj. William J. Knight	USAF
Maj. Albert H. Crews	USAF
Maj. Russell L. Rogers	USAF
Milton O. Thompson	NASA

X-15 pilots Neil Armstrong and William Dana (both of NASA) also participated as engineering test pilots supporting the X-20 development.

Figure A-10: Assigned Pilots for the X-20 Dyna Soar

4.4 Enduring Legacies of Dyna Soar

Several of the systems that were developed for the X-20 program found a place in the continued technology advance of the early 1960's.

(1) The ASSET program was initiated by the Air Force Flight Dynamics Laboratory (AFFDL) at Wright-Patterson Air Force Base (WPAFB) in 1961. The goals were to validate some of the critical technologies needed for lifting entry, and to support the Dyna Soar program (It was, however, funded separately from the Dyna Soar program). McDonnell Aircraft was to build and flight test an unmanned vehicle with a representative nose cap and heat shield to validate the "hot structure" design concept. Designed to accomplish a lifting reentry, the vehicle represented the forward 4 feet of the X-20 glider in most respects (Figure A-11). The nose cap, leading edges, lower surfaces, and upper surfaces were of the same material and design as the X-20. Six vehicles were built and tested between September 1963 and March 1965 (mostly after cancellation of the X-20 program). They were launched from either Thor or Thor/Delta rockets from Cape Canaveral, and they reached conditions which were very close to the peak heating environment for the X-20. One vehicle was lost as a result of a booster malfunction. The remaining five vehicles survived the reentry and transmitted research data to ground receiving stations as planned. Three of the successfully launched vehicles were equipped with recovery systems but only one vehicle was actually recovered. It is on display at the Air Force Museum at WPAFB. Although this program received little attention at the time, its success validated the X-20 "hot structure" thermal protection concept (Reference Hallion, Vol. I, 1987).

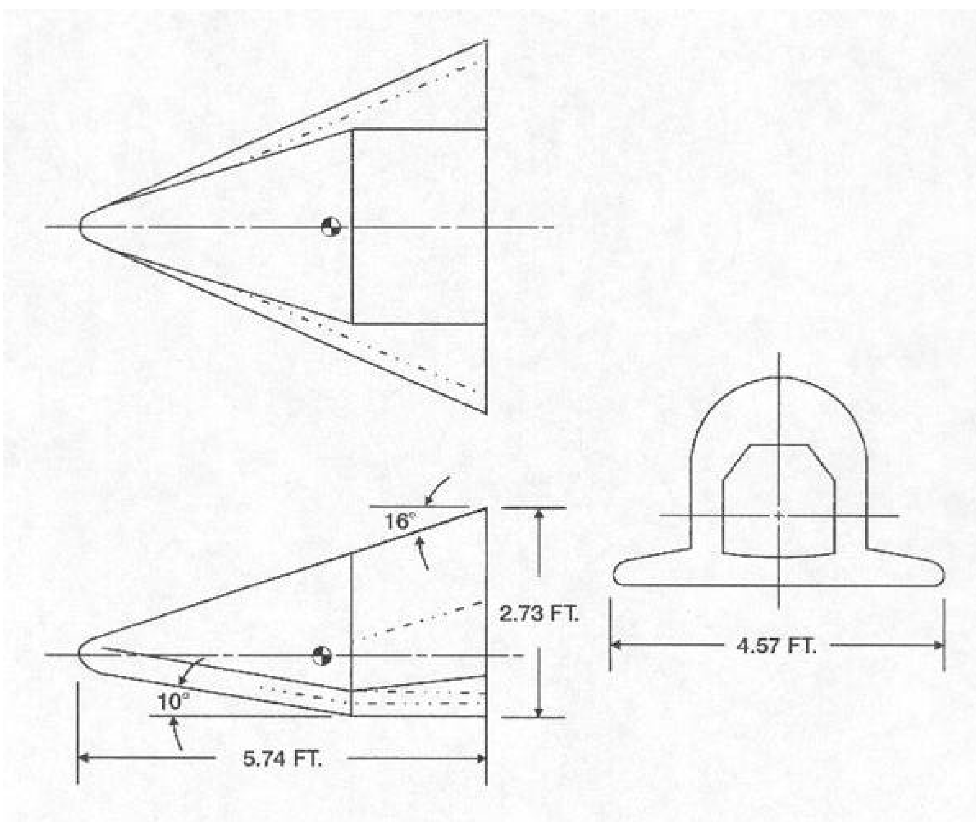


Figure A-11: ASSET Vehicle Configuration

(2) The fly-by-wire flight control system designed for the X-20 had been successfully demonstrated on an F-101 test bed aircraft. Even before cancellation of the X-20 program, the control system design (known as the MH-96 Flight Control System) was adapted to the X-15 mission and was installed in the #3 X-15 . The features of the system, including the autopilot and the merging of aerodynamic and reaction controls, were demonstrated on many successful X-15 flights. The pilots stated that the MH-96 system provided a significant improvement in the airplane's reliability and safety, as well as a reduction in pilot workload. The success of this system led to the development of a similar self-adaptive, triply-redundant, analog system for the F-111 fighter-bomber aircraft.

(3) A special instrumentation system under development for the X-20 flight test program became the first Pulse Code Modulation (PCM) airborne instrumentation system. It was well along in development at the time of X-20 cancellation. The NASA FRC at Edwards recognized the potential value of this system and continued support of its development. The hardware, known as the CT77 Instrumentation System, was used on all the lifting body programs as well as on many other research programs conducted at FRC in the 1960's and 1970's.

(4) The Inertial Guidance System that was developed for the X-20 program also found its way into the X-15 program, where it provided a major improvement in accuracy for the later high-altitude flights.

(5) The X-20 laid much of the ground work for the crew escape philosophy which is used in the Space Shuttle today. The decision to dispense with the escape capsule on the X-20 glider recognized that it was not practical to provide an escape mode for all aspects of a space flight. This philosophy was first accepted on the X-15, which was equipped with a rocket ejection seat. The seat was designed for successful ejections below approximately Mach 4 and 100,000 feet even though the aircraft could attain speeds above Mach 6 and altitudes above 250,000 feet. The probability of a need to escape from the higher altitudes and speeds was considered so remote by the designers and the procuring government agencies, that the additional weight, cost and complexity of a sophisticated escape system was not warranted. This philosophy has been carried through all U.S. manned space programs to date, including the Space Shuttle. In case of an emergency, the entry vehicle itself is considered the primary method for returning the crew to subsonic speeds. Design safety features, usually in the form of system redundancy, are incorporated in the entry vehicle to insure that it can function following most high-probability space emergencies.

(6) The booster man-rating concept was first addressed during the X-20 program. The smaller rocket engines which were developed to fly the early research airplanes contained sensors which automatically stopped the engine if an unsafe condition was detected. The pilot would then glide to a landing and the flight would be repeated on another day. For a single or twin-engine ICBM class booster, such as the Atlas or Titan, shutting down an engine after lift-off would have been disastrous. The escape towers and escape rockets used on the early manned flights of these boosters were designed to fly the manned vehicle away from the booster in the event of a fire or explosion. Later boosters designed to carry manned payloads incorporated various levels of redundancy and fail safety in the control and guidance systems and also multiple rocket engines which would allow the mission to continue even after the loss of one engine. One engine failed during the boost phase of Apollo 13, but the boost was completed successfully. Although the X-20 did plan to use an abort rocket, the program highlighted the need to merge the airplane and booster man-rating philosophies.

Appendix B

Pilot Comments

Lifting Body Handling Qualities

The X-20 Simulator

by Robert G. Hoey June 1994

The X-20 never reached the flight test phase. The only prediction of the potential handling qualities of this vehicle were through the engineering simulators that were in use at the time of program cancellation. Although I was a stability and control engineer and not a test pilot, I had accrued many hours in the X-20 simulators both at Edwards and at Boeing. (I also held a Private pilots license.)

There was ample wind tunnel data obtained on the X-20 glider configuration from Mach 20 to landing. There was, however, suspicion of the shock tunnels and other data sources for data above Mach 8 as well as in the prediction of real-gas effects at altitudes above 200,000 feet.

The Minneapolis-Honeywell, analog, fly-by-wire flight control system (which evolved into the MH-96 system flown on the X-15) was a very advanced concept in 1960 and incorporated a self-adaptive feature. This concept adjusted various parameters within the electronics to force the handling characteristics of the vehicle to remain essentially constant even though flight conditions were changing. One insidious aspect of the self-adaptive feature was its ability to mask a gradual degradation of handling qualities until the flight control system had reached its ultimate limits. The loss of control which followed was then very abrupt and usually unrecoverable.

At hypersonic speeds (above Mach 5) the X-20 was trimmable over an angle of attack range of 15 to 55 degrees. The windshield cover was to be in place until the vehicle was below Mach 4, so visibility during entry was limited to the two small side windows (a little like Lindbergh's "Spirit of St. Louis"). Piloting was done strictly using the instruments with no reference to the outside until the windshield cover was blown off.

The large angle of attack range of the vehicle raised an interesting discussion relative to the most suitable use of the rudder pedals and lateral stick deflections by the pilot. The normal fighter-type concept was to mix the controls such that lateral stick deflections produced a roll about the flight path of the vehicle. The rudder pedals were not used except for cross-wind landings. At 55 degrees angle of attack in the X-20, however, the pilot was well aware of the extreme nose-high attitude and, to some pilots, it was more natural to use the rudder pedals to "yaw" the fuselage to the desired bank angle rather than use lateral stick deflections. The decision was made to continue with the standard fighter-type control of lateral stick for bank angle control. This philosophy has been retained on the Space Shuttle Orbiter which uses a 40-degree angle of attack during entry.

The X-20 simulator had excellent handling qualities when the control system was functioning normally. The reaction control rockets were blended with the aerodynamic control surfaces during the early phase of the entry. The vehicle response to control inputs was very slow during this early phase of the entry. As soon as the aerodynamic controls became effective on their own (at about 15 pounds per square foot dynamic pressure), all three axes of the reaction control rockets were disengaged. The control response gradually improved until the dynamic pressure reached about 50 pounds per square foot at about Mach 20, then remained the same until the vehicle reached subsonic speeds. Vehicle response during most of the entry was more like a cargo airplane than a small, fighter-like research airplane. Subsonically the X-20 simulator became much more responsive. Handling qualities were excellent and much like the X-15. A speed brake capability was provided by flaring both rudders outboard. Speedbrake capability was shown to be necessary for landing accuracy during the X-15 program.

Unlike the Space Shuttle, the X-20 was statically stable in all axes during the entire entry. Malfunctions, or pilot selection, could place the flight control system in a "manual-direct" mode in any, or all axes. While in this mode, stick deflections produced direct and proportional motion of control surfaces with no electronic sensing or assistance. The manual-direct mode produced marginal handling qualities. The vehicle was neutrally damped in all axes and any small disturbance initiated an oscillation that was very difficult to stop. If the oscillations were allowed to become too large, the heating limits would be exceeded on the control surfaces. If only one axis was disengaged, a successful entry could be performed, but it required the full concentration of the pilot.

As the angle of attack was reduced below 20 degrees at high Mach numbers, the longitudinal stability and elevator effectiveness gradually deteriorated. Below about 13 degrees angle of attack the simulator would exhibit an uncontrollable "tuck" and heating and load limits would be exceeded very quickly. Maximum L/D was at 18 degrees angle of attack so there was little reason to fly intentionally into this region. This gradual deterioration was evident to the pilot if he was slowly reducing angle of attack in the manual direct mode, but was masked by the flight control system if it was fully engaged and final loss of control was very abrupt.

The energy management task also created a moderately high pilot workload. The large range of L/D's available to the X-20 pilot allowed him to merely monitor the energy situation until fairly late in the entry (about Mach 10). Simulation studies on the Edwards simulation showed that the test pilots could establish a series of selected bank angles and angles of attack, and stabilize at each condition for data gathering purposes during the initial phase of entry. While performing these tests, they were able to simultaneously monitor the energy management task so as to keep the desired landing site within the vehicle's capability. They could choose to stop doing tests at any time and concentrate on the energy management task of flying to the selected landing site.

Considering the strong probability that the aerodynamics and operation of subsystems would NOT have been exactly as predicted, the pilot work load during an X-20 entry would have been very high. (On the first X-15 flight after installation of the MH-96 control system, all three axes failed to the manual-direct mode at launch. All were successfully reset, but the pitch axis tripped, and was reset, 16 more times by pilot Neil Armstrong before landing.)

End: Hoey

Bruce Peterson and the M2-F2

The M2-F1, HL-10, and the M2-F2
by Bruce Peterson May 1994

The M2-F1 Handling Qualities

The M2-F1 had a conventional canopy design, a nose window, and a left side window on the forward fuselage. The transparencies had fairly good optical qualities although the nose window had a fairly small field of view. The left side window was generally used only for space positioning during left hand turns. The flight profiles were set up so that all major turning was to the left.

When the aircraft was towed, either by ground tow vehicles or airplane (C-47), the primary viewing was through the canopy. When the aircraft was rotated to the takeoff position, the nose window was the primary source of visibility. The curvature of the nose window and the limited field of view decreased the pilots ability to see attitude changes and hampered depth perception. When being towed by the C-47, the M2-F1 took off before the C-47 so as to stay out of the slipstream of the C-47 and to have good visibility of the tow aircraft through the nose window.

As I recall, the tow speed was about 95 knots. We towed to altitudes as high as 14,000 ft MSL (about 12,000 feet above the ground). When reaching the correct altitude and position over the ground, we lined up directly behind, and about 50 to 75 feet above the tow aircraft. This minimized lateral or directional transients and kept us out of the tow aircraft slipstream when the tow rope was released. Immediately after release a turn was made, usually to the left, to keep out of the turbulence from the tow plane.

The test maneuvers were then flown. On completion of the tests, the aircraft was on final approach. Pre-flare airspeed was about 110 knots and the flare to landing started about 300 feet above the lakebed. During the flare, viewing was transferred from the canopy to the nose window. That was when depth perception became somewhat more difficult. This fact contributed to at least one hard landing.

Directional control of the M2-F1 on the ground was accomplished through the use of differential braking when the nose wheel was on the ground, and with rudders with the nose off the ground. Once airborne heading control was accomplished with the lateral stick which controlled the outboard lateral control surfaces. Rudder was not used due to lag in control response and the high roll-to-sideslip characteristics.

The M2-F1 also had adverse yaw due to lateral stick inputs. Coupled with this was the high roll-to-sideslip characteristic. This caused an interesting control response: If you wished to turn left, you would apply left stick. The immediate aircraft reaction was a slight left yaw and right roll. After about one second the lateral control would overcome the roll due to sideslip and the aircraft would then roll to the left, as commanded. This characteristic was particularly noticeable while being towed. During towing the pilot gain is high, that is the pilot tries to make corrections as quickly as possible. The tendency was to correct for the initial roll that was in the wrong (uncommanded) direction. If you fell into this trap you could be in a lateral directional pilot-induced oscillation (PIO) very quickly. In fact, I believe that is why one pilot did lose control and ended up doing a complete roll while on tow. He did this on both of his tows from behind the C-47. In both cases he released from tow and landed safely. This pilot had very fast reactions which caused the PIO. Once off tow this characteristic was not so disconcerting since pilot gain was reduced and the aircraft only appeared to have a slight lag to lateral control inputs.

The M2-F1 in free flight had fairly good handling characteristics. Pitch control was positive and well damped. Steady state sideslips could be accomplished smoothly, although it required high pilot concentration. Control harmony between lateral and directional control was good if controls were applied slowly and smoothly. Level flight sideslips were accomplished to the maximum when lateral and directional controls were both at their maximum deflections.

The main landing gear used regular light aircraft wheels and brakes. The shock absorbers were Sears automotive shocks. These were filled with 90-weight oil to give them the desired shock absorbing characteristics for typical summer temperatures. In December 1963, on a cold day, a hard landing was made. The shock absorbers were very stiff due to the cold temperature. This combination caused both of the main wheels to break off on landing. Fortunately both wheels failed at the same time allowing the M2-F1 to decelerate rapidly, but straight ahead. No braking was required! On subsequent flights the shocks were replaced with bungee cords.

The aircraft had a small solid rocket engine to provide thrust to help in landing if extra energy was needed. This rocket provided about 250 pounds of thrust for about 10 seconds. The thrust vector was through the M2-F1's center of gravity. The ignition of the rocket motor caused almost no transients and the motor performed as expected. This engine was tested on ground taxi tests and in-flight during landing approaches. The rocket was used on two occasions to extend the flight time following emergency releases from the tow plane at low altitude.

The flight tests of the M2-F1 gave confidence that the heavy weight Lifting Body Program was feasible from a handling qualities, flight controls, and approach and landing (low L/D) standpoint. The M2-F1 program solved one part of the puzzle regarding the feasibility of using a Lifting Body for a space reentry vehicle to achieve a preplanned horizontal landing.

The HL-10 Handling Qualities

These pilot comments are limited to the configuration of the HL-10 on its first flight only. After the first flight the aircraft outboard fins were redesigned to remedy some of the problems observed on the first flight of the HL-10.

The HL-10 had a canopy that was conformal with the aerodynamic mold line. Forward of the canopy bow there was a conformal transparency. The blunt nose was entirely transparent and fairly close to the pilot. This arrangement gave the pilot a good field of view. The shape of the nose window caused a visual distortion so that the pilot was closer to the runway than visually perceived. This problem occurred during the landing flare when the pilot transferred his vision from the canopy to the nose window. A true perception of altitude did not occur until the aircraft reached a very low altitude.

The first launch of the HL-10 (December 22, 1966) from the B-52 was at 45,000 ft and .65 Mach No. The launch was very positive with only a slight roll and yaw excursion. The aircraft was well trimmed in all three axes. Immediately after launch a high frequency vibration was noted that increased in severity as speed increased. It appeared obvious the problem was in the flight control system. The ground station, which was monitoring many aircraft parameters through a telemetry system, identified the problem as a limit cycle in the yaw axis. The pilot had control of the gain on all of these flight control axes in the cockpit. The yaw gain was lowered and the major vibration went away.

The ground station also noted a small amplitude limit cycle in the pitch axis but this was not as apparent to the pilot. Several pitch control gains were made during the flight as directed by the ground station. Pitch sensitivity was high, and increased with speed.

One of the planned maneuvers during the flight was to do a practice landing flare at altitude to give confidence that the actual flare to landing would not present a problem. As the aircraft slowed and as the nose came up toward a landing attitude, the aircraft did not respond properly to roll commands. The stick ended up full left and aft with the aircraft not responding. The nose was pushed over and normal roll control returned. The reason for this problem was not determined by the pilot or the ground station.

The pilot immediately decided that the only way he could make a successful landing was to keep the angle of attack low (high speed) and land before lateral (roll) control and possibly pitch control was lost. The planned preflare airspeed was about 300 knots indicated airspeed (KIAS). The pilot nosed over early in the approach to get airspeed up to about 340 KIAS, so that the handling qualities could be evaluated while altitude and time were still available to make an ejection if the aircraft became unflyable. Pitch limit cycle again appeared and the pitch gain again reduced. Pitch control became very sensitive but remained manageable. The landing flare was initiated at about 320 KIAS. The flare was competed at about 30 feet altitude. The final part of the flare had a small, but abrupt, nose up command when the pilot realized he was closer to the ground than he thought he was earlier in the flare. He put the gear down at higher than planned speed, so he could land before any loss of control. Landing was at about 280 KIAS. The aircraft became slightly airborne after initial landing probably due to the pitch sensitivity. Landing rollout and braking was as expected. Flight time was 3 minutes and 9 seconds.

The problem of the limit cycle was shortly solved. Control effectiveness was higher than predicted by wind tunnel testing. There was a feedback through the SAS (stability augmentation system). This problem was solved by reducing SAS gains and altering the filters in the SAS electronics. The problem of stick sensitivity was solved by a simple reduction in the stick-to-elevator gearing.

The reason for the loss of lateral and pitch control at high angles of attack was difficult to determine. A great deal of analysis of the data was required. The final conclusion was that there was an airflow separation over the control surfaces at the higher angles of attack (AOA). This caused the loss of hinge moment (control effectiveness) and thus loss of control. The problem was isolated to flow separation over the outboard vertical fins. The fix to the problem was to add camber to the outboard vertical fins. This modification was accomplished along with changes in the flight control system and the second flight of the HL-10 was flown on March 15, 1968. All of the changes were successful and the HL-10 landed with no problems.

The M2-F2 Handling Qualities

The M2-F2 canopy was a bubble above the mold line of the basic aerodynamic shape. The cockpit was farther forward than the M2-F1. The M2-F2 also had a nose window that was needed for the final approach and landing. This combination gave the pilot reasonably good vision in all phases of flight. Unlike the HL-10, forward visibility through the window did not give an allusion of higher-than-actual altitude above the ground.

Upon launch from the B-52 at 45,000 feet and .65 Mach number, a roll and yaw excursion occurred that was very brief. The launch was very positive. The aircraft flew very much as wind tunnel tests, T-33 variable stability tests, and simulation had predicted. The only exception was the low angle of attack characteristics.

Flight tests with the variable stability T-33 (CALSPAN) showed a lateral directional instability at low angle of attack during the approach to landing. However, this problem occurred when the aircraft was just outside the flight envelope of "valid simulation". It was thought that the automatic (and pilot adjustable) aileron-to-rudder interconnect would compensate for this problem. This problem did show up on several flights. On at least one flight, the problem was deemed to be a mis-setting of the aileron /rudder interconnect. The "slight" lateral directional instability showed up on other flights at low angle of attack during landing approach.

On May 10, 1967, flight 16 of the M2-F2, the flight was to be terminated with a lower angle of attack on final approach than had been previously flown. As the angle of attack was lowered, the nose suddenly moved right (then thought to be wind shear affects brought about by a sudden increase of wind from the west on the lakebed). The pilot applied left rudder to bring the nose left, but encountered a severe lateral-directional oscillation. These oscillations caused the pilot to slam his head on the canopy, dazing him. The pilot knew he had to increase angle of attack to recover, but had to do it so he would be wings level on recovery to accomplish a landing. Recovery was made, but the designated runway was off-line, and no altitude was available to make a correction. A rescue helicopter was hovering at the new point of intended landing, and the pilot called the helicopter to move west. The pilot fired the emergency landing rockets to give him more time to execute the landing and to land under or just behind the helicopter. Since runway markers were no longer available, depth perception was a problem. Either due to the lack of depth perception or the rotor wash of the helicopter, the M2-F2 was closer to the lakebed than perceived. The landing gear was lowered, but one gear door struck the lake bed before the landing gear was fully extended. This caused the M2-F2 to roll and tumble a number of times before coming to rest inverted on the lake bed.

The pilot was severely injured, as was the M2-F2.

The M2-F2 was rebuilt as the M2-F3. The major modification was the addition of a middle vertical tail to resolve the lateral-directional problem.

End: Peterson

The HL-10, M2-F3, X-24A, and X-24B
By John Manke July 1994

The following handling qualities evaluations are based on my 42 flights in the four lifting bodies: 10 in the HL-10, 12 in the X-24A, 4 in the M2-F3, and 16 in the X-24B.

The primary similarities between the 4 vehicles are:

1) Performance parameters such as: L/D, maximum Mach number, maximum altitude, angle of attack range, approach and landing airspeeds and altitudes, were very similar.

2) They all utilized two basic flight control configurations: a subsonic configuration and a transonic configuration. To provide adequate stability and control at transonic speeds and above, the control surfaces are wedged open in the transonic configuration. It was characterized by high drag, with a maximum L/D too low to be able to successfully perform a power off, horizontal landing. Subsonically, the control surfaces could be boat-tailed to reduce drag and provide an L/D that was adequate for approach and landing. This "configuration change" is well documented in other parts of this report.

3) They all flew the same basic trajectories.

Basic Lifting Body Trajectories
The first few flights in each of the lifting body programs were glide flights. A glide flight consisted of carrying the lifting body to a predetermined altitude under the wing of a B-52 bomber, releasing and gliding to a lakebed landing. The rocket engine was not utilized during the glide flights, consequently, the maximum Mach number of about 0.75, and total flight time of approximately 4 minutes, were minimal. The glide flights were made to provide a cautious expansion of the Mach envelope, to optimize the energy management task, and to provide pilot and system checkouts under optimum conditions.

For a powered flight "word picture", I will describe a typical X-24B powered flight. Immediately after launching from the B-52 at about 0.7 Mach number and 45,000 feet, the pilot began the rocket engine-light sequence. The pilot could select two, three, or four thrust chambers, depending on the planned profile requirements. One chamber did not provide sufficient thrust to maintain level flight.

During the first 70 to 80 seconds of the flight, the pilot's primary control parameters were angle of attack and pitch attitude. Generally, the initial rotation was at as high an angle of attack as possible commensurate with adequate handling qualities. This was to get the aircraft out of the dense atmosphere as quickly as possible and into higher altitudes where rocket engines are most effective. Typical pitch attitudes during climb out were in the 45 to 55 degree range. At approximately 0.7 Mach number the pilot would reconfigure the aircraft to the transonic configuration. Before reaching 0.9 Mach number, usually at an altitude between 60,000 ft. and 65,000 ft., angle of attack was reduced somewhat to stay clear of a known area of reduced lateral-directional stability. At about 1.2 Mach number, a pushover to a programmed low angle of attack was initiated to allow the aircraft to accelerate to the planned maximum Mach number for the flight.

The powered portion of the flight was terminated either by a pilot-actuated engine shutdown or fuel burnout, depending on the desired maximum Mach number. On a typical flight, shutdown occurred at about Mach 1.7 and at an altitude of approximately 70,000 feet, after 132 seconds of rocket burn time.

After engine shutdown, the glide descent portion of the profile began. It was during this portion of the flight that the majority of the flight test data was gathered, because the aircraft was free of power effects. This portion of the flight, from shutdown to the beginning of the approach and landing phase was of about 3 minutes duration, so you can appreciate the necessity of comprehensive pre-flight planning to best utilize this short time period. Because of the rapid deceleration after shutdown, the duration of prime data time, which is defined as the time during which the vehicle flies above the maximum Mach number previously investigated, was usually only 10 to 15 seconds. The primary piloting task after shutdown was to arrive at planned Mach number and angle of attack combinations and perform stability and control, performance, or structural loads determination maneuvers as required. Because of the high drag of this type vehicle, it was not possible to stabilize at the higher Mach numbers. The data had to be acquired while passing through the desired test points. At some of the lower Mach numbers, approximately Mach 1.1 and below, we could occasionally stabilize for 5 to 10 seconds. The maneuvers performed by the pilot for data acquisition purposes consisted primarily of the following: rudder doublets followed by aileron doublets for lateral-directional stability and control, pitch pulses for longitudinal stability and control, slow pushover-pullups for lift and drag and trim data, steady state sideslips and slow sideslip sweeps for pressures and loads data. In addition to the maneuvers, the pilot performed energy management tasks as required.

At approximately 30,000 feet, the pilot reconfigured the aircraft to the subsonic configuration to provide a L/D range sufficient for approach and landing. At about 24,000 ft., the pilot began a 180 degree approach attaining 280 to 300 KIAS on the final glide slope. The flare was begun at about 1000 feet above the surface and touchdown occurred about 25 seconds later at about 180 to 200 KIAS. Total flight time for a powered flight was 7 to 8 minutes. Profiles for the other lifting bodies were similar except for event timing and engine burn times.

The piloting task was very busy and required considerable concentration and pre-flight training. I was never able to look out of the cockpit and enjoy the scenery until reaching the altitude to begin the approach and landing phase.Typical time in the fixed base simulators averaged about 20 hours per flight. In addition we flew 10 to 15 flights in an F-104 aircraft configured to represent the particular vehicle L/D characteristics during the approach and landing phase. The following handling qualities comments are all based on the piloting tasks required to fly the profiles just described.

HL-10 and X-24A Handling Qualities

Since the HL-10, X-24A, and the M2-F3 are generally similar in planform and basic shape, and exhibit many aerodynamic similarities, I will loosely group them together. However, the M2-F3 comments will be more focused, as my four flights were done at the latter part of the program after much of the early development had been completed.

General Flight Behavior

In general, lifting body vehicles fly like conventional aircraft, although they do not behave like their winged counterparts in every detail. In the subsonic configuration, the HL-10 handling qualities were as good as or better than those of most current fighter aircraft. In this configuration with dampers on, pilot ratings indicate that pilot compensation was not required for adequate performance. With all dampers off, the HL-10 handled better than an F-104 airplane with its dampers off. The HL-10 did exhibit an area of high pitch sensitivity in the approach. This will be discussed in more detail later. In the subsonic configuration, the X-24A exhibited some lateral-directional problems during the first few flights, mostly associated with upsets due to turbulence. Control system modifications and changes in roll and yaw damper gains improved the handling qualities so that they were as good as the HL-10 vehicle. In fact, the longitudinal handling qualities of the X-24A were superior to those of the HL-10 during the approach and landing. It should be mentioned here that these lateral-directional upsets due to turbulence were of considerable concern to the pilots early in the program. The culprit was the extremely high dihedral effect characteristic of these shapes, somewhere in the range of 5 to 10 times that of the conventional fighter aircraft that we were flying at the time. After we tamed the excursions somewhat with control systems modifications and, through experience, realized that the aircraft would not "un-cork", we learned to live with it and not to be unduly concerned. The experience factor in dealing with unconventional aircraft has a profound effect on pilot perceptions. When the hair on the back of your neck goes up, you tend to be highly critical of the situation; however, once you realize that vehicle response is not life threatening, you are able to ignore the problem and fly right through it. Our initial impressions of these vehicles were obviously based on our experiences flying conventional fighter aircraft. Anything radically different tended to raise a red flag until the condition was thoroughly analyzed.

For the HL-10 in the transonic configuration, handling qualities did not change significantly with increasing Mach number, except that damping seemed to decrease somewhat. Dampers-on handling qualities were superb. With dampers off, the HL-10 handling qualities were surprisingly good. Considerable maneuvering was performed, and numerous configuration changes were made with all dampers off. Pilot ratings indicated that considerable pilot compensation was required for desired performance but was primarily a nuisance factor. All pilots believed that the vehicle was completely flyable with the dampers off in this configuration, and that a mission could be completed successfully. Typical pilot comments indicated that with the dampers off, the vehicle had high control sensitivity in the roll axis and particularly good damping in the pitch axis. In the transonic configuration, the primary difference between the X-24A and the HL-10 was that the X-24A had considerably lower roll response than the HL-10, however, the response was considered adequate for the mission. Because of the extremely high dihedral effect of the X-24A, small angles of sideslip excursions frequently produced nuisance type roll inputs.

Longitudinal Handling Characteristics

In general, the longitudinal handling qualities of the HL-10 and the X-24A were conventional except for a few trim change problems that seem to be inherent to this class of vehicle. The M2-F3 had some serious shortcomings during rotation after launch; these will be discussed later. One of the major concerns, before the HL-10 was flown in the transonic configuration, was the predicted large longitudinal trim change resulting from transitioning between the subsonic and transonic configurations. Simulation studies had indicated that relatively large excursions in angle of attack and normal acceleration would occur during the transition because of the large change required in longitudinal stick position. The studies also indicated that the best technique would be to change configuration in several steps. We were pleasantly surprised in flight, as maintaining a constant angle of attack during the configuration change was no problem. We were able to maintain nearly constant angle of attack despite the large change in longitudinal stick position in the 5 seconds it took to reconfigure the vehicle. Additionally, we found that the best technique was to change the configuration in one continuous motion. Apparently, the motion and visual cues in actual flight significantly reduced the piloting task.

The configuration change for the X-24A was not a problem at all. In this vehicle, the rudder wedge position was biased automatically as a function of deflection of the upper flaps to significantly reduce the trim change. The rudder bias provided a pitching moment that counteracted the pitching moment of the flaps.HL-10 simulation studies indicated a sizable pitch trim change in the Mach range of 0.95 to 1.0, but also indicated that this region would be traversed at a rate that would present no great piloting problem. In flight, however, most of the trim change occurred in a much smaller Mach number range, between 0.97 and0.96. During the deceleration phase of the flight, this Mach range was crossed so rapidly that the trim change appeared to me as a constant speed pitchup - which immediately got my undivided attention! With more experience, we found that there was an optimum angle of attack that could be used to minimize the pitchup problem. In addition, the time of onset could be predicted accurately, therefore, on later flights the pitchup never came as a surprise. This area was eventually traversed with the pitch damper off with no significant problems. One of the lessons learned was that wind-tunnel data should be obtained at very close intervals near Mach 1 in order to have the best information possible with which to analyze any transonic trim change.

During the powered flight portion of the HL-10 program, no significant trim change due to rocket engine thrust was detected. The X-24A vehicle, on the other hand, exhibited a marked pitch-up trim change with engine thrust. Computations indicated that a misalignment of approximately 7 inches between the rocket engine centerline and the vehicle center of gravity would be required to account for the flight-measured trim change. However, precise measurements indicated a misalignment of less than 2 inches. We were never able to conclusively account for the effect, however, it was suspected that aerodynamic effects resulting from the engine exhaust plume contributed significantly to the problem. In powered flight, the X-24A exhaust plume was deflected upward in rooster tail fashion. Because it was a nose-up trim change, the upward deflected plume is probably significant. Effects such as this are virtually impossible to predict prior to flight. As a result of this trim change with thrust, the low angles of attack originally predicted during powered flight could not be attained. The X-24A also exhibited a marked change in directional stability with power. This will be commented on later.

An undesirable characteristic of the M2-F2, M2-F3, and the X-24A, in the category of a trim change, was a substantial nose-down pitching moment at landing gear extension. In all lifting body flights the landing gear was extended just before touchdown. The reason for this was that the landing-gear-down configuration drastically reduced the L/D ratio and could very easily compromise the final approach portion of the landing pattern. Because of this gear transient, touchdown on one of the early M2-F2 flights occurred less than 1 second after gear extension. This particular characteristic caused us pilots a great deal of concern, particularly on our first few flights. We eventually learned to partially compensate for the effect by leading with aft stick motion, but even then it was considered unsatisfactory. For an operational vehicle, this would have to be remedied. The gear transient of the HL-10 was not objectionable.

The longitudinal handling qualities on the early flights of the HL-10 vehicle demonstrated a pilot-induced-oscillation (PIO) tendency. The reason for this was that we originally thought we would require 60 degrees of elevon throw to provide adequate pitch control throughout the flight envelope. Total stick throw for this deflection was only 9 inches. After the first flight, it was apparent that the gearing ratio had to be decreased. Flight data indicated that only 38 degrees of total elevator travel would be necessary to cover the required Mach/angle-of-attack envelope. We tried several ranges of gearing ratios before we arrived at a satisfactory one. The final configuration was non-linear to provide the lower gearing required for landing and, at the same time, provide for the elevator range required for supersonic trim. The final configuration required about 2 inches of longitudinal stick deflection for approach and landing. The first flight required less than 1 inch! Even with the final gearing, we found the vehicle to be quite sensitive during the landing phase, but it was acceptable. It should be pointed out that these changes to the control system were possible only because the original design provided the mechanism with which the control system could be modified quickly. This built-in flexibility was a feature of all the lifting bodies, a real credit to the systems designers!

Lateral-Directional Handling Characteristics

The HL-10, X-24A, and M2-F3 have many similar lateral-directional characteristics. They have relatively high dihedral effect and low rolling moments of inertia, and they may have relatively low directional stability. Natural roll damping, normally provided by wings, was conspicuously absent. The lateral control surfaces were necessarily quite close to the rolling axis and were relatively ineffective. Due to the large dihedral effect, the rolling moment caused by a rudder deflection could very often be larger than the rolling moment that could be produced by the ailerons. These effects combined to produce some unusual dynamic lateral responses to control inputs and turbulence. As the X-24A flight envelope was expanded beyond Mach 1, a completely unexpected phenomenon developed - the rocket engine had a pronounced effect on vehicle directional stability. At mid-range angles of attack, static directional stability was less than zero. From a piloting standpoint this did not pose a big problem other than to make the aircraft appear to be sluggish, and occasionally, to require a modest amount of aileron to keep wings level. This phenomenon would disappear at engine shut down.

Another area of concern from a piloting standpoint in the X-24A was an apparent roll reversal that occurred in the transonic region at moderate angles of attack. When I first encountered it in flight, it was a bit disconcerting even though it had been predicted. It was quite easily overcome by judicious use of the rudder for roll control. Fortunately the designers had built in the capability to provide for a rudder-to-aileron interconnect that, when ratioed properly, completely eliminated the problem. The interconnect was also used on the M2-F2, but was not required on the HL-10 and the M2-F3.

M2-F3 Handling Qualities

This report is based on the four flights that I flew in the M2-F3. Because of the low number of flights flown and the fact that they came at the end of the program, this is not intended to be a comprehensive documentation of the M2-F3 flight characteristics. I've divided it into three parts based on control system configuration: I. The Basic Airplane; II. The Command Augmentation System (CAS); and III. The Reaction Augmentation System (RAS).

I. The Basic Airplane

The most difficult and most disconcerting part of each flight was the constant angle of attack portion of the initial rotation just after launch. The shape of the elevator angle versus angle of attack curve was such that almost any angle of attack was possible with any given elevator setting. This, coupled with large trim changes with Mach number in the transonic range, made precise control of angle of attack during this portion of the flight impossible. Adequate performance required an excessive amount of pilot compensation. Further compounding the situation was the knowledge that a pitch-up existed if angle of attack was allowed to exceed a certain value. I was certainly not satisfied with my ability to maintain a relatively constant angle of attack during rotation. At low angles of attack, the longitudinal characteristics were much better, with a comment that pilot compensation was not a factor in achieving desired performance.

Supersonically, the M2-F3 was similar to the X-24A in that things seemed to smooth out and the handling qualities were, in general,very good. As in the X-24A the control sensitivity decreases considerably when supersonic, this did not present a problem, in fact, it made for a very pleasant flying airplane.

In general, during the launch, rotation, and climb phase of the flight, the lateral-directional axes were never a concern and received high pilot ratings. Because of the difficulty in performing the pitch task during the boost portion of the flight, very little time was allowed to assess lateral-directional handling qualities. A testimony to the excellent lateral-directional characteristics is the fact that they could be ignored while concentrating on the pitch task.

Occasionally during the climb, I would get a spurious "wing" drop for no apparent reason. This same phenomenon occurred very frequently on the X-24A. It would seem that the theory that the "wing" drops are caused by climbing through wind shears is indeed a correct explanation.

A closer look at lateral-directional characteristics was allowed after engine shutdown. With SAS on, they were outstanding. With SAS off and at low angle of attack, roll sensitivity was very high, reminiscent of the X-24A. In this configuration it was very easy to get into a PIO. I felt that desired performance in this area required excessive pilot compensation. Rudder sensitivity was very low in all areas tested, but since rudder was never utilized by the pilot except to perform pulses, this was not considered a problem. Because of the large pitch trim change experienced during the configuration change, this portion of the flight for all lifting bodies had been approached cautiously. Of the three lifting bodies, the M2-F2 exhibited the least troublesome characteristics. As with the HL-10 and X-24A, the M2-F3 exhibited excellent handling qualities and flight characteristics during the approach and landing. Since the approach L/D was a bit lower in the M2-F3, the approach pattern altitudes were somewhat higher, but with the excellent simulation afforded by the F-104's, it presented no problems. The "riding qualities" in turbulence were better in the M2-F3 than in the other two lifting bodies. The response to turbulence was not nearly as quick as in the other two, instead it responded more like an F-104 in that it was manifested primarily as normal acceleration inputs rather than rapid roll inputs as in the X-24A.

All final approaches were flown with plenty of energy (300 KIAS or more) to insure adequate time from flare to touchdown. My 4 approaches were very comfortable. Visibility was considered good using just the canopy and not the nose window. Depth perception during the last 5 feet was not too good, but was considered adequate. I did notice a tendency for a slight PIO after gear deployment, but not severe enough to be of concern. All touchdowns were smooth with the roll out reminiscent of the X-24A except for less directional control both aerodynamically and with wheel brakes.

II. The Command Augmentation System

The Command Augmentation System (CAS) and its associated angle-of-attack hold feature were welcomed additions to the aircraft. A CAS is particularly effective in an aircraft that experiences so many pitch trim changes with Mach number as does the M2-F3.

On my CAS evaluation flight, an essentially hands-off boost (in pitch) was flown. The aircraft was rotated to 14 degrees angle of attack at which point the angle-of-attack hold was engaged. With no pilot inputs, angle of attack was observed to drift more than desired, + or - 1/2 degree. If I had not been prepared for this, it may have been disconcerting, especially when the angle of attack drifted above 14 degrees. Apparently this was the bandidth of the angle-of-attack hold feature and once I realized this, my apprehension disappeared. As the aircraft reached 40 degrees pitch angle, the angle-of-attack hold was disengaged. With no pilot input, and thus a 0 pitch rate commanded, the CAS held the aircraft at precisely 40 degrees. The rate command loop appeared to be much tighter than the angle-of-attack hold loop. I rated this portion of the flight considerably higher than I had rated the basic aircraft for the same task. Another area in which the angle-of-attack hold feature was particularly useful was the configuration change. As previously mentioned, the pitch trim change is very large when the aircraft is reconfigured. On my CAS flight a "hands off" configuration change was performed utilizing angle-of-attack hold. I rated the task very high.

The mechanization of the angle-of-attack hold system had one glaring deficiency. The side controller had to be in a "hard-to-find" detent located at the stick center position. If the stick was not in the detent, angle-of-attack hold could not be engaged. Because of the very narrow detent and the low break-out forces, the detent was very difficult to find and to hold, particularly during dynamic situations such as during turns and during situations that required both pitch and roll inputs to the side stick. The use of pressure suit gloves further compounded the problem. My first attempt to use angle-of-attack hold in a positioning turn required considerable pilot compensation to perform the task. I was forced to disengage the hold mode and concentrate on the task at hand. I found that experience and practice in the simulator with a pressure suit glove alleviated the problem somewhat, but it still was not satisfactory. From the time after the configuration change through the landing, the control task became similar to that encountered in conventional aircraft flying; that is, precise control of angle of attack is not a requirement. Under these conditions the angle-of-attack hold feature used in conjunction with the rate command of the CAS provided a near ideal control system. With rate command alone, if the stick is centered, the pitch rate commanded is 0. This means that in an unpowered vehicle, in all probability, angle of attack and thus airspeed will be changing. This would require constant attention of the pilot to stay on top of the situation. If on the other hand, angle-of-attack hold is engaged whenever the stick is centered, the pilot knows exactly what the aircraft is going to do, and consequently, he can direct some of his attention to other tasks such as the "housekeeping" chores necessary to prepare for landing. It was this aspect of the CAS/angle-of-attack hold combination that I felt offered the greatest promise.

III. The Reaction Augmentation System

One of the most interesting aspects of my exposure to the M2-F3 was the utilization of the Reaction Augmentation System (RAS) in the pitch axis. The pitch RAS was used as a substitute or replacement for the normal pitch SAS. It is significant that the pitch axis was the most challenging axis of the M2-F3 and that there were certain areas that it was felt that with 0 pitch damping, successful completion of a flight would be questionable. On my last flight, RAS was used as the only pitch damping through many of these questionable areas. At worst, I felt it was equivalent to about 1/2 the normal SAS gain. In some areas, I would be hard pressed to determine the difference between the RAS and an optimized SAS. I felt that I would have no qualms about landing the aircraft utilizing only RAS in the pitch axis. This was significant, as it was universally felt that a successful landing without pitch SAS would be very questionable.

As on my SAS M2-F3 flights, the most difficult control task occurred during the boost. Although we had RAS damping, it must be remembered that longitudinal trim was still aerodynamic through elevator position, consequently, the piloting task was still monumental in attempting to keep up with the many transonic trim changes. I felt that the damping was not as good on this flight during the boost as it had been on my SAS flight, but it must be remembered that I had estimated the SAS pitch gain to be over twice that of the RAS. The configuration change utilizing RAS was great and received a very high pilot rating.

The four flights went extremely well and presented no surprises. This was due almost entirely to a superb simulation and an excellent pre-flight briefing by the M2-F3 project pilot and project engineer.

X-24B Handling Qualities

This discussion format will be a bit different, as I will, for the most part, compare the X-24B handling qualities with the other vehicles. Two major differences between the X-24B and the other vehicles were: (1) unlike the others, the X-24B had ailerons, consequently, adequate roll control power in all flight regimes, and (2) it did not have the very high dihedral effect of the other three, in fact, its dihedral effect was lower than that of many winged aircraft.

Subsonic Configuration Handling Qualities

The X-24B, in this flight regime exhibited better handling qualities than any of the other lifting bodies, evidenced by very high pilot ratings. It was flown in this region with all dampers off quite frequently. With all dampers off it showed only a slight degradation in pilot ratings. On one occasion, I flew the entire approach pattern, except for the flare and landing, with all dampers off. My post flight comment was, "It just flew like a champ." In fact, if you put somebody in the airplane who hadn't flown it before, and had him fly it with dampers off in this configuration, I don't think he'd tell you that the airplane even needed dampers. That's the sort of feeling I got. The degradation in handling and riding qualities in turbulence during approach and landing with the other 3 lifting bodies was a continuing problem. The X-24B, on the other hand, exhibited absolutely superb handling and riding qualities during this phase. The primary reason for this was the much lower dihedral effect. Even when flying in significant levels of turbulence, the X-24B received very high pilot ratings.

Transonic Configuration Handling Qualities

The transonic range provided the most surprises and offered the biggest challenge to the stability and control experts and to the pilots. The major cause of the problems experienced in the transonic and supersonic flight regimes was a significant reduction in lateral-directional stability derivatives with the rocket engine running. This effect was expected to a degree, as we had experienced it to some extent with the X-24A. This effect manifested itself as non-periodic sideslip excursions in the transonic Mach range, and also at Mach numbers above 1.3. On my first exposure to it, I was not sure whether the aircraft was going to diverge in sideslip. The only thing that kept me from shutting down the rocket engine was the fact that I had excellent rudder response, thus I was able to maintain sideslip to a reasonable value. The major drawback to this was that I was devoting a considerable amount of attention and time to the lateral-directional task that would normally be spent controlling the profile. I rated this condition quite low and indicated that extensive pilot compensation was required for adequate performance. As previously mentioned, aircraft of this type occasionally show dramatic changes in aerodynamic characteristics with very small changes in Mach number and angle of attack in this transonic region. The next flight showed that by decreasing angle of attack by only 2 degrees in this region, the handling qualities were very acceptable. Although this did have an effect on total performance, we were able to continue with our envelope expansion flights by using a reduced angle of attack above Mach 1.3. Later in the program, a control system modification in the form of a lateral acceleration feedback loop, and increased confidence in the basic stability of the aircraft, allowed us to fly through this area at the higher angles of attack.

Another characteristic of the X-24B, as well as the other lifting bodies, was the large longitudinal trim change and decrease in elevator authority as the aircraft accelerated beyond Mach 0.95. The trim change increased the piloting task considerably, since constant attention was required to precisely control angle of attack during this portion of the flight. The reduced elevator authority drastically limited the angle of attack that could be investigated above Mach 1. For example, for the X-24B, the total available angle of attack range at Mach 1.6 was considerably less than one-half that available at Mach 0.5. In spite of these irregularities, the X-24B was considered a superb flying machine in the transonic and supersonic ranges.

Concluding Remarks

From my standpoint as a research pilot, the lifting body programs were extremely interesting, challenging and highly successful. As a project pilot, I've attempted to extract what I would consider the salient features responsible for these successes. I will call them "Guides to Success," and I highly recommend them for any advanced flight vehicle program:

<u>(1)Built-in Control System Flexibility</u>
There are always unpredicted problems, and it is much simpler to change a gain setting than to redesign and rebuild a control system in an existing aircraft.

<u>(2) Intelligent Wind Tunnel Data Analysis</u>
This is probably the most important. The backbone of any high performance research flight vehicle program is the flight simulator. It is the primary tool for pre-flight planning and pilot training. The accuracy of a simulator is only as good as the wind tunnel data and subsequent flight data that is loaded into its memory banks. Wind tunnel data, by themselves, do not begin to tell the story of a flight vehicle. It is the interpretation of these data by engineers, highly experienced in the flight characteristics of the vehicle type, that insures a high fidelity simulation. These unique interpretations techniques are not learned from text books or from conventional aircraft technology, they must be developed by experience in vehicle type. Our X-24B simulation was, unquestionably, the best of its time. The reason for this was that most of the aerodynamicists responsible for interpreting X-24B wind tunnel data and programming it into the simulator, were involved with the three previous lifting body programs. Some even worked with the X-15 program.

<u>(3) Early Integration of the Pilot into the Program</u>
The complete integration of the pilot into the program at the earliest possible time is essential. Handling qualities specifications relate and integrate a variety of experience and background and, therefore, form a useful guide to a designer. However, they don't answer many crucial design questions. If the proper simulation techniques are used, a team of experienced test pilots, working with engineers, can establish the best compromises, of which there will be many, of basic stability, control, and augmentation tradeoffs for specific missions. In all such studies, a careful estimate of possible uncertainties in critical stability and control parameters should be made and the design decision should be based on the most pessimistic derivatives. This philosophy was utilized throughout the lifting body programs and, in my opinion, the results have been outstanding.

Appendix C
Lifting Body Flight Log
Part One: Light Weight; M2-F1
Key to Flight Nomenclature
Light Weight M2-F1

ABT	Airborne time	J. R. Vensel **(JRV)**	Chief of Operations
FF	Free Flight	P. F. Bikle **(PFB)**	Director of Center
GRD	Ground	M. O. Thompson **(MOT)**	Test Pilot
LDG	Landing	D. E. Beeler **(DEB)**	Deputy Director
P/C-47	Car & Air Tow		

Heavy Weight Lifting Bodies: M2-F2, M2-F3, HL-10, X-24A, X-24B

FLIGHT	Flight Number Identification Example: M-11-18 **M** – Vehicle Type	M = M2-F2 or M2-F3 H = HL-10 X = X-24A B = X-24B
	-11	Sequential number of launches for vehicle (C = planned captive) (A = aborted launch)
	-18	Sequential number of captive flight attempts for vehicle

Mmax	Maximum Mach number achieved on the flight
Hmax	Maximum Altitude achieved on the flight
BURN	Rocket engine burn time in seconds

Part One: Light Weight Lifting Body Flight Log (M2-F1)

DATE	*GRD TOW	AIR TOW	PILOT	ABT SEC	FF SEC	VEHICLE	TOW-VEHICLE PILOT	REMARKS
3/1/63	2		THOMPSON	NONE	NONE	PONTIAC		First Ground Tow
4/5/63	11		THOMPSON	0:00:36	NONE	PONTIAC		First Airborne Time
4/22/63	9		THOMPSON	0:01:15	NONE	PONTIAC		
4/23/63	10		THOMPSON	0:10:50	0:00:13	PONTIAC		**First Free Flight**
4/29/63	5		THOMPSON	0:02:00	0:00:02	PONTIAC		
4/30/63	11		THOMPSON	0:11:00	0:00:22	PONTIAC		
5/1/63	3		THOMPSON	0:02:25	0:00:03	PONTIAC		
5/2/63	8		THOMPSON	0:08:00	0:00:16	PONTIAC		
5/6/63	14		THOMPSON	0:17:00	0:00:42	PONTIAC		
5/7/63	2		THOMPSON	0:04:00	0:00:04	PONTIAC		
5/8/63	2		THOMPSON	0:04:00	0:00:04	PONTIAC		Demo. Mr. Seamans
7/15/63	3		THOMPSON	NONE	NONE	PONTIAC		
7/16/63	6		THOMPSON	0:12:00	0:00:12	PONTIAC		
8/9/63	5		THOMPSON	0:08:00	0:00:30	PONTIAC		
8/12/63	2		THOMPSON	0:00:15	0:00:03	PONTIAC		
8/16/63		1	THOMPSON	0:19:30	0:02:00	C-47	MALLICK/DANA	**First Air Tow**
8/27/63	2		THOMPSON	0:01:09	NONE	PONTIAC		
8/28/63		1	THOMPSON	0:22:09	0:22:09	C-47	MALLICK/DANA	
8/29/63		1	THOMPSON	0:20:00	0:02:25	C-47	MALLICK/DANA	
8/30/63		2	THOMPSON	0:40:58	0:04:42	C-47	MALLICK/DANA	
9/3/63		2	THOMPSON	0:40:25	0:04:50	C-47	MALLICK/DANA	
10/7/63		1	THOMPSON	0:32:22	0:01:26	C-47	BUTCHART/DANA	
10/9/63		1	THOMPSON	0:43:29	0:01:51	C-47	HAISE/McKAY	
10/15/63		1	THOMPSON	0:20:00	0:02:20	C-47	BUTCHART/?	
10/23/63		1	THOMPSON	0:53:00	0:03:00	C-47	BUTCHART/McKAY	
10/25/63		2	THOMPSON	0:24:40	0:03:52	C-47	BUTCHART/MALLICK	
11/8/63		3	THOMPSON	1:10:00	0:07:45	C-47	MALLICK/McKAY/BUTCH	
11/12/63	12		PETERSON	NONE	NONE	PONTIAC		No Lift Offs
11/12/63	11		MALLICK	NONE	NONE	PONTIAC		
11/12/63	11		YEAGER	NONE	NONE	PONTIAC		
11/13/63	8		PETERSON	0:05:00	NONE	PONTIAC		
11/13/63	10		YEAGER	0:10:00	NONE	PONTIAC		
11/14/63	8		YEAGER	0:05:30	0:00:14	PONTIAC		
11/14/63	6		PETERSON	0:04:00	0:00:11	PONTIAC		
11/14/63	14		MALLICK	0:09:00	0:00:19	PONTIAC		
12/2/63	9		PETERSON	0:09:00	0:00:27	PONTIAC		
12/2/63	4		YEAGER	0:04:20	0:00:12	PONTIAC		
12/2/63	7		MALLICK	0:07:00	0:00:21	PONTIAC		
12/3/63		1	THOMPSON	0:12:00	0:01:00	C-47	DANA/MALLICK	
12/3/63		1	YEAGER	0:13:40	0:01:35	C-47	DANA/MALLICK	
12/3/63		2	PETERSON	0:28:40	0:00:00	C-47	DANA/MALLICK	Broke Main Wheels
1/27/64	3		THOMPSON			PONTIAC		
1/27/64	3		PETERSON	0:02:00		PONTIAC		
1/29/64		2	THOMPSON			C-47	DANA/McKAY	
1/29/64		2	PETERSON	0:22:00	0:04:44	C-47	DANA/McKAY	
1/29/64		2	YEAGER			C-47	DANA/McKAY	
1/30/64		2	YEAGER			C-47	DANA/McKAY	
1/30/64		2	MALLICK			C-47	DANA/McKAY	
2/6/64	10		SORLIE	0:10:00	0:00:10	PONTIAC		
2/6/64	10		WOOD	0:10:00	0:00:10	PONTIAC		
2/10/64	10		SORLIE	0:10:00	0:00:10	PONTIAC		
2/10/64	9		SORLIE	0:09:00	0:00:09	PONTIAC		

Light Weight Lifting Body Flight Log (M2-F1) (Continued)

DATE	*GRD TOW	AIR TOW	PILOT	ABT SEC	FF SEC	VEHICLE	TOW-VEHICLE PILOT	REMARKS
2/28/64		2	THOMPSON			C-47	BUTCHART/PETERSON	
3/18/64	AIR TOWS SCHEDULED – CANCELLED – C-47 HAD DIFFICULTIES							
3/30/64		1	PETERSON	0:24:00	0:02:25	C-47	BUTCHART/KLUEVER	Fired Lnding Rocket
4/9/64		2	THOMPSON			C-47	BTUCHART/KLUEVER	
4/9/64		3	PETERSON	1:21:00	0:08:00	C-47	BUTCHART//KLUEVER	
5/19/64		2	PETERSON	0:36:00	0:04:08	C-47	BUTCHART/McKAY	Rocket Ldg Assist
6/3/64		1	THOMPSON			C-47	DANA/PETERSON	
No Date	AIR TOWS CANCELLED BECAUSE OF WINDS							
7/24/64		3	PETERSON	0:56:00	0:06:50	C-47	DANA/HAISE	2- Flts Rockets used
8/18/64		1	THOMPSON			C-47	DANA/PETERSON	
8/21/64		4	THOMPSON			C-47	DANA/HAISE/WALKER	
1/22/65			THOMPSON			PONTIAC		Note # 1
1/26/65			THOMPSON			PONTIAC		Note # 1
1/26/65			DANA			PONTIAC		Note # 1
1/27/65			THOMPSON			PONTIAC		Note # 1
1/27/65			DANA			PONTIAC		Note # 1
1/28/65			THOMPSON			PONTIAC		Note # 1
1/29/65			DANA			PONTIAC		Note # 1
2/12/65			DANA			PONTIAC		Note # 2
2/15/65			DANA			PONTIAC	Note #2	Ldg Rockets Fired
2/16/65		1	THOMPSON			C-47	DANA/PETERSON	Airspeed Calib.
2/24/65	1		THOMPSON			PONTIAC		Note # 2
2/24/65			DANA			PONTIAC		Note # 2
3/29/65			DANA			PONTIAC		Note # 3
4/15/65			DANA			PONTIAC		Note # 3
4/15/65	4		SORLIE	0:04:00	0:00:08	PONTIAC		
5/27/65		4	THOMPSON			C-47	BUTCHART/HAISE	
5/27/65		3	SORLIE	1:10:00	0:06:00	C-47	BUTCHART/PETERSON	
5/28/65		1	THOMPSON			C-47	HAISE/PETERSON	
5/28/65		2	SORLIE	0:40:30	0:04:30	C-47	PETERSON/HAISE	
6/18/65			GENTRY			PONTIAC		Note # 4
6/30/65			GENTRY			PONTIAC		Note # 4
7/14/65			DANA			PONTIAC		Note # 5
7/14/65			GENTRY			PONTIAC	Note # 5	Thompson Assisted
7/16/65		1	THOMPSON			C-47	HAISE/KLUEVER	
7/16/65		1	DANA			C-47	HAISE/KLUEVER	
7/16/65		1	GENTRY		0:00:09	C-47	HAISE/KLUEVER	
8/30/65		3	THOMPSON			C-47	PETERSON/HAISE	
8/31/65	1	1	THOMPSON			P/C-47	HAISE/PETERSON	
10/5/65			THOMPSON			PONTIAC		Note # 5
10/6/65		2	THOMPSON			C-47	PETERSON/HAISE	
10/8/65		1	THOMPSON			C-47	HAISE/PETERSON	
3/11/66			THOMPSON			PONTIAC		Note # 5
3/28/66		2	THOMPSON			C-47	PETERSON/BUTCHART	
4/22/66	1		PETERSON		0:02:00	PONTIAC		
4/22/66			HAISE			PONTIAC		
4/22/66			ENGLE			PONTIAC		
7/19/66			THOMPSON			PONTIAC		Note # 5
7/19/66	1		PETERSON		0:01:00	PONTIAC		
7/21/66			GENTRY			PONTIAC		

Light Weight Lifting Body Flight Log (M2-F1) (Continued)

DATE	*GRD TOW	AIR TOW	PILOT	ABT SEC	FF SEC	VEHICLE	TOW-VEHICLE PILOT	REMARKS
7/21/66	3		PETERSON		0:04:00	PONTIAC		
8/2/66	6		PETERSON		0:09:00	PONTIAC		
8/4/66		1	PETERSON	0:22:00	0:02:00	C-47	BUTCHART/FULTON	
8/5/66		3	PETERSON	0:48:00	0:04:00	C-47	BUTCHART/FULTON	
8/10/66			GENTRY			PONTIAC		Note # 5
8/16/66		1	GENTRY			C-47	BUTCHART/FULTON	2ND SLOW ROLL
8/18/66	PROJECT CANCELLED BY JRV PFB MOT DEB							

Walter Whiteside drove the Pontiac for all Ground Tows

Notes:

All Note 1s: Total 44 car tows; number of flights per pilot unknown
All Note 2s: Total 32 car tows; number of flights per pilot unknown
All Note 3s: Total 10 car tows; number of flights per pilot unknown
All Note 4s: Total 12 car tows; number of flights per pilot unknown
All Note 5s: Total car tows and number of flights per pilot unknown

Compiled by Betty Love

Part Two: HEAVY WEIGHT LIFTING BODY FLIGHT LOG (CHRONOLGY)

FLIGHT	DATE	PILOT	Mmax	Hmax	BURN	REMARKS
M-C-1	10/21/65	Unmanned				Systems Checkout – Gear Up
M-C-2	10/21/65	Unmanned				Systems Checkout – Gear Down
M-C-3	3/23/66	Thompson				In flight Gear Extension
M-C-4	5/26/66	Thompson				Systems Checkout
M-C-5	6/7/66	Thompson				Systems Checkout
M-C-6	7/6/66	Thompson				Systems Checkout
M-A-7	7/11/66	Thompson				Landing Rocket Malfunction
M-1-8	7/12/66	Thompson	0.646	45.0		First Lifting Body Free-flight
M-2-9	7/19/66	Thompson	0.598	45.0		
M-3-10	8/12/66	Thompson	0.619	45.0		
M-4-11	8/24/66	Thompson	0.676	45.0		
M-5-12	9/2/66	Thompson	0.707	45.0		Thompson's last L/B flight
M-6-13	9/16/66	Peterson	0.705	45.0		Peterson's 1st L/B flight
M-7-14	9/20/66	Sorlie	0.635	45.0		Sorlie's L/B flight
M-8-15	9/22/66	Peterson	0.661	45.0		
M-9-16	9/28/66	Sorlie	0.672	45.0		
M-10-17	10/5/66	Sorlie	0.615	45.0		Sorlie's last L/B flight
M-11-18	10/12/66	Gentry	0.662	45.0		Gentry's 1st L/B flight
M-12-19	10/26/66	Gentry	0.605	45.0		
M-13-20	11/14/66	Gentry	0.681	45.0		
M-14-21	11/21/66	Gentry	0.695	45.0		
H- C- 1		Peterson				Numbered, not flown
H- C –2	12/20/66	Peterson				Systems Checkout
H- 1- 3	12/22/66	Peterson	0.693	45.0		Limit Cycle/Flow Separation
M-A-22	4/10/67	Gentry				SAS Malfunction
M-15-23	5/2/67	Gentry	0.623	45.0		
M-16-24	5/10/67	Peterson	0.612	45.0		Peterson's last/Landing Accident
H- C –4	2/29/68	Gentry				Systems Checkout – Mod II
H- 2- 5	3/15/68	Gentry	0.609	45.0		Mod II-Gentry's 1st HL-10 flight
H- 3- 6	4/3/68	Gentry	0.690	45.0		
H- A- 7	4/23/68	Gentry				Winds too high
H- 4- 8	4/25/68	Gentry	0.697	45.0		
H- 5- 9	5/3/68	Gentry	0.688	45.0		
H- 6-10	5/16/68	Gentry	0.678	45.0		
H- 7-11	5/28/68	Manke	0.657	45.0		Manke's 1st L/B flight
H- 8-12	6/11/68	Manke	0.635	45.0		
H- 9-13	6/21/68	Gentry	0.637	45.0		

HEAVY WEIGHT LIFTING BODY FLIGHT LOG (CHRONOLGY)
(Continued)

FLIGHT	DATE	PILOT	Mmax	Hmax	BURN	REMARKS
H- C-14	8/22/68	Manke				Engine Systems Checkout
H- C-15	8/30/68	Gentry				Engine Systems Checkout
H- A-16	9/4/68	Gentry				Pitch Back-up Malfunction
H-10-17	9/24/68	Gentry	0.682	45.0		
H-11-18	10/3/68	Manke	0.714	45.0		
H- A-19	10/22/68	Gentry				Source Too Low to Drop
H-12-20	10/23/68	Gentry	0.666	39.7	019.4	1st Pwr, Eng Malf, Rosamond Landing
H-13-21	11/13/68	Manke	0.840	42.6	186.1	3 tries to light
H- C-22	12/2/68	Gentry				Engine Systems Checkout
H- C-23	12/4/68	Gentry				Engine Systems Checkout
H-14-24	12/9/68	Gentry	0.870	47.4	181.1	
H- A-25	1/10/69	Manke				Low Release Pressure
H- A-26	1/17/69	Manke				Igniter test malfunction
X- C- 1	4/4/69	Gentry				Systems Checkout
X- 1- 2	4/17/69	Gentry	0.718	45.0		H.Q. Problems
H-15-27	4/17/69	Manke	0. 994	52.7	170.1	
H-16-28	4/25/69	Dana	0.701	45.0		Dana's 1st L/B/ flight
X- 2- 3	5/8/69	Gentry	0.693	45.0		H.Q. Problems
H-17-29	5/9/69	Manke	1.127	53.3	158.2	1st Supersonic L/B flight
H-18-30	5/20/69	Dana	0.904	49.1	185.9	
H-19-31	5/28/69	Manke	1.236	62.2	116.2	
H-20-32	6/6/69	Hoag	0.665	45.0		Hoag's 1st L/B flight
H-21-33	6/19/69	Manke	1.398	64.1	117.5	
H-22-34	7/23/69	Dana	1.271	63.8	116.1	
H-23-35	8/6/69	Manke	1.540	76.1	092.9	
X- A- 4	8/8/69	Gentry				TM Power Supply
H- A-36	8/15/69	Dana				Igniter test malfunction
X- 3- 5	8/21/69	Gentry	0.718	40.0		
X- A- 6	8/29/69	Gentry				SAS Status lites in Control Room
H-24-37	9/3/69	Dana	1.446	78.0	089.5	
X- 4- 7	9/9/69	Gentry	0.594	40.0		
H- A-38	9/16/69	Manke				Weather
H-25-39	9/18/69	Manke	1.256	79.2	074.9	
X- 5- 8	9/24/69	Gentry	0.596	40.0		
H-26-40	9/30/69	Hoag	0.924	53.8	172.6	
X- A- 9	10/15/69	Manke				Weather

HEAVY WEIGHT LIFTING BODY FLIGHT LOG (CHRONOLGY) (Continued)

FLIGHT	DATE	PILOT	Mmax	Hmax	BURN	REMARKS
X- 6-10	10/22/69	Manke	0.587	40.0		Manke's 1st X-24 flight
H-27-41	10/27/69	Dana	1.577	60.6	089.0	
H-28-42	11/3/69	Hoag	1.396	64.1	097.3	
X- 7-11	11/13/69	Gentry	0.646	45.0		
H-29-43	11/17/69	Dana	1.594	64.6	087.3	
H-30-44	11/21/69	Hoag	1.432	79.3	089.0	
X- 8-12	11/25/69	Gentry	0.685	45.0		
H- A-45	12/11/69	Dana				Weather
H-31-46	12/12/69	Dana	1.310	80.0	088.3	
H-32-47	1/19/70	Hoag	1.310	86.7	083.3	
H-33-48	1/26/70	Dana	1.351	87.7	086.8	
H-34-49	2/18/70	Hoag	1.861	67.3	091.3	**Fastest L/B flight**
X- C-13	2/20/70	Gentry				Full fuel Systems Checkout
X- A-13	2/20/70	Gentry				Instrumentation
X- 9-14	2/24/70	Gentry	0.771	47.0		
H- A-50	2/26/70	Dana				Elevon flap Asymmetry Switch
H-35-51	2/27/70	Dana	1.314	90.3	086.3	**Highest L/B flight**
X-10-15	3/19/70	Gentry	0.865	44.4	154.9	1st Powered X-24 flight
X-11-16	4/2/70	Manke	0.866	58.7	158.7	
X-12-17	4/22/70	Gentry	0.925	57.7	134.4	
X-13-18	5/14/70	Manke	0.748	44.6	252.3	Only 2 chambers lit
M- C-25	5/22/70	Dana				F3 Systems Checkout
M-17-26	6/2/70	Dana	0.688	45.0		1st M2-F3 flight
H-36-52	6/11/70	Hoag	0.744	45.0	044.2	L/D powered approach
X-14-19	6/17/70	Manke	0.990	61.0	128.4	
H-37-53	7/17/70	Hoag	0.733	45.0	060.4	Hoag's last/HL-10's last flight
M-18-27	7/21/70	Dana	0.660	45.0		
X-15-20	7/28/70	Gentry	0.938	58.1	123.1	
X-16-21	8/11/70	Manke	0.986	63.9	137.8	
X-17-22	8/26/70	Gentry	0.694	41.5	215.0	Only 2 chambers lit
X-18-23	10/14/70	Manke	1.186	67.9	125.4	1st Supersonic X-24 flight
X-19-24	10/27/70	Manke	1.357	71.4	135.3	Highest X-24 flight
M-19-28	11/2/70	Dana	0.630	45.0		
X-20-25	11/20/70	Gentry	1.370	67.6	121.6	
M-20-29	11/25/70	Dana	0.809	51.9	079.6	1st M2 -F3 powered flight
X-21-26	1/21/71	Manke	1.030	57.9	195.0	Alpha gage failure
X-22-27	2/4/71	Powell	0.659	45.0		Powell's 1st L/B flight

HEAVY WEIGHT LIFTING BODY FLIGHT LOG (CHRONOLGY) (Continued)

FLIGHT	DATE	PILOT	Mmax	Hmax	BURN	REMARKS
M-21-30	2/9/71	Gentry	0.707	45.0		Gentry's 1st M2/Last L/B flights
X-23-28	2/18/71	Manke	1.511	67.4	138.6	
M-22-31	2/26/71	Dana	0.773	45.0	119.4	Only 2 chambers lit, jettison fire
X-24-29	3/8/71	Powell	1.002	56.9	185.6	
X-25-30	3/29/71	Manke	1.600	70.5	135.7	Fastest X-24 flight
X- A-31	4/22/71	Powell				Weather
X-26-32	5/12/71	Powell	1.389	70.9	139.9	Delayed light
X-27-33	5/25/71	Manke	1.191	65.3	189.6	Only 3 chambers lit
M- C-32	6/1/71	Dana				Gear Mod checkout
X-28-34	6/4/71	Manke	0.817	54.4	264.2	Only 2 chambers lit/last X-24 A flight
M- C-33	7/1/71	Dana				Gear Mod checkout
M-23-34	7/23/71	Dana	0.930	60.5	110.4	
M-24-35	8/9/71	Dana	0.974	62.0	109.6	
M- A-36	8/23/71	Dana				Lox vent valve stuck
M-25-37	8/25/71	Dana	1.095	67.3	113.0	1st Supersonic M2-F3 flight
M-26-38	9/24/71	Dana	0.728	42.0	007.0	Engine malf, fire, Rosamond landing
M-27-39	11/15/71	Dana	0.739	45.0		New jettison location checkout
M-28-40	12/1/71	Dana	1.274	70.8	103.4	
M-29-41	12/16/71	Dana	0.811	46.8	180.3	Only 2 chambers lit
M- C- 42	7/7/72	Dana				Gear Mod checkout
M- A-43	7/12/72	Dana				Roll CAS malfunction
M- A-44	7/24/72	Dana				TM interference by F-111
M-30-45	7/25/72	Dana	0.989	60.9	135.7	1st CAS flight
M-31-46	8/11/72	Dana	1.101	67.2	090.5	
M-32-47	8/24/72	Dana	1.266	66.7	091.5	
M-33-48	9/12/72	Dana	0.880	46.0	182.8	Engine malfunction, small fire
M-34-49	9/27/72	Dana	1.340	66.7	095.0	
M-35-50	10/5/72	Dana	1.370	66.3	091.9	100th Lifting Body Flight
M-36-51	10/19/72	Manke	0.905	47.1	162.6	Manke's 1st M2-F3 flight
M-37-52	11/1/72	Manke	1.213	71.3	094.5	
M-38-53	11/9/72	Powell	0.906	46.8	159.4	Powell's 1st M2-F3 flight
M-39-54	11/21/72	Manke	1.435	66.7	096.7	Planned Rosamond Landing
M-40-55	11/29/72	Powell	1.348	67.5	095.1	
M-41-56	12/6/72	Powell	!.191	68.3	090.1	Planned Rosamond Landing

HEAVY WEIGHT LIFTING BODY FLIGHT LOG (CHRONOLGY) (Continued)

FLIGHT	DATE	PILOT	Mmax	Hmax	BURN	REMARKS
M-42-57	12/13/72	Dana	1.613	66.7	099.9	Fastest M2/Used L/D Rockets
M-43-58	12/20/72	Manke	1.294	71.5	093.7	Highest and last M2-F3 flight
B- C- 1	7/19/73	Manke				Systems checkout
B- A- 2	7/24/73	Manke				SAS Gyros
B- 1- 3	8/1/73	Manke	0.640	40.0		
B- 2- 4	8/17/73	Manke	0.650	45.0		
B- 3- 5	8/31/73	Manke	0.716	45.0		
B- 4- 6	9/18/73	Manke	0.687	45.0		
B- C- 7	10/3/73	Love				Pilot checkout
B- A- 8	10/4/73	Love				Rudder throwboards left on
B- 5- 9	10/4/73	Love	0.704	45.0		Love's 1st L/B flight
B- C-10	10/30/73	Manke				Full Fuel Systems checkout
B- A-11	10/31/73	Manke				Igniter Malfunction
B- A-12	11/13/73	Manke				Weather
B- 6-13	11/15/73	Manke	0.930	53.1	151.7	1st X-24B Powered Flight
B- 7-14	12/12/73	Manke	0.987	63.1	132.5	
B- 8-15	2/15/74	Love	0.696	45.0		
B- 9-16	3/5/74	Manke	1.086	60.7	117.5	
B- A-17	3/19/74	Love				Weather
B- A-18	4/22/74	Love				TV fire in B-52
B- A-19	4/23/74	Love				B-52 Lox System
B- C-20	4/25/74	Love				Aileron mod checkout
B-10-21	4/30/74	Love	0.876	52.0	143.8	Love's 1st powered flight
B-11-22	5/24/74	Manke	1.140	56.0	156.9	No lite #1, 1st overdrive flight
B-12-23	6/14/74	Love	1.228	65.4	106.9	
B-13-24	6/28/74	Manke	1.391	68.2	118.2	
B-14-25	8/8/74	Love	1.541	73.4	130.6	Pump oscillations
B-15-26	8/29/74	Manke	1.098	72.4	108.6	Fuel tank split/Early B/O
B-16-27	10/25/74	Love	1.752	72.2	135.5	Max. speed/X-24B flight
B-17-28	11/15/74	Manke	1.615	72.1	141.0	Lox cav'n, relite on #1 and #3
B-18-29	12/17/74	Love	1.585	68.8	134.2	
B-19-30	1/14/75	Manke	1.748	72.8	135.9	
B- A-31	1/31/75	Love				Weather
B-20-32	3/20/75	Love	1.443	70.4	119.3	
B-21-33	4/18/75	Manke	1.204	57.9	154.6	Faulty igniter on #3 chamber
B-22-34	5/6/75	Love	1.444	73.4	137.2	42K launch/B-52 engine #3
B-23-35	5/22/75	Manke	1.633	74.1	135.8	

HEAVY WEIGHT LIFTING BODY FLIGHT LOG (CHRONOLGY) (Continued)

FLIGHT	DATE	PILOT	Mmax	Hmax	BURN	REMARKS
B-24-36	6/6/75	Love	1.677	72.1	135.1	
B- A-37	6/24/75	Manke				Winds
B-25-38	6/25/75	Manke	1.343	58.0	125.0	
B-26-39	7/15/75	Love	1.585	69.5	132.5	
B-27-40	8/5/75	Manke	1.190	57.0	154.7	1st Runway Ldg/Manke's last flight
B-28-41	8/20/75	Love	1.548	71.1	134.0	Runway Landing/Love's last flight
B-29-42	9/9/75	Dana	1.481	69.7	127.6	Two tries on #1 chamber
B-30-43	9/23/75	Dana	1.157	56.8	152.1	Last Rocket flight/Dana's last flight
B-31-44	10/9/75	Enevoldson	0.705	45.3		Enevoldson's 1st L/B flight
B-32-45	10/21/75	Scobee	0.696	45.0		Scobee's 1st L/B flight
B-33-46	11/3/75	McMurtry	0.702	45.3		McMurtry's 1st L/B flight
B-34-47	11/12/75	Enevoldson	0.702	45.0		Enevoldson's last L/B flight
B-35-48	11/19/75	Scobee	0.700	45.0		Scobee's last L/B flight
B-36-49	11/26/75	McMurtry	0.713	44.8		McMurtry's last L/B flight/Last X-24B flight

Mmax= 1.861
Vmax= 1800.3 fps — Total Flight Time = 13:45:22.1
Hmax= 90.3 K ft — Total Burn Time = 3:05:42.5
Qmax= 371.7 psf — Total Time @ M > 1.0 = 1:02:55.8

Compiled by Jack Kolf

Appendix D

AFFTC/NASA Memorandum of Understanding

MEMORANDUM OF UNDERSTANDING BETWEEN AIR FORCE FLIGHT TEST CENTER AND NASA FLIGHT RESEARCH CENTER ON JOINT NASA FRC - AFFTC LIFTING BODY FLIGHT TEST COMMITTEE

PROGRAM DEFINITION AND PURPOSE: Two piloted, rocket powered research vehicles of different lifting body configurations are being constructed by Norair under a contract to the NASA Flight Research Center (FRC). These two vehicles are the M2-F2 configuration developed by the Ames Research Center and the HL-10 configuration developed by the Langley Research Center. These vehicles will be used to perform research on the landing characteristics and subsonic, transonic, and low supersonic handling qualities of lifting bodies.

The purpose of this memorandum of understanding is to formulate a joint NASA FRC - AFFTC Flight Test Committee for the purpose of conducting the research flight test program on these vehicles.

BASIS FOR A JOINT PROGRAM:

1. Both the NASA FRC and AFFTC have a direct responsibility for activities which affect the flight test program and decisions by either organization will have a direct input into the requirements of the other.

2. The operational capabilities at the FRC and AFFTC are mutually compatible for a research program of this type.

3. Both the AFFTC and FRC are greatly interested in the development of vehicles of this type and the expansion of flight testing technology for piloted hypersonic lifting vehicles.

4. Both the AFFTC and FRC will benefit in terms of direct operational experience with vehicles of this type.

BACKGROUND: The X-15 Flight Test Program has been performed as a joint NASA - USAF Program. Efficient use of all available resources has resulted by assigning individual tasks to those organizations within either NASA FRC or AFFTC which were best qualified to perform these tasks. As a result of this highly successful flight test program, an excellent working relationship exists between personnel of the NASA FRC and the AFFTC at all levels. Because of the similarity of the lifting body program to the X-15 program, similar assignment of responsibilities can be anticipated.

SCOPE OF COMMITTEE JURISDICTION: The Joint FRC - AFFTC Lifting Body Flight Test Committee shall be responsible for the conduct of a joint flight test program of the lifting body research vehicles. The committee shall work out on a local level those matters which would normally fall under the jurisdiction of the NASA FRC and the AFFTC.

The Joint Flight Test Committee shall receive all correspondence and requests from outside agencies, take timely action and disseminate all answers and information on matters which have a direct bearing on the Lifting Body Test Program. It shall assign overall responsibilities for carrying out the various detailed aspects of the test program through proper channels of the AFFTC and NASA FRC.

In general, the NASA FRC shall be responsible for maintenance, instrumentation, and ground support operations of the research vehicles. The AFFTC shall be responsible for the rocket power plant, launch aircraft, other support aircraft, pilot's personal equipment, and emergency medical support of the program.

Responsibilities for test missions planning, engineering data analysis and reporting, test piloting, range support under the Edwards Flight Test Range Agreement, and overall flight operations shall be jointly shared by AFFTC and FRC personnel.

COMMITTEE REPRESENTATIVES: The Joint FRC - AFFTC Lifting Body Flight Test Committee shall be chaired by the Director of the NASA Flight Research Center with the Commander, AFFTC acting as Vice-Chairman and shall consist of one representative (by name) from each of the following areas:

Pilots	1 FRC	1 AFFTC
Engineers	1 FRC	1 AFFTC
Project Officer	1 FRC	1 AFFTC
Instrumentation	1 FRC	
Medical Officer		1 AFFTC

DIRECTOR
NASA FRC
(Chairman)

COMMANDER
AIR FORCE FLIGHT TEST CENTER
(Vice Chairman)

Instr Engr Pilot Proj Mgr — FRC

Proj Off Pilot Engr Medical — AFFTC

FINANCIAL CONSIDERATIONS: Inasmuch as this is anticipated to be a joint AF/NASA program, reimbursement will not be considered.

Signed Irving L. Branch
IRVING L. BRANCH
MAJOR GENERAL, USAF
COMMANDER
AIR FORCE FLIGHT TEST CENTER

DATED 5 April 1965

Signed Paul F. Bikle
PAUL F. BIKLE
DIRECTOR
NASA FLIGHT RESEARCH CENTER

DATED 19 April 1965

ADDENDUM TO

MEMORANDUM OF UNDERSTANDING

BETWEEN

AIR FORCE FLIGHT TEST CENTER

AND

NASA FLIGHT RESEARCH CENTER

ON

JOINT NASA-FRC - AFFTC LIFTING BODY FLIGHT TEST COMMITTEE

PURPOSE: The scope of the Joint NASA-FRC AFFTC Lifting Body Flight Test Committee is expanded to include the SV-5P configuration in the research flight test program originally agreed upon for the M-2 and HL-10 configurations.

BACKGROUND: The SV-5P lifting body configuration is being constructed by The Martin Marietta Company under a contract to the Aeronautical Systems Division, AFSC. Reason for establishing a joint AFFTC/NASA-FRC program for the M2-F2 and HL-10 configurations remain valid for the SV-5P. Members of the Joint FRC-AFFTC Lifting Body Flight Test Committee have been working in similar functions on the SV-5P program with complete agreement by NASA and AFSC organizations.

SCOPE OF COMMITTEE JURISDICTION: Scope of responsibilities remain unchanged except to include the SV-5P lifting body within the committee's jurisdiction.

FINANCIAL CONSIDERATION: The joint AF-NASA program without reimbursement is not altered.

Hugh B. Manson
HUGH B. MANSON
MAJOR GENERAL, USAF
COMMANDER
AIR FORCE FLIGHT TEST CENTER

DATED 11 OCT 1966

Paul F. Bikle
PAUL F. BIKLE
DIRECTOR
NASA FLIGHT RESEARCH CENTER

DATED Oct. 11, 1966

Appendix E
List of Lifting Body Personnel

Last Name	First Name	Position	Aircraft	Organization
Anderson	Art	Mechanic	HL-10	DFRC
Anderson	Herb	Ops. Engineer	HL-10	DFRC
Anderton	Maj. Frank	Performance Engineer	X-20	AFFTC
Archie	Maj. Charles	Flight Test Engineer	X-24A	AFFTC
Armstrong	Johnny	AF Project Manager.	X-24A, X-24B	AFFTC
Armstrong	Neil	Test Pilot	F104 landing simulator	DFRC
Arnold	Bill	RMD On-Site Rep.	All	Thiokol
Ash	Lt. Lawrence	Performance Engineer	X-24A	AFFTC
Bacon	Don	Engineer	HL-10	DFRC
Barnicki	Roger	Pressure Suits	M2-F2, HL-10, X-24A, X-24B	DFRC
Barstow	Bill		X-24B	DFRC
Barto	LeRoy		X-24A	DFRC
Basko	Bill		X-24A	DFRC
Bergner	Chet	Crew Member	X-24A, X-24B	DFRC
Bikle	Paul	Director, Dryden	All	DFRC
Billeter	Orion	Elec.	M2-F2	DFRC
Blair	Richard	Instrument Tech	HL-10	DFRC
Boss	Dick	Mfg. Manager	X-24B	Martin
Brandt	Jerry	AF Propulsion Engr.	ALL	AFFTC
Briegleb	Gus	Sailplane Designer	M2-F1(shell)	Self
Browne	Ed	Fabrication	M2-F1	DFRC

List of Lifting Body Personnel (Continued)

Last Name	First Name	Position	Aircraft	Organization
Bruno	John	Inst.	M2-F2	DFRC
Buchart	Stan	DC-3, B-52 Pilot	M2-F1, M2-F2, HL-10, X-24A, X-24B	DFRC
Cates	Jack	SAS	M2-F2	DFRC
Caw	Larry		HL-10	DFRC
Clifton	Bill	Instr. Engineer	X-24A, X-24B	DFRC
Cochrane	John	Contractor Rep	X-24A, X-24B	Martin
Cosenza	Joe	Prog. Mgr.	ASSET, X-20	AFFDL
Cox	Mel		X-24A, X-24B	DFRC
Curtis	Howard	Fabrication	M2-F1	DFRC
Dana	Bill	Test Pilot	M2-F1, M2-F3, HL-10, X-24B, C-47	DFRC
DeGeer	Merle	Ops. Engineer	M2-F2	DFRC
DeMar	Norm	Ops. Engineer	X-24A, X-24B	DFRC
Draper	Al	AFFDL Branch Chief	X-20, X-24A, X-24B	AFFDL
Durrett	Capt. John	Flight Test Engineer	M2-F2	AFFTC
Edwards	John		HL-10	DFRC
Eldredge	Dick	Chief Designer	M2-F1	DFRC
Enevoldson	Einer	Test Pilot	X-24B	DFRC
Engle	Capt. Joe	Test Pilot	M2-F1	AFFTC
Fulton	Fitz	B-52 Pilot	M2-F2, HL-10, X-24A, X-24B	DFRC
Garcia	Dave	Instr. Engineer	HL-10	DFRC
Garrabrant	Dan		M2-F3	DFRC
Gentry	Capt. Jerry	Test Pilot	M2-F1, M2-F2, HL-10, X-24A	AFFTC
Green	Bob	Fabrication	M2-F1	DFRC
Greenfield	Lowell		HL-10	DFRC
Gordon	James	Inspector	X-24B	DFRC
Greishaber	Al	Instr. Technician	X-24A, X-24B	DFRC
Grogan	Mike	Lndg. Gear Loads	X-24B	AFFDL
Haise	Fred	Test Pilot	M2-F1, C-47	DFRC
Last Name	**First Name**	**Position**	**Aircraft**	**Organization**

List of Lifting Body Personnel (Continued)

Last Name	First Name	Position	Aircraft	Organization
Hamilton	Emmett	Mechanic, Pontiac	M2-F1	DFRC
Hamilton	Grierson	Fabrication	M2-F1	DFRC
Haney	Lt. Pat		HL-10	AFFTC
Hankins	Jim		X-24A	DFRC
Harer	Dick	Program Manager	X-15,M2-F2	AFFTC
Harris	Al	Electrician	HL-10	DFRC
Hoag	Major Pete	Test Pilot	HL-10	AFFTC
Hoey	Robert	AF Program Manager	X-20, M2-F2, X-24A, X-24B	AFFTC
Horton	Vic	Ops. Engineer	ALL	DFRC
Iliff	Ken	Engineer	M2-F2	DFRC
Kellog	Ray	Electronic	M2-F2	DFRC
Kempell				DFRC
LaVern				DFRC
King				DFRC
Kirsten	Paul	Stability & Ctrl Engr	X-24A, X-24B	AFFTC
Klein	Richard	Hardware Designer	M2-F1	DFRC
Kluever	Lt. Col. Jack	Test Pilot	C-47	ARMY
Koch	Berwin	Flight Planner	M2-F2, HL-10	DFRC
Kolf	Jack	Flight Planner	M2-F2, HL-10	DFRC
Kotfilm	Ron	Sperry Rand	X-24A	Sperry
Lamar	Bill	Program Manager	X-20	DFRC
Laub	Georgene	Engineer	HL-10	DFRC
Lawhead	Arden	Instr. Engineer	M2-F2, HL-10	DFRC
Layton	Gary	Program Manager	M2-F2, HL-10	DFRC
LePage	William	Crew Member	M2-F2 Crew Chief, M2-F3	DFRC
Link	Bill	Inspector	M2-F2	DFRC
Linn	Charles	Fabrication	M2-F1	DFRC
Lockwood	Millar	Electrician	M2-F2	DFRC
Lowder	Ernie	Models	M2-F1	DFRC
Little	Mary	Chief, Data Analysis	M2-F2, HL-10, X-24A, X-24B	DFRC

List of Lifting Body Personnel (Continued)

Last Name	First Name	Position	Aircraft	Organization
Love	Lt. Col. Mike	Test Pilot	X-24B	AFFTC
Lovett	Bill	Mechanic	HL-10	DFRC
Maag	Jay		X-24A	DFRC
Mallick	Don	Test Pilot	M2-F1, C-47	DFRC
Manke	John	Test Pilot	M2-F3, HL-10, X-24A, X-24B	DFRC
Martin	Wade	AF Rocket Shop	All	AFFTC
McMurtry	Tom	Test Pilot	X-24B	AFFTC
McTigue	John	NASA Program Mgr.	M2-F2, HL-10	DFRC
Mersereau	Bill	Mechanic	HL-10	DFRC
Mingelle	Ed	Plexiglass canopy	M2-F1	DFRC
Moore	Gaston	Inspector	X-24B	DFRC
Moshier	Bob	Martin	X-24A	Martin
Multhopp	Hans	Designer	X-24A	Martin
Nagy	Chris	Stability & Ctrl Engr.	X-24A, X-24B	AFFTC
Nichols	George	Fabrication	M2-F1	DFRC
Orahood	John	Hardware Designer	M2-F1	DFRC
Painter	Wen	Research Engineer	M2-F2, HL-10, X-24A	DFRC
Peterson	Bruce	Test Pilot	M2-F1, M2-F2, HL-10	DFRC
Powell	Major Cecil	Test Pilot	M2-F3, X-24A	AFFTC
Rampy	Capt. John	??	M2-F3	AFFTC
Reed	Dale	NASA Program Mgr.	M2-F1	DFRC
Reeves	John	Inspector	M2-F2	DFRC
Reedy	Jerry	??	M2-F3	DFRC
Retelle	Capt. John	Flight Test Engineer	X-24A	AFFTC
Richardson	Dave	Performance Engr.	X-24A, X-24B	AFFTC
Rickey	John	Aerodynamics	X-24A	Martin
Ridale	Jack	Martin ??	X-24A	Martin
Russell	Charlie	Crew Chief	X-24A, X-24B, Hl-10	DFRC

List of Lifting Body Personnel (Continued)

Last Name	First Name	Position	Aircraft	Organization
Russell	Jack	B-52 Launch Panel	M2-F2, HL-10, X-24A, X-24B	DFRC
Ruttle	Jack	Contractor Rep	X-24A, X-24B	Martin
Ryan	Bertha	Research Engr.	M2-F1, M2-F2, HL-10, X-24A	DFRC
Saltzman	Ed	Research Engr.	M2-F1, M2-F2, HL-10, X-24A	DFRC
Sanderson	Ken	Range/Instrumen t.	X-20	NASA
Schofield	Lyle	Aero Heating	X-20	AFFTC
Scobee	Major Dick	Test Pilot	X-24B	AFFTC
Scoville	Lt. Col. Curt	Program Manager	START, X-24A	SSD
Selegan	Dave	Research Engineer	X-24A, X-24B	AFFDL
Shuler	Billy	Fabrication	M2-F1	DFRC
Shimp	Lt. Jerry	USAF ??	HL-10	AFFTC
Sittlerle	George	Ops Engineer	HL-10	DFRC
Smith	Harriet	Research Engineer	M2-F1	DFRC
Sorlie	Major Don	Test Pilot	M2-F1, M2-F2	AFFTC
Sparks	Ralph	Shops	M2-F1	DFRC
Stewart	Al	Battery Shop	All	DFRC
Struz	Larry	??	HL-10	DFRC
Szuwalski	Bill	??	M2-F3	DFRC
Taylor	Larry	Flight Controls	M2-F1	DFRC
Thompson	Milt	Test Pilot	M2-F1, M2-F2	DFRC
Vensel	Joe	Chief of Operations	M2-F1, M2-F2, HL-10, X-24A, X-24B	DFRC
Veith	Bob	Instrumentation	M2-F2	DFRC
Wesesky	Jack	Program Manager	X-20	AFFTC
Whiteside	Walter (Whitey)	Ass't to Chief of Ops	M2-F1	DFRC
Wilson	Jerry	AF Rocket Shop	All	AFFTC
Wood	Major James	Test Pilot	M2-F1	AFFTC
Yeager	Lt. Col. Chuck	Test Pilot	M2-F1	AFFTC
Zima	Bill	Program Manager	X-24A, X-24B	AFFDL

Glossary

A3-4	Martin designation for early lifting body shape.
Ablation	Thermal process where surface melts or vaporizes at high temperature.
Ablator	Surface material which will be subject to ablation.
Active cooling	Cooling system which circulates a heat-conductive fluid between a hot region and a cool region.
AF or USAF	Air Force or United States Air Force
AFB	Air Force Base
analog computer	A simulator computer which solves equations of motion using analogous electrical circuits.
Apollo	NASA program to land a man on the moon and return him to earth.
ARC	Ames Research Center (NASA)
ASD	Aeronautical Systems Division (Air Force)
ballistic	Subject only to the forces of gravity and drag.
Ballistic Coefficient	Weight divided by the quantity drag coefficient times frontal area. (W/CD*A)
bank angle	Angle between the plane of the wings and the horizon.
base area	Non-streamlined, bluff area at the rear of a vehicle.
boat-tail	A reduction in cross-section toward the rear of a vehicle.
C-130	Four-engine, turboprop-powered cargo airplane.
capsule	A self-contained device capable of safely entering the earth's atmosphere.
CD	Drag coefficient. A non-dimensional parameter for measuring drag.

Glossary (Continued)

center of gravity	An imaginary location within an object which identifies its center of mass.
ceramic tiles	Small blocks of rigid material (primarily silica) that are poor conductors of heat.
CL	Lift coefficient. A non-dimensional parameter for measuring lift.
CLS/W	Lift coefficient divided by wing loading. A non-dimensional parameter that allows the glide performance of several aircraft to be compared at the same airspeed.
control laws	The relationship between the pilot's commands and the actual control surface movements of a flight control system.
cross-range	The distance that can be achieved during entry in a direction perpendicular to the starting flight direction.
Decoupled Mode	An entry concept that uses a different deceleration method for entry than for landing.
delta wing	A wing that has a triangular shape when viewed from above.
DOD	Department of Defense
drag	A force which resists motion that is produced by friction with the atmosphere.
Dyna Soar	Short for Dynamic Soaring. Name of a boost-glide research program that was cancelled in 1963 before the first flight.
eyeballs-in	A descriptive term used to identify the direction of a force due to acceleration.
F-11F-1F	Navy fighter aircraft built by Grumman
F5D	Navy fighter aircraft built by Douglas
FDL-7	Seventh entry design created at the Flight Dynamics Laboratory (Air Force)
FDL-8	Eighth entry design created at the Flight Dynamics Laboratory (Air Force)

Glossary (Continued)

flight path	The path of a moving object, usually measured in the vertical plane relative to the horizon.
fly-by-wire	A flight control concept that uses only electrical signals between the pilot's stick and the control surfaces.
frontal area	The area of an object as projected onto a plane perpendicular to the flight direction.
HYPER 3	A light weight, unmanned vehicle built by NASA FRC and patterned after the FDL-7 shape.
LaRC	Langley Research Center (NASA).
L/D	Lift to Drag ratio.
lift	A force on an object produced by aerodynamic reaction with the atmosphere,and which acts perpendicular to the flight direction.
Mach number	The ratio of an object's speed to the speed of sound.
Mercury	First U.S.manned space capsule program.
MSL	Mean sea level.
NACA	National Advisory Committee for Aeronautics.
NASA	National Aeronautics and Space Administration.
non-receding, charring ablator	A type of ablator that maintains its external dimensions while ablating.
operational	In the context of routine, repeatable flights; airline-like operation.
overdrive	Slang term used to describe the 14 percent increase in thrust that was available on the X-24B rocket engine.
PILOT	PIloted LOw speed Test. Early name for the X-24A program.
Pregnant Guppy	A one-of-a-kind C-97 cargo airplane which had been modified to carry oversize cargo.

Glossary (Continued)

PRIME	Precision Recovery Including Maneuvering Entry. Early designation for the SV-5D or X-23 program.
projected area	The area of an object as projected onto a horizontal plane parallel with the flight direction.
PSTS	Propulsion System Test Stand.
Radiative cooling	Cooling system which radiates heat away from the hot surface.
retrofire	Rocket engine ignition for a short time; designed to reduce speed of an orbiting object and to initiate entry.
Rogallo Wing	A wing-like parachute design which enables the parachuting object to move forward as well as to descend.
SAMSO	Space And Missile Systems Organization (Air Force).
second generation vehicle	A vehicle which has benefited from the previous design, development and testing of a similar vehicle.
self adaptive	A flight control concept which samples, then alters, internal electronic signals to compensate for changing flight conditions.
semi-ballistic	Subject to a small lift force in addition to the predominant forces of drag and gravity.
side-arm controller	A two or three axis control stick mounted on the side of the cockpit and operated by the pilots wrist movements.
simulator	A partial aircraft cockpit connected to an electronic computer which allows a pilot to simulate flying an airplane.
Sputnik	The first man-made object to be placed in earth orbit (Soviet program).
stability augmentation	Electronic control components designed to augment the stability of an airplane.
strakes	Wing-like appendages at the aft end of an aircraft that provide lift or added stability.
SV-5	Basic configuration of reentry vehicle that led to the SV-5P (X-24A) and SV-5D (PRIME).

Glossary (Continued)

SV-5J	Jet-powered version of the SV-5 configuration. Two were built, neither were flown.
test-bed aircraft	A conventional aircraft that has been equipped with some newly designed internal or external components for in-flight testing of those components.
Thor-Delta	Two stage rocket booster using a Thor 1st stage and a Delta 2nd stage.
triply redundant	Using three parallel components to accomplish a single function, with automatic deselection of any faulty component.
tufts	An array of short segments of yarn or string taped to an aerodynamic surface to allow airflow characteristics to be observed or photographed.
wedge angle	The angle of the aft control surfaces relative to the flight direction. Large angles produce shuttlecock-like stability.
wing loading	Vehicle weight divided by the projected area, W/S.
X-24C	A follow-on proposal to the X-24B to test advanced air-breathing propulsion.

Source Essay and Literature of the Field

Source Essay

Most of the information in this document is drawn directly from the authors memory, fortified by a few key documents on each of the individual vehicles, and validated by peer review by other program participants. Richard Hallion's excellent series of case studies published as "The Hypersonic Revolution" in two volumes was used throughout as a source for information on related programs. Most of the key documents were found in the Research Projects Office at the Air Force Flight Test Center at Edwards AFB or in the personal files of NASA Dryden FRC employees or retirees.

Chapter 1 draws from information in Richard Hallion's "The Hypersonic Revolution" Vol. 1. It also uses information from Clarence Syvertson's "Aircraft Without Wings" discussing the early studies at NACA on lifting entry.

Chapter 2 also draws from Richard Hallion's "The Hypersonic Revolution" Vol. 1 along with several Boeing Technical documents that are retained in the Research Projects Office at Edwards AFB.

Chapter 3 uses key information from Victor Horton, Richard Eldridge and Richard Klein's "Flight Determined Low-Speed Lift and Drag Characteristics of the Lightweight M2-F1 Lifting Body", but also relies on first-hand discussions with Dale Reed, the late Milt Thompson, Bertha Ryan, and flight logs retained at NASA Dryden FRC.

Chapter 4 draws primarily from Capt. John Durrett's summary report on the M2-F2, "Flight Planning and Conduct of the M2-F2 Glide Flight Program" and Clarence Syvertson's paper "Aircraft Without Wings" discussing the evolution of the M2 shape. Some of the M2-F3 information was obtained from interviews with Jack Kolf and John Manke.

Chapter 5 relies heavily on the recent work by Robert Kempel, Weneth Painter and Milton Thompson, "Developing and Flight Testing the HL-10 Lifting Body: A Precursor to the Space Shuttle" which is an excellent description of the HL-10 program.

Chapters 6 and 7 draw from a series of AF Flight Test Center Technical Reports published in 1971 through 1973 on the X-24A program, and between 1976 and 1977 on the X-24B program. The primary historical information was extracted from Johnny Armstrong's summary reports on each program, "Flight Planning and Conduct of the X-24A Research

Aircraft Flight Test Program" and "Flight Planning and Conduct of the X-24B Research Aircraft Flight Test Program".

Chapter 8 attempts to summarize the six primary programs that are discussed in the report. It also compares the characteristics of the 6 vehicles to each other, and to the Space Shuttle Orbiter. Space Shuttle information was drawn from personal experience, and was also extracted from the AFFTC report "Flight Test Results from the Entry and Landing of the Space Shuttle Orbiter for the First Twelve Orbital Flights." Much of the information on the effects of ablative surface roughness, although published in parallel with the Lifting Body Program, was not brought together until after completion of the Lifting Body program. The information was considered to be directly applicable to the flight test results from the Lifting Body program, so it was introduced as new material in the Epilogue. Source references for this material are included in the Epilogue.

Unless otherwise noted, all of the photos in this document were obtained from the NASA DFRC Photo Office, the AFFTC History Office, or from personal collections.

Some of the graphic figures were prepared by the author as original art work (for example, Figures 1-1 through 1-6). Some were extracted directly from the documents mentioned above and modified by the author for clarification (for example, Figures A-8, A-9 and 5-5). Other graphic figures were created by the author using data contained in one or more of these same documents (for example, Figures 8-1 and 8-2).

Literature of the Field

Anderton, Frank R., Capt. USAF. "Dyna-Soar Performance Simulation." AFFTC-TN-59-44, December 1959.

Angelis, V. M., and M. H. Tang. "Fin Loads and Control-Surface Hinge Moments Measured in Full-Scale Wind-Tunnel Tests on the X-24A Flight Vehicle." NASA TM X-1922, November 1969.

Armstrong, Johnny G. "Flight Planning and Conduct of the X-24A Lifting Body Flight Test Program." FTC-TD-71-10, August 1972.
___. "Flight Planning and Conduct of the X-24B Research Aircraft Flight Test Program." AFFTC-TR-76-11, December 1977.

Ash, Lawrence G., Capt. USAF. "Flight Test and Wind Tunnel Performance Characteristics of the X-24A Lifting Body." Vol. I and II. FTC-TD-71-8, June 1972.

Boeing. "Aerodynamic Stability and Control Data Model 844-2050." D2-80065, Boeing, Seattle, Washington, May 16, 1961.

___. "Glider Stability and Control Analysis Model 844-2050, D2-8083, Boeing, Seattle Washington, August 2, 1961.

Brackeen, R. E., and W. L. Marcy. "X-24B Growth Version Feasibility Study."

AFFDL-TR-73-116, October 1973.

Brandt, Jerome C. " XLR-11-RM-13 Rocket Engine Development and Qualification Program." FTC-TD-69-1, August 1969.

___. "X-24 Propellant System Development and Qualification Program." FTC-TD-69-7, August 1969.

Cambell, James F. "Effects of Tip-Fin Geometry on Stability Characteristics of a Manned Lifting Entry Vehicle From Mach 1.50 to 2.86." NASA TM X-1176, 1965.

Cambell, James F., and Carolyn B. Watson. "Stability and Control, Hinge-Moment, and Pressure Coefficient Data for the HL-10 Manned Lifting Entry Vehicle at Mach Numbers From 1.41 to 2.16." NASA TM X-1300, 1966.

Cambell, James F., and John T. McShera, Jr. "Stability and Control Characteristics From Mach Number 1.50 to 2.86 of a Model of a Manned Lifting Entry Vehicle." NASA TM X-1117, 1965.

Cambell, James F., and Josephine W. Grow. "Stability and Control Characteristics of a Manned Lifting Entry Vehicle at Mach Numbers From 1.50 to 2.16 Including Hinge-Moment and Pressure Distribution Data." NASA TM X-1314, 1966.

Cambell, James F., and Lloyd S. Jernell. "Effect of Various Center-Fin and Tip-Fin Arrangements on Aerodynamic Characteristics of a Manned Lifting Entry Vehicle From Mach Numbers 1.50 to 2.86." NASA TM X-1299, 1966.

Carver, D. B. "Mach Number/Flow Angle Surveys Within the Bow Shock of the X-24C Model at Mach Number 6." AEDC-TSR-79-V47, August 1979.

Cochrane, J., and K. Graham. "Pilot Safety for the X-24A Lifting Body Vehicle." Martin Marietta Corp., Baltimore, MD., 72N25969, May 1978.

Combs, Harry G. "Configuration Development Study of the X-24C Hypersonic Research Airplane, A." NASA CR-145103, January 1977.

___. "Configuration Development Study of the X-24C Hypersonic Research Airplane, Phase 2." NASA CR-145074, January 1977.

___. "Configuration Development Study of the X-24C Hypersonic Research Airplane, M Phase 1." NASA CR-145032, December 1976.

Combs, Harry G., D. H. Campbell, M. D. Cassidy, C. D. Sumpter, E. Seitz, B. J. Kachel, R. P. James, J. Walters, J. Love, and R. T. Passon. "Configuration Development Study of the X-24C Hypersonic Research Airplane." NASA CR-145274, October 1977.

Deriugin, V., H. N. Johnson, and B. E. Nelson. "Transpiration Thermal Protection System Study for the M2-F2 Vehicle." NASA CR-73069, September 1966.

Draper, Alfred C., and Thomas R. Sieron. "Evolution and Development of

Hypersonic Configurations." WL-TR-91-3067, September 1991.

Dunavant, James C., and Philip E. Everhart. "Investigation of the Heat Transfer to the HL-10 Manned Lifting Entry Vehicle at Mach Numbers From 0.2 to 1.2." NASA TM X-998, 1964.

Durrett, John C., Capt. USAF. "Flight Planning and Conduct of the M2-F2 Glide Flight Program." FTC-TR-67-13, September 1967.

Everhart, Phillip E., and H. Harris Hamilton. "Investigation of Roughness-Induced Turbulent Heating to the HL-10 Manned Entry Vehicle at a Mach Number of 8." NASA TM X-1101, 1965.

Gamse, B., and Kenneth W. Mort. "Full-Scale Wind-Tunnel Investigation of the Longitudinal Aerodynamic Characteristics of the M2-F1 Lifting Body Flight Vehicle." NASA TN D-3330, March 1966.

Hallion, Richard P. "The Hypersonic Revolution." Volumes I and II. Special Staff Office, ASD, WPAFB Ohio, 1987.

___."On the Frontier: Flight Research At Dryden, 1946-1981." NASA SP-4303, 1984.

___." Test Pilots: The Frontiersmen of Flight." Washington, D.C.: Smithsonian Institution Press, 1981.

Harris, Charles D. "Aerodynamic Characteristics of the HL-10 Manned Lifting Entry Vehicle at Mach 0.95 to 1.20." NASA TM X-1505, 1968.

___. "Control-Surface Hinge-Moment and Elevon Normal-Force Characteristics at Transonic Speeds on a Manned Entry Vehicle." NASA TM X-1241, 1966.

___. "Effect of Elevon Deflection and of Model Components on Aerodynamic Characteristics of a Manned Lifting Entry Vehicle at Mach Numbers of 0.20 to 1.20." NASA TM X-1226, 1966.

___. "Transonic Aerodynamic Characteristics of a Manned Lifting Entry Vehicle With and Without Tip-Fins." NASA TM X-1248, 1966.

___. "Transonic Aerodynamic Characteristics of a Manned Lifting Entry Vehicle With

Modified Tip-Fins." NASA TM X-(L-6619).

Harris, Julius E. "Longitudinal Aerodynamic Characteristics of a Manned Lifting Entry Vehicle at a Mach Number of 19.7." NASA TM X- 1080, 1965.

Harvey, William D. "Experimental Investigation of Laminar Heat-Transfer Characteristics of a Manned Lifting Entry Vehicle at a Mach Number of 20." NASA TM X-1306, 1966.

___. "Pressure Distribution on HL-10 Manned Lifting Entry Vehicle at a Mach Number of 19.5." NASA TM X-1135, 1965.

Henderson, W. P. "Static Stability Characteristics of a Manned Lifting Entry Vehicle at High Subsonic Speeds." NASA TM X-1349, 1967.

Hoey, Robert G. "A Dynamic Simulation of Pilot Controlled Boost for the X-20A Air Vehicle." AFFTC-TDR-63-21, March 1964.

___. "A Dynamic simulaion of Pilot Controlled Boost for the X-20A Air Vehicle." AFFTC-TR-65-24, August 1965.

___. "AFFTC Evaluation of the Space Shuttle Orbiter and Carrier Aircraft - NASA Approach and Landing Test.". AFFTC-TR-78-14, May 1978.

___. "Flight Test Handling Qualities of the X-24A Lifting Body." AFFTC-TD-71-11, February 1973.

Hoey, Robert G., and others. "Flight Test Results From the Entry and Landing of the Space Shuttle Orbiter for the First Twelve Orbital Flight." AFFTC-TR-85-11, June 1985.

Horton, V. W., R. C. Eldridge, and R. E. Klein. "Flight Determined Low-Speed Lift and Drag Characteristics of the Lightweight M2-F1 Lifting Body." NASA TN D-3021, September 1965.

Hunter, G. R., R. Sundberg, R. Melcher, K. Buck, and G. Pendergrass. "Evaluation of Rocket Engines for X-24C Aircraft, Vol. 1." Rockwell International Corp., Canoga Park, CA. R76-171-VOL.-1, March 1977.

___. " Evaluation of Rocket Engines for X-24C Aircraft, Vol. 2." Rockwell International Corp., Canoga Park, CA. R76-171-VOL.-2, March 1977.

Johnson, Joseph L., Jr., Joseph R. Chambers, and Lucy C. White. "Analytical Study of the Subsonic Dynamic Stability and Response of the HL-10 Entry Vehicle." NASA TM X-1348, 1967.

Johnson, K. L. "Mach Number/Flow Angle Surveys Within the Bow Shock of the X-24C Model at Mach Number 6." AEDC-TSR-80-V22, April 1980.

Johnson, Patrick J. "Stability Characteristics of a Manned Lifting Entry Vehicle at a Mach Number of 20.3 in Helium." NASA TM X-1156, 1965.

Jones, C. E. "Qualification Test on Technology Instruments type M2 Fixed Resistors." NASA TM X-60114, May 1965.

Kemp, W. B., Jr., and Linwood W. McKinney. "HL-10 Aerodynamic Stability and Performance Characteristics at Mach Numbers Below 1.5." Paper Presented in Lifting-Body Program Review at Flight Research Center, Edwards, Calif., Sept. 25-26, 1967, pp. 257-279. NASA LWP-545, 1968.

Kempel, R. W. "Analysis of a Coupled Roll-Spiral Mode, Pilot-Induced Oscillation Experienced With the M2-F2 Lifting Body." NASA TN D-6496, September 1971.

Kempel, R. W., W. D. Painter, and M. O. Thompson. "Developing and Flight Testing the HL-10 Lifting Body: A Precursor to the Space Shuttle." NASA Ref. Publ. 1332, April 1994.

Kempel, Robert W., William H. Dana, and Alex G.Sim. "Flight Evaluation of the M2-F3 Lifting Body Handling Qualities at Mach Numbers from 0.30 to 1.61." NASA Technical Note D-8027, 1975.

Kirlin, R. L. "Evaluation of Bond-On Insulation TPS Material for X-24C." AFFDL-TR-76-25-VOL.-1, March 1976.

___. "Development of Operational Techniques for Insulative X-24C Thermal Protection System TPS." AFFDL-TR-76-143, January 1977.

Kirsten, Paul W. "Measured Characteristics of the X-24A Lifting Body Flight Control System." FTC-TD-71-12, October 1972.

___. "Wind Tunnel and Flight Test Stability and Control Derivatives for the X-24A Lifting Body." AFFTC-TD-71-7, April 1972.

Kirsten, Paul W., and Lawrence G. Ash, Capt. USAF. "A Comparison and Evaluation of Two Methods of Extracting Stability Derivatives from Flight Test Data." FTC-TD-73-5, May 1974.

Ladson, Charles L. "Aerodynamic Characteristics of a Manned Lifting Entry Vehicle at a Mach Number of 6.8." NASA TM X-915, 1964.

___. "Aerodynamic Characteristics of a Manned Lifting Entry Vehicle With Modified Tip Fins at Mach 6.8." NASA TM X-1158, 1965.

___. "Aerodynamic Characteristics of the HL-10 Manned Lifting Entry Vehicle at a Mach Number of 10.5." NASA TM X -1504, 1968.

___. "Effects of Various Canopies on the Aerodynamic Characteristics of a Manned Lifting Entry Vehicle at Mach 0.06 to 6.8." NASA TM X-1321, 1966.

Ladson, Charles L., and Peter T. Bernot. "Comparison of Theoretical and Experimental Pressure Distribution on the HL-10 Manned Lifting Entry Vehicle at Mach 10.5." NASA TM X-1628, 1968.

Ladson, Charles L., and Robert W. Rainey. "Super-and Hypersonic Aerodynamic Characteristics of the HL-10." Paper Presented in Lifting-Body Program Review at Flight Research Center, Edwards, Calif., Sept. 25-26, 1967, pp.195-205. NASA LWP-545, 1968.

Lawing, P. L., and J. L. Hunt. "Aerodynamic Heat Transfer to a Hypersonic Research Aircraft Model /X-24C/ at Mach 6." Journal of Aircraft, vol.13, pp. 1018-1020, December 1976.

Lindsay, E. E "Aerodynamic Characteristics of the AFFDL, X-24B Configuration at Mach Numbers From 1.5 to 5.0." ARO-VKF-TR-74-58, September 1974, AEDC-TR-74-87.

Long, J. A., Jr., and R. L. Berry. "X-24B Ground Vibration Test Strake/Aileron, Fin Rudder Report." AFFTC-TR-73-23, June 1973.

Lyons, Austin J., Capt.USAF. "AFFTC Experiences With Hybrid Computation in a Real-Time Simulation of the X-15A-2" FTC-TR66-44, March 1967.

Manke, John A., and Michael V. Love, Lt. Col. USAF. "X-24B Flight Test Program." Society of Experimental Test Pilots, Technical Review, Vol. 13, No. 4, pp. 129-154, 1975.

Martin Marietta. "X-24C Research Vehicle." NASA CR-148832, Martin Marietta Corp., Denver, CO., October 1974.

Masser, C.C. "Vappor-Pressure Data Extrapolated to 1000 Atmospheres /1.01 Times 108N/m2/ for 13 Refractory Materials with Low Thermal Absorption Cross Sections." NASA TN-D 4147, October 1967.

Matranga, Gene J., and Neil A. Armstrong. "Approach and Landing Investigation at Lift-Drag Ratios of 2 to 4 Utilizing a Straight-Wing Fighter Airplane." NASA TM X-31, August 1959.

McKinney, Linwood W., and Richard P. Boyden. "Predicted Launch Characteristics of the HL-10 Manned Lifting Entry Vehicle Launched From the B-52 Airplane." NASA TM X-1668, 1968.

McShera, John T., Jr., and James F. Cambell. "Aerodynamic Characteristics From Mach 1.50 to 2.86 of a Lifting Entry Vehicle Alone, With Adapter Sections, and With a Saturn Launch Vehicle." NASA TM X-1125, 1965.

McShera, John T., Jr., and James F. Cambell. "Stability and Control Characteristics of a Manned Lifting Entry Vehicle at Mach Numbers From 2.29 to 4.63." NASA TM X-1019, 1964.

Miller, V. R., R. M. Shimovetz, and D. L. Smith. "Evaluation of the Noise Environment for the X-24C Research Vehicle." AFFDL-TM-76-47-FBE, May 1976.

Mort, Kenneth W., and Michael D. Falarski. "Full-Scale Wind-Tunnel Investigation of the Aerodynamic Characteristics of the X-24A Lifting Body Aircraft." NASA TN D-5932, August 1970.

Moul, Martin T., and Lawrence W. Brown. "Some Effects of Directional Instability on Lateral Handling Qualities of an Early Version of a Manned Lifting Entry Vehicle." NASA TM X-1162, 1965.

Nagy, Christopher J and Paul W. Kirsten. "Handling Qualities and Stability Derivatives of the X-24B Research Aircraft." AFFTC-TR-76-8, March 1976.

___. "A New Method of Test and Analysis of Dynamic Stability and Control." FTC-TD-75-4, November 1975.

National Advisory Committee for Aeronautic. NACA Conference on High-Speed Aerodynamics, A Compilation of the Papers Presented. Moffett Field, California: Ames Aeronautical Laboratory, March 18,19 and 20, 1958.

NASA (Anon). "Investigation of Landing Accident with the M2-F2 Lifting-Body Vehicle on May 10, 1967, At Edwards, California." NASA PAPER, June 1967.

___. "Flight Test Results Pertaining to the Space Shuttlecraft." A Symposium held at NASA FRC in June 1970. NASA TM X-2101, October 1970.

___. "Lifting Body Program Review." A compilation of papers presented Flight Research Center, Edwards, Calif., Sept. 25-26, 1967, NASA LWP-545, 1968.

___. "M2-F2 Lifting Body Accident Summary." NASA News Release, August 1967.

Neumann, R. D., J. L. Patterson, and N. J Sliske. "Aerodynamic Heating to the Hypersonic Research Aircraft, X-24C." AIAA PAPER 78-37, January 1978.

Norris, R. B. "Correlation of X-24B Flight and Wind Tunnel Pressure Data." AFFDL-TR-78-93, September 1978.

___. "Simulation of Rocket Plume Interference on the Aerodynamics of the X-24B at Transonic Speeds." AFFDL-TR-79-3160, July 1979.

___. "Simulation of Rocket Plume Interference on the X-24B at Transonic Speeds." AIAA PAPER 79-1666, 1979.

Northrop (Anon.) "Joint-Action Management Plan." A series of briefing charts describing the M2/Hl-10 Mgt. Concept, Northrop Corp., February 1966.

Office of Advanced Manned Vehicles. "Evaluation of the Space Shuttle Orbiter First Orbital Flight-Descent Phase." AFFTC-TR-82-21, July 1981.

___. "Evaluation of the Space Shuttle Orbiter Second Orbital Flight-Descent Phase." AFFTC-TR-82-1, February 1982.

Ono, C. "Evaluation of Rocket Engines for X-24C Aircraft." AFRPL-TR-77-12, March 1977.

Plank, P. P., W. L. Marcy, R. C. Haefeli. "Experiments Impact on X-24C." AFFDL-TR-75-37, May 1975.

Pyle, Jon S., and L. C. Montoya. "Effect of Roughness of Simulated Ablated Material on Low Speed Performance Characteristics of a Lifting Body Vehicle." NASA TM S-1810, July 1969.

Pyle, Jon S., and Robert H. Swanson. " Lift and Dray Characteristics of the M2-F2 Lifting Body During Subsonic Gliding Flight." NASA TM X-1431, August 1967.

Rainey, Robert W. "Description of HL-10 Vehicle." Paper Presented in Lifting-Body Program Review at Flight Research Center, Edwards, Calif., Sept. 25-26, 1967, pp. 217-239. NASA LWP-545, 1968.

___. "Summary of an Advanced Manned Lifting Entry Vehicle Study." NASA TM X-1159, 1965.

Rainey, Robert W., and Charles L. Ladson. "Aerodynamic Characteristics of a Manned Lifting Entry Vehicle at Mach Numbers From 0.2 to 1.2." NASA TM X-1015, 1964.

___. "Preliminary Aerodynamic Characteristics of a Manned Lifting Vehicle at a Mach Number of 6.8." NASA TM X-844, 1963.

Retelle, John P., Jr., Capt. USAF. "Measured Weight, Balance, and Moments of Inertia of the X-24A Lifting Body." FTC-TD-71-6, November 1971.

Richardson, David F. "Analysis of Approach, Flare and Landing Characteristics of the X-24A Lifting Body." FTC-TD-71-9, July 1972.

___. "Comparison of the Flight Test and Wind Tunnel Performance Characteristics of the X-24B Research Aircraft." AFFTC-TR-76-10, April 1976.

Richardson, David F., P. W. Phillips, and Robert G. Hoey. "Optimization of the Space Shuttle Reentry for High Crossrange Based on Flight Test Results." AFFTC-TR-83-64, December 1983.

Ryan, Bertha M. "Bath Tubs Fly Too." WOMAN PILOT. February/March 1994.

Schofield, B. Lyle , David F. Richardson, and Major P. C. Hoag. "Terminal Area Energy Management, Approach and Landing Investigation for Maneuvering Reentry Vehicles Using F-111A and NB-52A Aircraft." FTC-TD-70-2, June 1970.

Schofield, B. Lyle, and Robert G. Hoey. "Displays for Pilot Control During Hypersonic Lifting Re-entry." FTC-TDR-62-38, February 1963.

Schofield, B. Lyle, David F. Richardson, and Peter C. Hoag, Major USAF. "Terminal Area Energy Management, Approach and Landing Investigation for Maneuvering Reentry Vehicles Using F-111A and NB-52B Aircraft." FTC-TD-70-2, June 1970.

Silvers, H. Norman, and James F. Cambell. "Stability Characteristics of a Manned Lifting Entry Vehicle with Various Fins at Mach Numbers from 1.50 to 2.86." NASA TM X-1161, 1965.

Sim, Alex G. "Flight-Determined Stability and Control Characteristics of the M2-F3 Lifting Body Vehicle." NASA Technical Note D-7511, 1973.

Smith C. L. "Aerodynamic Characteristics of an 0.08-Scale X-24B Research Vehicle

Under the Influence of a Simulated Exhaust Plume at Free Stream Mach Numbers from 0.95 to 1.20." AEDC-TSR-78-P47, November 1978.

Smith, H. J. "Evaluation of the Lateral-Directional Stability and Control Characteristics of the Lightweight M2-F1 Lifting Body at Low Speeds." NASA TN D-3022, September 1965.

Spencer, Bernard, Jr. "An Investigation of Methods of Improving Subsonic Performance of a Manned Lifting Entry Vehicle." NASA TM X-1157, 1965.

___. "Effects of Elevon Planform on Low-Speed Aerodynamic Characteristics of the HL-10 Manned Lifting Entry Vehicle." NASA TM X-1409, 1967.

Spencer, Bernard, Jr., and Charles H. Fox, Jr. "Subsonic Longitudinal Control Characteristics of Several Elevon Configurations for Manned Lifting Entry Vehicle." NASA TM X-1227, 1966.

Spisak, John S., Capt. USAF. "Ablation Effects on the Aerodynamics of a Flight Tested Lifting Reentry Vehicle." AFFDL FXS TM 71-3. December 1971.

Stuart, John L.,Capt. USAF. "Analysis of the Approach, Flare, and Landing Characteristics of the X-24B Research Aircraft." AFFTC-TR-76-9, November 1977.

Stubbs, Sandy M. "Landing Characteristics of a Dynamic Model of the HL-10 Manned Lifting Entry Vehicle." NASA TN D-3570, 1966.

Syvertson, C. A. "Aircraft Without Wings." Science Journal, December 1968.

Tang, Ming H., and G. P. E. Pearson. "Flight-Measured X-24A Lifting Body Control Surface Hinge Moments and Correlation with Wind Tunnel Predictions." NASA TM X-2816, June 1973.

Tang, Ming H., W. J. Sefic, and R. G. Sheldon. "Flight-Measured X-24B Fin Loads and Control Surface Hinge Moments and Correlation with Wind Tunnel Predictions." NASA TM X-56042, January 1977.

Thompson, Milton O., Bruce A.Peterson, and Jerauld R.Gentry. "Lifting Body Flight Test Program," Society of Experimental Test Pilots, Technical Review, September 1966, pg. 1-22.

U.S. Air Force - National Aeronautics and Space Administration. Joint Conference on Lifting Manned Hypervelocity and Reentry Vehicles, A compilation of the Papers Presented, Part I, Langley Research Center Langely Field Virginia, April 11-12, 1960.

Vitelli, John, Capt. USAF. "History of the START Program and the SV-5 Configurations." Vol. I Narrative, AFSC Publ. Series 67-23-1, October 1967.

Ware, George M. "Aerodynamic Characteristics of Models of Two Thick 74˜ Delta Manned Lifting Entry Vehicles at Low-Subsonic Speeds." NASA TM X-914, 1964.

___. "Effect of Fin arrangements on Aerodynamic Characteristics of a Thick 74˜ Delta Manned Lifting Entry Vehicle at Low-Subsonic Speeds." NASA TM X-1020, 1965.

___. "Full-Scale Wind-Tunnel Investigation of the Aerodynamic Characteristics of the HL-10 Manned Lifting Entry Vehicle." NASA TM X-1160, 1965.

___. "Investigation of the Flight Characteristics of a Model of the HL-10 Manned Lifting Entry Vehicle." NASA TM X-1307, 1966.

Whoric, J. M. "Aerodynamic Characteristics of a 5.5-Percent Scale Model of the AFFDL X-24B Flight Test Vehicle." AEDC-TR-75-10, February 1975.

AFFTC Research Projects Office Memoranda

Edwards Air Force Base, California

All. "Space Shuttle Orbiter Flight Test Report of the STS-7 Entry and Landing." Memo, August 1983.

Anonymous. "Advanced Development Program Plan for PILTO." Headquarters Systems Division Air Force Systems Command, 68 ASZS -499 ., February 1969.

Audley, David, Capt. USAF. "Parameter Identification of the Reentry Aerothermodynamic Environment." Memo, March 1981.

Bourne, Cynthia A., Capt. USAF. "Orbiter Weight and Balance Tares Revisited." Memo, September 1981.

___. "STS-1 Post Flight Weight and Balance." Memo, May 1981.

___. "JSC Shuttle Night Landing Tests." Memo, June 1982.

___. "Orbiter Weight and Balance Tares." Memo, April 1981.

___. "Post STS-2 Weight and Balance." Memo, December 1981.

___. "Space Shuttle Carrier Aircraft In-flight Refueling Proximity Test Results." Memo, May 1984.

Bourne, Cynthia A., Capt. USAF and David F. Richardson. "Simulator Verification of Orbiter Autoland and Heads up Display." Memo, October 1981.

Bourne, and Kirsten. "Approach and Landing Characteristics of the Space Shuttle Orbiter." Memo, March 1983.

Hamilton, David, Capt. USAF. "Simulation of the Orbiter Auxiliary Power Unit/Hydraulics Subsystems." Memo, July 1980.

___. "Simulation of the Orbiter Reaction Control System and Aerodynamic

Interaction Effects." Memo, July 1980.

___. "Space Shuttle Orbiter APU Fuel Utilization from AFFTC Simulator Studies (Through May 1980)." Memo, June 1990. US Government Agencies and Contractors Only.

Hertzler, Phillips. "Flight Test Derived Heating Math Model for Critical Locations on the Orbiter During Reenrty." Memo, March 1983.

Hodge, James, Capt. USAF. "Aerothermo Study on AFFTC Engineering Shuttle Simulator." Memo, May 1980.

Hoey, Robert G. "AFFTC Overview of Orbiter Reentry Flight Test Results." Memo, August 1983.

___. "Impact of Weather Patterns on Space Shuttle Landing Opportunities Following Vandenberg AFB Launches." Memo, June 1982.

___. "Post Flight Visual Inspection of the SV-5D Heat Shield." Memo, May 1967.

___. "A Flight Test Program to Evaluate Terminal Energy Management and Landing Characteristics of Lifting Reentry Vehicles." Memo, March 1969.

Jacon. "Supersonic Flight Test Calibration of Orbiter Air Data System." Memo, August 1982.

Kirsten, Paul W. "A Proposed Fuel-Saving Reentry Flight Control System for the Space Shuttle Orbiter." Memo, August 1983.

___. "AFFTC Space Shuttle Simulation Validation." Memo, January 1980.

___. "Effect of STS-1 Flight Data on Orbiter Lateral CG Capability." Memo, August 1981.

___. "In-Flight Simulation of the Space Shuttle Orbiter Low Speed Handling Qualities Using the Calspan/USAF TIFS Airplane." Memo, October 1978.

___. "Limit Cycle and Structural Resonance Ground Testing of the DIGITAC II Aircraft." Memo, June 1980.

___. "Space Shuttle Orbiter Handling Qualities Study for 65 Percent CG and Fixed Body Flap." Memo, March 1980.

___. "STS-2 Maneuver Evaluation." Memo, August 1981.

Kirsten, Paul W and David F. Richardson and Lt. C. Wilson, USAF. "Predicted and Flight Test Result of the Performance Stability and Control of the Space Shuttle from Reentry to Landing." Memo, March 1983.

Nagy, Christopher J. "A User's Guide to the Computer Compatible Tape Interface Program." Memo, May 1978.

Nield, George C., Capt. USAF. "Flight Test Evaluation of the Space Shuttle Carrier Aircraft." Memo, July 1977.

___. "Space Shuttle Carrier Aircraft Ferry Test Results." Memo, April 1978.

Office of Advanced Manned Vehicles. "Interim Assessment of the space Shuttle Orbiter Entry and Landing Capabilities--STS-1 through STS-6." Memo, June 1983.

___. "Quick Look Evaluation of the Space Shuttle Orbiter Third Orbital Flight-Descent Phase." Memo, May 1982.

___. "Quick Look Evaluation of the Space Shuttle Orbiter Seventh and Eighth Orbital Flights--Descent-Phase." Memo, October 1983.

___. "Quick Look Evaluation of the Space Shuttle Orbiter Fourth Orbital Flight-Descent Phase." Memo, September 1982.

___. "Quick Look Evaluation of the Space Shuttle Orbiter Fifth Orbital Flight-Descent Phase." Memo, December 1992.

___. "Quick Look Evaluation of the Space Shuttle Orbiter Ninth Orbital Flight." Memo, January 1984.

Phillips, Paul W. "Aerothermo Study for STS-1 Abort Once Around (AOA) on the AFFTC Engineering Study Simulator." Memo, January 1981.

___. "Correlation of Space Shuttle Lower Surface Thermocouple Data with Axial Accelerometer Data in Determining Lower Surface Boundary Layer Transition During Entry." Memo, August 1983.

___. "Resistance-Capacitance Circuit Analogy to Thermal Conductance and Heat Capacity." Memo, March 1981.

Richardson, David F. "Contingency Abort Studies with Three SSME's Failed Using Shuttle Orbiter Simulation at AFFTC." Memo, February 1981.

___. "Interpretation of space Shuttle Orbiter Aerodynamic Data for the MAP Simulation." Memo, September 1976.

___. "Recent Updates to the space Shuttle Orbiter Aerodynamic Data Base for the AFFTC Simulator." Memo, June 1979.

___. "Shuttle Aborts To Rota, Spain." Memo, March 1981.

___. "Space Shuttle Orbiter Simulated Landing Flare Characteristics." Memo, April 1977.

___. "STS-2 Maneuver Plan Development Studies from Shuttle Orbiter Simulation at AFFTC." Memo, July 1980.

Richardson, David F., and James Hodge, Capt. USAF. "Initial through on the Use of

Pushover-Pull-up Maneuvers to Obtain Performance and Heating Data During the space Shuttle OFT Program." Memo, October 1978.

Simpson. "Effects of Solar Radiation on the Heating Rate of the Space Shuttle's Left OMS Pod Thermocouple No. 9976 During Entry." Memo, July 1983.

Sutton, J. P. "X-24B Landing Loads for Initial Flights." Memo, January 1974.

Woo Yuk, Capt. USAF. "Results of Wind Tunnel Test to Simulate the Space Shuttle AFRSI Thermal Protection System Failure Environment Experienced on STS-6." Memo, October 1983.

___. "Updated Space Shuttle Orbital Maneuvering System Pods Heating Model Using a Quasi Steady-State Data Analysis Technique." Memo, January 1984.

NASA FRC Memoranda

Edwards Air Force Base, California

Dana, William. "Special Tasks or Incidents Night Landings." Memo , 1967.

Lifting Body Project Group, "M2-F3 Flight Review, Flight 30 through Flight 43." Memo, August 1973.

___. "Results of the First Flight of the HL-10 Lifting Body Vehicle." Memo, July 1967.

NASA-FRC. "Incident Report X-24 Engine Fire." Memo, August 1970.

Pyle, Jon S. "Observation and Examination of the Heat Shield on the Prime SV-5D." Memo, June 1967.

___. "Preliminary Lift and Drag Results From the Second Flight of the Hl-10 Vehicle." Memo, March 1968.

Thompson, Milton O., William H. Dana. "Flight Simulation of Night Landings of Lifting Entry Vehicles." Memo, March 1968.

Watts, Joe D. "X-24B Incident Investigation Board." (Incident Involving Inadvertent Nose Gear Retraction on The X-24B, May 17, 1973.) Memo, May 1973.

About the Author

Robert G. Hoey was born in Seattle, Washington. He grew up in Bryn Mawr just south of Seattle, and attended Renton High School. His interest in aviation started early. At age 12 Bob started building model airplanes. His first paying job was "line boy" at the Renton airport where he turned most of his earnings into flying lessons. He obtained his private license at age 16. He attended the University of Washington and received an Aeronautical Engineering degree in 1955.

Mr. Hoey's professional career started at Edwards Air Force Base in March 1955. As an Air Force Lieutenant, he served two years at the Air Force Flight Test Center, working as a Flight Test Engineer in the Fighter Branch of the Engineering Division. He arrived at Edwards at a time in history when the "century-series" fighters (the first production supersonic fighters) were in early developmental testing. He worked as an assistant engineer on the early tests of the F-100, F-101, F-102, F-105 and F-106 fighters. As a Project Engineer, his first test program was the F-100C Stability and Control program. The project pilot for the program was Captain Melburn Apt who was later killed in the famous X-2 accident. Bob's second project was the F-104A Stability and Control test program. This time his project pilot was Captain Ivan Kincheloe who also flew the X-2 and attained an altitude record of over 126,000 feet. When Bob's stint was completed in 1957, he remained at Edwards in his same job, but now as an Air Force Civil Service employee. In 1958 Bob and "Kinch" both moved onto a team that resulted from the newly-formed AF/NASA X-15 Joint Operating Committee. This team would test the X-15 that was still under construction at North American. Bob learned to program and utilize the X-15 flight simulator which was, at that time, a new tool for the flight test engineer. During 1960 and 1961 he worked with Dick Day, his counterpart at NASA FRC, to plan the early envelope expansion flights of the X-15. The envelope reached an altitude of over 250,000 feet and a speed of 4200 miles per hour (Mach 6.1).

Between 1961 and 1963 Mr. Hoey divided his time between the X-15 program and the emerging Dyna Soar (X-20) program. He was designated as the lead Air Force Stability and Control Flight Test Engineer on the AF/NASA test team that was being formed to test the X-20. Upon the demise of the X-20 in late 1963, Bob moved into a supervisory role. He headed the small group of Air Force engineers that continued to work with NASA FRC on the X-15, the Lifting Bodies, and several other flight test programs that involved high speed research (including early AF tests of the SR-71).

In 1975, near the end of the X-24B program, Mr. Hoey returned to the classroom and earned his Master of Science degree in Systems Management from the University of Southern California. Upon his return to Edwards in 1976 he was tasked by the AFFTC Commander to form a new organization within the AFFTC to prepare for the upcoming Space Shuttle flights. The new organization, the Office of Advanced Manned Vehicles, was responsible for conducting an independent engineering assessment of the reentry and landing aspects of the Space Shuttle with respect to DOD requirements. Bob's office was also responsible for overseeing all AFFTC resources required to support Space Shuttle operations at Edwards (security, range, fire crash and rescue, and airspace control). He was named the 1983 Outstanding Federal Employee of the Year by the Federal Executive Board of Los Angeles in recognition for this effort. The Space Shuttle support activity was essentially completed in 1985 and the charter and title of Bob's organization was revised. He now headed the Office of Research Projects. Its primary function was the coordinated support of engineers and test pilots to several joint AF/NASA test programs (X-29, X-31, AFTI F-16, AFTI F-111 TACT) and the planning for future one-of-a-kind research test programs (F-15 STOL Fighter, X-30 Aerospace Plane, Boost-Glide Vehicle, F-16 VISTA).

Bob Hoey retired from civil service in 1987. Since then he has worked as a part-time flight test consultant. In this capacity he supported Defense Advanced Research Projects Agency (DARPA) and worked on the testing of one of Burt Rutan's designs, the Advanced Technology Tactical Transport. He has also used his simulation experience to assist Kohlman Systems Research in the testing and math-modeling of several small business-class aircraft for the purpose of creating pilot training simulators.

Bob's interest in aviation extended beyond the workplace. Between 1966 and 1968 he entered a partnership with another flight test engineer, and they constructed an all-wood sailplane (BG-12B). Bob attained his Diamond soaring badge in the sailplane in 1970. Between 1973 and 1979 he constructed a 4-place powered airplane (BD-4) which he is still flying.

His most recent interest has been in the study of soaring birds to better understand their method of lateral control without vertical tails. He successfully created a radio-controlled model of a soaring Raven (without a vertical tail) and reported the results at the 6th AIAA Biannual Flight Test Conference in 1992.

Bob is married and has two grown children. He resides in Lancaster California where he continues to monitor the aviation activities at Edwards.

Having actively participated as a flight test engineer in each of the primary programs addressed in this document (from the X-20 to the Space Shuttle), Mr. Hoey is uniquely qualified to present the history, discuss the technical aspects, and highlight the lessons learned from these programs.