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Office of Management

Scientific and Technical
Information Program

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1926–1993

Robert W. Kempel is currently a senior aerospace engineer with *PRC* Inc. assigned to the NASA Dryden Flight Research Center at Edwards, California. Mr. Kempel has been associated with *PRC* Inc. since his retirement from NASA Dryden in 1986. A native of Detroit, Michigan, Mr. Kempel's aerospace career has spanned more that 32 years. Mr. Kempel joined the X-15 Hypersonic Research Airplane flight test team at the NASA High-Speed Flight Station (which was later to become NASA Dryden) in 1960. One of the many highlights of Mr. Kempel's career included the responsibility as the principal stability and control, handling qualities, and flight simulation engineer on the experimental rocket-powered HL-10 and M2-F3 lifting-body flight research programs. More recently, he served as the remotely piloted vehicle systems manager/integrator on such programs as the highly maneuverable advanced technology (HiMAT) remotely piloted vehicle and the remotely controlled Boeing 720 impact demonstration (controlled crash) program. Mr. Kempel is a member of the Society of Flight Test Engineers. He is the author of numerous formal NASA publications and symposium papers as well as the recipient of numerous awards.

Weneth D. Painter is currently a senior flight test instructor at the National Test Pilot School at Mojave, California. In addition, Mr. Painter has taught at the California State Polytechnic University following his retirement from NASA Dryden in 1986. A native of Nebraska, Mr. Painter's aerospace career has spanned more that 30 years. Mr. Painter joined the NASA Flight Research Center, which was later to become NASA Dryden, in 1963. Mr. Painter worked on a variety of flight test programs including the F-100C variable stability airplane; M2-F2, HL-10, and X-24A lifting bodies; and F-8 supercritical wing. Mr. Painter was program manager on such projects as the F-111 transonic aircraft technology, NASA/Navy XV-15 tilt rotor, AD-1 oblique wing airplane, B-57 severe storms project, and the rotor systems research aircraft. Mr. Painter is a certified flight instructor with more than 4,000 flying hours. In his capacity at the National Test Pilot School, he has taught students from many countries including Indonesia, Taiwan, and South Africa. Mr. Painter is a member of the Society of Flight Test Engineers. He is the author of numerous formal NASA publications and symposium papers as well as the recipient of numerous awards. Mr. Painter and his wife, JoAnn, live adjacent to the Mojave airport where they have a flying business.

Milton O. Thompson, former NASA Dryden Chief Engineer, supported and encouraged the generation of this work. In addition, he provided many outstanding suggestions and useful comments. As was indicated earlier, Mr. Thompson flew the first lightweight and heavyweight M2 vehicles. The first heavyweight lifting-body flight, the M2-F2, took place on July 12, 1966 with Mr. Thompson at the controls. Without his vision, we may have never seen the success of the space shuttle. On August 3, 1993, Mr. Thompson completed his final editorial review of this work. His final comments were included and the manuscript was ready for publication preparation by the NASA editorial staff. On the evening of August 6, 1993, NASA planned a dinner celebration in honor of Mr. Thompson. This was to be a tribute to Mr. Thompson by all of NASA, his friends, and colleagues. However, on the morning of August 6, Mr. Thompson passed from this life. At the tribute we remembered the 37 years of NACA/NASA service he rendered as a true professional and as an aerospace pioneer. We remembered him as a friend and we remembered him as a visionary. We are the richer for having known him and the poorer with losing him. Milt, we salute you.

FOREWORD

The story we want to tell is a bit unique. The story of the development and flight testing of a unique aerospace vehicle—the horizontal lander HL-10—is from our perspective as primary members of the flight test team at the NASA Flight Research Center (now NASA Dryden Flight Research Center). Mr. Kempel was with the program eight months before the first flight and continued through the final (37th) flight. Mr. Painter's association with the HL-10 began approximately three years before the first flight and continued through the final flight. Mr. Thompson flew the first lightweight and heavyweight M2 vehicles. The first heavyweight lifting-body flight, the M2-F2, took place on July 12, 1966, with Mr. Thompson at the controls.

Others may be more qualified to relate the story of the birth of the HL-10; however, we have included a section that presents some insight that may not exist elsewhere. This section was compiled using some unpublished notes of Robert W. Rainey and Charles L. Ladson of NASA Langley Research Center. History written by those who did not participate in the events themselves may be inclined to be muted, and this may be the case with this section. Many unnamed pilots, engineers, technicians, mechanics, and support personnel made this program work. The successes of the HL-10 were the result of efforts of the entire team, real people. People made it work. The impressions of the flight operations are ours and we got some help from others who lived it too. We hope, after reading it, that you will also think it is a story worth telling.

ABSTRACT

The origins of the lifting-body idea are traced back to the mid-1950s, when the concept of a manned satellite reentering the Earth's atmosphere in the form of a wingless lifting body was first proposed. The advantages of low reentry deceleration loads, range capability, and horizontal landing of a lifting reentry vehicle (as compared with the high deceleration loads and parachute landing of a capsule) are presented. The evolution of the hypersonic HL-10 lifting body is reviewed from the theoretical design and development process to its selection as one of two low-speed flight vehicles for fabrication and piloted flight testing. The design, development, and flight testing of the low-speed, air-launched, rocket-powered HL-10 was part of an unprecedented NASA and contractor effort. NASA Langley Research Center conceived and developed the vehicle shape and conducted numerous theoretical, experimental, and wind-tunnel studies. NASA Flight Research Center (now NASA Dryden Flight Research Center) was responsible for final low-speed (Mach numbers less than 2.0) aerodynamic analysis, piloted simulation, control law development, and flight tests. The prime contractor, Northrop Corp., was responsible for hardware design, fabrication, and integration. Interesting and unusual events in the flight testing are presented with a review of significant problems encountered in the first flight and how they were solved. Impressions by the pilots who flew the HL-10 are included. The HL-10 completed a successful 37-flight program, achieved the highest Mach number and altitude of this class vehicle, and contributed to the technology base used to develop the space shuttle and future generations of lifting bodies.

NOMENCLATURE

Acronyms

AGL	above ground level, ft
AOA	angle of attack, deg
FRC	Flight Research Center (former name of NASA Dryden)
ICBM	intercontinental ballistic missile
MSL	mean sea level, ft
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
SAS	stability augmentation system
USAF	United States Air Force

Symbols

b^2	reference span squared, ft^2
C_L	coefficient of lift
D	drag, lb
g	acceleration due to gravity, 32.174 ft/sec^2
h	altitude, ft or m
L	lift, lb
L/D	lift-to-drag ratio
M	Mach number
p	roll angular rate, deg/sec
S	reference planform area, ft^2
δ_a	aileron deflection, deg
δ_e	elevon deflection, deg
δ_{es}	longitudinal stick deflection, cm
ϕ	bank angle, deg

INTRODUCTION

A significant percentage of the developed world's population has seen the space shuttle's launch and gliding return to Earth from orbit. Before these achievements could be realized and we could experience the thrill of a space-shuttle launch and landing, however, significant preparation had to be accomplished. Much of that preparation included successfully demonstrating unpowered landings by a new class of vehicle. This story is about that part of the preparation—the conception, design, development, and flight testing of a wingless experimental aircraft. The experimental aircraft was the HL-10, an aircraft that is referred to as a "lifting-reentry" or "lifting-body" vehicle, and the story is about its contribution to the development of the terminal gliding and horizontal landing technique currently used by the space shuttle.

Lifting-Body Concept

In the early 1950s the concept of lifting reentry from suborbital or orbital space flight evolved at the National Advisory Committee for Aeronautics (NACA)* Ames Aeronautical Laboratory, Moffett Field, California, by two imaginative engineers, H. Julian "Harvey" Allen and Alfred Eggers. As an example of the early work reference 1 presents a compilation of papers from the last NACA Conference on High-Speed Aerodynamics, which was held in March 1958. The initial work was accomplished in connection with the reentry survival of ballistic missile nose cones. Mr. Allen found that by blunting the nose of a missile, the reentry energy would be more rapidly dissipated through the large shock wave while a sharp nosed missile would absorb more energy, in the form of heat, through skin friction. The blunt-nosed vehicles were more likely to survive reentry while the pointed nosed vehicles may suffer severe damage from heating. Using the concept of blunt nose, Faget et al. (ref. 2) concluded that "the state of the art is sufficiently advanced so that it is possible to proceed confidently with a manned satellite project based upon the ballistic reentry type of vehicle." The same paper indicated that the maximum deceleration loads would be on the order of 8.5 *g*. Another paper from the conference (ref. 3) presented the results of a study using a blunt 30° half cone wingless reentry configuration. This configuration resulted in high lift and high drag, which would result in maximum deceleration loads on the order of 2 *g* (or lower) and would accommodate aerodynamic controls. In addition, this configuration would allow a lateral reentry path deviation of about ±230 mi and a longitudinal variation of about 700 mi. In the same conference the problems with winged reentry configurations were also discussed. Reference 4 presented an interesting informal synopsis of the tone and ideas presented at the conference. Less than four months after the NACA Conference on High-Speed Aerodynamics, Congress passed the National Aeronautics and Space Act, dissolving NACA and establishing NASA.

It would seem obvious that (following this conference) the logical choice for a piloted reentry configuration would be the proposed, blunt half-cone—a 2-*g* entry vehicle with controls and path deviation capability, in opposition to an 8.5-*g* ballistic entry vehicle with no control and almost no path deviation capability. This was not to be, however, because of more practical considerations. A blunt-nosed ballistic configuration became the United States' candidate for the first piloted spacecraft because of the lack of a large reliable rocket capable of boosting a wingless reentry configuration (ref. 4). The Atlas rocket-boosted Mercury capsule later evolved into the Apollo program that used the Saturn rocket.

The wingless reentry configuration concept had not died though, it was just that we had no experience with this class of vehicle. To better understand the advantages of a blunt half-cone or wingless reentry vehicle configuration concept, consider the following. Simply stated, lifting reentry would be achieved by flying, from space, to a conventional horizontal landing using such vehicles as a blunt half-cone body, a wingless body, or a vehicle with a delta planform (i.e., the space shuttle) by taking advantage of their ability to generate body lift and thus fly. We could not put conventional straight or even swept wings on these vehicles as they would burn off during reentry, although a delta planform with large leading-edge radius might work. These vehicles, or lifting bodies, would have significant glide capability downrange (the direction of their orbital tracks) and crossrange (the direction across their orbital tracks) due to the aerodynamic lift (L) that they could produce during reentry. Space capsules, on the other hand, reenter the Earth's atmosphere on a ballistic trajectory and decelerate rapidly due to their high aerodynamic drag (D). Capsules can produce small amounts of lift but produce large amounts of drag. Consequently they are subjected to high reentry forces due to rapid deceleration and have little or no maneuvering capability. These must then rely on parachute landings.

In contrast, the capability to produce lift (by a lifting body) would allow the selection of several possible

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*NACA was the predecessor of the National Aeronautics and Space Administration (NASA).

landing sites on the return to Earth from orbit. In addition, the deceleration forces are significantly reduced from about 8 *g* to 1 or 2 *g*. The solid line on figure 1 (ref. 5) represents a spacecraft's hypothetical orbital track following a launch from NASA Kennedy Space Center. The small triangular area, labeled Mercury/Gemini/Apollo, off the southeast coast of the United States, represents a typical landing "footprint" of a capsule type vehicle. By contrast, the lifting-body landing footprint, for a hypersonic (Mach $(M) \geq 5$) lift-to-drag ratio $(L/D) \approx 1.5$, includes the entire western United States and parts of Mexico—a significant improvement over a capsule. The prospect of achieving the goal of lifting reentry was somewhat exciting when one considers the limited capability of ballistic reentry capsules, as illustrated in figure 1.

The footprint for the lifting body is defined by, or dependent on, the ratio of aerodynamic *L/D*. Reference 6 states that lateral range during entry depends only on the ratio of *L/D* produced by an entering spacecraft. This is an important ratio in the dynamics of flight for all flight vehicles (birds too) and particularly for sailplane pilots. In general the higher the *L/D* the farther the vehicle will be able to glide.

Lift is that ability (it is really a force) of a wing or thin plane surface to overcome gravity by producing an opposite force as air moves over it when the leading edge is tilted slightly up. This force is generated by the moving air (molecules) coming in contact with or under the influence of the wing or surface and producing a higher pressure on one side. More specifically, the lower surface generally experiences higher than ambient pressure while the upper surface experiences significantly lower than ambient pressure. We usually associate this force with a wing although almost any type of surface, an umbrella for example, can produce lift (air has to be moving over or by it though). A wing, or airfoil as we call them, produces lift more efficiently, by virtue of its shape, rather than just some flat surface shape. As a demonstration of lift, put your hand out the window of a moving automobile, fingers pointing at 90° from the road, index finger forward and fingers close together with palm down. Slowly rotate your wrist so that the little finger is lower than the index finger. Feel the tendency of your hand to rise. That is lift. Drag is the force that resists the motion or that force that tends to bend your hand toward the back of the car. Rotate your palm so it is perpendicular to the ground and feel maximum drag (zero lift but lots of drag). The medium in which we are immersed is air, but the same characteristic happens in other fluids too.

The ratio of *L/D* is very important to an airplane, particularly one without power. This ratio is a direct measurement of how far a glider, sailplane, or airplane without power can glide. The higher the number the farther the glide can be. Everybody wants to reduce drag. Airline owners benefit from reduced drag by getting more miles per gallon. Sailplanes pilots want to increase lift and reduce drag so they can fly farther. Sailplanes with *L/D* of 20 and above are not uncommon, and values of about 60 have been recorded. This means that, if *L/D* = 20 at a given airspeed, for every 20 ft forward the sailplane moves, it will sink 1 ft for a glide ratio of 20 to 1 and have a glide angle less than 3°

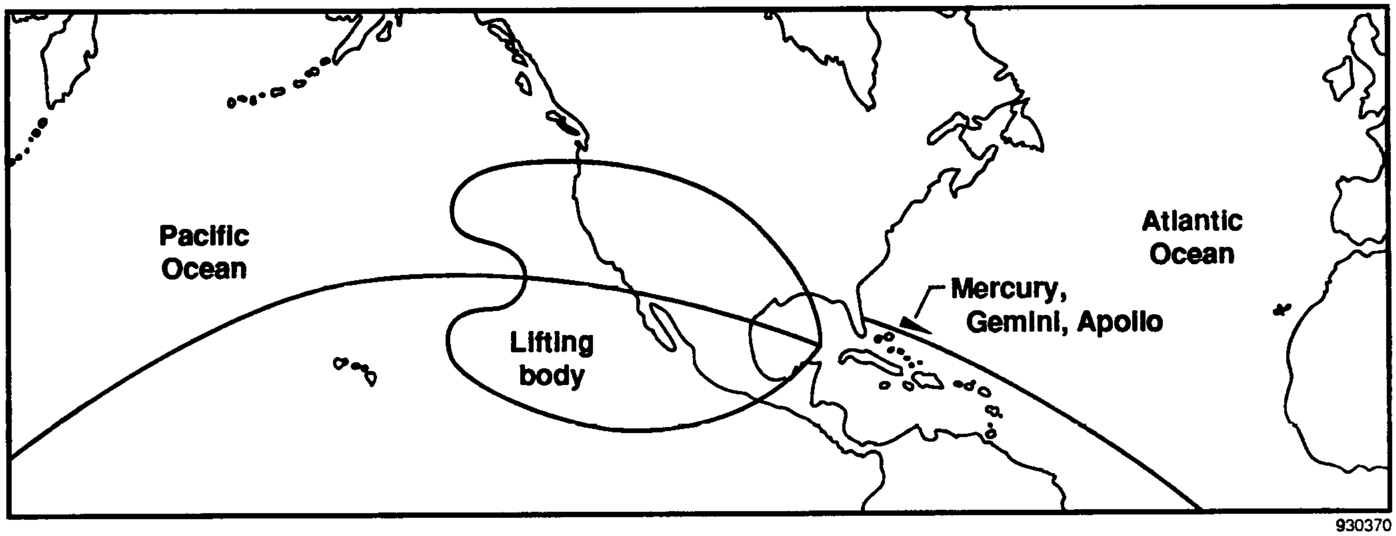

Figure 1. Orbital reentry footprints.

nose down. When we talk of lifting bodies, we are talking of vehicles with subsonic $L/D \approx 3$ or 4 at most.

Even though the concept of lifting reentry is relatively simple, the practicality of achievement was not. The salient question concerning lifting-body operations was how to land these vehicles. The initial answer, of course, was with *power* (except in an emergency). And in the event of an emergency, the next question was whether a pilot could successfully flare and land this class vehicle with no power.

Brief Area Description and Some History

In late 1946 NACA sent a small contingent of 13 engineers and technicians from Langley Memorial Aeronautical Laboratory to the Muroc Army Air Field to assist in flight testing the Army's XS-1 rocket-powered airplane. This small group was known as the NACA Muroc Flight Test Unit. Muroc Army Air Field, with the adjacent Muroc (Dry) Lake (now known as Rogers (Dry) Lake) and the home of Edwards Air Force Base, is where all HL-10 flight testing took place. (This group of people has grown into what is today the NASA Dryden Flight Research Center with more than 1100 people in support of premiere flight test activities.) Rogers Lake is located on the western edge of California's Mojave Desert, just south of Highway 58 between the towns of Boron and Mojave. It is a few miles southwest of the world's largest open-pit Borax mine and within sight of one of the first emigrant trails to California.

Muroc Army Air Field was named after the founding family of the area. The Corum family, who settled near the large dry lakebed in 1910, wanted a post office with their family name, but there was already one by that name in California. So they reversed the spelling of their name to Muroc.

This geographical area was a logical choice for flight testing. The flat, hard surface of Rogers Lake, at approximately 2300 ft above sea level, makes one of nature's best landing sites on the planet. The arid weather also makes for excellent flying conditions almost every day of the year. The lakebed area is approximately 64 mi^2, or three times the size of Manhattan Island.

Rogers Lake is the sediment-filled remnant of an ancient lake formed eons ago. Today, when it rains, several inches of water can accumulate on the lake, and in combination with the winds, a natural smoothing and leveling action takes place. When the water dries, a smooth level surface results, one better than man could produce. Lake water also brings to life an abundance of small shrimp, several unique species of prehistoric crustacean, prevalent only when wet, in many of the desert's lakebeds. Annual mean rainfall here is approximately 4–5 in., sometimes considerably less; in extremely wet years rainfall can be 6–9 in. or occasionally more than 15 in. Winds are usually predictable, from the southwest (240°) in spring and summer with a mean velocity of 6–9 knots. Sunrises and sunsets can be breathtakingly beautiful. If the rains are the right amount at the right time, the spring flowers are nothing less than spectacular. Actually, it is not a bad place to work and live.

The surrounding geography consists of typical California high desert rolling sand hills with some rocky rises, ridges, and outcroppings punctuated with dry lakebeds in the low spots. Mountains abound to the south and west and to the north the mighty Sierra Nevadas rise over 14,000 ft. Joshua trees abound among the chaparral and sagebrush and are quite dramatic. In some ways these trees are grotesque, but in other ways they are beautiful. The Joshua tree is a type of yucca (a member of the lily family) with clusters of very sharp bayonet-like or quill-like dark green, very sharp protrusions that are 6–10 in. long, which botanists call "leaves." These trees, like everything else in the desert, are well-suited for survival in the harsh climate. Extreme temperatures here reach from near 0 °F in the winter to 120 °F in the summer, with 10–15 percent humidity. Every living thing here is uniquely adapted for desert survival.

In the spring of 1843 Joseph B. Chiles, starting from Independence, Missouri, organized and led one of the first wagon trains to California. At Fort Laramie he met an old friend, Joe Walker, who joined the procession to California as a guide and companion. Running low on provisions, the wagon train split; Chiles and a group on horseback went north to circumvent the Sierra Mountains, while Walker led the wagons south. The Walker party arrived at (what was to be named) Walker Pass at 11:00 am on December 3, 1843 after abandoning their wagons just north of Owens Lake a short time earlier (ref. 7). Walker Pass, across the southern Sierra, is approximately 56 mi from current day Edwards AFB where another Joe Walker, prominent NACA/NASA X-15 test pilot would engage in a different kind of pioneering a little over 100 years later (refs. 8, 9, and 10).

Early aviators, airplane designers like John Northrop, and the military discovered the dry lake in the 1930s and used it as a place to test new designs and to rendezvous. During World War II the U.S. Army Air Corps conducted extensive training and flight testing in the area. In 1942 the Air Corps shipped their first turbojet-powered aircraft (the Bell XP-59A) to Muroc for flight testing. This airplane was fitted with a pseudo propeller made of wood, fitted on the nose so that curious eyes would not question or talk much about this new arrival. On October 2, 1942 the XP-59A airplane made the first turbojet flight in the United States with Bell test pilot Robert Stanley at the controls (ref. 11). This was also the location of a colorful social club and riding stable established by the famous aviatrix Florence "Pancho" Barnes (ref. 12), which was frequented by many early famous test pilots and aviation notables. In more recent years the USAF, NASA, and various contractors have conducted flight tests on exotic and unusual aerospace vehicles in this location.

GETTING STARTED

In the words of Dr. Hugh L. Dryden, the purpose of full-scale flight research "is to separate the real from the imagined... to make known the overlooked and the unexpected." These words give substance as to why a small segment of innovative NASA engineers and technicians live and work here in the western Mojave desert.

In the autumn of 1959, the NASA Flight Research Center (FRC) (which in May 1976 became the Hugh L. Dryden Flight Research Center) was assigned the task of conducting all of NASA's high-speed flight research. We were accustomed to conducting high-performance flight test and were accustomed to rocket-powered vehicles, which were required to land unpowered. With the vast expanse of Rogers Lake, unpowered landings with high-performance aircraft became relatively routine—but not risk free. Techniques were developed, however, and lessons were learned, sometimes the painful way. Through the 1940s, 1950s, and 1960s, programs such as the rocket-powered XS-1, X-1A, X-1B, X-1E, and X-15 were all tested here. In addition, in the 1950s high-performance turbojet aircraft such as X-3, X-4, X-5, XF-92A, and D-558-I were tested here. Reference 10 details early flight test activities.

We were well-prepared for accomplishing the lifting-body programs insofar as unpowered (dead stick) landing techniques were concerned. The HL-10 was not the first lifting body tested at the FRC. The first lifting body tested, in the spring of 1963, was the Ames-Dryden M2-F1, a blunt half-cone configuration (ref. 13). Lifting bodies were envisioned to be a new manned research program by R. Dale Reed, an innovative FRC engineer and private pilot. Mr. Reed reviewed the plan for the Apollo mission to the Moon and return to Earth. Mr. Reed found that the plan called for a ballistic reentry capsule and that the program planners thought that a lifting reentry vehicle configuration was still too risky, even though the Saturn booster by this time provided sufficient thrust and reliability. Mr. Reed felt that if a lifting body could demonstrate a horizontal landing, it would build confidence within all of NASA that this class of vehicle could be employed to great advantage. Mr. Reed had been interested in the work being done at NASA Ames with the M2 lifting body under Mr. Eggers. Mr. Reed then contacted Mr. Eggers, who at that time was Ames Deputy Director, and proposed the idea of building a large scale piloted demonstrator lifting-body vehicle. Mr. Eggers thought that Mr. Reed had a good idea and told him to pursue it further.

Mr. Reed had been an avid modeler since childhood and, as a NASA engineer, frequently used model airplanes to evaluate his ideas. The question that naturally came to Mr. Reed and others was: Could such a wingless vehicle be controlled and landed by a pilot? With Mr. Eggers' encouragement, Mr. Reed proceeded on his own to build a small free-flight M2 model that was towed aloft by a large radio-controlled model and released. The M2 model was so inherently stable that these flights were truly impressive. Mr. Reed's wife took some 8-mm home movies of successful glide flights and landings. Mr. Reed next approached Milton O. "Milt" Thompson, an FRC X-15 test pilot, and got him interested (ref. 14). Mr. Thompson indicated that he would be willing to "fly" the unusual configuration if wind-tunnel tests validated the design—even though it had the gliding characteristics of a well-polished brick. Mr. Reed and Mr. Thompson, armed with the home movies and other presentation material, briefed Mr. Eggers and Paul F. Bikle, director of the FRC. With Mr. Thompson's assurance that he was a proponent, Mr. Bikle and Mr. Eggers bought the idea on the spot.

Mr. Reed and others initiated a full-scale design employing a tubular steel primary structure around which several plywood shapes could be attached. The original idea was to build a full-scale wind-tunnel model, suitable for manned flight if the preliminary NASA Ames 40 × 80 ft wind-tunnel tests warranted. Mr. Eggers promised to give FRC all the wind-tunnel support needed.

One would think that, in a progressive organization such as NASA, innovative ideas such as a manned lifting-body program would be met with enthusiasm. This was not entirely so at FRC or within NASA with some of the more conservative engineers and scientists. This would be a high-risk venture, and there were some real skeptics. Some felt that a lifting-body program would be too high a risk and flying without wings was impractical. Even the FRC research director, "Tommy" Toll, a conservative and highly respected researcher, was opposed to flying the M2. Mr. Toll felt that the risk of flying was too high and that any research should be limited to wind-tunnel studies. Mr. Reed was never one to be discouraged, though. Once he focused on the idea, he developed a kind of tunnel vision and became almost obsessed. Frequently Mr. Reed would be seen gliding M2 models up and down the corridors only to be met with ridicule from fellow engineers. (We suspect that the Wright brothers suffered, on occasion, the same disdain.) Once Mr. Thompson, Mr. Bikle, and Mr. Eggers were sold on the idea, the actual launching of a new program within NASA was the next major obstacle. To accomplish this objective, the next phase of the lifting-body program was initiated.

With a modest budget from Mr. Bikle's discretionary fund and some dedicated volunteer help, a small team headed by Mr. Reed was established. This team enlisted the aid of Gus Briegleb, a well-known glider builder and operator of the nearby El Mirage dry lake glider port. Assisted by Mr. Briegleb and the NASA volunteers, the team launched the design and construction of what was to be the M2-F1. The M2 was basically a 13° blunt half-cone, flat on top and round on bottom. What resulted was a rather unusual creation that was nicknamed "the flying bathtub" by a reporter who saw the vehicle when it was completed. The vehicle consisted of a steel tube primary structure covered with plywood, cockpit with minimal instruments, control surfaces, and landing gear (fig. 2). This vehicle was planned to be unpowered from the outset, and it was only later in the program that a small landing rocket was added. Initially the M2-F1 was towed behind a highly modified convertible automobile with a racing engine. After the initial successes, NASA's R4D (Navy version of the C-47) towed the vehicle to altitude to accomplish longer glide flights. The entire M2-F1 program was accomplished for under $30,000, an unheard of sum even in those days. We can only guess what the government auditors must have thought when they discovered NASA's purchase of a convertible automobile. Reference 15 presents an excellent review of the overall lifting-body programs at FRC. The M2-F1 program was successfully completed in August 1964.

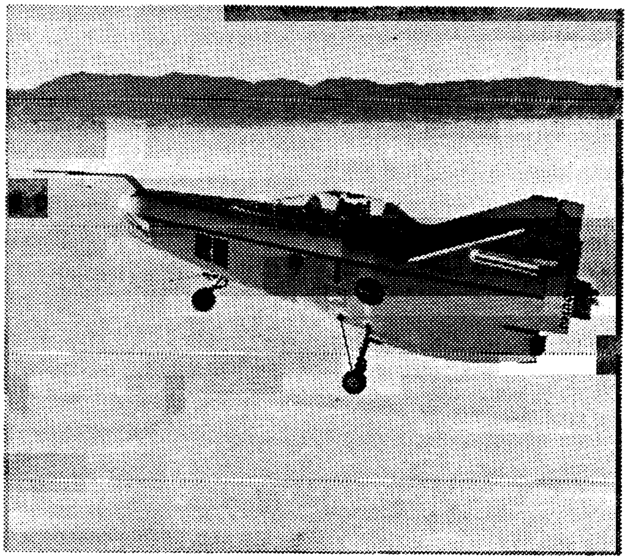
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Figure 2. M2-F1 in flight.

Mr. Reed now promoted the idea of a heavyweight M2 lifting-body program that would air-launch the vehicle by modifying the existing adapter for the B-52. He also favored using the XLR-11 rocket engines left from the X-1, D-558-II, and X-15 programs. The X-15 had upgraded to the XLR-99 rocket engine and no longer required the smaller rockets.

With the initial successes of the M2-F1 program, a group from FRC (Mr. Bikle, Mr. Thompson, and Mr. Reed) planned a trip to NASA Headquarters with their presentation material. This group originally proposed a follow-on program that called for designing and constructing two heavyweight aluminum M2 vehicles. It was proposed that one of the vehicles be reserved as a backup. This proposal called for the vehicle to be carried aloft and launched by the NASA B-52. This B-52 had been structurally modified and configured to launch the joint NASA/USAF X-15 hypersonic research aircraft. While at headquarters, it was proposed to the FRC people that NASA Langley's HL-10 be included in a flight test program as the second-candidate configuration. The FRC group agreed and as a result, NASA Headquarters approved the program and funding for the construction of two heavyweight vehicles—the Ames M2-F2 and the Langley HL-10.

CONFIGURING THE HL-10

Concept and Early Configuration

In addition to the lifting reentry work at the NACA Ames Aeronautical Laboratory in the mid-1950s, engineers and scientists at the NACA Langley Memorial Aeronautical Laboratory, Hampton, Virginia, were also considering this concept. Many hypersonic studies were conducted to evaluate various candidate aerodynamic shapes within the Langley Aerophysics Division. Their specified preliminary goals in the design and development of such a vehicle included minimization of refurbishment (time and money), fixed geometry, low deceleration loads (from orbital speeds), low heating rates, the ability of roll and pitch modulation, and horizontal powered landing.

The Langley studies indicated that a reentry vehicle with negative camber and a flat bottom, rather than a blunt half-cone, might provide higher trimmed lift-to-drag ratios over the angle-of-attack (AOA) range. In their theoretical and trade-off studies and wind-tunnel experiments this negative-camber concept was used in 1957 to develop a configuration stable about its three axes. A flat lower lifting surface was retained for better hypersonic lifting capability. This vehicle was first referred to as a manned lifting reentry vehicle. A vehicle with the combination of a nose tilted up at 20°, an aerodynamic flap, and a flat bottom, was found to be stable about the pitch, roll, and yaw axes and to trim at angles of attack up to approximately 52° at a lift coefficient in excess of 0.6. This vehicle configuration, now referred to as a lifting body, also would result in the retention of higher trimmed lift-to-drag ratios over lower angles of attack as compared with a vehicle with zero nose tilt. The advantage of lifting bodies over capsules was their relatively high-lift-to-high-drag ratio characteristics as compared with zero lift to high drag. In addition, lifting bodies could achieve the specified goals by their maneuverability during orbital reentry and in the terminal landing flight phase similar to conventional airplanes. The ability of lifting bodies to control both roll and pitch axes (to control the direction and magnitude of the lift vector and hence the flightpath) was felt to be a great advantage. This control was to be achieved using either reaction jets or aerodynamic control surfaces, or both.

NASA Langley's John Becker had also presented a paper on winged configurations (ref. 16) at the 1958 NACA Conference on High-Speed Aerodynamics. In this paper Mr. Becker concluded with the analysis of a small, winged satellite configuration embodying all of the desirable features identified by Langley earlier—a low *L/D* for range control, hypersonic maneuvering, and the capability for conventional glide-landing; a flat-bottomed wing with a large leading-edge radius; and a fuselage crossing the protected lee area atop the wing. This configuration would not, however, be selected to carry the first United States astronaut into space. As reference 4 points out, what "ruled out acceptance of his [Mr. Becker's] proposal, however, was the fact that the Atlas, the only ICBM anywhere [in the United States] near ready for use in 1958, did not have sufficient boost capability." This did not, however, deter the Langley researchers from developing concepts and design goals for a winged satellite.

In the early 1960s, two independent surveys conducted within the Astrophysics Division at Langley revealed that there were no studies underway to develop a configuration that would meet the preliminary mission goals. Continuing studies validated that entry vehicles with hypersonic $L/D \approx 1$ could provide numerous attractive characteristics. If this *L/D* could be provided without elevon deflections in the maximum heating portion of the trajectory, local heating problems near the elevons could be avoided. High trimmed lift coefficient would provide high-altitude-lift modulation. For horizontal runway landings without power (an emergency situation), a subsonic trimmed *L/D* of at least 4 was desired. The body should provide good volumetric distribution for multiperson application and acceptable heating rates and loads throughout the speed regime, possibly including superorbital speeds. Stability and control over the speed range and launch vehicle compatibility were also essential. Based on these studies, the refined and established mission vehicle goals were stated in 1962, as the following:

1. Hypersonic lift-to-drag ratio of approximately 1 (without elevon deflection)

2. High trimmed lift at hypersonic speeds
3. Subsonic lift-to-drag ratio of approximately 4
4. High volumetric efficiency, 12-person capability
5. Acceptable body shape at all speeds
6. Static stability and controllibility at all speeds
7. Launch vehicle compatibility

The low reentry deceleration loads, about 2 *g*, imposed on a vehicle of this type was an inherent characteristic and an implied goal. By comparison a capsule would be subjected to about 8-*g* reentry deceleration loads.

Refinements were now made to the evolving configurations in an effort to meet the mission goals by conducting tradeoff studies interrelating sweep, thickness ratio, leading-edge radius, and location of maximum thickness. In 1962 a negatively cambered lifting-body configuration emerged and was designated the HL-10 (HL standing for horizontal lander). Camber is the deviation of the mean line from the chord line and is normally on the upper surface of the wing. In respect to the HL-10, however, it was on the lower surface instead. This vehicle entered an intermediate or study stage of evolution at Langley involving almost every research division. Intensive research was undertaken to identify problems and to find solutions associated with this type of configuration. Figure 3 is the original 1962 sketch of the HL-10. Interestingly enough the debate on the issue of negative camber or no camber (symmetrical shape) continued. More detailed studies continued on the camber issue. Finally, following more detailed analysis, the negative-camber and symmetrical configurations were compared with the established mission goals. Three additional mission considerations were established as serious issues in the selection of camber as follows:

8. Lower heating rates and loads comparison
9. Lower AOA for a given subsonic lift coefficient
10. Reduced subsonic flow separation

The symmetrical configuration met only 5 of the 10 mission goals while the negative-camber configuration met 9 of the 10. The negative-camber configuration

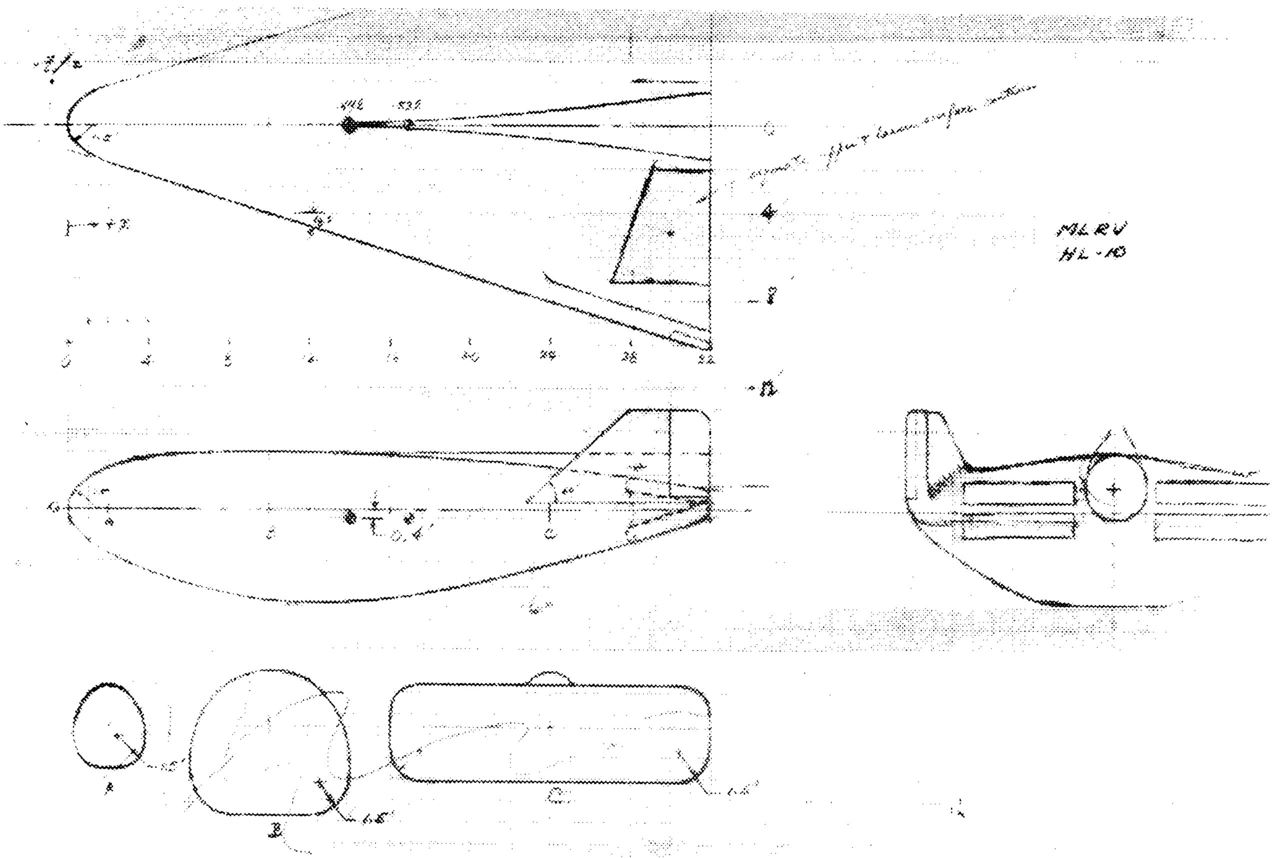

Figure 3. Original (informal) 1962 sketch of proposed HL-10 configuration.

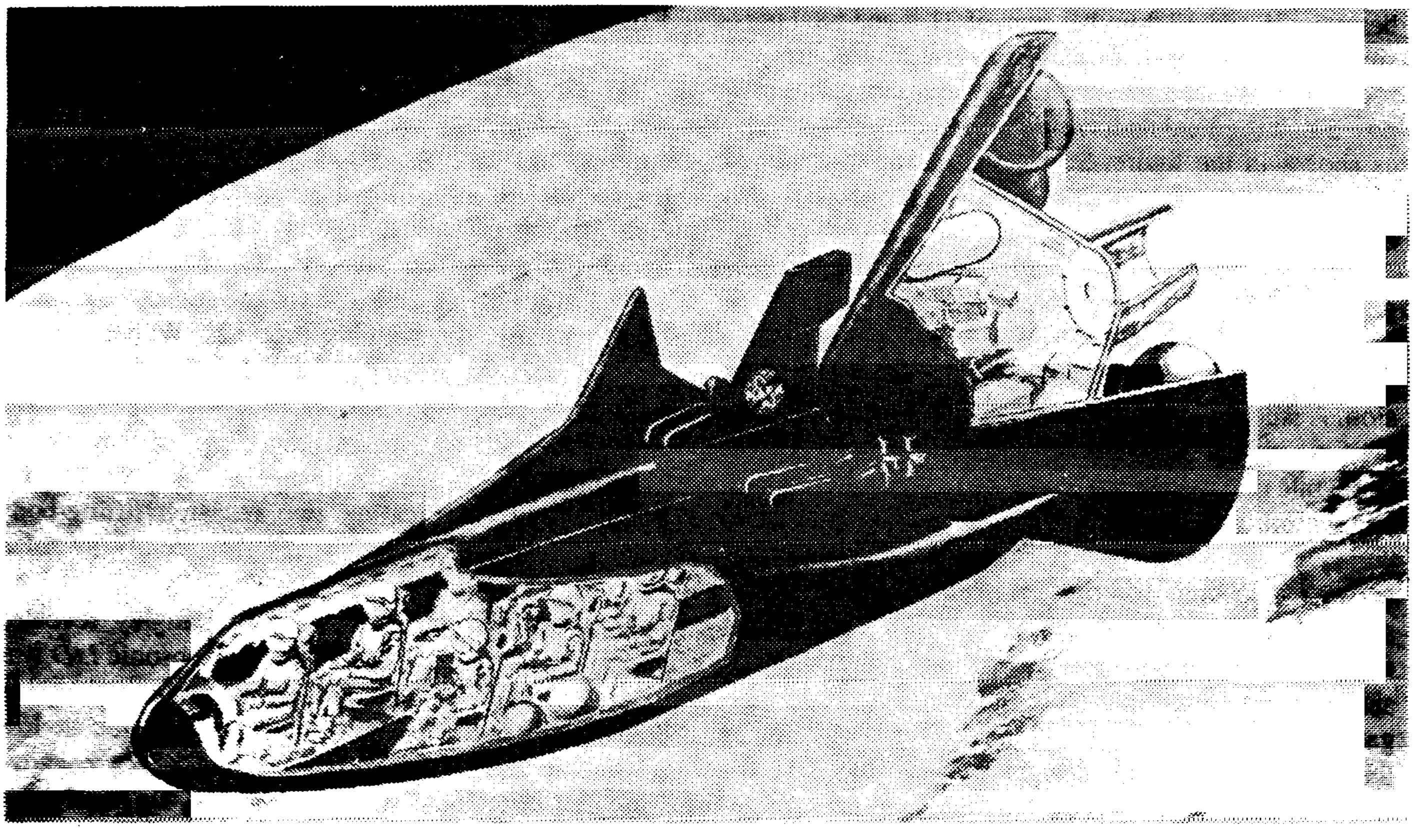

Figure 4. Proposed 12-crew hypersonic configuration of the HL-10.

was the winner. The only goal the negative-camber configuration did not meet was the lower AOA for a given subsonic lift coefficient (#9).

The HL-10 evolved as a flat-bottomed, fixed geometry body with negative camber and a split trailing-edge elevon capable of symmetric upward deflection that would provide the required pitch trim and stability for hypersonic reentry and subsonic flight. The trailing-edge elevon would also deflect differentially for roll control. Tip fins were added for additional directional stability. The negative camber of the lower surface provided the longitudinal trim. The gradual boattailing or tapering of the aft end of the upper surface reduced subsonic base drag and reduced transonic aerodynamic problems. The volumetric distribution provided crew and subsystem installation compatible with the center-of-gravity requirements.

Serious final vehicle configuration development and research now began. Research areas included trajectory analysis and entry environment, heat transfer, structures and thermal protection, aerodynamics, dynamic stability and controllability, handling qualities, landing methods, emergency landings on land and water, viscous effects (including Mach number, Reynolds number,[*] and vehicle length), and equipment and personnel layout. A lifting-body disadvantage, however, is that they suffer an aerodynamic heating penalty due to their longer duration in the entry trajectory as compared with a ballistic capsule. Extensive research was conducted into methods of thermal protection. Detailed wind-tunnel heat-transfer distributions were measured at Mach numbers of 8 and 20 using small thin-skinned Inconel® models (Inconel is a registered trademark of Huntington Alloy Products Division, International Nickel Company, Huntington, West Virginia). The experimental heating on the HL-10 model shape was measured in depth.

The volumetric efficiency for the proposed HL-10 was relatively high. The volumetric efficiency is the ratio of the useful internal volume to the total exterior vehicle volume. The exterior vehicle volume is defined by the volume encompassed by the external skin. A proposed 12-person vehicle configuration of the HL-10, shown in figure 4, has a length estimated to be

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[*] Reynolds number. See appendix A, Glossary, for definitions of this and other terms used in this paper.

between 25 and 30 ft with a span of 21 ft and total pressurized volume of 701 ft^3. This view also shows the rocket adapter module attached. In addition, it was proposed that the vehicle have a full-length raised canopy as shown in the figure. Some of the studies included proposed large-scale vehicles that were 100 ft and longer.

With the camber issue settled, a selection of proposed fin arrangements was now required. A variety of wind-tunnel models were constructed ranging from a 4-1/2 in. hypersonic model to a 28-ft, low-speed version. A study was undertaken to determine the best fin configuration. The hypersonic model had twin vertical fins while the 28-ft model had a single center dorsal fin. In attempting to identify an acceptable fin arrangement, emphasis was placed on achieving a compromise between subsonic trimmed performance and hypersonic trim and stability. Figure 5 shows some of the arrangements tested. (Lower outboard, dorsals, and single-, twin-, and triple-fin arrangements were investigated along with various modifications to the aft end of the vehicle body.) Ten designs were included in the various wind-tunnel studies. A basic triple-fin configuration was selected as the best compromise and is shown in the upper right portion of figure 5. Analyses and wind-tunnel tests were then focused on this basic configuration.

Final Configuration

With NASA Headquarters' approval for a heavyweight lifting-body program, NASA FRC compiled the requirements and specifications for the two lifting-body vehicles. As it turned out, Mr. Reed's last major contributions to the lifting-body program were developing the statement of work for the heavyweight M2-F2 and HL-10, and leading the source evaluation board to select the winning proposal. With the statement of work completed, four airframe manufacturers responded with proposals. On April 13, 1964 the Norair Division of the Northrop Corp. of Hawthorne, California, submitted a proposal to NASA for designing and fabricating two research lifting-body vehicles (M2/HL-10) and was subsequently awarded the contract.

Meanwhile wind-tunnel tests at Langley revealed that the basic configuration trimmed subsonic *L/D* was only slightly in excess of 3. This was considerably below the established goal of 4. In addition at low supersonic speeds and some angles of attack negative values of directional stability resulted. To rectify this situation and to increase subsonic *L/D*, an ejectable tip-fin scheme was briefly considered. However, the ejection of tip fins during the final phase of a mission was considered unacceptable. From wind-tunnel results, a tip-fin configuration was developed that included

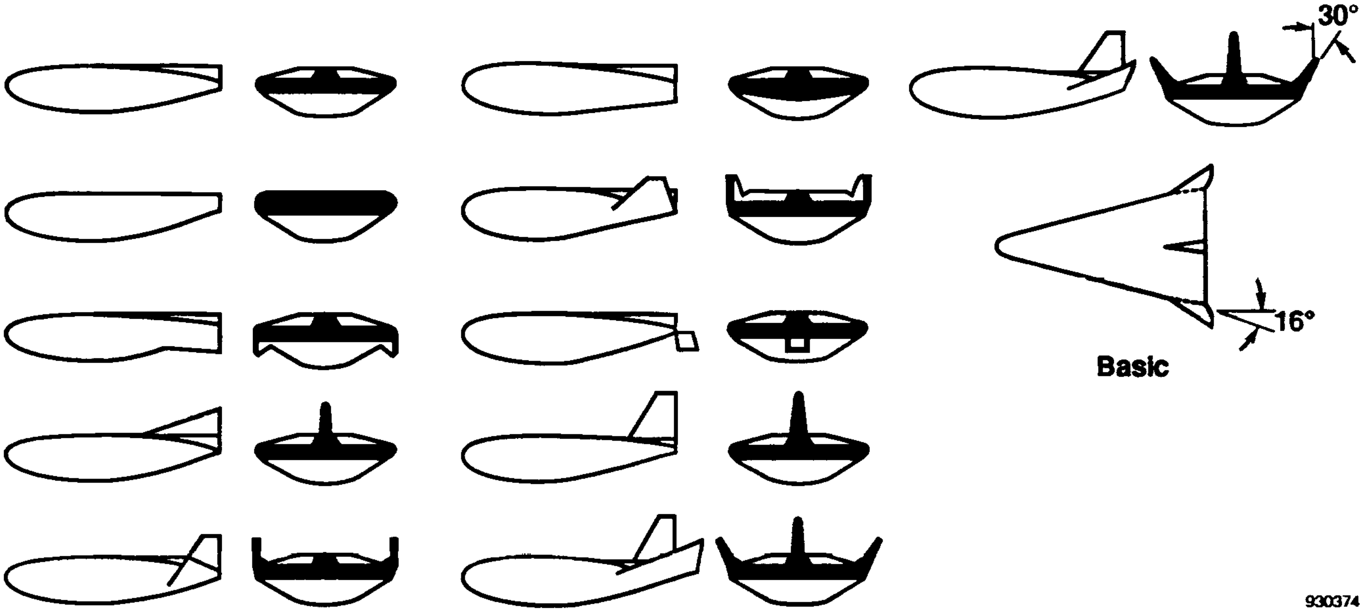
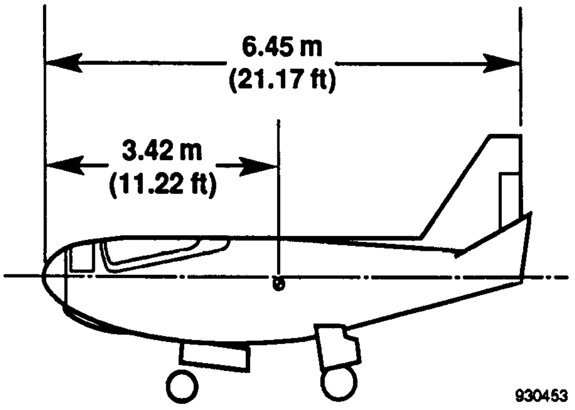
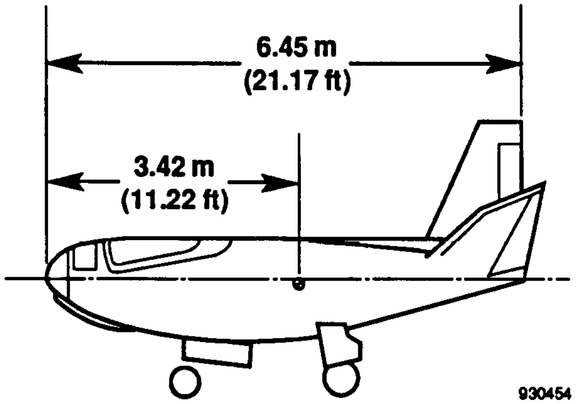


Figure 5. Variations of negatively cambered HL-10 configurations tested in NASA Langley wind tunnels.



(a) Basic.



(b) Final.

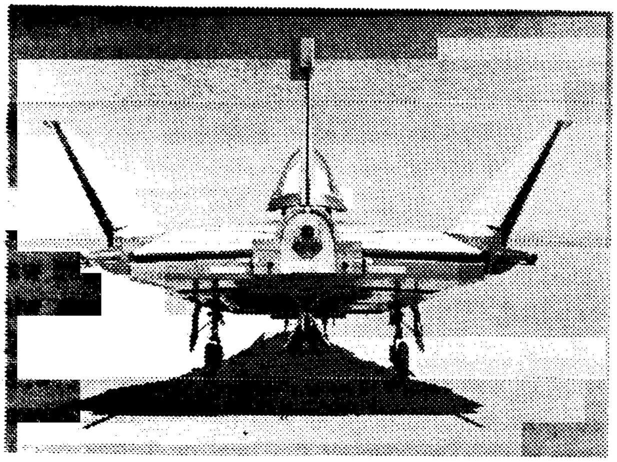
Figure 6. Comparison of HL-10 configurations.

changes in the tip-fin shape that resulted in increased area, toe-in angle, and roll-out angle that provided the required subsonic trimmed maximum *L/D*. In addition, simple two-position flaps were added to the trailing edge of the tip fins and upper elevon to vary the base area and, consequently, the subsonic base drag. Closing these flaps would minimize base drag. This modification also improved the directional stability problem. This change was now required to be incorporated into the design specification.

On February 3, 1965, almost 10 months following contract award, a meeting was scheduled at FRC to present the modified tip-fin and two-position flap proposal. Several top engineers from NASA Langley, including Eugene S. Love, Robert Rainey, and Jack Paulson; and from NASA Headquarters, Fred DeMerritte, Office of Advanced Research and Technology, and chief of the lifting-body program, from whom we received all of our funding, visited us and presented their proposal. They wanted to add more control surfaces to the HL-10. These would be two-position surfaces and consisted of elevator flaps (located on the upper surface of the elevon) and outboard tip-fin flaps (two each). This meant that a design change and modification to the existing contractual agreement was now required. This was not a popular request with the HL-10 program managers and engineers at FRC. The change was made, but did not have our overwhelming support at the time. Later in the program, however, it was viewed as one of the best decisions made. This modification allowed a simpler flight control design and allowed the vehicle to fly from subsonic to supersonic speeds with less trim change in the pilot's control stick position.

Figure 6 shows a side-view comparison of the basic and final configuration. The enlarged center and tip-fin modification on the final configuration are obvious in this illustration. This final modification to the HL-10 configuration, based on wind-tunnel tests, improved trim and stability characteristics in the transonic and supersonic speed ranges and increased *L/D* in the landing approach. The two-position flap configuration consisted of flaps on the upper elevon surface, split rudder, and tip fins. Figure 7 shows details of these flap positions. In the subsonic speed regime and landing approach the configuration was designated the subsonic configuration. In this configuration the movable upper elevon flap, rudder, and tip-fin flaps were retracted to provide maximum boattailing (minimum base area) on the aft portion of the vehicle. In the high subsonic and transonic speed range where the flow on the upper surface of the vehicle becomes sonic, the movable flaps were deflected to minimize flow separation in the region of the control surfaces. This was known as the transonic configuration. This was the configuration that would also be used at all supersonic speeds.

The design and fabrication of both lifting bodies continued at the Norair Division of the Northrop Corp. in Hawthorne, California. The M2-F2 was delivered on June 15, 1965, and the HL-10 on January 18, 1966. Figure 8 presents the HL-10 as it appeared on rollout. The FRC tail numbers assigned to the M2-F2 and HL-10 were 803 and 804, respectively.



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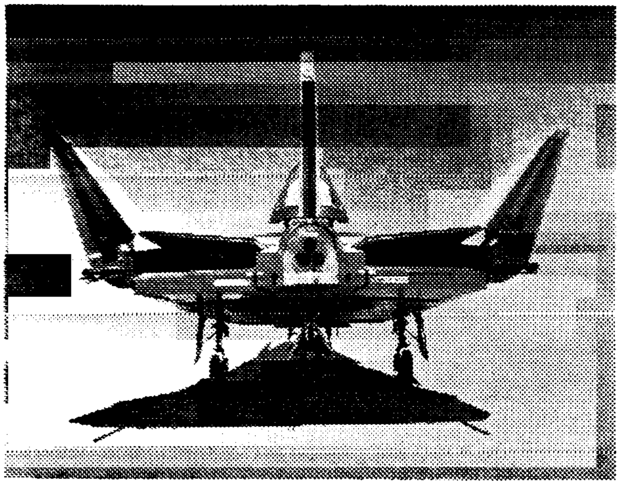
(a) Subsonic.



E-21536

(b) Transonic.

Figure 7. HL-10 lifting-body flap positions.

ECN 1061

Figure 8. HL-10 at rollout at Northrop Norair.

Following delivery to FRC, the next phase of the lifting-body program began. This phase consisted of installing and checking out extensive flight test instrumentation, vehicle systems, and subsystems. This phase lasted approximately one year for each of the vehicles following delivery. The first heavyweight lifting-body flight, the M2-F2, took place on July 12, 1966, two years following contract award, with a glide flight from 45,000 ft with Milt Thompson at the controls.

The development of the two heavy lifting bodies was an unprecedented NASA and contractor effort. Each of the involved organizations contributed their talents and resources to the fullest, which contributed to the success of the program. The program was based on the idea of innovation, initiative, and above all, simplicity where possible. Unneeded management was eliminated, as were unnecessary paperwork and red tape. Program decisions were made at the technical level with a minimum of higher management interference. Engineers and technicians from FRC worked with their contractor counterparts at the Northrop facility. This approach facilitated the making of important design decisions between NASA and Northrop engineers almost on the spot. This kind of team approach resulted in the development of confidence among the individuals involved. The result was a superior end product with no cost overruns or significant schedule delays. One industry representative had predicted that these vehicles would cost as much as $15 million each but the final cost was only $1.2 million each—an unheard of price, even in 1965, for a new research aircraft.

Through the years the FRC and USAF Flight Test Center at Edwards AFB had developed close ties through various joint research programs (ref. 10). The Air Force had plans for their own lifting-body program, the X-24A. Therefore, a formal joint NASA/USAF Lifting-Body Program was established in April 1965. The X-24 would be maintained by and operated from the FRC, just as the M2-F2 and HL-10 would be. Piloting responsibilities for all three programs would be shared by NASA and USAF along with various engineering research, flight test, and simulation activities. Even though the HL-10 and M2-F2 were experimental vehicles, no X identifications were assigned. The X designation is reserved for Department of Defense experimental aircraft only.

FLIGHT VEHICLE DESCRIPTION

The final flight configuration (fig. 9) was a single-place vehicle with a relatively conventional 1960s aircraft cockpit and instrument panel (fig. 10). It was a negatively cambered airfoil with a 74° sweepback delta planform with three aft vertical fins. The vehicle length was 21.17 ft; figure 11 and table 1 present all critical dimensions and physical characteristics. Vehicle launch weight, with propellants, was 10,009 lb and landing weight was 6,473 lb. The center of gravity ranged from 53.14 percent of the body length for the launch weight configuration to 51.82 percent for the landing condition.

Cockpit pressurization was maintained at 3.5 lb/in^2 differential for altitudes above 50,000 ft with mixed air (nitrogen and oxygen). A pressurization schedule maintained ambient pressure from 5,000 ft and below. In free flight the air for cockpit pressure, defogging, and pressure suit ventilation was stored in pressure tanks at 3,000 lb/in^2, which was adequate for 30 min. Heated defog air was supplied by two blowers with integral 1,000-W heaters. The pilots wore full pressure suits on all rocket-powered missions. The pilot had 13.7 ft^3 of breathing oxygen, which was sufficient for 30 min. During captive flight the B-52 supplied most expendables to the HL-10, so that the vehicle could be launched with nearly maximum capacities.

Rocket power was provided to boost the vehicle to test Mach numbers and altitudes. The rocket motor was an upgraded off-the-shelf item that had been used on earlier programs at FRC. The rocket motor consisted of a four-chambered XLR-11 RM-13, which produced 2120 lb of thrust per chamber, at 265 lb/in^2 chamber pressure. Individual chambers could be operated for thrust modulation to achieve the desired flight test conditions. Liquid oxygen was the oxidizer and water alcohol was the fuel. Total propellant weight was 3536 lb. The propellants were delivered to the chambers by a turbopump driven by decomposed hydrogen peroxide. Typical rocket motor burn time was about 90 to 100 sec at maximum thrust using four chambers.

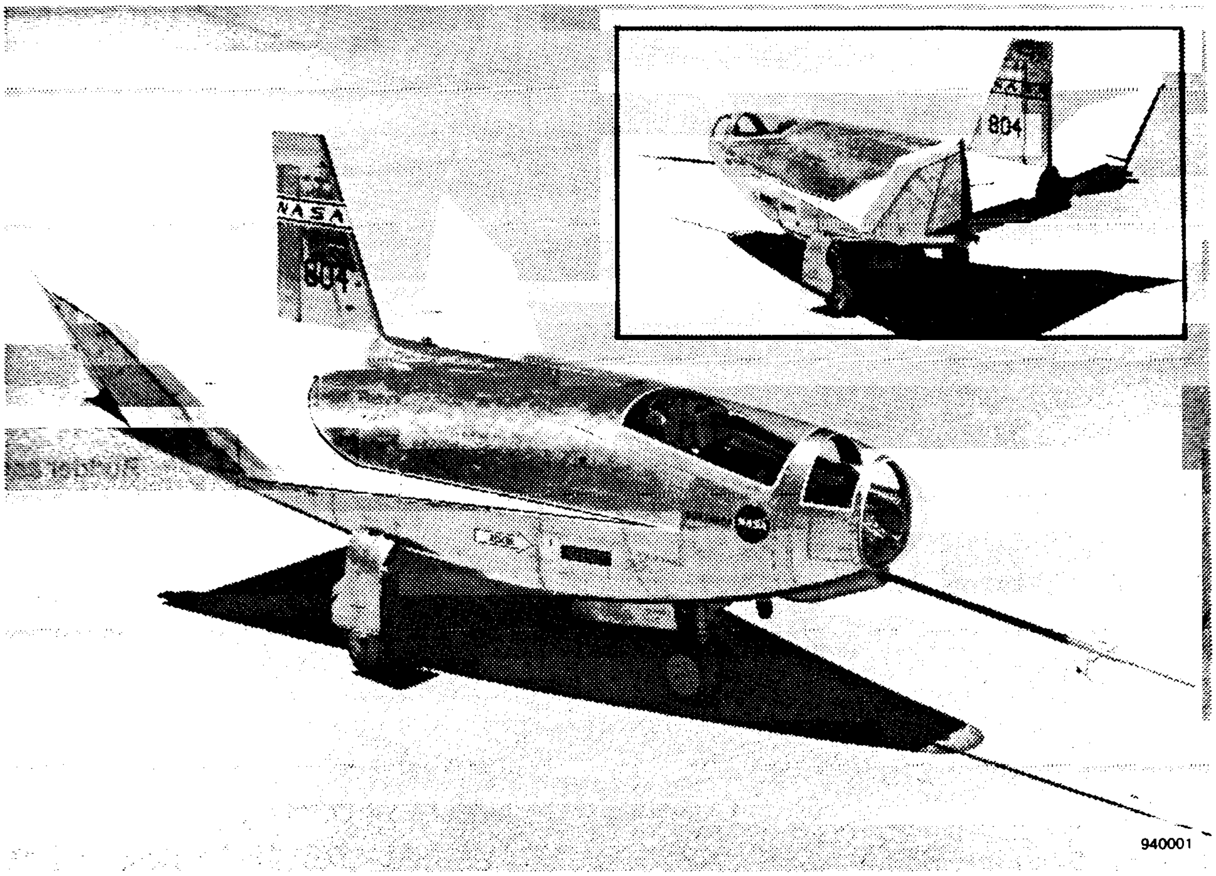


Figure 9. Right front view and left rear quarter view (inset) of HL-10 lifting-body vehicle.

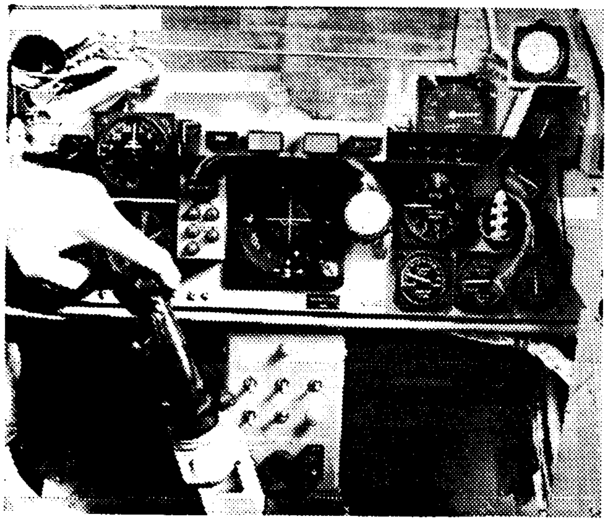


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Figure 10. Instrument panel arrangement.

Note that the rocket motors were used in the early X-15 program, and at least one of the XLR-11 rocket engines had been on loan to a museum and was returned to the FRC for use in the lifting-body program.

The XLR-11 rocket engine history can be traced back to early 1946 when the Bell XS-1 airplane was tested (ref. 10). The U. S. Navy also flew experimental aircraft in the early 1950s using the same basic rocket engine; however, it was designated XLR-8 (the Navy wanted an even dash number). These rocket engines were available and had a long history of reliability in manned research aircraft application; so they were a logical choice for use in the HL-10 and M2-F2/F3 programs from both reliability and economic standpoints.

In addition to the XLR-11 primary rocket engine, two small hydrogen-peroxide landing rockets were installed in the vehicle. These rockets could produce 500 lb of thrust each for 30 sec and were provided in

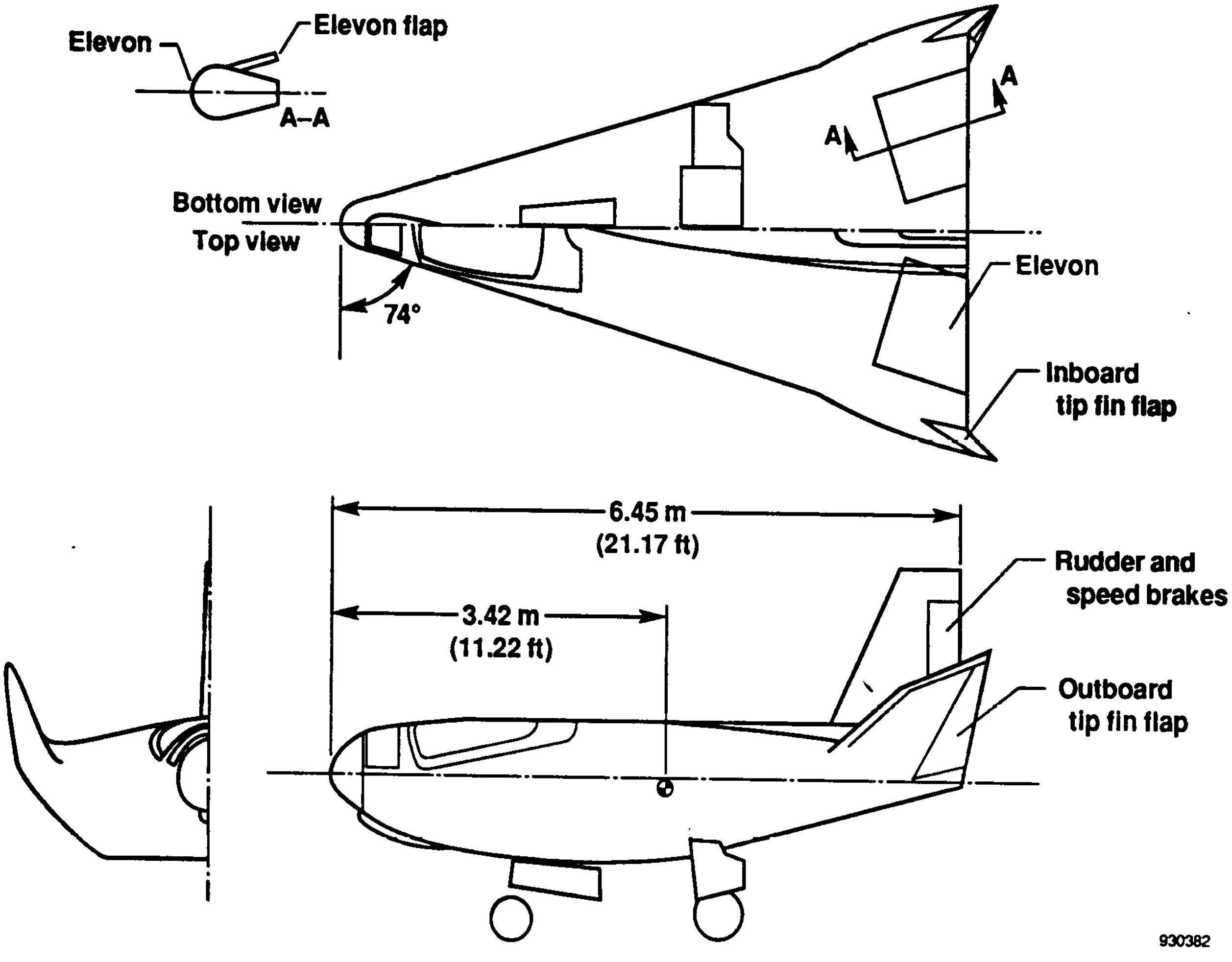


Figure 11. Three-view drawing of HL-10.

Table 1. Physical characteristics of HL-10 lifting body vehicle.

Body	
Reference planform area, ft^2	160
Reference length, ft	21.17
Reference span, ft	13.60
Aspect ratio, b^2/S	1.156
Leading edge sweep, deg	74
Elevons (two)	
Area, each, ft^2	10.72
Span, each, ft	3.58
Chord	
Root, ft	1.93
Tip, ft	4.06
Elevon flap (two)	
Area, each, ft^2	7.50
Span, each, ft	3.58
Chord	
Root, ft	1.58
Tip, ft	2.63
Vertical stabilizer	
Area, each, ft^2	15.80
Span, each, ft	5.02
Chord	
Root, ft	4.32
Tip, ft	1.97
Leading-edge sweep, deg	25
Rudders (two)	
Area, each, ft^2	4.45
Span, each, ft	4.12
Chord	1.08
Outboard tip fin flaps (two)	
Area, each, ft^2	3.77
Span, each, ft	4.50
Chord perpendicular to hinge line, ft	0.84
Inboard tip fin flaps (two)	
Area, each, ft^2	2.48
Span, each, ft	3.31
Chord perpendicular to hinge line, ft	0.75
Mass properties	
Maximum gross weight, lb	10,009.3
Glide flight weight, lb	6,473.4
Referenced to body axes	
Roll moment of inertia, slug-ft^2	
Maximum gross weight	1,522
Glide weight	1,363
Pitch moment of inertia, slug-ft^2	
Maximum gross weight	6,262
Glide weight	5,769
Yaw moment of inertia, slug-ft^2	
Maximum gross weight	7,132
Glide weight	6,509
Product of inertia, slug-ft^2	
Maximum gross weight	555
Glide weight	520
Center of gravity, fuselage station, in.	
Maximum gross weight	135.0
Glide weight	131.6
Center of gravity, water line, in.	
Maximum gross weight	4.1
Glide weight	5.6

case a landing approach needed to be extended. In actuality, these rockets were never used as an aid to landing. The only time they were used was for experimentation purposes during the last phase of the program.

The pilots required that the design specification include speed brakes. The brakes were to provide added drag, on demand, much like an inverse throttle to vary the landing pattern parameters. In addition the brakes were lightweight and required no fuel. The HL-10 speed brake was accomplished through the use of the split rudder. Speed brake authority was 0° to 32° and was pilot actuated through a cockpit switch. (The speed-brake requirement was later specified for the space shuttle; to the uninitiated this requirement would seem absurd since the maximum L/D is so low on the basic vehicle.)

Electrical power was provided by 28-V silver-zinc battery packs. These batteries provided electrical power to hydraulic pump motors and all other vehicle equipment and subsystems including cockpit heating and canopy defogging. A dual hydraulic power system controlled all primary flight control actuators at 3000 lb/in^2. Sufficient battery power was available for approximately 40 min. Before launch electrical power was received from the B-52 aircraft. An extendable ram-air turbine provided hydraulic pressure, in the event of an electrical failure, with the capability of providing approximately 50-percent control surface rate limit.

Aerodynamic control was provided by the primary control surfaces: elevons and rudder. Symmetric deflection of the elevons provided pitch control, and differential deflection provided roll control. A split rudder on the center vertical fin provided both yaw control and speed brake. Pitch, roll, and yaw damping was provided through the limited authority stability augmentation system (SAS) to the elevons and rudder. Trim was provided by the elevons for pitch and roll and by the rudder for yaw or directional trim.

The primary control surfaces were actuated by irreversible hydraulic power actuators. These actuators accepted commands from the pilot and SAS. Table 2 presents the pilot's stick and rudder pedal characteristics and corresponding control surface gearing and limits. The pilot was provided with stick and rudder pedal force feel by coil-spring bungees, which provided a force proportional to stick or pedal position. The changes in authority and gearing (table 2) resulted from pilot in-flight evaluations and trim data. Table 3 presents control surface authority, rate, and command input. Figure 12 presents a summary of the pilot's longitudinal stick gearing and modifications accomplished over the course of the flight test program. The stick gearing of 6.9° of elevon per inch of stick on the first flight was excessively sensitive and dictated the subsequent modifications. This will be discussed in detail in a later section.

The limited authority SAS provided angular rate feedback about all three axes for damping augmentation operating through servoactuators. The feedback signals were provided by conventional angular rate gyros. The pilot could select SAS gains using switches on the SAS control box, located on the left-hand console. SAS gains ranging from 0 to 1.0 were available in increments of 0.1 and were in terms of degrees of surface deflection per degree per second of angular rate. The yaw rate signal was modified by an electronic high-pass, washout filter so that the rudder would return to zero deflection as yaw rate approached steady state. This kept constant rate turns from being impeded, through the system, by the command of an opposite rudder deflection (top rudder) in response to the steady yaw rate. This system was all analog (electrical wires connected to resistors, capacitors, operational amplifiers, etc.) with electromechanical interface and was relatively simple by comparison with today's digital computer-based flight control systems (ref. 17).

Table 2. HL-10 cockpit control summary.

Pilot's longitudinal stick

Flight	Longitudinal stick authority,[*] in.	Elevon authority, deg	Force gradient, lb/in.	Gearing, deg/in.
1	-3 to 6	36.2 to -26	8.4	6.92
2	-3.9 to 5.2	10 to -25	8.4	3.75
4	-3.9 to 5.2	10 to -25	8.4	3.75
6	-3.8 to 5.4	3.8 to -26	8.4	3.24
10	-3.9 to 5.3	13 to -24	8.4	approx. 3.5 (non-linear)

Pilot's lateral stick

Flight	Lateral stick authority,[**] in.	Aileron authority, deg	Force gradient, lb/in.	Gearing, deg/in.
1	±2.93	±12.5	2.74	4.27
2	±2.65	±19.2	2.74	7.25
4	±2.80	±12.1	2.74	4.32
6	±2.80	±12.1	2.74	4.32
10	±4.05	±17.0	2.74	4.27

Pilot's rudder pedal

Flight	Rudder pedal authority,[***] in.	Rudder authority, deg	Force gradient, lb/in.	Gearing, deg/in.
All	±3.1	±10.0	13.72	3.41

[*] + is stick aft which results in a more negative elevon deflection

[**] + is right stick deflection

[***] + is a left rudder pedal deflection

The SAS system gains were predetermined based on flight conditions for particular planned flight profiles; the pilots did not adjust system gains indiscriminately. Some gain changes were required because of varying vehicle dynamics, and some were purely for research purposes. Occasionally, select SAS gains would be reduced to zero to accomplish specified research maneuvers.

Table 3. HL-10 control surface authority.

Surface	Input	Travel, deg	Rate, deg/sec
Elevon	Pitch trim switch	–19 to 6	2
	Pitch control stick	–24 to 13	25
	Pitch SAS	± 5	25
	Aileron trim switch	± 5	0.6
	Aileron control stick	± 17	50
	Roll SAS	± 5	50
Elevon flaps	Switch	0 to 29	3
Tip fin flaps	Switch		
Outboard		0 to 32	3
Inboard		0 to 30	3
Rudder	Rudder trim switch	± 5	1
	Pedal	± 10	25
	Yaw SAS	± 5	25
Speed brake	Switch	0 to 32	3

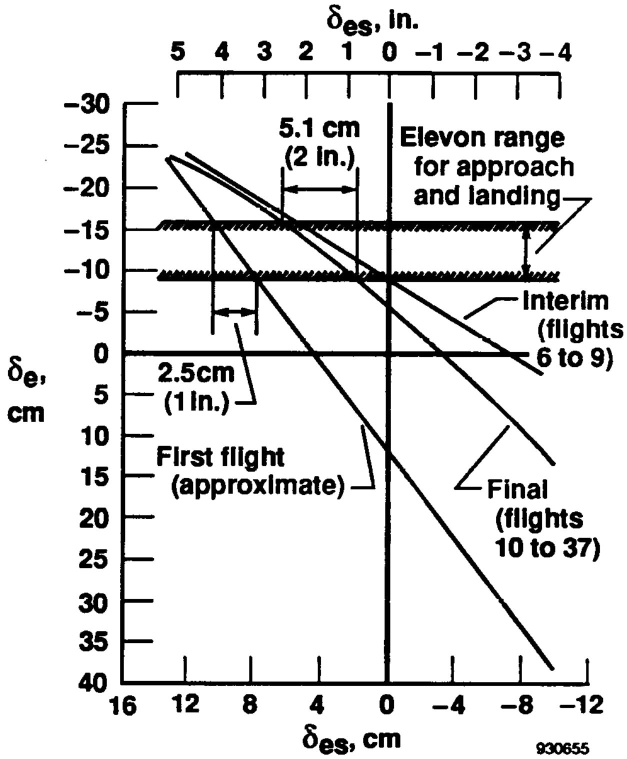


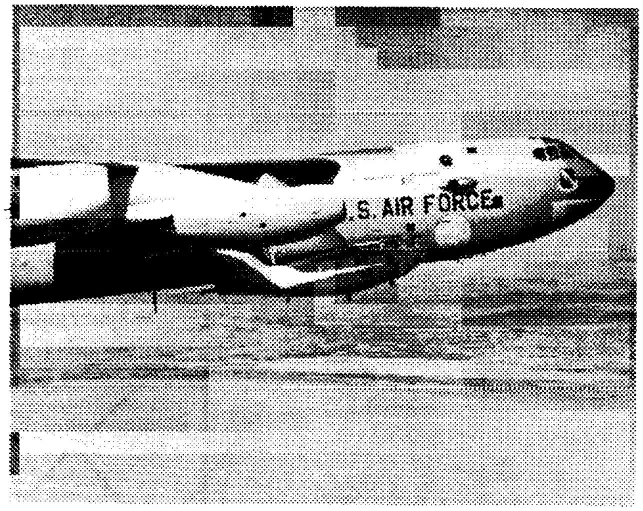
Figure 12. Elevon gearing used during flight tests.

Secondary movable surfaces were located on the inboard and outboard trailing edges of the tip fins and the upper surface of the elevons. An electric motor actuated these surfaces in two-position flaps in either a closed position for the subsonic configuration or an opened position for the transonic configuration (fig. 7). The transonic configuration was essentially a shuttlecocklike configuration with all surfaces extended to maintain transonic and supersonic stability. The secondary flap positions for the subsonic and transonic configurations were 5° to 29° for the elevon, 0° to 8° symmetric rudder, 0° to 32° for outboard tip fin, and 0° to 30° for inboard tip fin. The subsonic flap positions were changed after the second flight because the data results from flight indicated that flight elevon trim deflection and wind-tunnel predictions differed. Data for in-flight trim, with the elevon flap at 5°, closely approximated wind-tunnel data for zero elevon flap.

Landing gear comprised off-the-shelf parts from several airplanes: The main gear wheels, tires, brakes, and gear and door toggle locks were T-38 hardware; the main gear shock strut was F-5A hardware; the nose gear shock strut, wheels, and tires were T-39 hardware. Main and nose gear were pneumatically actuated and had extension times of approximately 1.2 and 1.5 sec, respectively. Once lowered, the gear could not be retracted while airborne.

FLIGHT VEHICLE MISSION

The HL-10 was carried aloft by NASA's B-52 launch aircraft (fig. 13), as were all lifting bodies excluding the lightweight M2-F1. The B-52 aircraft had been modified earlier specifically to launch the X-15 hypersonic airplanes from a right wing pylon. To carry and launch the lifting bodies, a special adapter was constructed and fitted to the B-52 wing pylon. The use of this airplane was complicated because the X-15 program was still operating. The final (199th) flight of the X-15 was launched October 24, 1968, and this very successful program ended December 20, 1968.



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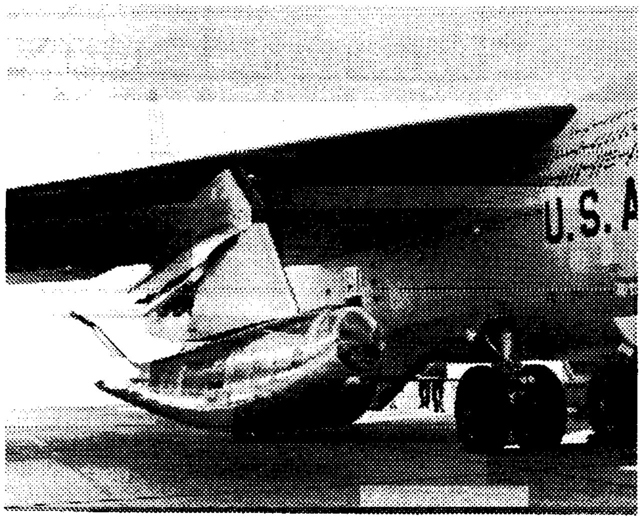
(a) In-flight view.



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(b) Ground view.

Figure 13. Mated configuration for HL-10 and B-52.

A typical HL-10 mission was launched at 45,000 ft at a Mach number of 0.65. Eleven glide flights preceded the powered flights so that the pilots could become familiar with the vehicle handling qualities and aerodynamic characteristics, and so that vehicle systems could be checked. Figure 14 shows the ground track of flights in the terminal approach and landing pattern. The launch point for the powered flights is located southwest of the glide flight launch point by about 40 nmi. The point labeled "runway intersection" is where runways 4 and 17 met and is the point where the vehicle normally transitioned from the transonic to the subsonic configuration. During flight, ground radar tracked the vehicle and provided mission control with ground track and altitude information. Deviations from planned profiles such as high- or low-energy states were radioed to the pilot for appropriate corrective action. The low key point, shown on the ground track (fig. 14), occurred at an altitude of about 20,000 ft. The low key point was the point at which research data acquisition was terminated and the pilot's full attention given to the landing approach pattern. Geographical positioning at the intersection differed from flight to flight depending on energy state; however, the low key point was achieved consistently. A 180° turn was then made to the final approach and landing. The landing approach technique used in the lifting-body programs was basically the same as that used in the X-15 program.

The average time for a glide flight was 4.2 min and for a powered flight, 6.7 min. The average rate of descent in gliding flight approached an unbelievable 11,000 ft/min. One pilot indicated that if a brick were dropped from the B-52 at the same time he launched, he would beat the brick to the ground. These descents were exciting to witness—a real dive-bombing type of operation. The pilots indicated that it was relatively easy to return to the planned flight profile from a high- or low-energy condition before reaching the low key point. They commented that before entering the approach pattern and in the event that the track was outside the pattern something other than visual reference was needed to assess the energy situation. In the pattern the pilots could estimate their energy state well.

Most lifting-body landings were executed on the well-marked Rogers Lake runway 18. This runway was about 4.5 mi, or 24,000 ft, long. The final approach and landing flare was accomplished by establishing a preflare aim point (fig. 15), during the 270- to 300-knot final approach (approximately 4000 ft above ground level (AGL)).The unpowered approach and landing of the HL-10 was relatively typical of each of the lifting bodies. The execution of the landing was done in three parts: the final approach, flare, and postflare deceleration (fig. 15). The final approach was typically done at 300 knots at a flightpath angle of 16° to 18° nose down. The flare was typically initiated at 300 to 270 knots and 1000 ft AGL (lakebed elevation is 2300 ft mean sea level (MSL)). The flare was done at approximately 1.5 *g* to bring the vehicle to a relatively level flight attitude at approximately 100 ft. At this altitude the vehicle's

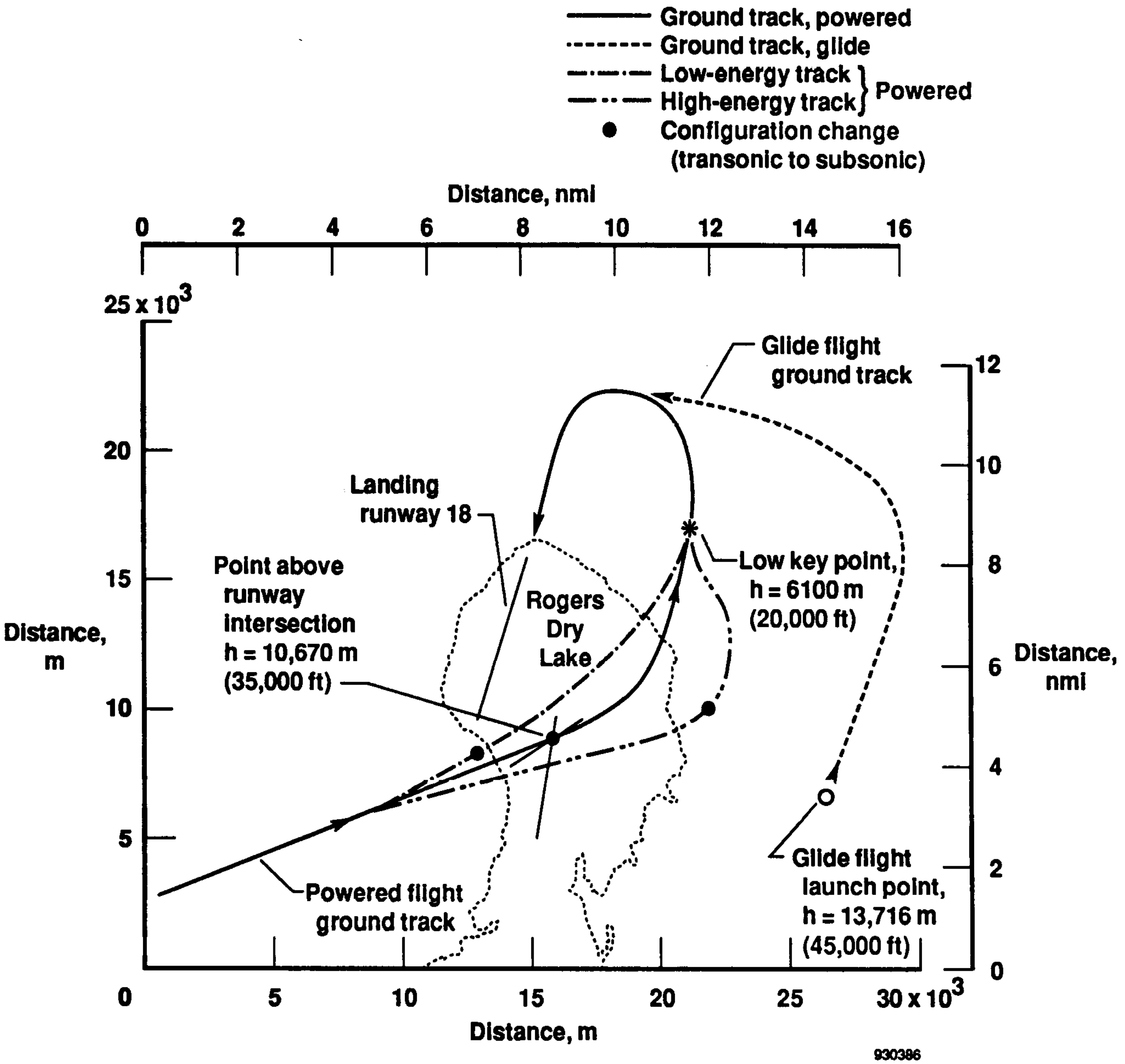

Figure 14. Typical HL-10 powered and glide flight ground track in terminal approach and landing pattern.

speed had decreased to about 220 to 240 knots and the landing gear was lowered. The postflare deceleration was made with touchdown between 155 to 223 knots. Once the landing gear was down, maximum *L/D* was reduced by approximately 25 percent. To the uninitiated the approach, flare, and touchdown speeds seem excessive and much concern was expressed. To the pilots, however, the landing speeds were no problem. An advantage to the higher speeds was that the handling qualities were better.

FLIGHT TEST PREPARATION

This phase of the story has to begin with the setting of the scene and will include situations and events as recalled by the authors. The story begins in early spring of 1966 at the FRC.

The lifting-body program had now grown into a full-scale mature program at FRC and was fully sanctioned and funded by NASA Headquarters. We now had adequate funding to accomplish all our work, but we also had the added burden that a larger, and consequently

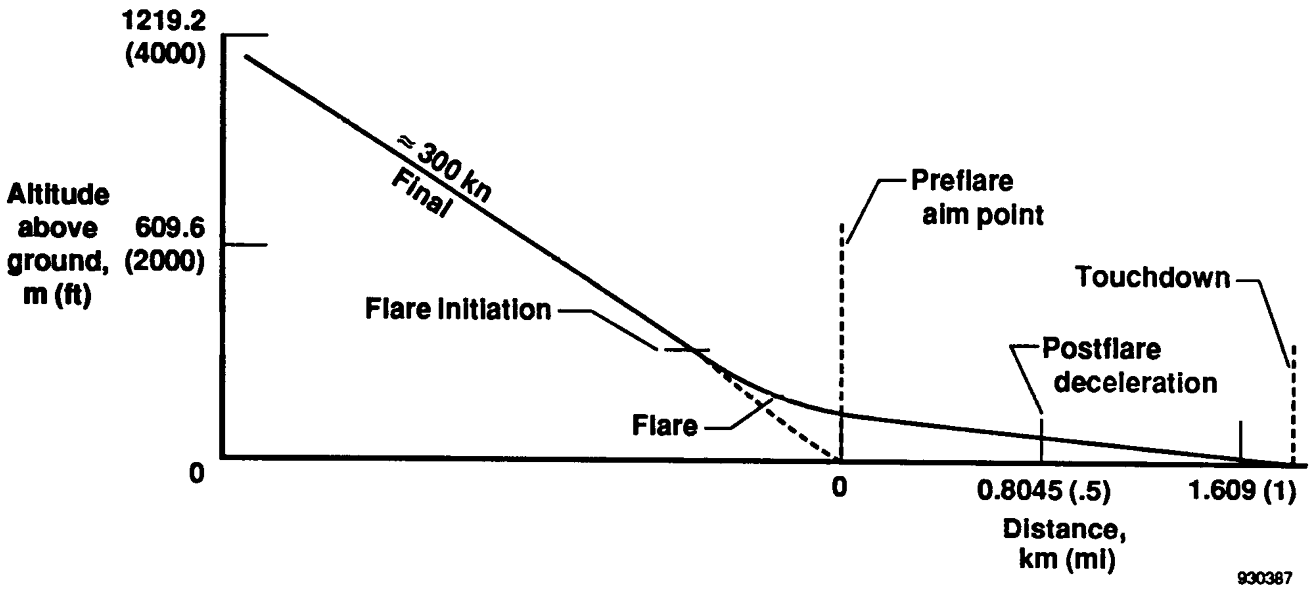

Figure 15. Typical lifting-body unpowered final approach, flare, and landing segments.

more complex, organization brings to the working troops. All of FRC's disciplinary managers were now involved, which resulted in an increase in the number of meetings and added paperwork. Mr. Bikle did an excellent job of keeping the burden of a more complex organizational structure from impeding progress, but there were some things even he could not do. As a consequence the team just had to adapt to this new situation.

Mr. Bikle was able to shield Dale and the small FRC team when they were developing the "unofficial" M2-F1, but now with Headquarters approval the situation was different. Paul recognized that Dale would have to change his style as an innovative maverick to a more conventional engineering approach, involving many more people, to which the Center and Headquarters managers could relate. Dale had promoted the lifting-body concept of using the existing B-52/X-15 pylon with an adapter. He also promoted the idea of using the old XLR-11 rocket engines left from the X-15 program.

Mr. Bikle now presented Mr. Reed with some options concerning his career. The options included remaining as lifting-body program manager, with limited technical activity or remain as an innovator of new ideas. Mr. Reed decided to remain the innovator and stepped aside. Mr. Bikle then formally recommended that Mr. Reed could benefit FRC more in the role as a generator of new ideas. John McTigue ("Tiger John") was named the new lifting-body program manager, having had extensive management experience on the X-15 program at FRC.

Within FRC an assigned group of engineers, technicians, and mechanics was concerned with preparing each vehicle for the experimental flight program. NASA's resources were stretched to the maximum, because the X-15, with three airplanes, was still very active and a large percentage of our resources were devoted to this program. As a result (and because the USAF desired to maintain their expertise in the rocket airplane business) it was mutually decided that the M2-F2 simulation and general flight planning activities would be accomplished by the USAF at the neighboring Flight Test Center. FRC would maintain the aerodynamic data responsibility and stability and control coordination as well as some research functions. In addition, all instrumentation and maintenance functions would be continued at FRC. This freed the FRC simulation facilities and other engineering personnel to concentrate on the HL-10.

M2-F2 Team

The USAF team was headed by Robert G. (Bob) Hoey, program manager, and Johnny Armstrong, program engineer, both of whom had extensive experimental flight test and X-15 experience. USAF Capt. John Durrett was also a key player and assisted with general engineering functions. This team was relatively young but had considerable experimental flight test experience. Mr. Hoey had been at Edwards approximately 12 years and Mr. Armstrong, about 10 years. Mr. Hoey had a very good relationship with NASA management and with Mr. Bikle. Mr. Bikle had been the AFFTC's technical director before assuming directorship of NASA FRC on September 15, 1959. Mr. Armstrong and Mr. Hoey had been closely related to the very successful X-15 program as USAF flight test engineers and had a large credibility base within FRC. So this team was considered to be the experts.

HL-10 Team

The new FRC HL-10 team, with the departure of Mr. Reed to more advanced programs, was now taking shape. This team was relatively new and unproved; it consisted of Garrison P. "Garry" Layton as project engineer; Wen Painter and Berwin Kock as vehicle systems engineers; Jon Pyle, vehicle performance (*L/D*); and Mr. Kempel was responsible for stability, control and handling qualities, and later included aero data following the departure of Georgene Laub. Don Bacon was the simulation engineer. NASA's Bruce Peterson was named HL-10 program pilot. For a partial list of the HL-10 team members, see appendix B; figure 16 shows some of the team members.

This team had only three to six years of experience. We were the neophytes. We were all under Mr. McTigue, although we also all had disciplinary managers over us. Our task was to prepare the HL-10 for its maiden flight. Our work progressed steadily. The real-time simulator was checked out and declared operational. The pilots who flew the HL-10 simulation felt that its handling qualities and *L/D* (performance) were "too good" by comparison with the M2-F2. According to the simulator the HL-10 appeared to be much more stable and in general handled significantly better than the M2-F2 and had better *L/D*. We always had a difficult time convincing the pilots that we knew what we were doing. Before flight they remained skeptical. Our desire, of course, was to have simulations somewhat pessimistic rather the other way around. We did not want to foster overconfidence.

Some of the program pilots, the NASA program manager, Mr. Bikle, and the USAF M2-F2 team (experts) were suspicious and skeptical of our results. We were the new kids on the block, untried and unproven. Managers would pass us in the corridors and

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Figure 16. Members of NASA/USAF HL-10 test team. From left to right are Don Bacon, Bob Kempel, Alex Sim, Berwin Kock, George Sitterle, Jack Cates, Wen Painter, Bill Link, Richard Blair, Al Harris, Bill Lovett, Herb Anderson, Bill Mersereau, Charles Russell, Art Anderson, Jerry Gentry, Bruce Peterson, and John McTigue.

shake their heads. Comments to us were, "It can't be that good!" Our work, however, progressed and Mr. Layton attempted to keep us on track. We really were not a team just yet. We were a group of individuals, working as individuals toward a common goal—but not a team. Our approach to completing our tasks was not necessarily lacking in quality, but rather lacking in experience. We were somewhat unsure of ourselves. Even so we accomplished all objectives in preparation for flight.

FLIGHT TESTING

Before the first free flight of each heavy-weight lifting-body, a series of captive manned check flights was planned. These captive flights were planned to evaluate all lifting-body systems and subsystems before actual launch. The HL-10 completed two captive flights in late 1966.

The Maiden Flight

Shortly before Christmas 1966 the HL-10 team convinced Mr. Bikle, the rest of NASA, and USAF management that we were ready for our first glide flight. All the necessary engineering, systems, and mechanical work on the airplane, piloted simulation, paperwork, and briefings were completed. By this time our project pilot, Mr. Peterson, had flown 2 unpowered flights in the M2-F2, and the M2-F2 had completed 14 flights since July with 4 different pilots.

On December 21, the HL-10 was positioned beneath the right wing of the B-52 and lifted into position. The vehicle was attached to the B-52 and preflight checks completed. Later that day the flight was aborted because of a tip-fin flap electrical failure. On this flight the tip fins did not need to be repositioned, so the wiring was disconnected and stowed. Early the next day, December 22, all preparations for the first free flight were completed. Mr. Peterson (fig. 17) took his place in the cockpit, the crew strapped him in, and he initiated preflight checks. The canopy was lowered and all ground preparations were now complete. The B-52 started engines and taxied to the Edwards AFB main runway 04 for takeoff. The takeoff was smooth, as were all prelaunch HL-10 checks. Everything was ready. The flight plan called for a launch point approximately 3 mi east of the east shoreline of Rogers Lake abeam of the landing lakebed runway 18 (fig. 14). A launch heading to the north was followed by two left turns. The launch point was almost directly over the USAF Rocket Propulsion Test Site. This ground track looked much like a typical left-hand pattern with the launch on the downwind leg, a base leg, a turn to final, and a final approach to runway 18.

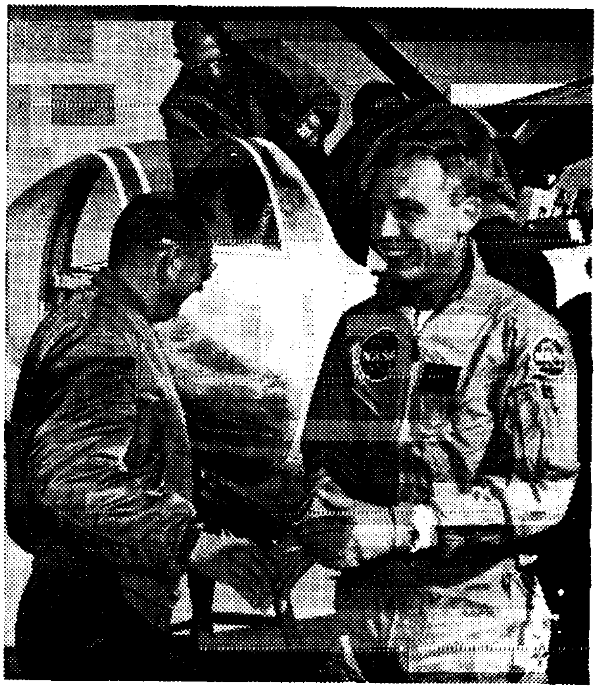

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Figure 17. NASA pilot Bruce Peterson, following first HL-10 glide flight.

Launch from the B-52 was from 45,000 ft at an airspeed of 170 knots at 10:38:50 am Pacific standard time. The actual launch was very similar to simulator predictions. Airplane trim was much as expected although the pilot sensed what he described as a high-frequency buffet in pitch and some in roll, later specifically identified as a flight control system limit cycle, and as speed increased it got noticeably worse. In addition to this, as the first turn was executed, the pilot noticed that the pitch stick sensitivity was excessively high. The stick sensitivity resulted in too much (objectionable) pitching motion for relatively small pilot pitch stick movement. As the flight progressed the high-frequency limit cycle increased in amplitude and it was obvious that longitudinal stick was excessively sensitive. Difficulties in the roll axis were masked by the pitch problems. The landing was accomplished

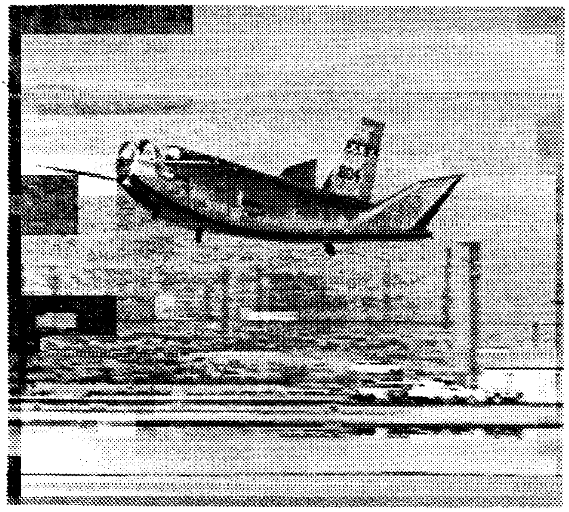

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Figure 18. First HL-10 glide flight landing flare.

somewhat prematurely because of the sensitive control problem. The landing flare (fig. 18) was initiated at approximately 320 knots with touchdown at about 280 knots, or about 30 knots faster than anticipated. The total flight time was 189 sec (3 min and 9 sec) from launch (45,000 ft MSL) to touchdown (2,300 ft MSL). The average descent rate was almost 14,000 ft/min.

Mr. Peterson was greatly concerned with the pitch sensitivity and limit cycles. The amplitude of these became larger as a function of vehicle airspeed and system gain setting (ref. 17). The pilot made several adjustments to the pitch gain in an attempt to alleviate the problem. He gave the pitch axis a Cooper-Harper pilot rating of 4 for the entire flight. A rating of 4 indicates that the deficiencies warrant improvement and are not satisfactory without improvement. The limit cycle was a 2.75-Hz oscillation feeding through the SAS. The problem was primarily in the pitch axis and was most severe during the last third of the flight despite the fact that the pitch SAS gain was reduced from 0.6 deg/deg/sec to 0.2 deg/deg/sec during the flight. The problem was also manifested in the roll axis, but to a much lesser degree. Toward the end of the flight the pitch limit cycle oscillation magnitude was approximately 0.4 *g* peak-to-peak at 2.75 Hz.

The flight was very disappointing to us and confirmed the opinions of the experts that the HL-10 team really did not know what they were up to. The flight was quite poor as compared with our preflight simulation and analyses. Our morale (perhaps pride) was at a low ebb. We felt that NASA management must be even more skeptical of our abilities and we felt that our Air Force M2-F2 brethren were looking down their noses at us too. Fortunately, NASA management was patient, and because the holiday season was upon us, we all took a few days off and came back to consider what our options were.

The haphazard arrangement of the mountain of data that were transmitted from the vehicle during flight to the ground station for the engineers to view (real-time) was indicative of our inexperience. The data were not arranged in a logical manner that would facilitate postflight analysis. (That is, certain physical relationships exist between certain sets of data; and when they are viewed as sets, better insight is given into how a vehicle behaves dynamically.) This resulted in the initial oversight of certain types of vehicle dynamic behavior that, perhaps, should have been more obvious to the test team, as we found later.

Following the holidays, initial discussions seemed to lead us to the conclusion that if we fixed the stick sensitivity and lowered the SAS gains we could probably try another flight. There was, however, a lone dissenter in the group. Mr. Painter was not convinced that we had completely understood all the problems. He continued to analyze the flight results and argued against another attempt, even though the project pilot convinced Mr. Bikle that we should attempt a second flight. Our confidence shaken, we initiated an in-depth unified analysis of the flight data at the beginning of 1967 with a fresh perspective.

Very subtly we found ourselves being welded into a real team. Each of us knew what our job was and expended all effort to understand exactly what happened on that first flight and to fix the problems—whatever they were. We found two almost immediately.

Postflight Analysis

Two serious problems were identified even before touchdown. Postflight data evaluation substantiated the following:

- Large amplitude (limit cycles) in the SAS; a 2.75-Hz elevon oscillation feeding through SAS.
- Extreme sensitivity in the longitudinal stick from the high pitch stick gearing of 6.92° of elevon travel per inch of stick travel; large vehicle motions for small stick deflections.

The first problem was apparently caused by higher-than-predicted elevon control effectiveness and feedback of a 2.75-Hz limit cycle oscillation through the SAS (fig. 14). The problem was alleviated by modifying the structural resonance 22-Hz mode lead-lag filter, which was installed before the first flight. The modification consisted of a notch filter and a lead-lag network in the SAS electronics (refs. 18 and 19). (A notch filter is a device that filters a nuisance frequency while having relatively little effect on lower and higher frequencies.) The problem was solved by installing a structural notch filter, with a center (or notch) frequency of 22 Hz, and using lower SAS gains.

The second problem, stick sensitivity, was solved by a relatively simple gearing modification of the longitudinal stick. Figure 12 presents the pilot's longitudinal stick gearing used on the first flight and subsequent flights. On the first flight the gearing was 6.9°/in. of elevon per unit stick. This was much too sensitive. The result was large vehicle motions for small stick deflections. The nonlinear gearing used from flights 10 to 37 was nonlinear and was approximately 3.5°/in. in the elevon range for landing or approximately half of that used for the first flight. This type of problem was easy to miss when all preparation for flight was accomplished on a fixed-base engineering simulator. In the simulation environment, the situation is relatively relaxed and participating pilots usually feel they are in a safe environment. If anything goes wrong, they can always reset the computers. In addition, the trim characteristics of a new airplane are not precisely known. Stick sensitivity, whether longitudinal or lateral, has always been difficult to determine in fixed-base simulations. Pilots (particularly fighter pilots) always want a very responsive airplane; however, when real-world motion and visual cues are experienced their opinion frequently is revised, and this case was no exception.

A third problem was more illusive and was not really apparent to the pilot or test team during the initial postflight analysis. This problem was found to affect controllability of the vehicle at some points in the flight profile. The problem was a lack of longitudinal and lateral-directional control at some portions of the flight. (This problem was not identified by the pilot and was not immediately obvious to the engineers on the program until further analysis was accomplished.) As mentioned before, most members of the test team, including the project pilot, felt that if we could reduce system gains and fix the longitudinal stick gearing problem and then fly another flight we would be better able to pin down other problems. We had Mr. Bikle talked into another flight except for the dissenting vote from Mr. Painter. Mr. Painter felt that we were missing something. When he spoke, we listened—at least on this occasion. We, therefore, postponed plans for another flight until we had done additional analysis.

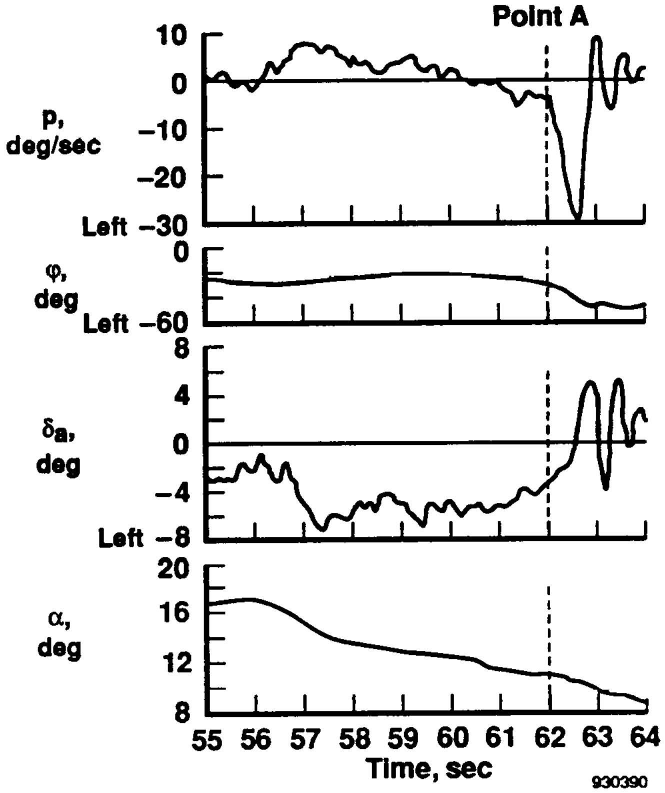
An in-depth investigation was completed by Mr. Kempel. His investigation is described in the following paragraphs. These paragraphs are recollections from 26 years ago (late 1966 to mid-1993) and may be subject to errors in memory.

We had generated the HL-10 simulation from wind-tunnel results. In essence we constructed a computerized (analog computer) mathematical model or aerodynamic characteristic representation of the HL-10. Before we had flown, we made the assumption that this model was a relatively accurate representation of the actual flight vehicle. We reasoned that if we input flight-recorded control inputs to the computerized model, and this model was an accurate representation of the flight vehicle at the same flight conditions, then the model dynamics, calculated motions, should be similar to the flight vehicle. (This technique has been used over the years to validate aerodynamic data from actual flight tests.) If, for some reason, the flight vehicle motions did not resemble the model motions, adjustments are then made to the model aerodynamic parameters to attempt to obtain a relatively close duplication of the flight motions. Ideally, the model would exactly match the flight. This situation is seldom realized, however. Some adjustments to the aerodynamic parameters are always necessary to match flight as closely as possible. In this way we then determined where the wind-tunnel aerodynamics differed from flight. We also needed to understand *why* they were different.

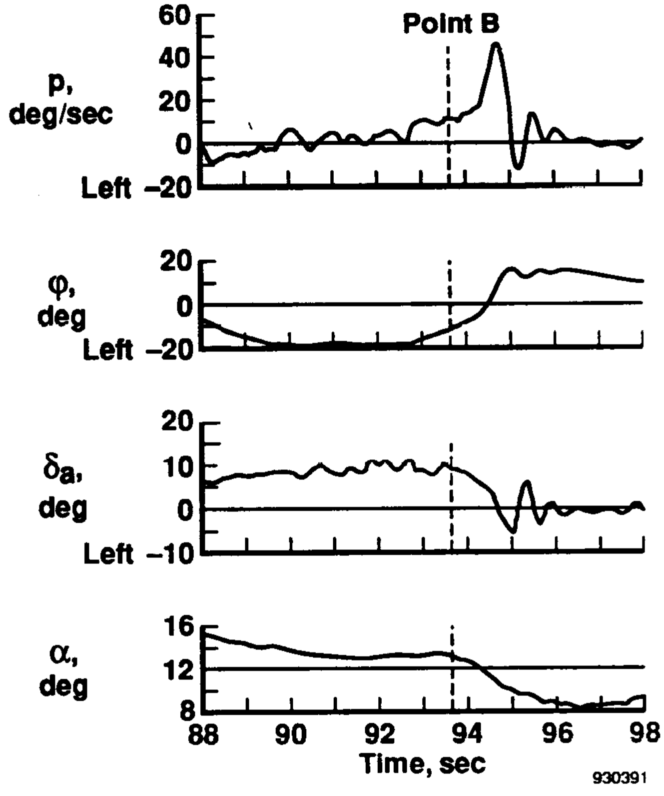
From the first flight results, 12 specific maneuvers were selected as candidates for computer matching. These maneuvers were from 5 to 15 sec in duration. Of the 12 maneuvers only 7 were matched successfully, and these matches were considered only marginally acceptable. A good match is one in which the computer solution overlays all of the flight recorded parameters, within the specified time interval, with little differences between the two. The remaining five maneuvers were impossible to match; the computer solutions did not remotely resemble the flight data, the actual vehicle response. The obvious reason for this was that the mathematical model was not accurate. With that being the case, the task then became to find out why. From what we knew we should have been relatively close, but we were not. A further examination of the flight data was needed.

The entire flight recorded data were played back through the ground station, with the data recorded on magnetic tape, and then reviewed the results. This time, however, we selected new groupings for parameters. The data were now arranged in a logical manner that would facilitate postflight analysis so that the physical relationships between certain sets of data would give us better insight into how the vehicle was behaving dynamically. We selected families of specific data such as accelerations, angular rates next to the control inputs, and control surface strain gauges. All of these data were plotted as a function of time. Using this approach we could look at eight channels of data on each strip chart. This approach was very revealing. The three sets of data indicated some very interesting features. Each of the traces, although of different parameters, generally moved with the appropriate responses, indicating the motion of the vehicle. However, during certain portions of the flight some of the traces became blurred and fuzzy, particularly the control surface strain-gauge data as some higher frequency disturbance appeared. With all the data lined up on a common time interval, many data traces displayed a similar phenomenon. In addition it was discovered that there were two significant intervals (figs. 19(a) and 19(b)) during which the pilot had commanded significant amounts of aileron, but the vehicle did not respond until the AOA was reduced. This particular problem was not apparent to the pilot, and he made little or no comment about this during the flight or postflight discussions. Something did, however, disturb him relative to the vehicle response to control input, which caused us to investigate further.

It was apparent that each time this situation occurred, the AOA was above 11° to 13° (to the left of points A and B on figs. 19(a) and 19(b), respectively) and as AOA decreased through these values the ailerons suddenly became very effective by producing significant amounts of roll angular rate (30° to 45° per second). We then attempted to computer-match these two time intervals. The two computer matches of these time intervals showed that in each case the initial part of the response would not match. As the AOA was reduced to the point that the ailerons became effective, the mathematical model began to match the flight data. We still did not know why.



(a) Point A.



(b) Point B.

Figure 19. Intervals of insignificant roll response.

We began to think that a massive flow separation was possible over the upper aft portion of the vehicle at the higher angles of attack, causing the control surfaces to lose a large percentage of their effectiveness. Figure 20 presents a 55-sec recording of the inboard right and left tip-fin strain-gauge data traces from flight. Note that the flight-measured AOA trace in this figure is *indicated* and not *corrected* as in figures 19(a) and 19(b), so no direct comparison of AOA can be made. Significant postflight AOA corrections were required for such things as the angular difference between the noseboom and the vehicle's longitudinal reference axis, upwash, boom bending due to normal acceleration, pitch angular rate, etc. AOA is included in figure 20 as a qualitative indicator of the flow separation, 0° AOA on this scale will correspond to approximately 7° on figure 19.

Figure 20 encompasses the same time interval as figures 19(a) and 19(b), and points A and B are illustrated for comparison. At the beginning, time is 0 sec of figure 19(a), the AOA is 17°, and the flow is separated. As the AOA is reduced, through 11° (point A), the flow attaches abruptly. Between 5 and 10 sec, the AOA is increased to approximately 15°, and the flow separates (the trace gets fuzzy). At approximately 34 sec the AOA is reduced through 13.5° (fig. 19(b)), and the flow becomes dramatically attached once more (point B). This flow separation can be likened to the sudden loss of lift and increase in drag of a conventional wing as AOA is increased and the wing stalls. As the AOA was decreased the airflow would suddenly reattach and the controls would behave in their normal fashion. The more we looked at the data, the more plausible this theory seemed; although the wind-tunnel data did not indicate a problem to the degree that we had experienced in flight. The data also indicated a significant loss of lift-to-drag ratio above Mach numbers of 0.5 and AOA of 12°. This finding further convinced us that the problem was caused by massive flow separation.

About this time we decided to call the team at NASA Langley and give them a preliminary assessment of our findings. They agreed to reenter the wind tunnel with the 0.063-scale model (16 in. long) almost immediately. This was highly unusual because, typically, wind-tunnel schedules are made at least a year, and sometimes years, in advance. This was, however, their "baby."

With NASA Langley's urging, we made the trip east to present first-hand our results and hypothesis. At Langley's high-speed 7 × 10 ft wind-tunnel building, we gathered in the middle of an office room at a large table. Those present from Langley included Linwood (Wayne) McKinny, Bill Kemp, Tommy Toll, and Bob Taylor; from FRC, Mr. Painter, Mr. Kock, Mr. Layton,

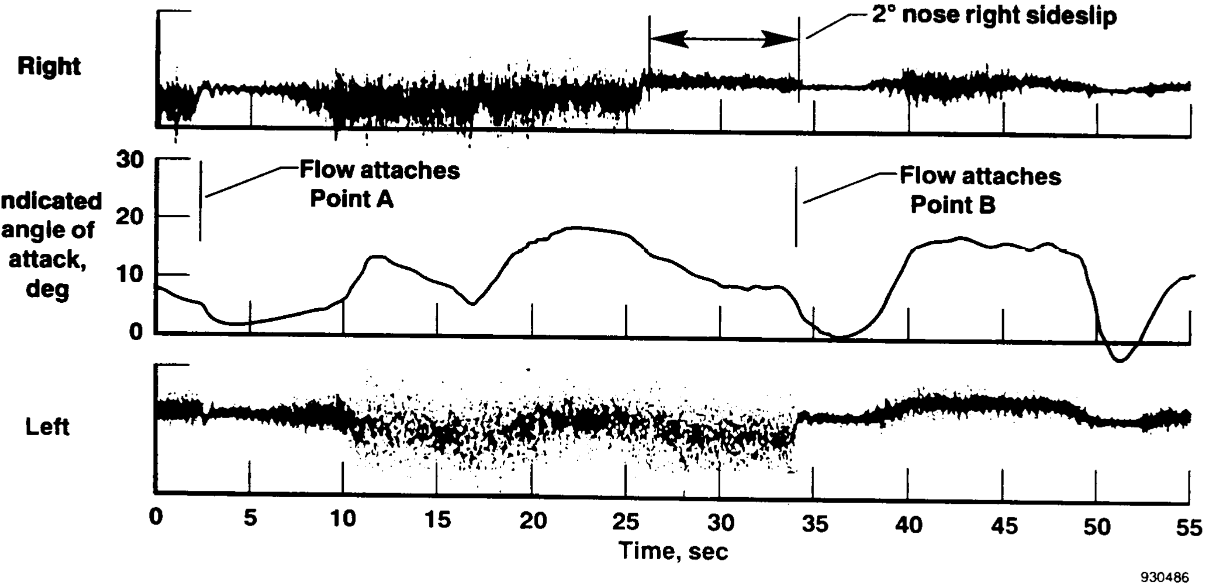


Figure 20. Inboard tip-fin flap strain-gauge and angle-of-attack response.

and Mr. Kempel. We presented our hypothesis that the problem was massive flow separation. At one point Bob Taylor jumped up from the table and angrily slammed his mechanical pencil to the floor, as he gave forth a stream of oaths. We were all shocked by this outburst. When Mr. Taylor calmed down he resumed his place at the table, saying, "I knew that this would be a problem!" He had a gut feeling earlier, he said, that the flow separation they had seen on the wind-tunnel model would be worse in flight. Mr. Taylor was upset with himself that he had not followed his instincts as an aerodynamicist and taken preventative measures in the design of the HL-10 before the vehicle had been built. Further discussion was limited to figuring out how to proceed. The NASA Langley people promised to give the problem their immediate attention and to propose a remedy.

Upon arrival back at FRC we agreed not fly the HL-10 until we had some kind of aerodynamic configuration change. We still had other problems to solve. We enlisted the aid of Northrop to design the electronic notch filter to eliminate the 2.75-Hz limit cycle mode from feeding back through the flight control system. In addition to this we had the stick sensitivity problem. We busied ourselves with solving these problems while keeping in touch with the Langley people.

On May 10, 1967 the M2-F2 crash landed, seriously injuring our project pilot, Bruce Peterson. He would have to be replaced, but we would have to worry about that later.

Throughout the winter and spring of 1967 the Langley team continued to work the problem and they came up with two possible fixes. These were identified as modifications I and II. Both modifications concentrated on changes to the outboard vertical fins. Modification I proposed a thickening and cambering of the inside of the fins while modification II proposed slightly extending and cambering the leading edges. Figure 21 presents a comparison between modifications (refs. 20 and 21). NASA Langley ran a full set of wind-tunnel tests on both proposed modifications and sent the data to FRC for review. Although the Langley team presented their assessment of the wind-tunnel results, they would not decide which modification should be selected for the flight vehicle. This decision was left to the FRC team.

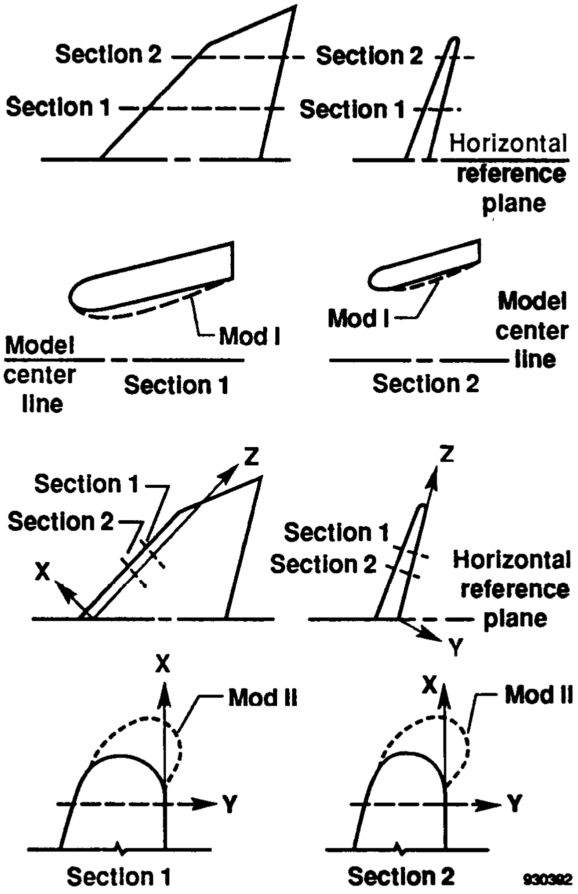


Figure 21. Comparison of proposed modifications I and II.

During the summer of 1967, with all the wind-tunnel preliminary data in hand, an extensive evaluation was made by Mr. Kempel. "Preliminary data" was the wind-tunnel guys way of telling us that they had worked most of their magic in data reduction, but that they were not going to say that this was the last word. Mr. Kempel began to plot all the data, from digital listings, by hand. Thousands of points were plotted in this manner. This may shock modern-day engineers who have computer-plotting routines, but in those days this was the way we did it. This approach also made us live with the data. Mr. Kempel plotted the data from both modifications as a function of AOA for constant Mach numbers. All of the plot scales were made uniform so comparisons would be easier.

When the plotting was completed, all data were lined up for comparison. These data, at first glance, did not seem a lot different from the data set used to generate the original HL-10 simulation. Some subtle but significant differences were there, though. Some nonlinearities in the original data were not present. Mr.

Kempel hypothesized that if these nonlinearities indicated flow separation, then the lack of these would indicate either no flow separation or separation to a lesser degree. Based on this premise, modification II was selected as the fix. Mr. Kempel presented his hypothesis to his FRC disciplinary boss, Hal Walker, a competent aerodynamicist, and he agreed with him. Mr. Kempel then presented the results to FRC management and, with the NASA Langley team concurrence, we proceeded to modify the vehicle.

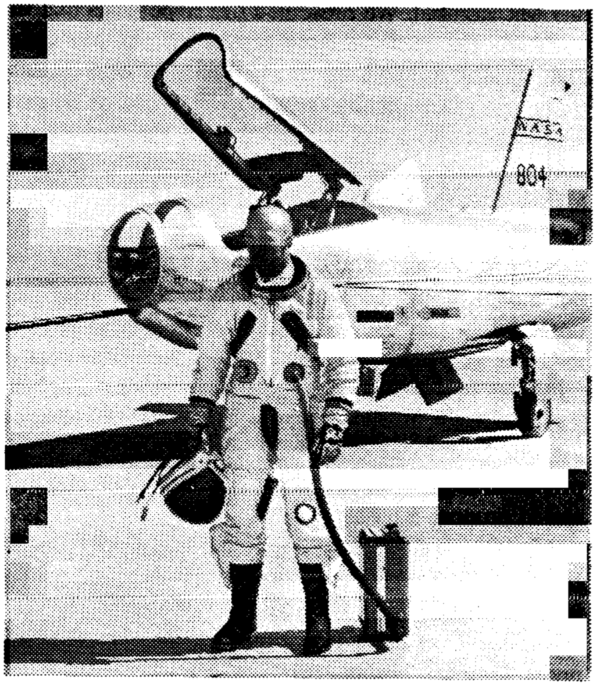
To modify the configuration, we contracted with Northrop Norair once again in early autumn 1967. Northrop and NASA decided that a fiberglass glove backed by metal structure would accomplish all configuration objectives very nicely. Work continued on the glove through the winter. In the NASA hangar, Norair's Fred Erb shed his normal working attire—a suit—and donned coveralls to assist in installing the glove. He was a senior-level engineer with over 25 years with Northrop, rolling up his sleeves and getting his hands dirty.

In the spring of 1968 the final stages of vehicle preparation—flight controls work, aerodynamic configuration change, and internal systems work—were completed. With the injury of Mr. Peterson in the M2-F2 landing accident, Air Force Capt. Jerry Gentry was named as HL-10 program pilot. Capt. Gentry approached the simulation preparation with just a little apprehension. His apprehension was never verbalized, but we could tell he felt that the simulation really did look too good. But it did look good by comparison with the M2-F2. Capt. Gentry, a true professional, gave the flight preparation his complete attention. After many hours of simulation time, he was finally ready to fly.

This was what we were all waiting for. For Capt. Gentry, this was his profession. For us, the engineers, we wanted very much to vindicate ourselves. Fifteen months after the first flight we were ready for the second flight. The struggles of the past year had transformed us into a first-rate team. Now we had a second chance to prove it to ourselves, FRC, NASA Langley, the USAF, and the world.

The Second Flight

The second flight was made on March 15, 1968 with Capt. Gentry (fig. 22) at the controls. It was a typical lifting-body flight, launched from 45,000 ft at a Mach number of 0.65. The flight plan called for pitch and roll maneuvering to allow the pilot to feel the airplane. Mild pitch and roll maneuvers were performed up to 15° AOA to evaluate the possibility of control degradation similar to the first flight. The pilot executed a simulated landing flare, to 2 *g*, at altitude to assess the potential flare characteristics. A motion-picture camera was installed on the tip of the vertical fin to view the right inboard tip-fin flap and right elevon. These surfaces were tufted so that in-flight photographs could be taken and the flow field could be qualitatively assessed. Tufting was an old method by which flight testers attached strips or strands of wool yarn, approximately 6 in. long, to one end of suspected problem portions of an airplane to assess the quality of the airflow. If the airflow was attached the tufts would lie flat along the surface in the direction of the flow. If the flow was separated the tufts would follow the disturbed flow in a random fashion. In general it was concluded that the flow did not significantly separate and there was no degradation of control; however, some sensitivity to AOA was observed. Total flight time, from B-52 launch to touchdown, was approximately 4.4 min.



E-18875
Figure 22. USAF Capt. Jerry Gentry, HL-10 project pilot.

The flight was a success from everybody's point of view. From the pilot's point of view, the HL-10 performed as well as an F-104 airplane making a similar approach. The longitudinal stick was a bit sensitive, but was considered acceptable. The pilot felt that the vehicle flew satisfactorily, and for the next flight no additional improvements were required. From the team's point of view, we had done it and we really were a team. There was no hint of flow separation or control system problems. We had vindicated ourselves. The dynamics of the HL-10 in flight looked as good as indicated by the simulator. The dynamics of the HL-10 were significantly better than those of the M2. We established our credibility. From this point on all the pilots wanted their shot at flying the HL-10.

Now it was time to fine-tune the airplane as required. After pilots have established confidence in a new airplane and have more time to evaluate things, their opinions frequently change. The HL-10 was no exception, although no additional major modifications were required. Throughout the life of the program, the HL-10 underwent minor adjustments to make it the best of the best. Following the first (somewhat unsuccessful) flight, the HL-10 made 36 successful flights with 4 different pilots participating in the program.

Simulation of the HL-10

The HL-10 real-time simulation was an engineering tool and not specifically a pilot training simulator, as one would think of training airline pilots. The HL-10 simulator was fixed base, with a instrument panel similar to the flight vehicle and pilot's control stick and rudder pedals closely approximating the actual airplane. No visual displays were available, so all piloting tasks were accomplished using instruments. The instrument panel included airspeed, altitude, AOA, normal acceleration, and control surface position displays. A three-axis attitude indicator provided vehicle attitude and sideslip information. Both the engineers and pilots used the simulation extensively. Engineers used the simulation as a final validation of control system configuration. Control gearing selection was always difficult with the fixed base; the pilots always wanted high sensitivity until they were airborne, then we had to decrease gearing.

Later, the simulation was used to plan each research flight mission. So that mission objectives would be achieved, research maneuvers were specified and flight profiles determined that included Mach numbers, altitudes, angles of attack, and ground track. Emergency procedures were practiced by inducing various failure modes and selection of alternate landing sites. The pilots were relatively willing subjects once they knew that they would fly the actual mission and the training paid large dividends. From all this, flight cards would be assembled and distributed at crew briefings to all personnel such as chase and B-52 pilots, the mission controller, participating flight test engineers, and NASA and USAF managers. Coordination was critical to the success of each mission.

An interesting aspect of flight test planning was that all of the pilots reported that, once in flight, the events of the mission seemed to progress more rapidly than in the simulator. As a result, we experimented with speeding up the simulation integration rates or making the apparent time progress faster. We found that making simulation time move so that approximately 40 sec of simulation time represented approximately 60 sec in flight, then the events in actual flight would seem to occur at the correct rate. Only the final simulation planning sessions for a given flight were conducted in this way.

The initial simulation of the HL-10 was accomplished on the analog computers at the FRC. The real capability of the analog computer was its ability to integrate differential equations. And because the equations of motion for the lifting bodies were differential equations, as are all aerospace vehicle equations of motion, we mechanized these on the available analog computers. Digital computers of the early to mid-1960s were used primarily for data reduction, not real-time simulation. The analog computers were fast and there were no problems with cycle time. The big problem with analog computers was their inability to easily generate nonlinear functions such as aerodynamic data. In short, analog computers left much to be desired when mechanizing highly nonlinear functions.

With the HL-10 modification-II aerodynamic data and our desire to mechanize the highest fidelity simulation possible, we purchased a relatively high-speed digital computer to generate the nonlinear aerodynamic functions. We interfaced this computer with the analog computer, where the integrations were accomplished, and moved into the world of hybrid computation. This approach proved to be successful and allowed us to make fast, efficient changes to the aerodynamic database when required.

Although the program engineers did not know it, the simulation engineers experimented with moving all of the mathematical computations, including the integrations, to the digital computer. When this work was completed, they demonstrated an all-digital, real-time simulation to the program engineers. Neither the program engineers nor the pilots could tell the difference. Another milestone was achieved. The HL-10 successfully transitioned from the analog computer to the all-digital computer, real-time simulation world.*

The First Lifting-Body Powered Flight

The first lifting-body powered flight was attempted with the HL-10 on October 23, 1968 with Capt. Gentry at the controls. The rocket failed shortly after launch requiring propellant jettison and an emergency landing on Rosamond (Dry) Lake, 10 mi southwest of Rogers Lake, but within the boundary of Edwards AFB. The first successful lifting-body powered flight was subsequently made on November 13 with John Manke at the controls.

The First Supersonic Lifting-Body Flight

The first supersonic flight achieved by a lifting body was accomplished on May 9, 1969 by Mr. Manke (figs. 23(a) and 23(b)) in the HL-10 on its 17th flight. On this date the HL-10 reached a maximum altitude of 53,300 ft and a Mach number of 1.13.

The flight plan called for a launching approximately 30 mi northeast of Edwards AFB, igniting three rocket chambers, rotating to an AOA of 20°, maintaining 20° AOA until pitch attitude was 40°, and maintaining 40° pitch attitude until an altitude of 50,000 ft was reached. At 50,000 ft, a pushover to 6° AOA and acceleration to a supersonic Mach number of 1.08 was planned. This was to be followed by changing AOA and turning off another rocket chamber and maintaining constant Mach number while gathering data. The maximum Mach number was to be 1.08. Landing was to be the typical 360° approach with a landing on runway 18.


E-18880

(a) Pilot John Manke.


E-20492

(b) Left to right, John Manke (in pressure suit), Wen Painter, Herb Anderson, Jack Kolf, and Joe Huxman.

Figure 23. Members of HL-10 project.

Mr. Manke later reported that during the flight "everything went real well." Although there were some comments concerning the preflight checks, flight, and comparisons with the simulator and the landing approach, everything went according to plan. This flight experience contrasted significantly with the initial ground simulation preparations for it. Some interesting

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*All NASA Dryden flight simulation work in the 1990s so far has been accomplished using small, high-speed digital computers.

occurred leading up to this first lifting-body supersonic flight.

In preparation for the flight, a complete review of the wind-tunnel aerodynamic data was made. In addition, the predicted dynamic characteristics and vehicle controllability in the transonic and supersonic flight regimes were reassessed. Between the Mach numbers of 0.9 and 1.0 the data indicated an area of low, or even slightly negative, directional stability at angles of attack of 25.5° and above. Predictions and the simulator indicated acceptable levels of longitudinal and lateral-directional dynamic stability at all angles of attack and Mach numbers. A detailed technical briefing was given to NASA and USAF management teams.

The HL-10 (and lifting bodies in general) had very high levels of effective dihedral, and this, in combination with positive angles of attack and acceptable levels of directional stability, ensured lateral-directional dynamic stability almost everywhere in the flight envelope. It was demonstrated that the HL-10 would exhibit dynamic lateral-directional stability, even if the static directional stability was zero or slightly negative, provided the AOA did not approach zero. To prove to our pilot, Mr. Manke, that even with the directional stability set to zero the vehicle would remain dynamically stable, we generated a special simulation demonstration data set with the static directional stability set to zero at all Mach numbers and angles of attack. This would be true if, and only if, the AOA was some positive value and did not approach zero. We successfully demonstrated to Mr. Manke that even with this purely fictitious, gross adjustment to the data set, the HL-10 would remain dynamically stable.

As fate would have it, Mr. Manke, being a diligent test pilot, was in the simulator practicing for his first supersonic flight during his lunch hour (brown bag beside him). At this particular simulation session, no program engineers were present and the simulation engineer inadvertently loaded the wrong aerodynamic data set into the computer—the data set with the directional stability everywhere set to zero. This was a demonstration data set and not to be used for flight planning. With the program loaded, the simulation engineer departed for lunch. He left thinking that nothing could possibly go wrong, because all Mr. Manke had to do was hit the operate and reset switches. As the simulator run progressed and Mr. Manke achieved the planned altitude for the acceleration to supersonic speed, he pushed the nose over (toward zero AOA) and the vehicle became violently unstable in a lateral direction. The flight plan called for the pilot to pushover to only 6° AOA, but he must have inadvertently approached AOA $\approx 0°$. Mr. Manke crashed in the simulator. Not knowing exactly what to do, Mr. Manke expressed his intense concerns to NASA management before reporting the problem to the program engineers, who were off having lunch someplace.

Before the program engineers knew what was happening, we were all summoned to one of the wood paneled executive offices—the "Bikle barrel" as we called it. Those present from the project were Mr. Layton, Mr. Painter, Mr. Kock, and Mr. Kempel. From the management side Mr. Bikle, Joe Weil, Director of Research, and Jack Fischel, his deputy, were there. The project pilot, Mr. Manke, was not among the crowd. So there we stood in the boss' office, trying to explain why we would try to kill a perfectly good research pilot, a guy we all kind of liked, even if he was from South Dakota. The scene turned ugly. We can remember that the door seemed such a long distance from where we were and a formidable barrier of high-level managers stood between us and it. We had obviously been judged guilty, and all that remained was for the sentence to be passed. After the feeding frenzy abated, we were given our say. It dawned on us what had happened. We explained the problem and followed this up with a demonstration in the simulation lab. Once the correct aero data set was loaded into the simulator, the situation was much improved and no dynamic instability was encountered (as predicted) either in the simulation or in flight. We again (remembering the words of Dr. Dryden) *separated the real from the imagined and made known the overlooked.* In this situation we project engineers were the victims of the unexpected.

This story indicates how at least one of the pilots viewed the simulation once credibility was established—he believed what he experienced. We had intentionally programmed the wrong data into the simulation, for demonstration purposes, and our cleverness backfired. Simulation is an extremely powerful engineering tool; however, great care must be taken in its mechanization or the results may be totally misleading and could even be catastrophic.

Following this, on May 9, 1969 (a beautiful spring day in the Mojave Desert), Mr. Manke made history by successfully completing the world's first supersonic lifting-body flight. We do not think the actual flight was as exciting as the events leading up to it. From what we remember of the flight, it was relatively uneventful except for going supersonic. Richard P. Hallion, in his book, *On the Frontier* (ref. 10), calls this first supersonic flight "a major milestone in the entire lifting-body program." He goes on to say that "the HL-10 thus became the fastest and highest flying piloted lifting body."

The Fastest and the Highest

On February 18, 1970, in the 34th flight of the HL-10, USAF Captain Pete Hoag (fig. 24) achieved a Mach number of 1.86; nine days later, on the 35th flight, NASA pilot William H. "Bill" Dana (fig. 25) reached an altitude of 90,303 ft. The fastest flight was launched approximately 30 mi southwest of Edwards, heading 059° magnetic, at an altitude of 47,000 ft. The flight plan called for igniting all four rocket chambers immediately after launch. The vehicle was rotated to 23° AOA until a pitch attitude of 55° was attained. The 55° attitude was maintained until an altitude of 58,000 ft was reached. At 58,000 ft a pushover to 0 *g* was executed (AOA ≈ 0°) and maintained until fuel exhaustion occurred. The maximum Mach number was 1.86 at 67,310 ft. This was the fastest that any of the lifting bodies would fly. The remainder of the flight was relatively routine with a typical lakebed landing. The duration of this flight from B-52 launch to touchdown was 6.3 min.

E-20777

Figure 24. USAF Major Pete Hoag, HL-10 project pilot.

E-20288

Figure 25. HL-10 pilot Bill Dana.

Mr. Dana was the third NASA research test pilot to fly the HL-10. Mr. Dana had flown the final (199th) X-15 flight in late October 1968 and made his first HL-10 glide flight on April 25, 1969. His flight to maximum altitude was also launched approximately 30 mi southwest of Edwards, heading 059° magnetic, at an altitude of 45,000 ft. The flight plan called for the ignition of all four rocket chambers immediately after launch. The vehicle was rotated to 23° AOA until a pitch attitude of 55° was attained. The 55° attitude was maintained up to 76,000 ft. At this altitude Mr. Dana performed a pushover to an AOA of 7° until a Mach number of 1.15 was attained. At Mach 1.15 and 7° AOA the speed brakes were deployed, increasing the AOA to 15°. The maximum Mach number was 1.314 and altitude was 90,303 ft. This was the highest altitude that any of the lifting bodies would achieve. The remainder of the flight was routine, except that the landing was accomplished on lakebed runway 23 (to the east of runway 18, not shown on fig. 14) because of a high crosswind on the normal landing runway. The flight to maximum altitude, from B-52 launch to touchdown, lasted 6.9 min.

Flight-Determined Lift and Drag

Certainly any aerospace vehicle must have adequate controllability to achieve success. The modified HL-10 possessed very good control characteristics. Equally important, as indicated earlier, was its ability to generate and control lift. Much of the success of the HL-10 was its relatively high *L/D* in its subsonic configuration. The maximum *L/D* for the HL-10, measured in flight, was 3.6 at an AOA of approximately 15° in the modified subsonic configuration with the landing gear up and no speed brake deployed. Figure 26 presents the flight-determined *L/D* for this configuration, as a function of coefficient of lift, at $M = 0.6$ (ref. 22). This curve presents a faired line through numerous flight data points from trimmed flight conditions. Both the front and back sides of the *L/D* curve are illustrated. The lift curve slope from this reference is a linear function of trimmed AOA. Typical of a negatively cambered airfoil, the coefficient of lift at zero AOA was a negative value. This figure presents the angles of attack for three coefficients of lift. While reference 22 presents flight results, reference 23 presents the full-scale wind-tunnel results of the actual HL-10, without the modified tip fins.

Pyle (ref. 22) made a comparison of the flight-determined *L/D* characteristics of the HL-10 and M2-F2. Even though the two vehicles had considerably different configurations, their missions were similar, and therefore, a comparison of their characteristics is of interest. The maximum subsonic *L/D* for the HL-10 was 14 percent higher than the M2-F2. Pyle indicated that these vehicles had similar lift-curve slopes; the M2-F2, however, had a much lower AOA at a specific lift coefficient when compared with the HL-10. The 300-knot approach, for both vehicles, was initiated at a lift coefficient of approximately 0.15. For the M2-F2 this resulted in an AOA of about –2° and for the HL-10, about 10°. At this lift coefficient and these angles of attack the M2-F2 landing approach was at a flight path of about –25° (nose down), while the HL-10 was at about –8°. By comparison the approach angle of airliners in the 1990s is approximately –3°. The steep approaches were never a problem for the pilots, although they were breathtaking to watch. The M2-F2 descents were particularly spectacular in their steepness.

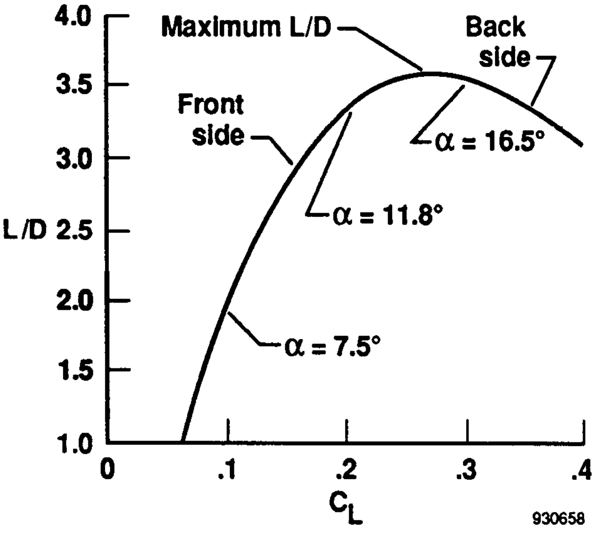

Figure 26. Flight-determined *L/D* for HL-10.

At a Mach number of about 0.6, the *L/D* of the HL-10 transonic configuration was approximately 26 percent lower than the subsonic configuration. Lowering the landing gear decreased the *L/D* by about 25 percent, which supported the landing technique of flaring in the clean subsonic configuration and, to an observer on the ground, seemed to be lowering the landing gear at the last instant of flight (ref. 5).

The Best Flying of the Lifting Bodies

The HL-10 was indeed a very good flight vehicle. The modified HL-10 was typically rated as the best flying of the lifting bodies. On a rating scale from 1 to 10 (1 being the best), the HL-10 was rated a 2 overall. Typically, each pilot was asked to evaluate various piloting tasks or maneuvers during each flight. Following each flight the pilots were then asked to complete a questionnaire, which included numerical evaluations and comments. Of the 419 numerical ratings given, 43 percent were a 2 (ref. 24). Ninety-eight percent of all pilot ratings were 4 or better. Three percent of all ratings were a 1—the best possible. Only 0.7 percent of the ratings were a 6, which was the highest (or worst) rating received by the HL-10. By contrast the M2-F3 was rated overall a 3 (32 percent of all 423 ratings), with 89 percent of all ratings a 4 or better (ref. 25).

Piloting the HL-10

Test pilots, typically, do not really believe the wind-tunnel data mechanized in the simulations until they have flown the actual vehicle. The HL-10 simulation was no exception. As stated earlier, before the first flight many of the more experienced engineers indicated that the HL-10 looked "too good" in the simulation and, therefore, thought it to be suspect. Before the first flight the pilots did not spend much time in the simulator. But following the needed modifications and the second flight, we engineers had no difficulty getting pilots in the simulator to prepare for missions.

After the upgrade, designated modification II, piloting the HL-10 presented no serious problems (ref. 26). Each pilot found it relatively easy to fly; that is, it was no more difficult to fly than an F-104 making a similar approach. (Typically, the pilots had nothing but praise for the F-104.) To the uninitiated the unpowered approach and landing appeared rather sporting. Often designers and engineers fail to appreciate the advantages of the steep, unpowered approach. The high-energy approach was felt to be more accurate, safer, and actually less critical than a low-energy approach. This type of approach can be related to a dive-bomber profile. In dive bombing it was known that the steeper the dive angle, the greater the accuracy. The HL-10 approach task posed basically the same problem: position the vehicle on a flightpath or dive angle to intercept a preflare aim point on the ground. The difficulty of this task was minimized by using a relatively steep approach (–10° to –25°).

The whole approach pattern, then, was just a means of establishing the vehicle on this flightpath. Because the approaches were generally well on the front side of the *L/D* curve (i.e., at high speeds and relatively low AOAs below that for maximum *L/D*), there was never a problem of being short of energy. Energy was modulated to arrive on the desired flightpath either by slowing or accelerating, or remaining at approximately the same speed and using the speed brakes to alter flightpath as required. Too much emphasis cannot be made for requiring speed brakes on this class vehicle. The brakes can be used much like a throttle to vary the landing pattern parameters. In addition, their weight is minimal and they require no fuel. To the ground observer these landings were rather spectacular. The angles seemed too steep and the speeds too high. But from the pilot's point of view they was really no problem. The small landing rockets provided were never used except for experimental purposes. The speed brakes were consistently used.

A sequence of photographs illustrates the unpowered approach, touchdown, and final portions of a typical flight. Figure 27 shows the HL-10 vehicle preparing

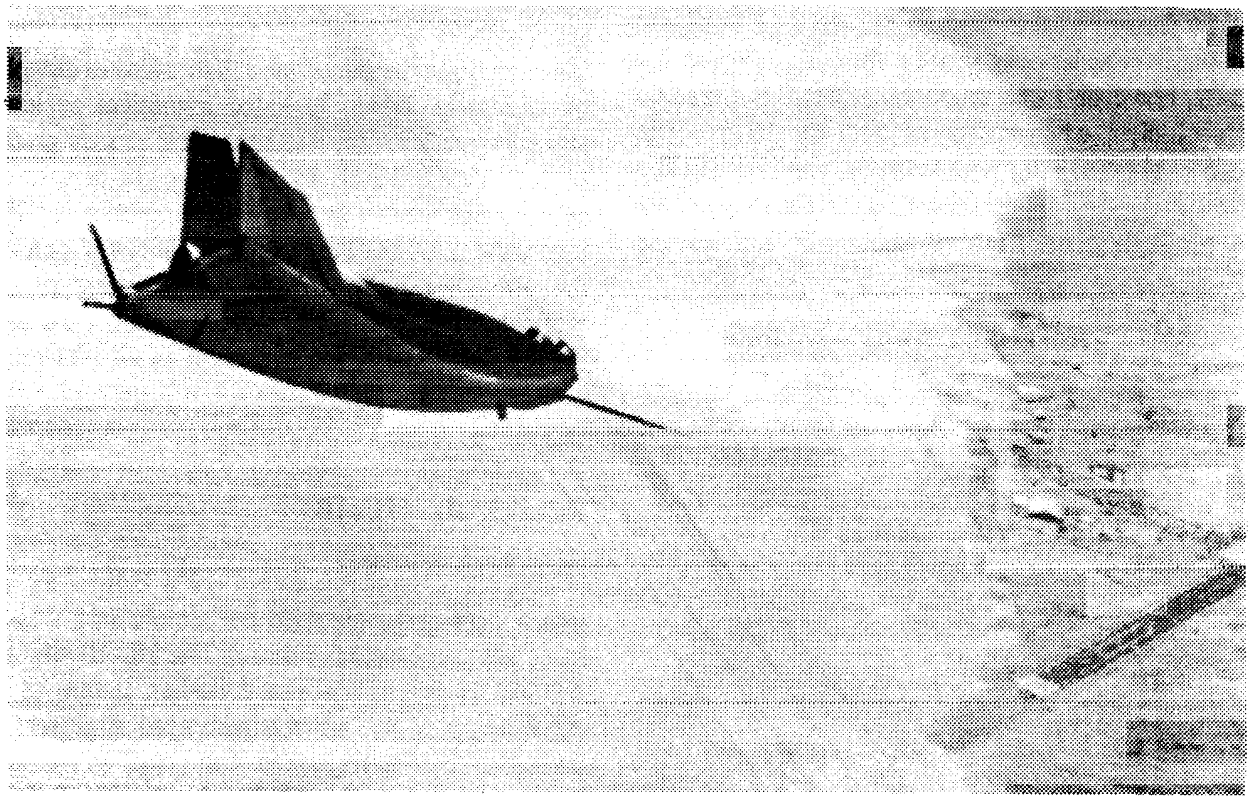

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Figure 27. HL-10 in terminal approach and landing pattern.

to make a left turn to final approach. In this figure, the landing runway, runway 18, is immediately below and to the right of the nose of the vehicle. Figure 28 shows the vehicle on final approach. The railroad tracks, to the north of Rogers Lake, are to the right and below the vehicle. In figure 29 the HL-10 is shown in its nose-high attitude at touchdown on runway 18 and an airborne F-104 chase aircraft just a few feet above the lakebed in the background. Figure 30 shows the vehicle following landing, soon after the pilot (Mr. Dana) emerged from the cockpit, as the B-52 launch aircraft makes a low salutatory pass.

Later in the program, many spot landings were attempted in keeping with the idea that runway landings would someday be a requirement, i.e., for the space shuttle (ref. 26). The average miss distance was determined to be less that 250 ft, with stops within a mile.

The higher speed approaches also provided better controllability of the vehicle. A conventional approach

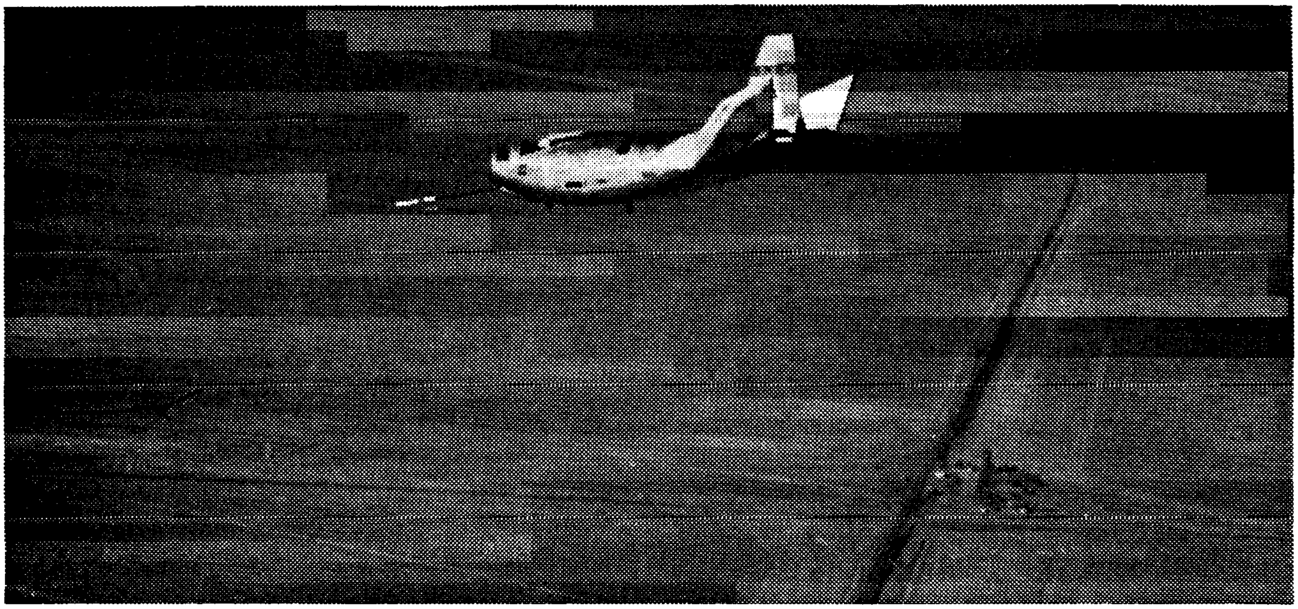

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Figure 28. HL-10 on final approach.

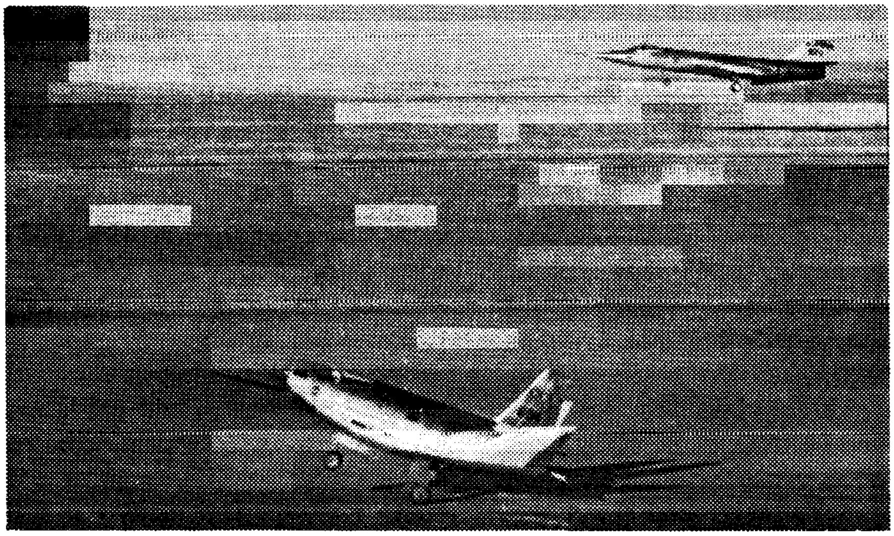

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Figure 29. HL-10 on touchdown (F-104 aircraft in background).

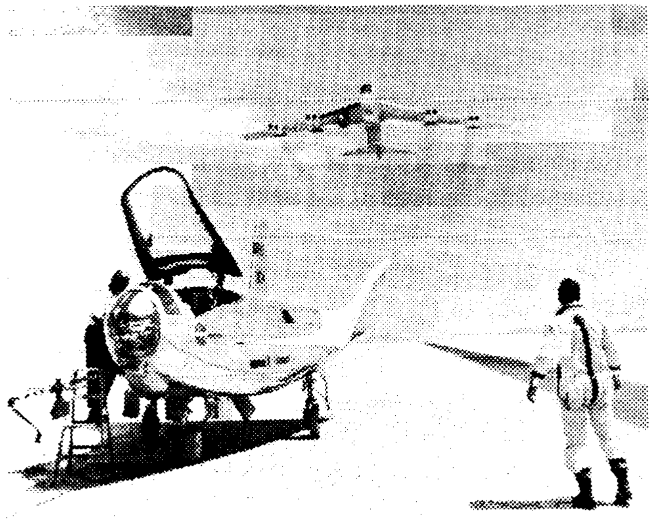

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Figure 30. NASA pilot Bill Dana looks on as B-52 flies over HL-10 following touchdown.

at high power and low speed is much more demanding upon a pilot. The aircraft is being operated on the back side of the *L/D* curve (i.e., at low speeds and relatively high AOAs above those for maximum *L/D*), where engine failure can be catastrophic and vehicle stability, controllability, and handling qualities are degraded.

The visibility out of the HL-10 was not considered good by most of the pilots. Even though the pilots were located far forward, there was no cockpit bulge for the canopy. The canopy rails, the lower extent of the canopy, were relatively high, which provided a sideward field-of-view depression angle of approximately 16° to the right and somewhat less on the left because of the canopy defrost duct. The pilots were supplied a squirt bottle of water in the event the canopy defrost duct flow was insufficient to clear the fog at critical portions of flight.

The clear plastic glass nose window provided excellent forward vision for navigation and maneuvering for touchdown. Unfortunately, this was lenticular in shape and served as a large demagnifying lens near the ground. This effect gave the pilots the impression that they were higher then they really were. On one flight Mr. Manke reported, "I touched down before I wanted to. Here again the distortion out of that nose window is still a problem to us, and I think it is always going to be." Some pilots, on their initial flights, waited until they were critically close to the ground before they extended the landing gear. This problem was alleviated with pilot experience.

Vehicle Dynamics, Control, and Turbulence Response

As one might imagine, the lifting bodies possessed some unique aerodynamic characteristics. A most unusual characteristic is what we call the "dihedral effect." For a conventional winged airplane the dihedral is the acute angle between the intersecting planes of the wings (usually measured from a horizontal plane). In addition, the dihedral effect is an aerodynamic effect, produced by wing dihedral, which is related to the tendency of an airplane to fly with wings level or that effect which produces a rolling tendency proportional to sideslip angle. Even though lifting bodies do not have wings as such, they possess very large amounts of dihedral effect. This means that for a little bit of sideslip, a large amount of rolling tendency is generated. This was the primary reason that lifting bodies were flown with the pilot having both feet on the floor (i.e., deliberately keeping their feet off the rudder pedals). The rudder would induce sideslip and the vehicles would respond primarily in roll.

Each of the lifting bodies experienced flight through turbulence, which caused pilot anxiety that was out of proportion to the upsets involved. These upsets (uncommanded disturbances of unknown origin) were so different to the pilots that they were frequently disturbed when encountering any turbulence. Aerodynamically, the lifting bodies were significantly different from winged airplanes and one might predict that they would respond to turbulence differently, but we were experiencing something new. There was no common opinion among the pilots as to what particular sensations triggered the anxieties. The pilots frequently felt that they were on the verge of an instability and early in the program felt that the vehicles would "uncork" on them. Once convinced that no real instability was present and that the vehicle disturbances were caused by turbulence, the pilots became accustomed to riding through the disturbances with little concern. With no wings on the HL-10, the gust response was considerably different from that for conventional airplanes. Conventional airplanes are primarily affected in the vertical or "seat of the pants" by turbulence. In lifting bodies, turbulence would produce small amounts of sideslip disturbance which would result in more of a high-frequency rolling response and sensation to the pilots. This was particularly true at the lower altitudes where turbulence could be the most severe. Following the crash landing of the M2-F2 in May 1967 the pilots were even more sensitized to any upsets near the ground. The pilots felt that they might be encountering or on the verge of some sort of dynamic instability even though the engineers assured them that they were not.

Mysterious upsets occurred at altitude too. These upsets frequently occurred during the powered portion of a profile and they would spook the pilots. The engineers hypothesized that these were instances of wind shear. To prove the point, on one flight a motion picture camera was positioned on the ground, directly beneath the planned ground track. The XL-11 rocket motor always left a distinctive white exhaust condensation trail (contrail) no matter what the atmospheric conditions were. Just before launch the camera was turned on to record the launch and powered portion of the profile along with the pilot's radio transmissions. As the pilot flew the powered profile he called out the portions of the profile where the vehicle felt "squirrelly" laterally. A playback of the film revealed that the vehicle had indeed encountered wind shear as revealed by the disturbed rocket contrail, which correlated with the time segments of the flight report by the pilots.

With experience the pilots came to accept the fact that the turbulence response of the HL-10 was different from conventional winged airplanes and that they were not on the threshold of dynamic instability. This was new ground and they (the pilots) and we (the engineers) were indeed separating the real from the imagined.

Training for and Flying Chase for Lifting-Body Missions

The F-104 aircraft (fig. 31) was clearly the pilots' choice for both preparation for lifting-body flights and chasing lifting bodies. This airplane had a high-speed landing gear and large speed brakes, which enabled it to duplicate lifting-body *L/D* characteristics. The aspect ratio of the F-104 was only about 2.46. The subsonic clean configuration maximum *L/D* was 5.7. With the engine at idle, gear down and flaps set for takeoff, the *L/D* could be made to simulate each of the lifting-body configurations by modulation of the speed brake. Using this technique, the minimum *L/D* achievable was approximately 2.9. Thus, the F-104 envelope

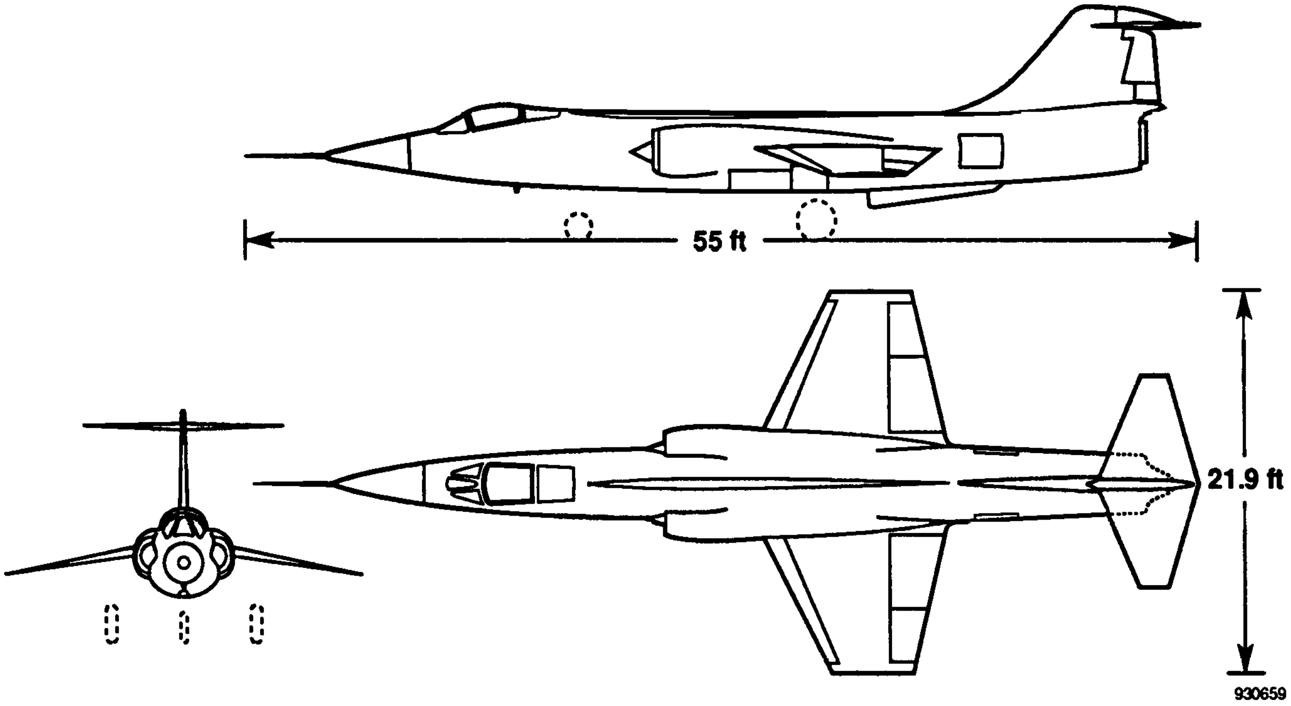

Figure 31. Three-view drawing of F-104 airplane.

essentially blanketed the *L/D* values for all of the various lifting bodies (ref. 27).* In addition, the F-104 airplane was reliable and had the pilots' full confidence.

Chasing lifting bodies in the F-104 was not totally without risk, as experienced by one NASA pilot. While chasing a lifting-body flight, this pilot inadvertently entered an uncontrolled spin. The F-104 was not known as an airplane to spin and successfully recover.

In the later stages of the program an F-104 incident happened at 35,000 ft altitude and 210 knots airspeed while maneuvering to join up with the lifting body. The airplane configuration was gear down, takeoff flaps, speed brakes out, and idle power. In maneuvering into position the pilot rolled to 45° of bank and sensed the airplane starting to slice to the right. As this was happening the airplane was in heavy buffet and the nose pitched up. An uncontrolled flight condition had been entered and the airplane was in a spin. One of the other chase pilots, witnessing the event, radioed a call for full-forward stick and full-forward trim. The F-104 was now in a flat, uncontrolled spin. The airplane was rotating to the right at about 40° to 50° per second and the pilot could not really believe he had gotten into a spin. The airplane made four or five full turns. The rotation was stopped by holding full left rudder, neutral aileron, and full nosedown stick with full nosedown pitch trim. The recovery seemed to be very abrupt at approximately 180 knots and 18,000 ft. The engine did not flame out, and the only configuration change made during the spin was that the speed brakes were retracted. The pilot held the nose down until reaching 300 knots and then pulled out at slightly over 4 *g* of normal load factor. The bottom of the pullout was at 15,000 ft.

Following this mission the postflight debriefing consisted mostly of the F-104 pilot's experiences of getting into the spin and, most importantly, his successful recovery. Discussion of the lifting-body mission that day was relatively trivial by comparison.

The Final Flights

Following flight 35 and the accomplishment of the major program objectives, the HL-10 was reconfigured to conduct a two-flight, powered approach and landing study. The modification included removing the XLR-11 rocket engine and installing three small hydrogen-peroxide rockets. The objective of this study was to look at shallower glide angles during the final approach. The rockets were ignited during the approach portion of the flight profile and reduced the approach angle from approximately 18° to 6°. The three rockets were ignited simultaneously and provided a relatively low level of thrust (approximately 300 lb each) and had the effect of reducing drag and hence increasing *L/D*, which permitted a higher glide ratio or shallower glide angle. The 37th and final flight, made on July 17, 1970, with Capt. Hoag piloting, was the last of the powered approach flights.

The overall result of this study was largely negative as compared with unpowered landings. A shallower powered approach was concluded to provide few of the benefits that were normally obtained with power. Further, it was concluded that even if airbreathing engines with go-around capability were installed, the normal approach technique for the space shuttle should be to operate the vehicle as if it were unpowered and to rely on the engines only if the approach were greatly in error. This result was a significant contribution to the decision not to install landing engines on the space shuttle (ref. 15).

Table 4 presents a summary of the 37 flights. The total actual flight time accumulated on the HL-10 was only 3 hr, 25 min, and 3 sec—not much free-flight time. Nonetheless, we are reminded that we proved the concept every time we watch a space shuttle landing.

Pilots Participating in the Program

A total of five pilots (fig. 32) participated in the HL-10 flight test program; three were NASA pilots and two were USAF pilots. Mr. Peterson piloted the first flight, his only one before being injured in an M2-F2 landing accident. Capt. Gentry, the second HL-10 pilot, made nine flights and later transferred to the X-24A program. Before participating in the HL-10 program, Capt. Gentry piloted five M2-F2 flights. Capt. Gentry piloted the first lifting-body powered flight on October 23, 1968. The remaining NASA pilots were Mr. Manke, who made 10 flights, and Mr. Dana with nine flights. Mr. Manke flew his first flight on May 28, 1968, and Mr. Dana's first flight was on April 25, 1969. The last pilot to fly the HL-10 was Capt. Pete Hoag, with eight flights.

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* Note that reference 27 was coauthored by a young NACA/NASA FRC research pilot by the name of Neil Armstrong, who later became the first human to walk on the moon.

Table 4. HL-10 lifting body flight log.

No.	Date	Flight number	Pilot	Maximum altitude, ft	Maximum Mach/ mph	Flight time, sec	Remarks
1	22 Dec 66	H-1-3	Peterson	45,000	0.69/457	187	First free flight
2	15 Mar 68	H-2-5	Gentry	45,000	0.61/425	243	
3	3 Apr 68	H-3-6	Gentry	45,000	0.69/455	242	
4	25 Apr 68	H-4-8	Gentry	45,000	0.69/459	258	
5	3 May 68	H-5-9	Gentry	45,000	0.69/455	245	
6	16 May 68	H-6-10	Gentry	45,000	0.68/447	265	
7	28 May 68	H-7-11	Manke	45,000	0.66/434	245	
8	11 Jun 68	H-8-12	Manke	45,000	0.64/443	246	
9	21 Jun 68	H-9-13	Gentry	45,000	0.64/423	271	
10	24 Sep 68	H-10-17	Gentry	45,000	0.68/449	245	XLR-11 rocket motor installed
11	3 Oct 68	H-11-18	Manke	45,000	0.71/471	243	
12	23 Oct 68	H-12-20	Gentry	39,700	0.67/449	189	First powered flight premature shutdown
13	13 Nov 68	H-13-21	Manke	42,650	0.84/524	385	Powered flight, 2 chambers for 186 sec
14	9 Dec 68	H-14-24	Gentry	47,420	0.87/542	394	2 chambers
15	17 Apr 69	H-15-27	Manke	52,740	0.99/605	400	3 chambers
16	25 Apr 69	H-16-28	Dana	45,000	0.70/426	252	Glide flight
17	9 May 69	H-17-29	Manke	53,300	1.13/744	410	First supersonic flight 3 chambers
18	20 May 69	H-18-30	Dana	49,100	0.90/596	414	
19	28 May 69	H-19-31	Manke	62,200	1.24/815	398	2 chambers
20	6 Jun 69	H-20-32	Hoag	45,000	0.67/452	231	Glide flight
21	19 Jun 69	H-21-33	Manke	64,100	1.40/922	378	2 chambers
22	23 Jul 69	H-22-34	Dana	63,800	1.27/839	373	2 chambers
23	6 Aug 69	H-23-35	Manke	76,100	1.54/1020	372	First 4-chamber flight
24	3 Sep 69	H-24-37	Dana	77,960	1.45/958	414	4 chambers
25	18 Sep 69	H-25-39	Manke	79,190	1.26/833	426	4 chambers
26	30 Sep 69	H-26-40	Hoag	53,750	0.92/609	436	2 chambers
27	27 Oct 69	H-27-41	Dana	60,620	1.58/1041	417	
28	3 Nov 69	H-28-42	Hoag	64,120	1.40/921	439	
29	17 Nov 69	H-29-43	Dana	64,590	1.59/1052	408	
30	21 Nov 69	H-30-44	Hoag	79,280	1.43/952	378	
31	12 Dec 69	H-31-46	Dana	79,960	1.31/871	428	
32	19 Jan 70	H-32-47	Hoag	86,660	1.31/869	410	
33	26 Jan 70	H-33-48	Dana	87,684	1.35/897	411	
34	18 Feb 70	H-34-49	Hoag	67,310	1.86/1228	380	Maximum Mach number
35	27 Feb 70	H-35-51	Dana	90,303	1.31/870	416	Maximum altitude
36	11 Jun 70	H-36-52	Hoag	45,000	0.74/503	202	Glide landing study
37	17 Jul 70	H-37-53	Hoag	45,000	0.73/499	252	Final flight

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Figure 32. HL-10 project pilots (from left to right) Jerry Gentry, Pete Hoag, John Manke, and Bill Dana.

THE FUTURE AND LEGACY OF LIFTING BODIES

Much of the wind-tunnel and flight test work we accomplished and published was unclassified. As a result, the Soviet Union took advantage of our work with their design and flight testing of the subscale BOR-4 vehicle in 1982.

The HL-10 currently stands proudly as a gate guardian at the entrance of NASA Dryden Flight Research Center, mounted on a pedestal with a bronze plaque (fig. 33). In this photograph the yellow ribbon was to remember and honor the military personnel involved in the Desert Shield and Desert Storm campaign. With the flight research of the lifting bodies completed, the future for the application of this technology is as valid today as it was 25 or 30 years ago, when the data were obtained.

With today's microprocessor technology and with this technology integrated into a sophisticated airborne computer onboard a lifting reentry vehicle, the advantages of lifting reentry can be exploited in ways that we

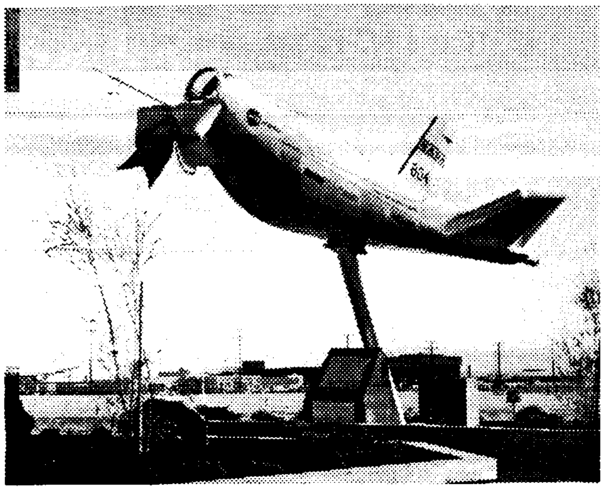

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Figure 33. HL-10 as it appeared in February 1991.

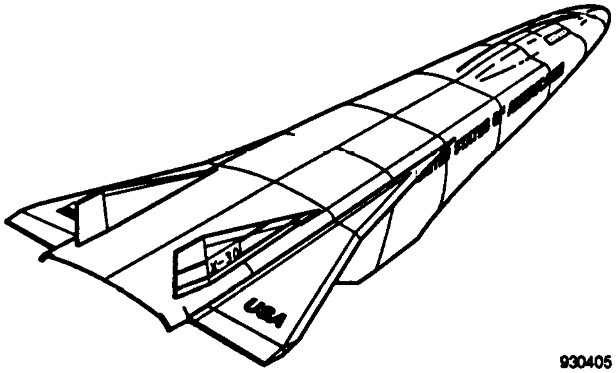

Figure 34. Proposed concept of National Aero-Space Plane.

could have only wished for. In addition, the advances in materials and fly-by-wire technology make the concept even more attractive.

The configuration selected for the National Aero-Space Plane (NASP) is that of a lifting body (fig. 34). In addition, NASA Langley is currently working on the HL-20 lifting body (fig. 35) as a personnel launch system in conjunction with the proposed space station.

Reference 28, *The Legacy of the Lifting Body*, presents interviews with some of the leading personalities associated with flight test programs at Edwards AFB. (Appendix C lists a bibliography for the topic of lifting bodies.) This article contains the last known interview with Paul F. Bikle before his death on January 19, 1991, and to whom this work gratefully is dedicated.

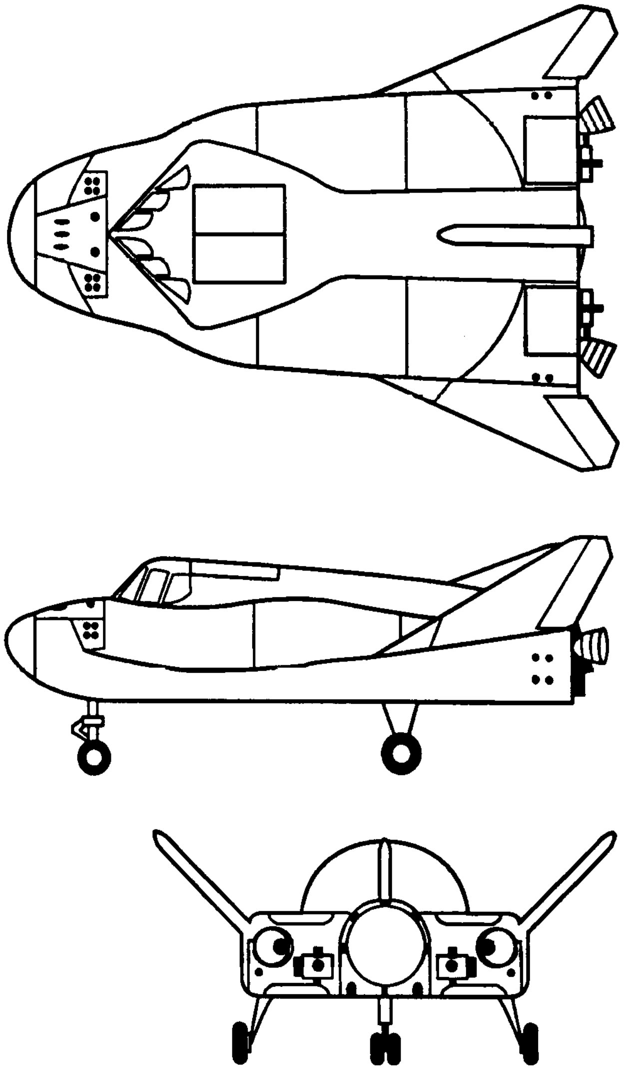

Figure 35. NASA Langley proposed HL-20.

SIGNIFICANT ACCOMPLISHMENTS AND LESSONS LEARNED

The following lists significant contributions and lessons learned by the low-speed HL-10 and lifting-body programs conducted at the FRC:

- The organizational structure of the HL-10 program allowed decisions to be made at the technical (engineer) level between NASA and the contractor, thus eliminating unneeded management and unnecessary paperwork. The result was a surprisingly low unit cost for the M2-F2 and HL-10 of only $1.2 million.

- The hybrid simulation of flight by interfacing analog computers with high-speed digital computers to generate complex nonlinear aerodynamic functions was demonstrated.
- The first all-digital real-time simulation at FRC was accomplished by moving the equations-of-motion integrations onto a high-speed digital computer.
- The first powered lifting-body flight was made on November 13, 1968.
- The first supersonic lifting-body flight was made on May 9, 1969.
- The maximum Mach number (1.86) achieved by any lifting body was reached on February 18, 1970.
- The maximum altitude (90,303 ft) reached by any lifting body was reached on February 27, 1970.
- Along with the other lifting bodies in the program, the HL-10 demonstrated that piloted reentry vehicles can execute steep, high-energy landing approaches that are part of an accurate and safe operational technique.
- The HL-10 assisted in demonstrating the importance and inherent reliability of speed brakes for unpowered reentry vehicles.
- The program demonstrated that lifting bodies equipped with speed brakes can fly steep, high-energy approaches and can spot land with an average miss distance of less than 250 ft.
- A class of vehicle with very high dihedral effect, a characteristic of lifting bodies, was shown to fly safely.
- The program demonstrated that atmospheric turbulence response was in the roll axis (due to the high dihedral effect of lifting bodies) rather than pitch axis and that this was not an apparent impending instability.
- Powered landings using shallower approaches were demonstrated to provide fewer benefits as compared with the steeper unpowered landing technique.
- The M2-F1 demonstrated that a pilot could fly and land a lifting-body shaped vehicle.
- The short total flight time and low costs of the HL-10 and M2-F2 programs were sufficient to provide confidence and knowledge upon which to make very crucial decisions pertaining to the space shuttle orbital entry landing concept.
- The effectiveness and versatility of the B-52 launch concept was demonstrated conclusively. This system remains a valuable national resource.

CONCLUDING REMARKS

The development, design, fabrication, and flight testing of the HL-10 was a significant effort accomplished by a team of NASA and contractor employees. Significant efforts and contributions by many individuals within NASA Langley, NASA Dryden, and the Northrop Corp. made the program a success. This story of the HL-10, as told here, is but a small part of what really happened. The rest is only contained in the living memory of those who have since retired. We wish that we could have included the comments of everyone involved in the program. It was and always will be the people who make programs work.

In 1970 one of Dryden's premiere test pilots, Milton O. Thompson, said, "We have been convinced of the feasibility of a lifting entry, horizontal landing spacecraft since we flew the M2-F1 seven years ago … . On the basis of our own experience, we cannot discuss the practicality of the proposed launch, boost, and orbit operations, nor can we assess the status of required technology in such critical areas as materials, structures and thermal protection systems … . If all the other NASA Centers, in conjunction with the Department of Defense and industry, can get the [space] shuttle off the ground, into orbit, and insure that it survives the entry, we at the Flight Research Center can guarantee that it can be flown to the destination and landed safely." As we all have seen, this statement has become reality.

Dryden Flight Research Center
National Aeronautics and Space Administration
Edwards, California, August 10, 1993

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APPENDIX A

Glossary

Ambient pressure	The pressure in the surrounding environment about a flying airplane but undisturbed or unaffected by it.
Angle of attack	The angle between a reference line fixed with respect to an airframe (body) and the velocity vector.
Angle of sideslip	The angle between the vertical reference plane through the centerline of an airframe (body) and the velocity vector.
Ballistic trajectory	The path followed by a body being acted upon only by gravitational forces and the resistance of the medium through which it passes.
Camber	The rise or curvature in the mean line (mean between upper and lower surface) curve of an airfoil or airfoil section from its chord line from leading edge to trailing edge. *Upper camber* refers to the upper surface of an airfoil and *lower camber* to the lower surface.
Coefficients	In aerospace engineering (and engineering in general) it is common practice to express *dimensionless* coefficients of various measured quantities. Coefficients are numbers obtained in experiments under certain specified conditions that can be used to relate subscale (wind-tunnel) measurements to full-scale (flight) measurements at similar conditions or expressed as a ratio.
Dihedral	The dihedral is the upward or downward inclination of the wings from the root to the tip showing a V (or inverted V) shape from a front or rear view. Downward is sometimes referred to as anhedral.
Dihedral effect	Dihedral effect is an aerodynamic effect, associated with the wing dihedral, which is the rolling tendency of an airplane due to sideslip.
Directional stability	The property of an aircraft enabling it to restore itself from a sideslip condition. Also called weathercock stability as in a weathervane.
Elevon	A control surface on the trailing edge of an airfoil that serves as elevator (pitch control) and aileron (roll control) on an aircraft without a horizontal tail.
Fixed-base	This pertains to a simulator that has no moving cockpit platform.
Flare	That portion of a flight profile, just before touchdown, when the rate of sink is arrested so that a smooth landing is accomplished.
Flight cards	The printed version of the entire chronological sequence of maneuvers, significant pilot activities, and events for a flight profile recorded on 3×5-in. flip cards for ease of pilot viewing. These also contain alternate profiles, emergency procedures, etc.
Hypersonic	Pertaining to speeds of Mach 5 and above.

L/D curve	When *L/D* is plotted as a function of AOA, an increasing value for *L/D* is realized with increasing AOA until some maximum is reached and a further increase in AOA results in decreasing values of *L/D*. The *front side*, at relatively low AOA, means that as AOA is increased, the *L/D* also increases, while on the *back side* the reverse is true.
Limit cycle	A condition in a feedback control system that produces an uncontrollable oscillation of limited amplitude of a flight control surface due to closed-loop phase lag resulting from excessive hysteresis, accumulated free-play of mechanical linkages, and power actuator nonlinearities.
Low key	A time point within the flight profile when the pilots devote their attention to making the landing approach.
Mach number	Ratio of reference speed to the speed of sound in the free air about an aircraft or missile. Named in honor of Ernst Mach (approximately 1887) who proved that important flow variations were not a function of the stream velocity but of the ratio of the stream velocity to the speed of sound in the stream.
Notch filter	An electronic filter with a signal input/output that filters a certain specified, relatively small, frequency band (on the input) that if allowed to remain (on the output) would produce an undesirable response in vehicle dynamics through the flight control system.
Pitch gain	A flight control pitch angular rate feedback signal quantitative setting. In the HL-10 this was pilot selectable.
Reynolds number	A nondimensional parameter representing the ratio of the momentum forces to the viscous forces in fluid flow. Named after Osborne Reynolds (1842–1912).
Shock wave	A surface or sheet of discontinuity set up in a supersonic field of flow, through which the fluid undergoes a finite decrease in velocity accompanied by a marked increase in pressure, density, temperature, etc.
Trajectory	The path traced by any body moving as a result of an externally applied force, considered in three dimensions.
Unit stick	One inch of stick deflection.
Upsets	(In this paper) HL-10 disturbances or vehicle motions that were not a result of pilot command inputs, but were caused by some external source.
Washout filter	An electronic filter with a signal input/output that filters specified low frequencies or frequencies approaching zero in a flight control system to eliminate unwanted control surface commands due to signal feedback.
Visual display	This pertains to a simulation that presents a simulated visual scene to the occupants of an engineering or flight training simulator.

APPENDIX B

The HL-10 Lifting-Body Team

Many of the people on this list participated in more than one of the lifting-body programs as well as other major NASA and USAF programs. This list may not be complete. Those unnamed individuals contributed to the success of the HL-10 program too. (Figure 16 is a group photograph of 18 of the HL-10 project personnel.)

Paul F. Bikle	Flight Research Center Director
R. Dale Reed	Lifting-Body Program Manager
John McTigue	Lifting-Body Program Manager
Garrison P. "Garry" Layton	Project Manager
Bruce A. Peterson	Project Pilot
Capt. Jerry Gentry, USAF	Project Pilot
William H. "Bill" Dana	Project Pilot
John Manke	Project Pilot
Capt. Pete Hoag, USAF	Project Pilot
Meryl DeGeer	Operations Engineer
Herb Anderson	Operations Engineer
George Sitterle	Operations Systems Engineer
Andrew "Jack" Cates	Operations Systems Engineer
Berwin Kock	Systems Engineer
Weneth D. Painter	Systems Engineer
Robert W. Kempel	Stability and Controls Engineer
Larry Strutz	Stability and Controls Engineer
Don Bacon	Simulation Engineer
Lowell Greenfield	Simulation Engineer
Larry Caw	Simulation Engineer
Georgene Laub	Aerodynamist
Jon Pyle	Performance Engineer (Lift and Drag)
William D. Clifton	Instrumentation Engineer
Capt. John M. Rampy, USAF	Flight Controls/ Simulation Engineer
Fred R. Erb	Northrop Norair, Systems and Mechanial Design Engineering Supervsor
R. C. Hakes	Northrop Norair, M-2/HL-10 Project Director
Charles W. Russell	Crew Chief
Art Anderson	Mechanic
John W. "Bill" Lovett	Mechanic
William "Bill" Mersereau	Mechanic
Richard L. Blair	Instrumentation Technician
Albert B. "Al" Harris	Electrical Technician
Bill Link	Inspector
John Reeves	Inspector
Bertha Ryan	M2-F1/F2 Stability and Control Engineer
Alex "Skip" Sim	Cooperative Student (Engineering)
2d Lt. Pat Haney, USA	Data Processing Officer
2d Lt. Jerry Shimp, USA	Data Processing Officer

APPENDIX C

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11. SUPPLEMENTARY NOTES

Mr. Kempel is currently employed by PRC Inc., Edwards, CA. Mr. Painter is affiliated with the National Test Pilot School, Mojave, CA. Mr. Thompson (1926–1993) was employed at NASA Dryden upon his death.

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13. ABSTRACT (Maximum 200 words)

The origins of the lifting-body idea are traced back to the mid-1950s, when the concept of a manned satellite reentering the Earth's atmosphere in the form of a wingless lifting body was first proposed. The advantages of low reentry deceleration loads, range capability, and horizontal landing of a lifting reentry vehicle (as compared with the high deceleration loads and parachute landing of a capsule) are presented. The evolution of the hypersonic HL-10 lifting body is reviewed from the theoretical design and development process to its selection as one of two low-speed flight vehicles for fabrication and piloted flight testing. The design, development, and flight testing of the low-speed, air-launched, rocket-powered HL-10 was part of an unprecedented NASA and contractor effort. NASA Langley Research Center conceived and developed the vehicle shape and conducted numerous theoretical, experimental, and wind-tunnel studies. NASA Flight Research Center (now NASA Dryden Flight Research Center) was responsible for final low-speed (Mach numbers less than 2.0) aerodynamic analysis, piloted simulation, control law development, and flight tests. The prime contractor, Northrop Corp., was responsible for hardware design, fabrication, and integration. Interesting and unusual events in the flight testing are presented with a review of significant problems en-countered in the first flight and how they were solved. Impressions by the pilots who flew the HL-10 are included. The HL-10 completed a successful 37-flight program, achieved the highest Mach number and altitude of this class vehicle, and contributed to the technology base used to develop the space shuttle and future generations of lifting bodies.

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