# Energy Management of Manned Boost-Glide Vehicles: A Historical Perspective

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May 2004

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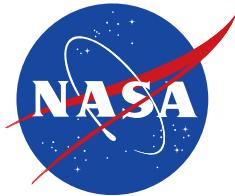
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PREFACE

This paper is a collection of the author's experiences working with pilots and engineers during the decades of research flights from the early days of rocket aircraft to the present. The paper is also based on information from many technical reports published from the late 1940s to the present.

ACKNOWLEDGMENTS

The author wishes to thank the following for their contributions to this review of the development of energy management techniques for manned, high-energy boost-glide vehicles.

A special thanks to Edwin J. Saltzman who came to NACA (the predecessor of NASA) in 1951 and for 50 years has specialized in the field of aerodynamic performance, particularly lift and drag, the prime components in the study of boost-glide energy management. Ed's advice, recommendations, exhaustive search for remote but very relevant materials, and excellent editorial comments were extremely helpful.

William H. Dana, NASA X-15 pilot and former Chief Engineer, NASA Dryden Flight Research Center. Bill flew sixteen X-15 flights including the last flight, October 24, 1968. Most of these flights were high-energy altitude flights, qualifying Bill as an excellent source of information for this paper.

Neil Armstrong, NACA/NASA experimental test pilot, flew seven X-15 flights, including the longest and most revealing of low lift-to-drag ratio (L/D) energy management boundaries. This flight demonstrated that low L/D aircraft could handle extreme anomalies in energy management and was a great influence in the design of the Space Shuttle. Neil's early engineering energy management work in analog and flight simulations contributed greatly to this paper. These accomplishments, among many others, provided Neil impeccable credentials for astronaut selection in 1962.

Robert Hoey, retired Air Force Flight Test Center (AFFTC) engineer, for his help in developing the methods used in boost-glide energy management, the footprints, their display and control. Bob was the Air Force X-15 project engineer counterpart to the author during the early X-15 flight planning.

Gene Matranga, retired NACA/NASA flight test engineer, for his contributions to early X-1E and X-15 energy management analysis. These efforts using analog simulations and F-104A flight simulations laid the groundwork for future X-15 energy management techniques. His reference reports and his paper on details of the first thirty X-15 flights were substantial contributions to the current historical report.

John McTigue, retired NACA/NASA aeronautical engineer, came to the High-Speed Flight Station in 1953. He was the original project engineer on X-15 no. 3, and was later program manager of the five original heavyweight lifting bodies. His counsel through the years has been a contributory factor to this report.

Kenneth W. Iliff, Chief Scientist, NASA Dryden Flight Research Center, for pioneering a method to determine aircraft aerodynamic characteristics to an increased degree of accuracy. Data obtained by this method and reported in his and other papers have been invaluable.

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Ryan Dibley, Dryden Flight Research Center research engineer, who has overseen the preliminary editing and layout of *Energy Management of Manned Boost-Glide Vehicles: A Historical Perspective*.

There were many engineers and pilots involved in the core studies of energy management concepts and their development, three of whom should be acknowledged posthumously: Milton O. Thompson, NACA/NASA test pilot and aeronautical engineer, flew fourteen X-15 flights and was formerly Chief Engineer at Dryden. The flight testing and publication of his many concepts and techniques for handling high-energy, low L/D, unpowered vehicles, produced a large portion of reference materials for this report.

Joseph Walker, former NACA/NASA research pilot, flew rocket-powered X-series aircraft from the X-1A to the X-15. Joe became chief pilot at Dryden in 1955. He flew twenty-five X-15 flights and was the prime NASA pilot in the envelope expansion flights—the flights where most energy management techniques were developed.

Walter C. Williams, first director at the High-Speed Flight Station, intuitively understood the importance of energy management. He approved the engineering concepts and access to property and assets required to implement energy management. Walt permitted engineers to develop theories and operational procedures with a minimum of supervision, expediting the development of energy management. Walt later carried these concepts to the Manned Spacecraft Center (MSC), Houston, Texas, when he transferred as Director of Operations for Project Mercury.

ABSTRACT

As flight progressed from propellers to jets to rockets, the propulsive energy grew exponentially. With the development of rocket-only boosted vehicles, energy management of these boost-gliders became a distinct requirement for the unpowered return to base, alternate landing site, or water-parachute landing, starting with the X-series rocket aircraft and terminating with the present-day Shuttle. The problem presented here consists of: speed (kinetic energy)—altitude (potential energy)—steep glide angles created by low lift-to-drag ratios (L/D)—distance to landing site—and the bothersome effects of the atmospheric characteristics varying with altitude. The primary discussion regards post-boost, stabilized glides; however, the effects of centrifugal and geopotential acceleration are discussed as well. The aircraft and spacecraft discussed here are the X-1, X-2, X-15, and the Shuttle; and to a lesser, comparative extent, Mercury, Gemini, Apollo, and lifting bodies. The footprints, landfalls, and methods developed for energy management are also described. The essential tools required for energy management—simulator planning, instrumentation, radar, telemetry, extended land or water range, Mission Control Center (with specialist controllers), and emergency alternate landing sites—were first established through development of early concepts and were then validated by research flight tests.

NOMENCLATURE

Acronyms

AFB	Air Force Base
AFFTC	Air Force Flight Test Center, Edwards AFB, California
ALT	(Shuttle) approach and landing tests
APU	auxiliary power unit
ARS	American Rocket Society (became AIAA in 1963 with IAS)
FRC	Flight Research Center, Edwards, California (later NASA Dryden)
GEDA	Goodyear Electronic Differential Analyzer
HSFS	High-Speed Flight Station
IAS	Institute of Aeronautical Sciences (became AIAA in 1963 with ARS)
JPL	(NASA) Jet Propulsion Laboratory, Pasadena, California
JSC	(NASA) Johnson Space Center, Houston, Texas
KSC	(NASA) Kennedy Space Center, Florida
MH	Minneapolis-Honeywell (now Honeywell, Inc.), Minneapolis, Minnesota
NAA	North American Aviation, Downey, California
NACA	National Advisory Committee for Aeronautics

NASA   National Aeronautics and Space Administration

OMS   orbital maneuvering system

RAPP   Research Airplane Projects Panel

RCC   reinforced carbon-carbon

RCS   reaction control system

RMI   Reaction Motors Incorporated, Rockaway, New Jersey

STS   Space Transportation System

TAEM   terminal area energy management

TPS   thermal protection system

UHF   ultrahigh frequency

USAF   United States Air Force

XLR   experimental liquid rocket

Symbols

a_c centrifugal acceleration, ft/sec^2

a_g geopotential acceleration, ft/sec^2

C_L coefficient of lift

g acceleration of Earth at mean sea level, ft/sec^2

h altitude above surface of Earth, ft

L/D   lift-to-drag ratio, dimensionless

R   radius of Earth, ft

V velocity normal to the geocentric radius, ft/sec

W/S wing loading, lb/ft^2

α angle of attack, deg or rad

γ flightpath angle, deg or rad

2

INTRODUCTION

For the ancient mariner reaching a destination required setting a course by stars and the sun, spotting the first land birds at sea, followed by a landfall leading to a harbor, and eventually a port and dock. Space navigation for boost-glide vehicles follows a similar pattern, but in a three-dimensional, more technically advanced series of navigational landfalls and position locators.

During a span of some five decades, from the days of Kitty Hawk to the advent of rocket-powered research aircraft, a requirement for boost-glide energy management did not exist. The problem first presented itself at the Rogers Dry Lake testing site in California (fig. 1) when rocket-boosted research aircraft supplied an unprecedented amount of energy, presenting the possibility of the unpowered (glide) flight overrunning a point of no return or falling short of the landing site. The constant increase in rocket power would eventually demand a terminal area footprint larger than Rogers Dry Lake, and larger than emergency landing lakes along the flight corridor for high-energy flights from remote launch sites.

Entries from orbit are "retro-glide" and from lunar orbit to the surface of the moon are "retro-ballistic." Because each of these is originally boosted to reach the energy level for terminal recovery, the title of this paper contains the generic term of "boost-glide."

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Figure 1. Rogers Dry Lake with 68 miles of lakebed runways and a 15,000-ft concrete runway.

This paper discusses the maps, landmarks, navigational aids, and techniques as they apply to the many facets of energy management for high-energy, boost-glide vehicles from the late 1940s to the present, primarily the experimental rocket research airplanes. During this period, the essential tools required for energy management—simulator planning, radar, instrumentation, telemetry, extended land or water range, a mission control center with specialist controllers, and emergency alternate landing sites — were first established through development of early concepts and were then validated by research flight tests conducted by the NACA/NASA and the Air Force Flight Test Center (AFFTC) at Edwards AFB, California. These tools were passed on to the Mission Control Centers of Johnson Space Center (JSC) (Houston, Texas), Jet Propulsion Laboratory (JPL) (Pasadena, California), and other future space organizations.

The evolution of manned flight has been that of glider, to propeller, to jet, to rocket, and eventually back to glider. The boost-glide vehicles of the last half-century range from winged bodies to blunt bodies with ever-decreasing range capabilities.

Energy Management and Footprints

The term "energy management," as used in this paper, includes management of the total energy of boost-glide vehicles from ground or air; from launch to landing. The boost portion determines the downrange location, vector, and total energy at thrust termination. The unpowered portion, beginning at thrust termination for suborbital vehicles, or retrofire for reentry, commits the vehicle to a landing within its down-range and cross-range glide capabilities; its footprint.

A "footprint" is a bounded ground or water area that outlines the perimeter of the glide capabilities for the unpowered portion of a flight or mission. Figure 2 shows a ground-monitored cathode-ray tube displaying a map and footprint of an X-15 mission. The display shows the X-15 footprint from launch to landing as the flight proceeds. The launch lake, contingency landing dry lakes, and destination lake (always Rogers Dry Lake, adjacent to Edwards Air Force Base) are generated graphically on a cathode-ray tube. The ground features are fixed displays. The footprint grows and diminishes as the energy does likewise. The shape of the footprint and how it is generated and utilized is discussed in Chapter 4, "The X-15 Aircraft." [1]
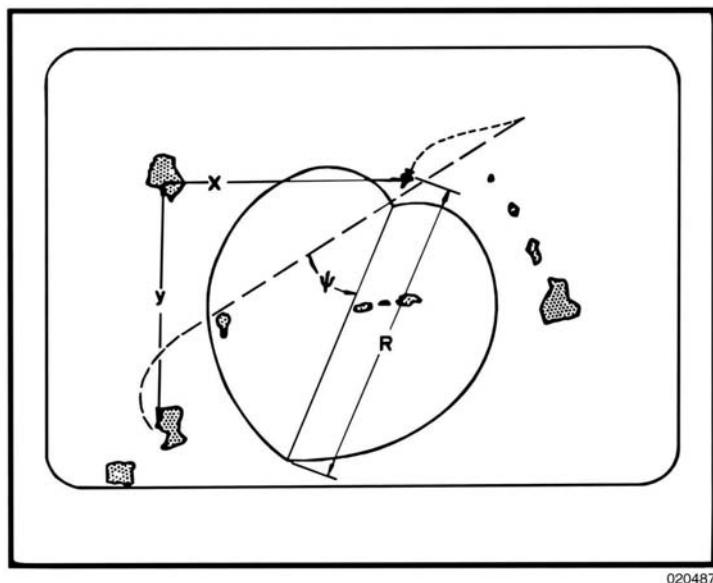
Figure 2. Ground monitor display of energy management footprint of the X-15 aircraft.
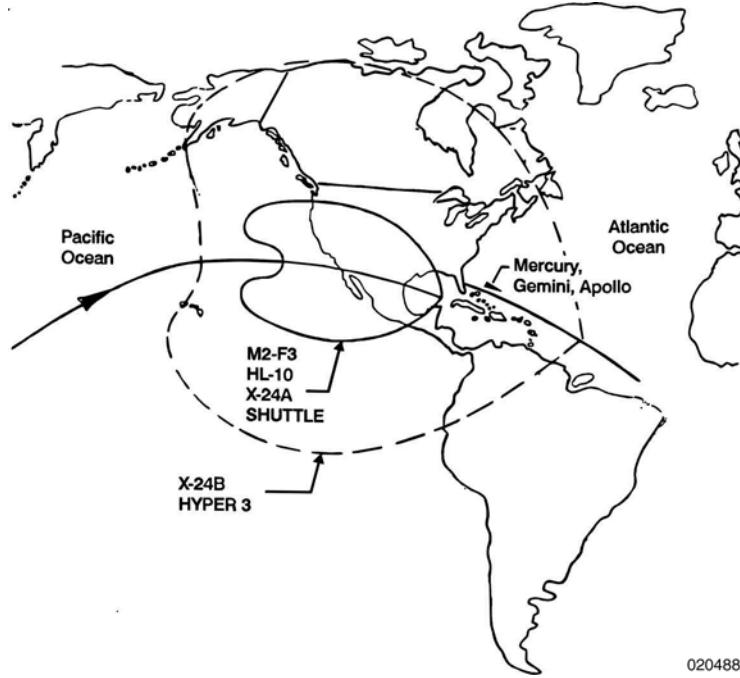
Figure 3. Footprints of various vehicles.

Figure 3 shows the footprints of various space vehicles and lifting bodies.

- **Blunt bodies** Mercury, Gemini and Apollo shown from a launch abort (east of Florida). Mercury was pure ballistic. Gemini and Apollo produced small but significant footprints by controlling the bank angle of the low L/D vector.

- **Lifting bodies** Footprints shown for lifting bodies are calculated.

- **Shuttle** Thermal problems of atmospheric reentry were solved by presenting a heat-protected underside to atmosphere at high angle of attack. Roll control was used to manage the footprint and prevent atmospheric skip. Lifting bodies were designed to use these same techniques.

The task of properly managing the total energy of the unpowered vehicle consists of directing it to a suitable landing within a predetermined area. The total energy is a function of the mass, velocity, and altitude of the vehicle—the square of the velocity (kinetic energy), the three-dimensional velocity vector (direction), and altitude (potential energy). These parameters, coupled with the lift-to-drag ratio, L/D, of the unpowered glider determine a footprint. Centrifugal and geopotential effects were considered when applicable and are discussed in Chapter 4, "The X-15 Aircraft." Second-order geodesic effects used in orbital and interplanetary trajectories were not considered.

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The Development of Energy Management

The calculation of energy management would be pure Newtonian ballistics (as in lunar landings) except for the bothersome effects of varying atmospheric properties as altitude decreases. Mach number effects on lift and drag, and speed effects on heating and skip must be factored into the equation when vectoring an unpowered craft for safe recovery.

The vehicles utilized in developing the techniques for energy management are air-launched research aircraft equipped with the Experimental Liquid Rocket (XLR) series rocket motors: the X-1, D-558-II, X-2, and X-15.

NACA/NASA and AFFTC engineers and pilots at Edwards, California, developed many of the energy management techniques for future high-energy boost-glide vehicles. These techniques included:

- Simulator flight planning.
- Appropriately configured aircraft for simulating boost-glide vehicles; e.g., the F-104A.
- Development of energy management locators called the "high key" and "low key."
- Flight crew training methods.
- A range radar-communications complex and a mission control center.
- The terminal area portion of the Shuttle reentry.
- The flight simulator and training for the lunar landing.

CHAPTER 1

FIRSTS—EARLY BOOST–GLIDE VEHICLES:
A BRIEF HISTORY OF MANNED ROCKET–PROPELLED AIRCRAFT

An abbreviated history of manned boost-glide vehicles should not neglect a chronology of first flights of the vehicles designed for rocket flight only. These vehicles advanced in successive decades from solid-rocket equipped gliders to liquid-rocket military vehicles to rocket research aircraft. Although these early flights did not produce sufficient energy to require sophisticated energy management techniques, most—including the first—did employ an energy saving technique known as *air launch*. A more detailed description of the energy saving, and other advantages of air launch is provided in Chapter 4, "The X-15 Aircraft." The enormous energy of present-day space program vehicles has evolved from these initial efforts. Some of these first flights are described below.

Prewar Era

In Germany, June 11, 1928, a rocket mounted tailless glider—the *Ente* (duck), designed by Alexander Lippisch and flown by Fredrich Stamer, was the first manned flight of an aircraft designed for rocket propulsion only. In 1929, the craft flew approximately 70 sec and traveled 4300 feet.[2,3] The solid rockets that provided the propulsion for these early aircraft were limited in both power and sustained burning. R. H. Goddard and Eugene Sänger realized the inadequacies of powder rockets in the early 1920s, but liquid-rocket engines for manned aircraft would not prove practical for some time.

War Era

From the mid-1930s to mid-1940s, the Germans, driven by military urgency, developed a series of rocket motors that were installed in various aircraft. The first military aircraft designed for rocket flight only, using liquid fuel, was the He-176, flown on June 20, 1939, followed by the first operational rocket aircraft, the Me-163B, in August of 1943.[2,3]

The first American flight of an aircraft designed for rocket flight only was not the X-1, but the MX-324 (fig. 4), a prototype of the proposed XP-79 interceptor fighter. This flying wing was designed at Wright Field, Dayton, Ohio and built by John Northrop. The aircraft was equipped with a 200-lb thrust Aerojet XCAL-200 acid-aniline liquid rocket engine. On June 22, 1944, after being towed to an altitude of approximately 8000 ft by a P-38 Lightning, the aircraft was released. After rocket ignition, the aircraft attained a maximum speed of 350 mph. The pilot, Harry Crosby, made a successful landing on Harper Dry Lake without incident.[4, 5]
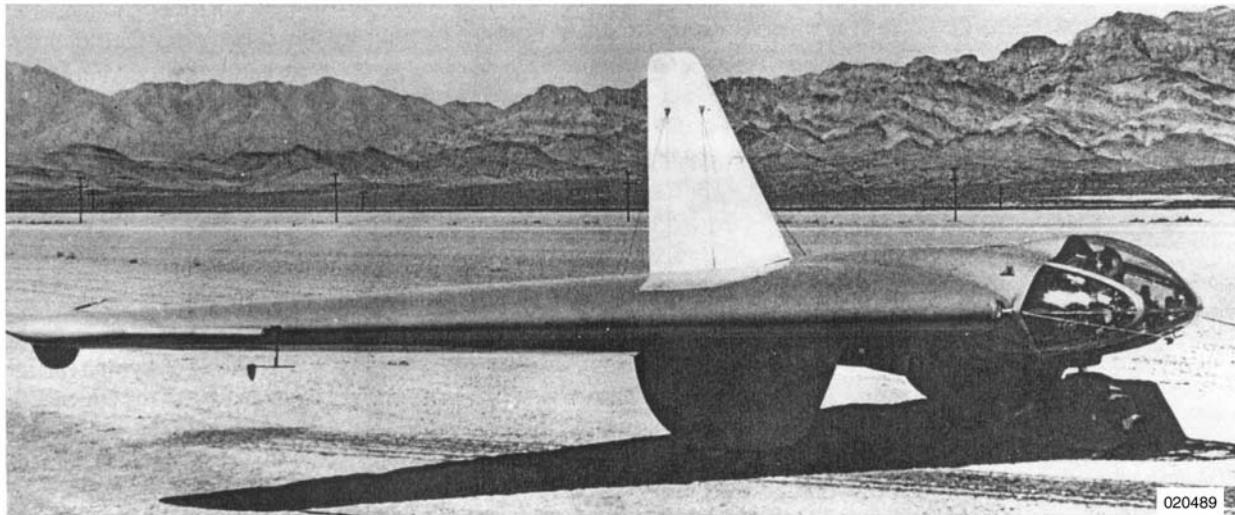
Figure 4. The first American aircraft designed for rocket only, the Northrop MX-324, preceded the Bell XS-1 by nearly two and one-half years.

The MX-324 tests were conducted at Muroc and Harper dry lakes in the California Mojave Desert. Later chapters will describe the role of these and many other similar dry lakes as emergency landing areas encompassing the X-15 High Range.

The MX-324 first flight preceded the Bell X-1 first powered flight by nearly two and one-half years. (The first powered flight of the X-1 aircraft was on December 9, 1946.) In addition to being the first American aircraft designed for rocket only, the MX-324 anticipated and utilized many of the flight test techniques of later X-series rocket research aircraft: taxi tests, air launch, glide test flights, chase planes, dry lakes, and telemetry of flight test data by radio to ground-based recorders.[3]

Postwar Era

The Germans were most prominent in advancing rocketry during the war. However, because of military restrictions applied to Germany, and the booty of "rocket scientists" appropriated by the Allies, post-World War II advances in rocketry were made in Russia and the United States. The Russians led initially in orbital space launches, while advances in rocketry for aircraft were made primarily in America.

Summary

Table 1 provides a tabular summary of the information in Chapter 1. This table includes dates, airplanes, and places where each event occurred.

Table 1. A summary of notable manned-rocket flight firsts, by decade.

Decade	Date	Aircraft	Place of Origin	Comments
1920s	June 1928	*Ente*	Germany	Solid rocket mounted glider, flown by Fredrich Stamer
1930s	June 1939	He-176	Germany	First aircraft designed for rocket-only flight
1940s	June 1944	MX-324	United States	First American manned rocket-only flight.
	October 1947	X-1		Breaks sonic barrier
1950s		X-15	United States	First manned hypersonic flight, developed boost-glide energy management, and was an innovator for Shuttle design
1960s	April 1961	Vostok 1	Russia	Yuri Gagarin. First manned orbital flight
	July 1969	Apollo11	United States	Neil Armstrong. First man on moon.
1970s	1977	Shuttle	United States	Shuttle glide flights, approach and landing tests (ALT)
1980s	1981	Shuttle	United States	First Shuttle orbital flight, STS-1.

CHAPTER 2
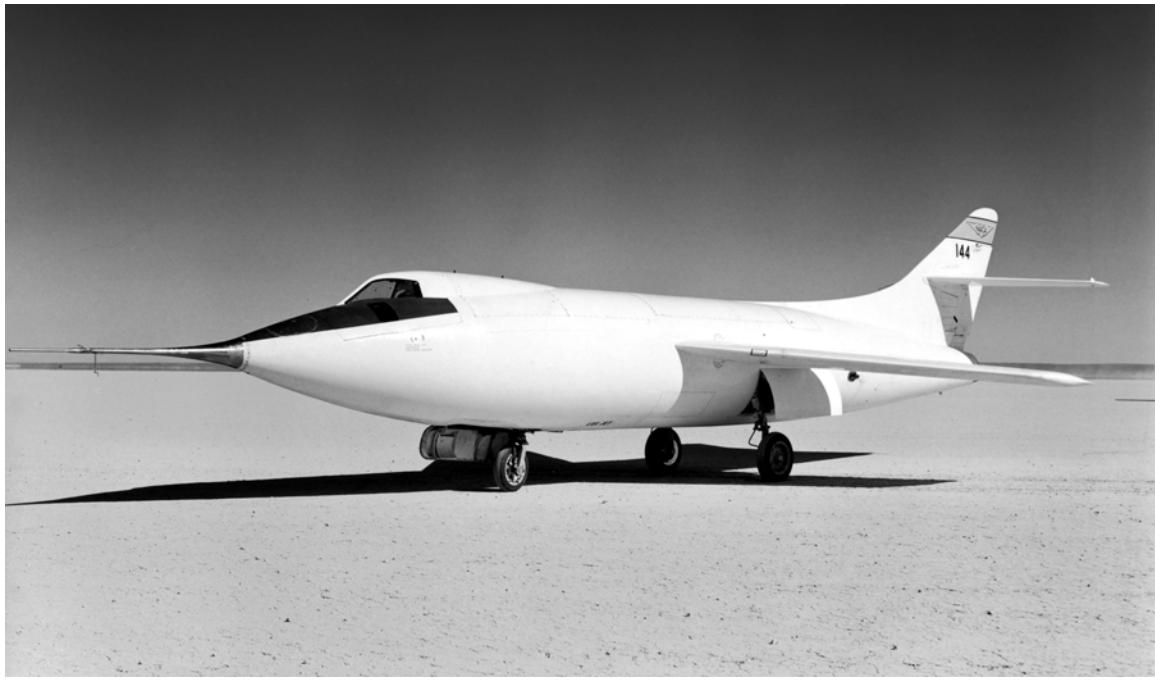
XLR–11 ROCKET POWERED AIRCRAFT

Birth of Manned Rocket Research Airplanes: 1946 to 1975

The first reliable, effective rocket engine that would provide boost for experimental research aircraft was produced by four members of the American Rocket Society (ARS) who combined forces to form Reaction Motors Incorporated (RMI) (Rockaway, New Jersey) for developing the Experimental Liquid Rocket (XLR-11) rocket motor.[3]

The XLR-11 engine had four separate rocket chambers. Each chamber provided 1500 lb of rated thrust and could be operated independently as a means of throttling thrust in quarters, up to 6000 pounds.

The XLR-11 possessed remarkable longevity, powering an impressive fleet of rocket aircraft for more than a quarter of a century (1946 to 1975). This fleet of vehicles were the first rocket aircraft devoted solely to high performance experimental flight research. They were not constrained by military or commercial demands and ranged from being the first to break the sound barrier (XS-1), to the first to reach Mach 2.0 (D-558-II [fig. 5]), to the first to exceed the X-2 Mach 3.2 record (X-15 with two XLR-11 engines).

E-1441

Figure 5. The D-558-II airplane on Rogers lakebed.

Operations and Performance of XLR-11 Powered Aircraft

Table 2 shows the beginning and ending dates of powered flights and maximum performance for each series.[6]

Table 2. Research rocket aircraft powered by XLR-11 rocket engines.

Aircraft	Powered flight, dates	Maximum speed, Mach number	Maximum altitude, ft
X-1E	12/09/46 to 11/06/58	2.24	90,440
D-558-II	01/26/51 to 12/20/56	2.0	83,235
X-15 interim engine	09/17/59 to 02/07/61	3.5	136,500
HL-10	10/23/68 to 07/17/70	1.86	90,303
X-24A	03/19/70 to 06/04/71	1.60	71,400
X-24B	11/15/73 to 09/23/75	1.75	74,100
M2-F3	11/25/70 to 12/20/72	1.61	71,500

The X-1E – Early Development of Energy Management

Design efforts to extend aircraft performance produced increased wing loadings, *W/S*, and decreased lift-to-drag ratios, L/D. These design changes were beneficial in reducing drag to achieve supersonic and hypersonic speeds, but were also detrimental in that they reduced the area of the maneuvering footprint and presented difficulties in the approach and landing.

As L/D values decreased, the glide slope angle and the rate of descent increased, making it more difficult for pilots to estimate distances and times required for acceptable landings. The X-1E (fig. 6) was modified with a low-aspect-ratio wing having a thickness-to-chord ratio of four percent—the only aircraft of the X-1/D-558 series to have sufficiently low L/D values to require unique energy management techniques. This X-1E was the first to experiment with approach patterns designed to give the pilot more time in the traffic pattern to manage energy.

Figure 7 shows a profile and plan view of a typical landing pattern for the X-1E. The landing pattern was approached in a conventional manner except that altitudes and speeds were somewhat higher than for powered aircraft. The initial reference point was established at 12,000 ft (mean sea level) on a downwind heading (180 deg remaining to turn). The downwind leg was offset some four miles from the centerline of the landing runway. On downwind, abeam the touchdown point, landing gear and partial flaps were deployed at a speed of 240 knots. Full flaps were usually deployed on the final approach. At the initial reference point the pilot had almost three minutes until touchdown—additional time for handling increased speeds and sink rates.[7,8]

Figure 6. The X-1E airplane on Rogers lakebed.
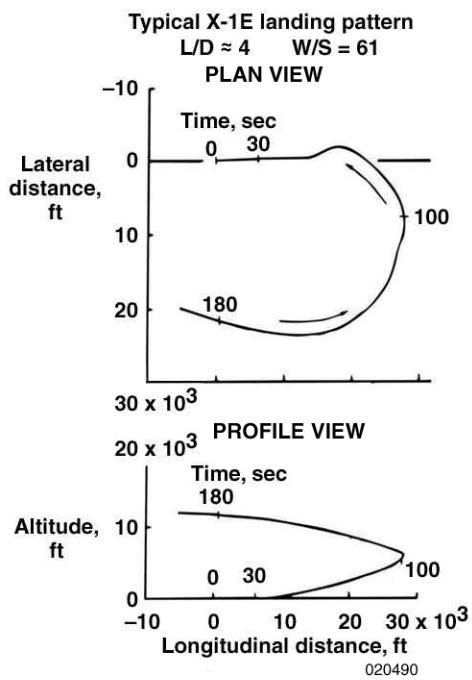
Figure 7. Typical X-1E landing pattern.

As the considerably lower wind tunnel values of X-15 L/D ratios were becoming available, HSFS engineers began analog simulation and flight test programs to determine what landing techniques would be required to satisfy these lower values. By changing configuration and thrust of an F-104A, pilots could match the L/D characteristics of the X-15 approach and landing patterns to establish *high key* and *low key* locators (discussed in Chapter 4, "The X-15 Aircraft").

Another candidate for harnessing XLR-11 power was the underpowered X-3 (fig. 8) built by Douglas Aircraft Company (Long Beach, CA). Wind tunnel and engine tests indicated that the X-3 could not reach Mach 1.0 in level flight, which indeed it did not. With interim J34 engines, the maximum speed attained in flight tests was Mach 1.21, in a dive.[6]

Other than being underpowered, the X-3 was a prime candidate for supersonic flight test. Realizing the potential loss—two years prior to delivery to the NACA—of a front line high-speed research airplane, researchers made a proposal to modify the X-3 by using thrust from two XLR-11 rocket engines and from initial conditions provided by air launch. Hand calculations indicated that the X-3 could attain Mach 4.2.[*] The Research Airplane Projects Panel (RAPP) did not consider the X-3 effort worthwhile in view of the rapidly developing F-104—that would have Mach 2.0 capabilities—and an imminent contract award for the X-15.[6]

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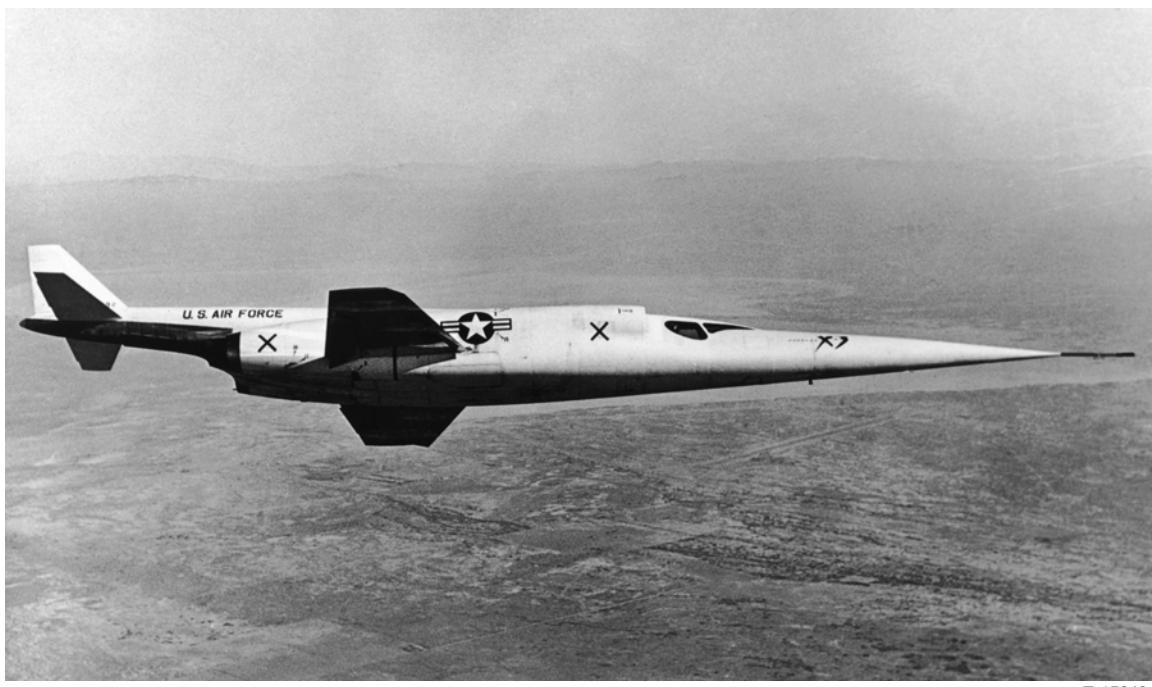
Figure 8. Photograph of the Douglas X-3 research airplane. Considered for replacement of jet engines with two XLR-11 engines for Mach 4.2 capability, 1952.

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[*]Drake, Hubert W., and Day, Richard E., *Proposed Modification of X-3 Airplane to Rocket Power and Air Launch*. Memorandum for Chief of Research, NACA High-Speed Flight Research Station, Edwards, California, October 24, 1952.

These calculations, using the archaic slide rule for graphical construction and a planimeter for integration, required many hours for solution. Personal computers today can calculate and plot the same problem in a matter of seconds with a greater degree of accuracy.

With an air launch near Rogers Dry Lake, this performance at Mach 4.2 would not have permitted a landing on the launch lakebed. At this early date, 1952, no thought was given to energy management, alternate launch sites, or interim emergency landing sites.

Between 1968 and 1975, the XLR-11 came out of hibernation to boost a new breed of odd-looking wingless vehicles that defied the name "airplane" and were consequently named "lifting bodies." During this period of time, the engine thrust had been increased by one-third.

XLR-11 Contributions to Boost-Glide Energy Management

Hundreds of flights of the XLR-11-equipped aircraft provided considerable background experience for boost-glide operations and data relevant to energy management. The X-1E established the fundamentals of landing site energy management for low L/D aircraft by originating new approach and landing techniques.

CHAPTER 3
X–2 AIRCRAFT DELINEATES A REQUIREMENT
FOR ENERGY MANAGEMENT

Each generation of rocket powered aircraft produced more propulsive energy than the preceding one. The next generation in this series of rocket research aircraft, the X-2—with approximately twice the thrust of its predecessors—became the first boost-glide vehicle to demonstrate a need for energy management.

Background of the X-2 Aircraft

The X-2 (fig. 9), built by the Bell Aircraft Corporation (Buffalo, New York), was air launched from a modified B-50 bomber (fig. 10). After rocket burnout, it glided unpowered on an extendible skid landing gear to a landing on the hard playa surface at Rogers Dry Lake. The airplane was powered by the XLR-25 twin-chamber rocket engine. Built by the Curtiss-Wright Aircraft Corporation (Caldwell, New Jersey), the chambers provided 10,000 and 5,000 lb of thrust respectively. Propellants provided an expected burn time of approximately 140 seconds. During the period of August 1954 to September 1956, the X-2 made 4 glide flights and 13 powered flights, all landing within the bounds of Rogers Dry Lake except for the last powered flight.[9,10]

E-2817

Figure 9. Photograph of the X-2 rocket research airplane.

Figure 10. Air launch of X-2 rocket research airplane.

Operations

Energy management for the X-2 was based on experience gained from all preceding launch-to-landing rocket flights. The air launch had to be located in the vicinity of Rogers Dry Lake, such that the aircraft could land near the shoreline of Rosamond Dry Lake in the event of rocket ignition failure. On the other hand, the landing site must take into account a successful rocket burn of expected maximum duration that would position the X-2 far downrange. Therefore, the energy management footprint must cover the landing areas of the dry lakebed at all times. These logistics were a prime factor in driving the X-2 into a veritable trap on powered flight 13, demonstrating a requirement for precision energy management.

The Air Force Flight Test Center conducted the flight demonstration program for the X-2 at Edwards AFB with the NACA HSFS providing data recording instrumentation, radar tracking, and engineering support. Powered flights began in November 1955.

As the flight test program proceeded, the X-2 reached increased speeds and covered a more expansive range. Lt. Col. Frank Everest attained a Mach number of 2.87 on powered flight 9 and was able to land on

the lakebed. As shall be described below, Mach 3 appeared to be the X-2 speed limit for remaining within the bounds of the dry lake.

At this point in time, Everest was reassigned and Captain Milburn Apt was designated the X-2 pilot. On September 27, 1956, the X-2 established a world speed record of Mach 3.2 (2118 mph) but, after rocket burnout, became the victim of three distinct, but separate, instabilities, each leading directly into the next, culminating in the loss of the airplane and pilot.[10]

In the previous year (1955), the Air Force had obtained a Goodyear Electronic Differential Analyzer (GEDA) analog computer. NACA engineers provided the equations, controls, and displays to develop the X-2 simulator using this computer. NACA engineers also provided X-2 simulator operations and pilot training and briefing. The simulator did not have sufficient equipment to compute the performance, trajectory, or range in the three degrees of longitudinal freedom; consequently the simulations were confined to the simpler five degrees of lateral-directional freedom, enabling the pilots to assess the handling qualities of the aircraft at a fixed (simulator) altitude and speed. The sixth degree of freedom determines the velocity vector, altitude, and total range capability required for monitoring and managing the energy. Real-time, six-degree-of-freedom analog simulation would not be available until the time when the X-15 made its appearance.

The X-2 pilots made many runs on the simulator to investigate unsafe flight conditions. They were taught how to recover from control instability if motions were beginning to diverge, by executing a pushover to lower the angle of attack. Prior to each high-speed flight the pilots were instructed to maintain a low angle of attack after burnout until slowing to Mach 2.4, at which speed it was safe to increase angle of attack for turns. On his record-breaking flight, Everest decelerated from Mach 2.87 to Mach 2.2 before entering a turn (increasing angle of attack) to return to Rogers Dry Lake. Everest, however, was not painted into a corner, as Apt would be.

Scenario of the Final Flight

Apt had "flown" the simulator and received briefings on July 29, 1956, plus several non-logged informal simulator sessions between that date and September 24 of the same year, to prepare for the 13th powered flight. On September 27, 1956, the mother ship, with the X-2 attached, climbed to 30,000 ft and, on Apt's command, launched the X-2. He flew a flawless maximum-performance trajectory, and the rocket burned longer than expected in reaching propellant depletion. This unexpected increase in performance, which propelled the aircraft to Mach 3.2, positioned the X-2 further from the landing site (Rogers Dry Lake) than planned, placing the airplane at a possible point of no return. At this point, Apt was literally painted into a corner. He had to decide whether to decelerate to Mach 2.4, as briefed, and then make a safe turn, thus increasing the distance even further from the landing site, or try to make the turn immediately and risk the instabilities that had been predicted and "flown" on the simulator.

The simulator was a new device that had never been used previously for training or flight planning. Most pilots had, in fact, expressed a certain amount of distrust of it. Whether distrust of the simulator or a fear of not making it back to the landing site affected Apt's decision, he opted for the turn. His radio message was, "O.K. She's cut out. I'm turning." There was an ominous silence of 20 sec before Apt uttered an almost unintelligible, " -- she goes!"

Postflight records indicated that the X-2 remained stable up to a Mach number of 3.2 while at low angles of attack. After rocket burnout, Apt attempted a bank for return to the dry lake, increasing angle of

attack and thus decreasing directional stability, sending the aircraft into roll inertial coupling and wildly divergent motions. Shortly after these divergences, the pilot made two recovery attempts, then pulled the "T" handle initiating cockpit separation. After separation, the radar operator indicated that the radar image was in two parts, one larger than the other. Ground control instructed him to follow the smaller image (the capsule). The stabilization parachute that deployed did not slow the capsule sufficiently to provide time for escape from the cockpit. The pilot jettisoned the cockpit canopy but could not escape from the capsule in time to use his personal parachute and died on impact.

After the location of the crash site was reported by the B-50 pilot, the oscillograph data recorders were salvaged and developed. When the film was unrolled to view, it was déjà-vu. The film traces looked exactly like the strip recorder traces of simulator runs and, in particular, the training runs made prior to the flight. It was immediately apparent what the events were, how they happened, and why they happened.[10]

A proposal was made to salvage the X-2—which was relatively intact—and modify it to a hypersonic configuration.[7] The X-15, however, designed to achieve hypersonic speeds, was waiting in the wings. The X-2 was not approved for the modification, making Apt's tragic flight the last in the program.

Extended Range Requirements

The vast area of Rogers Dry Lake was no longer capable of encompassing the range requirements for the emerging generation of high-energy boost-glide vehicles. At this point in time, late 1956, there were sufficient X-15 data from wind tunnel and engine tests to predict X-15 performance and future range requirements. As a result, a contract was awarded to initiate Project High Range, an instrumented flight corridor for monitoring the X-15 flights from distant remote launch sites to the NACA site at Rogers Dry Lake (see Chapter 5, "Project High Range").

CHAPTER 4

THE X–15 AIRCRAFT

Foundations for Space Operations

Background

The X-1 series rocket aircraft with landing configuration L/Ds as low as 4.0 were the forerunners in establishing the necessity for key locations and new landing techniques. All were air launched in the vicinity of, and landed on, Rogers Dry Lake, precluding the need for an extended range and alternate emergency landing sites.

The X-2 demonstrated that energy management must consist not only of guidance after burnout but also performance calculations that predetermine the total energy vector of the vehicle at all times, from launch to landing. If there had been X-2 performance calculations to determine range, speed, and altitude, it would no doubt have altered the flight planning and outcome of the final, fatal flight.

The demise of the X-2 prevented the NACA from obtaining anticipated quantitative high supersonic heating data. Postflight examination at the crash scene indicated that although the aircraft had sustained a period of 15 sec above Mach 3, the stainless steel skin had not suffered from aerodynamic heating. This finding indicated that the time had come to expand the experimental research program into the hypersonic speed regime (speeds exceeding Mach 5.0). The need for such expansion had been recognized some years earlier. In 1952, the NACA Committee on Aeronautics urged that the NACA study requirements for piloted hypersonic aircraft. From this study, "Project 1226," the X-15 emerged. On September 30, 1955, the Air Force informed North American Aviation (NAA), Inc. (Los Angeles, California), that it had won the X-15 contract.[6] In February 1956, the company that developed the XLR-11 rocket motors, Reaction Motors, Inc., was given a contract to develop the XLR-99 rocket engine (more on XLR-99 later). By September 1956, enough wind tunnel and structural data had been collected to allow construction of the first X-15 to be started.

The X-15 program was a joint effort of the NACA/NASA and the military. NACA/NASA provided conceptual design, technical direction, instrumentation, and flight operations. The U.S. Air Force and the U.S. Navy provided funding. The USAF provided and operated the launch aircraft. Each of these partners furnished X-15 pilots.

XLR-11 Interim Engine Operations

Several delays in development of the XLR-99 rocket engine presented a potentially prolonged delay in the program. As a result, aircraft numbers 1 and 2 were each equipped with two XLR-11 engines for interim flight operations. The first X-15 arrived at NASA in October 1958. The first flight powered by the alternative XLR-11 engines was delayed almost a year, and the first flight equipped with the XLR-99 engines was delayed more than two years. Flight planning for these operational programs was intermingled; however, the X-15 simulator had the capability of switching from one propulsion system to the other.

Locally launched early flights with the XLR-11 engines (fig. 11) held maximum speeds below Mach 3.0 and required no footprint. Later flights exceeding Mach 3.0 were remote launches from Silver Lake.

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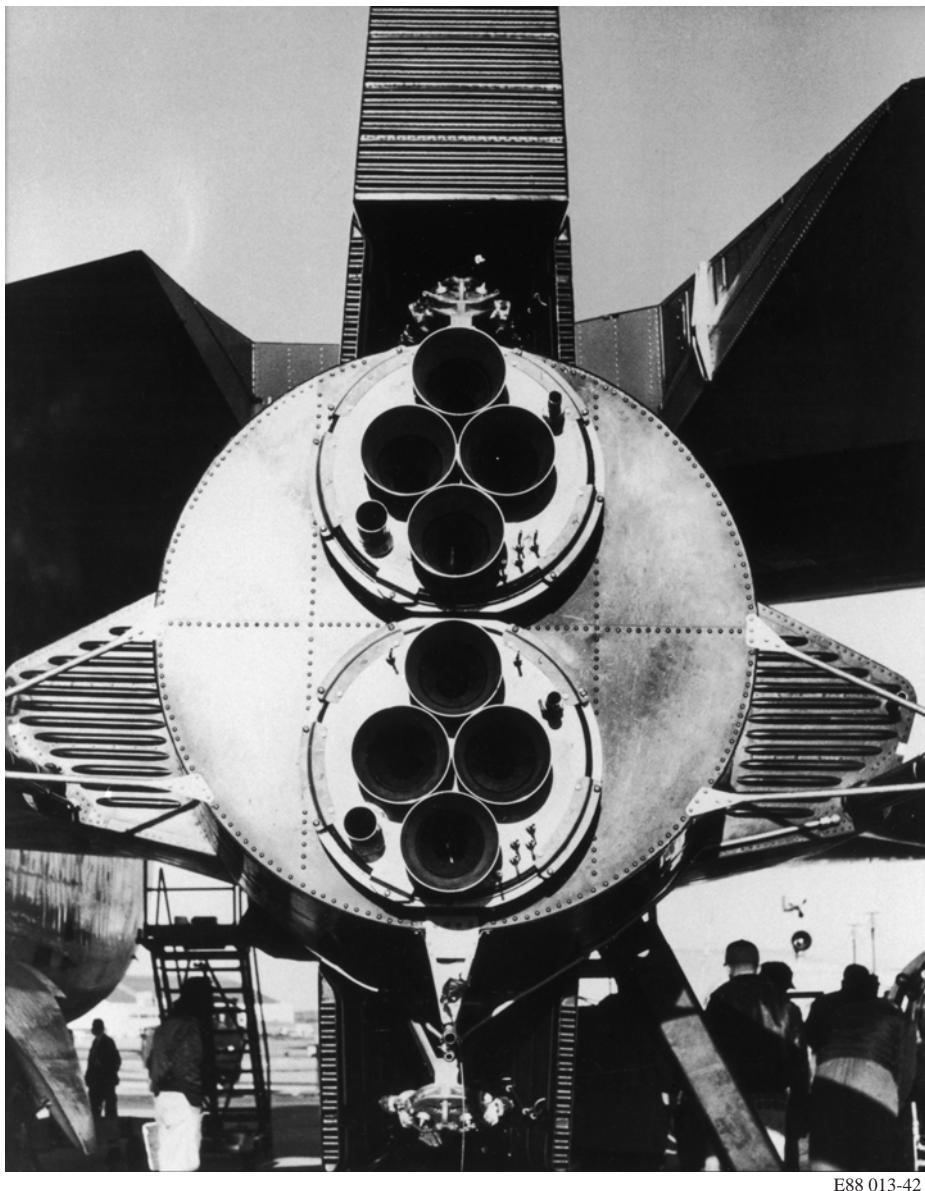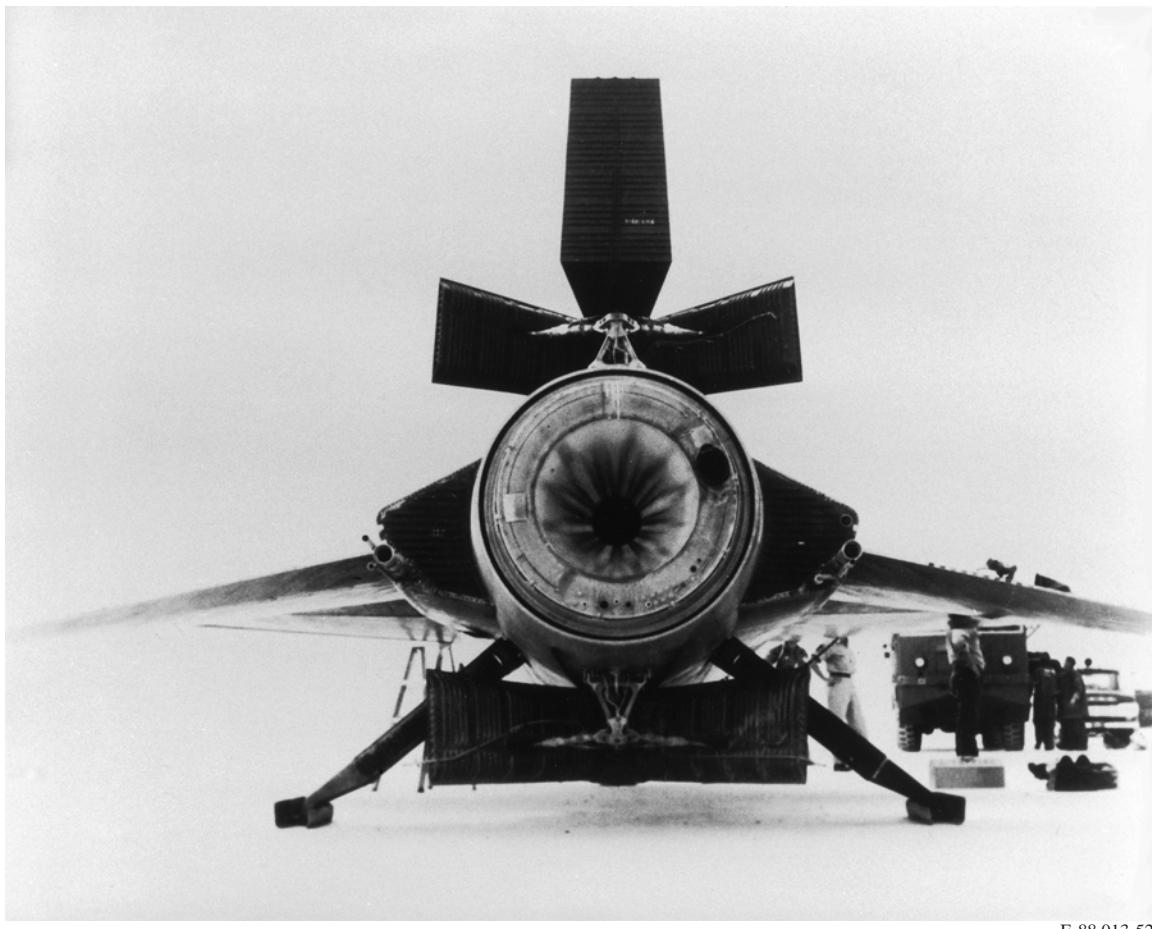
Figure 11. The X-15 aircraft equipped with dual XLR-11 engines for interim operations prior to installation of XLR-99 engine.

The XLR-99 Engine

When the XLR-99 engine (fig. 12) finally became operational, the contractor made three acceptance flights. Each was planned on the simulator and was designed to keep speed below Mach 3.

The XLR-99 engine, with maximum rated sea-level thrust of 50,000 lb, was capable of restart and was throttleable from full thrust to half thrust. The XLR-11 engine thrust could only be varied in increments by cutting or restarting one or more of its four chambers. Table 3 lists a comparison of the configuration and thrust capabilities of three of the XLR series engines and the aircraft they powered.[11]

Figure 12. Rear view of the X-15 aircraft with the XLR-99 engine. Also shown are the upper and lower speed brakes fully extended, the wedge shaped upper rudder and the landing skids.

Table 3. Comparative sea-level thrust of three XLR rocket engines.

Engine	Aircraft	Configuration	Total rated thrust, lbf
XLR-11	X-1	4 chambers, 1,500 lbf each	6,000
XLR-25	X-2	2 chambers, 5,000 and 10,000 lbf	15,000
XLR-99	X-15	Single chamber	50,000

The X-15 Six-Degree-of-Freedom Simulator

Advancing technology vastly increased the performance of the X-15 over that of previous boost-glide vehicles. Fortunately, technology also increased the capabilities of the primary flight test analytical tool, the simulator (figs. 13 (a) and (b)). Earlier five-degree-of-freedom simulators could provide only stability and control analyses at fixed speeds and altitudes. The X-15 six-degree-of-freedom analog simulator had the capability of calculating and plotting the velocity vector, altitude, and total range, providing the tools for energy management studies. These studies revealed a quantum leap of energy management requirements, from remote launches through intermediate energy conditions, to landing.
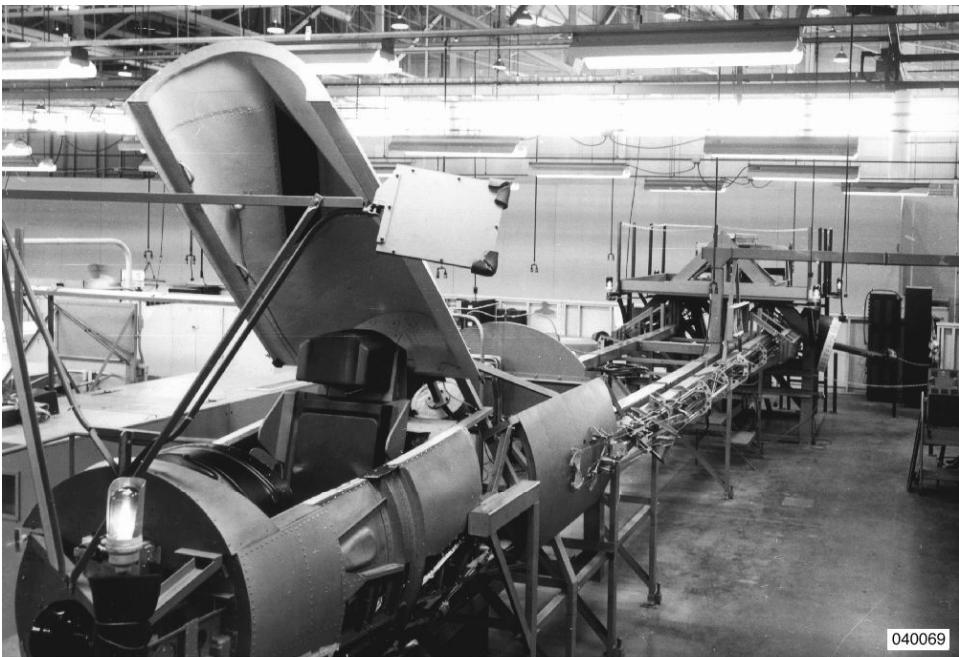
The X-15 program was the first to use the simulator for studying and planning the expansion of the flight envelope, for individual flight planning, and especially for the energy management analysis and operations. Milton Thompson, an X-15 pilot, and later the NASA Dryden Chief Engineer, stated: "I personally do not believe we could have successfully flown the aircraft without a simulation, particularly in regard to managing energy."[11]

Long before X-15 simulator operations at NASA Dryden, the X-15 simulator was built at the NAA facility on the south side of the Los Angeles airport. The simulator was fabricated for design and test of hardware and software, primarily for the dynamics of the control system.
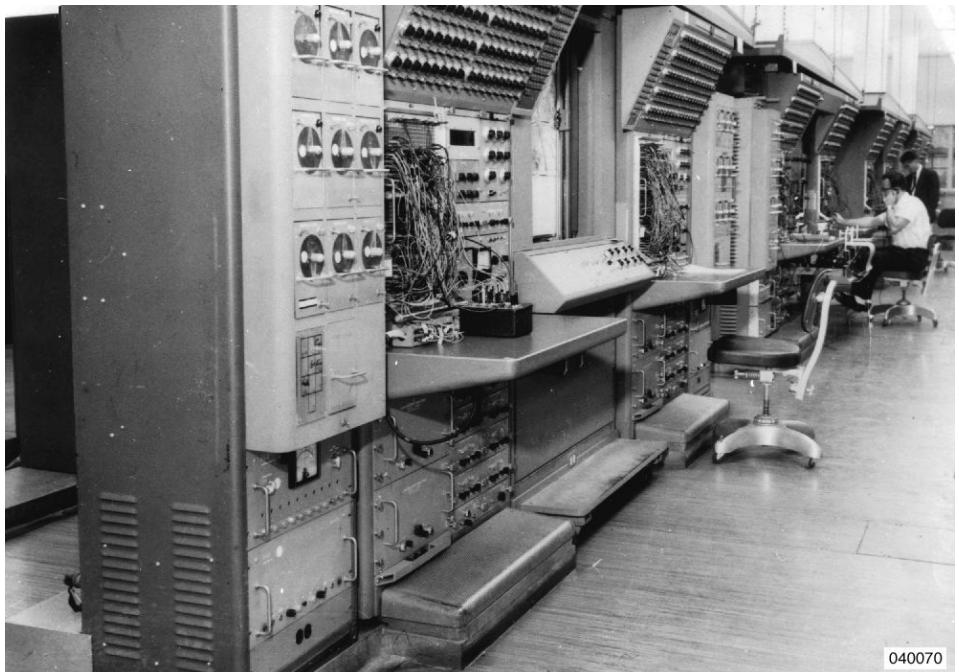
The simulator complex consisted of the following for computing and recording the three translational and three rotational degrees of freedom aircraft motions in real time:

- Operational amplifiers, function generators, servomechanisms and electronic multipliers for computing trigonometric and algebraic terms.

- Cockpit controls, display panel, and integrated control system hardware test bed.

- Several multichannel strip chart recorders.

- A large, vertical x-y recorder for plotting longitudinal and lateral ground distances to determine geographical locations, as well as altitude versus range.

- Smaller horizontal x-y recorders used for various plots and as input devices for aerodynamic derivative matching.

- The capability to switch from simulated XLR-11 to XLR-99 engine operations.

- A malfunction generator for generating major systems failures.

Prior to the simulator moving to the NASA Dryden facility in 1960, NACA and NASA engineers were allowed simulator time for early flight planning. During this period of time, envelope expansion studies, the ventral removal study (removal of the lower rudder to improve lateral-directional stability and control), and early energy management studies were done.

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(a) Cockpit controls, display panel, and integrated control system hardware test bed.

(b) Electronic analog calculating and recording equipment.

Figure 13. The NAA X-15 six-degree-of-freedom simulator.

Simulator Flight Planning for the X-15 Aircraft

Simulator flight planning was a rather lengthy process for the X-15 aircraft, with energy management consuming a disproportionate amount of the time but paying benefits as the operational program progressed.

The time consumed for various phases of planning and operations evolved as follows:

- *Months*   Envelope-expansion. Using wind tunnel values of aerodynamic characteristics and manufacturers values of physical characteristics, simulator flights were conducted in increments of altitude, Mach number, dynamic pressure, angle of attack, and acceleration loads. Maneuvers were performed at each level to evaluate limits. Results of the envelope expansion study were presented to the NACA HSFS director and staff for approval and eventually at a Wright Field conference. Energy management was not considered during this phase.

- *Weeks-Days*   Flight planning prior to each flight. Flight planners distributed a memorandum of the proposed flight to the Flight Operations Directorate and to the branches of Research Engineering requesting engineering inputs for data maneuvers at various flight conditions. Flight planners, who were usually ex-military or civil pilots, then converted the requests into maneuvers and a timeline for the flight. All conceivable emergency situations were considered. Energy management was folded into these simulations. Pilots often participated in this flight planning phase.

- *Days-Hours*   Pilot training. Since the pilots had other flying commitments, they could not participate in the full flight planning sessions. Pilots would "fly" the timelines, performing the required maneuvers time and again until they had memorized the entire flight including emergency situations and energy management profiles. Nominally, the pilot would spend 40 to 50 hours distilling all this information into a 10-minute flight.[11,12] After each flight, new values of the aircraft's characteristics, obtained from flight data maneuvers, replaced the wind tunnel and theoretical values in the simulator.

The above requirements and capabilities of the X-15 simulator and its history, including many anecdotes concerning the simulator and simulator operations, are described in reference 12. This book is an excellent history of all the aircraft and space simulators used by the FRC from the X-2 to the Lunar Landing Research Vehicle (LLRV) and lifting bodies.

Geocentric Effects

Note the additional effects influencing the design of energy management—the accelerations produced by extreme radial velocities and altitudes.

Definitions of Terms

Geocentric	Measured as from the center of the Earth
Geodetic	Distance in which the curvature of the Earth is taken into consideration
Geometric altitude	Actual altitude (h) above surface of the Earth
Geopotential energy	Potential energy at h, above the Earth
Geosynchronous orbit (Geostationary orbit)	A satellite's angular velocity equals the Earth's angular velocity in the equatorial plane and the satellite appears to be stationary from Earth.

Centrifugal acceleration is a function of the vehicle's velocity and altitude and is determined by the equation $a_c = V^2 / (R + h)$, where a_c is the centrifugal acceleration, V is the vehicle's velocity normal to the geocentric radius, $(R + h)$. R is the Earth's radius and h is the vehicle's geometric altitude (fig. 14).

Geopotential acceleration decreases as the inverse square of the geopotential radius and is determined by the equation $a_g = g \, [R / (R + h)]^2$ where a_g is geopotential acceleration, g is the acceleration of the Earth's gravity at sea level.

Considering geopotential as positive and centrifugal as negative effects, one can calculate an altitude for which there is a velocity that will produce zero acceleration (microgravity), or as it is sometime referred to, "zero g," for orbiting satellites or vehicles.
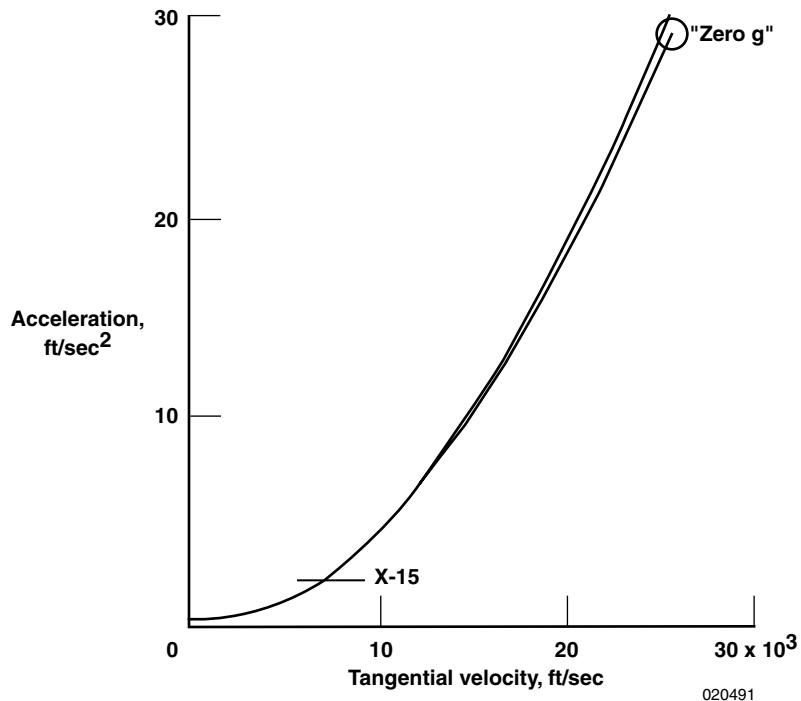
Figure 14. Centrifugal acceleration as a function of tangential velocity.

The tick on the curve labeled "X-15" in figure 14 shows the rather low incremental acceleration produced by the X-15 at maximum performance. The circle symbol located on the right curve indicates the velocity required (25,405 ft/sec) to produce "zero g" at an altitude of 1 million feet.

The curves of figure 14 show centrifugal acceleration calculations for two altitudes. The curve on the left is for zero altitude (h). The curve on the right is for one million ft, indicating the very small decrease in centrifugal effect with lower altitudes. There is also little effective decrease in geopotential acceleration with altitudes up to one million ft—a nominal orbiting altitude. Considering the radius of the Earth to be 21 million ft, the geopotential acceleration at 1 million ft altitude (h) is $(21/22)^2 g = 0.91 g$, a loss of only about 10 percent. The effect becomes more prominent with increasing orbital altitudes such as geosynchronous orbit.

Lift to Drag Ratio Spectrum

Because the X-15 was the first boost-glide aircraft with abnormally low L/Ds and sufficient energy to require an instrumented range and remote emergency landing sites, it might be advisable at this juncture to examine the spectrum of L/Ds of all types of air and space vehicles to review their glide characteristics as a function of L/D.

Figure 15 shows the glide angle (γ) as a function of L/D for stabilized glide angles (no centrifugal or geopotential effects). The glide angle is determined from the first order equation: $\tan \gamma = 1/(L/D)$. Labels for various types of vehicles show that the spectrum of L/Ds extends roughly from zero for ballistic bodies to impressively high values for clean, high-aspect-ratio gliders and sailplanes.
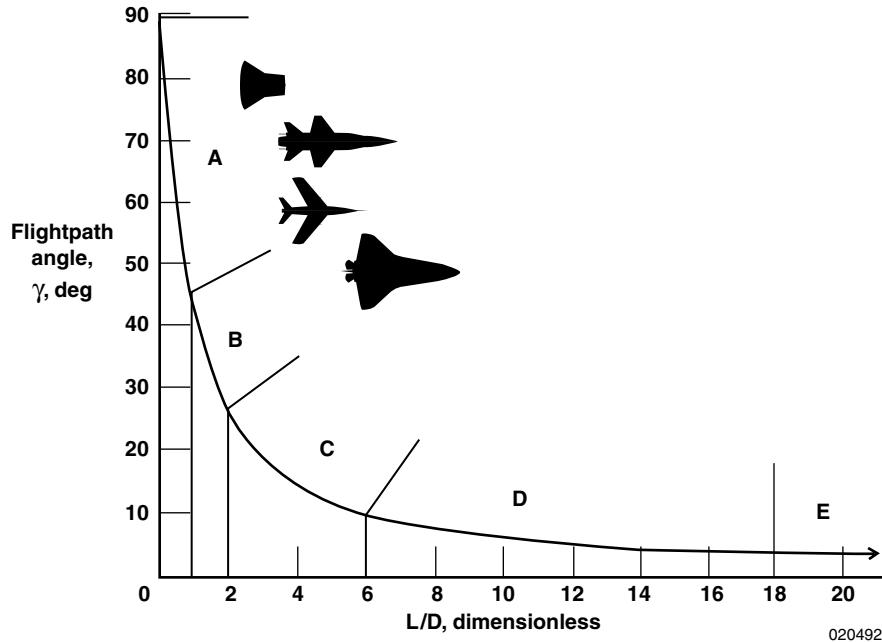
Figure 15. Lift-to-drag ratio spectrum of air and space vehicles. Flightpath angle, γ, plotted as a function of L/D for stabilized glide angles.

The labeled portions of the curve indicate the range of L/Ds and their various characteristics, from plummeting to soaring, for various types of air and space vehicles.

Lift-to-drag ratio

- A – (0-1) Ballistic and semi-ballistic: Mercury, L/D = 0; Rolling entry for Gemini and Apollo to control footprint; Shuttle during stabilized portion of 40-deg α reentry

- B – (1-2) X-15, hypersonic and reentry[13]

- C – (2-6) Covering the knee of the curve; landing configuration L/Ds for XLR-11-equipped vehicles, X-2, X-15, and Shuttle

- D – (6-18) Commercial, civil, and military

- E – (18-40+) Gliders and sailplanes

A, B, and C are primarily the boost-glide vehicles that require customized range and energy management facilities.

Development of Low Lift-to-Drag Ratio Operational Techniques and Position Locators

Ground Simulations

During the design phase and wind tunnel tests of the X-15, it became apparent that a lower than normal lift-to-drag ratio, L/D, and a higher than normal wing loading, *W/S*, would present the pilot with a more difficult approach, flare, and landing. As stated previously, L/D determines the glide angle; the lower the ratio, the steeper the glide angle. A higher wing loading, *W/S*, increases the speed of the descent. This combination, in addition to high energy remote launches, affects many aspects of controlling the unpowered glide to a successful landing.

- **Ranging**   Lesser ranging capabilities means smaller footprints.

- **Location**   Necessitates locators; such as *high key* and *low key.*

- **Margins**   Simulator flight planning is required to avoid "undershoot" or "overshoot" of the high key location.

- **Timing**   A steeper glide angle and increased vertical velocity provide less time for judging the final approach, flare, and landing distances.

The X-15 Aircraft High Key and Low Key Locators

Because the X-15 L/Ds were considerably lower than those for the X-1E and launches were from remote sites, a more rigorous definition of the terminal area key locators was required. In addition, locations such as high key and low key are so interdependent that it is difficult to discuss one without reference to the other.

The bothersome effects of decreasing values of L/D were beginning to plague test pilots of advanced fighter jets. While making flameout approaches and landings, in low L/D configurations, pilots were having some difficulty in judging vertical velocities and distances, resulting in some damage to the aircraft. Knowing that the X-15 would have even lower L/Ds, High-Speed Flight Station engineers initiated a series of studies on analog simulators and on jet aircraft configured to match the L/D of the X-15 in the landing configuration.

High key

High key is the location (altitude, airspeed, and heading) at the end of the boost-glide where a spiral turn is initiated over the intended touchdown point. This locator is at a sufficiently high altitude to prevent overshoots and undershoots and to establish adequate time and distance required for low key tasks.

Low key

Low key is that point in the descent from high key, opposite the intended touchdown point, where the final turn is initiated. In the final turn, position and speed are established for the approach, flare, and landing.

These key locations and conditions are a function of L/D and are tailored to a particular aircraft and its energy and distance from landing at burnout. For example, the aircraft with the lowest L/D of the X-1 series, the X-1E, was launched and landed locally. It did not establish a key locator. The high and low key altitudes of the X-15 were increased as the energy and launch distances of the flights increased. These incremental requirements of energy management are discussed later.

Facing the fact that the X-15 would be operational in the near future, the NACA HSFS engineers and pilots began laying plans for circumventing the energy management obstacles. During the period between mid-1955 and the start of X-15 operations in mid-1959, there were enormous amounts of ground simulator studies and flight research regarding low L/D energy management flight techniques. These efforts established footprints from remote launch sites as well as high key and low key space locations. The footprints and key locators provided a potential energy marker to prevent overshoots and undershoots, thus permitting wider latitude for judgment of time and distance in the landing pattern. The in-flight simulations were accomplished by modulating the L/D of such aircraft as the F-104A, by extending gear, and by varying flaps and speed brakes at reduced throttle settings.

Early Analog Simulations

During the period of time spent at the manufacturer's facility prior to X-15 operations, NACA/NASA engineers conducted envelope expansion studies on the X-15 simulator. Before many simulated high-energy flights took place, it became obvious that overshoots and undershoots of the intended landing site would be common unless energy management became an integral part of flight planning.

If low on energy, the pilot of a powered aircraft can apply throttle. After burnout, the pilot of the X-15 had no power, so he maintained the (preplanned) excess energy by flying at the airspeed for maximum L/D and using speed brakes to bleed off excess energy as necessary. Consequently, during simulations, flight planners made sure that at burnout the X-15 had energy in excess of that required to return to high key at Rogers Dry Lake. When deflected, the speed brakes exposed considerable area to the airstream and were quite effective as decelerators (essentially reverse thrusters). The upper and lower extended segments of the X-15 speed brakes are shown in figure 12.

Studies Prior to First Flight of the X-15 Aircraft—Analog and Flight Simulations

The envelope of L/D as a function of lift coefficient (landing configuration) for boost-glide vehicles preceding the X-15 is shown in the shaded area of figure 16. The envelope shows flight test data of L/D ratios for the landing configuration, the highest L/D of approximately 6.0 for the X-2 and the lowest of approximately 4.0 for the X-1E. The figure also shows 1958 wind tunnel values of the L/D range for the clean (solid line) and landing configuration (dashed line) of the X-15 with landing L/Ds of approximately one-half those of its predecessors.

Because the X-15 would have considerably lower L/Ds and higher wing loadings (W/S) than the X-1E (see figure 7), it would undoubtedly need to establish its own key positions and perhaps new or refined landing pattern techniques. Fortunately there was an operational aircraft in the FRC stable capable of closely approximating the X-15 low-speed performance characteristics. The Lockheed F-104A (fig. 17) had many of the attributes for closely matching these requirements. Figure 18 shows the nearly identical X-15 wind tunnel values compared to F-104A flight values of L/Ds as a function of lift coefficient, C_L.
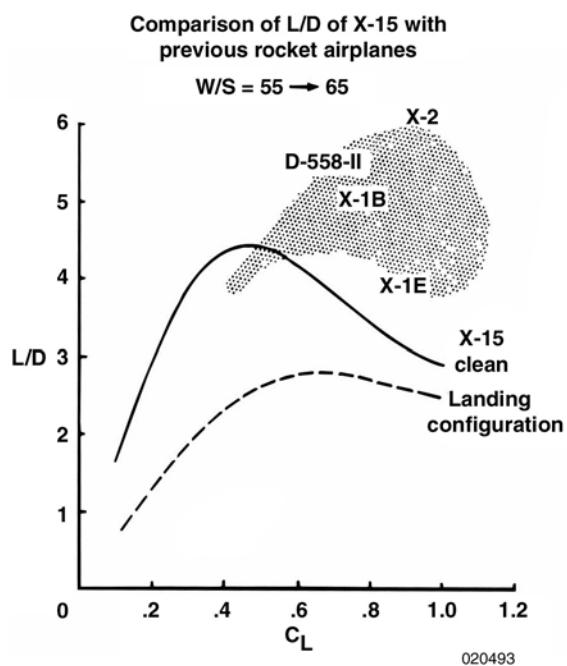
Figure 16. Flight test data of L/D as a function of lift coefficient (landing configuration) for boost-glide vehicles preceding the X-15 aircraft and wind tunnel data for the X-15.

Figure 17. An F-104A airplane on the lakebed. Flight simulator for X-15 landing patterns.

**Comparison of L/D obtained in
F-104A landing tests with X-15**
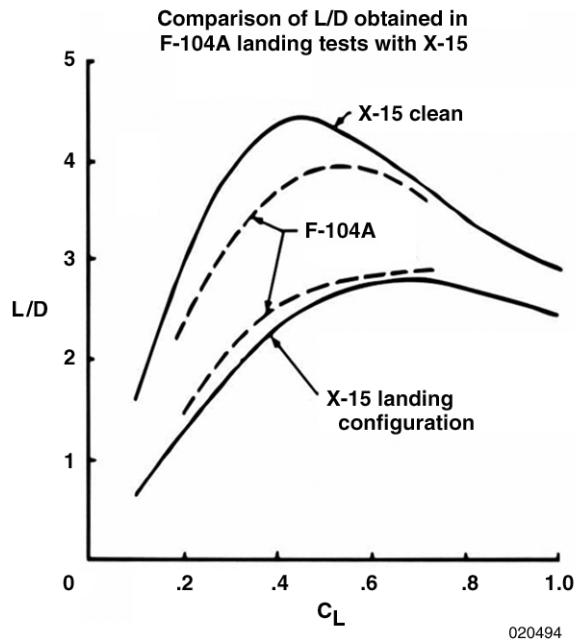
Figure 18. The X-15 wind tunnel values compared to F-104A flight values of L/Ds as a function of lift coefficient in the landing configuration.

Many F-104A flights were made to select the best locators and flight pattern for future X-15 operations. Figure 19 illustrates a typical landing flight pattern of the F-104A with L/D and wing loading (*W/S*) closely approximating that of the X-15. Comparing this figure with figure 7 of Chapter 2 indicates that with a L/D of approximately one-half that of the X-1E, the high key for the X-15 aircraft (20,000 ft) is nearly double that of the X-1E from 12,000 to 21,000 feet.

Figure 19 shows a typical high key approach starting at 21,000 ft and an indicated airspeed of approximately 275 knots on a 270-deg heading from the intended runway—vertical velocities of 300 to 400 ft/sec were encountered on the turn to the base leg. The final approach was started at an altitude of 2500 ft, where sink rate was reduced to less than 200 ft/second. By increasing normal acceleration at approximately 500 ft, the pilot reduced the sink rate to below 100 ft/sec at 275 knots. Vertical velocity was progressively decreased to about 5 ft/sec at 20 ft above the ground, at an air speed of 235 knots. Excess speed at this point permitted the pilot 8 seconds to touchdown at a speed of 185 knots.

Various approach headings were flown, but a 270-deg heading above the touchdown point was usually preferred for initial orientation prior to turning.[14] During these flight tests, analog simulations were run concurrently to assist in the analysis.
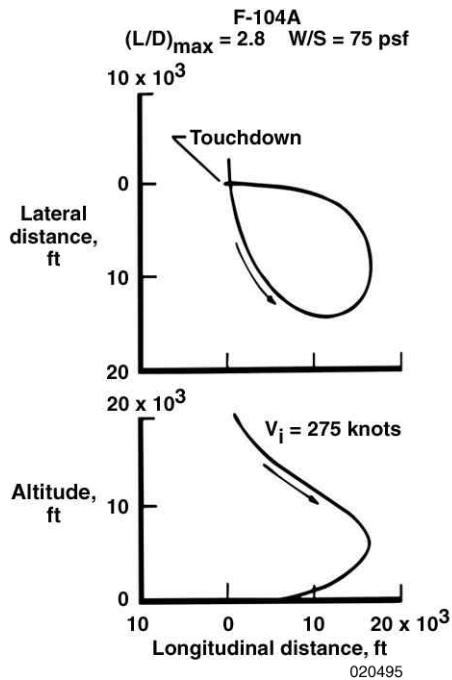
Figure 19. Typical high key approach with the F-104A aircraft configured to match wind tunnel values of the X-15 aircraft.

- **An alternate approach** During this period of time, an alternate method of accomplishing low L/D approaches was demonstrated at Ames Research Center (Moffett Field, California), also using an F-104A airplane. The method was designed to simplify landing patterns and techniques by omitting high key above the touchdown point and instead making a straight-in approach. The Ames method was accomplished in three phases. *Phase I* started with a constant-attitude, high-speed dive from a specific altitude aimed at a precise point short of the approach runway. During *Phase II* a constant *g* pullout was made from a specified altitude and speed, flaring to a shallow flight path angle. *Phase III* consisted of a deceleration to a touchdown point.[15] This method resulted in precise and controllable landings but left a somewhat ambiguous high and low key that did not account for remote high-energy launch overshoots and undershoots.

At a later period in X-15 operations—discussed later in this chapter—an acceptable composite method was adopted for the final approach after performing a circular pattern from high key over the touchdown point.[11]

The F-104A proved to be an excellent flight simulator for establishing X-15 high key, low key, approach, flare, and landing procedures. These tests were more definitive than those of the X-1E in establishing landing performance requirements. The F-104A was also quite prolific in producing data, having the capability of making frequent flights and several landing patterns in a single flight. The F-104A not only served as a simulator to determine future energy management parameters and techniques for high-energy boost-glide vehicles; it also served as a flight simulator to hone a pilot's experience prior to each X-15 flight—at Edwards and at remote emergency sites. In addition to all the above, an especially modified F-104 also served as a Reaction Control System (RCS) trainer for flight control in the tenuous atmosphere of X-15 high altitude flights and later space vehicle flights.[16]

- **Centrifuge Program** An X-15 simulation was run in six degrees of freedom at The Naval Air Development Center, Johnsville, Pennsylvania. The centrifuge as such, did not contribute to energy management studies but did, inadvertently, demonstrate the effect of extreme deceleration in atmospheric reentry. During a simulated reentry from the maximum design altitude, Captain Robert White (USAF X-15 pilot) forgot to lower the head bumper (an extendible block to restrain forward motion of the pilot's helmet). At four longitudinal and seven normal *g*s, the pilot was experiencing eight *g*s at a downward angle of 55 degrees. His head slumped forward. The "dead man" switch release stopped the centrifuge motion.

The kinesthetic reaction of extreme energy from atmospheric deceleration, as opposed to maximum boost phase longitudinal acceleration of 4 *g*s, was so obviously demonstrated that the head bumper was used on many of the high-energy flights.

Early X-15 Operations

First thirty flights: Refinement of high and low key positions

With the beginning of X-15 operations in June 1959, the first 30 flights were completed in 18 months. All types of approaches were flown—S-shaped, 180 deg, 270 deg, and 360 degrees. These flights resulted in the following average values.[17]

- **high key** 20,000 ft, airspeed of 300 knots, wing loading of 72 lb/sq ft

- **low key** 12,000 ft, airspeed 250–300 knots.

- **final flare** 1200 ft at 270 knots, a vertical velocity of 110 ft/sec from a 1.4 *g* flare.

- **touchdown** with 30 deg flaps, angle of attack of 8 deg, L/D of 3.5 and a vertical velocity of ~ 4 ft/second. Pilots were able to touch down within ± 1000 feet. At least one landing was made by each of the seven pilots assigned at the time, during this 30-flight interval.[16]
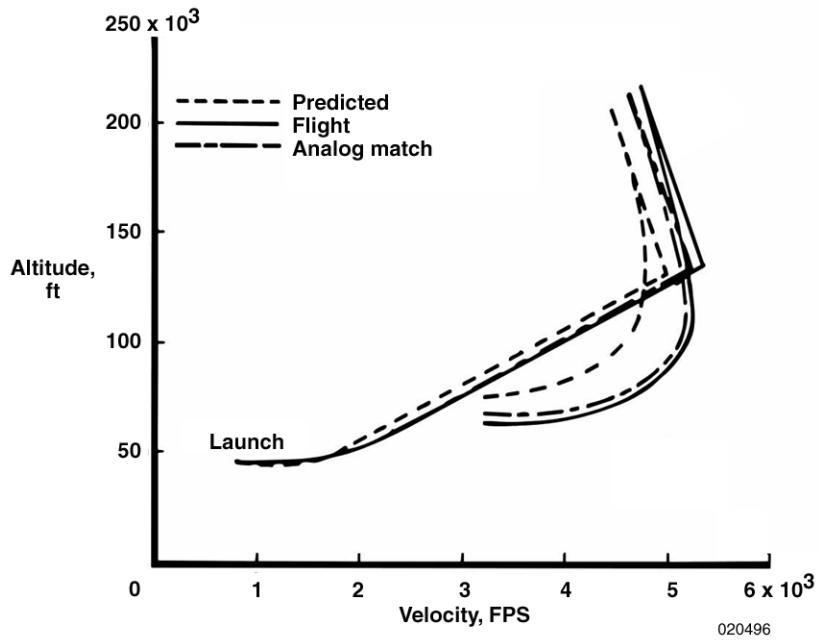
The first remote launches were made from Silver Dry Lake located about 100 statute miles east-northeast of Edwards near the California-Nevada border. The various launch lakes and emergency landing lakes and how they were selected are described in Chapter 5, "Project High Range."

Later operations: After first thirty flights, increased energy requires greater tolerances
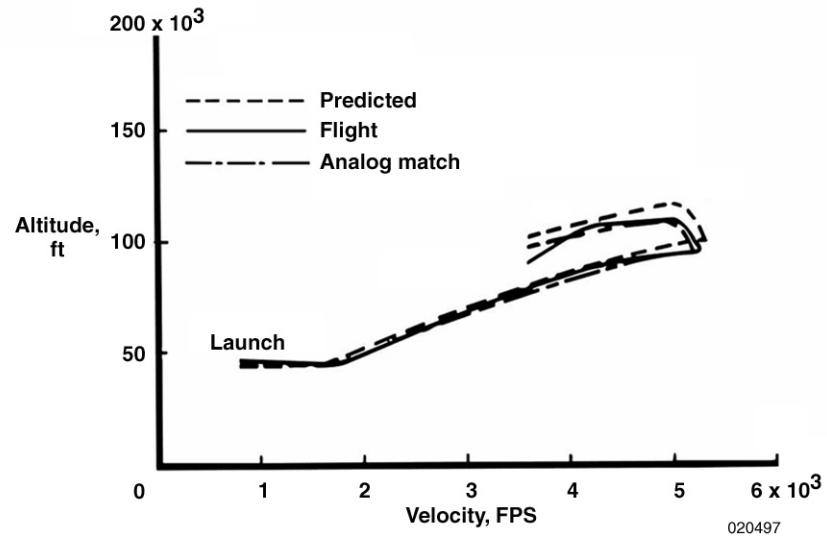
The first 30 launches determined nominal high and low keys of 20,000 and 12,000 ft respectively. However, these flights were of insufficient energy to establish a window of high and low key positions for remote high-energy launches. There were subtle changes made in energy management techniques as experience accumulated during the remaining 169 flights.

As stated previously, the properties of the atmosphere are the most troublesome for determining a footprint or maximum range available. Total energy at burnout does not always determine maximum range. Figures 20 (a) and (b) indicate the performance values of altitude versus Mach number for an altitude flight and a speed flight respectively. As indicated on the figures, the total energies at burnout are practically identical; however, the resulting ranges, or footprints, are considerably different.

At burnout of the altitude flight, figure 20 (a), the X-15 has a high rate of climb and is above 99 percent of the atmosphere. With negligible forces other than gravity acting during ballistic flight, the range and footprint are considerably increased over those of the speed flight, figure 20 (b), where burnout is at a lower altitude and the rate of climb is minimal. The drag of the increased atmospheric density shows a loss of speed, considerably diminishing the range and footprint.

(a) Altitude flight profile.

(b) Speed flight profile.

Figure 20. The X-15 aircraft mission performance comparison.

The dashed lines of figures 20 (a) and (b) again indicate the value of the X-15 six-degree-of-freedom simulator for flight planning, pilot preparation, and energy management.

Maximum performance flights

Figures 20 (a) and (b) indicated that although the energies at burnout of these build-up speed and altitude flights were nearly identical, the range of the altitude flight was considerably greater because of the ballistic portion of the profile. Table 4 indicates that the same is true for the maximum performance flights of the X-15 program.

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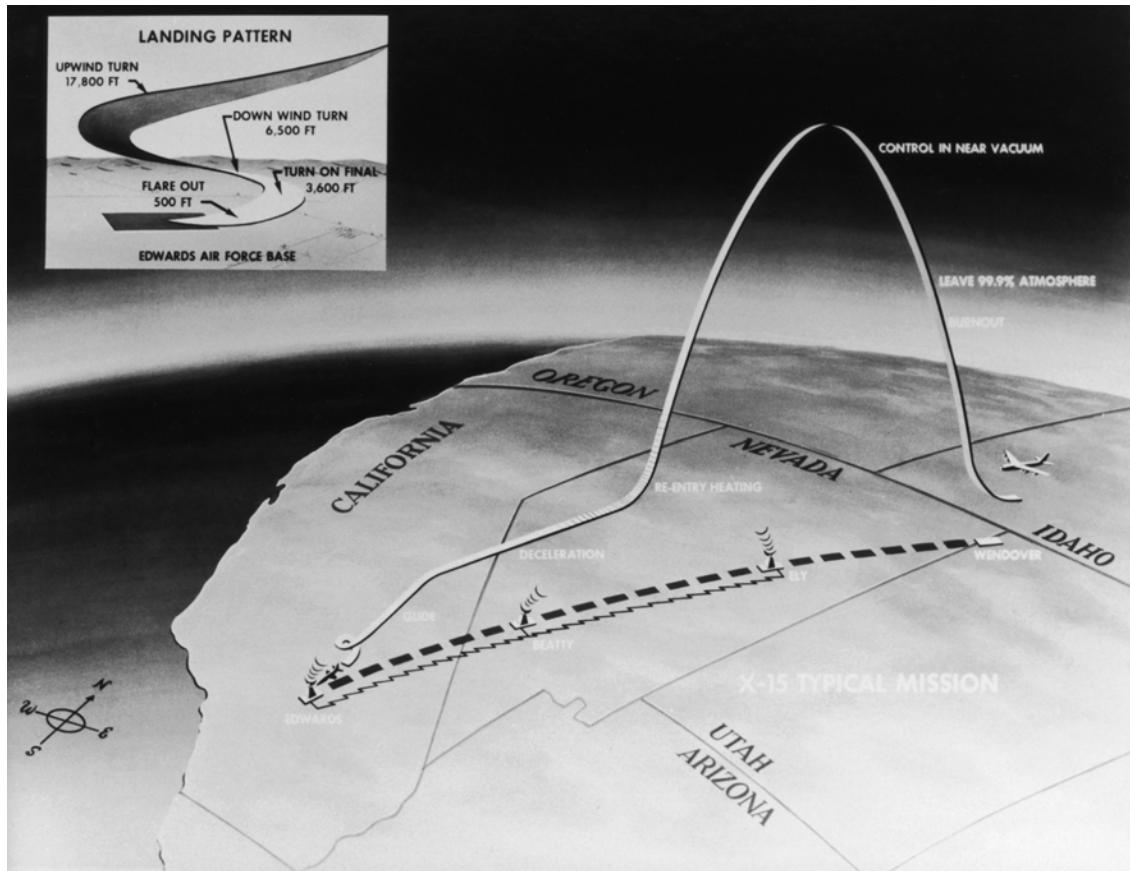
Table 4. Energy values and ranges for the X-15 aircraft maximum performance flights.

Flight number	Date	Maximum speed, Mach number, Velocity	Maximum altitude, ft	Energy burnout, ft-lb $\times 10^{-9}$	Range to Edwards, statute miles
91 Maximum altitude	08/22/1963	M = 5.58 V = 5565 ft/sec	354,200[*]	9.8	Smith's Ranch 280
188 Maximum speed	10/03/1967	M = 6.7 V = 6629 ft/sec	102,000	11.7	Mud Lake, 200

[*]Although maximum altitude for Flight 91 was above 300,000 ft, the altitude at burnout, required for calculating the potential energy was 148,000 ft.[9]

During X-15 operations from High Range remote launch sites, high key, as shown in figures 21 and 22, was nominally at an altitude of 35,000 ft directly over, and aligned with, the lakebed landing runway at 250 to 300 knots airspeed, from which a spiraling 360-deg descent was made. At the 180-deg point, the lateral separation from the intended touchdown point was approximately 4 miles. This point was the low key location at a nominal altitude of 18,000 to 20,000 ft and an airspeed still at 250 to 300 knots. The final approach, flare, and landing were quite similar to those previously established.

This final definition of high and low key for the X-15 aircraft was sufficient to embrace the window-defining limits for overshoots and undershoots.

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Figure 21. Altitude mission showing trajectory, ground range, and radar tracking station locations for the X-15 aircraft.
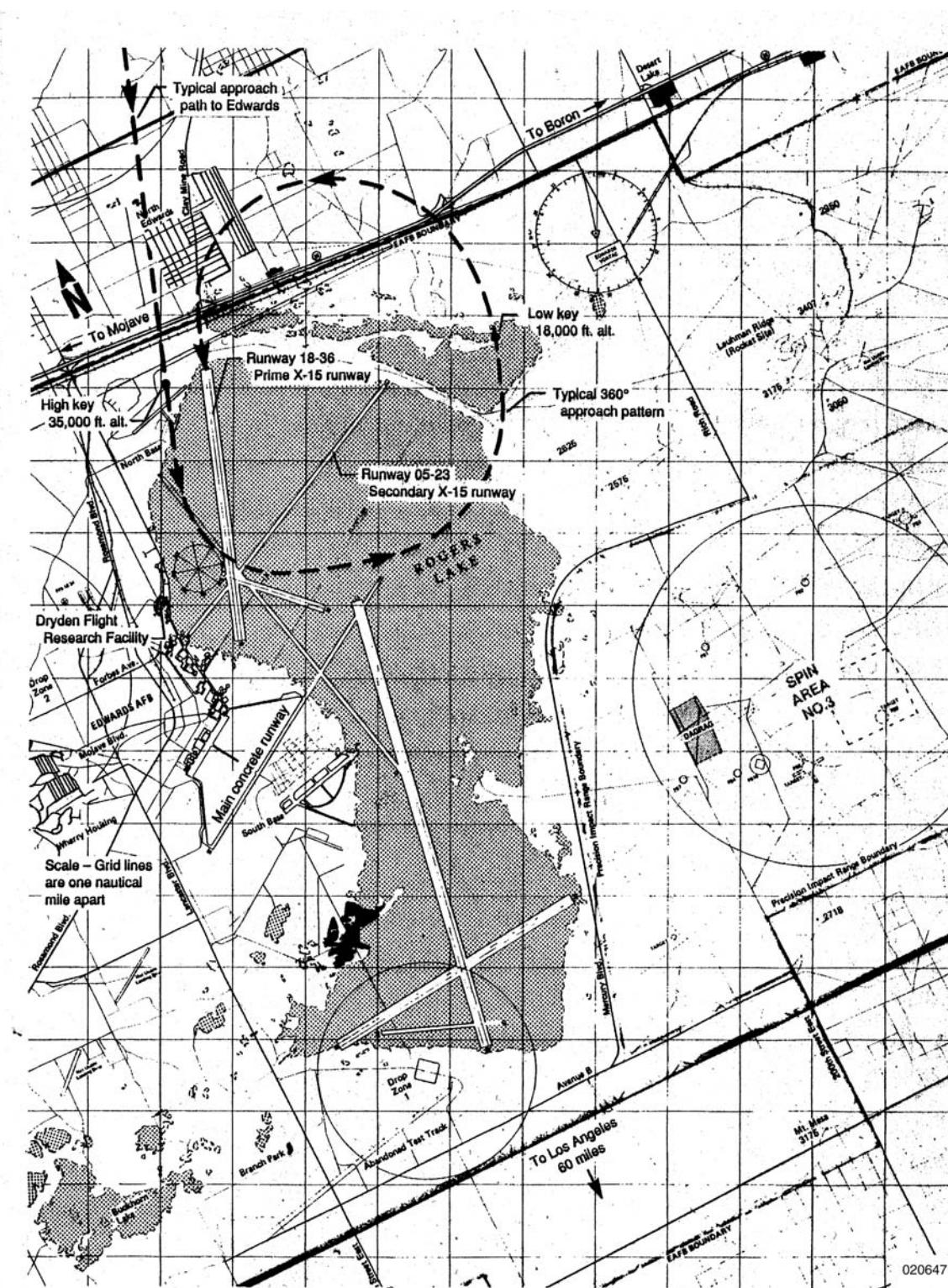
Figure 22. Typical approach pattern from remote launch site showing high key, low key, and runways for the X-15 aircraft.

Flight Planning for the X-15 Aircraft

Each flight was initially practiced on the X-15 simulator for many hours to determine a timeline of flight maneuvers and the energy management aspects of the total flight, with some degree of excess energy as a device to prevent undershoot. The excess energy could be attenuated by variable extension of the speed brakes. On the other hand, adding excess energy could not exceed the ability of the speed brakes to attenuate possible overshoots. The prime reason for this was that all emergency dry lake landing sites were to the north and east; there were no emergency landing sites south of Rogers Dry Lake. A nonrecoverable overshoot would be much like an overshoot on an aircraft carrier without the capability of a wave-off and go-around.

The simulator exercises were followed with X-15-configured F-104 flights to verify and refine the analog simulations. The F-104 flights were not only flown at Rogers Dry Lake but at the designated emergency lakes.

The analog and F-104 exercises were so successful in establishing energy management criteria and techniques that several anomalous incidents of extreme overshoots and undershoots were dealt with successfully through pilot-control-room coordination.

The additional advantages of establishing a high key reference location are described in the section "Anomalous Incidents – Overshoots and Undershoots" (page 40).

Development of Energy Management Footprints for Ground Monitoring

Prior to operations with the XLR-99 engine, NAA developed a set of generic footprints using a digital computer. These digitally generated patterns were difficult to use operationally but served as a guide for determining operational footprints by "flying" the X-15 six-degree-of-freedom analog simulator. Using initial conditions of mass, velocity vector, altitude, and ground position, the simulator was "flown" to maximum forward, cross, and reverse range by flying the airspeed for maximum L/D. After several runs, points were established for outlining one-half of a symmetrical footprint.

Because the analog computer did not have the power of a digital computer, and the digital was too slow at that time, neither method was capable of real-time display for ground monitoring. Fortunately the footprints closely resembled an analytic geometry shape resembling a heart, called a "cardioid." The equation expressed in polar coordinates used much less data and could be calculated in real time for display on a cathode-ray tube for ground monitoring. During operations, flight data was sent to the analog for calculating and displaying the cardioid for real-time monitoring. The more powerful and faster digital computers of today easily generate such figures in real time.

Figure 2 in the "Introduction" shows a cardioid as displayed on a cathode-ray tube for ground monitoring. Figure 23 shows a series of cardioid footprints as an X-15 aircraft progresses for an altitude mission. The first cardioid represents range capability for an ignition failure at launch, $t = 0$, the same size as the footprint for an air-launched glide flight. The launch lake had to be within this footprint.
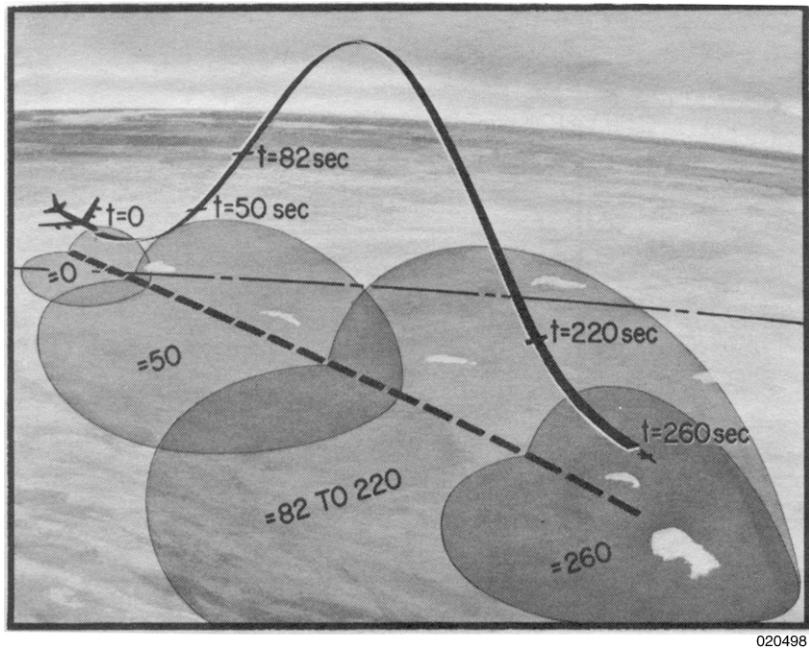
Figure 23. Progression of footprint during an X-15 aircraft altitude mission.

At t = 50 sec, the climb angle and speed increased such that the cardioid would move ahead of the X-15 aircraft and gradually grow larger. At burnout, t = 82 sec, the cardioid, representing the maximum total energy, attained its maximum size. The footprint retained its size, shape, and position because the aircraft was above 99 percent of the atmosphere and in pure ballistic flight, at constant energy. There was no significant drag, only gravity, to influence the conservation of energy. Therefore the kinetic energy plus the potential energy represented total energy and remained constant as speed and altitude varied until reentry into the atmosphere. This constant energy trend is shown in figure 20 (a) by the straight-line trajectories from burnout to reentry. At burnout the footprint covers several emergency landing lakes and ample room at Rogers Dry Lake for a high key approach. At reentry the cardioid shrinks rapidly until reaching high key.

Energy management was eventually controlled by the time of the rocket burn. A hundred-second clock, mounted at the top of the instrument panel automatically was started and stopped by engine chamber pressure. Simulator flight planning determined the time of rocket burn for returning to the launch lake, time for intermediate lakes, and time for reaching high key at the destination. At all times during a flight ample dry lakes, shown in the figure, were available for emergency landings (fig. 23).

Benefits of Air Launch

The energy-saving advantages of air launch, as opposed to ground launch, are so obvious that the very first German and American rocket-only aircraft, described in Chapter 1, employed this energy-saving technique. A photograph of an air launch of an X-15 airplane is shown in figure 24. The various benefits of air launch are listed below.

Figure 24. Air launch of X-15 from B-52 carrier aircraft.

- **On-board fuel conservation** The launched aircraft doesn't have to carry the fuel required to climb from a ground launch to air launch altitude.

- **Kinetic energy** The launched vehicle has the free velocity benefits (V^2) of the launch aircraft.

- **Potential energy** The benefits of the launch altitude (h), nominally 45,000 ft for the X-15 aircraft.

- **Air density** Air launch also avoids the energy-gobbling density of the atmosphere. For a launch at 40,000 ft the aircraft is above three-quarters of the atmosphere. At equal speeds, the drag is one-fourth that of sea level.

- **Increased thrust** As the atmospheric pressure decreases with altitude, rocket thrust increases. The thrust of the XLR-99 increased from 50,000 lbf at sea level to 57,250 lbf at 45,000 ft pressure altitude, the nominal launch altitude for the X-15 aircraft.[18]

- **Propellant "top-off"** The ability to transfer propellants from the mother ship to an X-15 airplane permits replacement of propellant "boil-off" during the climb to launch altitude.

- **Safety** If the rocket engine does not ignite, shuts down after launch, or produces only partial power, the air-launched vehicle can jettison propellants and land. A ground launch, in most cases, ends in disaster under such conditions.

Unlike multistaged orbital rockets, the air launch altitudes and speeds of the X-15 aircraft, as stated previously, were insufficient to appreciably benefit from the geopotential altitude and centrifugal effect.

Anomalous Incidents – Overshoots and Undershoots

Simulator flight planning produced excellent energy management results for the X-15 aircraft flights, however various anomalous incidents occurred to produce flight deviations resulting in overshoots or undershoots of the predicted altitude or range. Almost all of these incidents were overshoots due to the difficulty of hitting all the flight plan checkpoints required for altitude flights. Undershoots were primarily caused by some system malfunction shortly after launch. High key altitude was progressively increased such that undershoots, when they occurred, were not a problem. In addition, alternate contingency lakebeds were always accessible for landings.

A small variation in timing, climb angle, or thrust could produce the following variations in predicted altitude:

- **Timing** For altitude flights, the rate of climb at shutdown or burnout was normally over 4000 ft/second.

- **Engine performance** Calculations plus simulator flight planning experience indicated that an extra 1000 lb of thrust would add about 5000 ft to maximum altitude. Performance among different engines indicated that thrust could vary by 3000 lbf.

- **Climb angle** A one-degree error in climb angle could produce a 5000 ft change in maximum altitude.

If each of the above variations were cumulative to increase rate of climb, the additive effect could result in an overshoot of tens of thousands of feet. Described below are five examples of overshoots that occurred during the program.

Neil Armstrong On a mission to check out a new Minneapolis Honeywell (MH) (Minneapolis, Minnesota) adaptive flight control system, Neil Armstrong was launched from Mud Lake, April 20, 1962 (Flight 51). The planned altitude was 205,000 ft, with maneuvers during ascent and descent to test the new control system. The MH system included reaction controls blended with aerodynamic controls as dynamic pressure changed during ascent and reentry. Neil only slightly exceeded the planned altitude. However, while he was monitoring the control system *g*-limiting feature, the airplane had completed the entry and was in a climb. He flew by Edwards at approximately Mach 3 at 100,000 ft. At this altitude, making a 180-deg turn back to base is impossible. Neil continued for about 45 miles south of Edwards to La Canada and the Rose Bowl before completing a turn towards Edwards. He barely limped into Edwards South Base, skimming the Joshua trees, in an unprecedented landing to the North. This was primarily a range overshoot rather than an altitude overshoot. This space-related experience was only one of many that honed Neil's talents for lunar energy management.[11]

Robert White This was also a flight checking and demonstration of the MH adaptive control system. White was launched from Delamar Lake, on a flight planned for an altitude of 282,000 ft but achieved 314,750. Bob, late on shutdown and several degrees high on climb angle, reached an altitude of 314,750 ft, an overshoot of 32,750 ft. Following the altitude overshoot, the pullout was completed almost over the north lakebed at Edwards with a high key of 80,000 ft at Mach 3.5. At this speed and altitude, and with no appreciable rate of climb, White was able to make a wide 360-deg turn and approach at a more reasonable high key of 28,000 ft.[11]

John McKay On a launch from Delamar Lake to conduct scientific experiments, May 15, 1963 (Flight 83), McKay overshot a planned altitude of 98,000 ft by 26,200 ft. McKay recovered to high key and the mission was completed without further incident.[11]

Joseph Walker On an altitude buildup flight, planned for 315,000 ft, Walker was launched from Smith's Ranch July 19, 1963 (Flight 90). After launch and pull-up to a one-and one-half degree error in climb angle, a higher than expected thrust, and a longer than expected engine burn, the X-15 airplane climbed to 347,800 ft, for an overshoot of 32,800 ft—almost precisely White's overshoot of 32,750 ft on Flight 62. Walker recovered and proceeded to high key without further incident.[11]

William Dana November 1, 1966, Bill Dana was launched from Smith's Ranch, (Flight 174) on a planned altitude mission to 267,000 ft to perform various scientific experiments. In establishing his climb, Bill attained and maintained a climb angle of 39 deg until engine shutdown. Because of an error in the climb attitude indicator, Bill was climbing at an attitude of 42 deg instead of 39. In addition, the engine burned longer than predicted. Realizing this, Bill shut down the engine immediately but extra time was added to the burn. During a portion of this time Bill was out of contact with the mission control center and was not advised of the flightpath and high-energy conditions. As a result, the extra time and attitude angle carried the X-15 airplane to an altitude of 306,900 ft, an overshoot of almost 40,000 ft! Bill recovered nicely, made high key, followed by a normal landing. The overshoot did not compromise the scientific experiment objectives.[11]

Wind tunnel tests indicated that the Shuttle would have L/D ratios comparable to those of the X-15 aircraft, consequently, the capability of the X-15 aircraft to handle large variations of excessive energies for boost-gliders was not lost on the design of the Shuttle, especially in the decision to eliminate the internally stored cruise and landing engines.

Accomplishments of the X-15 Aircraft

In the hierarchy of experimental research airplanes, the X-15 aircraft exceeded the others in all categories of achievement. It was the only X-series aircraft that was designed for, and would fly to, hypersonic speeds and extreme altitudes. The X-15 aircraft still holds the record for speed and altitude for manned single-staged boost-glide vehicles. The three X-15 airplanes flew 199 flights covering nearly a decade from June 1959 to October 1968. The X-15 aircraft were the most successful in returning research data for future design criteria of hypersonic boost-glide aircraft and orbital vehicles. These aircraft also served as a test bed for future space range and control center design, established requirements for six-degree-of-freedom simulation, flight planning, and the fundamentals of boost-glide vehicle energy management.

CHAPTER 5

PROJECT HIGH RANGE

Development of High-Energy Boost-Glide Operations

The final flight of the X-2 airplane on September 27, 1956, had demonstrated that moderately low L/D boost-glide vehicles, launched locally, could overrun the Rogers-Rosamond footprint unless constrained to Mach 3.0 (see Chapter 3). Also by September 1956, enough wind-tunnel data had been collected and analyzed on the X-15 aircraft to indicate that for the higher energy flights this aircraft would require remote launches which, in turn, would require extensive real estate and support facilities.

These requirements, outlined in a 1956 NACA HSFS report[19] resulted in the Project High Range contract award to the Electronic Engineering Company of California (Los Angeles, California) (Air Force Contract number AF 04(611)-1703, March 9, 1956[†]) with an expected completion date of March 1959. The aerodynamic test range would require an instrumented ground range capable of monitoring the flight through its entire trajectory and would basically consist of sites at Edwards, California; Beatty, Nevada; and Ely, Nevada, with the prime control center at the FRC (Edwards). The original selection for the northernmost site was Wendover Air Force Base in Utah with Salt Lake as a launch contingency landing site, but these were later rejected as unsuitable for X-15 aircraft landings. Figures 25 (a) and (b) show the geographical location and information flow of the radar sites.

The uprange Beatty and Ely sites were agreed upon by the AFFTC, the NACA, and the Project High Range contractor. In addition to these radar sites, a contract was awarded to Reeves Instrument Corporation (New York, New York) by EAFB for construction of a van-mounted radar unit. The mobile radar unit could be incorporated at any point within the radar range. This mobile radar could be stationed at any of the suitable dry lakes or, if desired, make a four-station radar range.[‡]

The Engineering Plan called for the following development:

- Perform a suitability evaluation at the two uprange sites.

- Lay out and construct access roads to each uprange site.

- Design and construct shelters at uprange sites.

- Install radar, telemetry, and communications equipment.

- Design and construct a radar tracking station in addition to the NACA (Edwards) building

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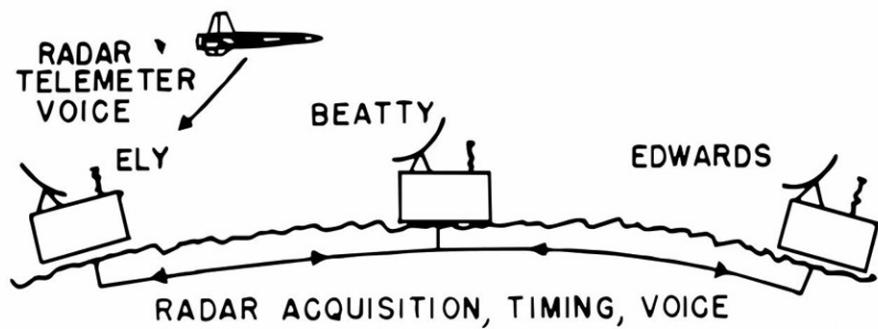
[†] Schock, R.L., Project High Range, Engineering Plan, Electronic Engineering Company of California, Los Angeles, California, March 9, 1956.

[‡] NASA Aerodynamic Test Range Facilities Handbook, NASA Flight Research Center, Edwards, California, February 1971.

(a) Location of the X-15 aircraft ground range.

(b) Information flow on the X-15 aircraft range.

Figure 25. High Range sites and information flow.

Radar Site Evaluation and Development

In addition to the physical shelters, requirements included the following:

- Establish radar sites capable of line-of-sight overlap from furthest launch point to Edwards radar.

- Establish control centers with visual displays for radar and telemetry information and intercommunications, at and between centers.

- Provide long-range UHF communications.

- Ensure capability for tracking launch ship for navigational information.

- Provide backup performance data to the pilot: velocity, altitude, angle of attack, flightpath angle, ground track, and position.

- Monitor safety of flight system status, for ground analysis and transmission of critical information to pilot.

- Provide rendezvous information to escort (chase) aircraft.

- Vector the pilot to key locations for approach.

- Provide a record of radar and telemetry data for subsequent research analysis.

- Ensure availability of an airfield near uprange sites.

After performing site suitability evaluations, the contractor proceeded to construct access roads and buildings to house the range equipment. For compatibility, structures and equipment at the two uprange shelters were to be identical. A photograph of the Ely radar site is shown in figure 26.

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Figure 26. Tracking station, Ely, Nevada.

Figure 27 shows the continuous high-range radar coverage and data transmission capabilities. Each station had a 218-mile radius coverage that assured continuous coverage for even the most remote sites. A range switch had the capability of increasing the coverage radius to 436 miles. With the switch in the long-range position, any one station overlapped the entire range.
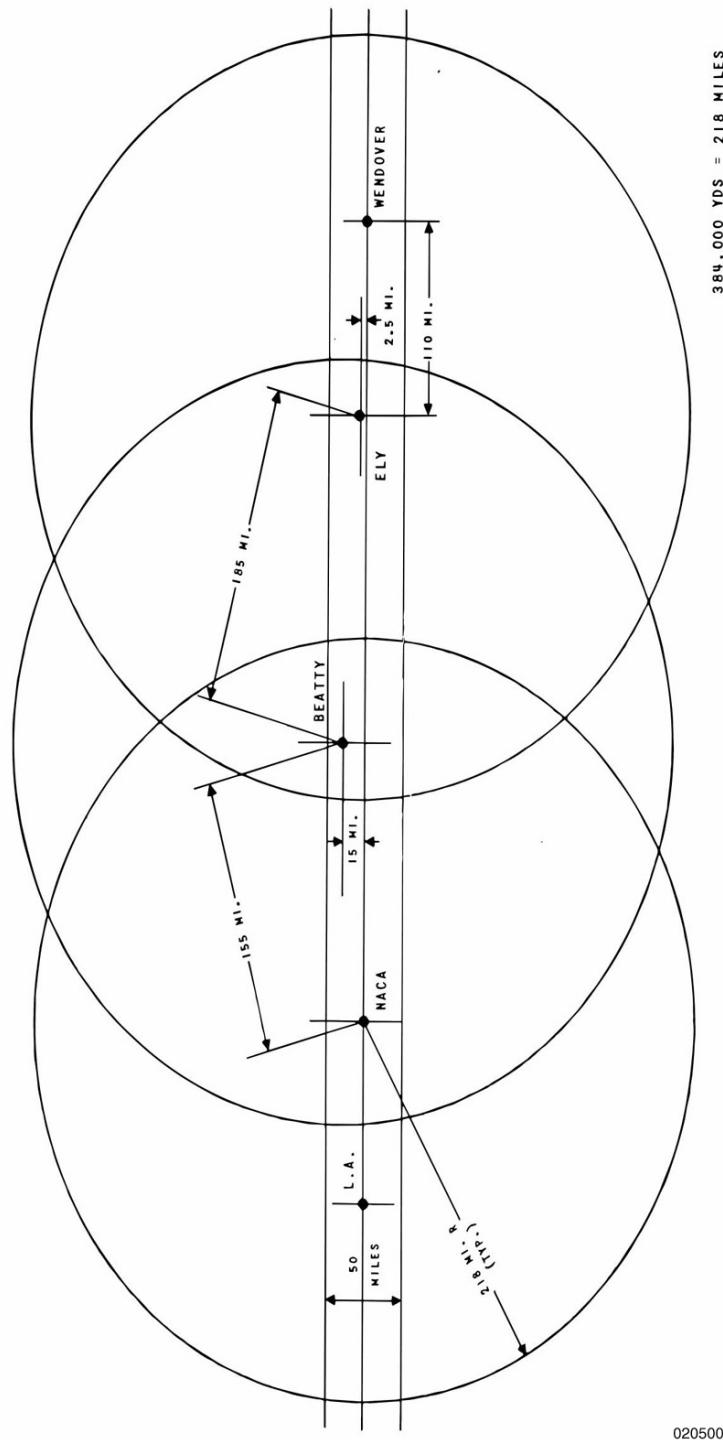

Figure 27. Overlap of radar coverage for the Ely, Beatty, Edwards radar range.

Telemetry data were received at both the FRC and Ely sites, recorded on magnetic tape, and processed in real time at FRC. Ground-to-air communications were provided by long range UHF equipment.

In the control rooms, the flight information relayed to flight controllers was displayed at consoles, meters, and plotting boards. All the instrumentation required for safety of flight was monitored and downloaded for future research information. The various critical items being monitored were:

- **Propulsion** – Pressures, APUs, oxidizer, fuel, temperatures.

- **Stability and control** – Angle of attack, angle of sideslip, angular rates and positions, linear and angular accelerations.

- **Control systems** – Stability augmentation, aerodynamic surface positions, reaction controls (RCS).

- **Energy management** – Geometric location, velocity vector, time, air data.

- **Scientific experiment parameters**

- **Medical** – Vital signs, *g* forces.

Operational Logistics

Prior to each flight, operational personnel and equipment were flown to the launch site in an AFFTC C-130 cargo aircraft; at times, the personnel would be flown separately in the NASA R4D. The operational personnel consisted of technicians, flight test engineers, and an X-15 pilot to serve as flight controller. NASA pilots flew range checkout flights to check radar and telemetry with T-33, F-100, and F-104 aircraft.[11]

The NASA site at Edwards was the primary flight control center, with an X-15 pilot at the director's console, in direct communications with the X-15 pilot flying the airplane. This operational procedure was the basis for future space operations, establishing the pilot, or astronaut, as the capsule communicator (Cap Com) and with a complement of engineers monitoring all aspects of the mission.

Control Room Anecdotes

For nearly a decade of X-15 aircraft operations, numerous personnel participated in the FRC control room. During such a prolonged period of time, it is not surprising that some unusual or improbable incidents occurred. Three that come to mind are described below:

1. One of the strip chart recorders in the control room recorded time histories of medical parameters, with one channel recording the pilot's breathing. The medical recorder was monitored by Air Force flight surgeon Lt. Col. Burt Rowen. During the first flight, while the X-15 was still attached to the carrier aircraft, the pilot, Scott Crossfield, who loved to taunt the medics, radioed down to Rowen, "Burt, how am I doing?" Rowen replied—"Fine Scott. You're doing OK." To which Scott replied, "Burt, I've been holding my breath for two minutes."

2. During one of the early local launches, the North American Aviation flight controller, Q.C. Harvey, kept getting reports of accumulating bad weather. Just prior to launch, Harvey gave the order to abort the mission because of bad weather. The pilot of the B-52 carrier aircraft replied, "Harvey, there isn't a cloud in the sky." With the weather settled, the mission continued.

3. It was well known that during stressful activities, such as automobile racing, the participants have inordinately high heart rates. Prior to entering the hypersonic rocket aircraft era, the medical community wondered if the X-15 pilots could endure the anticipated high heart rates during critical periods of flight test. The primary test for the 42nd flight was to test stability and control with the lower rudder removed. The ventral rudder was designed to increase directional stability. The simulator had indicated that at the higher angles of attack the X-15 was uncontrollable with the ventral attached, and controllable with the ventral removed. During the critical portion of this flight, the engineer who proposed removal of the ventral took his pulse and found that it was higher than the pilot's. Observations showed that the same was true for most participating ground personnel in later flights and during the space program.

Selection of Launch and Intermediate Emergency Lakes

Prior to and during the High Range development at Ely and Beatty, suitable dry lakes were selected along the flight corridor for air launch locations and for emergency landing dry lakes. In comprehensive surveys, the only suitable dry lakes for launch and emergency landings were in the quadrant northeast of EAFB, with none south of Rogers Dry Lake. As explained in Chapter 4, this southern boundary presented some difficulty in establishing energy management procedures that would prevent the X-15 aircraft from overshooting Rogers Dry Lake.

Remote Lake Requirements

Because the X-15 aircraft landed on skids, the only acceptable landing areas were dry lakebeds, which (with the exception noted above) were plentiful in the arid Southwest. Surveys were undertaken by the NACA/NASA, the AFFTC, and NAA. In selecting the lakes, several characteristics had to be considered:

- The surface had to be hard and smooth.

- The desired landing strip had to be at least three miles long.

- The landing approach had to be unencumbered by hills or mountains.

- There could be no railroad, road, ditch or power lines crossing the landing strip.

- There had to be means of vehicular access for recovery of the X-15 airplane.

- A launch lakebed had to be within gliding distance of the launch point and alternates had to be located at appropriate intervals, to allow coverage in case of shutdown occurring at any time during the flight.

- The launch site and intermediate lakes had to be within line of sight (LOS) radar coverage.

After the lake sites were selected, they were marked by the Air Force with standardized eight-foot-wide tar stripes 300 ft apart for reference dimensions. Hardness was checked with a five-in. steel ball dropped from six ft and the resulting diameter was checked to compare with predetermined lakes—similar to Brinell metallic testing.[11, 20]

The proximity of launch sites was determined during flight planning simulator sessions, primarily from energy management considerations:

- *Local*: Local-launches were for the lowest energy flights and did not exceed Mach 3.0, as described earlier. These flights were launched near Rogers Dry Lake and were primarily for the manufacturer's airworthiness demonstrations and pilot check-out.

- *Short range*: These launches were for moderate energy buildup flights of the XLR-11 engine envelope expansion program. Most were launched from Silver Dry Lake.

- *Long range*: Launches for XLR-99 envelope expansion flights, heating data, and various research flights took place at all northeast quadrant lakes.

- *Maximum range*: Launches for maximum energy flights, primarily maximum altitude attempts, departed from Smith's Ranch and Delamar Dry Lakes.

Early Dry Lake Survey

After the X-15 aircraft had exhausted the Rogers Dry Lake footprint with flights limited to Mach 3.0, and before the later high-energy flights, NASA and the U.S. Air Force were eager to continue flights in the lower end of the envelope expansion program—flights requiring launches approximately 100 statute miles from Edwards. For these buildup flights, the launch lake had to be within the range of the Edwards radar with suitable intermediate emergency landing lakebeds. For these purposes Joe Walker (an X-15 pilot) and the author undertook a lakebed survey in the octant east-northeast of Edwards in a U.S. Air Force helicopter. A primary launch site, Silver Dry Lake, was found approximately 100 miles from Edwards near the Nevada border with intervening emergency sites at Three Sisters, Cuddeback, Harper, and Bicycle Dry Lakes, as shown in figure 28.

Survey Conducted by the Air Force Flight Test Center and North American Aircraft

A survey was made of some 50 dry lakes north of Edwards in California, Nevada, and Utah. Among those that were deemed suitable for X-15 landings were Cuddeback, Hidden Hills, Ivanpah, Delamar, Smith's Ranch, and Mud. This survey included Salt Lake at Wendover AFB, Utah, which was in the original proposal, but was not considered usable. Figure 28 shows the location of the dry lakes by longitude and latitude with symbols for suitability of the X-15 aircraft landings.[20] Figure 29 is a political map showing many of the lakes used.[11]

Seven uprange lakes were eventually chosen. Only four were used in the early program: Silver, Hidden Hills, Mud and Delamar. Smith's Ranch and Delamar were used for maximum energy altitude flights. Railroad Valley was uniquely located for two scientific experiment flights. Cuddeback, although suitable, was used only once for air launch and twice for emergency landings. Table 5 lists all the launch lakes for the 199 flights and the lakes utilized for landings of the ten aborted flights of the X-15 airplanes.
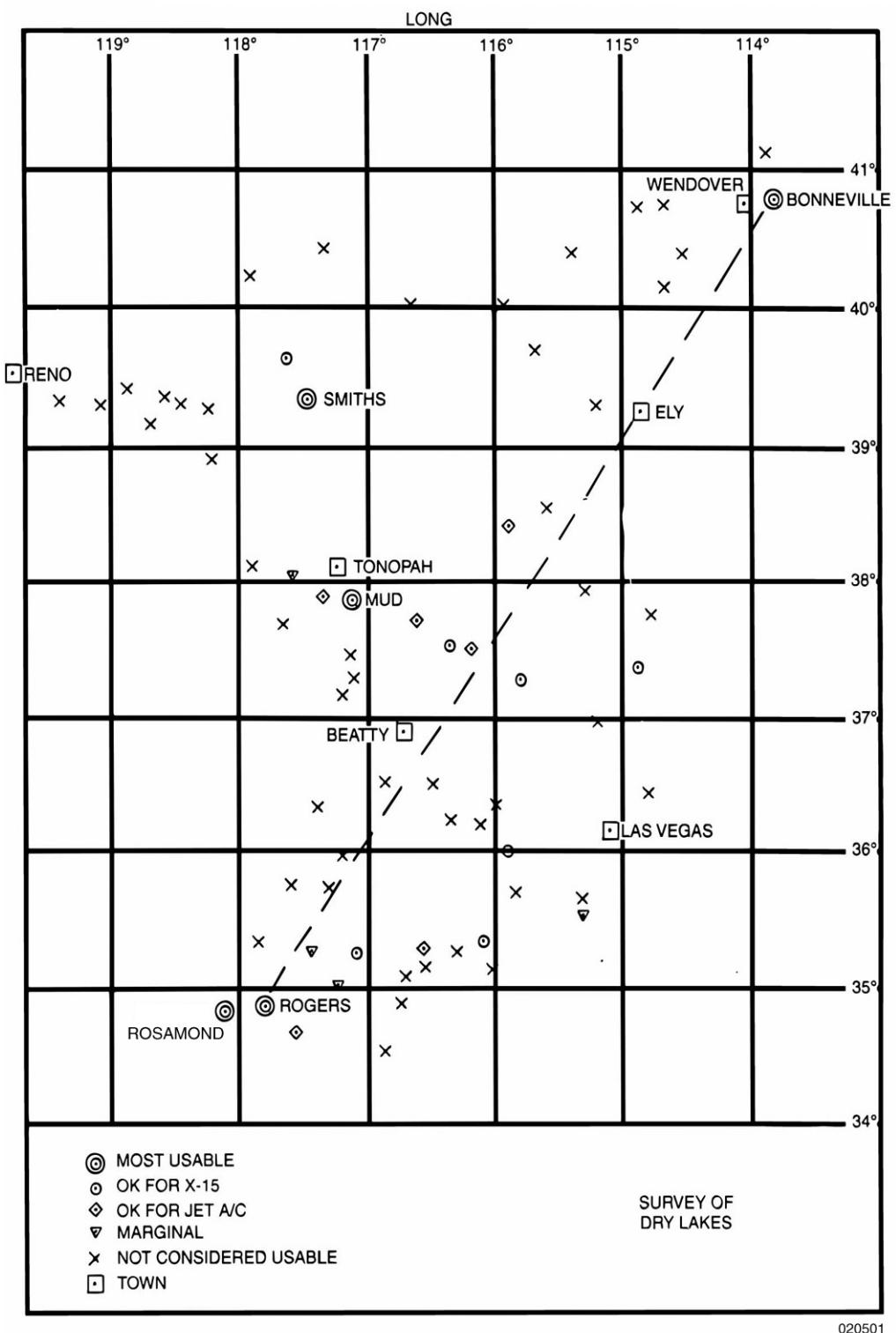
Figure 28. Location of the dry lakes by longitude and latitude with symbols indicating suitability for X-15 aircraft.
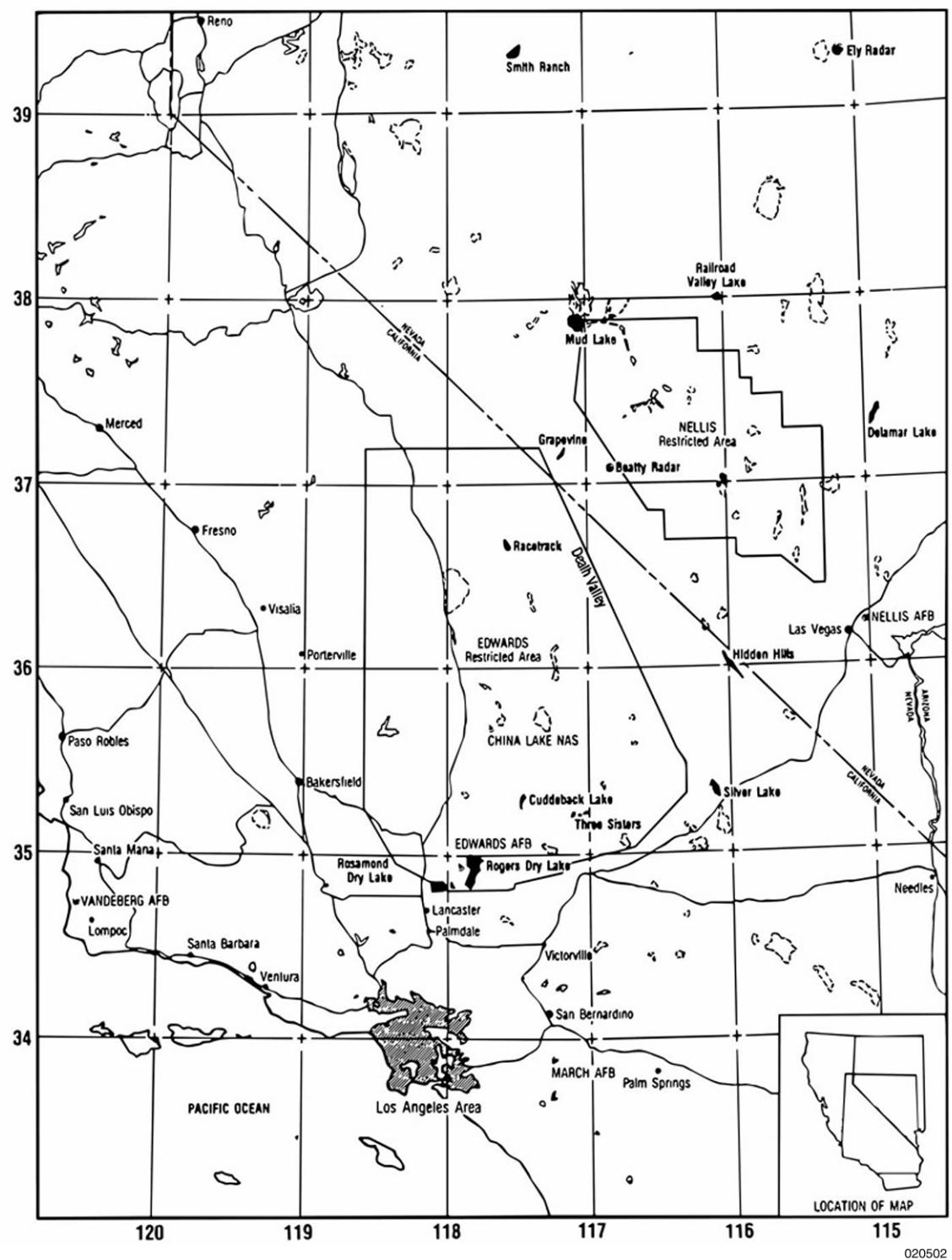
Figure 29. Political map of all the X-15 program lakebeds.

Table 5. High Range dry lake launch sites selected for emergency landings during the X-15 program.

Dry lake	Distance, statute miles	Total launches	First launch date	Emergency landings
Rogers	0	8	09/23/60	0
Rosamond	5	18	06/08/59	1
Silver	105	14	05/12/60	1
Hidden Hills	130	50	03/30/61	0
Mud	200	34	05/25/61	4
Delamar	220	62	06/01/62	1
Smith's Ranch	280	10	07/19/63	1
Railroad Valley	230	2	07/16/68	0
Cuddeback	30	1	11/03/65	2

Air launches were not made directly over the selected launch lake, but usually in-line with the launch lake-to-Rogers trajectory and close enough to the lake to glide to an emergency landing. This extended the range for the entire trajectory by approximately 20 miles. For example, the maximum performance flights shown in table 4, Chapter 4, encompass 305 miles (Smith's Ranch launch) and 220 miles (Mud Lake launch).

Another energy management problem that placed a vital demand on the High Range radar sprang from the fact that remote lakebeds were not at the same altitude as Rogers Dry Lake at Edwards. High and low key altitudes for remote sites had to be adjusted for the difference. For example, the difference between Smith's Ranch altitude of 6100 ft (highest lake) and Edwards, 2270 ft, is 3830 feet. Considering the launch altitude to be 40,000 ft, a failure to light at launch, would make the geometric altitude for Edwards = 37,700 (above nominal high key of 35,000 ft) and for Smith's Ranch = 33,900 (below nominal high key).

This variation in launch altitude turned out not to be a problem since pilots had practiced straight-in and S-turn approaches since the days of the X-1 aircraft. The altitude difference presented much the same problem but was less severe than the altitude overshoots and undershoots at Rogers. However, prior to flight, pilots always flew the F-104A jet aircraft to the designated launch lake for practice approaches. In addition to honing energy management, the pilots could become oriented to the mountain terrain and unfamiliar lakebed.

In addition to selecting dry lakes at increasing intervals to satisfy the demands of increasing energy flights, it was fortunate that the lakes were dispersed over a vast area covering three Western states. If one launch lake was weathered-in, another might be open. The open lake would be satisfactory for launch as long as the emergency lakes along the flight corridor were not obscured and the alternate launch site had been considered satisfactory during flight planning.

High Range Legacy and Enduring Value

During the near-decade of X-15 aircraft flight operations, the radar, telemetry, and communications capabilities of the High Range successfully served as a link binding the pilot, the aircraft, flight controllers, systems engineers, and technicians together to function smoothly as a unit during flight operations. The prospect of the X-15 aircraft high-energy boost-glide flights created a demand for Project High Range which in turn served as a model for the fundamentals and logistics of future global range and Mission Control Center operations for flights to destinations from Mercury to Mars.

Milton Thompson, who flew many of the X-15 flights and later became DFRC chief engineer, provided an excellent summary of the contributions of the High Range to later space programs:

> We were monitoring the same kinds and type of data on the X-15 that NASA is currently monitoring on the Space Shuttle. In fact, much of our research aircraft operational experience at NASA Dryden was passed on to the space program through key individuals who transferred to the original Space Task Group, planning for Project Mercury, the first American space venture.
>
> Walt Williams, the first chief of the NASA Dryden Center became the deputy for flight operations. Williams, along with a number of other Dryden personnel who also transferred, established a space version of Dryden's experimental aircraft test complex. Many of the flight test procedures developed at Dryden were applied directly to the Mercury spacecraft flight operation. The man who conceived and developed the X-15 tracking range, Gerry Truszynski, transferred to NASA headquarters and proceeded to develop the space tracking net and later the Deep Space Tracking Network. He subsequently became NASA's Chief of Tracking and Data Acquisition.[11]

In addition to serving as a model for early space program operations, the NASA DFRC range site, control center, and Rogers Dry Lake were utilized for the air-launched, subsonic, Shuttle Approach and Landing Tests (ALT) program. The complex also served as the primary landing site for the initial Shuttle flights and still serves as an alternate landing site for Shuttle missions.

During X-15 operations and since, the Range has been periodically upgraded as technology improved. The NASA range control station still serves the newer lifting body boost-glide X-model air and spacecraft.

CHAPTER 6

THE SPACE SHUTTLE

In the early 1970s NASA was selected to develop the Space Shuttle for a new Space Transportation System (STS). After design, manufacture, and subsonic testing of a prototype, the Space Shuttle started space launches in the early 1980s.

First Space Transportation System

Background

Some of the original launch studies included bundles of strap-on solid rockets looking much like an overloaded Russian Vostok. The final launch design consisted of two jettisonable, reusable solid rockets and a large jettisonable strap-on external tank carrying liquid propellants for the three Space Shuttle main engines. Shortly after launch, the solid rockets are jettisoned and the external tank provides propellants to just-short of orbital velocity and is jettisoned. Two intermediate thrust rockets of the orbital maneuvering system (OMS) act as the third stage, thrusting the Shuttle into orbit. The OMS also serves for orbital adjustments, station keeping, and pre-entry retrofire.

The Shuttle spacecraft was originally designed to house two extendible cruise and landing jet engines. Fuel tankage, engine storage, and deployment mechanisms created a structural, weight, and plumbing nightmare making reentry and landing impractical. Many flight tests defining energy management were performed at Edwards, California by NACA, NASA, and the AFFTC. The X-15 aircraft had been so successful at hypersonic and extreme altitude energy management and bull's-eye lakebed runway landings—including large anomalous energy deviations—that during a symposium at the Flight Research Center (FRC) in 1970 to discuss flight test results pertaining to the Shuttle, the FRC highly recommended deletion of the cruise-landing jet engines.[21] During 1969-70, shortly after the end of the X-15 program, the AFFTC conducted low L/D tests with an F-111A and an NB-52B with L/Ds from 3.2 to 8.0 that included Terminal Area Energy Management (TAEM).[22] These data from NACA, NASA, and AFFTC were the greatest influences for eliminating the extendible landing-cruise engines, permitting a lighter, less complex structure with more payload capability.

New thermal protection concepts were adopted for the extreme heating of gliding reentry. The Thermal Protection System (TPS) included Reinforced Carbon-Carbon (RCC) for the nosecone and heat-bearing leading edge structures. Lightweight ceramic tiles and coated NOMEX® (Dupont, Richmond, Virginia) were located on other heat-bearing surfaces.[23] Figure 30 shows the Space Shuttle configuring for a landing.

Figure 30. Space Shuttle configuring for landing.

Retro-Glide Energy Management

Not unlike blunt body capsules, the Shuttle—at high angle of attack (α)—presented a heat shield to the atmosphere during the high-energy, heat portion of reentry. Also, similar to Gemini and Apollo, the Shuttle utilized a roll program—a roll-reversal program—to control the geometry of the footprint and, unlike the blunt bodies, to prevent atmospheric skip.

During the hypersonic and supersonic phases of reentry, the Space Shuttle is plagued by unstable or nonexistent stability and control parameters. The initial portion of the Shuttle reentry regime is designed primarily from heating considerations to be flown at extreme angles of attack. In addition to thermal protection, the high angles of attack serendipitously provide longitudinal stability. As shown in figure 31, a constant angle of attack of 40 deg is flown to Mach 12 where a linear transition is flown to 10-deg α at Mach 1.5.[24]
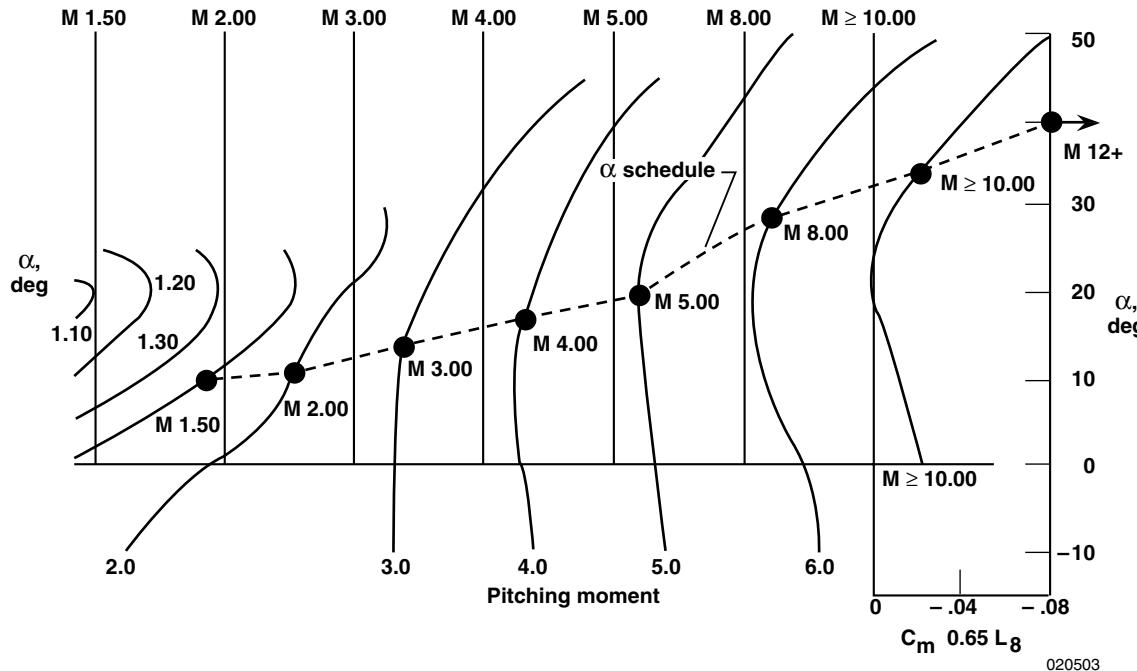
Figure 31. Pitching moment coefficient as a function of angle of attack at various Mach numbers for the Space Shuttle.

The Shuttle, while at a constant α of 40 deg, maintains L/D of approximately 1.0 while decelerating from the Mach 25 entry interface to Mach 12. During this period the Shuttle is on the back side of the L/D versus α curve. As the α is reduced to 20 deg at Mach 4.0, L/D increases to a maximum of 1.8. As speed enters the transonic range and the α is further reduced, the L/D, now on the front side of the curve, is reduced to 1.3 at 6 deg α,[25, 26] and the Shuttle enters the Terminal Area Energy Management (TAEM) approach and landing interface.

STS-1 First Orbital Flight—Reentry and Landing at Edwards

The Shuttle Columbia made the first orbital flight. It was launched from the Kennedy Space Center (KSC) April 12, 1981 and landed at Edwards on April 14. Although the Columbia's approach was from the west over the Pacific Ocean—as opposed to the X-15 airplane approaches from the north and east—the primary station of the High Range, Dryden, was used for the first TAEM entry interface from orbit by the Shuttle.

The photograph that is figure 32 shows a portion of one of the Dryden mission control rooms during the approach and landing. The overhead and desk monitors display television of the landing area of Rogers lakebed, the Shuttle attitude indicator, and various other mission parameters. The large X-Y recorder, second from right, displays a map of the reentry track from the California coast to Edwards.

Figure 32. Portion of one of the Dryden mission control rooms during first Space Shuttle landing, 1981.

As the Shuttle crossed the Pacific coast north of Vandenberg AFB, at approximately Mach 5.5 and at an altitude of 120,000 ft—quite similar in speed, altitude and range to the X-15 aircraft maximum energy post-boost-glides flights—the engineer in front of the recorder would place tick marks on the reentry track for each descending Mach number called by the astronauts. It was an eerie feeling to watch the first reentry Mach numbers and ground track exactly match those predicted and marked on the plot.

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ABOUT THE AUTHOR

Richard E. Day

Before Pearl Harbor, Dick Day volunteered for and flew with the Royal Canadian Air Force. After Pearl Harbor he transferred to the U.S. Army Air Forces and flew B-17 combat missions in Europe in World War II. After the war Dick enrolled at the University of Indiana. In 1951, with a degree in physics and mathematics in hand, Dick joined the National Advisory Committee for Aeronautics (NACA) at the High-Speed Flight Station at Edwards Air Force Base, California, as an aeronautical research engineer. Among his early assignments were the X-1 rocket research aircraft and the XF-92 delta-wing research airplane

In 1953, Day acquired access to the analog computer owned by the U.S. Air Force at Edwards Air Force Base. He programmed the computer with the characteristics of an airplane (as recorded by that airplane in flight), then added a control stick and a cathode ray tube which served as a pilot's display. Thus, he had constructed a rudimentary flight simulator.

Dick soon had the simulator programmed with the characteristics of the Bell X-2 airplane. Data from the most recent flight would be programmed into the simulator. Then, the estimated degradation in stability due to the proposed next increase in Mach number or angle of attack would be added to the program, and the pilot could estimate the controllability that the airplane would exhibit at the predicted flight condition.

Predictions were made for flight 13 of the X-2 that the airplane would experience control reversal if flown to high angle of attack at a speed in excess of Mach 2.4. On flight 13, the X-2 airplane reached Mach 3.2, a speed much faster than predicted. The pilot may have been concerned that he was flying past his landing site (Rogers Lake) at a high rate of speed. A turn was initiated above Mach 2.4, and the angle of attack limit was exceeded. Control reversal ensued, followed by an inertial roll coupling, a pitchup, and a spin. The X-2 airplane was lost and the pilot was killed.

Analysis in the months following the X-2 airplane crash revealed that there was another hazard awaiting the newer, faster rocket research airplanes. The new threat was high energy—high potential energy because of the high altitudes the new, fast rocket airplanes were able to achieve, and high kinetic energy resulting from the high speeds.

The lower-powered rocket airplanes that preceded the X-2 airplane had not required a "launch lake"; that is, a dry lake that could be reached safely for landing if the rocket engine did not light. Their launch lake was also their destination (Rogers Dry Lake). With flight 13 of the X-2 airplane the aeronautical community had outgrown the "one lake" concept when planning rocket aircraft flights.

Soon, the X-15 aircraft was in its speed-altitude buildup, and as the maximum speed of its flights increased, the simulator indicated that the X-15 aircraft could no longer get back to the lake it launched over. Using the simulator, Dick planned a flight that used both a launch lake (Silver Lake) and the destination lake (Rogers Lake). This pair, with the launch lake 100 nmi from Edwards, filled the range requirements for X-15 aircraft flights that went to speeds slightly over Mach 3. For faster flights, Day was able to move the launch out to 200 nmi or even farther. As the flight distances grew longer, the required number of dry lakes increased. An X-15 aircraft launched at Silver Lake might attain a speed

less than that required to glide all the way to Edwards, but too fast to turn back and reach Silver Lake. In order to use Silver Lake as a launch lake, the flight planner had to find a suitable lake along the route of flight that the X-15 airplane could reach after flying out of range of the launch lake and before it could reach Edwards. Some of the long range X-15 aircraft flights required, in addition to the launch lake and destination, three intermediate dry lakes, in order to ensure a landing site, no matter what maximum speed was reached.

With the subject of high-speed aircraft energy management understood, Dick moved on to other challenges. Dick's friend and the former director of the High-Speed Flight Station, Walt Williams, was Director of Operations for Project Mercury at Houston, Texas. Williams knew Dick's capabilities from their work together at Edwards, and in 1962 persuaded him to take the job of Assistant Division Chief for Astronaut Training in the Mercury Project. There, in addition to training astronauts on the simulator, he wrote astronaut tests, served on the astronaut selection board, and devised training programs. One of the subjects taught to the astronauts was energy management.

Dick left NASA in 1964 to join the Aerospace Corporation (El Segundo, California) and work on the Manned Orbiting Laboratory (MOL). His position was Director of Operations. One of the areas under his oversight was astronaut training. When the Manned Orbiting Laboratory was canceled in 1969, Dick left the Aerospace Corporation and worked in a variety of positions in the aerospace private sector. He worked on diverse test programs that included serving as chief aerodynamicist and flight test engineer on the Super Guppy, a C-97 aircraft modified to air-transport segments of large rocket boosters.

In 1975, the High-Speed Flight Station (now renamed the NASA Dryden Flight Research Center) asked Dick to return, to work in Space Shuttle simulation. Dick has worked here as a civil servant or contract engineer ever since.

Dick Day has worked in almost every area of aeronautics and astronautics. His writings are always educational and interesting. *Energy Management of Manned Boost-Glide Vehicles: A Historical Perspective* maintains the standard.

William H. Dana
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As flight progressed from propellers to jets to rockets, the propulsive energy grew exponentially. With the development of rocket-only boosted vehicles, energy management of these boost-gliders became a distinct requirement for the unpowered return to base, alternate landing site, or water-parachute landing, starting with the X-series rocket aircraft and terminating with the present-day Shuttle. The problem presented here consists of: speed (kinetic energy)—altitude (potential energy)—steep glide angles created by low lift-to-drag ratios (L/D)—distance to landing site—and the bothersome effects of the atmospheric characteristics varying with altitude. The primary discussion regards post-boost, stabilized glides; however, the effects of centrifugal and geopotential acceleration are discussed as well. The aircraft and spacecraft discussed here are the X-1, X-2, X-15, and the Shuttle; and to a lesser, comparative extent, Mercury, Gemini, Apollo, and lifting bodies. The footprints, landfalls, and methods developed for energy management are also described. The essential tools required for energy management—simulator planning, instrumentation, radar, telemetry, extended land or water range, Mission Control Center (with specialist controllers), and emergency alternate landing sites—were first established through development of early concepts and were then validated by research flight tests.

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