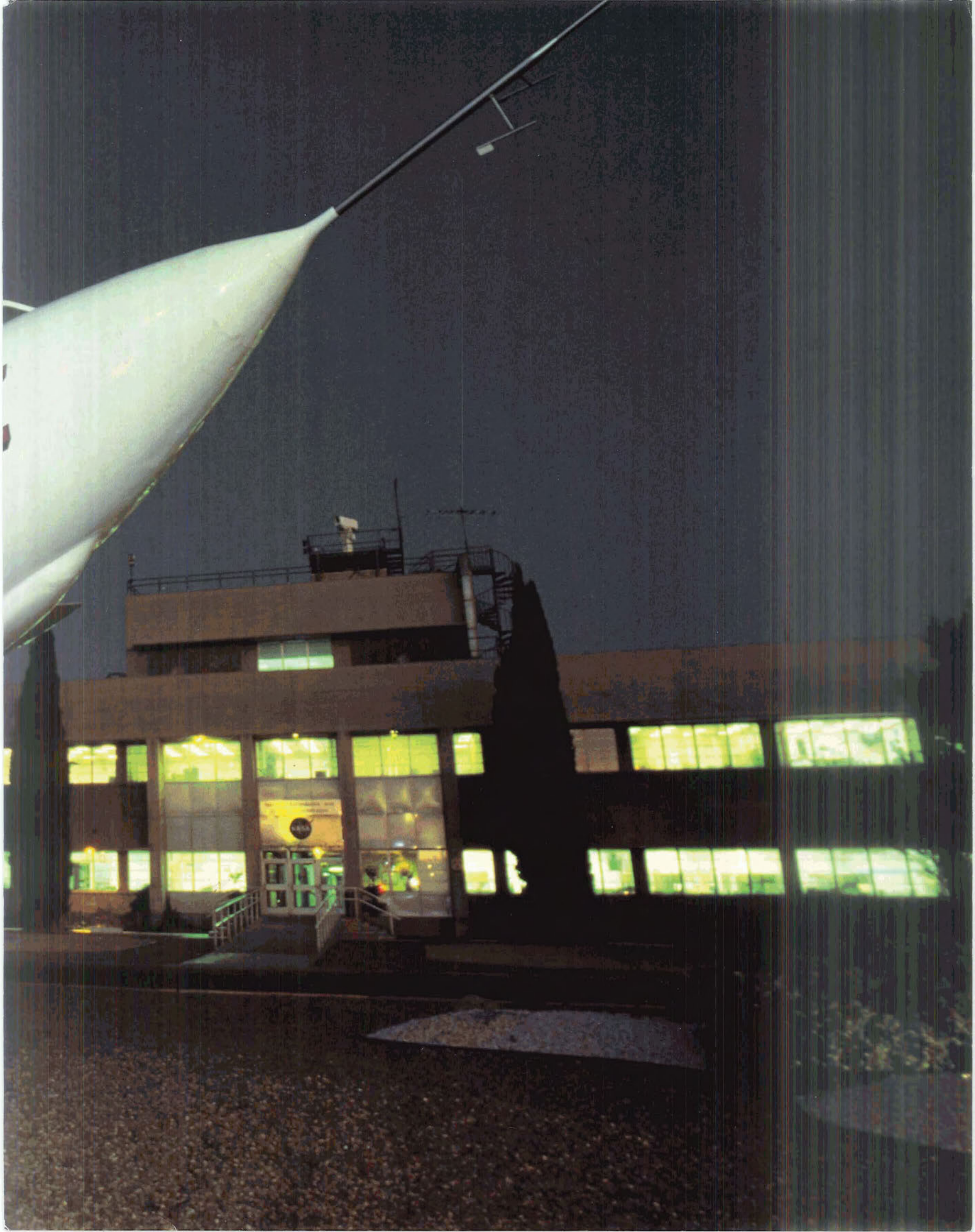


FLIGHTS OF DISCOVERY

50 YEARS AT THE
NASA DRYDEN FLIGHT RESEARCH CENTER





Cover photo:
William S. Phillips' painting of Mach 2 Dawn from the NASA art program. The painting depicts the first Mach 2 flight, which NACA pilot Scott Crossfield achieved on 20 November 1953. In a D-558-2, he climbed into the heavens under a P2B Superfortress (the Navy designation of the B-29), dropped clear of the bomber at 32,000 feet, and climbed to 72,000 feet before diving to 62,000 feet, where he became the first pilot to attain the Mach 2 milestone.

Inside front cover:
The X-1E on a pedestal in front of the Dryden Headquarters building (NASA Photo ES96 43421-1)

Inside back cover:
Moonrise over Atlantis. Following the STS-76 dawn landing at Dryden on 31 March 1996, the orbiter Atlantis was prepared for delivery to Kennedy Space Center and placed atop NASA 905, one of two modified Boeing 747 Shuttle Carrier Aircraft the evening of 5 April 1996. (NASA Photo EC96 43493-1)

FLIGHTS OF DISCOVERY

by Lane E. Wallace



50 YEARS AT THE
NASA DRYDEN FLIGHT RESEARCH CENTER

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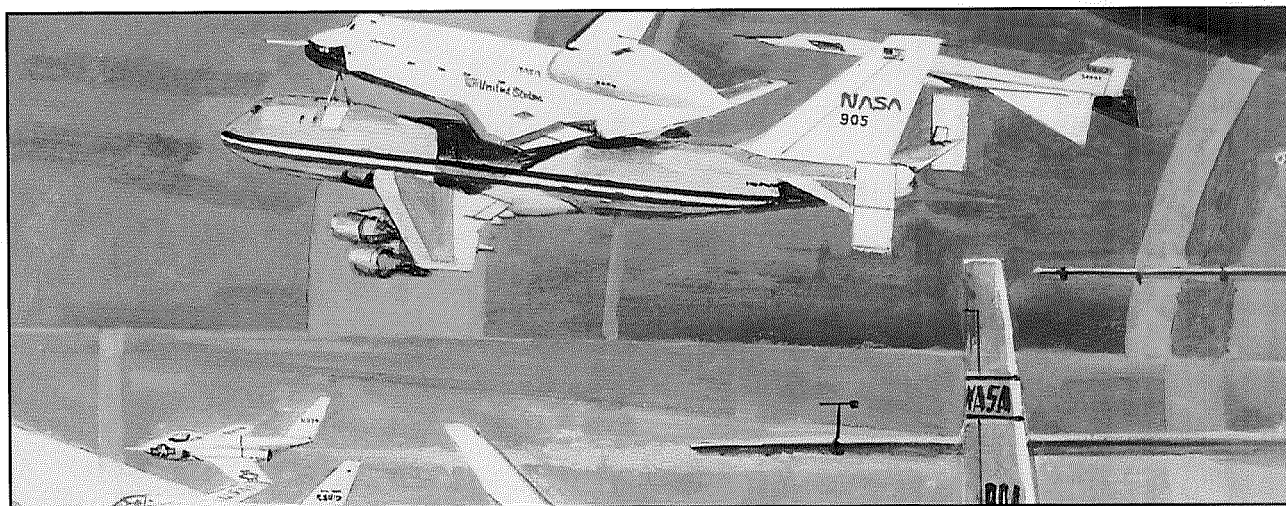
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**To my friend Jim
For believing**

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► Foreword



This volume adds another dimension to the existing literature about the history of the Hugh L. Dryden Flight Research Center (DFRC). While previous accounts—most notably Dick Hallion’s superb *On the Frontier: Flight Research at Dryden, 1946-1981*—cover part of Dryden’s history from one perspective or another, this is the first book to provide an overview of the entire 50 years of the Center’s history from several perspectives.

In this book, Lane Wallace also provides insights into the process of research engineering. She differentiates between flight testing and flight research, and she describes the

“technical agility” of researchers at Dryden—a quality that has been an enormously important ingredient in the process of discovery through flight here in the Mojave Desert. She has also captured the spirit of the role flight research plays in the aeronautics research and development chain.

Lane Wallace has included some “behind-the-scenes” events that provide additional insight into the human side of this highly technical discipline. Dryden frequently puts the innovations and ideas of others to the ultimate test of real flight conditions. The products of theory, wind-tunnel testing, and computational

Early members of the Dryden Team, although the organization that became the Dryden Flight Research Center was then called the NACA High Speed Flight Research Station. Left to right, standing: Beverly Smith, Lilly Ann Bajus, unidentified, John Cardon, John Rodgers, unidentified, Hubert "Jake" Drake, Walter C. Williams; seated and kneeling: Mary Little, Harry Claggett, Ed Holleman, Angel Dunn, Roxanah Yancey, De E. Beeler (early 1950s) (NASA Photo E96 43403-12)



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"The history of any institution is really the history of its people. The advances in aeronautics and space technology at Dryden were literally bought with blood, sweat and tears."

.....
fluid dynamics—often developed elsewhere—are absolutely critical ingredients in the process of aeronautical discovery. In this book, Lane Wallace has captured very effectively many of the ways in which Dryden has cooperated with its partners over the past half-century to advance the process of aeronautical discovery that has so often begun with Dryden's partners.

An important part of the Dryden spirit was bequeathed by its first Director, Walter C. Williams. He joined the National Advisory Committee for Aeronautics (NACA) in August of 1940. During World War II, he was a project engineer in the evaluation of several fighter aircraft—the P-47, P-51, and F6F—looking at handling qualities, low- and high-speed flight characteristics. As a member of Hartley A. Soulé's stability and control branch at Langley Memorial Aeronautical Laboratory, he was one of the NACA's foremost research airplane advocates. He led the first NACA team at Muroc and became the first Director of what was to become DFRC

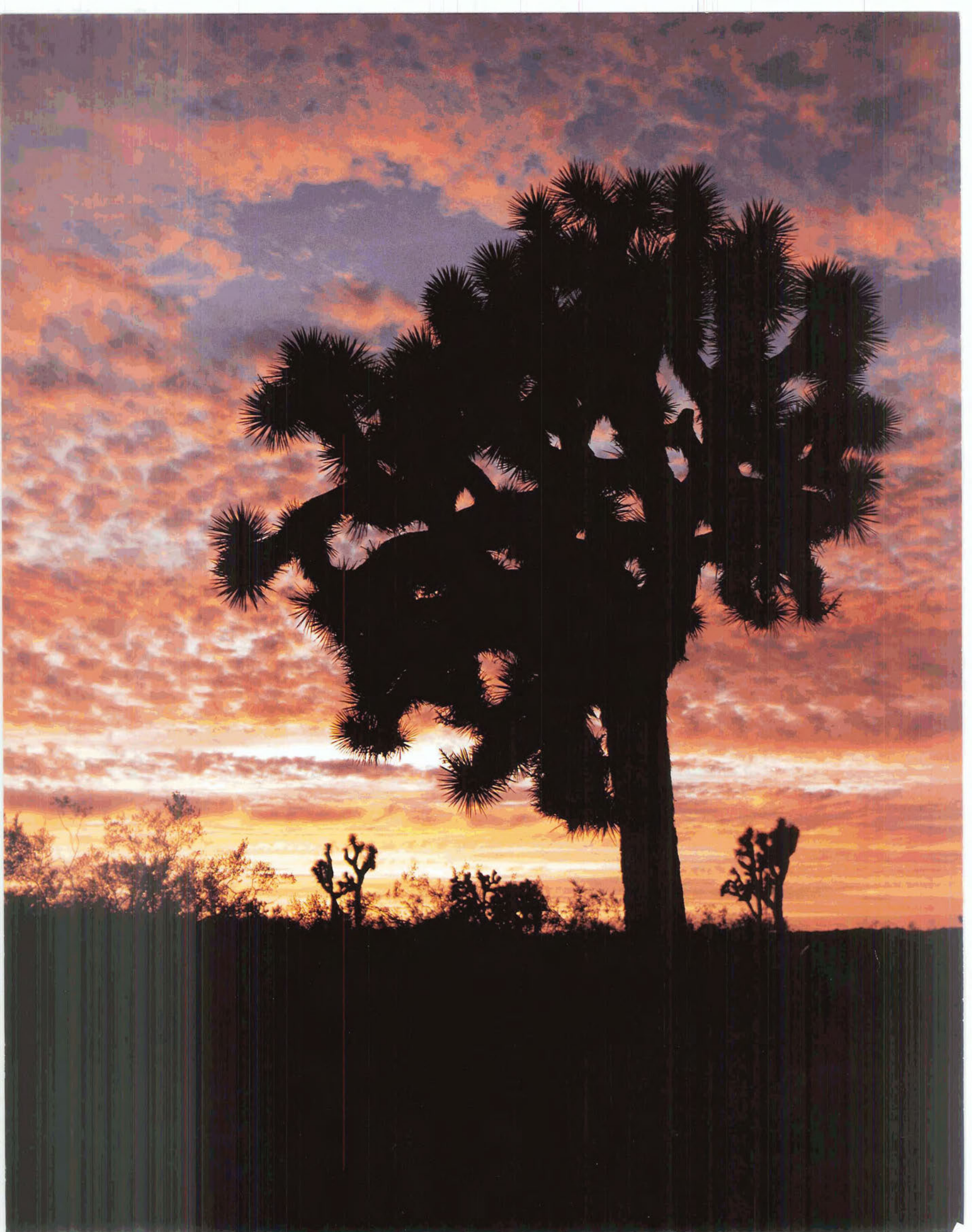
He had tremendous experience in the flight testing of high-performance aircraft. As Dick Hallion noted in *On the Frontier*, Walt "was an inquisitive, take-charge sort of engineer, a man who believed that useful research had to confront actual problems and not be limited to studying theoretical aspects of aeronautical science." This outlook continues to be the basis of our work here at Dryden—the study of aeronautical phenomena and the applications

thereof, the solving of practical problems.

It's clear that Dryden owes its heritage to Walt, who died peacefully at his home in Tarzana, California, on 7 October 1995. To him, for example, we owe our emphasis on research instrumentation, on getting the data we need; on safety and quality assurance; on careful flight planning by a small, integrated, and highly competent team. We also got from him our willingness to tackle the most difficult and seemingly impossible tasks. The project structure we use today was really invented in these early years.

History records all of the technical accomplishments in terms of Mach number, altitude, maneuverability, orbits, and the like. For these alone, Walt will be remembered and honored. But historians will never capture in words the zeal and zest that Walt put into his life and work. This same spirit lives on today at NASA Dryden. The history of any institution is really the history of its people. The advances in aeronautics and space technology at Dryden were literally bought with blood, sweat and tears. I therefore dedicate this book to the Dryden Team that has given so much to accomplish the flight research mission for 50 years.

17 April 1996 Kenneth J. Szalai
Director
Dryden Flight Research Center



► Chapter One:

A Place for Discovery

A large, stylized, decorative initial letter 'L' in a serif font, positioned at the start of the first paragraph.

Less than 100 miles north of the bustling international city of Los Angeles lies a barren, windswept landscape known as the Mojave Desert. It is an unfriendly environment known for blazing summer temperatures and bone-chilling winter winds, a place once described by then-Colonel Henry H. “Hap” Arnold as “not good for anything but rattlesnakes and horned toads.”¹

Yet for all of its desolation, the desert also contains unique gifts. It offers unending days of piercing blue skies; dawns and sunsets that dust its rocky mountain sides with breathtaking hues of color. And while its arid landscape and dry lakebeds support little vegetation, for the past half century they have provided an ideal environment for pilots, researchers and engineers to test and explore new concepts in flight.

Joshua trees in desert at sunrise



It was above this stark expanse of land that the notorious “sound barrier” was finally broken; that innumerable speed and altitude records were set and quickly surpassed; that the first Space Shuttle proved it could land safely without power. It was here that the X-15 taught researchers valuable lessons about hypersonics and space; that the first fully digital fly-by-wire aircraft was flown; and that a pilot successfully landed a transport aircraft using only thrust for engine control.

Over half a century, this desolate location has allowed innumerable technologies to be explored, improved upon, and given enough credibility for industry to accept and apply them. And what began as a small, temporary detachment to support a single research project

has evolved into a substantial National Aeronautics and Space Administration (NASA) facility known today as the Hugh L. Dryden Flight Research Center.

There are three things that made the Mojave Desert so well suited for flight research. The first was the area’s flying conditions, which included clear skies and 50 or 100 miles of visibility almost every day of the year. The second was Rogers Dry Lake—a 44-square-mile natural landing site that General Albert Boyd referred to as “God’s gift to the Air Force.”² The third factor was that the lakebed was surrounded by miles and miles of virtually uninhabited desert, providing a buffer zone where rocket and jet aircraft could be operated safely and with far fewer restrictions than a

X-1 with crew: left to right, Eddie Edwards; Bud Rogers, Dick Payne, crew chief; Henry Gaskins (NASA Photo E-49-00039)

Although the NACA and the Air Force would continue until June of 1948 "neither [to] confirm nor deny" the story of Capt. Charles "Chuck" Yeager's breaking the sound barrier on 14 October 1947, the *Los Angeles Times* was one of a number of publications that reported the story in late December. Apart from the facts that Yeager had exceeded the speed of sound in the XS-1, the reporting was rife with so-called "facts" that were nothing more than sheer speculation. Nearly two years would elapse, for example, before the XS-1 came close to the 70,000 feet the *Times* reported as already reached. The *Times* also reported that NACA research pilots Howard Lilly and Herbert Hoover had already "duplicated Yeager's feat." In fact, Hoover became the NACA's first supersonic pilot nearly three months after the article appeared, in early March 1948, followed by Lilly about three weeks later. (Air Force Photo)

more populated area would require.

The Army's initial interest in the area around Rogers Dry Lake was as a bombing and gunnery range in the years preceding World War II, and a formal army air base was established near the town of Muroc in July 1942.³

But it was the advent of jet engines and higher speed aircraft that highlighted the real strengths of the desert location. The new experimental jet aircraft, starting with the Bell XP-59A, required longer runways than most air bases had, and the classified nature of the research required a remote site for flight testing. The Muroc Army Airfield, officials realized, was the perfect choice for this kind of work.

These same reasons led the Army Air Forces, Bell Aircraft, and the National Advisory Committee for Aeronautics (NACA) to choose Muroc as the test site when they undertook the challenge of designing and building a research aircraft to break the notorious "sound barrier." In the fall of 1946, the first NACA contingent of 13 engineers, instrument technicians, and support staff arrived at the Muroc Army Airfield to support the X-1 effort.⁴

The X-1 project was just one of many

research efforts the NACA had undertaken to expand the country's knowledge and understanding of aeronautics. Established in 1915, the NACA's mission was to "supervise and direct the scientific study of the problems of flight, with a view to their practical solution."⁵

The committee was to help the fledgling aeronautics industry by conducting research that manufacturers could not, either because the work was too expensive, long-range, or required facilities industry lacked.

By 1946, the NACA had already made numerous contributions to aeronautics. But the coming of the high-speed jet age at the close of World War II brought new

challenges. Ground facilities did not exist that could adequately simulate the dynamics of the transonic environment, which included speeds above Mach 0.85 but below Mach 1.2. The first slotted-throat transonic wind tunnel, which provided much better data at speeds approaching and surpassing the speed of sound, was not developed until 1950.⁶ A large part of the rationale for building the X-1 was because at that time there was no other way to gather reliable information about transonic flight.



The Role of Flight Research

It was not only the lack of ground facilities that provided the justification for exploring ideas in flight, however. The importance of trying out new concepts and designs in flyable aircraft was understood even by Wilbur Wright, who in 1901 argued that “if you are looking for perfect safety you will do well to sit on a fence and watch the birds, but if you really wish to learn you must mount a machine and become acquainted with its tricks by actual trial.”⁷

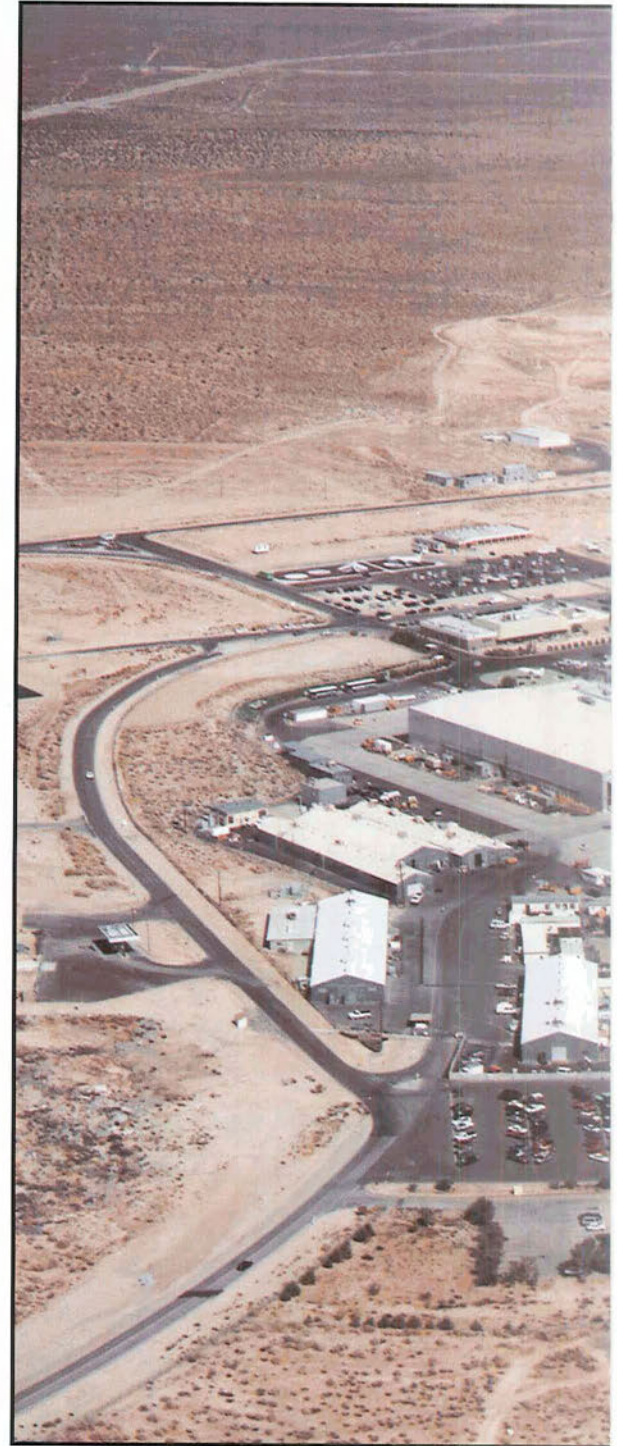
The NACA shared Wright’s belief, and flight research has always played a critical role in the work of both the NACA and its successor agency, NASA. By the mid-1960s, ground facilities were much more capable than they had been in the days of Wilbur Wright or the X-1, but NASA administrator James E. Webb still considered flight research a critical activity. In 1967 he testified before Congress that

Flight testing of new concepts, designs, and systems is fundamental to aeronautics. Laboratory data alone, and theories based on these data, cannot give all the important answers. . . . Each time a new aircraft flies, a “moment of truth” arrives for the designer as he discovers whether a group of individually satisfactory elements add together to make a satisfactory whole or whether their unexpected interactions result in a major deficiency. Flight research plays the essen-

tial role in assuring that all the elements of an aircraft can be integrated into a satisfactory system.⁸

That argument still holds true today. No matter how sophisticated laboratory technology becomes, computers can only simulate what is known. The unknown is always, in a sense, unpredictable. A computer can extrapolate what *should* happen as a logical extension of what has happened up to that point, but the outcome cannot be assured until it is tested in realistic conditions. Flight research is where that testing occurs. It is that unique point where the rubber meets the road, where the aircraft, human, and real-life flight conditions come together for the first time. And because flight research explores that ragged edge between the known and the unknown, it is a place where discovery happens.

Discovery is that moment of divergence where something other than what was expected occurs. Indeed, researchers say a discovery is marked less often by a shout of “Eureka!” than by a perplexed murmur of “That’s odd. . . .” And for all the improvements in ground and laboratory facilities, there has yet to be a flight research project conducted at Dryden that did



Aerial of NASA facility and desert beyond as of 1992 (NASA Photo EC92 10204)



not have at least one such moment.⁹ Sometimes, the discovery shows only that the computational codes used to predict the performance of the aircraft need to be adjusted. Other times it turns the research in an entirely different direction, opening up a whole new set of questions from those envisioned at the start of the project.

In either case, it is these discoveries that

slowly expand our understanding of the world of aeronautics. And it is the pursuit of these discoveries that differentiates flight research from the closely related discipline of flight test.

The Air Force Flight Test Center (AFFTC) is situated just a short hike down the flightline from the Dryden Flight Research Center at what is now Edwards Air Force Base. The flightlines of both centers display an impressive array of high performance aircraft and, to a casual observer, there might seem little difference in the work the two facilities do. Both centers employ highly skilled pilots who fly new and experimental aircraft configurations to precise test points. In both cases, data from those maneuvers is collected by various types of instrumentation and recorded or sent back to the ground, where it is processed by engineers, technicians and analysts.

The difference between flight test and flight research lies not in the mechanics of each operation, but in the questions that drive the work and how unexpected discoveries are viewed. In flight test, the objective is to compare the airplane's performance against set specifications it is supposed to meet. The idea is not to explore new realms of aeronautical knowledge, but simply to make sure that a new aircraft design or configuration performs in an acceptable manner. Unless the anomaly is better-than-predicted performance, unexpected results in a flight test program indicate problems that need to be fixed. The information gained through flight test is also directed toward a specific customer with regard to a specific product.

Flight research, on the other hand, gathers information that can be used by a much wider audience for a wide variety of applications. In addition, flight research involves



much broader questions. The objective is not simply to determine if an airplane performs in a certain way, but to understand why it does and to explore various factors that affect that performance. Discoveries are not problems to be fixed but doors opening into new realms of possibility. They give researchers a glimpse into the world beyond what we know, raise new questions and often lead to entirely new lines of research.

Discovery can and does happen in all types of research settings. But the potential for discovery is particularly great in flight research because it is an arena where so many variables

and unknowns come together. For all of our technological advances, there is still much we do not understand.

Supersonic aircraft, for example, have been flying since the late 1940s. Yet although aeronautical engineers have learned how to design aircraft that can function in the supersonic realm, even researchers do not fully understand the dynamics of that environment. As Marta Bohn-Meyer, project manager of Dryden's supersonic laminar flow research program, says, "The more we get into this, the more I realize how little we really know about what happens in the transonic and supersonic

NB-52A (tail number 003) making a pass over one of the X-15s following a lakebed landing. One of only three B-52As produced, 003 was one of a pair of highly modified Stratofortresses—the other being NB-52B number 008—that were used to launch X-15s at speeds of 600 miles per hour and at altitudes of up to 45,000 feet. Scenes such as this typically took place 20 minutes or more after the X-15 had touched down, because the NB-52 returned from a launch point 200 to 300 miles northeast of Edwards. (NASA Photo EC61 0034)



Group airplane photo, X-24B, F-15 Remotely Piloted Vehicle, F-111 Transonic Aircraft Technology, F-8 Digital Fly-By-Wire, F-104s, T-38, PA-30, Jetstar, Aerocommander, R-4D (Gooney Bird), F-111 Integrated Propulsion Control System, and the small remotely-piloted research vehicles in the foreground (6 May 1974). (NASA Photo ECN 4029)

regions.”¹⁰

The problems have also become more complex. In 1946, researchers were simply trying to see if it was possible for an aircraft to surpass the speed of sound. Today, the goals are broader. We want not just supersonic aircraft, but efficient, environment-sensitive supersonic aircraft, or highly maneuverable supersonic aircraft. So despite all the advances in aeronautics, flight research is still operating at the cutting edge of knowledge.

Even elements that are understood individually may interact in an unexpected manner when they are brought together in a

realistic flight environment. This is especially true for any aircraft that requires a human pilot. Time after time, for example, computerized flight control systems for aircraft have been tested successfully in simulators, only to exhibit different tendencies in actual flight. One reason for this is that simulators rely on predicted data to model a new aircraft or system’s performance. But another cause is the simple fact that pilots react differently in simulators, where even the worst mistake will cause them only embarrassment, than in an aircraft where the stakes are very real and very high. Yet if the end goal of aeronautical research is to improve



the design of practical, flyable aircraft, it is essential to explore those reactions and discover potential problems with configurations or technology.

Indeed, another important function of flight research is that it forces researchers to focus on those particular problems that are truly critical to developing usable technology. Many interesting questions can arise in the course of laboratory and ground research. But putting a piece of technology on a flyable aircraft quickly differentiates those questions that are low-priority curiosities from those that suggest critical issues to address. Furthermore, a problem identified as critical cannot simply be put aside to be studied later. It has to be solved.

In part because so many operational problems have to be addressed and solved before a concept can be tried on an aircraft, flight research can also play an important role in winning industry's acceptance for new technology. Technology that has been explored in flight is generally more mature than concepts investigated only in laboratory or simulator settings, leaving a smaller gap for industry to bridge in order to incorporate it into commercial

products.

Furthermore, there is a measure of credibility that can be achieved, almost instantaneously, from a successful demonstration of a technology on an actual aircraft in realistic flight conditions. As a former vice president of engineering at the Boeing Commer-

cial Airplane Company argued, "laboratory development has great appeal and usually gets substantial government support. However . . . the attainment of credibility is [also] an important national issue. It is during this second phase that a technical concept achieves a state of readiness, validation and credibility such that private industry and financing can assume the attendant risks."¹¹

In some cases, laboratory research is sufficient for industry to see the benefits of a concept and invest in it. But especially as technology becomes more complex and expensive, making a commitment to a new technology is an increasingly difficult and risky gamble for industry to make. An idea that has been proven successful in realistic flight conditions is much more convincing, because while it might still be uneconomical or impractical, industry decision-makers at least know it can work.

Giving aerospace manufacturers the confidence to invest in new technology can, in turn, increase their global competitiveness. This has important implications, because aerospace is one of the few remaining fields in which the United States still has a trade surplus. If the



Above left: SR-71 crew members with aircraft. (NASA Photo EC91 056.Fr 16)



*SR-71B Mach 3 trainer
at sunset.
(NASA Photo
EC95 43351-1)*

country is to improve its balance of trade and overall economy, the aerospace industry must remain competitive.

Supporting National Priorities

Of course, global competitiveness has not always been the driving national concern that it has become in recent years. But the flight

research conducted at Dryden¹² over the past half century has played an important role in furthering the country's priorities, whatever they were.

In the post-World War II era and the Cold War of the 1950s, the drive was to develop aircraft that could go higher and faster, exploiting speed and power to maintain superiority over Soviet aircraft and defense systems. Dryden's work reflected this theme with its X-



planes and its efforts to improve a variety of military jet aircraft designs. After the launch of Sputnik in 1957, the space race also became a high national priority, culminating in the Apollo effort throughout the 1960s. At Dryden, those priorities were paralleled by its X-15 and lifting bodies research, as well as efforts such as the Paresev and the Lunar Landing Research Vehicles.

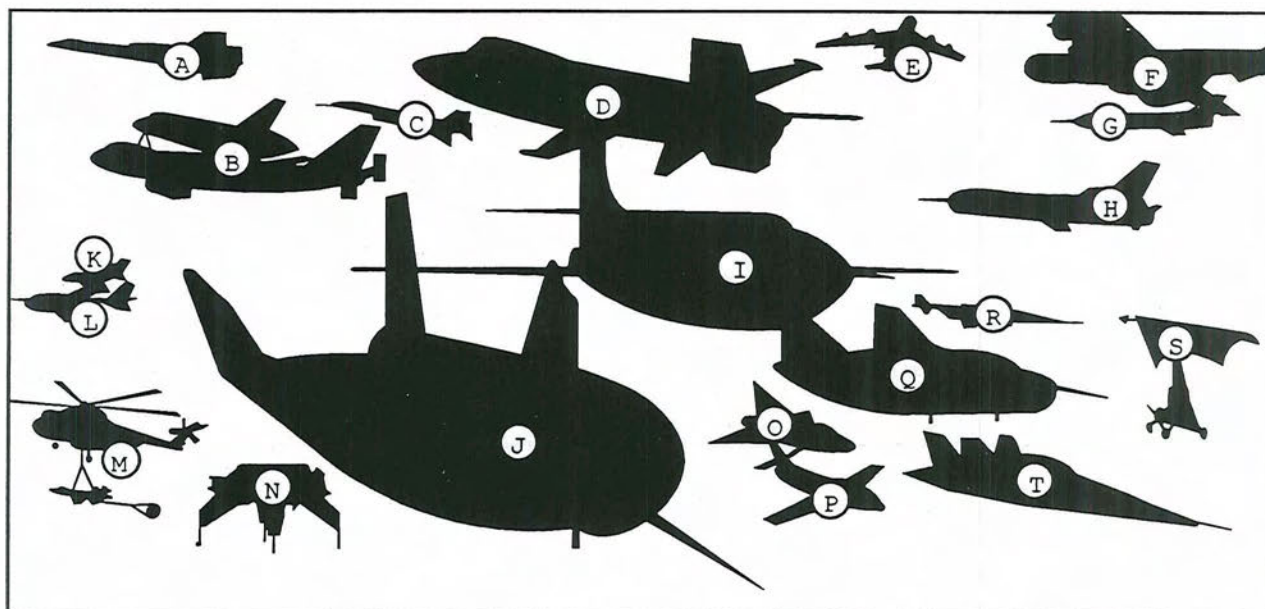
Another national priority in the 1960s was the development of a civil Supersonic Transport (SST). This goal spawned a number of high-speed research projects at Dryden, including work with the Mach 3 XB-70 and YF-12 aircraft. But environmental concerns, an economic recession and a burgeoning fuel crisis in the 1970s shifted the country's priorities to improving the fuel efficiency and internal

systems of aircraft. Dryden's focus shifted with the nation's, leading to projects such as the Supercritical Wing and winglets, which made aircraft more aerodynamically efficient, and to the world's first purely digital fly-by-wire airplane, which opened a whole new realm of efficient and capable aircraft design.

The country's need for higher performance aircraft continued into the 1980s, leading to research at Dryden that focused on understanding the dynamics associated with more maneuverable and capable configurations. The X-29, the HiMAT, the F/A-18 High Alpha Research Vehicle (HARV) and the X-31 research planes all reflected this priority in one way or another.

Interestingly enough, the 1990s have brought a renewed national interest in higher

Robert McCall's famous mural entitled The Spirit of Flight Research depicts the aircraft flown during Dryden Flight Research Center's first 30 years. McCall completed the painting the year after the renaming of the Center in honor of Hugh Latimer Dryden. (NASA Photo EC96 43416-3)



Key to Aircraft

A. YF-12: Predecessor to the SR-71, flew at Dryden in a high speed research program from 1969-79.

B. 747/Orbiter Enterprise:

747 shuttle carrier aircraft carried *Enterprise*, prototype orbiter, aloft during 1977 approach and landing tests at Dryden.

C. XB-70: flown from 1967-69 in a high speed research program.

D. X-15: Rocket-powered research aircraft flew 199 missions from 1959 to 1968. The X-15 still holds the world's absolute speed (4520 mph) and altitude (345,200 ft) records for winged aircraft.

E. B-52: Pictured carrying the X-15, NASA's B-52 air launch aircraft, NASA 008 has been used since the late 1950s to air launch a variety of piloted and unpiloted vehicles.

F. B-50: A modified B-50, and an earlier B-29, were used to air drop research and experimental aircraft in the 1940s and 1950s.

G. D-558-2: The D-588-2 Skyrocket, dropped from the B-50 launch aircraft, flew from 1948-56 to investigate the swept-wing configuration at supersonic speeds. First aircraft to fly twice the speed of sound.

H. F-8SCW: Supercritical wing research was carried out at Dryden

on a modified F-8 from 1971-73. Concept now used on many transport and fighter aircraft.

I. X-1: The X-1 became the first aircraft to fly faster than sound on October 14, 1947. Pilot was then-Captain Charles E. Yeager, one of the several project pilots assigned to the joint NACA/Army Air Corps project. History of Dryden dates to 1946 and the X-1 project.

J. HL-10: Fastest and highest flying of the five lifting body designs flown at Dryden from 1966-75. Research aided space shuttle program. HL-10 now displayed at Dryden entrance.

K. X-4: Semi-tailless vehicle flown from 1948-54 in studies of stability and control at transonic speeds.

L. X-5: First aircraft capable of sweeping wings in flight, flew from 1950-54.

M. HH-53: HH-53 aerial recovery helicopter carries NASA's F-15 3/8 scale remotely-piloted research vehicle used in stall-spin research program.

N. LLRV: Lunar Landing Research Vehicle, flown in mid -1960s, developed control system used on the Apollo lunar module to land astronauts on the moon's surface and on the Apollo astronauts' training vehicle.

O. XF-92: First delta-wing aircraft flew at Dryden from 1951-1953.

P. D-558-1: D-588-1 Skystreak was flown from 1947-53 in a program to investigate safety of flight at transonic speeds.

Q. M2-F2: First heavyweight lifting body was the M2-F2, flown from 1966-67. Damaged in a landing accident and rebuilt as M2-F3 with a third vertical tail and flown from 1970-72. Now displayed at the Smithsonian National Air and Space Museum.

R. X-3: Dubbed the Flying Stiletto, X-3 flew from 1952-55 to gather data on supersonic flight and use of titanium and stainless steel in aircraft construction.

S. PARESEV: Between 1962-64 the PARESEV 1A vehicle (paraglider research vehicle) studied wing configurations as possible methods of returning vehicles through the atmosphere from space.

T. X-24B: Last of the lifting bodies, the X-24B flew from 1973-75 in a program aiding in development of the space shuttle. It was developed from the X-24A airframe.



Shuttle mate/demate facility with Space Shuttle Endeavour in it. Endeavour had just completed its first flight (STS-49) from 7 May 1992 to 16 May 1992, when this photo was taken. (NASA Photo EC92 05169-1)

and/or faster aircraft—but with a twist. The impetus for high flying aircraft is fueled largely by the need to gather information on the Earth's atmosphere, and that avenue of research is focusing primarily on small, remotely piloted vehicles. NASA's initiative for a High Speed Civil Transport (HSCT) differs significantly from the 1960s goal of a Supersonic Transport in that it now must be economical and environmentally sensitive as well as fast. Not surprisingly, therefore, the work Dryden is conducting to support NASA's High Speed Research program is looking not just at speed, but at technologies such as achieving supersonic laminar flow and mapping the parameters of sonic booms. A national concern with making access to space more economical is also driving Dryden's current research into reusable launch vehicles such as the X-33.

Not all of the research conducted at Dryden fits neatly into these chronological national themes. Efficiency, for example, is an important issue in any aircraft design and has always been a concern for aerodynamicists working on furthering the basic research and technology knowledge base. Layered on top of those basic research efforts, however, are more focused research programs such as the X-15, the Aircraft Energy Efficiency (ACEE) program, or the Space Shuttle, which are more closely tied to shifts in national concerns. And on this level, there have always been inescapable parallels between the focus of Dryden's research and the nation's technological and economic priorities. This is hardly surprising, of course, given that NACA/NASA has always been funded by the national government. Congress is unlikely to approve funding for research that is totally irrelevant to national concerns. Yet it is not just funding that drives

the type of research Dryden performs.

The managers and researchers at the Dryden Flight Research Center understand that their mission is not only to advance their own ideas but also to provide support to other NASA centers, government agencies, the military, industry and, in the end, the American public. Consequently, only perhaps 50 percent of the work the Center does is "exploratory" research stemming from long-term objectives developed with its various research partners. The other half of its work comes from requests by other centers, government agencies, the military, or industry for help on other programs or efforts. Programs on stall-spin characteristics of small airplanes, tests of an experimental anti-misting fuel, and research on shuttle thermal tiles and tires are just a few of the many such projects Dryden has undertaken over the years.

Dryden Contributions

Yet whether the research was initiated by Dryden, industry, or by another center or agency, the work conducted by the Center and its research partners over the past 50 years has made some very important contributions to the aerospace efforts of both government and industry. In some cases, the impact of the research has been clear and direct. The flight experience with the X-15 and the lifting bodies, for example, provided the space program with critical information about the use of reaction controls and gave the designers of the Space Shuttle the confidence to have it land without power. Research with the X-3 led to the identification of both the cause and a cure for a lethal inertial roll coupling problem that had plagued the F-100 jet fighter and other aircraft of the 1950s. The Supercritical Wing has been applied

to numerous aircraft, including all new large commercial transports and the AV-8B Harrier, and winglets tested at Dryden have been used on many corporate jets as well as on the Boeing 747-400 and McDonnell Douglas MD-11 airliners.

After a potentially dangerous pilot-induced oscillation (PIO) was discovered in the final pre-launch landing test of the first Space Shuttle, Dryden engineers were able to design a suppression filter that fixed the problem without forcing a redesign of the Shuttle's entire flight control system. Research into a Digital Electronic Engine Control (DEEC) system with a Pratt & Whitney F100 turbofan engine resulted in a DEEC system being incorporated into the company's production model engines. A problem with compressor stalls in an upper corner of the F100's operating envelope was also successfully analyzed and solved as a result of the research.

In other cases, the Center's research has advanced technology or understanding in areas that have yet to be applied. The X-29, for example, demonstrated the feasibility of a composite, forward-swept-wing design. There is currently no production aircraft that incorporates this particular technology, but that does not mean that there won't be one some time in the future. The variable-camber, supercritical, variable-sweep wing Dryden investigated on an F-111 proved the validity of the technology, although it has yet to be used. Dryden researchers, in partnership with industry, also developed an integrated, computerized flight and engine control system that allowed a NASA pilot to successfully land both an F-15 fighter jet and an MD-11 transport airliner using only throttle controls. This technology is too recent a development to have spurred any commercial appli-

cations yet, but several tragic airline accidents have been caused by partial or complete loss of hydraulic power that rendered the flight controls useless. Since a propulsion control system could help prevent this kind of accident, it might be incorporated into airliners before too long.¹³

Harder to trace, but no less important, are the less direct contributions made by research conducted at Dryden. There are many instances where, although the technology was not applied directly, the Center's research expanded the knowledge base of aeronautical engineers or changed people's thinking on what was possible. In addition to the direct technology that was developed and transferred to industry through the Digital Fly-By-Wire program, for example, the research created an important element of confidence in the basic concept. The fact that Dryden research pilots had flown the fly-by-wire research aircraft without any mechanical back-up controls was a factor in determining how decision-makers' viewed the technology's reliability. That, in turn, led to the design of pure digital fly-by-wire systems for the F-16 C/D and the F/A-18 Hornet fighters, and eventually the Boeing 777 airliner.¹⁴

By the same token, Dryden's structural flutter research with a Remotely Piloted Vehicle (RPV) led to improved real-time flutter analysis algorithms for designers to use. The F/A-18 HARV is exploring actual airflow dynamics at extremely high angles of attack in order to make the formulas used to predict this flow more accurate. This information, in turn, can allow engineers to design aircraft that will perform better in that flight regime. And a series of mathematical procedures developed by Dryden researchers to extract previously unob-

tainable aerodynamic values from actual aircraft responses in flight, a process known as parameter identification, has become an international standard. This definitive contribution allowed flight researchers for the first time to compare certain flight results with predictions.

In short, the contributions Dryden has made over its 50-year history have been as varied as the aircraft its pilots have flown.

Sometimes the contribution was a small piece of technology, a design approach, or a new element or degree of accuracy in the basic aeronautical knowledge base. And sometimes, like the faint traces of pioneer wagon wheels that might still be found decades later, Dryden's contribution was simply to have gone into new territory first,

exploring a new configuration or concept that was too advanced, risky, or expensive for industry to pursue on its own.

Conclusion

The road to discovery is not an easy one. In order to make contributions to technology or to our understanding of aeronautics and aerospace, research has to be working on the cutting edge of knowledge. There is a constant tension in flight research that is characterized as "risk

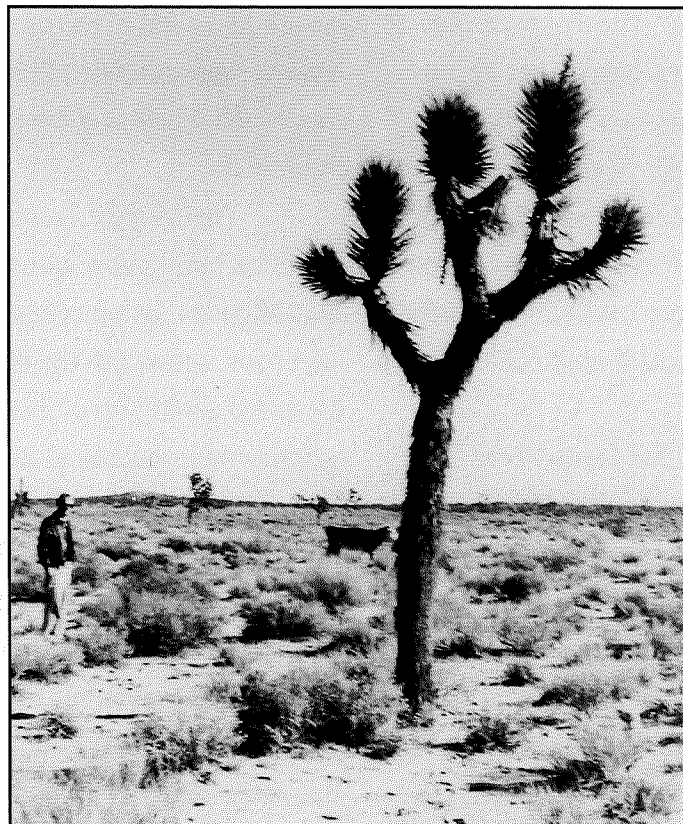
versus reach."¹⁵ To take too small a step is to discover nothing new. To take one too large is to invite catastrophe. And the burden of constantly walking the thin line between those two extremes is one that every researcher at Dryden carries.

Walt Williams, head of the small NACA contingent that arrived at Muroc to support the X-1 program, recalled that the engineers "devel-

oped a very lonely feeling as we began to run out of data" near the speed of sound.¹⁶ It is a feeling well understood by anyone who has ever stood on the brink of the unknown. The designers of the Northrop B-2 must have felt it the morning of the Flying Wing's first flight. The managers at the Johnson and Kennedy Space Centers undoubt-

edly grappled with it as they gave the go-ahead for the first Shuttle mission. At Dryden, it is a feeling researchers confront almost every time they approve new configurations and modifications for flight.

For no matter how well engineers and analysts try to anticipate every possible problem and reaction, physical exploration of the unknown is never without risk. There is always a moment when someone has to make the decision that "enough" has been done and it is time to go fly, knowing that if a mistake has been



*Joshua tree with cow and unidentified person
(NASA Photo E96 43403-5)*

made, someone can die. Yet it is the willingness of people to step into that lonely abyss of the unknown—whether it was Lewis and Clark exploring the western wilderness, Wilbur and Orville Wright launching the first powered aircraft, Charles Lindbergh setting off across the Atlantic, or Captain Charles “Chuck” Yeager pushing the X-1 through the speed of sound—that has allowed progress to occur.

“We do these things,” President John F. Kennedy said in his famous 1961 space challenge, “not because they are easy, but because they are hard.”¹⁷ For 50 years, the Dryden Flight Research Center has been a place where “hard” problems have been welcomed. It is a place where people are encouraged to question and look for the unexpected, where it is understood that the answers exist and the challenge is to find them.

Hugh L. Dryden, the former NACA director of research for whom the NASA flight research center is named, once said that flight research separates “the real from the imagined.”¹⁸ His statement is true in more ways than one. In many cases, flight is that critical element in the interdependent disciplines of laboratory, wind tunnel and simulator research that finally turns an idea into hard, tangible reality. In every case, however, it forces researchers to go beyond imagined difficulties and grapple with those very real, critical problems that will make or break a technology or design.¹⁹

It is an effort not without risks or cost. Out of the original “X-series” and Douglas D-558 research airplanes, for example, four

exploded while still attached to the launch aircraft, one crashed in a stall-spin accident, one came apart in mid-air, and one crashed after a catastrophic engine failure on take-off. Over the years, no fewer than nine aircraft have been lost and a number of pilots and crew members have given up their lives in the course of flight research projects associated with Dryden.²⁰ But the research conducted at the Center has also resulted in innumerable advances that have saved lives, led to the design of better and more capable aircraft, and expanded our understanding of the world and the atmosphere that surrounds it.

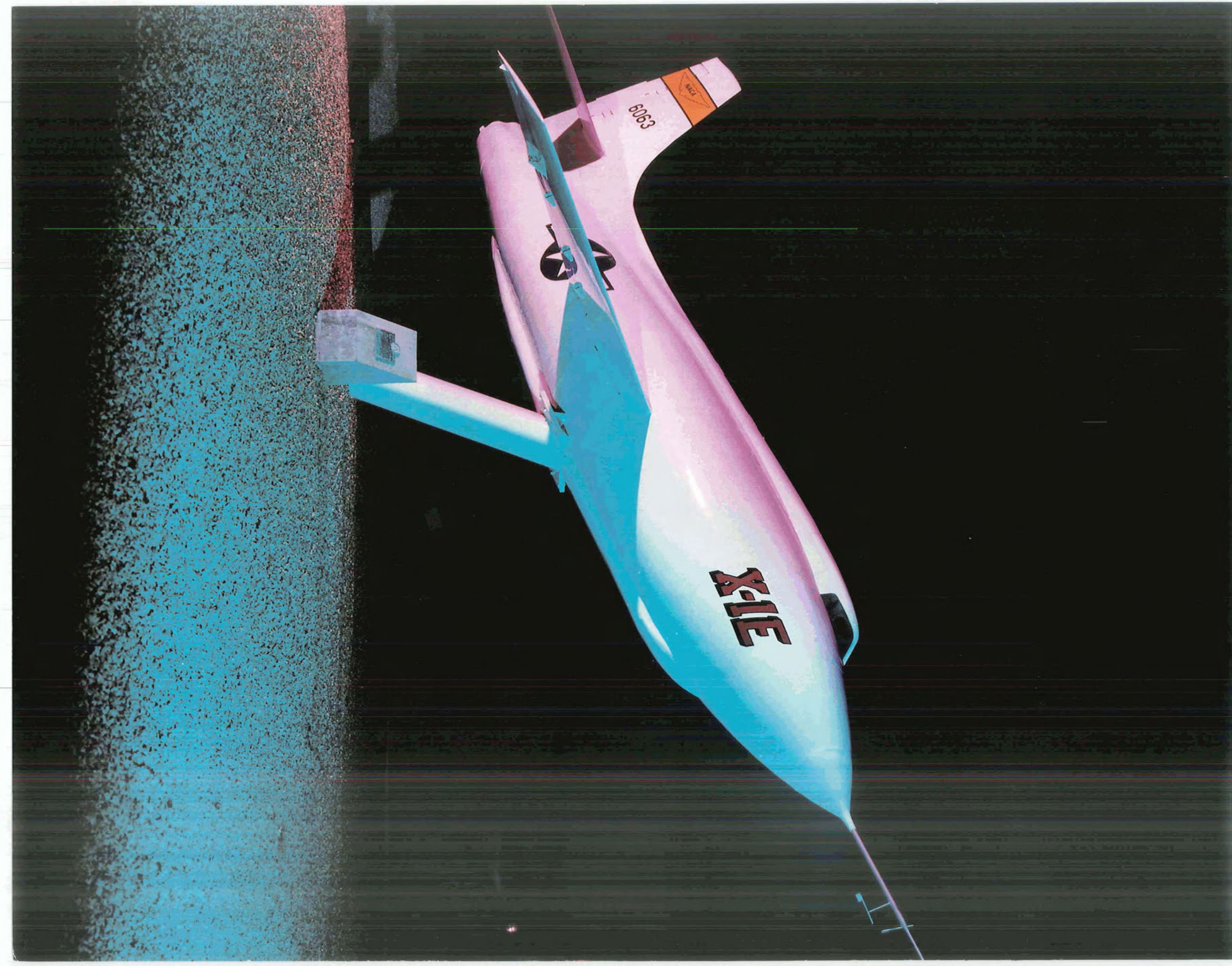
The Mojave Desert may be windy and desolate but, in retrospect, it is far from barren. For 50 years, its open spaces have contributed and been witness to the birth of discoveries that have repeatedly revolutionized the art and science of aeronautical design.

Cradled in the midst of that desert world, the Dryden Flight Research Center has grown from a small, temporary detachment to the premier flight research center in the country. And while Dryden has undergone a number of changes over the past half century, one thing has never varied. No matter what its size or research focus, the Center has always been a unique place where people work at the cutting edge of knowledge, where theoretical principle and real life come together, where discovery happens and where the imagined becomes real.

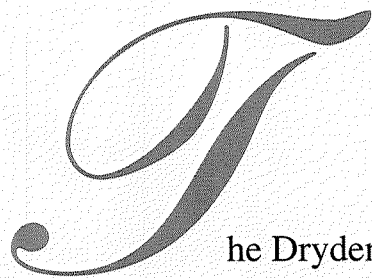




Brig. Gen. Albert Boyd, Commander of Muroc Army Airfield (which became Edwards Air Force Base on 5 December 1949) from September 1949 until February 1952, and Walter C. Williams, Director of the NACA High Speed Flight Research Station during the same period, examining a model of the Northrop X-4 research aircraft, which flew at Dryden from August 1950 through September 1953 (NASA Photo E95 43116-7)



► Chapter Two:
The Right Stuff¹



The Dryden Flight Research Center is not a large facility. At its largest it employed 669 people, and as of 1995 its government staff complement was approximately 450. (By way of comparison, the civil service staff of the Langley Research Center in Hampton, Virginia, has numbered as high as 4,485; the Lewis Research Center in Cleveland, Ohio, 5,047; and the Marshall Space Flight Center in Huntsville, Alabama, 7,740.²) Yet this small desert facility has managed to make a tremendous number of contributions to NACA/NASA, the military, and the aerospace industry over the past 50 years. What made those contributions possible is a combination of facilities, people, partnerships, and a unique approach to management and problem solving that has characterized Dryden since its earliest days.

*X-1E aircraft in front
of the headquarters
building at
the Dryden Flight
Research Center
(NASA Photo
EC96 43434-7)*

Aerial view of Muroc Army Airfield, 10 October 1946, just ten days after Walt Williams and his small team had arrived and one day before the XS-1 (later redesignated the X-1) test program got underway with Bell test pilot Chalmers "Slick" Goodlin's first glide flight in the experimental rocket plane. The village of Muroc appears near the top-left corner of this photo with the tracks of the Atchison, Topeka & Santa Fe Railroad extending eastward across Rogers Dry Lake. (They would continue to bisect the lakebed until they were removed in late 1953.) The XS-1 fueling area and loading pit were located at the corner of the far west (left) end of the flightline, and a giant Northrop XB-35 Flying Wing prototype bomber may be seen taxiing across from the West Main Hangar. Williams' NACA team shared space, next door, in the East Main Hangar. Two smaller hangars are visible in a recessed area to the right of the main hangars. The one on the far right would be transferred to Williams' Muroc Flight Test Unit in April of 1948 and it would serve as "home" for NACA flight research operations for the next six years. (Air Force Photo)





The Place

The NACA engineers, technicians and support personnel from the Langley Memorial Aeronautical Laboratory³ who arrived at the Muroc Army Airfield in September 1946 were faced with conditions that could only be described as primitive. Muroc had been divided into two areas: a South Base, where all training activities took place, and a more remote North Base, which was used for the Army Air Corps flight test work. At first, South Base had been little more than a tent encampment. Barracks, a control tower, a concrete runway and a sewage system had been added in 1943, but the conditions were still appallingly rough.

For work space, the NACA personnel were given part of one of two main hangars at South Base, and two small rooms for offices. The hangars were unheated and the desert sand and dirt blew through them constantly, creating an ongoing problem for technicians working with delicate instrumentation. Engineers would frequently have to sweep a layer of dirt off their desks in the morning before starting work. Flight test equipment was also rudimentary, especially by today's standards. The "control room" for the X-1 flights, for example, consisted of a small, mobile van with a radar antenna on top of it and a radio in the office of the Chief of Operations.⁴

Living quarters for the NACA employ-



Early “computers” at work, summer 1949. In the terminology of that period, computers were employees—typically females—who performed the arduous task of transcribing raw data from roles of celluloid film and strips of oscillograph paper and then, using slide rules and electric calculators, reducing it to standard engineering units. Clockwise from desk in center: Gertrude (Trudy) Valentine, Dorothy Clift Hughes, Roxanah Yancey, Geraldine Mayer, Mary (Tut) Hedgepeth, John Mayer.
(NASA Photo EC49 00053)

ees were even more problematic. Initially, the mechanics and engineers lived in a small, ramshackle shantytown halfway between the South and North Bases. The cluster of firetrap buildings there was known as “Kerosene Flats” because all heating and cooking had to be done with kerosene. An appalled visitor from the Langley Laboratory reported that the NACA employees at Muroc had “the choice of working or going to bed to keep warm. Reading or writing in your quarters is impracticable because of facilities and temperature.”⁵

In late 1946, the Marine Corps closed its air station in the town of Mojave, some 25 miles away from the Muroc Army Airfield. As a result, Walt Williams, the head of the NACA contingent, was able to obtain permission for the married NACA personnel to move into the former base housing there. The single NACA

employees, however, had to remain at Kerosene Flats until Williams finally won the battle to build new barracks for his staff at Muroc.

The battle over the barracks was actually part of Williams’ effort to improve all of the NACA’s facilities at Muroc. In addition to better housing, Williams wanted more hangar space and permission to build lean-to offices off the hangar. Somewhat ironically, the difficulty in getting permission to upgrade facilities stemmed from the fact that Muroc’s base commander, a Col. Signa Gilkey, had a grander scheme of facility improvement in mind. Gilkey had created a “master plan” for the base that included expanding its property, building a new runway, and constructing new, permanent facilities halfway between the South and North bases. He apparently thought that if he allowed the NACA to build better facilities in its present

location, it might hurt his chances of getting approval for his master plan.

In the end, it took intervention by members of the National Advisory Committee for Aeronautics (NACA) itself to gain approval for new facilities. But in 1948, with the assistance of personnel

from the NACA Ames Aeronautical Laboratory near San Francisco, lean-to offices and new men's and women's dormitories were finally constructed. Even then, the facilities were far from plush. The single men's and women's dormitories were wooden buildings with shared bathrooms, living room, and kitchen. Unlike the women, the men were not allowed to eat at

the base officers club, but they did have their own cook.

There were not many women who came out to work at Muroc, but those who did fulfilled an important role in the research program. A couple of them served as secretary/clerks, but in those pre-automation days, someone with a strong mathematics background had to take the raw data from flight instrumentation and convert it into a format the engineers could process. The women who did that were known, even then, as "computers," and they were a respected and essential part of the research team.

Interestingly enough, both the women and men who worked at the Muroc station

seemed to take the inconveniences imposed by their harsh surroundings largely in stride. In part, they knew they were going to a remote outpost and hardly expected the lush green surroundings that existed at Langley. But there was also an acute awareness among the staff members that they were being given the chance to witness and help create history, and that that privilege was worth some sacrifices.

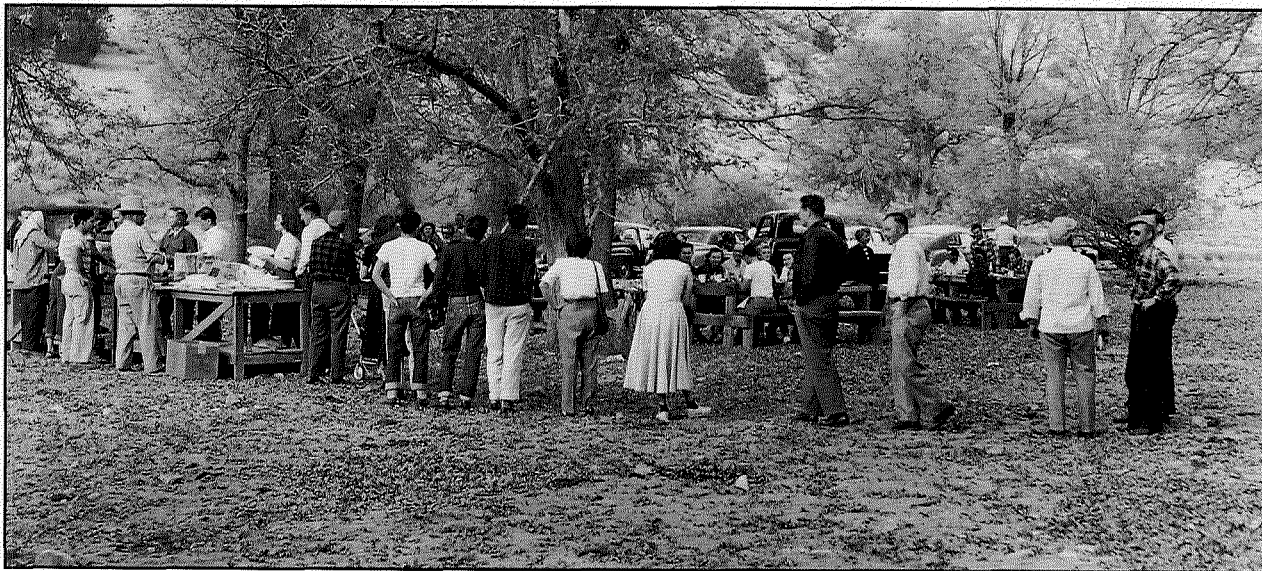
Muroc's isolation also helped the NACA staff become a close-knit group that both worked and socialized together. Group picnics, ski trips, and outings to local desert sites such as Willow Springs, the Tehachapi Mountains or even Los Angeles on the weekends helped mitigate the lack of entertainment on the base itself. Not surprisingly, more than a few marriages developed between the single women and men assigned to the NACA station.

The initial cadre of NACA personnel went to Muroc on a temporary duty status from the Langley Laboratory. By the fall of 1947, however, it had become clear to NACA managers that the group was going to be there awhile. In early 1947, the Army Air Forces and NACA had signed an agreement for joint cooperation on a complete series of X-planes from the X-1 to the X-5, all of which would be flown at Muroc. Consequently, the NACA contingent was made a permanent facility, still under Langley management, known as the NACA Muroc Flight Test Unit.

In 1949, Muroc was renamed Edwards Air Force Base, in memory of Captain Glen W. Edwards, an Air Force test pilot who had been killed in the crash of a YB-49 Flying Wing. That same year, the name of the NACA facility was changed to the NACA High Speed Flight Research Station (HSFRS), underscoring the emphasis of the work the group was conduct-



Walt Williams in 1949. He began the year as Director of the NACA Muroc Flight Test Unit and remained the director on 14 November 1949 when the roughly 100 people working there became employees of the NACA High-Speed Flight Research Station. (NASA Photo E49 00170)



Top left. Workers constructing NACA building, December 1949 (NASA Photo E49 00234)

Top right. NACA Muroc personnel with snowman (1949). Standing (viewer's left to right): Mary (Tut) Hedgepeth, Lilly Ann Bajus, Roxanah Yancey, snowman, Emily Stephens, Jane Collons, Leona Corbett, Angel Dunn. Kneeling (left to right): Dorothy Crawford Roth, Dorothy Clift Hughes, and Gertrude (Trudy) Wilken Valentine. (NASA Photo E49 00212)

ing. Yet it remained a division of Langley until 1954, when it was redesignated the NACA High Speed Flight Station (HSFS) and made an autonomous facility reporting directly to NACA headquarters. That same year, the Station's employees, who now numbered 250, moved into new facilities halfway between the South and North Bases. Those facilities have been expanded since that time, but they are still in use today.⁶

To many people who worked at the HSFS, the 1950s were their golden years. Jet noise, rocket sounds, and sonic booms shattered the desert air throughout the day, and NACA's

"stable" was filled with exotic X-planes and new configuration fighters. Speed and altitude records were being set on a regular basis, and there was a tremendous public fascination with the activities at Edwards that grew as the X-planes reached higher and higher altitudes and speeds. The Station's fame, prestige and priority status at the NACA probably reached its peak with the X-15 program, which made its first flight in 1959, just after the NACA became the National Aeronautics and Space Administration (NASA) and the space race began. That same year, NASA renamed the Edwards station once again, redesignating it as the NASA Flight

Left. NACA Muroc unit staff barbecue, 1949 (NASA Photo E49 00236)



Paresev and crew with one of its tow aircraft, a Stearman biplane, on lakebed; Milt Thompson seated in Paresev and, to his right, a motorcycle with driver who served as the chase observer during lift-off and low-level flights. (NASA Photo E 8713)

Research Center (FRC).

In terms of size, the era of the X-15 was the high-water mark for the Flight Research Center. The X-15 was a joint project with the Air Force and Navy, but it still required a tremendous number of support personnel. The FRC staff during that time grew to over 600, and the NASA facilities at Edwards were expanded in 1963 to accommodate the larger staff. The X-15 also received a tremendous amount of public attention, since its pilots were flying much faster and higher than anyone had ever gone before. Slowly, however, the X-15 began to be eclipsed by the Mercury, Gemini and Apollo space programs. A craft that could fly back from space had been put on the back burner in favor of a simpler ballistic capsule design and, with the Mercury missions, more of NASA's resources and the nation's focus turned toward the space centers of Johnson and

Kennedy.

In an effort to keep the concept of a flyable space vehicle alive, FRC engineers began flight research of lifting body shapes and concepts. That work later contributed valuable information to the Space Shuttle program, but its worth was not universally recognized at the time. In fact, as the X-15 program wound down in the mid-1960s, the House Committee on Science and Astronautics recommended the closing of the Flight Research Center, as "no future activity beyond the X-15 would require the existence of the center."⁷

This evaluation was proven wrong, but it pointed out to FRC Director Paul Bikle the danger of having the Center dependent on a single research project. In 1963, Bikle's staff compiled a 5-year plan for the Center that outlined a number of projects the Center could pursue that would support both the space



SR-71 being worked on at night on ramp. The aircraft was one of three SR-71s loaned to NASA by the Air Force for use as high-speed, high-altitude testbeds for research in such areas as aerodynamics, propulsion, structures, thermal protection materials, and instrumentation. Data from the SR-71 research program could aid designers of future supersonic/hypersonic aircraft and propulsion systems. (NASA Photo EC92 3103-8)

program and the development of a Supersonic Transport (SST). Fortunately, both of those programs were high national priorities in the late 1960s, and congressional funding for the Center was kept intact.⁸

The late 1960s and 1970s, then, saw the Center diversifying into several different research areas—not only because Bikle wanted to develop a broader base of research, but also because the Center was receiving a growing number of external requests for joint research efforts. In addition to lifting body and Lunar Module research to support the space program, the FRC conducted high-speed research with the XB-70A and the YF-12 supersonic aircraft. At the same time, the Center delved into digital fly-by-wire, supercritical

wing and winglet research, wingtip vortex analysis and a number of other research programs. It was during this time that the Center was renamed once again, in honor of Hugh L.



Dryden, the internationally renowned aerodynamicist who had been the NACA's Director in the FRC's early days. On March 26, 1976, the Center became the Hugh L. Dryden Flight Research Center.

This painting by Stan Stokes of the X-15 rocket aircraft is part of the NASA Art Program. First flown in 1959 from the NASA High Speed Flight Station (renamed the NASA Flight Research Center that year and the Dryden Flight Research Center in 1976), the rocket-powered X-15 was developed to provide data on aerodynamics, structures, reentry characteristics, heating, reaction and other flight controls, instrumentation, and the physiological aspects of high speed, high altitude flight. Three were built by North American Aviation for NASA, the Navy and the Air Force. They made a total of 199 flights during a highly successful research program lasting almost ten years. Their speed and altitude records for winged aircraft remained unbroken until the Space Shuttle first returned from Earth orbit in 1981. (NASA Photo EC94 42909-1)

Despite its efforts to diversify, Dryden once again faced a challenge when the YF-12 program ended in 1979. The number of employees was scaled back, and the Center was forced

Ames was actually one of several consolidation moves NASA made in 1981 in an effort to conserve money and resources. Combining Dryden and Ames, it was reasoned, would

eliminate duplication of many administrative functions. Yet regardless of the reason, going from an autonomous facility to one that required Ames' approval for its activities was a difficult change for the independently-minded Dryden employees to accept. Part of the problem was that having to obtain approval from managers



These wingless, lifting-body aircraft sitting on Rogers Dry Lakebed are, from left to right, the X-24A, M2-F3, and HL-10. The lifting-body aircraft studied the feasibility of maneuvering and landing an aerodynamic craft designed for reentry from space. Launched by a B-52 mothership, the lifting bodies flew, powered by their own rocket engines, before making an unpowered approach and landing. They helped validate the concept that a Space Shuttle could make safe, accurate, landings without power. (NASA Photo ECN 2359)

to reevaluate its future direction. Then, while it was still in the process of redefining itself for the needs of the 1980s and beyond, the Center was hit with another rough adjustment. Its

over 300 miles away, who often went months without ever seeing the people they were supervising, slowed down the speed with which projects could proceed. The Ames directors did

attempt to maintain the flexible and exploratory communication style that managers and employees at Dryden had developed over the years, and they remained strong supporters of the flight research Dryden was conducting. But it was sometimes difficult for off-site managers to understand the need or importance of some of Dryden's activi-



The No. 2 X-29 technology demonstrator aircraft, flown by NASA's Dryden Flight Research Center in a joint NASA-Air Force program to investigate the unique design's high angle-of-attack characteristics and its military utility. Angle of attack is the angle of an aircraft's body and wings relative to its actual flight path. This aircraft was flown at Dryden from May 1989 until August 1992. (NASA Photo EC90 0039-4)

status as an independent NASA center was taken away, and it was redesignated as a Flight Research Facility under the administration of the Ames Research Center near San Francisco.

Putting Dryden under the auspices of

ties or requests, and both communication and management relations were hampered by the 300 mile distance between the two facilities.

Nevertheless, the merger was the way of the world, at least for the time being, and the

work at Dryden continued. In fact, the 1980s saw the development of the first significant X-plane since the X-15. In 1984, the radical forward-swept wing X-29 made its first flight. And if speed was perhaps less of a driver than it had been, especially in military aircraft design, there was a great deal still to be learned about improving systems and making aircraft more maneuverable and efficient.

Dryden's work in the 1980s included the beginning of the High Alpha (Angle of Attack) Research Vehicle (HARV) F/A-18 program, the Highly Integrated Digital Electronic Control (HIDEC) F-15 program, the Advanced Fighter Technology Integration (AFTI) F-16 project, and the AFTI F-111/Mission Adaptive Wing (MAW) effort, as well as the Highly Maneuverable Aircraft Technology (HiMAT) remotely piloted vehicle research. The facility also broke ground in 1987 for a new \$16.1 million Integrated Test Facility (ITF).⁹ The new building would include not only office space, but hangar space designed for working on modern, computerized aircraft; simulator facilities that could even be connected to the actual aircraft cockpits; and facilities for rapid aircraft systems check-out and troubleshooting. With the ITF, Dryden would be better prepared for the computer-driven information age, both in aircraft and on the ground.

By 1990, NASA headquarters had come to the conclusion that Dryden's dependence on Ames for all its decision-making was causing more difficulties than it was solving, and a number of administrative functions were relegated back to Dryden. The head position of Dryden was upgraded from a "site manager" to a "director" level, reflecting the increase in control over the facility's activities. Over the next four years, Dryden moved slowly back

toward independent operation, and in March 1994, Dryden was officially redesignated as an autonomous NASA Center.¹⁰

The move in part reflected NASA's recognition of the continuing importance of flight research and the invaluable resources that Dryden's clear skies and open-desert surroundings provided. In fact, soon after Dryden was redesignated as a center, senior staff at NASA began investigating the idea of moving all of the agency's aircraft and flight research activities to Dryden.

But more than anything else, Dryden's shift back to the status of an autonomous center reflected NASA's recognition of the fact that bigger was not always better. Left on its own, the small, sometimes irreverent center in the desert could operate much like the innovative and effective "Skunk Works" that Kelly Johnson had created for the Lockheed Corporation in 1943. Dryden's particular mission, location, personnel and circumstances had created what Center Director Kenneth J. Szalai described as "a unique way of doing business" that operated more effectively than anything outside managers could impose.¹¹

A Unique Approach

Dryden's "unique way of doing business" was a result of a number of factors that have characterized the Center throughout its 50-year history. First, the Center has always been small, remote, and independent. From the early days, there were never quite enough people for the tasks at hand, so employees got used to being flexible and performing whatever job had to be done. The fact that it was small and not easily accessible also meant that it had to contend with less bureaucracy and politics than

many other NACA/NASA centers. Even today, managers are likely to simply “run into” anyone they need to consult several times in the normal course of their day, either in the halls or the center’s small cafeteria. This allows an informal, face-to-face management and problem-solving style that is low on paperwork and still highly efficient and effective.

Dryden’s small size also meant that it often had to draw on the expertise and cooperation of other NASA centers, research facilities, and industry in order to accomplish its research. As a result, the Center has developed strong ties with external sources that have led to many important joint research efforts and have helped transfer new technology back to others who could use it.

Furthermore, Dryden’s single mission of flight research has given the Center a very practical focus around which all activities and efforts revolve. Although it retains a nominal organizational structure based on research disciplines, such as aerodynamics, structures, etc., Dryden has always relied on matrix management to operate its flight research programs. A matrix structure creates a team of people from various disciplines to work on a particular project, led by a program manager. At the center of each team is not any particular discipline of research, but an aircraft. This “real world” tie requires people to work as a team and forces everyone to remain focused on practical applications and solutions.

This practical mind-set is reinforced by the fact that many of Dryden’s employees have worked there a long time. Much of their expertise, therefore, comes not from a textbook or procedure manual but from the numerous projects they have worked on before. In fact, Dryden’s official operating manual still consists

of a mere two pages of policies. The rest of its five volumes are simply procedures that offer guidelines based on what has worked with previous Center projects.

The structure of Dryden’s operating manual reflects not only a reliance on a human corporate memory, but also a belief on the part of Center management in empowering its employees to simply “get the job done.” If a problem arises at 8:00 at night and the airplane is scheduled to fly at 8:00 in the morning, the most important goal is to find a solution that works. In the minds of Dryden’s managers, a thousand procedures cannot cover the myriad of contingencies encountered in flight research as well as the resourcefulness of employees challenged and empowered to find creative solutions.

This attitude also creates an environment where innovation and experimentation are more likely to occur. The lifting body research, for example, started as a “backyard” project by several researchers who believed a craft could be flown back from space. Knowing it would be difficult to get approval for a formal program through accepted channels, they went about proving the concept themselves first, with a small amount of FRC money, a steel-tube-and-plywood wingless aircraft, and a souped up Pontiac tow vehicle. The success of their design led to a formal research program which, in turn, significantly influenced the design of the Space Shuttle. But without feeling that they had the freedom to innovate; to venture ever so slightly beyond the lines imposed by formal procedures and programs, the researchers who instigated the lifting body effort would never even have attempted the project.

This kind of support for individual innovation at Dryden has endured over the

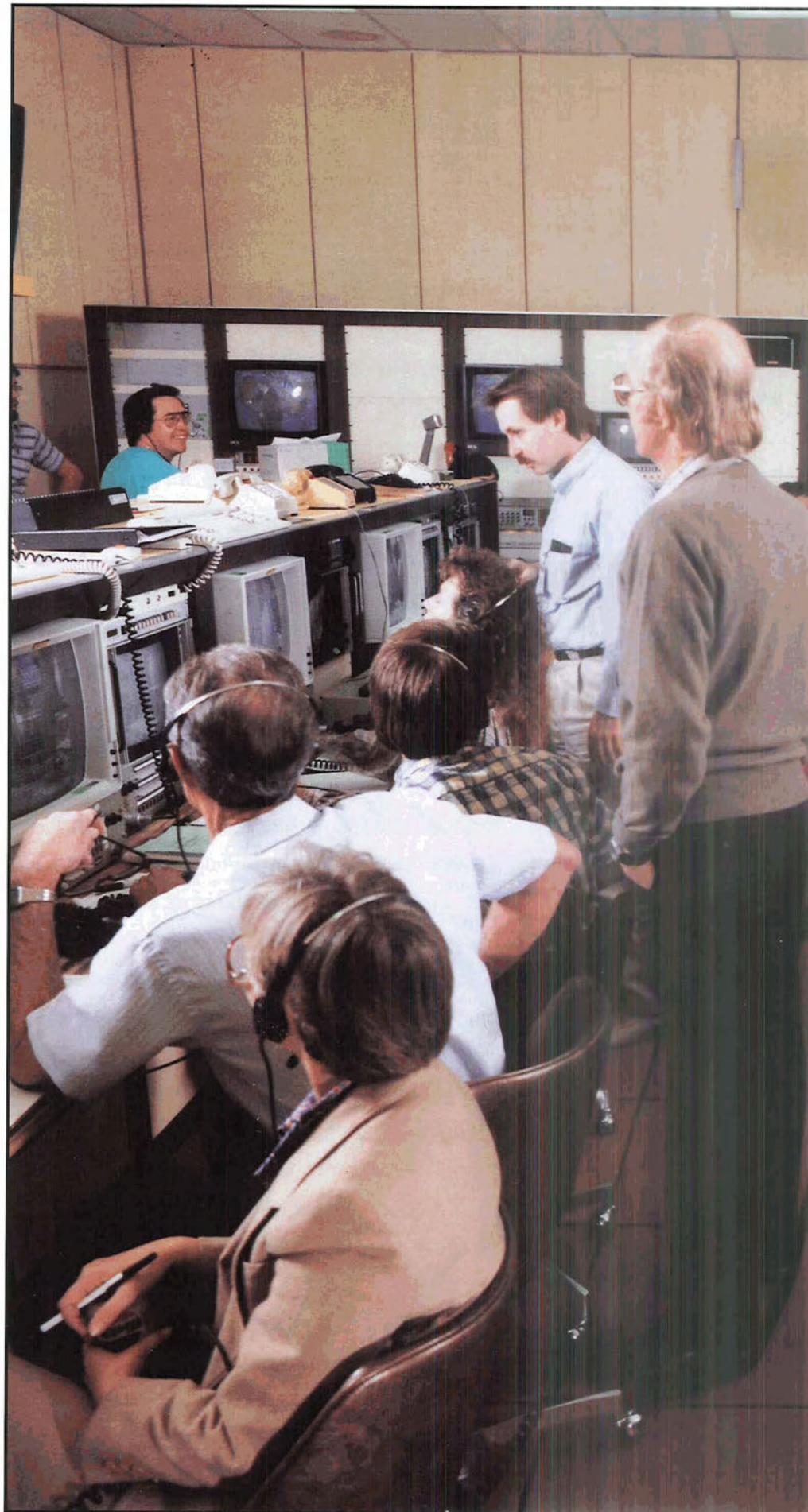
years. And NASA supports this kind of grass roots effort by including a small “director’s discretionary fund” in centers’ budgets to allow researchers to explore concepts that might be outside the scope of existing formal research programs, but which still might generate important results.¹²

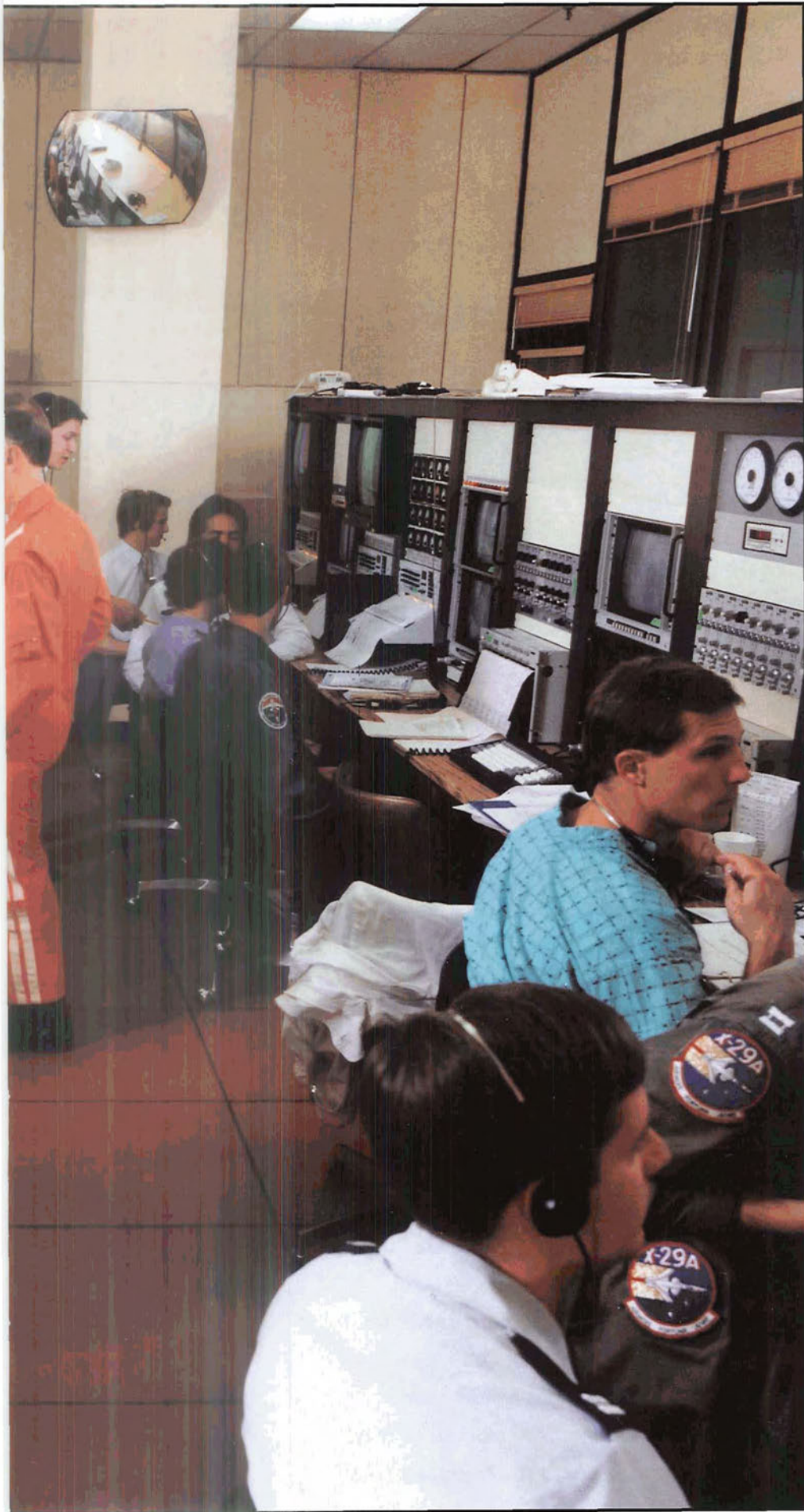
All of these elements—this individual empowerment, a freedom to innovate, a staff accustomed to being flexible and working on several projects at once, a long corporate memory, the informal management style allowed by the center’s small size, and an ever-present focus on practical solutions—have created a unique atmosphere at Dryden that is particularly well suited for flight research. These same elements have also given the center a capability described as “technical agility,” or the ability to adapt and adjust resources to meet constantly changing needs. It is this quality that has allowed Dryden to accommodate not only changing national research goals, but also the estimated 50 percent of its research projects that are requests for help from other sources.¹³

The People

Without question, the facilities themselves and the Center’s unique environment have played a big role in the contributions Dryden has made over the years. But another of the Center’s most valuable resources has always been its people.

From its very earliest days, it took a special kind of individual to work at the desert station. Even today, with all the growth that has come to the Palmdale and Lancaster communities south of Edwards Air Force Base, a prospective employee is unlikely to choose Dryden





*Gold control room during X-29 flight.
(NASA Photo EC89 0300-1)*

because of its location. For the past 50 years, most of those who have come to work at the Center have done so for one reason: they love airplanes, and they want to do flight research badly enough that they are willing to live in the Mojave desert in order to do it. The advantage of this fact, of course, is that Dryden's employees have always tended to be very dedicated to their work.

The most visible of those employees have always been the pilots. They are the ones whose pictures appear next to the airplanes, the "Iron Men" of the rocket era who became heroes to millions of American children. One reason pilots have always had such a high profile is simply that they perform the most visible piece of the many elements involved in any research project. For all the sketches, calculations, wiring, and measurements that are completed ahead of each flight, the pilots are the ones who actually climb into the hardware and take it up in the air. But by the same token, the flight crews are also the only members of the research team who actually risk their lives to gain new knowledge or understanding.

Some features of NACA/NASA pilots have changed over the years. In the early days, although Dryden research pilots had Bachelor of Science degrees, they were more likely to be "stick and rudder" men who knew more about flying than they did about systems and who taught themselves the observation and reporting skills necessary for flight test or flight research. Today, NASA research pilots typically possess

not only Bachelor of Science degrees, but also quite possibly Masters degrees, and have formal test pilot school training or some equivalent experience. The few pilots hired in recent history at Dryden who had not already completed test pilot training were sent through the Air Force school at Edwards Air Force Base. As a result, current NASA pilots tend to be more knowledgeable about systems and systems safety than their predecessors were.

Yet many aspects of the research pilot's job have not changed. The job has always required excellent, almost faultless,

flying skills. For researchers to get the data they needed, the pilots need to be extremely precise in all of their maneuvers, because at the edges of an aircraft's performance envelope or at speeds of Mach 3 or Mach 6, there is little margin for error. In addition, no matter how they got their training, the pilots have to be able to observe and report the nuances and peculiarities of an aircraft's performance in clear, specific terms.

Being a research pilot also has always entailed a certain degree of risk. Street names at Edwards Air Force Base that memorialize pilots who didn't come back are a constant reminder

of the price sometimes exacted for progress in knowledge or aircraft designs. Pilots rarely talk of danger or fear, but they do acknowledge risk. "If we're doing something new, then by its very



F-18 simulator with Martha Evans, simulation group leader, at the controls (NASA Photo EC93 3171-1)

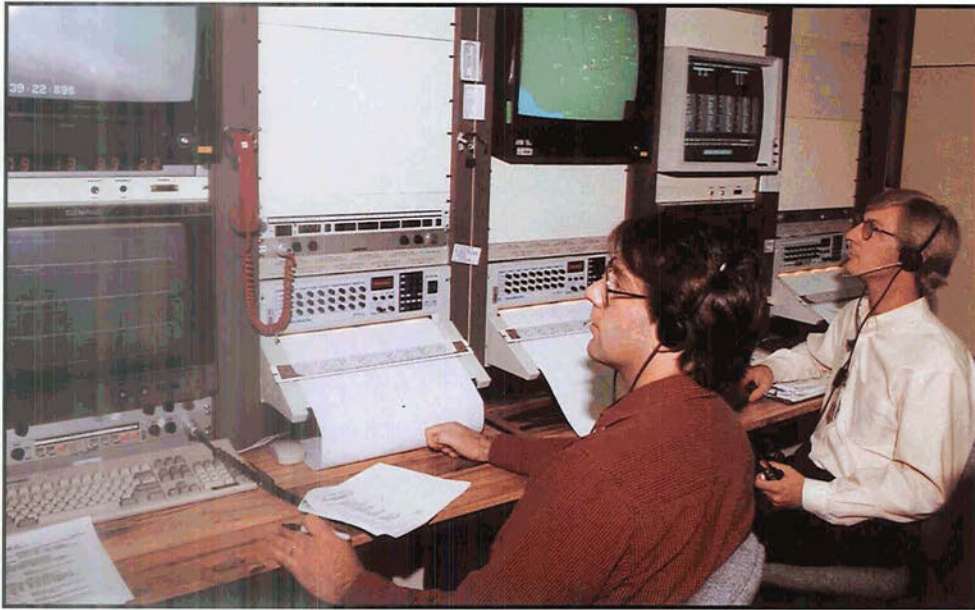
nature, we are stepping into arenas where we use all of these capabilities, all of these tools, to minimize the risks and maximize the chance of success, but there are still elements there that are unknown," says NASA research pilot Rogers Smith.¹⁴

Thirty or forty years ago, the risks were higher because computer ground test and simulation technology was not nearly as advanced. The X-15 pilots, for example, were exploring altitudes and speeds far beyond anything that was known. No amount of wind tunnel model testing could really predict what an actual aircraft would do at Mach 6 or 50

miles above the Earth's surface. Not surprisingly, the accident and pilot loss rate was also much higher thirty years ago than it is today. Yet the risk is always there. Despite all the advances in technology and simulation, an X-31

uncurl his toes. Some of the maneuvers required for test purposes would be more uncomfortable than most people could stand. A textbook definition of an F-18 spin, for example, might describe it as having "a medium yaw rate mode, oscillatory in all three axes," with a note that "a post-stall gyration may occur." What this means for the research pilot, however, is that he will be thrown about as if he were inside a washing machine, and after he stops the spin, the aircraft is likely to snap upside down suddenly and hang motionless in the air.¹⁶

It takes a special kind of person to be both able and eager to take on these kinds of challenges. Certainly, many different types of pilots have climbed into Dryden's cockpits over the years, but they seem to share several important traits. Beyond simply being highly capable, confident, and observant, good research pilots possess a driving curiosity for new challenges and knowledge that could be described as "technical passion." They want to learn what is



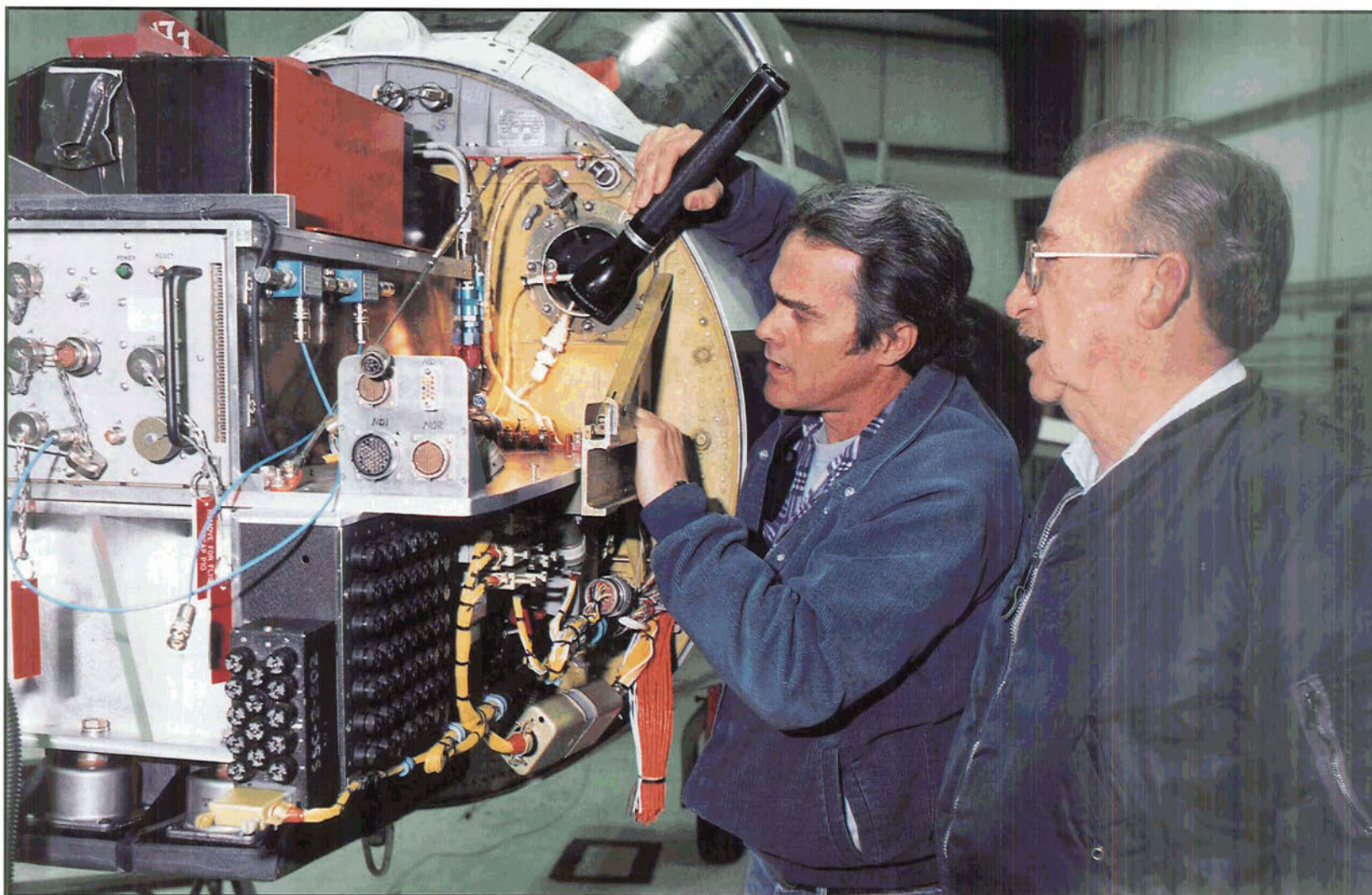
*Close-up of researchers in control room for the F-15 HIDEAC flight research; John Orme, (on right) and Gerard Schkolnik (center)
(NASA Photo EC93 42219-5)*

*Electronics technician Bill Clark making a cannon plug as Jim Lewis looks on
(NASA Photo EC91 134-29)*

research plane was still lost in January 1995. The pilot managed to eject safely, but he only had approximately two seconds to identify that a problem existed, gauge its severity, make a decision and punch out of the aircraft.¹⁵

Even normal operating circumstances in research flying can be extremely challenging, both physically and mentally. One of NASA's SR-71 pilots reported that he could tell how proficient he was in the Mach 3 airplane by how long into the flight it took him to





beyond the limits of our current knowledge—badly enough that they are willing to take the calculated risks and discomfort the journey may entail. And while they all have undoubtedly had moments of anxiety or high tension, they focus on preparing well for each new challenge and handling any contingencies in a professional manner. As veteran research pilot William H. Dana said, “I’ve been scared a few times flying research missions, but my real fear was screwing up.”¹⁷

This fear of not measuring up reflects a pride in their profession that NASA’s research pilots all seem to share. “The flying we do is a craft,” explains pilot Ed Schneider. “Your hands, your brain, and your artistic talent literally are combined together . . . and, like the

guilds in the middle ages, we pass that knowledge down to new pilots.”¹⁸

Yet despite the visibility of their position, the research pilots are very aware that they constitute only one element of the project team. A typical project will include research engineers, operations engineers, and a project manager, in addition to data systems engineers, technical and support staff. Research engineers work on designing the experiments and analyzing the results, while operations engineers make sure the modifications will not compromise the integrity or safety of the aircraft. The project manager is responsible for keeping the project on schedule and budget and coordinates the various efforts and work tasks. These three forces clearly have slightly different agendas,

F-104 nose instrumentation and technicians Keith Wright (holding flashlight) and Gaston Moore (NASA Photo EC91 134-4)

*Gold control room during
F-15 flight.
(NASA Photo
EC93 42219-Fr.2)*

but they are designed to balance each other to keep research efforts both on track and safe. Indeed, staff members are so acutely aware of the real-life consequences of any mistakes that they tend to be very outspoken about their views. As Dryden employees say, “there are no secrets in flight research.” There cannot afford to be. And any project team member, from research engineer to the pilot himself, has the power to stop a flight if he or she feels there is a safety-of-flight issue left unresolved.¹⁹

In addition, Dryden is such a small facility that most employees can see, within one or two steps, the direct impact of their efforts on a flyable aircraft. This helps maintain the high morale and enthusiasm that, in turn, make the Center’s “technical agility” possible. Delaying an ongoing project to incorporate a new research effort can be frustrating; yet it is the ability to reassign personnel according to need that allows Dryden to conduct such a wide range of research with its relatively small staff. Seeing the tangible results of their efforts helps staff members cope with these kinds of frustrations. It also makes employees more aware of the fact that the efforts of many other people may hinge on successful completion of their particular task. Consequently, when a problem occurs that could stop a scheduled flight the next day, it is not unheard of for researchers and technicians to work through the night to find a solution.²⁰



The Partnerships

Dryden’s own employees are not the only people whose dedication has been essential to the Center’s contributions, however. Since the first group of engineers came to Muroc with Walt Williams to support the Army/Bell Aircraft/NACA X-1 effort, Dryden’s research has been characterized by partnerships. Some were fairly simple pairings, involving only Dryden and a single contractor, or Dryden and another NASA center. Others—such as the X-1, X-15 and X-29 projects—have involved one or more contractors, several NACA/NASA centers, and one or more branches of the military. And the X-31 program involved not only U.S. contractors, the U.S. Navy, the U.S. Air Force, the Advanced Research Projects Agency (ARPA) and NASA, but the German Air Force and a German contractor as well.

In a sense, the type of work Dryden does requires partnerships. In many cases, Dryden has been the last stop on an idea’s journey from

someone's mind to a flyable system. That idea might have originated in a researcher's mind at the Ames Research Center, as in the case of the M2 lifting bodies, or in the mind of an engineer at the Langley Research Center, as was the case with the supercritical wing. It might have come from the Defense Advanced Research Projects Agency (DARPA), like the X-29, or from an individual contractor's shop, as the Pegasus project did. The ideas may have been run through computational fluid dynamics analysis and wind-tunnel tests elsewhere. They come to Dryden to be explored in a real-world environment, but that work requires a partnership between flight research specialists and the people who have developed the original idea.

Dryden's partnerships also stem from the fact that flight research requires hardware, which NASA is not usually in the business of building. As a result, Dryden has always had ongoing partnerships and relationships with the aircraft manufacturing industry. Furthermore, the fact that Dryden is located on Edwards Air Force Base and uses Air Force facilities on a regular basis has required an ongoing partnership between the Center and the Air Force.

Although all of these relationships have had their advantages and have allowed Dryden to accomplish the work it has over the past half century, maintaining partnerships can be a challenging task. NASA and the Air Force, for example, have not only different agendas and missions but different operating cultures as well. Over the years, both the Air Force Flight Test Center and Dryden have learned a lot about working together, but creating and maintaining a smooth working relationship still requires effort.

In some ways, the success of a partnership depends on the dynamics of the particular

project. On the X-1, for example, the Army Air Forces and the NACA had different objectives. The NACA wanted to proceed methodically and gather as much data as possible, while the Army wanted to forge ahead and conquer the sound barrier as soon as possible.²¹ With the X-15, on the other hand, the two organizations had more compatible goals, which helped the partnership work more smoothly. In general, partnerships have seemed to work best when there were clear, common objectives. If members began to feel that the program was moving away from their area of interest or expertise, however, problems were more likely to occur.

Yet even when there are common objectives, there are still challenges to be overcome for a partnership to be successful. Lines of authority in joint efforts are not always clear, and different organizations' procedures and requirements do not always mesh. Successful partnerships, therefore, require skillful negotiation, cooperation, and team-building efforts. Individual relationships are critical, and many partnerships evolve from a rocky beginning to a point where the members have developed enough of a rapport and trust among themselves to develop procedures and approaches that are agreeable to everyone. Team cooperation is so important that, as one Dryden manager said, "You draw up an organizational chart, but if you ever have to pull it out of the drawer and actually look at it, you're in trouble." With a partnership as complex as the X-31, some of the potential turf issues were diffused by consciously downplaying all individual identities in favor of an "X-31 team" identity. The partnership was also aided by the fact that the new Integrated Test Facility (ITF) at Dryden could house all the different team members in the same place. That close proxim-

ity encouraged both individual interaction and informal problem solving, which helped the team overcome its significant organizational challenges.²²

Clearly, successful partnerships require a lot of work. But they also offer benefits that

and concerns of those who will actually apply new technology. In addition, joint efforts help transfer new technology by strengthening individual relationships between NASA and industry or military personnel and creating champions for new concepts within organiza-

Walter C. Williams Research Aircraft Integration Facility (formerly, Integrated Test Facility) soon after the dedication of the facility to the first director of what became the Dryden Flight Research Center (NASA Photo EC96 43393-1)



make the effort worthwhile. One obvious benefit is that partnerships can support projects that are beyond the capabilities of any one organization. But there are other advantages as well. Through some of its industry partnerships, for example, Dryden has found itself simultaneously in the position of both teacher and student, learning about the practical applications of technology as it shares its expertise in developing and testing new concepts. Partnerships also give Dryden's researchers a real-world anchor and a "customer" orientation, helping them understand the needs, pressures,

tions or companies.

Furthermore, if budgets continue to decrease and pressures to "downsize" increase, partnerships will undoubtedly become even more common. In 1995, for example, the Dryden Flight Research Center and the Air Force Flight Test Center signed an Alliance agreement seeking to develop any and every opportunity to cooperate and share resources, from aircraft flight time and laboratory space to on-site child-care facilities.²³

Conclusion

The contributions the Dryden Flight Research Center has made to aeronautics and aerospace technology over the past half century have been the result of many people's efforts and many factors that have helped make those efforts possible. Since its origins as a small desert outpost of the Langley Laboratory, Dryden has been a unique place. Certainly its physical environment is unlike that at any other NASA center. But its desert location and single-minded mission have also attracted a certain type of person and encouraged the development of a particular management style well-suited to flight research.

Without question, the physical surroundings at Dryden are very important for its flight research activities. But the most valuable assets at Dryden are not its open skies or even its aircraft, but its people. Without all the individual research team members, the pilots, and a set of pragmatically minded managers, and without the ideas and efforts of its many partners, no flight research would have occurred. It was the unique combination of these factors—the Center, its people, its particular management style, and its partnerships—that gave Dryden “the right stuff” to make its many contributions possible.



Reprinting of an article from the Dryden newspaper, the X-Press, summarizing the life of Hugh L. Dryden on the occasion of the renaming of the NASA Flight Research Center in his honor on 26 March 1976.

Painting of Hugh L. Dryden, for whom the Dryden Flight Research Center was named, by Albert Murray of New York. (NASA Photo EC94 42724-1)

50 Years of Flight Research

Dryden Flight Research Center Dedication Ceremonies, March 26, 1976

This year we celebrate Dryden's anniversary year. In recognition of this event, the X-Press will reprint historical articles, features and photos of events in the past 50 years.

The following is a reprint of an article from the March 26, 1976 edition of the X-Press, commemorating the occasion of the dedication and renaming of the NASA Flight Research Center in honor of Hugh Dryden, with slight corrections for accuracy.

Hugh Latimer Dryden knew Orville Wright and knew John Glenn.

Dr. Dryden was born in Pocomoke City, Maryland, on July 2, 1898. He was five years old when the Wrights first flew off the dunes at Kill Devil Hill, North Carolina, in 1903. Years later he was fond of remarking, "the airplane and I grew up together."

In 1907 the Dryden family moved to Baltimore where young Dryden saw his first airplane. He was fascinated by the birdlike silhouette of the craft, but he was not much impressed by its performance.

In 1913, at the age of 14, he graduated from Baltimore City College, which in that day was a high school. He went to Johns Hopkins University to receive his bachelor's degree in three years, which he took with honors in 1916. He went on to graduate school to receive his master's degree in 1918. The title of his master's thesis was *Airplanes: An Introduction to the Physical Principles Embodied in Their Use*.

In June of 1918, Dryden joined the staff of the National Bureau of Standards as an inspector of gauges. With the encouragement of Dr. Joseph S. Ames, who at that time was head of the Department of Physics at Johns Hopkins, and a member of the newly created National Advisory Committee for Aeronautics (NACA), Dryden obtained a transfer to the Bureau's recently created wind tunnel section. At the same time Dr. Ames arranged to give advanced courses for a number of Hopkins graduates. This allowed Dryden to complete his doctoral requirements while being employed full time.

Youngest Ph.D.

Dryden received his Ph.D. in physics and mathematics in the spring of 1919. He was only 20 years old and he remains the youngest student ever to have received a Ph.D. from Johns Hopkins. The title of his thesis was *Air Forces on Circular Cylinders*; in it he described experiments on the drag and distribution of air flowing around cylinders perpendicular to the wind.

It was also in Baltimore that Dryden met Mary Libbie Travers. On Jan. 29, 1920 they were married.

In the same year Dryden became the head of the Bureau's Aerodynamics section, and continued his researches on turbulence.

In 1924, collaborating with Lyman J. Briggs, his mentor and friend and later director of the Bureau, he made some of the earliest scientific investigations of airfoil characteristics at flows up to the speed of sound -- and even slightly beyond. In a day when the fastest racing planes did well to fly at 280 mph, Dryden was already probing the transonic range of supersonic flight.

Since 1931 Dryden had been a member of the NACA's Committee on Aerodynamics, and in 1934 he became Chief of the Bureau of Standards' Division of Mechanics and Sound.

When the National Defense Research Committee and later the Office of Scientific Research and Development (OSRD) were created in 1940, Dryden took charge of one of the OSRD's guided missile sections. He was specifically charged with the development of a radar guided missile of aerodynamic characteristics, or a glide bomb. For his work on the BAT (glide bomb) he received the Presidential Certificate of Merit.

Dryden's work with OSRD marks his first experience in managing a large research and development project from concept to hardware; and it marks the beginning of the end of his original, creative scientific career and the start of his administrative career. Concurrently with his work for the Bureau of Standards, OSRD and NACA, he was also the Deputy Director, Scientific, of the U.S. Army Air Forces

Scientific Advisory Group headed by Dr. Theodore von Karman.

Medal of Freedom

Von Karman's group produced a series of reports, titled collectively *Where We Stand, and Toward New Horizons*. For his contributions to these reports and by the direction of General Henry H. "Hap" Arnold, Chief of the U.S. Army Air Forces, Dryden was awarded the Medal of Freedom. Years later, after many other awards had been received, Dryden remarked that he prized this award above all others.

In 1946 Dryden became Assistant Director of the Bureau of Standards, and six months later he became the Bureau's Associate Director. Then in 1947 a new horizon of his own suddenly appeared. Dr. George W. Lewis, Director of Aeronautical Research of the NACA, was in failing health, and Dryden was asked to succeed him. In 1949 he was named to the newly created post of Director of the NACA.

At the NACA Dryden worked with others to find a solution to what might be called "The Great National Wind Tunnel Problem."

The result was the Unitary Wind Tunnel Plan, which saved millions of dollars and millions of man-hours of duplicating effort.

In these same years he played a key role in guiding policy and development of a great series of high speed research airplanes which culminated in the X-15, an aircraft that almost became a spacecraft by reaching the very limits of the Earth's atmosphere. As missiles pierced the atmosphere to hurtle out into space, Dryden pushed for solutions to the critical re-entry problem.

On Oct. 4, 1957 the Soviet Union launched into orbit the world's first artificial Earth satellite, *Sputnik 1*.

Congress and the White House immediately made plans of their own to compete with the Russians. These plans included the creation of a civilian agency to conduct the exploration of space. The NACA was to be the nucleus of this new National Aeronautics and Space Administration (NASA).

NASA formed

T. Keith Glennan, president of the Case Institute of Technology was selected to be the new agency's Administrator. Glennan insisted that Dryden be NASA's Deputy Administrator. Together they worked through the new agency's most difficult years.

Dryden brought with him to NASA not only the loyalty of the NACA employees, but also the high regard in which he was held throughout the aeronautical world.

When the White House finally chose James E. Webb to become NASA's second Administrator, Webb replied that he would accept the position only on the condition that Dryden remain as his deputy. And so Dryden remained until his death in 1965.

Methodist Minister

A powerful factor in Dryden's life was his devotion to the Methodist Church. He originally wanted to become a minister, but when he graduated from high school at the age of 14 he was regarded as too young for acceptance in any divinity school. Although he found a second calling in the

realms of physics and mathematics his faith experienced no erosion; indeed it broadened and deepened over the years. He became a licensed local preacher of the Methodist Church.

While many scientists and philosophers have whined and cried about "contradiction" between science and religion, Dryden found no difficulty in achieving a durable synthesis of the two. And when he spoke on the subject his auditors were inclined to agree with him. He realized that we live in an imperfect world populated by imperfect men; and although it might be impossible to achieve perfection in this world, it was incumbent upon everyone to strive for the best.

The honors, offices and awards bestowed upon Dryden were great in their significance and in number. A sampling might include the President's Award for Distinguished Civilian Service, the Langley Gold Medal of the Smithsonian Institution, the Daniel Guggenheim Medal, the Wright Brothers Memorial Trophy, the Elliot Cresson Medal of the Franklin Institute, the Rockefeller Public Service Award, the John Fritz Medal, and the Robert A. Goddard Memorial Trophy. He was honored by election to honored foreign member status in the National Academies of France and Germany, and to the aeronautical societies of Great Britain and Canada. His honorary degrees, awarded in the United States and overseas, numbered 16.

Layman of the Year

In 1962 the Methodist Union named Dryden the Methodist Layman of the Year. It was a distinction that he cherished every bit as much as the many scientific prizes and awards and all of the honorary degrees that were bestowed upon him in his lifetime.

Dryden was hospitalized in October of 1961 for some weeks and exploratory surgery determined that he had an incurable malignancy.

Before he entered the hospital for the last time, he kept busy with conferences, meetings, and lectures. Dryden conceded nothing to his illness. He packed each day with more commitments and accelerated his schedule.

At 7:46 p.m. of Thursday, Dec. 2, 1965 High L. Dryden was no longer of this world.

Dryden's career was devoted to solving problems of turbulence -- in the realm of aeronautics and in the affairs of men. As far as any one man's influence can be felt, he was incredibly successful on both accounts.

The legacy of Dryden is described here in one of his sermons: "None of us knows what the final destiny of many may be, or if there is any end to his capacity for growth and adaptation. Wherever this venture leads us, I am convinced that the power to leave the earth - to travel where we will in space and to return at will - marks the opening of a brilliant new stage in man's evolution."

Today's Events (March 26, 1976)

Formal activities today will begin with a ceremony in the calibration hangar. Music will be provided by the Antelope Valley High School Symphonic Band, under the direction of Mr. Joseph Acciani.

Among those addressing the gathering will be Center Director Dr. David Scott, NASA Administrator Dr. James C. Fletcher, Senator Frank Moss, and T. Keith Glennan, first Administrator of NASA. Mrs. Hugh L. Dryden, guest of honor, will unveil a bust of her husband, which will eventually be placed in the Center's lobby.

After the ceremony, visitors will be invited to view a static display of aircraft in the main hangar. As of press date, aircraft scheduled to be on display included the YF-12, YC-15, F-16 and F-17, X-24B and HL-10 lifting body, F-111 TACT and IPCS aircraft, Firebee and F-15 Remotely Piloted Research Vehicles, the two F-8 Digital Fly-By-Wire and Supercritical Wing aircraft, the full-size F-15, the Mini-

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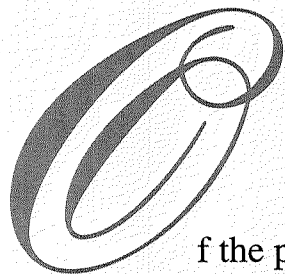
HUGH L. DRYDEN - NASA Flight Research Center photo #29389



UNVEILING THE BUST - During a Center dedication ceremony on March 26, 1976, Mrs. Hugh L. Dryden unveils the bust of her husband which is now in the lobby of Bldg. 4800. NASA photo ECN 5137.



► Chapter Three:
Higher, Faster



f the planned “exploratory” research conducted at the Dryden Flight Research Center over the past half century, a good portion was devoted to exploring ways for aircraft to fly higher and faster—especially in the Center’s early years. After all, the whole reason for the establishment of the Muroc Station was the development of faster jet and rocket aircraft that could not be tested safely at other NACA locations. Furthermore, the driving thrust of aircraft design from the late 1940s through the 1960s was primarily for increasingly faster and higher-flying airplanes. So it was hardly surprising that the research at NACA’s “High Speed Flight Station” during that time focused on technology and advances to help make these goals possible. More surprising, perhaps, is the renewed emphasis on high and fast flight in recent years, although the latest focus is significantly different from the initial work. Today, aircraft such as the proposed High Speed Civil Transport (HSCT) must meet new criteria for fuel efficiency and environmental impact as well as speed and performance. In the early days, the goals were less complex, and the focus was on paving the way to supersonic flight and space.

*X-15 contrail after launch
(NASA Photo EC65 884)*

Breaking the Sound Barrier

The most famous of all the research projects conducted at Dryden and its predecessor NACA/NASA facilities in the Mojave Desert is probably the X-1—the rocket plane that first broke the infamous “sound barrier” in October 1947.

The X-1, a joint effort of the Army Air Forces, NACA, and the Bell Aircraft Corporation, was built to get answers about flight in the transonic region (approaching and immediately surpassing the speed of sound) that researchers were unable to get through conventional ground and wind tunnel tests. Aircraft design had progressed rapidly during World War II, but as high-performance fighters such as the Lockheed P-38 Lightning developed the capability of dive speeds approaching Mach 1, they began to encounter difficulties. Shock-wave, or “compressibility,” effects could cause severe stability and control problems and had led to the in-flight break-up of numerous aircraft. Many people began to believe that supersonic flight was an impossibility.

Clearly, more information about flight dynamics at these higher speeds was needed, but that information was proving difficult to obtain. In the 1940s, no effective transonic wind tunnels existed. The NACA Langley Laboratory

X-1 being loaded under mothership, B-50 Superfortress. The aircraft had originally been lowered into a loading pit and the launch aircraft towed over the pit, where the rocket plane was hoisted into the bomb bay. By the early 1950s, a hydraulic lift had been installed on the ramp to elevate the launch aircraft and then lower it over the rocket plane for mating. On 9 November 1951, however, after a so-called “captive” flight in which this particular X-1 (tail number 6-064) remained attached to the launch airplane, both aircraft were destroyed by a postflight explosion and fire that also injured Bell test pilot Joseph Cannon. (NASA Photo E51 593)





was conducting re-
search with small airfoil
models mounted on the
wings of P-51 fighters,
which could experience
local transonic and low
supersonic air flow
even if the aircraft
speed was subsonic, as
well as with rocket
models fired from its
Wallops Island, Vir-
ginia, facility, but
neither approach was
really satisfactory.
Several researchers,
including John Stack of
the Langley Laboratory,
began arguing the need
for a research aircraft to
explore the transonic
region and determine if, in fact, supersonic
flight was possible.

Although numerous researchers across
the country agreed on the need for such an
aircraft, they did not all agree on its design.
Stack and other NACA engineers, along with
the U.S. Navy, favored a jet-powered plane,
while the Army Air Forces (AAF) wanted to
pursue a rocket-powered design. As a compro-
mise, the researchers decided on a two-pronged
approach to their research plane. The AAF and
NACA teamed up with Bell Aircraft to build
three models of the X-1 rocket aircraft, while
the Navy and NACA worked with the Douglas
Aircraft Company to create the D-558-1 jet-
powered Skystreak. The Skystreak's perfor-
mance would not be as great as the X-1 design,
but a rocket-powered aircraft was seen as a
much riskier proposition. The dual approach,



therefore, was thought to provide a greater
assurance of success in a transonic research
program.¹

The X-1 was modeled after the shape of
a bullet, which was the only shape that had been
proven capable of stable transonic or supersonic
flight. Its four-chamber, 6,000-pound thrust
rocket engine would give it a mere 150 seconds
of powered flight, which led to the decision to
air-launch the aircraft from a specially modified
Boeing B-29 Superfortress. In December 1945,
only nine months after Bell Aircraft received an
Army contract to build the plane, the first X-1
rolled out of the factory.² A test group, includ-
ing a NACA contingent led by Walt Williams,
took the airplane a month later for its initial
glide tests to Pinecastle Field near Orlando,
Florida. Pinecastle had one of the country's
very few 10,000-foot-long runways, but the

*NACA pilots Bob Champine
and Herb Hoover with X-1
(tail number 6-063), in
which both pilots first
flew supersonic
(NASA Photo E 005)*



X-1E being loaded under mothership, with a technician servicing the rocket plane (NASA Photo E 2509)

area proved less than ideal for the X-1 flights. Among other things, scattered cloud decks and the landscape surrounding Pinecastle could make it difficult for a pilot to keep the airport in sight. On the X-1's very first flight, in fact, Bell's test pilot Jack Woolams did not quite make the runway, touching down on the hard grass beside it. Woolams and the test team recommended that the powered flight tests be conducted at Muroc, where they would have the advantage of clear skies, open landscape and dry lake landing sites.³

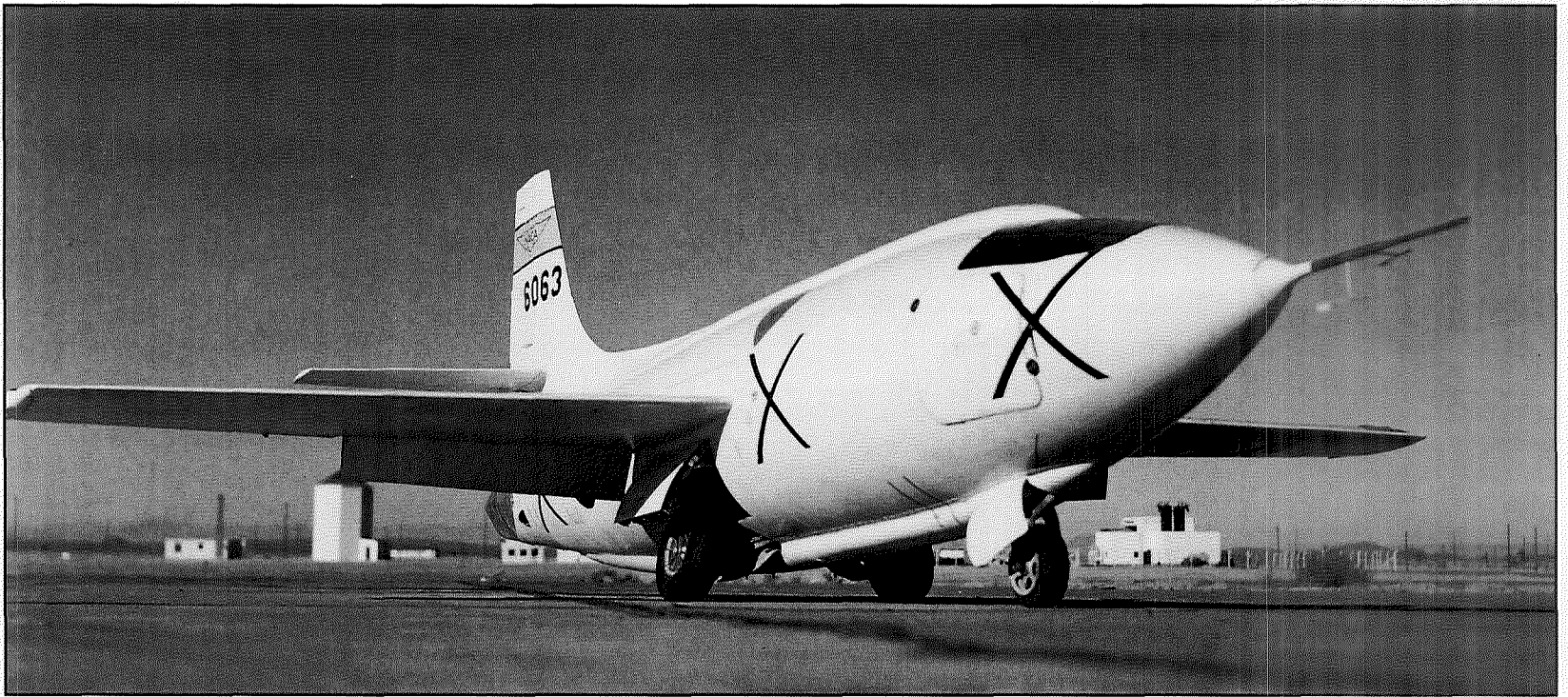
The NACA team, still headed by Williams, arrived at Muroc on 30 September 1946, and the second X-1 aircraft arrived a week later. This second X-1, which had a thicker wing than the first model, had been designated for the more thorough transonic research NACA wished to conduct. The first X-1 was to be used

as quickly as possible, while the NACA wanted to make sure it got all possible data from every flight. The two goals were often in direct conflict, as instrumentation issues often slowed the pace of the research flights.

This problem was intensified by the fact that although NACA's instrumentation was state-of-the-art for its time, it was still fairly rudimentary and temperamental. Aside from the fact it weighed 500 pounds, the equipment was susceptible to frequent failures, and some flights failed to return much data.⁴

Yet despite the conflicts created by the different approaches and agendas of the two organizations, nobody on the team lost sight of the common goal. Almost 50 years later, with supersonic flight a standard capability of most military and even some transport aircraft, it is difficult to fully appreciate the enormity of the

by the AAF to make a more focused, aggressive assault on the sound barrier and to explore the maximum speed and altitude capabilities of the aircraft. The NACA was responsible for providing technical supervision for all the test flights and the instrumentation for both aircraft, however. This created some degree of tension between the AAF and NACA personnel. First of all, the AAF wanted to push ahead and get past the magic "Mach 1" mark



challenge the X-1 team faced. Many scientists and researchers, even within NACA, thought the X-1 would blow up or break apart in flight. (In fact, one of the X-1's four engine combustion chambers did explode on a flight in May 1948, but the aircraft was landed safely.) The researchers and pilots involved with the project were convinced supersonic flight was possible, but they knew how many things could go wrong. Just a year earlier, for example, Geoffrey DeHavilland had been killed in a British D.H. 108 Swallow while attempting to break the sound barrier.

Even without catastrophic failures, the road to that October flight was not an easy one. On a flight in early October 1947, for example, the Air Force's primary X-1 pilot, Captain Charles "Chuck" Yeager, achieved an indicated airspeed of Mach 0.94 but found that when he pulled back on the control stick, nothing happened. The speed had created a shock wave on the surface of the elevator, rendering it useless and leaving him with no pitch control. Yeager recovered by shutting down the engines and

reducing his speed, but the incident taught the researchers the value of a movable horizontal stabilizer. From then on, Yeager used the elevator to control the X-1's pitch at subsonic speeds but relied on small trim adjustments of the entire stabilizer at speeds near or past Mach 1. An all-movable stabilizer proved to be such a critical component for transonic and supersonic flight, in fact, that virtually every transonic/supersonic aircraft since then has had one.⁵

On another flight just four days before the sound barrier was broken, the X-1's canopy frosted over during Yeager's descent and chase pilots had to talk him down to a blind landing. To prevent a recurrence of the problem on future flights, crew members coated the X-1's windscreen with Drene shampoo—illustrating the desert team's ability to find creative and effective solutions to unexpected problems. Finally, however, success was theirs. On 14 October 1947, flying with two broken ribs, Captain Yeager took the X-1 to a speed of Mach 1.06 at 43,000 feet, proving for the first time that a piloted aircraft could successfully

*X-1-2, later rebuilt
as the X-1E
(NASA Photo E 668)*



Technicians servicing X-1 attached to B-29 mothership (NASA Photo E 595)

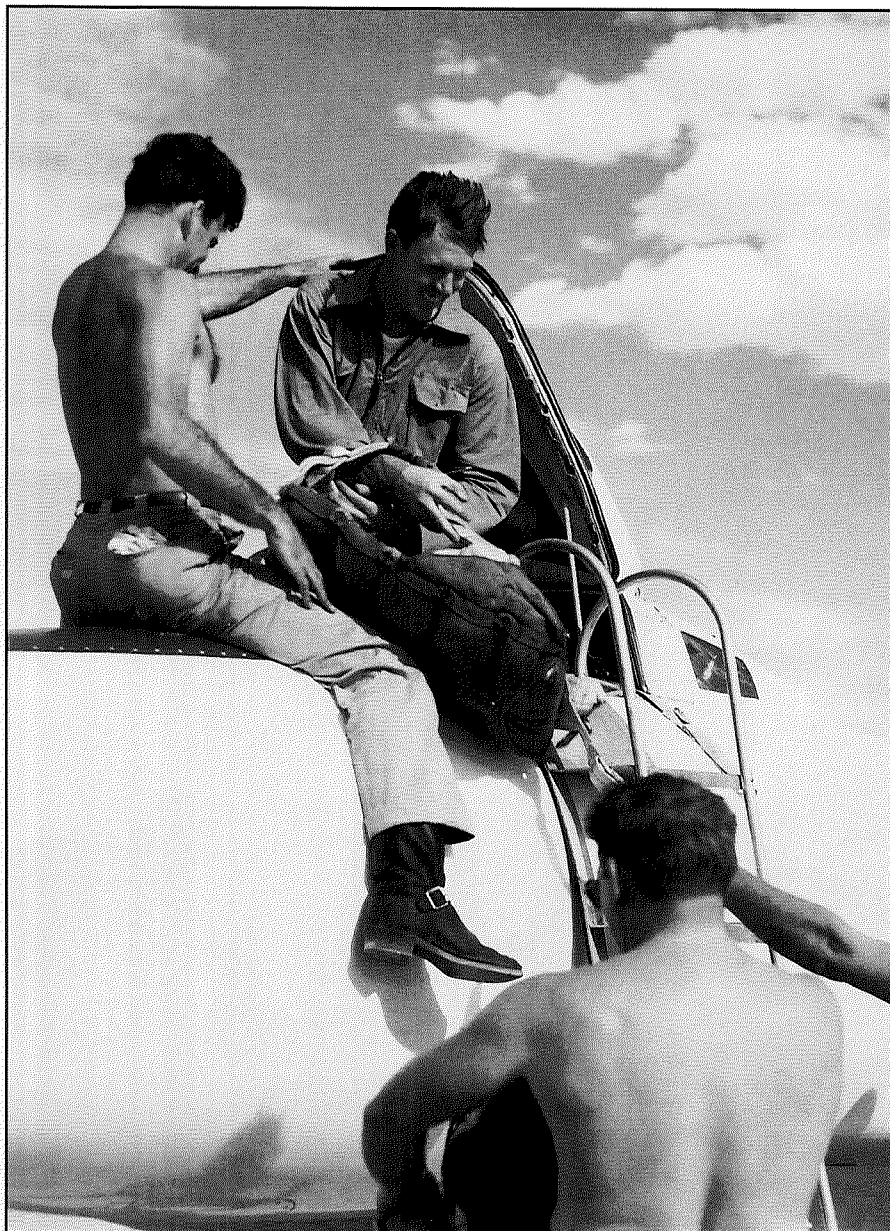
surpass the speed of sound and making the sound “barrier” a myth of the past.⁶

The X-Planes

While the breaking of the sound barrier is the landmark the world remembers, it was actually just one research mark of many for the NACA unit at Muroc. NACA began flight research with the second X-1 just one week after Yeager’s Mach 1 flight, and NACA pilot Herbert H. Hoover became the second man to fly supersonically on 10 March 1948. The NACA also received the first of its two jet-powered Douglas D-558-1 Skystreaks in No-

vember 1947.

The lower-performance D-558-1 took backseat to the X-1 aircraft, but it did achieve some useful research on flight in the transonic region approaching Mach 1. The Skystreak showed that adding vortex generators, or small vertical tabs, to the wing of an aircraft could reduce buffeting and wing-dropping tendencies.⁷ John Stack of the Langley Laboratory came up with the idea and, in a typical example of the Muroc unit’s independent, nonbureaucratic management style, Walt Williams simply instructed his technicians to try it out. The small tabs they glued on the Skystreak’s wing allowed its speed in level flight to increase by .05



*D-558-1 on ramp with
NACA pilot (Bob Champine)
and crew
(NASA Photo E49 00204)*

sound, became the first NACA pilot at Muroc to give his life in pursuit of research.⁹

The three X-1s and the D-558-1 were, in a sense, the first generation of research aircraft planned by NACA and the military. The second generation was not far behind—in fact, follow-on aircraft were already in the planning stages before the X-1 even reached powered flight. The first D-558-1 had not yet been delivered when the Douglas design team came up with a more advanced version of the aircraft, incorporating a swept wing and both a jet and a rocket engine. The new model, designated the D-558-2 “Skyrocket,” entered the line-up of

Mach—and proved effective enough that vortex generators were subsequently incorporated into Boeing’s B-47 bomber design. Since then, vortex generators have been used to improve the performance of air flow over the external surfaces and even through the engine inlets of a great many production aircraft.⁸

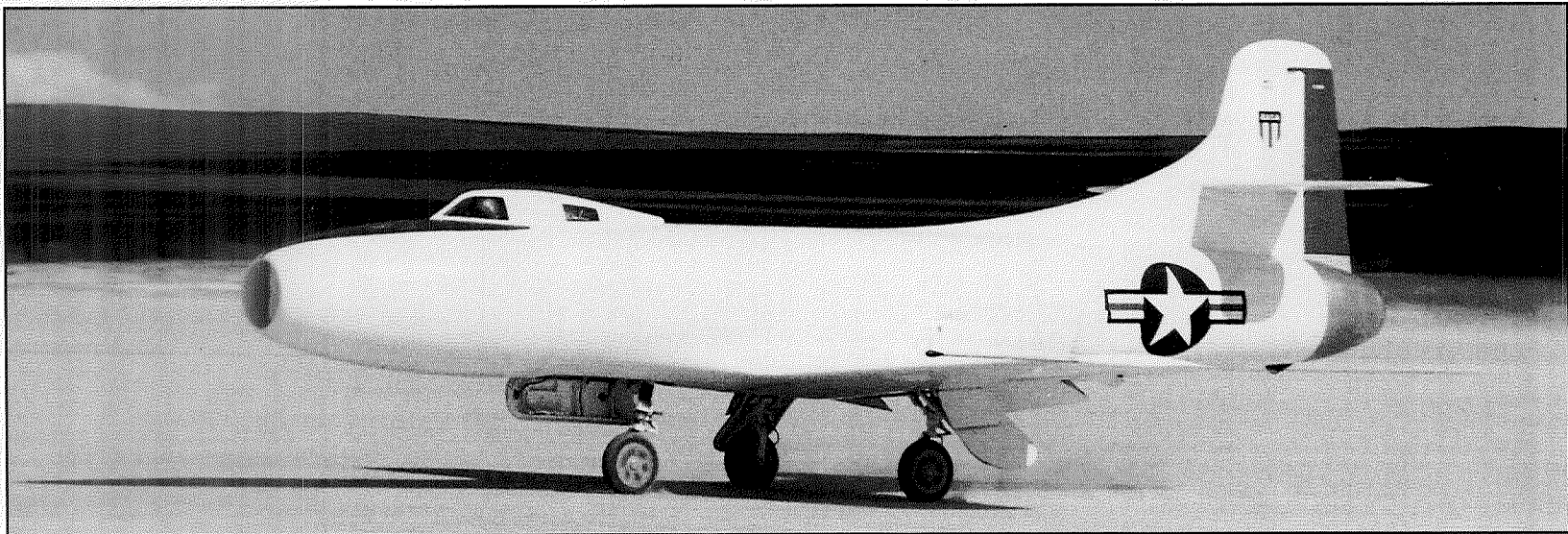
Unfortunately, one of the Skystreaks also claimed the life of NACA research pilot Howard “Tick” Lilly in May 1948, when its jet engine compressor suffered a catastrophic failure on take-off. Lilly, who had been the third person to fly an aircraft past the speed of

research aircraft in 1948. To increase the D-558-2’s performance further, Douglas removed the jet engine from one of the three Skyrockets, using the extra space and weight for extra rocket fuel, and configured the airplane for air-launch instead of ground take-off.¹⁰ The Army Air Forces and NACA also signed an agreement in February 1947 detailing a joint effort for additional research aircraft, designated the X-2, the X-3, the X-4 and the X-5. And while the first X-1s were still conducting flight research, an order was put in for three updated versions called the X-1A, the X-1B, and the X-1D. An

X-1C was designed, but its funding and resources were reallocated to the other “X” aircraft and it was never built.

The goals of this multi-aircraft flight research effort were twofold. The derivative versions of the X-1, as well as the X-2 and the D-558-2, were built to explore higher speeds and altitudes, both to help manufacturers build aircraft that could operate in that realm and to provide information useful for future space flight. The X-3, X-4, and X-5, as well as the delta-wing XF-92A, explored the behavior of various configurations in the transonic range.¹¹

useful research. For one thing, flights using the X-4’s large speed brakes were able to gather data about the flight characteristics of an aircraft with a low lift/drag ratio that helped the X-15 research program. The airplane also made it clear to designers that the X-4 configuration, which was modeled after not only the Swallow but also the Messerschmidt Me-163 rocket plane, was totally unsuitable for transonic or supersonic flight. Like the Swallow, the X-4 experienced severe oscillations about all three axes as it approached Mach 0.9. Increasing the thickness of the elevon trailing edges helped



Turbojet-powered D-558-1 taking off from lakebed (NASA Photo E49-226)

The X-4, for example, was a semi-tailless design similar to the D.H. 108 Swallow that had broken apart while trying to reach supersonic flight in 1946. The X-4 was a twin jet, swept wing aircraft built by Northrop, which had also designed a “flying wing” bomber prototype for the Air Force. Not surprisingly, the X-4, which had a vertical but no horizontal stabilizer, used the flying wing’s concept of a combination elevator/aileron called an “elevon” to control its pitch and roll.

The X-4 was something of a maintenance nightmare, but it did accomplish some

somewhat, but the problem could not be completely alleviated.¹² Nevertheless, the X-4 supported General Jimmy Doolittle’s assertion that “in the business of learning how to fly faster, higher, and farther, it is sometimes very important to learn what won’t work.”¹³

The X-5, which was a variable-sweep wing design built by Bell, arrived at Edwards in 1952. It had vicious stall/spin characteristics that caused NACA pilot Joe Walker to lose 18,000 feet recovering from a stall during one flight and eventually killed Air Force test pilot Ray Popson. But its problems were determined

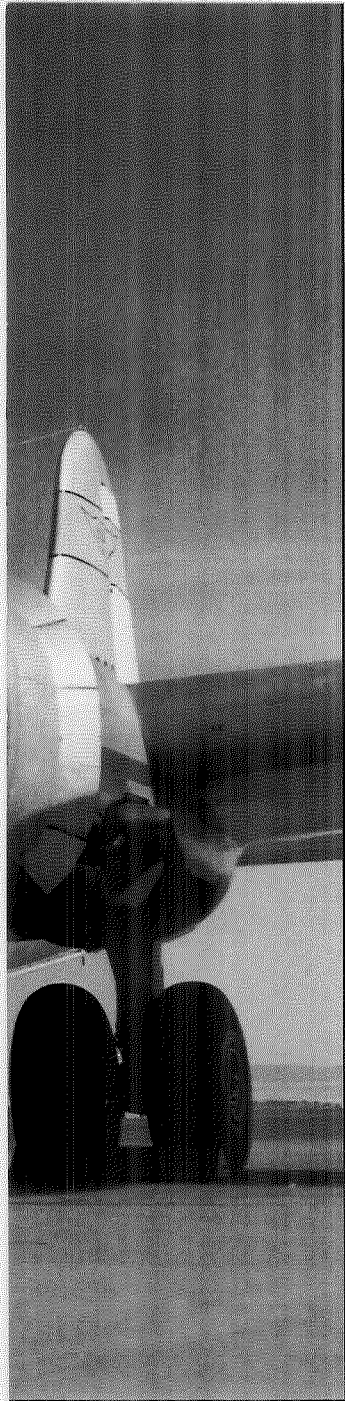


to be design flaws of the X-5, not the concept of variable sweep. In fact, the aircraft proved the feasibility of the concept and allowed researchers to learn a lot about the dynamics involved with that configuration throughout the transonic range.

Likewise, the Convair XF-92A proved the suitability of the delta-wing design for transonic flight. Yet it, too, had some unpleasant flight characteristics, the most problematic of which was a tendency to pitch up violently during maneuvering, resulting in positive forces as high as 8 Gs and, even more alarmingly, negative forces as high as -4.5 during recov-

ery.¹⁴ “Pitch up” was, in fact, a problem inherent in any swept-wing design at transonic speeds, but research with the X-planes gave engineers an opportunity to examine it in various configurations. One of the major research contributions of the D-558-2 Skyrocket, in fact, was its investigation into the dynamics and possible solutions to the pitch-up problem. Over a 27-month flight program with the Skyrocket, NACA researchers examined the use of wing fences (vertical strips running from the leading edge to the trailing edge of the wing), a sawtooth-shaped leading edge, and retractable leading edge slats to control pitch-up.

*Two B-29s, one with X-1E attached. The silhouettes on the side of the mothership indicate it had completed 31 launches.
(NASA Photo E-2082)*



Judging from their experience with these aircraft, the NACA researchers determined that the best solution to the pitch-up problem actually was to place the aircraft's tail low and far back on the fuselage, to keep it out of the wing's disturbed airflow and downwash. A delta wing design like the XF-92A, of course, would require another solution because it lacked a horizontal tail. The NACA engineers therefore tried a series of wing fences on the XF-92A, including a combination planned for the follow-on F-102 delta-wing interceptor that Convair was in the process of building. The results were sent to Convair, although the F-102 was subsequently changed quite significantly to take advantage of the "area rule" design concept developed by a Langley Laboratory research engineer named Richard Whitcomb.

Yet the problem swept wing aircraft had with pitch-up almost paled in comparison with another difficulty NACA researchers, and a few unfortunate F-100 fighter pilots, were discovering with aircraft designed for supersonic speeds. The technical term for it was "inertial coupling" or "roll divergence," but to the pilot it meant that the airplane had a tendency to go suddenly and violently out of control during rolling maneuvers. The F-100 jet was the nation's first fighter designed to fly past Mach 1 in level flight, and it had just gone into full production in 1954 when the inertial coupling problem surfaced. It was already a suspected cause in several accidents that had claimed the lives of F-100 pilots when NACA pilot Joe Walker experienced it in the Douglas X-3 research aircraft later that same year.

The X-3 was actually designed for sustained Mach 2 jet-powered research, but the aircraft's engines were so underpowered that it could not go supersonic in level flight. The

fastest it ever went was Mach 1.2 in a powered dive. Yet it was still susceptible to inertial coupling because, like the supersonic "Century Series" fighters, it had a thin, short wing and most of its mass was concentrated along its fuselage.¹⁵ The highly instrumented X-3 was able to give engineers their first detailed data and analysis of the dynamics, and therefore the cause, of the inertial coupling problem.¹⁶ As a result, NACA advised North American Aviation to extend the wingspan and increase the vertical tail surface of the F-100 design. The modifications turned the F-100A into a highly effective supersonic fighter, and the knowledge gained through the X-3 flights and the F-100 experience has been applied in one form or another to virtually every supersonic fighter built since then.¹⁷

The configuration research conducted by NACA and the Air Force from 1950 to 1956 was particularly important to manufacturers because they were at the cutting edge of a revolution in aircraft design and performance that was taking them into realms they knew very little about. They could not have predicted the surprises that Joe Walker found in the X-3 and the X-5 any better than NACA or the Air Force. Furthermore, the work with the D-558-1, the X-3, the X-4, the X-5 and the XF-92A was in the same speed range, and in most cases used the same types of materials and powerplants, that the manufacturers were beginning to incorporate. So even if the aircraft did not always measure up in performance to NACA's hopes or expectations, the research was of great interest to industry designers and engineers. The information provided could mean the difference between the success or failure of an aircraft design. And in the case of the F-100A, the flight research at Dryden prevented the death not only

of the aircraft program but of numerous pilots as well.

This is not to say that Dryden had neglected work in the high-speed arena while it explored various transonic configurations. Indeed, it was the high-altitude and high-speed achievements at Edwards Air Force Base that garnered the biggest headlines during the early 1950s.

The X-1A, X-1B, and X-1D derivatives of the X-1 design were designed to have greatly expanded capabilities. They had larger tanks for rocket propellant and were designed to use a turbine-driven pump instead of the X-1's more cumbersome nitrogen pressure-feed system. They also had, for the first time, an ejection seat for the pilot. Unfortunately, the follow-on X-1s were plagued with accidents and problems.

The X-1D was the first new-generation

X-1 to arrive at Edwards, delivered by Bell in mid-1951. On its very first powered flight attempt, however, the aircraft exploded while still attached to the B-50 mother ship. The Air Force pilot, Major Frank K. Everest, managed to get back into the B-50 safely, but the stricken X-1D had to be jettisoned. Thus the X-1D program ended before it began, and the accident set the X-1A and X-1B programs back almost two years.

The X-1A joined the Air Force/NACA research fleet in 1953. It was designed for speeds in excess of Mach 2, but it encountered serious stability problems as it approached its design speed. On one flight at the end of 1953, Chuck Yeager set a new speed record of Mach 2.44, or approximately 1,650 miles per hour, only to lose control of the airplane immediately thereafter. The X-1A gyrated wildly for 70



Early NACA aircraft in front of the South Base hangar used by the NACA unit from the late 1940s to 1954.

From viewer's left: D-558-2, D-558-1, X-5, X-1, XF-92, X-4

(NASA Photo EC 145)

seconds, losing 10 miles in altitude before it slowed to a subsonic speed and went into an inverted spin, from which Yeager was able to recover. As was the case with many X-plane partnerships between NACA and the Air Force, the X-1A was flown first by the Air Force and then turned over to the NACA for more in-depth research. Unfortunately, NACA's time with the X-1A was brief. On its second NACA flight attempt, the X-1A experienced a minor explosion while still attached to the B-29 mother ship, just as the X-1D had. NACA pilot Joe Walker managed to get out, but the X-1A had to be jettisoned, ending the X-1A program.

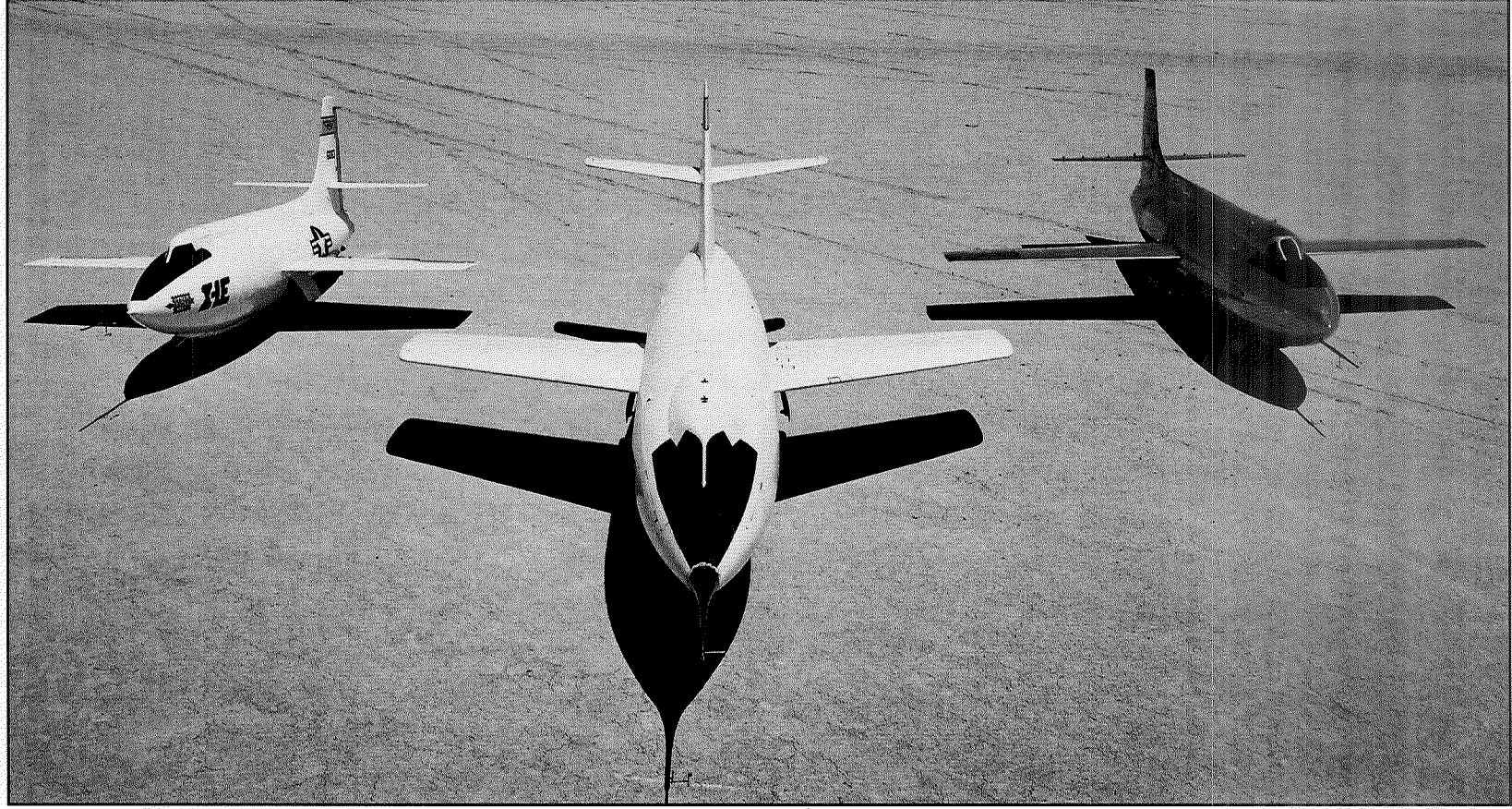
The X-1A had given researchers an unpleasant taste of some of the surprises that still awaited them as they reached for higher speeds. In fact, although both the X-1B and the X-1E that followed were designed for faster

speeds, neither one was ever flown above Mach 2.3 because of the stability problems encountered with the X-1A. The X-1E was not in the original plans for research aircraft, but the destruction of the X-1D and X-1A left a need for a back-up aircraft. To fill that need, the X-1E was created by modifying one of the existing X-1 research aircraft and the modified plane flew with the X-1B from 1955 until 1958. Both aircraft were used to gather data about the forces on an aircraft at high speeds and altitudes, including the effects of aerodynamic heating. Aircraft that could fly hypersonically, or above Mach 5, and potential spacecraft were already in the planning stages, and researchers needed information on the flight environment and forces with which those craft would have to contend.

The X-2 was, in a sense, a third genera-

X-4 in flight
(NASA Photo E 17350)





tion research aircraft, designed to go further in investigating problems of aerodynamic heating as well as stability and control by operating at speeds of Mach 3 and at altitudes between 100,000 and 130,000 feet. To make the plane more heat-resistant, the X-2 was made of stainless steel and a nickel alloy. Its 15,000-pound-thrust Curtiss-Wright rocket engine also had more than twice the thrust of the X-1 family engine.

Unfortunately, the X-2's research career was destined to be short. The first X-2 exploded during Bell Aircraft's initial flight testing of the airplane. The explosion occurred while the X-2 was attached to its B-50 launch plane, resulting in the death of not only the X-2 pilot but one of the B-50 crew members as well. The second X-2 made its first Air Force powered flight in November 1955. Its performance was, in fact, impressive, and on its 12th powered flight, Air Force Captain Iven C. Kincheloe took it higher than anyone had ever flown. His flight to approximately 126,000 feet prompted *Popular Science* to dub Kincheloe "First of the Space-men." Yet on its very next flight, the last Air

Force flight before turning the plane over to NACA for its more thorough research program, tragedy struck. Captain Milburn G. Apt, flying his very first rocket flight, took the X-2 to a record speed of Mach 3.2, or 2,094 miles per hour. But as he turned back to the base, the X-2 went out of control and began spinning. The X-2 had been designed with a jettisonable nose, which was supposed to protect the pilot until he reached a speed slow enough for a normal bail out. But when Apt jettisoned the nose cone, the shock knocked him unconscious. He came to in time to jettison the canopy but was unable to bail out before the cockpit section crashed into the desert.

The accident ended the X-2 research program, but it did lead to a couple of changes in the X-15 program that followed. First, the idea of a jettisonable cockpit was abandoned in favor of an ejection seat. Second, a possible factor in the X-2 accident was thought to be Apt's cockpit instruments. Some researchers thought Apt might have believed he was going slower than he really was, leading him to initiate a turn sooner than he should have. As a

Research aircraft from viewer's left to right: X-1E, D-558-2, X-1B on lakebed (1955) (NASA Photo E 1914)



D-558-2 dropping at launch from B-29 mothership (Navy designation: P2B) (NASA Photo E 2478)

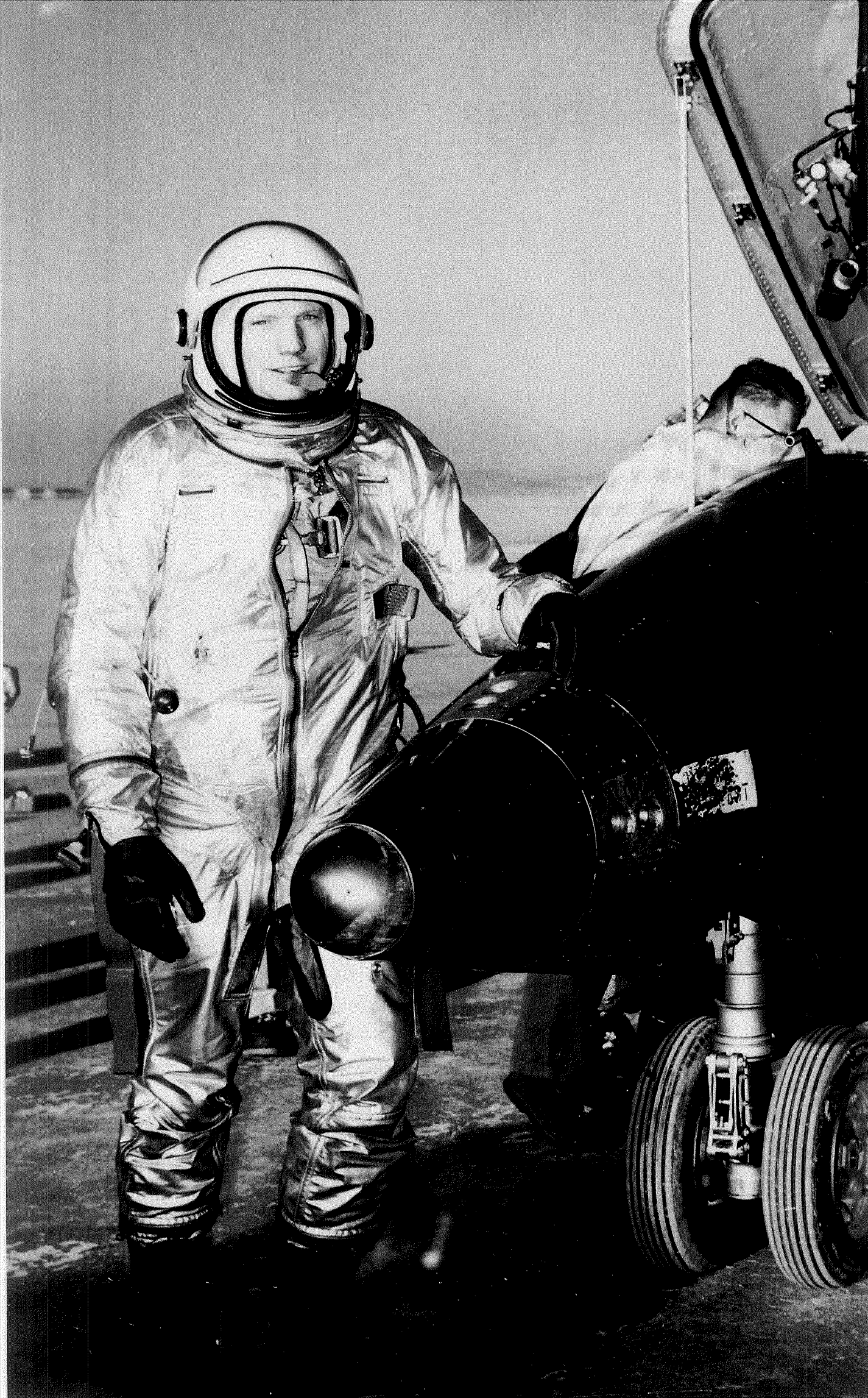
result, the X-15 was equipped with a gyro-stabilized inertial navigation system (INS) and flight instrumentation that would give the pilot much more precise and accurate flight information.

The second and third generation rocket planes had produced some valuable information about flight at high speeds and altitudes. But it had come at a cost. So it was against a mixed background of triumphant records and tragic failures that the NACA flight research team at Dryden began working on the X-15—a program that aimed to achieve not only what the early rocket planes had left undone but also goals two or three times as high.¹⁸

The X-15

The X-15 program actually started in

1952, when several prominent researchers began lobbying for a research vehicle that could begin investigating some of the basic problems that human space flight would entail. At that time, however, NACA had its hands full with the problems of Mach 2 flight, so it was 1954 before serious studies began on an aircraft design for the ambitious goal of flight at speeds from Mach 4 to Mach 10 and altitudes 12-50 miles above the Earth. In December 1954, NACA, the Air Force and the Navy signed an agreement for the research plane that gave the Air Force responsibility for administering its design and construction and NACA responsibility for technical supervision. The Air Force and the Navy would share responsibility for the program's cost. This partnership proved smoother in many ways than the X-1 project, due in large part to the fact that although it was



Right: X-15 in flight. Once the X-15 flew, researchers at Dryden used the data collected during flight to understand better the relationship of theory, wind-tunnel data, and the realities of actual flight. During the early years of the X-15 program, comparisons of flight data with those from wind tunnels had to be done by traditional methods that were time-consuming and not fully consistent. Moreover, the methods in use at that time were unable to provide values for many dynamic aircraft responses in flight. In 1966 Dryden researchers Lawrence W. Taylor, Jr., and Kenneth W. Iliff began developing a more automated technique for obtaining numerical values for aircraft behavior. This involved theoretical contributions resulting in computer programs (later improved by Richard E. Maine) for manipulating multiple differential equations to

X-15 with Neil Armstrong next to nose. The future astronaut and first human to walk on the Moon completed seven flights in the X-15. (Air Force Photo)

obtain the unknown values of the parameters that define aircraft behavior. Called **parameter identification**, this technique allowed researchers to determine precisely the differences between values predicted from wind tunnel data and those actually encountered in flight. Such precision is essential for understanding and fixing undesirable or dangerous flight characteristics. This significant flight test and flight research technique has been used on over 50 other aircraft at Dryden, including all of the lifting bodies, the XB-70, the SR-71, the Space Shuttles, and the X-29. This technique has spread to virtually all flight test organizations throughout the world and has been used to enhance the safety, flight procedures, and control system designs of most current supersonic aircraft as well as to improve flight simulators, submarines, economic models, and even biomedical models. (Air Force Photo)



a joint military/NACA program, the goals of the participants were similar. The X-15 was far enough beyond any operational aircraft the military had that it was seen as a pure research aircraft by all three participants. In November 1955, North American Aviation was awarded a contract for three X-15 aircraft, which were to be capable of going 6,600 feet-per-second and reaching an altitude of 250,000 feet.

Despite the huge leap in performance that those figures represented, scientists and engineers knew the foundations upon which the X-15 was based were sound. By the same token, however, they knew that they couldn't wait to have all questions answered before going ahead with the program. When the contract for the X-15's airframe was awarded, for example, the technology for its 57,000-pound-thrust rocket engine (representing 608,000 horsepower at 4,000 miles per hour) did not yet exist. A contract for the powerplant went to Reaction Motors in September 1956, but the engine was still not built when the first X-15

was delivered in 1958. In fact, the first XLR-99 motor was not installed in an X-15 until 1960. In the interim, the X-15s were equipped with two XLR-11 engines from the X-1 program.¹⁹

North American was also forging new ground with the X-15 airframe. The structure of the X-15 had to withstand forces up to 7 Gs, and the friction generated by its high speed was expected to create temperatures on the airframe as high as 1,200 degrees Fahrenheit. That was beyond the tolerance of any aircraft material used up until that time, including stainless steel. So North American built the X-15 out of a new, heat-resistant nickel alloy called Inconel X. The X-15 also incorporated rocket engine-powered reaction controls and was outfitted with 1,300 pounds of instrumentation, including no fewer than 1,100 sensors.²⁰

The main research goals of the X-15 were to investigate aerodynamic forces, heating, stability and control (including reaction controls), reentry characteristics, and human physiology at extremely high speeds and altitudes.

Accomplishing this research was particularly difficult, not only because it required flying far beyond any condition or speed anyone had attempted before, but also because it required operating an aircraft throughout an incredibly wide envelope. The X-15 was air-launched at approximately 45,000 feet, would accelerate to anywhere between Mach 2 and Mach 6 while climbing as high as 350,000 feet, execute a successful hypersonic reentry through Earth's atmosphere and then glide back to a 200-mile-per-hour, unpowered landing on a dry lakebed. This created a real challenge for the X-15's designers. Just as an example, the broad speed range of the X-15 led them to put three control sticks in the cockpit. A conventional center stick was used at slower speeds, and a right-

hand side stick was used for high-G maneuvering when it was critical not to over-control the plane. A left-hand side stick operated the reaction controls when the aircraft was outside the Earth's denser atmosphere.²¹

The complexity of the X-15 program also required special ground and air support. The B-29 and B-50 launch planes were replaced by a B-52 with a special pylon for the X-15 mounted under one wing. A formal control room replaced the portable van and radio used to control previous test programs, in order to better monitor and respond to the many pieces of information the X-15 would be transmitting to engineers during each flight. The control room later made famous at the Johnson Space Center was based on the Dryden facility.

X-15 after Jack McKay's mishap. In November 1962 McKay was forced by an engine failure to land at Mud Lake, Nevada. The X-15's landing gear collapsed, flipping the aircraft on its back. McKay was injured but recovered sufficiently to fly again. This aircraft was later restored and is on display at the Air Force Museum near Dayton, Ohio. (NASA Photo E 9149)



Tracking an aircraft traveling 6,600 feet per second was also a new challenge for NASA and the Air Force. A special flight corridor, known as the “High Range,” was created for the X-15 flights. It measured 485 miles long and 50 miles wide and stretched from Wendover, Utah, to Edwards Air Force Base. In addition, radar tracking and telemetry sites capable of receiving 600,000 pieces of information a minute were set up at Beatty and Ely, Nevada, as well as at Edwards, to provide continuous coverage. The route was also structured to follow a string of dry lakes from the Wendover launch point back to Edwards so the X-15 pilots would always have an emergency landing field within reach.²²

Even preparing for a single launch was a

tremendous undertaking. It took the ground crew the better part of a week just to complete the ground checkout of all the X-15’s complex systems and instrumentation. The night before a mission, crews and equipment had to be flown to each of the High Range tracking stations, and emergency personnel were stationed at key emergency dry-lake sites. Then the morning of a launch, about 25 ground-crew personnel would work from the predawn hours to fuel and ready the aircraft for flight.²³

The X-15 pilots and engineering crew did benefit from the use of an analog simulator that could assist both pilot training and flight planning. The first simulators that could be used for basic pilot training as well as engineering analysis became available during the X-2

X-15 after a hard landing on the lakebed by Scott Crossfield. On 5 November 1959, the aircraft experienced a small engine fire—a dangerous occurrence in a rocket plane. Crossfield made an emergency landing on Rosamond Dry Lake with a large quantity of propellants still on board. This caused the “back” of the X-15 to break, requiring three months of repairs without significantly delaying the program. (NASA Photo E 9543)





program, but they were not as capable as the ones developed for the X-15 program. The X-15 pilots spent many hours in the simulator before each flight, which helped reduce the number of surprises they encountered.

Nevertheless, the program remained one of the most challenging the Dryden pilots and staff had ever undertaken. It could hardly have been otherwise. After all, the X-15 team was attempting to fly an aircraft at six times the speed of sound and virtually into space at a time

when airlines were still flying piston-engine, propeller airplanes and even primitive computers were in their early development stages. It would be an impressive program today; at the time, the X-15 was a staggering effort of sheer brute force.

Jack Kolf, who was an X-15 project engineer, remembered the program as unique because “everything it did was being done for the first time. We had problems in all areas every day, and every day it would be different.

*Neil Armstrong with X-15.
(NASA Photo E 6286)*

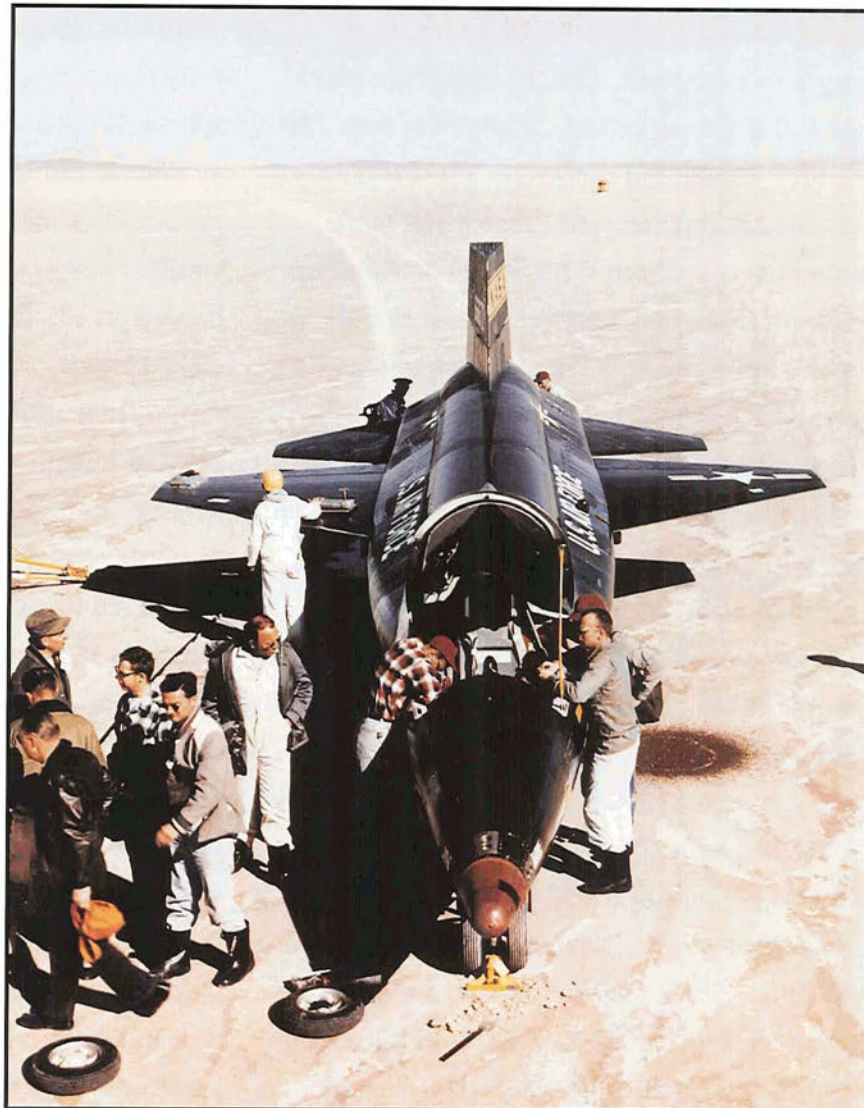
We'd get hit with totally unknown things because we were operating in an area we didn't understand. Fortunately, the airplane was overbuilt in all areas that allowed us to learn from our mistakes. We could heat cables and landing gear and crack windows . . . the X-15 could deviate from its optimum (flight) profile, and it would still come home."²⁴

Or at least it almost always came home.

The nearly ten-year, 199-flight program was a tremendously successful one in terms of safety, especially considering the difficulty of what the X-15 team was trying to achieve. Yet the program did suffer four accidents. Two of them involved emergency landings on alternate lakebed sites when engine problems occurred after launch. North American test pilot Scott Crossfield escaped without injury when his fuel-heavy X-15 broke in two on touchdown, but NASA pilot Jack McKay crushed four vertebrae when his X-15 rolled over on landing at Mud Lake, Nevada.²⁵ Less than a year after his first mishap, Crossfield was in the cockpit when the X-15's new XLR-99 engine exploded during a ground test. The 15-foot aircraft cockpit section that was left intact shot across the ramp and was engulfed in flames, but Crossfield waited out the fire and emerged unharmed.

Air Force pilot Mike Adams was not so

fortunate. On a 1967 flight that reached Mach 5.2 and an altitude of 266,000 feet, Adams was distracted by a malfunctioning experiment and apparently misread a cockpit instrument, causing him to slip the X-15 sideways as it was approaching reentry to Earth's atmosphere. At that speed and altitude there is little margin for error, and the X-15 went out of control and broke apart. The death of Adams was a tremen-



Right. X-15 being secured by ground crew after landing (Air Force Photo)

dous blow to the X-15 project team, and some people who worked on the program attribute the end of the program a year later in part to that tragic accident.²⁶

Nevertheless, even the X-15's accident rate proved that a pilot was an important ele-

ment of a high-performance near-space craft. Post-flight data revealed that without pilot intervention and system redundancy, the X-15 would have crashed on 13 of its first 44 flights, and that the success rate of its first 81 missions, based on whether or not the research objectives for the flight were achieved, would have dropped from 56 to 32 percent.²⁷

Actually, the X-15 proved a whole lot more than that. In fact, it has been described as one of the most successful flight research programs ever conducted. In almost ten years and 199 flights, it produced no fewer than 750 research papers and reports on a broad range of aeronautics and aerospace topics and made more than two dozen significant contributions to future flight both within and outside the Earth's atmosphere.²⁸ The research that produced these monumental results fell into three major categories: exploring the upper boundaries of flight speeds and altitudes, filling in the area within those boundaries with additional information, and doing "piggyback" experiments that used the X-15's speed and altitude capabilities to conduct research unrelated to the X-15 itself.

In terms of exploring boundaries, the X-15 reached a maximum speed of Mach 6.7 and a maximum altitude of 354,200 feet, or 70 miles above the Earth.²⁹ The maximum-speed flight was achieved with the repaired and modified X-15 that McKay had crash-landed on Mud Lake. When it was rebuilt, the fuselage was lengthened and additional fuel drop tanks were incorporated to give it enough endurance to reach Mach 8. It was then redesignated the X-15A-2. Because the heating experienced above Mach 6 was expected to be too great for the X-15's initial design structure, researchers planned to apply a spray-on, heat-resistant ablative coating

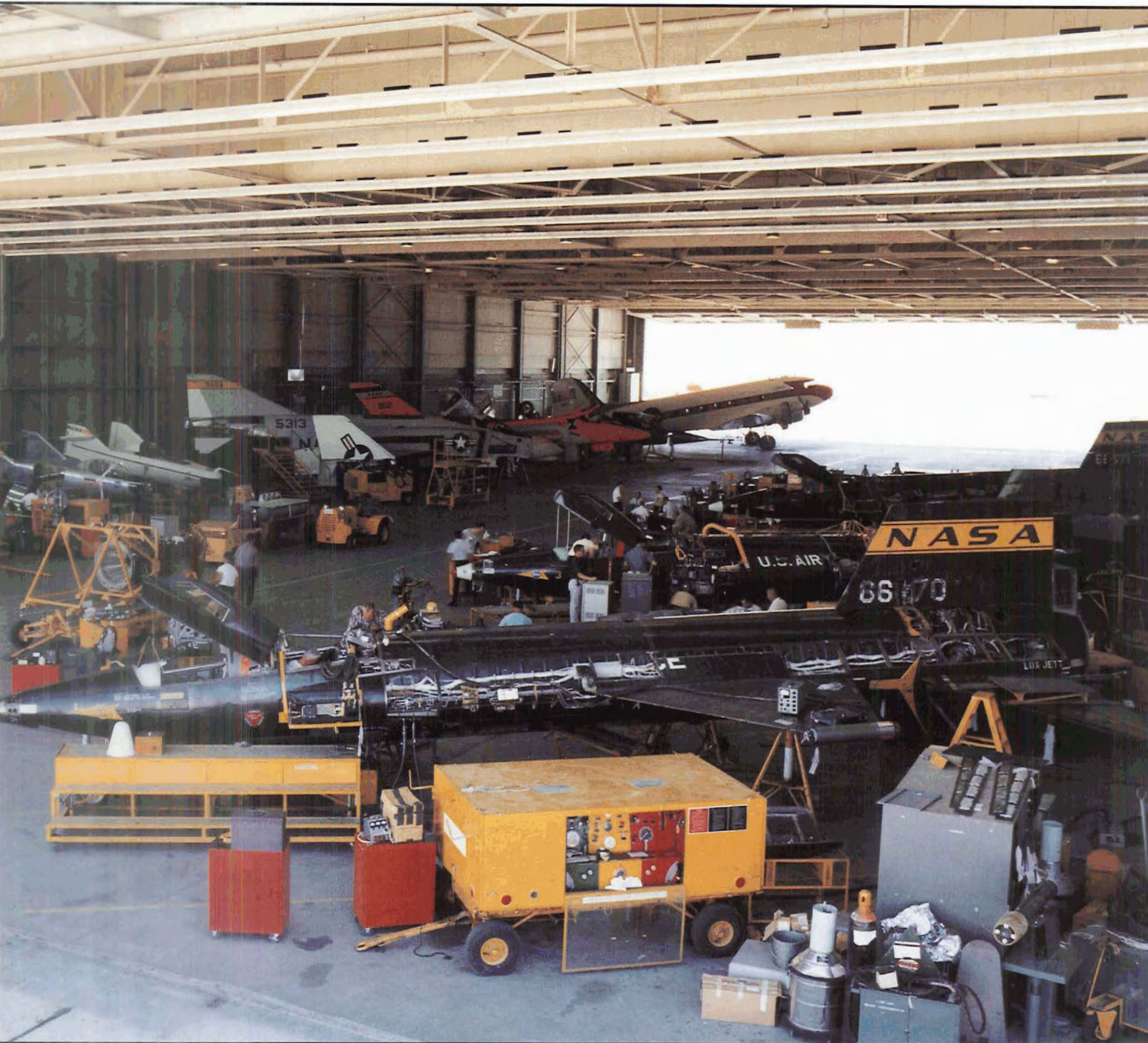
on the aircraft before each flight. The Mach 6.7 record flight used the ablative coating, but the non-reusable spray-on material proved too difficult to work with and maintain for it to be a good operational thermal-protection system for an X-15 type of vehicle.

The X-15 program also produced a tremendous amount of information about hypersonic and exoatmospheric flight. Perhaps most importantly, it demonstrated that a high-performance reusable vehicle could be successfully flown by a pilot outside Earth's atmosphere, brought through reentry, and returned to an unpowered landing. In the process, the X-15 gave researchers a much clearer picture of the combined stress of aerodynamic loads and heating in a hypersonic, high-dynamic-pressure environment.

In addition, the X-15 led to the development of numerous technologies that would benefit future programs. The X-15's engine, for example, was the first large, restartable, throttle-controllable rocket engine. The aircraft's blunt-ended, wedge-shaped tail was found to solve directional stability problems at hypersonic speeds. The X-15 also led to the development of the first practical full-pressure suit for protecting a pilot in space and to a high-speed ejection seat. It successfully tested a "Q-ball" nose-cone air-data sensor, an inertial flight data system capable of functioning in a highly dynamic pressure environment, and the first application of energy management techniques. The X-15 pilots also successfully demonstrated the use of reaction controls outside the Earth's atmosphere. Reaction controls were small rocket-powered jets placed strategically in the aircraft's wingtips and nose that could be fired to control the plane even when thin air rendered its aerodynamic flight controls useless. The idea



NASA Hangar 4802 in 1966 with lifting bodies (HL-10, M2-F2, M2-F1), F-4, F-5D, F-104, C-47 (one row), and X-15s (second row), from viewer's left (NASA Photo EC66 1461)



grew out of the stability problems experienced with the X-1A at high altitude and were initially researched using one of Dryden's F-104s, but reaction controls were a critical technology for not only the X-15, but also the Mercury capsule, the Apollo Lunar Landing Module, and every piloted craft to ever fly in space. The Mercury capsule also used a variation of the X-

15's controls, including the side-stick controller, on its orbital missions.³⁰

The X-15 flights also revealed an interesting physiological phenomenon that indicated just how difficult the pilots' job was and provided a baseline for monitoring the health of future astronauts. The heart rate of the X-15 pilots (and, in fact, the astronauts that

followed) during their missions ranged between 145 and 180 beats a minute instead of a more typical 70-80. Aeromedical researchers found that the high pulse rates were not due to the physical stress of the pilots' environment, but to the psychological keyed-up, highly-focused state the missions required of them.³¹

The third phase of the X-15 program yielded many other valuable contributions, including measurements of the sky brightness and atmospheric density, data from micrometeorites collected in special wing-tip pods, and an opportunity to explore Earth-resources photography. The X-15 also tested a number of prototype systems that were subsequently used in the Apollo program. For example, the aircraft tested the insulation later used on the Apollo program's Saturn booster rockets, and the X-15 pilots tested horizon-measuring instrumentation that aided development of navigation equipment for the Apollo capsule.³²

Some of the biggest benefits reaped by the space program from the X-15 and other rocket aircraft efforts, however, did not come from tangible pieces of hardware or technology but from the intangible assets of people and experience. Since the Mercury spacecraft was being developed during the early stages of the X-15 research program, the aircraft had a somewhat limited impact on the design of the Mercury capsule. But the success of the X-15 flights provided the Mercury program managers with a level of confidence that was tremendously valuable. Furthermore, a number of the people at Dryden who had been involved with the rocket-powered X-planes and the X-15 went on to assume key leadership positions in the space program. Walt Williams, for example, became the operations director of the Project

Mercury and Gemini Programs. And NACA research pilot Neil Armstrong, who had evaluated the use of reaction controls with both the F-104 and the X-15, went on to apply his knowledge to the Apollo program, hand-flying the Lunar Landing Module to the first landing on the moon in July 1969.³³

After 199 flights and over 18 hours of supersonic and hypersonic research, the X-15 program came to an end in December 1968. Adams' accident the previous year may have had some impact on the final decision, but the biggest factor was simply that the focus of NASA and the nation had shifted to space flight. By 1965, 80% of NASA's budget was earmarked for space-related research.³⁴ Much more research information might have been gained by continuing the X-15 program or developing a follow-on effort, especially in terms of preparing for the Space Shuttle, the X-30 National AeroSpace Plane, or the High Speed Civil Transport projects that followed. But at the time the X-15 program was seen as having decreasing value, because NASA's space program, at least in the 1960s, was centered around a ballistic capsule rather than a lifting reentry vehicle.

The Lifting Bodies

Understandably, a number of people at Dryden were not happy about NASA's choice of a capsule over a lifting reentry space vehicle, and a few of them were not content to close the book on the subject. The result was the lifting-body research program—an effort that exemplified more than any other the independent, innovative, pragmatic and pioneer mind-set of the people who chose to work at Dryden.



*M2-F1 over base on tow line
(NASA Photo ECN 408)*

A lifting body is a vehicle that generates enough lift from its fuselage shape to permit it to fly without wings. Alfred Eggers and others at the NASA Ames Laboratory conducted early wind-tunnel experiments on the concept, discovering that half of a rounded nose-cone shape, flat on top and rounded on the bottom, could generate a lift-to-drag ratio of perhaps 1.5 to 1. Eggers even sketched out a preliminary design of what would later become the M2 lifting body design. Several other researchers at the NASA Langley Research Center were toying with their own lifting-body shapes.

The aircraft-oriented researchers at Dryden liked the lifting-body concept because in their view, it offered a pilot/astronaut the more dignified option of flying his spacecraft back to an Earth landing instead of being ignominiously dumped into the ocean in an unflyable capsule. With the decision for the Mercury capsule already made, NASA headquarters would have been very unlikely to

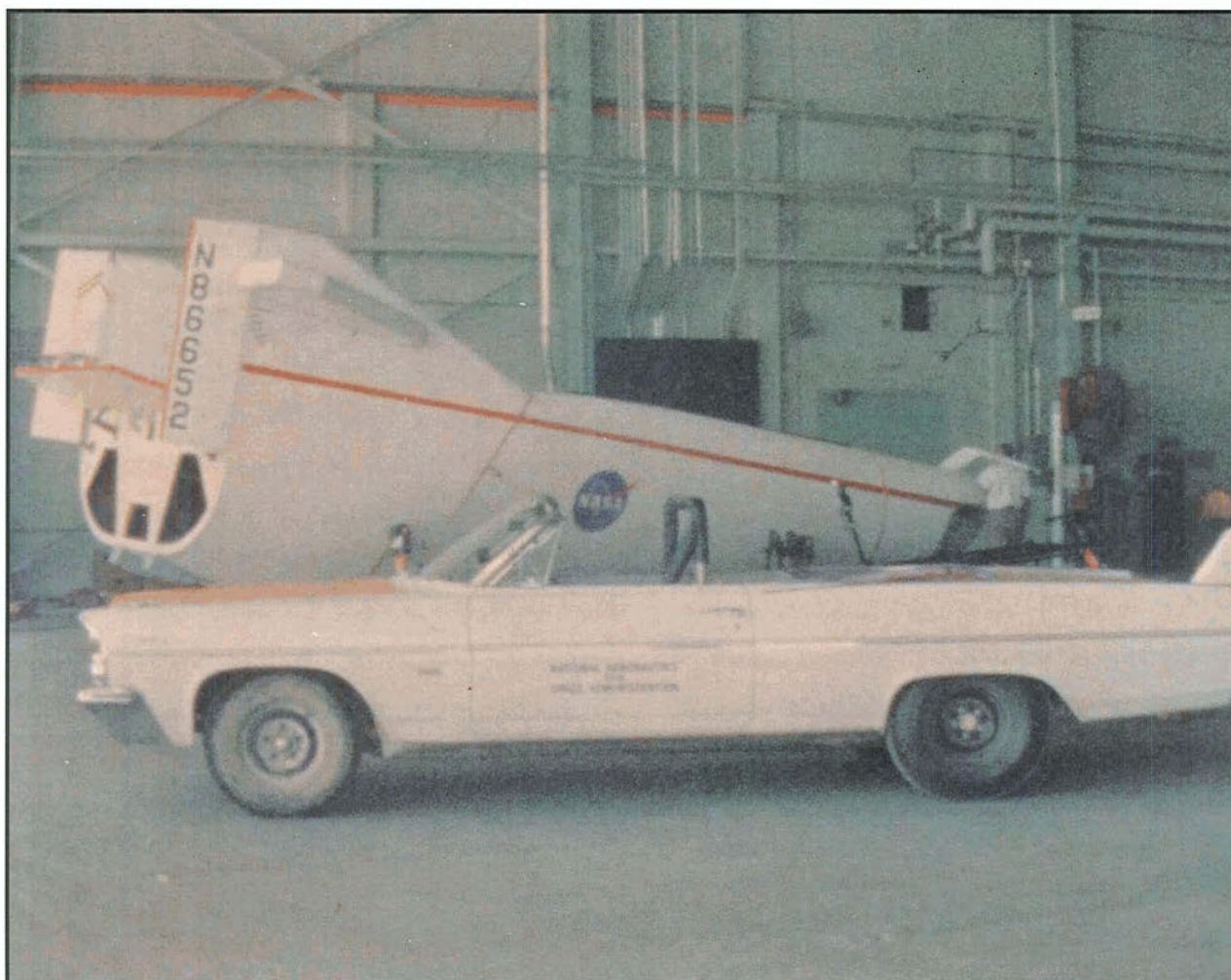
divert funds to study, construct, or flight-test a lifting-body aircraft. But in the minds of engineers like R. Dale Reed and pilots like Milt Thompson, that was not an insurmountable obstacle.

Reed, a model aircraft builder and private pilot in his spare time, was intrigued with the lifting body idea. Using Eggers' concept, he built a lightweight, free-flying lifting body model that he launched repeatedly into the tall grass near his house, modifying its control and balance characteristics as he progressed. He then attached it to a larger free-flying tow aircraft to allow it to glide from a slightly higher altitude. Pleased with the result, he had his wife film some of its flights with their 8-mm home camera to help him present the lifting body concept to others at the Flight Research Center.

Reed recruited fellow engineer Dick Eldredge and research pilot Thompson to help him prepare a plan to test a lifting body vehicle.



*Above: M2-F3 launch
from B-52
(NASA Photo ECN 2774)*



*Left: M2-F1 and modified
Pontiac tow vehicle
in hangar
(NASA Photo
EC92 04152-1)*

*M2-F1 lightweight lifting
body behind a C-47
(NASA Photo E 10962)*

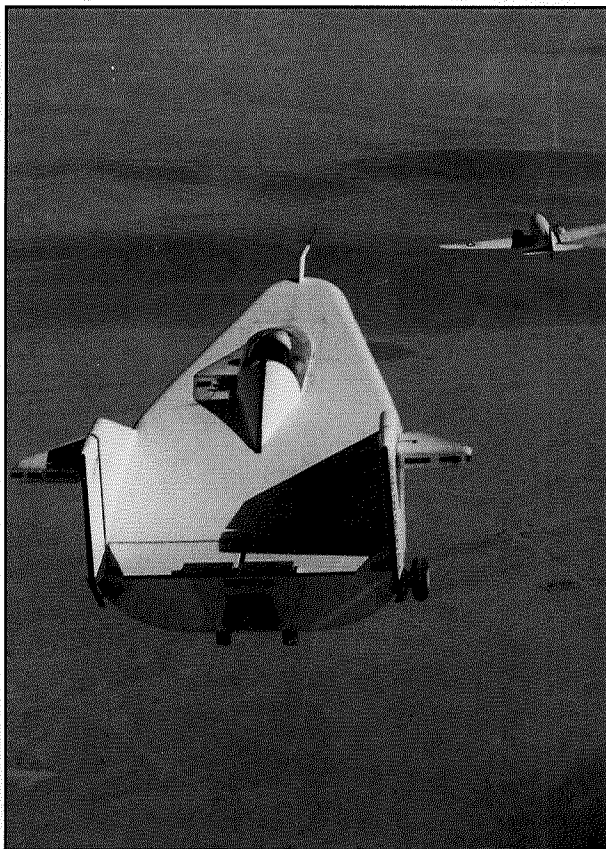
Dryden's staff was always characterized by a passion for airplanes, and Reed hoped to take advantage of that fact. Throughout the Flight Research Center staff there were numerous talented machinists, welders, and sheet-metal workers who were involved in building homebuilt aircraft in their spare time. Reed and Eldredge's plan was to utilize this on-site talent and enthusiasm to build a low-cost test lifting-body vehicle. Reed, Eldredge and Thompson prepared a proposal and convinced Eggers to come down from Ames to hear them present it to Center Director Paul Bikle. Eggers enthusiastically offered wind-tunnel support for the project, and Bikle gave the trio the go-ahead to build a full-scale wind tunnel model of the M2 design. Although the official permission was for wind tunnel testing only, Bikle noted that if the aircraft happened to be built so that it was

capable of actual flight, well, that would be something beyond management's control. The message was clearly received, and the M2-F1 lifting-body team went to work.

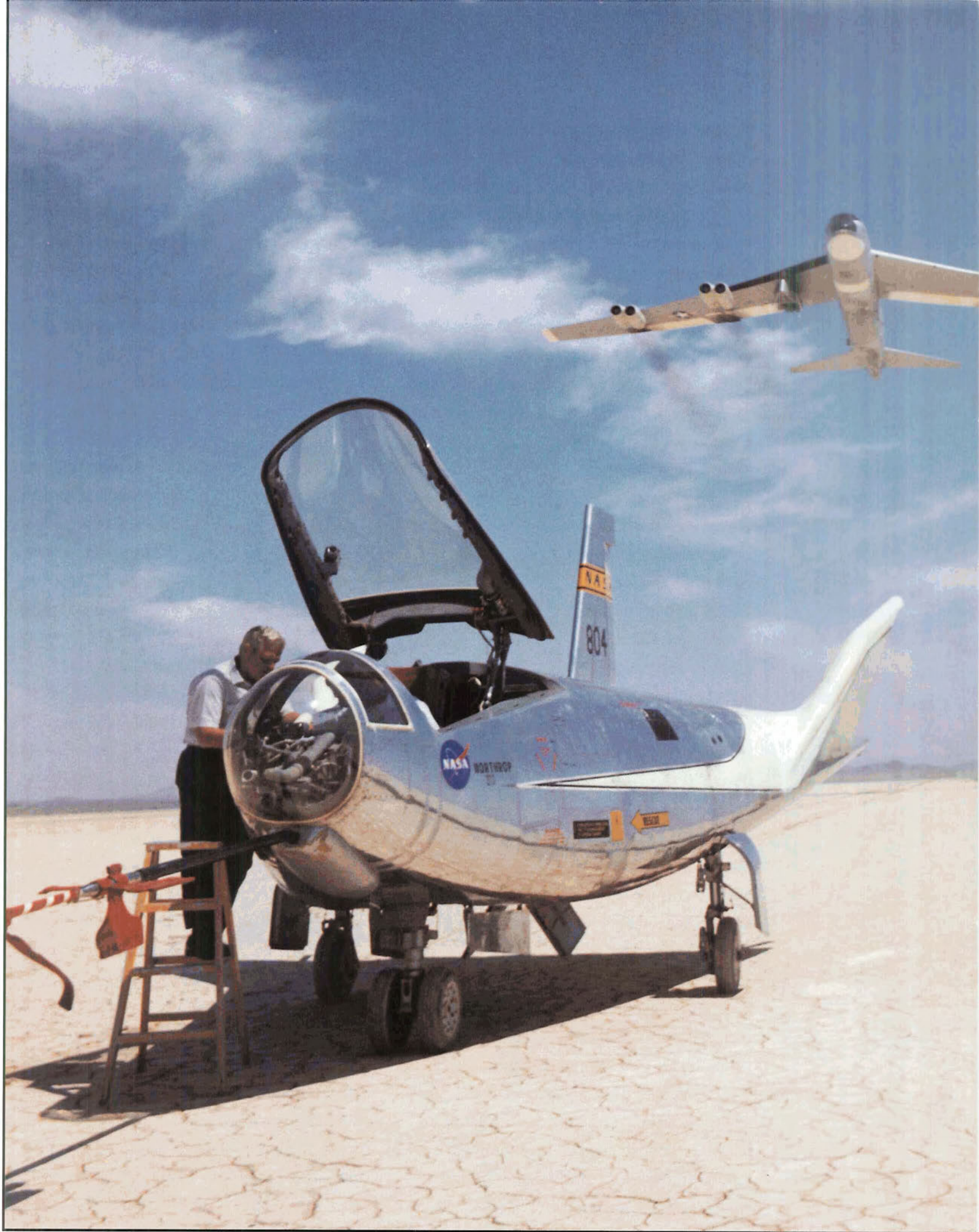
A small hand-picked cadre of engineers and fabricators set up shop in a corner of a hangar at Dryden and began designing a steel tubular frame and control system for the aircraft. They designed the aircraft with a flat top and rounded nose and belly, with two vertical

fins to give it directional stability and control. Constructing a lightweight fuselage shell was more of a problem, but Bikle, who was a world-record-holding sailplane pilot, knew a sailplane builder on nearby Lake El Mirage that he thought could make one out of plywood. He allocated \$10,000 from his discretionary fund for a fuselage shell contract, and contributed the services of Ernie Lowder, a NASA craftsman who had worked on the building of Howard Hughes' mammoth "Spruce Goose" wooden flying boat.

While the aircraft was being constructed, the team began scouting for a tow vehicle that could allow them to try some taxi tests with the M2-F1 before taking it to Ames for wind-tunnel testing. Fortunately, one of the project's volunteers, a man named Walter "Whitey" Whiteside, was active in the hot-rod racing circuits. He supervised the purchase of a Pontiac Bonneville convertible



and sent the car to Mickey Thompson's renowned hot-rod shop in Los Angeles for modification. The car arrived back at Edwards capable of pulling the 1,000 pound M2-F1 at speeds over 100 miles per hour—which was, just coincidentally, fast enough to get the aircraft airborne. The slightly irreverent but enthusiastic group also arranged for the car to be painted with racing stripes and a NASA logo on the side.

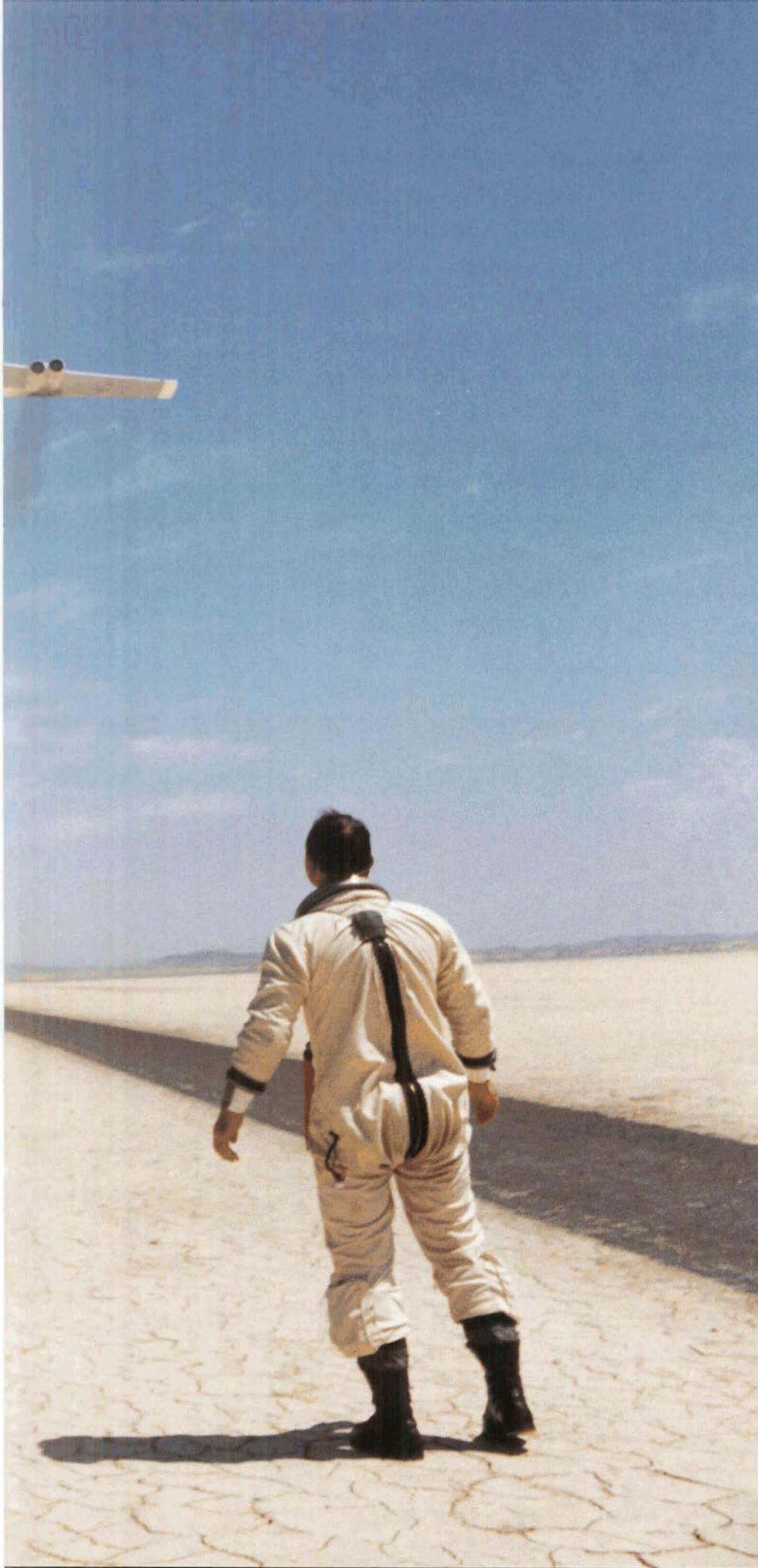


*Research pilot Bill Dana with HL-10 to his left and B-52 flying overhead. Bending over the cockpit is John Reeves.
(NASA Photo ECN 2203)*

The plan was only to conduct ground tests of the vehicle, but sitting in the fully operational cockpit, Milt Thompson remarked that “maybe it really wouldn’t be flying if we just lifted it off the lakebed a couple of inches.” Bikle’s response to the group was, “Go for it, but be careful.” After some changes to the control system, the plywood M2-F1, now dubbed the “flying bathtub” because of its bulbous shape, was successfully towed by the Pontiac to an altitude of 20 feet, where Thompson released the tow line and glided back to touchdown.

After a successful series of wind-tunnel tests on the vehicle at Ames, the group came back to Bikle for permission to actually fly the aircraft. Headquarters had not sanctioned the project, and Dryden’s director of research engineering at the time went on record opposing any flight testing other than towing a few inches off the ground because he felt the information they stood to gain was not worth the risk to Thompson. But Bikle believed in the project. Fully aware that he was putting his NASA career on the line, Bikle authorized the flights anyway. It was a display of courage equal to that shown by any of the research pilots, and it was a reminder of an important fact. Bravery comes in many forms, and managers with the courage and faith to back their people and projects were just as important to Dryden’s success as the pilots who flew the actual aircraft.

On 16 August 1963, the M2-F1 team



towed the aircraft to 12,000 feet behind the Center's DC-3 aircraft and Thompson successfully glided back to a lakebed landing, inaugurating Dryden's lifting body flight research program. Some people at NASA headquarters were aware of the project, but the Administrator was unaware that it had flown until, while testifying before a congressional committee, he was asked about it by a congressman who had read about the M2-F1's flight in the newspaper. Some feathers were ruffled, but Bikle's defense was aided by the fact that the flight had been successful and the whole project had cost only \$30,000.

The M2-F1 went on to conduct approxi-

mately 100 research flights. Ten different NASA and Air Force pilots flew it successfully, although they did find that it had a nasty tendency to develop a pilot-induced roll oscillation. On pilot Jerry Gentry's first air tow flight with the vehicle, the rolling motion increased so severely that he ended up inverted behind the DC-3, still attached to the tow line. As the ground crew watched in horror and the ground controller called for Gentry to eject, Gentry released the tow line and managed to turn the maneuver into a full barrel roll, touching down on the lakebed at the bottom of the roll. When the M2-F1 did the same thing a year later, Bikle ordered it grounded.³⁵

*Group shot of remotely piloted vehicles on lakebed, with "mother" ship in background
(NASA Photo ECN 1880)*



By then, however, the success of the M2-F1 program had proven the concept sufficiently to win broader support within the agency. In 1964, NASA authorized the building of two “heavyweight” lifting-body aircraft for further research. One was a metal version of the M2-F1, designated the M2-F2, and the other was a design known as the HL-10 that was developed at the Langley Research Center. Both aircraft were to be built by the Northrop Corporation and would be equipped with an XLR-11 rocket engine to allow pilots to explore the crafts’ characteristics at higher speeds, including transonic and supersonic flight. The design also called for small hydrogen-peroxide rockets for the pilot to use if some additional flare time was needed at touchdown. The flight research program itself was to be another joint effort between Dryden and the Air Force Flight Test Center at Edwards.³⁶

The heavyweight lifting-body flights began in July 1966, with the vehicles launched from the same B-52 aircraft that was being used to drop the X-15s. In their first configurations, the lifting bodies were not the best handling of aircraft. The first flight of the HL-10 was so marginal that NASA instantly grounded the vehicle and sent it back to Northrop for modifications. The M2-F2, on the other hand, had the same poor lateral-directional stability as its lightweight predecessor, which eventually led to the program’s only serious accident.

On 10 May 1967, NASA pilot Bruce Peterson was bringing the M2-F2 down to a lakebed landing when a wind gust started a rolling oscillation. The rolling turned Peterson off his original heading, which increased his problems because without the tar markings of the runway on the lakebed, it was difficult for

pilots to tell exactly how far off the ground they were. As he was trying to dampen out the rolling motion, a rescue helicopter appeared in front of him, adding another distraction at a critical time. Realizing he was very low, Peterson fired the M2-F2’s hydrogen peroxide rockets to reduce his angle of descent and extended the landing gear, but it was too late. Before the gear could lock, he hit the lakebed. The gear sheared off and the M2-F2 cartwheeled over and over across the hard lakebed surface at more than 250 miles per hour. The film footage of the accident was so spectacularly horrifying that it became the opening sequence of the television series *The Six Million Dollar Man*. Fortunately, Peterson was protected by the M2-F2’s rollover structure, so while he lost an eye he managed to survive the accident.

Peterson’s accident was actually the fourth time the M2-F2 had demonstrated a severe rolling oscillation, and the modified HL-10 looked like it was going to have much better flying characteristics. So there was not a lot of support among NASA’s managers for rebuilding the M2-F2 aircraft. But once again, there was a small group of believers who refused to say die. Researchers at Ames conducted wind tunnel tests to determine what modifications might alleviate the M2’s instability and determined that adding a third fin in between the two existing tail fins would correct the problem. A couple of champions for the program eked successive small amounts of money out of headquarters to permit the modification and rebuilding of the aircraft. Northrop did the major work and delivered a “kit” for the redesigned M2-F3 back to Dryden for final assembly. Three years after Peterson’s accident, the

M2-F3 made its first flight.³⁷

The lifting-body flight research program eventually added two other Air Force-sponsored configurations: the Martin-Marietta built X-24A and its derivative, the X-24B. The X-24B, which was literally built around the existing fuselage of the X-24A, was by far the sleekest looking and highest performing of the lifting body designs. It had a higher lift-to-drag ratio than the rounder models, which allowed it to glide for a much longer distance. The Air Force's interest in the X-24B design was motivated partly by a desire for a near-space capable reconnaissance craft that could take pictures over the Soviet Union and then still have enough gliding power to make it back to the United States for landing. Although an operational vehicle never materialized, the X-24B proved a successful lifting body design with very pleasant handling characteristics.³⁸

The lifting-body flights contributed a lot of useful research information about that kind of aircraft configuration. Advocates of the program, in fact, had hoped that the research results would lead NASA to select a lifting-body shape for the planned Space Shuttle. That did not happen, but the program made a significant contribution to the Shuttle design by demonstrating that a horizontal landing spacecraft configuration with a very low lift-to-drag ratio could be landed successfully and accurately without propulsion. The initial Rockwell design for the Shuttle called for air-breathing jet engines to power it to landing in addition to the rocket engines it needed for launch. The Dryden experience with the lifting bodies, however, convinced the Shuttle managers that the craft could be landed safely as a glider, saving weight and increasing the Shuttle's payload. Five years later, mission planners were still

debating whether the Shuttle could be landed within the confines of a runway. To demonstrate that it could be done, NASA pilot John Manke and Air Force pilot Mike Love performed spot landings on Edwards' concrete runway with the X-24B, touching down precisely where they were supposed to. The debate came to an end.

The lifting-body flights also contributed to the Shuttle program by demonstrating not only the fact that unpowered landings *could* be done, but also *how* they could be done. The lifting-body pilots' approaches to landing, which used steep descents to maintain high speed that could then be transferred into excess energy for a flare and gentle touchdown, is the same technique used by the Shuttle pilots today.³⁹

The lifting-body program came to an official end in 1975. Yet like a Phoenix rising from the ashes, the concept has appeared several times since then in proposed NASA spacecraft. When the Langley Research Center revealed its HL-20 design for an emergency crew return vehicle or small mini-Shuttle in 1990, the shape was remarkably similar to the HL-10 and X-24A designs. Lockheed's proposal for an unpiloted X-33 single-stage-to-orbit cargo vehicle is also a lifting-body configuration. And even one proposed crew return vehicle, designed to carry sick or wounded astronauts back from a space station, is a lifting body design that would be programmed to fly back into the atmosphere and descend only the last few thousand feet by a steerable parachute.⁴⁰

The lifting-body design has not yet made it into an operational spacecraft, but it has survived as a design concept longer than the ballistic capsule that dominated NASA's focus

in the 1960s. And although the final Shuttle design was neither an X-15 nor a lifting body, it incorporated the knowledge learned from both research programs. The sleek and swift X-15 and the stubby-looking lifting bodies might have shared little in appearance, but between the two of them, they demonstrated that it was possible to fly a high-performance lifting reentry vehicle into space and bring it, unpowered, to a runway landing back on Earth.

Jet-Powered Speed Research

Although a great many of Dryden's resources were devoted to the rocket-powered X-15s and lifting bodies in the 1960s and early 1970s, rocket planes and space were not NASA's only concern. Advances in jet engines and jet-powered transport aircraft had given rise to the idea of a national supersonic transport, commonly known as the SST. President John F. Kennedy, in fact, had instigated an initiative in 1961 to produce a national supersonic transport capable of flying Mach 3. Soon after, Dryden began research to support such an aircraft. The Center's first effort involved a series of flights with a Navy A-5A Vigilante to explore the approach and let-down considerations of an SST in a crowded air traffic environment. Over the course of several months in 1963, Dryden research pilots flew the aircraft on a series of supersonic approach profiles both at Edwards and into the Los Angeles International Airport.⁴¹

Dryden's next research effort in this area was with the XB-70. North American Aviation had actually begun work on this supersonic, intercontinental bomber even before Kennedy's initiative. It was a mammoth, six-engine, primarily stainless steel aircraft weigh-

ing over 500,000 pounds and capable of Mach 3+ speeds. It had an advanced design that incorporated two vertical fins, a forward horizontal control surface called a canard, and a highly swept delta wing with droop tips. Before the bomber went into production, however, the program was canceled. Nevertheless, the Air Force continued to fund the two XB-70 prototypes to be used as research aircraft.

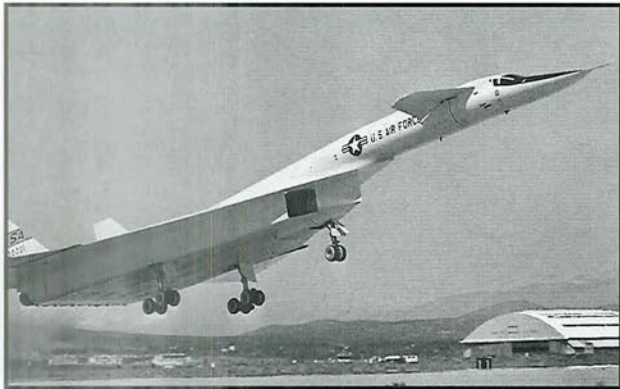
The Langley Research Center was already involved in SST research, and the XB-70A Valkyrie was appealing to researchers because its configuration closely matched many elements they expected a supersonic transport would include. The XB-70 was to be another joint effort between Dryden and the Air Force Flight Test Center, and research instrumentation was incorporated into the aircraft from the start. The plan called for the Air Force to manage the initial test, evaluation, and early research flights with the airplane, with NASA eventually taking over management of one of the two aircraft.

The XB-70 earmarked for NASA was scheduled to be turned over to Dryden in mid-June 1966. But on 8 June 1966, the Valkyrie was involved in a disastrous mid-air collision with a NASA F-104N piloted by Dryden's veteran chief pilot Joe Walker. The XB-70A and the F-104N had gone up with an F-4B, a YF-5A, and a T-38A for a photo mission, and Walker was flying just off the XB-70A's wingtip. Suddenly, Walker's F-104 collided with the XB-70's wingtip, flipped over and crashed into the top of the bomber, taking off both the Valkyrie's vertical stabilizers. The XB-70A went out of control and crashed. Of the three pilots involved, Walker in the F-104N and North American test pilot Al White and Air Force Major Carl Cross in the XB-70A, only White survived, and he was seriously injured. In

less than two minutes, the Air Force and NASA lost two aircraft and two talented test pilots.

The accident severely set back plans for the joint research program. The remaining XB-70A aircraft was not as capable or as well instrumented, but it became the primary research aircraft. The Air Force and NASA flew it for several months in late 1966 and early 1967 to test the ground impact of its sonic boom at different altitudes and speeds—research that helped determine that the American public would not tolerate overland supersonic flight.

NASA began research with the airplane in April 1967, using it to correlate NASA wind tunnel and simulator predictions at Ames and Langley, as well as those of Dryden's General Purpose Airborne Simulator (GPAS), which was a variable stability Lockheed Jetstar aircraft. In the most comprehensive drag correlation effort ever attempted for a supersonic cruise configuration, researchers found that



*Above: XB-70 taking off
(NASA Photo E 16695)*

*Right: XB-70 in flight over
mountains
(NASA Photo EC68 2131)*







SR-71B take-off from Edwards with "shock diamonds" in the exhaust (NASA Photo EC92 1284-01)

drag prediction for the cruise condition was reasonably close but that there was an astounding 27 percent discrepancy at the transonic drag peak, with the predicted value being too low. This sobering result will require much attention to transonic drag by future promoters and designers of supersonic cruise airplanes.

The NASA flights also looked at the structural dynamics of the aircraft at high speeds, investigating methods future supersonic aircraft manufacturers might be able to use to reduce vibrations in the aircraft's structure. By the end of 1968, however, the research results could no longer support the program's cost, and Dryden was already getting involved in the YF-12, which could yield much of the same high-speed data. So the XB-70A was retired.⁴²

The Lockheed YF-12A was the prototype of a fighter/interceptor version of the SR-71 "Blackbird" spy plane that, even today, remains the world's fastest jet-powered aircraft.⁴³ Because its routine operations at altitudes above 80,000 feet and at speeds of Mach 3 subjected it to extremely high temperatures,

the aircraft was constructed of titanium and painted a characteristic flat black color. In the mid-1960s, and indeed for many years, the YF-12 and SR-71 programs were highly classified. Fortunately for NASA, the YF-12/SR-71 program personnel decided they could also use some help from NASA on a flight test program they were conducting at Edwards. While working with the Air Force team getting the SR-71 ready for Strategic Air Command use, NASA asked if it might get access to an SR-71 for some of its own research. The Air Force said no on the SR-71, but offered NASA two YF-12s that it had in storage at Edwards.

So just two days before Neil Armstrong walked on the Moon, Dryden found itself with two Blackbirds and yet another joint research effort with the Air Force. In addition, the partnership included several other NASA centers that were interested in what flights with the YF-12 might yield. Langley wanted information on aerodynamics and structures, Lewis wanted data on propulsion, and Ames was looking for information on the aircraft's com-



*SR-71B over
snow-capped mountains
(NASA Photo
EC94 42883-4)*

plex engine inlet aerodynamics and data to correlate its high-speed wind-tunnel predictions.

The YF-12 flights provided information about numerous areas, including aerodynamic loads and structural effects of sustained Mach 3 flight, thermal loads, the dynamics of the engine inlet system, and stability and control issues with the aircraft. The YF-12 had a very narrow flight envelope at high speeds, and if the stability augmentation system failed, for example, the aircraft could become extremely difficult to fly. The Blackbird also had sensitive and complex engine inlets, which varied their position based on the aircraft's speed, altitude, attitude, and

other factors. They also were susceptible to an unpleasant occurrence known as an "inlet unstart," which occurred when the shock wave formed by the aircraft's high speed flight jumped from its normal position just inside the inlet to outside the inlet opening. The effect on the aircraft was described by one pilot as "kind of like a train wreck," because it jolted the aircraft so badly.⁴⁴

As with the X-15, some of the research conducted with the YF-12s was unrelated to the aircraft itself. One project, for example, was a "cold wall" experiment that involved super-cooling an insulated test fixture on the aircraft



YF-12A (06935) and YF-12C (06937) in formation at dusk, showing the insulated cylinder beneath the YF-12A that was used in the "Cold-Wall Experiment." (NASA Photo ECN 4767)

before take-off, and then explosively removing the coating once the aircraft reached Mach 3. This test, which achieved laboratory standards at 14 miles above the Earth's surface, became a benchmark heat transfer and fluid dynamics experiment.

The YF-12 flight research program was much more trouble-free and successful than the XB-70A, completing almost 300 flights and 450 flight hours in nine years. Both aircraft, however, gave NASA researchers an opportunity to study an area even the X-15 could not cover: *sustained* flight at speeds of Mach 3. By the late 1970s, however, the SST project was long dead and fuel efficiency had become a much greater national concern than extremely high-speed flight. So at the end of 1978, the YF-12 program was canceled. The staff at Dryden was disappointed, of course. The rocket aircraft were already gone, and the Blackbirds represented a kind of wonderful, sleek mystery and excitement that systems research at transonic speeds just couldn't match. But the program had served its purpose, and no research project

lasts forever.⁴⁵

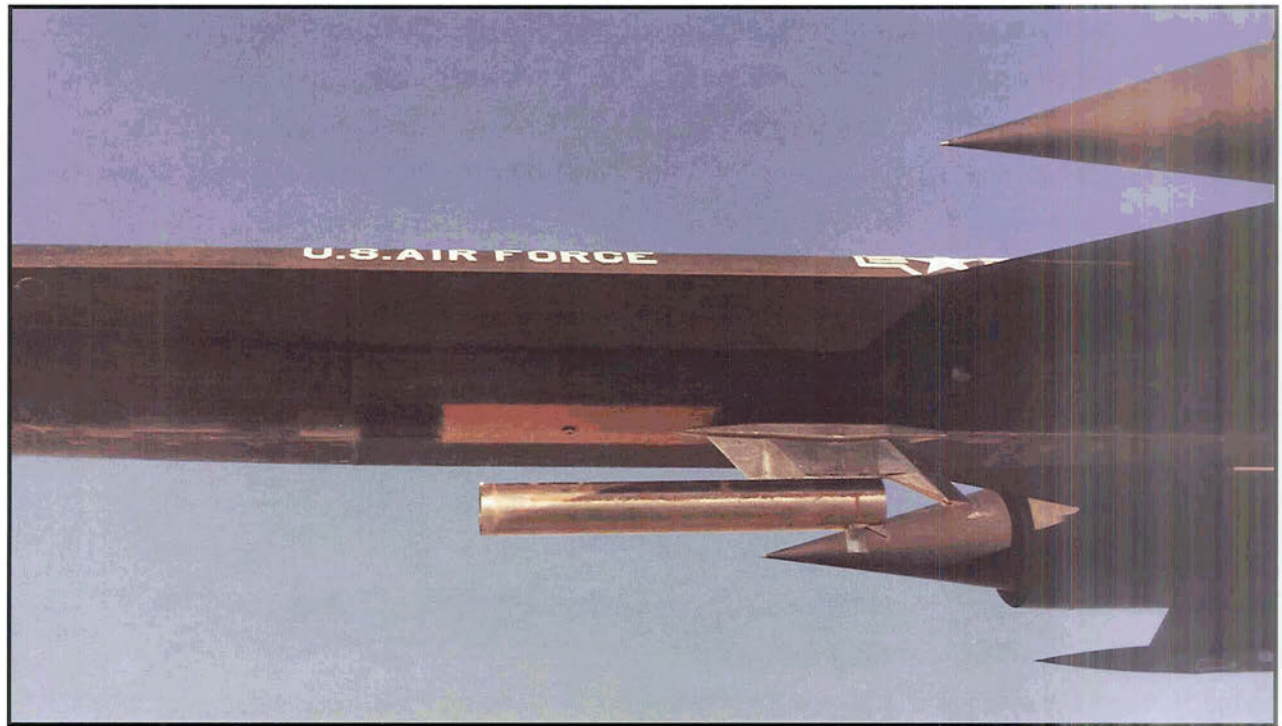
If Dryden's researchers could have looked 12 years into the future, however, they might have felt better. In 1990, the Air Force made the shocking announcement that it was retiring the SR-71s. Spy satellites, it was announced, could adequately perform the Blackbird's role.

Scientists at NASA had shown renewed interest in the SR-71s for a couple of years prior to the Air Force's announcement. Some atmospheric researchers wanted a platform that could perform research at higher altitudes than the U-2 aircraft the Center was then using. In 1987-88 Ames had inquired about getting an SR-71 for its use, but the Air Force at that time had limited airframes at its disposal. That changed with the retirement announcement. Suddenly, the Air Force offered NASA not one but *three* Blackbirds on long-term loan. Researchers at Ames and Dryden weren't immediately sure what they would do with three aircraft, but they snapped them up.

The official agreement was for two SR-

YF-12A showing the hollow cylinder flown beneath the aircraft to obtain flight data about heat transfer and skin friction for correlations with theoretical findings and data from wind tunnels. During one flight, researchers insulated the cylinder from the effects of aerodynamic heating while cooling it with liquid nitrogen. As the aircraft accelerated to nearly Mach 3, a primer cord blew off the insulation, and instruments measured temperatures, pressures, and friction. The same cylinder and sensors were also exposed to Mach 3 conditions in the Langley Research Center's Unitary Plan Wind Tunnel. The correlations of flight data with both theory and wind-tunnel data were excellent, making this "Cold-Wall Experiment," as it was called, a significant achievement in the field of fluid mechanics.

(NASA Photo ECN 4777)



71As and one SR-71B training aircraft, along with appropriate spare parts. But Dryden, which was given the aircraft to manage and fly, found itself overwhelmed by the generosity of the Air Force line personnel who were responsible for dispensing those parts. The Dryden managers discovered that there was an intensely loyal group of SR-71 supporters within the Air Force who were concerned that the SR-71s might be wanted again someday. Consequently, they wanted to make sure that Dryden had not only what it needed for its own research but also sufficient quantities of critical parts and materials so that if somebody ever wanted to reactivate the SR-71s, the necessary support equipment and materials would still exist.

The foresight of these people was rewarded just four years later, when Congress authorized the reactivation of three SR-71 aircraft for Air Force reconnaissance use. NASA's spare parts and current, trained personnel suddenly became a key component to allowing that reactivation to happen. Dryden returned one of its three SR-71s, supplied

necessary spare parts and equipment, and then took on the job of retraining Air Force personnel and pilots and conducting functional test flights for the Air Force.

In the meantime, Dryden's SR-71s have performed a variety of research programs. Some have been follow-on research to the XB-70A/YF-12 work in the 1960s and 1970s, sparked by NASA's new High Speed Research program begun in 1990. One flight program, for example, used the SR-71 to map not just the ground impact but also the actual shape, size and characteristics of sonic booms from behind and below the aircraft all the way to the ground. This information may lead to supersonic aircraft that produce sonic-boom levels acceptable to communities underneath their flight path. Another set of flights has explored the radiation effects on the crew (and future passengers) for sustained flight above 60,000 feet, which is another consideration for a High Speed Civil Transport.

The Blackbirds have also been used as platforms for more unusual research projects.

Because of their high speed and altitude capabilities, they have been able to test communications satellite hardware before it is launched in an unretrievable satellite. And in 1996 they were scheduled to perform airborne tests of a linear aerospike rocket engine that Lockheed plans to incorporate into its proposal for an X-33 single-stage-to-orbit spacecraft. The aerospike engine, while theoretically more efficient than standard rocket engines, had never been flown on an aircraft or spacecraft. Lockheed wanted some high-altitude, high-speed flight test data from the engine before the competition was decided, and the SR-71 provided the most capable testbed. Research plans called for a scale version of the rocket engine to be mounted on the back of the SR-71 and fired when the aircraft achieved the desired speed and altitude.

The SR-71 has also been used to conduct research in an environment (above 90% of the Earth's atmosphere) that no other aircraft could reach. For example, the Blackbird has carried experiments that looked at the ultraviolet (UV) ray penetration and UV backscatter in the atmosphere. It has also used a forward-looking laser to gather more "pure" air samples and to try to predict clear air turbulence as far as two miles ahead of the aircraft.

More than 30 years after its first flight, the SR-71 remains a flexible, capable tool, and it is still the only aircraft capable of sustained Mach 3 flight at altitudes above 60,000 feet. As such, it offers a unique kind of service both to NASA and, as it turns out, the Air Force. The aircraft has already provided valuable atmospheric and aeronautical data, and all expectations are that it can continue to play a valuable research role for some time to come. Yet although it was not intended, one of the biggest

contributions of NASA's SR-71 program was that it provided a way for items critical for an SR-71 reactivation to be preserved. The Air Force Blackbird program had been dismantled with a vengeance that seemed designed to ensure that it would never be resurrected. Had it not been for the existence of Dryden and its flight research program, the flexible, fast and secretive reconnaissance capabilities provided by the Blackbird probably would have been lost to the Air Force forever.⁴⁶

High Flight Revisited

The increased interest in the Earth's atmosphere among scientists that spurred interest in obtaining an SR-71 for NASA has, in fact, spawned numerous flight research projects at Dryden. As opposed to the X-15 days, however, this new effort in high altitude flight is dominated not by piloted high-performance rocket aircraft, but by low-powered Remotely Piloted Vehicles (RPVs).

RPVs have been used for flight research at Dryden since the 1960s, when model builder Dale Reed was conducting his experiments with lifting-body designs. Although his initial models were free-flight designs, the development of radio-controlled aircraft technology allowed him to innovate further with his model research. By the late 1960s, he and fellow engineer Dick Eldredge had built a 14-foot-long radio-controlled "Mother" ship that they used to drop a variety of radio-controlled lifting-body designs. By late 1968, "Mother" had made 120 launch drops, including a sleek lifting-body design Reed dubbed the "Hyper III." The Hyper III followed the concept of the X-24B lifting body design, with a predicted low-speed lift-to-drag ratio as high as 5:1. Reed envisioned the Hyper

Perseus high-altitude, remotely controlled research aircraft on lakebed at night (1991). This high-altitude, lightweight, remotely-piloted aircraft—designed and built by Aurora Flight Sciences Corp. of Manassas, Virginia—was part of what came to be called the Environmental Research Aircraft and Sensor Technology (ERAST) program to study high-altitude, long-endurance aircraft for evaluation (and ultimately, protection) of the upper atmosphere. (NASA Photo EC91623-7)



III as a hypersonic lifting body with small, retractable wings that would be extended for better maneuvering at slow speeds.

The Hyper III was along the lines of a vehicle the Air Force was pursuing, and NASA

controlled work went well.

The radio controlled research with the Hyper III, which was “flown” by pilot Milt Thompson in a simulator-type cockpit on the lakebed, went well, although it had a lower lift

to-drag ratio than predicted. But for a variety of reasons, NASA headquarters turned down plans for follow-on piloted research, and the vehicle was retired.⁴⁷

Dryden has conducted a variety of other RPV projects over the years, ranging from small models to a full-scale Boeing 720 jet aircraft. But in recent years, support for RPV research has come with the

Perseus high-altitude, remotely controlled research aircraft being towed over the lakebed in 1994. Built by Aurora Flight Sciences Corp. of Manassas, Virginia, to carry scientific payloads to high altitudes for study of atmospheric conditions, Perseus had to be towed to about 700 feet and then released for flight under its own power. (NASA Photo EC94 42461-2)



thought it might have potential as a second-generation Space Shuttle. So in 1969, Reed received permission to build a lightweight full-scale version of the aircraft to be drop tested from a helicopter. Reed’s initial idea was to make the aircraft a pure unpiloted vehicle, but unpiloted flight vehicles were not popular at Dryden in those days. RPVs were difficult for

desire and need to find out more about the Earth’s atmosphere. Concerns about a diminished ozone layer, ultraviolet ray penetration and greenhouse effects have launched an entirely new cooperative research effort at Dryden known as the Environmental Research Aircraft and Sensor Technology (ERAST) program. The program is an example of a new kind of govern-



*The DAST (Drones for Aerodynamic and Structural Testing) being calibrated in a hangar. The DAST was one of many remotely piloted vehicles used in Dryden research programs because they provide a safer way of obtaining data in high-risk situations than do piloted vehicles.
(NASA Photo ECN 20288)*

ment-industry research partnership that is emerging as global competition and the high cost of developing new technology make it necessary for manufacturers to cooperate with each other in high-tech research.

The ERAST program operates under guidelines called a Joint Sponsored Research Agreement (JSRA). Under the terms of a JSRA, government funding is split among several industry partners who agree to pursue different aspects of pre-competitive basic research and share the results with each other. These kinds of agreements were not allowed until 1984, when Congress passed the National Cooperative

Research Aircraft Act. The act revised nearly 100-year old restrictions imposed by the Sherman Antitrust Law prohibiting any kind of cooperative research and development effort among competing companies.

The ERAST program was formed between NASA and four industry partners who were developing high-altitude RPVs: Aerovironment, Inc., Aurora Flight Sciences Corporation, General Atomics, and Scaled Composites, Inc. The goal of the consortium is to develop high altitude, long endurance aircraft that might evolve into commercially viable products.⁴⁸

Right: NASA ERAST
(Environmental Research
Aircraft and Sensor
Technology)/ Aerovironment
pod on Pathfinder aircraft
at sunrise
(NASA Photo
EC95 43207-8)

Center: Pathfinder solar
powered, remotely controlled,
high-altitude research aircraft
on lakebed at sunrise. This
all-wing aircraft weighing less
than 600 pounds set a record
for the highest altitude
reached by a solar-powered
airplane, 50,567 feet, on 11
September 1995.
Aerovironment, Inc. of
Monrovia, California, built
and operates the aircraft.
(NASA Photo
EC93 42240-37)

Bottom: Pathfinder in flight
above lakebed.
(NASA Photo EC93 42240-25)



As of 1995, two of the ERAST aircraft had flown. The Perseus A, built by the Aurora Flight Sciences Corporation, was designed for sustained flight at 80,000 feet. It was built with an experimental gasoline/liquid-oxygen engine, because one of the technical challenges to lightweight, high-altitude flight is that the air is too thin to support normally aspirated gasoline engines. The Perseus A did, in fact, reach 50,000 feet on one flight, but subsequent testing revealed that the engine was in need of more development work. The engine is a complex “closed-cycle” design that reuses its own exhaust, mixing it with liquid oxygen and fuel to keep the engine firing. This would allow it to operate at high altitudes, but it also creates a high-temperature, caustic engine environment that led to numerous engine problems. One Perseus was also lost in November 1994 when an autopilot gyro malfunctioned, but the company planned to continue flight testing after additional engine development work was completed.

The second flying ERAST aircraft is the solar-powered Pathfinder, built by Aerovironment, whose founder Paul MacCready designed the innovative human-powered Gossamer Condor aircraft. The Pathfinder is an extremely lightweight aircraft with a wing loading of only 0.6 pounds per square foot⁴⁹ and six solar-powered electric motors, designed to reach altitudes of 65,000 feet. A follow-on version might be able to stay aloft for literally months at a time to monitor atmospheric conditions and changes. The Pathfinder was actually designed in the early 1980s and was evaluated as part of a classified “black” military program, but it was shelved because the technology needed to make extremely lightweight solar-powered engines did not yet

exist. Advances in electronic miniaturization and performance over the next 10 years, however, brought the concept within the realm of feasibility and led to the current research program. In September 1995, the Pathfinder set a national electric-powered aircraft altitude record, reaching a height of 50,567 feet.

The other two aircraft designs in the ERAST program are Scaled Composites' D2 and General Atomics' Altus, both of which are powered by gasoline, aided by multi-stage turbochargers. Plans called for these two RPVs to begin flight research programs in 1996. It is too soon to know the outcome of the ERAST efforts, but researchers see applications for this type of technology and aircraft not only for atmospheric research but also as an inexpensive type of communications "satellite," as well as reconnaissance and weather-tracking tasks.⁵⁰

Conclusion

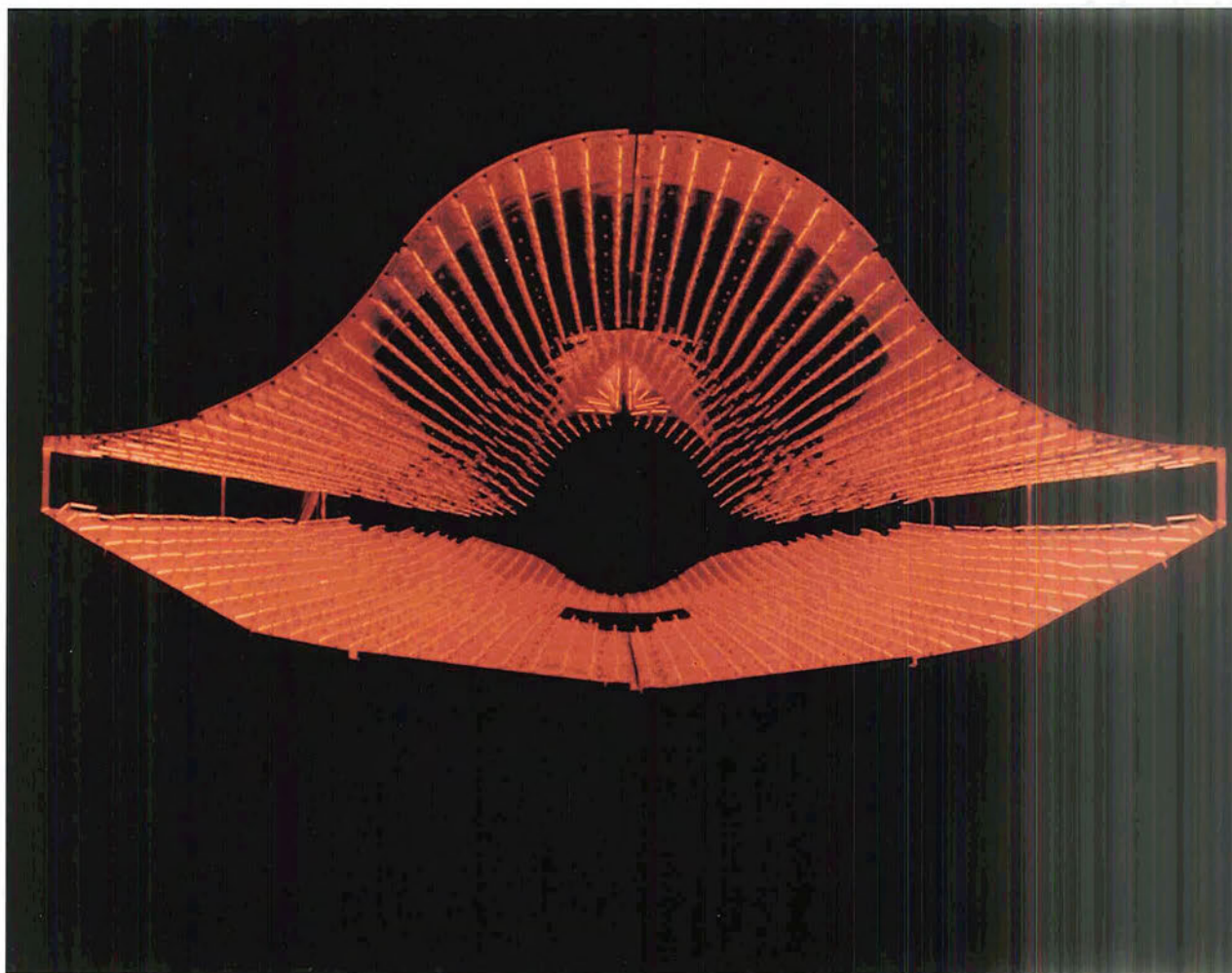
The amount of research effort devoted to exploring the world of high speed and high altitude flight at the Dryden Flight Research Center, and the knowledge gained from those efforts over the past 50 years, have been substantial. When the first group arrived at Muroc, reliable jet aircraft were still a thing of the future, and the speed of sound was a towering wall that seemed an impenetrable barrier to any flight beyond it. Yet as a result of the research conducted with the early X-planes, aircraft have been flying routinely at two or three times that speed for many years. The X-15 was a concept years ahead of its time—closer to the Space Shuttle of the 1980s than the Mercury and Gemini capsules of its day—and the hypersonic

rocket plane developed numerous technologies that aided the space exploration that followed. The lifting bodies were not the exact shape chosen for that Space Shuttle, but they dramatically influenced the thinking of decision-makers who chose to make the Space Shuttle a horizontal landing vehicle that would glide back to its runway landing.

Because NASA's research goals and efforts reflect national concerns, there was a decline in high speed and altitude research as fuel economy and systems improvement became higher national priorities in the 1970s and 1980s. In more recent years, however, an increasingly global economy, advances in technology and environmental concerns have prompted NASA researchers to revisit the field again. Once, the challenge was to develop the ability to go fast and fly high. Now, it is to fly high and fast without negatively impacting the environment or people below. Or to go into space more cheaply and more efficiently. Or to develop the ability to fly high for long enough periods of time so that changes to the atmosphere can be detected and measured.

The rules have changed; the standards have gotten higher. Yet it is not human nature ever to say "We have learned enough." The projects may have to wait until technology can make them economical, or a need exists to make the technology worthwhile. But as long as we know we have not reached the limits of possibility, there will always be a desire to explore the world that is a little higher and a little faster than we have ever gone before.





*YF-12 forebody heater undergoing a lamp check in the Thermal Loads Facility for a Mach 3 heating simulation to support **flight loads research** on supersonic aircraft. The facility, which has gone under different names over the course of its history, was constructed in 1965 to perform combined mechanical and thermal load tests on structural components and complete flight vehicles. The measurement of structural loads had long been an important part of flight*

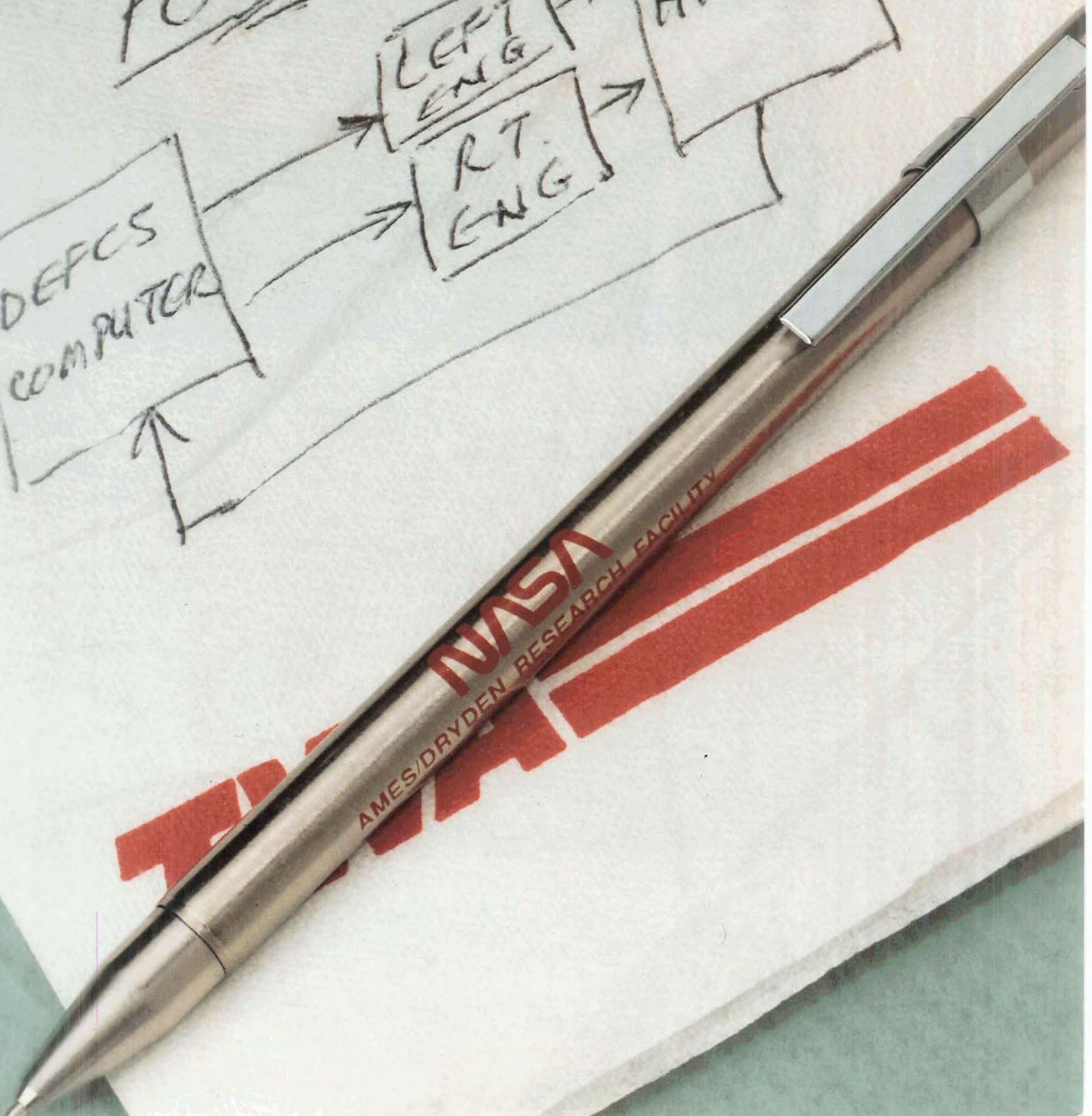
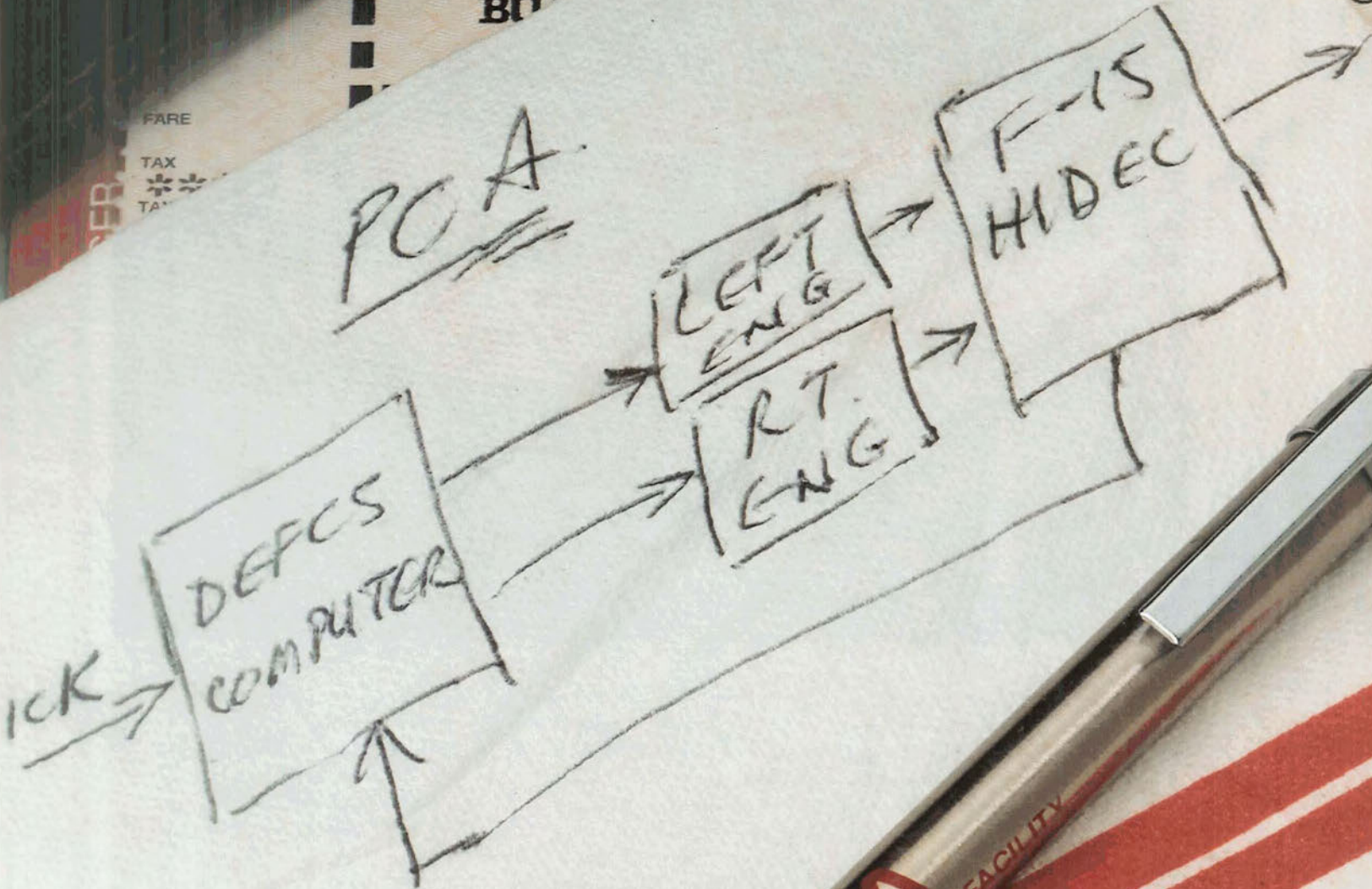
research through the use of strain gauges to measure the forces operating on the aircraft structures, but this method only worked at subsonic and transonic speeds. At the supersonic speeds of the YF-12, the high temperatures produced by friction with the atmosphere required more sophisticated techniques involving thermal calibration of the aircraft and the system of strain gauges. Because of these high temperatures, it was difficult to separate the aerodynamic from the thermal effects upon the airplane. As a result, Dryden conducted one of the most complex series of

tests ever done on an aircraft, combining both flight and ground-facility techniques and resources. The enormous data base collected during this effort led to methods for separating the aerodynamic and thermal forces operating on an aircraft—a capability that will be of great importance for the design, structural integrity, and safety of future supersonic and hypersonic aircraft.
(NASA Photo EC71 2789)

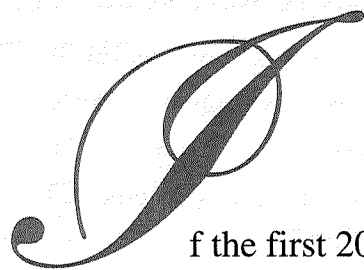
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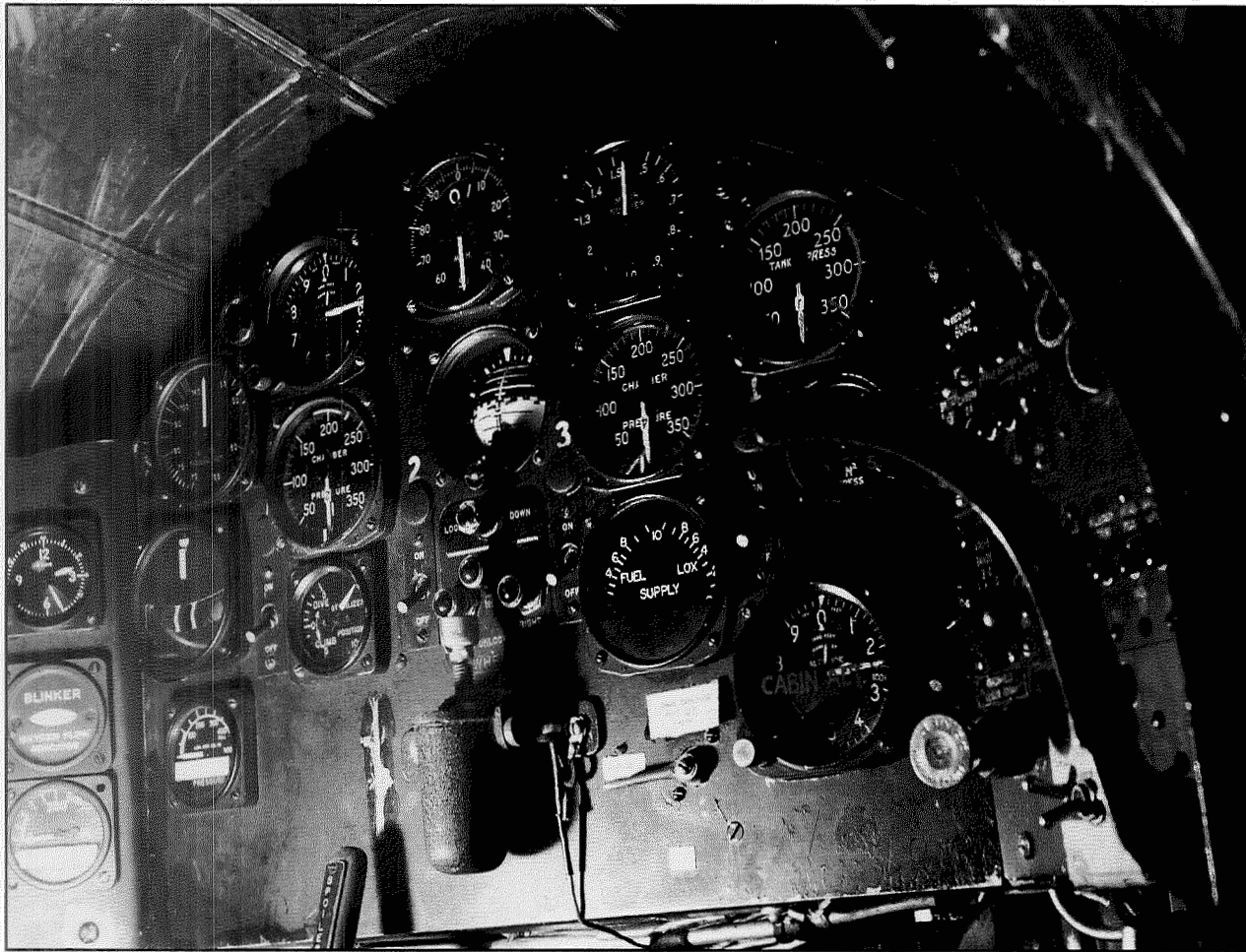
► Chapter Four:
**Improving Efficiency,
Maneuverability
and Systems**



f the first 20 years of planned, exploratory flight research at Dryden focused predominantly on developing aircraft that could fly higher and faster, the second 20 years were characterized by research efforts to allow aircraft to fly “better.” Almost two dozen flight programs at Dryden since the late 1960s have explored technology and concepts to make aircraft more fuel-efficient and maneuverable and to create vastly improved operating systems.

There were two catalysts that helped spur these research efforts at Dryden. One was a shift in national research priorities sparked by the end of the era of cheap fuel. The fuel crisis of the early 1970s made commercial aircraft that attained speed from brute horsepower, like gas-guzzling cars, a luxury the country could no longer afford. Increasing fuel efficiency suddenly became a higher public-policy priority, driving focused research programs in those areas.¹

Dryden engineer Bill Burcham's diagram on a napkin that began Dryden's involvement with the Propulsion Controlled Aircraft program. In the diagram, DEFCS stands for Digital Electronic Flight Control System, a computer that integrates engine and flight controls; HIDECS stands for Highly Integrated Digital Electronic Control. (NASA Photo EC94 42805-1)



*X-1 instrument panel
(compare with that of F-18
on next page)
(NASA Photo E49 00010)*

The other driving force behind the research was the exponential growth of electronic and computer technology. When Apollo 11 went to the Moon in 1969, the onboard computer had a memory of 36,000 words,² and the pilot interface consisted of a simple number keyboard with two buttons marked “noun” and “verb.” Commands were issued by selecting either the noun or verb key and then a number that represented a specific word. Verbs told the computer what action to take; nouns identified the item with which the action should be taken. Ten years later, technology had advanced far enough for IBM to build computers with one megabyte of main memory, and the field of computerized flow analysis and design had begun to flourish. Of course, a one-megabyte computer in 1979 still took up the better part of an entire room and cost around \$365,000. By

1989, however, an IBM personal computer (PC) with one megabyte of main memory could fit on a desktop and cost around \$3,000. A mere five years later, the memory available in PCs had jumped to an almost hard-to-comprehend number called a gigabyte.³

The advances were staggering, and they were matched by equally significant leaps in miniaturization and electronics. All of this technology opened up an entirely new field of aeronautical design. Flight computers made unconventional, unstable aircraft configurations possible for the first time, allowing the design of significantly more maneuverable aircraft. The forward-swept wing X-29, the thrust-vectoring X-31, and even the General Dynamics F-16 “Falcon” fighter jet were all products of the computer age.

Advances in computers and electronics

*F-18 instrument panel
(compare with that of X-1 on
preceding page)
(NASA Photo
EC95 43155-7)*



also made it possible to vastly improve aircraft systems. Electronic signals became a viable alternative to hydraulic and mechanical control linkages, and researchers began to explore “smart” components that could increase efficiency by seeking optimum engine and control settings or compensate for malfunctions in other parts or systems.

All of these new technologies might not be as dramatic as a rocket-powered X-15 streaking across the sky at Mach 6. Indeed, some of these modifications did not change the look of an aircraft at all. But the impact this research had on aircraft design, the capabilities of U.S. military and civil aircraft, and the competitiveness of the U.S. aircraft industry was just as significant as the high speed projects that had come before.

Efficiency

The Supercritical Wing/Mission Adaptive Wing

The Supercritical Wing (SCW) was a design concept envisioned by Dr. Richard T. Whitcomb, a research engineer at the NASA Langley Research Center. He had already won a Collier Trophy for developing the “area rule” approach to supersonic aircraft design,⁴ which was first incorporated into the Convair F-102A and flight tested at Dryden. With regard to the SCW, Whitcomb theorized that a wing could be shaped to modify shock-wave formation and associated boundary-layer separation⁵ and therefore delay the typically sharp increase in drag that occurred as an aircraft approached the speed of sound. If the rise in drag could be

delayed until almost Mach 1, it could make a transonic aircraft much more fuel-efficient, either increasing its speed or range, or decreasing the amount of fuel it needed to burn.

Whitcomb had worked on the concept since the early 1960s and had tested numerous shapes in the wind tunnels at Langley. But the question of how his design would perform on an actual aircraft still remained. To research the concept in flight, Langley chose a Vought F-8A Crusader, an older Navy jet fighter that could perform easily in the transonic range. The Crusader also had a distinctive variable-incidence wing that was raised by a hydraulic actuator to allow the aircraft to land at a slower

speed with better cockpit visibility. This feature meant the wing could be replaced with a test airfoil more easily than most aircraft.

Since Whitcomb's smooth, supercritical wing design could not integrate the F-8's adjustable-wing feature or wing flaps, the F-8 SCW would need an extraordinarily long landing and take-off area. One of the main reasons the F-8 SCW research was conducted at Dryden instead of Langley, where Dr. Whitcomb worked, was Dryden's exceptional high-speed take-off and landing facilities. The modified F-8 could take off from Edwards' 15,000-foot paved runway toward the Rogers Dry Lake, and it could land on the lakebed itself.

F-8 modified with Langley research engineer Dr. Richard Whitcomb's Supercritical Wing, in flight (NASA Photo EC73 3468)



NASA acquired three F-8 aircraft, and the one modified with a Supercritical Wing began its flight research in March 1971. The program showed promise, and follow-on flights also incorporated fairings on the fuselage to give it a more efficient “area-ruled” shape. The results of this flight research indicated that a transport aircraft with a similar design could go as much as 20 percent faster. But even as the research was being conducted, OPEC (Organization of Petroleum Exporting Countries) tripled the price of crude oil. Airlines suddenly wanted efficiency, not speed. So Whitcomb modified the wing design for maximum aerodynamic efficiency. The modified wing showed

the potential for substantial fuel savings, and the design was subsequently incorporated into many transport airplanes.⁶

At the same time as the F-8 SCW research was investigating the civil applications of a supercritical wing, the military was beginning a research effort called the Transonic Aircraft Technology (TACT) program. The TACT research involved applying a supercritical wing to a General Dynamics F-111 to see how the concept might benefit military aircraft. The F-111 was chosen because like the F-8, it had an easily replaceable wing. Furthermore, the Air Force was looking for retrofit technology that could improve the performance

F-8 Digital Fly-By-Wire and Supercritical Wing aircraft in formation over snow-covered mountains (NASA Photo ECN 3495)



of its active-duty F-111s. In addition to Langley and Dryden, the TACT program involved the Air Force Flight Dynamics Laboratory and the NASA Ames Research Center, which undertook the development of the advanced wing configuration.

The F-111 TACT began its flight research program in February 1972. In three

years, it proven itself and was incorporated into future military aircraft designs.

The F-111 TACT actually kept flying through the early 1980s, testing different drag-reducing aerodynamic modifications. The program's success also influenced the development of a "next-generation" wing research effort under a program called Advanced Fighter



F-111 Advanced Fighter Technology Integration (AFTI) research aircraft in flight (NASA Photo EC86 33385-5)

years of flight research, it showed that a supercritical wing could, in fact, improve the performance of a military aircraft, generating up to 30 percent more lift than a conventional F-111 wing. The research also showed that attaching external munitions to the wing did not cancel out these gains, and that a supercritical wing did not degrade performance at supersonic speeds. Ultimately, the Air Force decided not to retrofit the F-111s, but the technology had

Technology Integration (AFTI). The initial AFTI experiment was something called a "Mission Adaptive Wing" (MAW) that was tested on the modified F-111 TACT aircraft. Venturing one step further than the Supercritical Wing, internal controls in the MAW flexed the aircraft wing to adjust the amount of its camber (curvature), depending on the flight conditions. It could flex enough to generate the additional lift needed for slow



MD-11 showing one application of the winglet concept in a production aircraft. Winglets produce a forward force component (thrust) in the vortices that usually swirl off of conventional wingtips, thereby reducing the overall drag of the airplane. Developed by Richard Whitcomb at Langley Research Center, winglets demonstrated in flight research at Dryden in 1979 and 1980 that they could increase an aircraft's range by up to seven percent at cruise speeds. (NASA Photo EC95 43247-5)

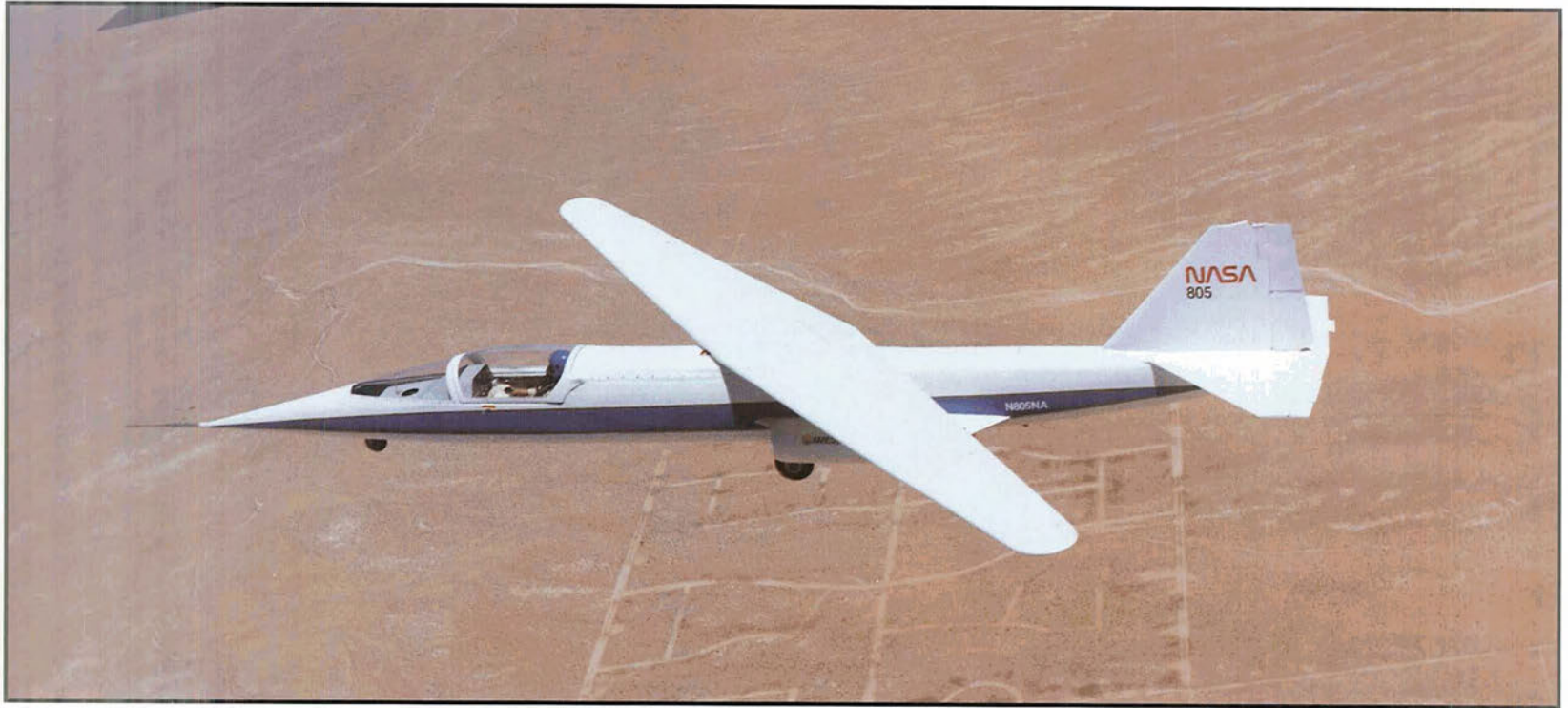
speeds, eliminating the need for lift-producing devices such as slats and flaps; change to a Supercritical Wing planform for transonic flight, and adjust to a near-symmetrical section for supersonic speeds. The F-111 AFTI flight research lasted three years, from 1985 to 1988, and indicated that the drag reduction from a MAW design could increase performance in different flight conditions anywhere from 8 to 20 percent. The information from the AFTI flight program came too late to be incorporated into the Advanced Tactical Fighter (ATF) designs, but it may well be incorporated into the next generation of aircraft.⁷

Winglets

The search for ways to make transonic aircraft more fuel-efficient also led to another Dryden flight research program prompted by the work of Richard Whitcomb. This one involved the use of winglets, which are small,

nearly vertical fins installed on an airplane's wing tips to help produce a forward thrust in the vortices that typically swirl off the end of the wing, thereby reducing drag. The winglet concept actually dated back as far as 1897, when an inventor took out a patent on the idea, but it was not until Whitcomb began a focused investigation into winglet aerodynamics that they matured into an applicable technology. Whitcomb tested several designs in the wind tunnels at Langley and chose the best configuration for a flight research program.

The winglets were installed on a KC-135A⁸ tanker on loan from the Air Force and flight tested in 1979 and 1980. The research showed that the winglets could increase an aircraft's range by as much as seven percent at cruise speeds, a significant improvement. The first industry application of the winglet concept was actually in general aviation business jets, but winglets are now being incorporated into most new commercial and military transport



jets, including the Gulfstream III and IV business jets, the Boeing 747-400 and McDonnell Douglas MD-11 airliners, and the McDonnell Douglas C-17 military transport.⁹

The AD-1 Oblique Wing

A more radical approach to making wings more efficient was a concept called the “oblique wing,” which involved a wing that would pivot laterally up to 60 degrees around a center point on top of the fuselage. At higher speeds, having the wing more closely aligned with the direction of flight would reduce the aircraft’s drag significantly. A researcher at the NASA Ames Research Center named Robert T. Jones pioneered the concept and had analyzed it on paper and in the center’s wind tunnels. Based on his work, Jones predicted that a transport-size aircraft with an oblique wing, traveling at 1,000 miles per hour, might be twice as fuel efficient as conventional aircraft designs and could also create a milder sonic boom.

To test the concept in flight, Ames and Dryden researchers proposed first building a low-cost, piloted vehicle that could investigate the flight mechanics of an oblique wing at low speeds. If the results were encouraging, funding might then be approved for a higher-performance research aircraft that could reach transonic speeds. In 1977, construction began on the low-speed AD-1, named after the Ames and Dryden research centers sponsoring the research effort. The AD-1 was a twin-engine, jet-powered composite aircraft designed by Ames, Dryden and the Rutan Aircraft Factory, and built by the Ames Industrial Company. The wing would be kept perpendicular to the fuselage for take-off and landing, and then pivoted around up to 60 degrees for the higher-speed portions of the flight. It was a simple vehicle, with unaugmented controls and a top speed of only 175 knots, but its entire design and construction cost less than \$300,000.

The aircraft completed 79 research flights between 1979 and 1982, demonstrating satisfactory handling qualities through a 45-

AD-1 (Ames-Dryden 1) oblique-wing aircraft, which demonstrated in 79 research flights between 1979 and 1982 that such an aircraft was controllable and that a wing rotated to an oblique angle with the fuselage could provide improved flight efficiency, as predicted by Robert T. Jones at Ames Research Center. (NASA Photo ECN 13305 Fr.4)



Two-seat F-16XL, showing asymmetric wings and (on the left wing, as viewed by the pilot) the bottom portion of the Supersonic Laminar Flow Control (SLFC) glove designed to help keep air flow smooth. (NASA Photo EC95 43267-2)

degree angle of wing sweep, and acceptable qualities up to a 60 degree wing pivot configuration. It even performed three landings with the wing pivoted 45 degrees. The concept has yet to be incorporated into any production aircraft, but the research provided engineers with additional information on both the airplane's dynamics and an unconventional approach to making aircraft more fuel efficient. It also showed, once again, the benefits that could be drawn from a simple, low-cost aircraft and flight research program.¹⁰

Laminar Flow Research

Another way to increase the fuel efficiency of aircraft was through the use of laminar flow airfoil designs. "Laminar flow" is a term used to indicate air flow that follows the contour of an airfoil in a smooth manner, instead of burbling and separating from the wing. Because laminar airflow generates less drag it can make aircraft more fuel-efficient, which enables them to have either a longer range or larger payload capability. Laminar-flow designs actually date back to World War II, and the North American P-51 was known for its highly efficient, laminar-flow wing. But even the P-51's wing achieved laminar flow for only a very short distance from its leading edge.

As fuel efficiency became a higher priority in the 1970s and early 1980s, however, finding ways to increase the amount of laminar flow on a wing began to generate more interest. Dryden and Langley conducted a number of laminar-flow experiments, starting with a Natural Laminar Flow (NLF) experiment on the variably-swept-wing F-111 TACT in the late 1970s. The goal of the NLF research was to see how changing the sweep of a wing affected the degree of its laminar flow. An extremely smooth NLF airfoil glove was bonded onto the F-111 TACT wing and flown at various sweep angles. The F-111 TACT/NLF program was followed up with similar research with a Navy Grumman F-14 "Tomcat," which also had a variable-sweep wing but could investigate sweep angles greater than those of the F-111. Both of these flight research projects gave researchers valuable information on how much sweep could be incorporated into a subsonic wing before it began to lose its laminar-flow properties. The research also provided data on

the impact of other factors on subsonic laminar flow, ranging from the speed of the aircraft to bugs splattered on the wing's leading edges.

Up until the late 1980s, however, most of Dryden's laminar-flow research had been limited to subsonic and low transonic speeds. Laminar flow had never been achieved with a production supersonic aircraft, because it did not occur natu-

rally.¹¹ Creating supersonic laminar flow required some kind of active control mechanism to help keep the air flow smooth.

Dryden researchers had begun investigating a possible method for subsonic laminar-flow control using a four-engine Lockheed "Jetstar" business jet. The Jetstar experiments involved bonding

two kinds of perforated skins on the Jetstar wings and using a turbo compressor to suck air through the perforations to keep the air flowing smoothly along the contour of the wings. The Jetstar flew simulated airline operations in various areas around the country to investigate what impact factors such as different weather conditions and bug strikes had on its laminar flow. These flights did prove the feasibility of the concept, but the equipment necessary to make the system work was too heavy to make the approach worthwhile for subsonic aircraft.

With a supersonic transport aircraft, on

the other hand, an active laminar flow control system might prove very cost-effective, indeed. On a Mach 2+ aircraft concept like the High Speed Civil Transport (HSCT) for example, the 9 percent reduction in drag that a laminar-flow wing might offer could translate into a similar increase in either payload or range. Rockwell had begun research on this kind of technology



on its own, and in 1988 Dryden acquired two cranked arrow wing F-16XL prototypes that the Air Force was preparing to scrap but agreed to loan to the Center instead. Rockwell approached Dryden and suggested a joint supersonic laminar-flow-control research effort, using the F-16XL aircraft and a test section glove manufactured by

Rockwell.

A first set of research flights began in 1991, using a small, perforated titanium wing glove and a turbo compressor for the laminar flow control. The implementation was a little crude, but the experiments were still successful enough to prompt a follow-on research effort with the second F-16XL. The second program is a more extensive effort among Dryden, NASA Langley, Rockwell, Boeing, and McDonnell Douglas. As opposed to the first research effort, which was designed to see if supersonic laminar flow was possible to

Two-seat F-16XL with a look-down view of the glove being used for Supersonic Laminar Flow Control research beginning in 1995. On the wingtips are red flutter exciters to promote structural frequencies. Researchers then measure the response in the airframe with the glove installed to ensure the aircraft is safe to fly in that configuration. (NASA Photo EC95 43297-2)

achieve, the second program aims to find out more information about the behavior of supersonic laminar flow under various flight conditions.

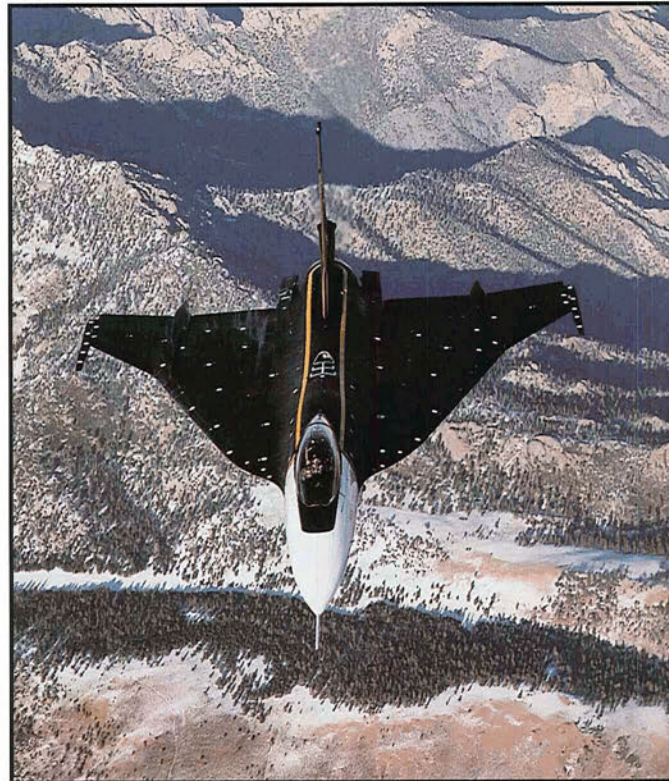
The newest set of experiments uses a titanium glove approximately four times as large as the initial test section. It is perforated with 12 million microscopic holes and the active laminar-flow control is provided by a modified Boeing 707 cabin pressurization pump. The goal of the flight research program, which began in October 1995, is to achieve laminar flow across 60 percent of the total wing chord (from the leading edge to the trailing edge).

In one sense, the F-16XL Supersonic Laminar Flow Control (SLFC) research is an unusual program for Dryden, because it is geared specifically toward a particular application—the High Speed Civil Transport (HSCT). But it is also an example of how ongoing work at Dryden can sometimes suddenly receive additional support and attention as national priorities shift. Dryden engineers have been working on laminar-flow research for a long time. But when the nation decided to pursue a formal HSCT program, the smaller-scale laminar-flow research that had been conducted at Dryden was suddenly pulled into a high-profile, focused

program that provided more funding and support for that work. Even if the HSCT is never built, the information gained on supersonic laminar flow would be useful to future aeronautical engineers, but the program is clearly directed toward that particular application of the technology.

As a result of the HSCT focus of

Dryden's supersonic laminar-flow research, the program staff at Dryden have found themselves working directly with the transport aircraft manufacturing industry, which has been a educational experience for everyone involved. The engineers at Boeing and McDonnell Douglas, for example, were not accustomed to some of the considerations involved in



Single-seat F-16XL with cranked-arrow wings painted black and with white spots that served as points of reference for airflow visualization studies using smoke or tufts of cloth to indicate patterns of airflow (NASA Photo EC94 42885-1)

high-performance flight research, such as the fact that an F-16XL flying at supersonic speeds cannot execute turns without considering the airspace available and the sonic-boom footprint. By the same token, research engineers at Dryden understood the need for supersonic aircraft to time turns so that their sonic booms did not offend communities below them, but they did not have experience with some of the constraints of the transport industry, such as the need to maneuver in a manner that will always provide a smooth, comfortable ride for passengers. Consequently, the F-16XL partnership has



generated an unintended side benefit apart from the actual technology being investigated. The cooperative effort has helped to give Dryden's research engineers some useful perspectives on the needs and technology constraints of an industry that will ultimately apply some of the technology they help to develop.¹²

Maneuverability

HiMAT

In the 1950s and 1960s, the driving design objective of military fighter aircraft was speed. Speed was life, and fast entry into and exit from a combat area was thought to provide the best combat edge for a fighter pilot. In the post-Vietnam era, however, that thinking began

*X-29 with tracer smoke flowing from tiny ports in the nose to show airflow while the aircraft was flying at a high angle of attack and with small strips of cloth called tufts attached to the aircraft for further visualization of airflow patterns.
(NASA Photo EC91 491-1)*



HiMAT (Highly Maneuverable Aircraft Technology) remotely piloted vehicle in flight (NASA Photo ECN 14281)

to change. In a dogfight, maneuverability was more important than speed alone. The advent of computerization also made more unconventional, but potentially more maneuverable, design concepts possible for the first time.

fighter and was launched from the same B-52 mother ship that carried the X-15s and the lifting bodies. It could perform maneuvers production fighters could not achieve, such as sustained 8 G turns at an altitude of 25,000 feet

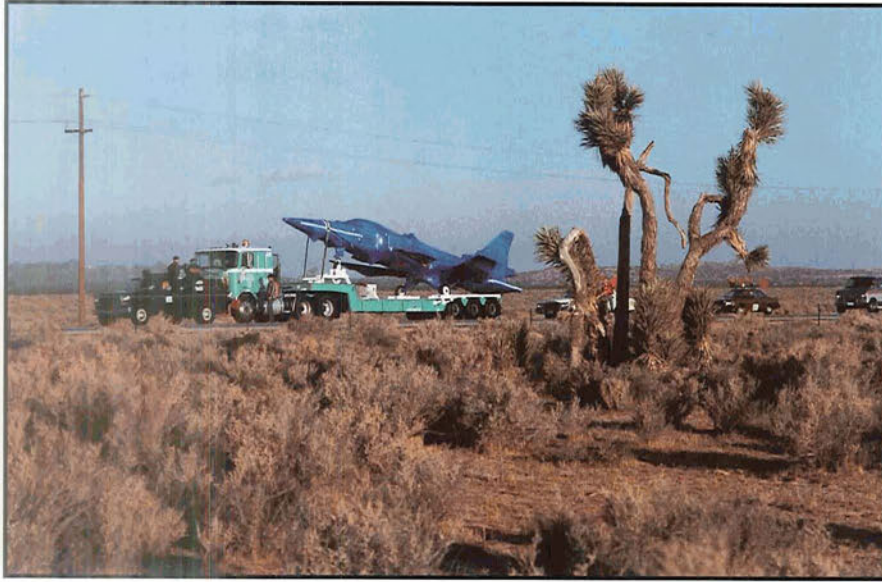


X-29 in flight at an angle that highlights the forward swept wings (NASA Photo EC90 039-4)

One of the first research efforts at Dryden to explore more maneuverable and advanced aircraft configurations was the Highly Maneuverable Aircraft Technology (HiMAT)

and a speed of Mach 0.9, due to its very low wing loading. An F-16, by comparison, could sustain only approximately 4.5 Gs in similar flight conditions.

The two Rockwell-built HiMAT vehicles had a top speed of Mach 1.4 and were flown 26 times between 1979 and 1983. Because of its ability to sustain high-G turns at high speeds, the HiMAT could execute turns almost twice as tight and therefore almost twice as fast as operational fighters. The design also demonstrated the ability of composite construction to provide unidirectional stiffness in a



*X-29 in protective cover
being transported to Dryden
(NASA Photo EC88 221-11)*

Germans had built and flight tested a forward-swept wing bomber called the Junkers Ju-287. The HFB 320 Hansa business jet built in the 1960s also had a forward-swept wing. Proponents argued that a forward swept wing (FSW) could produce up to a 20 percent decrease in the drag produced by maneuvering and could provide

structure. The HiMAT helped manufacturers gain confidence in composite construction, but it also strongly influenced the design of a piloted research aircraft that would go even further in demonstrating and researching advanced aircraft technology—the X-29.¹⁴

The X-29

In a sense, the X-29 was the result of an industry-funded follow-on project to the HiMAT. The Grumman Corporation had also submitted a proposal for the HiMAT vehicle and, after losing the contract, the company conducted a series of wind-tunnel tests to see why the design had not won the competition. Retired Air Force Col. Norris J. Krone, Jr., an aeronautical engineer who had written a thesis on forward-swept-wing configurations, happened to be at the NASA Langley Research Center when Grumman conducted its wind-tunnel tests there. Krone suggested that Grumman might improve the aircraft's performance by switching its aft-swept wing to a forward-swept wing design.

Forward-swept wing designs were not new; indeed, as early as World War II, the

better control and performance at high angles of attack (AoA), or what researchers often called high "alpha."¹⁵ The problem with the design was that at high speeds, the aerodynamic forces on the wing would lead to something called "structural divergence." In simple terms, that meant the wings would fail and rip away from the fuselage. Using conventional materials, the only way to make the wings strong enough not to fail was to make them extremely heavy, which negated any advantage of a forward-swept wing design.

The composite materials demonstrated in the HiMAT, however, offered the possibility of a lightweight construction material that could give the unidirectional stiffness necessary to make a forward swept wing feasible. With Colonel Krone's input, Grumman decided to conduct wind tunnel tests on an FSW version of its HiMAT vehicle. The tests proved successful enough that Grumman decided to build a full-scale version, funded with its own money. Krone, by that time, had gone to work at the Defense Advanced Research Projects Agency (DARPA) and lobbied successfully for the development of a DARPA-funded forward swept wing technology demonstrator aircraft.

A pair of X-29 forward-swept-wing advanced technology demonstrator research aircraft silhouetted on the tarmac by the sunlight, with the shadow emphasizing the forward sweep of the wings (NASA Photo EC90 357-4)

Grumman ultimately won the contract for what became the X-29, and the first of the two aircraft built for the program made its first flight from Edwards Air Force Base in December 1984. It was the first time an “X” aircraft had flown at Dryden in 10 years.

The X-29 was a combined effort among DARPA, the Air Force, NASA, Grumman, and numerous other contractors, and its goal was to investigate a number of different advanced aircraft technologies. The primary focus, of course, was the X-29’s dramatic forward-swept wing configuration. But the composite wing also incorporated a thin supercritical-wing section that was approximately half as thick as the one flown on Dryden’s F-8. The aircraft also featured a variable-incidence canard located close to the main wing, three-surface pitch control (flaperons on the wing; the canard; and flaps on aft fuselage strakes), and an inherently unstable design. Artificial stability was provided by the aircraft’s digital flight-control system (FCS) that made control surface inputs up to 40 times per second.

An unstable design could be much more maneuverable, but if the computerized flight-control system failed, the aircraft would be lost. Researchers also calculated that if the failure happened at certain points in the X-29’s flight envelope, the aircraft would break up before the pilot could eject. Consequently, the X-29’s FCS had three digital computers, each of which had an analog backup. If one computer failed, the other two would “vote” the malfunctioning



computer out and take over. If all the digital computers failed, the aircraft would still be flyable using the analog backup mode.

Knowing how critical the FCS was, researchers spent hours upon hours trying to foresee any and every conceivable failure point that might endanger the aircraft. Yet even after the X-29 had been flying some time, researchers discovered several “single-point-failure” problems that underscored the difficulty of predicting every contingency in an advanced technology aircraft. During a ground test, for example, a small light bulb short-circuited, sending strange voltages to the digital flight-control computers. It was a minor item, but if it had failed in the air it would have taken out all three digital computers simultaneously, as well as the telemetry system. The aircraft would have reverted to its analog flight-control system, but the only person who would have known it was still flying would have been the pilot himself. Fortunately, this X-29 problem was discovered on the ground. Several years later, however, a similarly unforeseen single-point failure would cause the loss of an X-31 research airplane.

The X-29 performed very successfully



throughout its flight research program. The flights conducted with the first X-29 aircraft explored its low-altitude, high-speed performance. The results showed, first and foremost, that a highly unstable, forward-swept aircraft could be flown safely and reliably. The X-29 also was able to maintain a higher sustained G load in turns and maneuver with a smaller turn radius than comparable fighters with aft-swept wings.

Based on the success of the first phase, a

follow-on research effort to explore the aircraft's behavior at low speeds and high angles of attack was approved, using the second X-29. The follow-on program also investigated some possible benefits the X-29 configuration might have for a future fighter aircraft. For one portion of the follow-on program, the X-29 was also modified with a vortex flow control system that injected air into the vortices coming off its nose to investigate whether that technology could help control an aircraft at high angles of

F/A-18 High Angle of Attack Research Vehicle (HARV) during an engine run, with paddles behind the nozzles deflecting the exhaust upwards; in flight, this would have the effect of rotating the rear of the aircraft downward. (NASA Photo EC91 075-38)

attack. Although the vortex control system was not designed to substantially affect the behavior of the X-29 itself, the technology showed a lot of promise for future designs.

In general, the phase two flights showed that the X-29 configuration performed much better than expected at high angles of attack. Pilots found they had good control response up to an angle of attack of about 40 degrees, a marked improvement over conventional fighter designs. Even when the control response began to degrade between 40 and 50 degrees, it did so “gracefully,” in the words of one pilot, and one flight even reached an angle of attack of 67 degrees.¹⁶

The X-29 program concluded in 1992 after completing 362 research flights in eight years. It is still too soon to say whether its forward-swept wing design will ever be incorporated into a production fighter aircraft. But the X-29 had an immediate impact on aircraft design by adding to engineers’ understanding of composites, which are being used more and more extensively in military and civilian aircraft. It also generated valuable information on the

use of digital flight-control systems, especially with regard to highly unstable aircraft designs. In addition, the X-29 program paved the way for future research into the realm of highly maneuverable, high-angle-of-attack flight, both with Dryden’s F/A-18 High Alpha Research Vehicle (HARV) and the International Test Organization’s (ITO) X-31 aircraft.¹⁷

The F/A-18 HARV

The X-29 follow-on research program was just one of several research projects in the late 1980s that were focused on trying to over-

come a limitation of flight every bit as challenging as the sound barrier had been 40 years earlier. The X-29 follow-on research, NASA’s F/A-18 HARV¹⁸ and the X-31 aircraft all attempted to expand the envelope beyond what researchers dubbed the “stall barrier” that limited aircraft performance at low speeds and high angles of attack.

The tendency of aircraft to stall and become uncontrollable at high angles of attack and slow speeds was the greatest limiting factor in an airplane’s maneuverability. The



F/A-18 High Angle of Attack Research Vehicle (HARV) banking in flight (NASA Photo EC94 42513-19)



X-31 flying at a high angle of attack and demonstrating an entry into a Herbst maneuver—a rapid, 180-degree turn at an extremely high angle of attack, named after the German originator of the X-31 program, Wolfgang Herbst (NASA Photo EC94 42478-4)

X-31 Enhanced Fighter Maneuverability research aircraft, equipped with thrust vectoring paddles and advanced flight control systems, is shown here banking over Edwards Air Force Base. The X-31 flew from 1992 to 1995, completing a total of 555 flights. (NASA Photo EC93 42152-8)



X-29 explored one potential design feature that might produce better high alpha performance. But if aeronautical engineers were going to make substantial progress in designing aircraft that could operate more effectively in that realm, they had to understand it better. The F-18 HARV research program was designed to tackle this problem.

The F-18 HARV is a combined effort among the NASA Dryden, Langley, Ames and Lewis research centers. The HARV is a McDonnell-Douglas F-18 modified with thrust-vectoring paddles to help stabilize the aircraft at extremely high angles of attack. This capability allows researchers to study and document the aerodynamic forces in that region more accurately.

Phase one of the HARV effort began in 1987, before the aircraft was modified with the thrust-vectoring paddles. Researchers used tufts of yarn, dye, and smoke released through ports in the aircraft's nose to study air flow over the vehicle up to 55 degrees angle of attack. After two and a half years and 101 research flights, three Inconel thrust-vectoring paddles were installed on the aircraft exhaust nozzles. The paddles can withstand temperatures of almost 2,000 degrees Fahrenheit and can rotate up to

25 degrees into the engine exhaust to help control the aircraft's pitch and yaw.

With the thrust-vectoring paddles, the HARV reached a controllable AoA of 70 degrees and could execute relatively fast rolls up to 65 degrees. In addition to providing data to improve wind-tunnel and computational design predictions, the F-18 HARV also provided a testbed for numerous high alpha experiments. At one time, the aircraft was conducting no fewer than 26 separate experiments. In addition, although the HARV thrust vectoring was designed primarily as a tool to achieve controllable high alpha flight, the aircraft began to explore some of the maneuverability and control benefits of thrust vectoring.

In 1995, the airplane was outfitted with two retractable nose strakes to continue its research into flight at high angles of attack. The strakes were deployed in high alpha conditions to influence the vortices coming off the aircraft's nose and significantly improved the controllability of the aircraft in those conditions.

The particular thrust-vectoring technology used by the F-18 HARV is not likely to find application in a production aircraft. Aside from maintenance concerns, the system adds

2,100 pounds to the airplane's weight. But the aeronautical data produced through its flights and testbed experiments have already provided engineers and designers of future aircraft with valuable information, and the program (as of 1996) is still gathering additional flight data. Furthermore, even in achieving controllable high alpha flight, it generated interest in and support for the thrust vectoring technology, a design concept that would receive even more attention through the X-31 research aircraft program.¹⁹

The X-31

The X-31 research aircraft was largely the brainchild of German aerodynamicist Dr. Wolfgang Herbst. Herbst recognized that in the close constraints of an air war in the European theater, maneuverability was a critical element for a successful fighter. If an aircraft could fly good maneuvers at high angles of attack it would be able to turn inside and win over an opponent, and thrust vectoring was a technol-



ogy that might allow aircraft that kind of maneuverability.

However, Germany did not have the funds to pursue a research aircraft on its own. So German researchers approached the United States about a possible joint project to explore thrust-vectoring technology further.

The result was the X-31 program—a highly unusual, international research effort involving DARPA, the U.S. Navy, Deutsche Aerospace,²⁰ the German Federal Ministry of Defense, Rockwell International and, in the last three years of the

program, NASA and the U.S. Air Force. The primary goal of the program was to research the tactical utility of a thrust-vectoring aircraft with advanced flight-control systems.

Like the X-29, the X-31 was designed with a movable canard, but the X-31 had a delta-shaped, composite, twisted camber wing. The wings, the carbon-carbon²¹ thrust-vectoring paddles and parts of the flight control laws were designed and built in Germany, while the fuselage was built by Rockwell in the United States. Construction began in the late 1980s, and the first of the two X-31 aircraft flew in

*X-31 photographed head-on while in flight
(NASA Photo EC94 42478-13)*



F-15 Highly Integrated Digital Electronic Control (HIDEC) aircraft and F/A-18 chase aircraft. Among other things, by integrating the flight-control and air-data systems on the aircraft with electronic engine controls, the HIDEC technology permitted researchers to adjust the operation of the engines to suit the flight conditions of the aircraft. This extended engine life, increased thrust, and reduced fuel consumption. (NASA Photo EC91 677-1)

February 1990.

The original plan was for the initial aircraft development work to be completed at Rockwell's Palmdale, California, facility. The aircraft would then be transferred to the Naval flight test center at Patuxent River, Maryland, for further flight research. But the development and flight testing of the airplane proved more challenging than anticipated. In a search for additional resources and funding, the X-31 program team asked NASA and the Air Force Flight Test Center at Edwards Air Force Base to become involved. So in 1992, the X-31 flight

research program moved to Dryden.

The fact that the X-31 was an international effort made it a particularly complex program to manage. The biggest challenge was getting a diverse team of not just government and industry but government and industry partners from two different countries to work together well. Differences in cultures as well as in approach had to be resolved, and it took some time for the team members to build up trust in each other's expertise. Fortunately, when the flight research moved to Dryden, the representatives from all the various participat-

ing organizations were able to be housed together in the new Integrated Test Facility (ITF) building.²² This arrangement helped strengthen the personal relationships among the partners and produced a highly successful integrated team.

Not everyone at Dryden thought the X-31 was an appropriate research project for the Center to undertake, because its goal was to investigate practical military applications of thrust-vectoring technology. Others pointed out, however, that a lot of valuable research information could be gained by participating in the program. Interestingly enough, however, there was less tension between the NASA and mili-

a nasty surprise. The aircraft “departed” and spun completely around before he regained control. The X-31 team suspected that asymmetrical nose vortices were the problem and thought nose strakes might provide added lateral stability for the aircraft.

The process of adding nose strakes to the X-31 took just seven days, illustrating the efficient approach and “technical agility” the flight research engineers at Dryden and other NASA centers relied on to keep flight programs on schedule. On a Tuesday, the Dryden research engineers decided they wanted to add nose strakes. The strakes were already manufactured, but researchers needed to make sure that adding



tary team members than in many previous joint efforts once Dryden made the decision to join the X-31 program, because there was only one agenda.

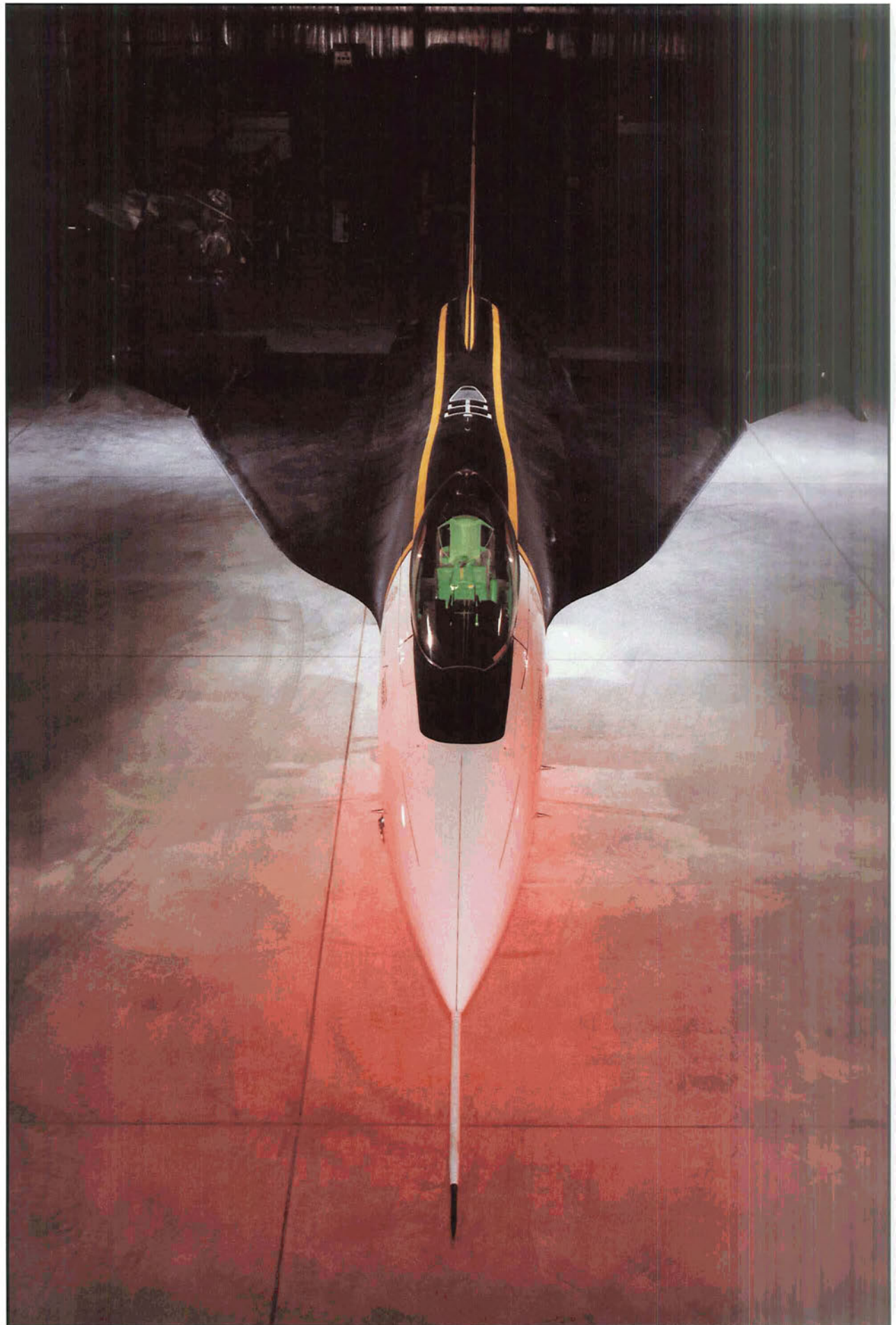
Soon after the program moved to Dryden rear fuselage strakes were added to the design to help the aircraft’s pitch control. Once that was done, the X-31 successfully reached stabilized flight at 70 degrees AoA. But when one of the team’s research pilots attempted to reach that mark dynamically, while flying at a higher speed and pulling two or three Gs, he got

them to the aircraft would not produce any undesirable side effects. They called an engineer at the Langley Research Center, who agreed to squeeze an X-31 model with the strakes into the schedule for one of the center’s wind tunnels that Friday night. The results were good and, after analyzing the data over the weekend, the research team flew the X-31 with the strakes attached the following Tuesday.

The X-31’s flight-control system also went through five major software changes during its years at Dryden, but with the changes

An F-15 equipped with advanced, digitally controlled engines that allowed stall-free performance throughout the aircraft’s entire flight envelope, faster throttle response, improved airstart capability, and increased altitude. (NASA Photo ECN 18899)

*F-16XL used in the first set of laminar flow control research flights, after the titanium glove had been removed from the wing. Since doing laminar flow research beginning in 1991, the single-seat F-16XL has been used in sonic boom research and in the Cranked Arrow Wing Aerodynamic Project to gather data about various issues such as pressure distribution and skin friction.
(NASA Photo EC95 43029-2)*



and modifications, the program became extremely successful. In addition to simply achieving controllable maneuvering flight at angles of attack up to 70 degrees, the aircraft clearly demonstrated the tactical advantage thrust-vectoring could give a fighter. Simulator experiments predicted that the X-31 would have a 3:1 kill ratio. In actual combat maneuvers against an F-18 fighter, however, the X-31 won approximately 30 dogfight engagements for every one it lost. It also demonstrated maneuvers no other aircraft was able to do, including one named after program originator Wolfgang Herbst. The "Herbst maneuver" is a rapid, 180-degree turn at an extremely high angle of attack, using the X-31's post-stall maneuverability characteristics.

In its later flights, the X-31 also investigated the dynamics of "quasi-tailless" flight. The flight-control system was set up to simulate an aircraft without a vertical tail, depending entirely on the thrust-vectoring system to maintain its lateral directional stability. The results were promising, which could have important implications for future military aircraft, as a tailless design would be a lot lighter and would have a much lower radar cross-section.

Yet for all its accomplishments, the program did have one black mark. In a sharp reminder of how difficult it is to cover every contingency in a research program exploring new technologies and little-understood regions of flight, a single-point-failure problem caused the loss of the first X-31 on its last scheduled research flight in January 1995. The aircraft's sole pitot tube²³ iced over, which sent incorrect airspeed information to the flight control system. "Thinking" the aircraft was traveling slower than it was, the control system com-

manded flight-control surface changes that were too severe, and the aircraft went out of control. The pilot ejected safely, but the airplane was lost.

The accident was a shock to the Dryden community, which had gotten accustomed to an excellent safety record. But it illustrated the double-edged sword of advanced technology. The tremendous gains in computer technology made possible much more accurate simulators and computer predictions, so pilots faced fewer unknowns than they had in the Center's early days. But as computer technology became more capable, it also made aircraft systems more complex, creating more opportunities for something to go wrong.

Nevertheless, the program contributed extremely valuable information and credibility to the field of integrated thrust-vectoring technology. As with the F-18 HARV, the X-31's paddle system for thrust vectoring is unlikely to find its way onto production aircraft. But three months after the loss of the first X-31, the second one was cleared back to flight status and taken to the Paris Air Show in June 1995. The Pratt & Whitney engine company was displaying its experimental "pitch-yaw balance beam nozzle" thrust-vectoring engine at Paris (the same powerplant that was installed on Dryden's F-15 ACTIVE research aircraft discussed below). Pratt & Whitney's system bears no resemblance to that of the X-31. But after a dramatic flight demonstration by the X-31 that showed the capabilities made possible by thrust-vectoring technology, the Pratt & Whitney booth was swamped with potential future customers. The research hardware might not be transferred but, as with many research projects, the X-31 helped develop the basic technology, proved its potential and gave it a

critical level of credibility. In the case of integrated thrust vectoring, the results were impressive enough that the technology may not only be incorporated into next-generation designs, but also retrofitted to some existing fighter aircraft.²⁴

Aircraft Systems

Digital Fly-By-Wire

One of the main technologies that made unconventional aircraft like the X-29 and X-31 possible was the computerized, fly-by-wire flight-control system, and Dryden played an important role in making that technology available. Researchers at Dryden did not invent computerized flight-control systems, but they did conduct the first flight of a pure digital fly-by-wire aircraft.

A fly-by-wire airplane uses electric wires instead of mechanical linkages to connect the pilot's control stick with the airplane's flight-control surfaces. When the pilot moves the stick, an electronic signal is sent to the appropriate control surface to command a corresponding movement. The signals are processed through a flight-control computer, which can also integrate complex control laws and control surface movements that would be impossible with a simple mechanical system.

The Digital Fly-By-Wire (DFBW) program at Dryden began in the late 1960s. The Center had worked on analog fly-by-wire systems for the Lunar Landing Research Vehicle (LLRV) program, and both industry and the research community were interested in applying computerized flight-control systems to aircraft. In 1969, a group of Dryden engineers

developed a plan to investigate an analog flight-control computer in a new research airplane. Using an unconventional aircraft would demonstrate not only the feasibility of a computerized control system, but also the type of unstable configuration the technology would allow. The proposed research vehicle, designed by Rockwell International, was a modified Vought F-8 Crusader with a canard and ventral fins instead of a conventional tail.

The researchers proposed the idea in late 1969 to NASA's Associate Administrator of Aeronautical Research and Technology, who just happened to be Neil Armstrong. In addition to his renown as the first man to set foot on the Moon, Armstrong had been a Dryden research pilot and had flown numerous research aircraft, including the X-15. Armstrong asked why Dryden was proposing an analog system instead of a more advanced digital one. The researchers explained that there was no flight-capable digital computer in existence. Armstrong reportedly replied, "I just went to the Moon on one. Have you looked at the Apollo system?" The Dryden engineers had not, but shortly after that meeting, they hooked up with the Draper Laboratory, an instrumentation lab operated by MIT that had developed the Apollo computer.

In the end, NASA Headquarters approved the digital fly-by-wire research, but with a conventional F-8 aircraft. The research aircraft proposed by Dryden was simply too radical and, in fact, was probably too advanced to be successfully implemented in 1970. Interestingly enough, however, the thrust-vectoring X-31 built by Rockwell in the late 1980s shared numerous design elements with the company's earlier DFBW airplane concept.

The concept of fly-by-wire aircraft control systems was actually not new in 1970.



Aircraft had been flying for years with autopilot systems that were, in essence, simple fly-by-wire designs. Bombardiers in World War II, in fact, relied on simple fly-by-wire systems to fly aircraft precisely over the target area. But all of those designs were supplemental control systems. The main system linking the pilot's input to the aircraft's flight controls was still mechanical. Some aircraft had control systems that were boosted by hydraulic or electric power, but there were still mechanical linkages to all the control surfaces.

What made the F-8 DFBW such a leap forward was that it removed all of the aircraft's mechanical control linkages, replacing them with electronic systems. The decision to rely entirely on electronic systems was made for two reasons. First, it would force the research engineers to focus on the technology and issues

that would be truly critical for a production fly-by-wire aircraft. Second, it would give industry confidence in applying the technology. If an experimental system could not rely entirely on digital electronic technology, it would suggest that digital fly-by-wire was still beyond reach. So the Dryden researchers decided the F-8 DFBW had to be a pure fly-by-wire aircraft.

The DFBW program consisted of two phases. The first goal was simply to prove that a DFBW aircraft could be flown safely and effectively. For this initial phase, an Apollo 11 flight control computer served as the primary system, with a modified analog flight computer taken from one of the Center's lifting body vehicles as a backup. In addition to being a proven system, the Apollo computer had the advantage of an incredibly robust design. Knowing that a system failure in a spacecraft

F-16XL in hangar for test section installation during 1995. The titanium glove on the left wing was perforated with 12 million microscopic holes that, together with a modified cabin pressurization pump, induced smoother air flow from the leading to the trailing edge of the wing. (NASA Photo EC95 43003-1)

would be disastrous, the Apollo engineers designed the system to be extremely reliable. In fact, the computer's demonstrated mean time between failures was more than 70,000 hours. Of course, its robust design meant that the Apollo computer would be far too heavy and expensive for a production aircraft, but it gave the researchers a welcome amount of confidence in flying a fully fly-by-wire aircraft for the first time.

F-15 Highly Integrated Digital Electronic Control (HIDEC) aircraft touching down on the runway at Edwards during tests of a computer-assisted engine control system that permitted a plane to land safely using only engine power if normal control surfaces are disabled. The system worked effectively in a landing of the Propulsion Controlled Aircraft (PCA) in April 1993.

The tie-in to the Apollo system also had another, even more significant, advantage for the Dryden engineers working on the project. In retrospect, the project staff acknowledged that they had underestimated the effort involved in designing a full fly-by-wire system from scratch. But using the Apollo hardware let them tap into a multi-billion-dollar, seven-year research effort that had already faced and

tackled many of the problems inherent in computerized flight control systems. One of the first things Dryden engineers realized after making the decision to eliminate all mechanical back-ups in the F-8 DFBW, for example, was that software verification and validation²⁵ would be the single most critical issue in the program. But how exactly did one go about creating software that would have no critical errors in it? Nobody had ever designed a flight-critical system where a small software error could cost somebody's life. Nobody, that is, except the Draper Laboratory, which had developed an extensive software development process to address that very issue with the Apollo system. Using Dryden's specifications and the processes they had developed for the Apollo program, engineers at the Draper lab developed the software for the F-8 DFBW



(NASA Photo EC93 2081-1)



program. Dryden engineers, in turn, adapted those methods to develop all the subsequent flight-control system software used at the Center.

The F-8 DFBW flew for the first time on 25 May 1972, and the first flight and the phase one flights that followed were very successful. After the F-8 had successfully

demonstrated the feasibility of a fully digital fly-by-wire system, the program moved into a second phase. This segment involved replacing the Apollo hardware with a triply redundant digital computer system that would be closer to something industry might use. By the time the phase two modifications began in 1973-1974, General Dynamics had designed the analog fly-

by-wire F-16 fighter, and some digital flight computers were being developed for aircraft. Dryden finally selected three IBM AP 101 computers for the F-8 system. Switching the airplane from the single Apollo computer to the three IBM computers was a lot harder than researchers anticipated, however. In

MD-11 Propulsion Controlled Aircraft (PCA) about to touch down in the milestone first throttles-only landing of a transport aircraft on 29 August 1995, with F/A-18 chase aircraft in the background (NASA Photo EC95 43247-4)

MD-11 Propulsion Controlled Aircraft (PCA) preparing to touch down in the first throttles-only landing of a transport aircraft (NASA Photo EC95 43247-2)



addition to other issues, the computers were prototypes and were the company's newest digital computers designed for use in an aircraft. Not surprisingly, they did not operate flawlessly. When one of the three computers failed on the F-8's second flight and several failures occurred during ground testing, the aircraft was temporarily grounded.

After a manufacturing problem with the computers was found and corrected, the F-8

only gave Shuttle engineers more confidence in the system, since it provided actual flight test data on the equipment, but it also gave IBM a chance to work out problems in the hardware before it was installed in the Space Shuttle.

In addition to proving the capability of both the basic DFBW concept and a production-like DFBW system, the F-8 proved a very capable testbed, and its research helped develop numerous other pieces of technology in its 13-

Apollo computer interface box used in the first phase of the F-8 Digital Fly-By-Wire program (NASA Photo EC96 43408-1)



DFBW became a very successful flight research aircraft. And although it was an unintended benefit, detecting and fixing the problems with the IBM computers aided the Space Shuttle program as well. A year after the IBM AP 101 computers were selected for the F-8 aircraft, the Space Shuttle program managers chose the same equipment for the Space Shuttle flight control system. The F-8 DFBW research not

year program. In the phase one flights, the proposed side-stick controller for the new F-16 fighter was tested in the airplane to make sure it would be acceptable to pilots. The phase two research also investigated various new control laws developed by engineers at the Langley Research Center. In some cases, pieces of technology that were developed out of necessity for the F-8 were picked up by manufacturers or

other research programs.

The Resident Back-Up Software (REBUS), for example, was an F-8 DFBW software program that looked for anomalies in the parallel software running on the three flight computers. The experimental software was only flown six or seven times, but that was sufficient for it to be picked up by industry and incorporated into several experimental and production aircraft. The F-8 program also developed a remotely augmented vehicle system, which downlinked the signals from the pilot's control inputs to a mainframe computer on the ground. That computer processed the signal and uplinked a command to actually move the airplane's control surfaces. The system was developed to allow the testing of new control laws and software without having to make each new change robust enough for flight.

Yet one of the significant contributions of the F-8 DFBW program was simply proving the feasibility of a DFBW aircraft and giving the technology enough credibility to encourage industry to incorporate computerized flight-control systems in new aircraft designs. There was great interest in the technology, and industry engineers were on the phone with their Dryden counterparts regularly during the F-8 program. In fact, some F-8 researchers believe those personal contacts were crucial in transferring the DFBW technology. Because equally important as the fact that Dryden had successfully flown a DFBW aircraft was *how* it had done that. As Dryden collaborated with many companies on subsequent flight research programs, the original Draper Lab/Apollo software development processes were incorporated by numerous industry manufacturers.

In 1978, six years after the F-8 DFBW made its first flight, the McDonnell Douglas F-

18 Hornet became the first production digital fly-by-wire aircraft. Other aircraft would follow. At its most basic level, fly-by-wire technology reduced the weight and maintenance costs of aircraft by replacing heavy mechanical systems with lightweight wires. But its real significance was its impact on aircraft design capability. Fly-by-wire technology made the first inherently unstable fighter, the F-16, possible. The highly maneuverable X-29 and X-31, as well as the F-117 Stealth Fighter and B-2 bomber, not to mention the YF-22 Advanced Tactical Fighter, all would have been impossible without computerized flight-control systems.

By the same token, accidents in the future may stem less from wings breaking off than from problems in the aircraft's information and electronic systems. One problem encountered in Dryden's F-8 DFBW program, for example, stemmed from a short time delay in the system when it switched from the primary to the backup flight-control computers. The transition involved a delay of about a second, during which the aircraft would pitch up slightly. In the simulator, the delay was not a problem. But in an actual flight environment, the pilot tended to sense the pitch-up and try to correct for it. The delay meant that the controls would not respond immediately, and the pilot would end up with far too much control input by the time the backup system kicked in.

It was an important lesson with far-reaching consequences that even the F-8 researchers did not fully realize at the time. To this day, one of the biggest problems with computerized control-system aircraft is a phenomenon called a pilot-induced oscillation, or PIO. When the linkage is no longer a simple, direct mechanical line between the pilot's



F-8 Digital Fly-By-Wire (DFBW) aircraft flying over the mountains near the Dryden Flight Research Center. The DFBW project at Dryden demonstrated the feasibility of computerized, fly-by-wire flight control, which reduced the weight and maintenance costs of airplanes and made such inherently unstable aircraft as the F-16, X-29, and X-31 possible for pilots to fly with the aid of their flight-control computers. (NASA Photo ECN 3478)

control stick and the control surfaces, there is a greater possibility that the pilot's input and the aircraft's response will fall out of synchronization. Time delays, variable gain settings (controlling the amount of control surface response for a given input), and other software issues can cause a pilot to over-control an aircraft.

The systems usually work well on ground computers, and even in simulators. But none of that takes into account the dynamics of putting a pilot into the loop in a real flight situation, where the consequences are very real and very serious. In a high-performance flight environment, pilots react differently than they do on the ground, and it is the ongoing chal-

lenge of computerized and increasingly complex flight control systems to find a way to adapt to these human responses. The 1992 crash of a prototype YF-22 Advanced Tactical Fighter (ATF) and a 1989 accident with a prototype Swedish JAS 39 "Gripen" fighter were both attributed to PIO problems associated with their advanced flight control systems. Even Boeing's new 777 fly-by-wire transport aircraft experienced PIO problems in its flight test phase.²⁶ In fact, one of the significant contributions of the F-8 DFBW was not part of the official DFBW program, but was an unplanned, high-priority research effort that helped solve a potentially dangerous PIO problem with the

Space Shuttle.²⁷

The PIO problem that accompanied the advent of computerized flight-control systems illustrates a characteristic of technological progress described by scholar Thomas P. Hughes as “reverse salients.” Hughes noted that new technology is often a double-edged sword that creates whole new fields of issues and problems even as it overcomes existing limita-

flight control system, Dryden began an Integrated Propulsion Control System (IPCS) effort with a General Dynamics F-111E to look at electronic engine control. The IPCS research program was an Air Force Aeropropulsion Laboratory initiative which ran from 1973 to 1976 and involved Lewis, Dryden, Pratt & Whitney, Boeing, and Honeywell. An F-111 was chosen as the research plane because it was



F-15 with 10-degree cone experiment to improve predictions based on wind-tunnel data. The cone had been used as a standard reference device to measure the quality of flow in 23 transonic and supersonic wind tunnels. It was then flown at transonic and supersonic conditions in the natural atmosphere, mounted on the F-15, to compare flow conditions in the real flight environment with those in the wind tunnels. This experiment provided an assessment of the ability of models in each wind tunnel to simulate the actual flow on full-scale counterpart aircraft. Thus, the 10-degree cone provides valuable insights for interpreting data from models in individual tunnels and for choosing which tunnels should be used for some particular transonic and supersonic tests. (NASA Photo EC78 9554)

tions.²⁸ Computerized flight-control systems were no exception. The dependence of advanced designs on computerized flight-control systems means that aircraft can do things today that they could never do before. But it also means that software has become as critical to an aircraft as the spar in its wing.²⁹

Digital Engine Control/Integrated Control Research

Soon after the F-8 DFBW proved it was possible to fly an aircraft with an electronic

one of the few Air Force aircraft that had variable inlets and two turbofan engines. That allowed one engine to be modified with the second as a safety backup in case something went wrong.³⁰

The reasons for the interest in digital engine control were similar to those driving the digital flight control research. Computerized systems could not only control the operation of an aircraft or engine more precisely and therefore efficiently, they could also allow integration of different components. Integrated systems would allow a pilot to simply command

what he wanted the aircraft to do, and leave it up to the “smart” controls to execute whatever combination of power and flight controls were necessary to make that happen. Clearly, this kind of technology would give an aircraft vastly expanded capabilities.

The F-111 IPCS program replaced the hydromechanical controls for inlet position, fuel flow, and afterburner on one of the aircraft’s

The potential advantages of an integrated flight and engine control system were then demonstrated convincingly with the Center’s YF-12C “Blackbird” in 1978. Because of its unique flight environment, the Mach 3 Blackbird was a challenge to control, both in terms of flightpath and inlet management. To see if a computerized system could improve the YF-12’s performance, Dryden integrated the

inlet control, autothrottle, air data and navigation functions on the aircraft. The integration was not optimized, but it made a dramatic improvement. The improved performance and flightpath control increased the airplane’s range by seven percent. The more precise inlet management also reduced the incidence of inlet “unstarts,”



*Close-up of F-15
10-degree cone
experiment.
(NASA Photo
ECN 9811)*

engines with a computerized, electronic system. The goal was simply to see if digital engine control could increase the performance of the engine by operating it more efficiently, while still functioning as reliably as a mechanical control system. As with many pioneering concepts, the F-111 IPCS system was somewhat rudimentary. But although it was not an ideal set-up, the research still proved the worth of the basic Digital Electronic Engine Control (DEEC) concept. Even at its worst, the technology still performed as well as a conventionally controlled engine.³¹

which were violent disturbances that occurred when the shock wave formed by the aircraft’s high speed jumped from inside to outside the engine inlet. In fact, the improvements Dryden demonstrated with the integrated controls were significant enough that the system was retrofitted on the entire operational SR-71 fleet as part of an avionics upgrade in 1983.³²

These experiments generated additional interest within both NASA and industry in the digital engine control and integrated control concepts. To pursue this research further, Dryden recruited an F-15 fighter it had obtained

in 1976 from the Air Force as a Flight Research Facility. The F-15 was used for a number of different research projects in the late 1970s, but in the early 1980s, it began flight research with an advanced digitally controlled engine designed by Pratt & Whitney. The Air Force had told Pratt & Whitney that the engine with Digital Electronic Engine Control (DEEC) technology was too high-risk for the service to fund as a production concept. So the company approached Dryden and asked if the center would consider a joint flight research program to develop the engine technology further.

The experimental engines were put on Dryden's F-15 and flown from 1981 to 1983. The flight research identified several problems with the engine design, which Pratt & Whitney subsequently corrected, but it also showed the potential of the technology. The DEEC engines allowed engine stall-free performance throughout the entire F-15 flight envelope, faster throttle response, improved airstart capability and an increase of 10,000 feet of altitude in afterburner capability. The results were impressive enough that the Air Force committed to full-scale development and production of what became the F-100-PW-220/229 engines. Pratt & Whitney also applied the Full Authority Digital Engine Control (FADEC) technology to its PW 2037 commercial turbofan engines, which were incorporated into Boeing's 757 transport aircraft.

Following the DEEC research, Dryden engineers wanted to continue exploring technology that could integrate engine- and flight-control systems. The result was the Highly Integrated Digital Electronic Control (HIDEC) program, which was implemented on the same F-15 Flight Research Facility aircraft, modified with digital flight and engine control systems so

it could explore integrated systems technology. The first project was called the Adaptive Engine Control System (ADECS).

The concept behind ADECS was that conventional engine operation had to be based on a "worst case" scenario of what the aircraft might be doing. If the airplane was at a very high angle of attack, for example, the airflow going into the engine would be irregular, so the engine could not be operating close to its stall margin. Unfortunately, that also meant that when the aircraft was in straight and level flight, the engine was still operating well above its stall margin, even though the slack was not necessary at that point. This led to inefficient engine operation. By integrating the flight-control and air-data systems of the HIDEC aircraft with electronic engine controls that adjusted the engine exhaust nozzles, researchers could adjust the operation of the engine to suit the flight condition of the aircraft.

The results of the ADECS flight research indicated that the system could reduce engine temperature while holding engine thrust constant, which could extend the life of the engines as much as 10-12 percent. By allowing higher engine pressures in less demanding flight environments, the system also increased the thrust of the engines by 8-10 percent, allowing an increase in climb rate of 10-25 percent or a reduction in fuel consumption of 7-17 percent. As a result of the HIDEC flight research, integrated control-system technology was incorporated into Pratt & Whitney's Improved Performance Engines and the engines designed for the Advanced Tactical Fighter (ATF).

The limitation of the ADECS technology was that it was based on preprogrammed tables that assumed average engine performance on an average day. To generate truly optimum

performance would require real-time onboard sensing of engine and aircraft behavior. This next step was accomplished through a follow-on HIDECS research project called Performance Seeking Control (PSC). The PSC technology also added control of the engine inlet ramps to the other variables in the system. This advanced system offered a three to five percent increase in thrust over the ADECS technology.³³

Self-Repairing Flight Controls and Propulsion Control Research

Integrated engine- and flight-control systems offered the potential of more than just performance increases, however. If an aircraft could sense problems with individual components and could manage all the other flight and engine controls, it might be able to compensate for damage or malfunctions in an emergency situation. The first research project in this area using the F-15 was a Self-Repairing Flight Control System (SRFCS) concept sponsored by the Air Force. Dryden's F-15 was chosen for the research because it was already equipped with the digital system technology to make such a research effort possible at a reasonable cost.

The SRFCS itself was developed by the McDonnell Aircraft Company and General Electric's Aircraft Control Division. In essence, it used new integrated flight-control software that would adjust the operation of the remaining flight-control surfaces to compensate for the damage whenever a malfunction in a component was detected. The research flights, which took place in 1989 and 1990, demonstrated that an integrated control system could compensate successfully for loss of individual control surfaces. The aircraft would not have its full maneuvering capabilities, but the SRFCS was

also configured to alert the pilot to the problem and the new operating limitations of the airplane.³⁴

An even more ambitious research effort in the area of emergency aircraft control was prompted by the 1989 crash of a United Airlines DC-10 in Sioux City, Iowa. Dryden's propulsion branch chief Bill Burcham was on a business trip when he read about how Captain Al Haynes and his crew had flown and attempted to land the crippled DC-10 using only the throttles after losing the aircraft's hydraulic system. Burcham was traveling with James Stewart, Dryden's F-15 HIDECS program manager, and the two began talking about whether a computerized propulsion-control system could have allowed the DC-10 to land safely. Burcham drew a diagram on a cocktail napkin of how such a system might work, and in five minutes, the two men had outlined a Propulsion Controlled Aircraft (PCA) research effort for the F-15.

Burcham actually began by going down to the Center's simulation room and attempting to fly an F-15 simulator using the throttles only. By increasing or decreasing thrust, he could make the airplane climb or descend, and by using asymmetric thrust with the two engines, he could make it yaw left and right. It was not a pretty way to fly an airplane, but it seemed the idea could work. Burcham then enlisted the help of Gordon Fullerton, a former Space Shuttle commander who had gone to work at Dryden as a research pilot when he left the space program. After a few attempts, Fullerton was able to put the simulator F-15 on the runway every time, so the researchers felt confident trying the concept in flight. The goal of the initial research flights was to see how well the aircraft could be controlled using only

the throttles, without the computerized system. Typically, simulators are more difficult to fly than the actual aircraft, so Fullerton expected the first flight to go well.

But as researchers at Dryden had been learning for years, flight into new territory did not always go as expected. As Fullerton recalled from that first throttles-only F-15 flight, "I was looking at the sky, and then the dirt, and all over. I could barely herd [the airplane] through the sky in the general direction of the airport." It turned out that the aircraft performance in the simulator assumed identical engines and very smooth response. The engines in the real airplane, however, had slightly different performance and response. The differences were small, but without the stability augmentation provided by the flight-control system, they were enough to make the aircraft almost uncontrollable.

The good news was that as soon as the computerized throttle-control system was implemented, the aircraft became very controllable. It took nine flights to refine the system satisfactorily, but in April 1993 the F-15 made its first complete PCA landing. The concept not only worked, it clearly made the difference between a controllable and uncontrollable airplane.

Yet the most significant application for the technology would not be in a fighter, where the pilot had the option of ejecting, but in a transport aircraft. So after the F-15 flights, Burcham talked to the McDonnell Douglas Company about trying the system on an MD-11 airliner. McDonnell Douglas agreed to work with Dryden on the program, and an MD-11 successfully demonstrated the first throttles-only landing of a transport aircraft in August 1995, using the PCA system. The PCA software

is also being researched in a Boeing 747 simulator at the NASA Ames Research Center. It is still too soon to say whether the system will find its way into today's or tomorrow's airliners, but the PCA technology could be a powerful weapon in preventing accidents caused by flight-control or hydraulic-system failures. It is a compelling argument that makes it likely the PCA software will find its way onto air transport aircraft sometime in the future.³⁵

The F-15 ACTIVE

Although it was not a direct outgrowth of the HIDEDEC/F-15 program, one of the significant applications of integrated engine- and flight-control systems has been with thrust-vectoring aircraft such as the X-31. Thrust-vectoring technology depends on an integrated system that can vector the engine thrust depending on the aircraft's flight attitude and situation. The thrust-vectoring paddles on the X-31 and Dryden's F-18 HARV were not a suitable system for a production aircraft, but Pratt & Whitney and others have been working on a gimbaling nozzle design that could be commercially applied. Like the first electronically controlled engine, the Pratt & Whitney "pitch-yaw balance beam nozzle" concept is high risk, so NASA agreed to work on a flight research program to develop the technology further.

The resulting research program is a joint effort among Pratt & Whitney, Dryden, the Air Force, and McDonnell Douglas Aerospace and is called the Advanced Control Technology for Integrated Vehicles (ACTIVE) program. The aircraft selected for the project is a highly specialized F-15 that had been used by the Air Force for a Short Take-Off and Landing (STOL) program but which the Air Force

*F-15 Advanced Control
Technology for Integrated
Vehicles (ACTIVE) aircraft
showing the thrust-vectoring
nozzles that promised to
improve aircraft
efficiency and control
(NASA Photo
EC95 43273-4)*



agreed to loan to Dryden for this research effort. This particular F-15 is well-suited for the research because it already has a quadruple-redundant digital FBW system. The redundancy is important because one of the goals of the ACTIVE research is to explore thrust-vectoring technology throughout the entire F-15 envelope, including speeds up to Mach 2. At that speed, a failure in the system could cause the loss of the aircraft.

As opposed to the X-31 program, which focused on the maneuverability benefits of thrust-vectoring, the F-15 ACTIVE program is looking at what other benefits a more production-like thrust-vectoring engine might create. Possible benefits include reduced fuel consumption, increased range, and decreased trim drag by substituting thrust-vectoring for control surface deflection. The program will also continue the YF-12C and HIDEDEC research into performance optimization and will be looking at potential aerodynamic side-effects of a more effective, production-like system. Wind-tunnel tests at the Langley Research Center, for example, have already indicated that the vectoring nozzles create a tremendous rolling effect on the airplane at moderate angles of attack. Based on the information gained through the ACTIVE research program, Pratt & Whitney plans to commit to a production thrust-vectoring engine.

The first flights of the modified F-15 ACTIVE occurred in February and March 1996 and, for the first year, the focus of its work will be on the thrust-vectoring engine technology. Yet as was the case with many other research aircraft at Dryden, the F-15 ACTIVE will eventually be used as a testbed for other research projects, such as a High Stability Engine Control (HISTEC) program being developed by the NASA Lewis Research Center.³⁶

The F-18 SRA

The F-15 ACTIVE is actually one of two aircraft at Dryden currently dedicated to advanced systems research. While the F-15 ACTIVE is investigating integrated flight propulsion systems, an F-18 modified into a Systems Research Aircraft (SRA) is being used to research numerous advanced components and sub-systems. The F-18 SRA began its Dryden career in the 1980s as a chase aircraft. Its evolution into a research vehicle began when some engineers decided that perhaps the F-18 could conduct some small systems research while still flying as a chase airplane. When industry engineers became aware that Dryden had a potential testbed for advanced systems technology, the number of research efforts grew and the aircraft became a full-time flying testbed. As of the end of 1995, there were 12 different experiments flying on the F-18 SRA and 11 more planned, involving most of the major electronic manufacturers in the country.

The initial research with the airplane has focused on “distributed” aircraft system technology that is designed to replace many centralized systems with smaller, self-contained components. Decentralized systems could have many advantages, including less susceptibility to electromagnetic interference (EMI), less susceptibility to battle damage, and reduced maintenance costs. The technology might also enable designers to use active flutter-suppression techniques, which could make aircraft more efficient by reducing the need for heavy aircraft structure.

The first such experiment on Dryden’s F-18 SRA involved a “smart” actuator that could sense whether the control surface deflec-

tion was consistent with what the pilot had commanded and make any necessary corrections. The smart actuator technology was sponsored by the Naval Air Warfare Center and built by the HR Textron company in California. It was a marked advance over conventional actuators, which had to send signals back through a central flight-control-system computer to accomplish that task. Two follow-on research efforts scheduled for flight in 1996 involve an Electrically Powered Actuator Design (EPAD) sponsored by the USAF Wright Laboratories. The two EPAD designs, an electrohydrostatic actuator and an electromechanical actuator, do not even need the aircraft's central hydraulic system to operate. The electrohydrostatic version has its own hydraulic fluid to move the actuator, and the electromechanical model uses an electrically powered screw to move the control surface.

The SRA has also been used to research fly-by-light technology. In 1993, the aircraft

flew a Fiber-Optic Control System Integration (FOCSI) experiment sponsored by the Lewis Research Center that compared fiber optic airframe and engine sensors with electrical ones. The results indicated that some designs were more reliable than others. A follow-on research effort is planned for 1997 that would depend on fiber-optic sensors to operate selected control surfaces in a flight-critical application. One of the reasons the F-18 SRA is a good testbed for this kind of research is that it has two of most components, including engines and vertical stabilizers. Consequently, engineers can modify one control surface or engine with experimental sensors or components and still have another that is conventionally configured, which increases the safety margin of the research.

The SRA has also explored technology such as a flush-mounted air data system developed by Dryden and Langley researchers, and also an actuator made of composite materials.

*Main hangar at the Dryden
Flight Research Center
showing a pair of F/A-18s
inside
(NASA Photo
EC95 43079-6)*



In addition, the plane is scheduled to research a propulsion-controlled aircraft system similar to the one flown on Dryden's F-15. The goal of that project, which is a cooperative effort between Dryden and McDonnell Douglas, is to collect information necessary to implement a PCA system on an F-18 aircraft. McDonnell Douglas also hopes to use that data to implement a PCA system on its testbed C-17 military cargo aircraft at Edwards Air Force Base. If these research efforts go well, PCA systems could well be included in future production F-18s and C-17s.

Many of the research projects being flown on the F-18 SRA are technologies that could lead to more advanced aircraft. As with the original fly-by-wire system, the technologies are still too high-risk for industry to commit to them in production aircraft. But the F-18 SRA is providing a testbed that can research individual components safely and develop the technology and confidence in its reliability enough that manufacturers and the ultimate users of production aircraft can consider more advanced systems for future airplanes.³⁷

Conclusion

In the past 25 years, computer technology has not only advanced by quantum leaps, it has also evolved from a supporting technology to one that is a critical element for many daily functions of our society. In the same manner, computers have evolved from supporting ground machines into critical flight components for advanced aircraft. When the F-8 DFBW flew in 1972, it was the only computerized, fly-by-wire aircraft at Dryden. Today, almost all of the Center's research aircraft use fly-by-wire

systems.

As changes in technology and national priorities focused attention on making aircraft "better," Dryden's research efforts shifted to support that goal. In the late 1960s and 1970s, Dryden and other NASA centers worked together to develop efficiency-oriented concepts like the supercritical wing and winglets. Other programs, like the F-8 DFBW, the X-29, the X-31, and the F-15 and MD-11 Propulsion Controlled Aircraft also helped develop a wide variety of improved aircraft design concepts. Most of these projects were joint efforts with other centers, the military, and/or industry. But by researching these concepts in flight, Dryden helped these technologies gain a critical level of maturity and credibility that allowed military and industry leaders to consider them for production aircraft.

The production versions of the technology did not always look or operate much like the systems researched at Dryden. The gimbaling nozzles under development by Pratt & Whitney, for example, are a very different design from the paddle-dependent thrust-vectoring systems on the X-31 and F-18 HARV. In some cases, like the F-8 DFBW, some of the significant elements transferred to industry were design processes and guidelines, rather than any one system or piece of technology. But even if the final commercial design bore little resemblance to the research configuration, the research flights at Dryden were often watershed events that changed people's ideas of what was possible.

When Dryden engineers flew an aircraft totally dependent on electronic systems, for example, it proved that a fly-by-wire aircraft could be flown reliably and safely. That proof was critical in convincing designers and pilots

that fly-by-wire technology could be a real alternative to mechanical systems. When Bill Burcham began his research into propulsion-controlled aircraft, many people told him the system could never land an aircraft safely. But the moment Gordon Fullerton touched down in Dryden's PCA F-15, the debate ended. Whatever else anyone could say about the technology, a throttles-only landing was clearly possible. By the same token, the success of the X-29 and X-31 flights shattered decades-old ideas about aircraft design. Previously unthinkable concepts like post-stall maneuvering suddenly became real design possibilities. And as the horizons and minds of design engineers open and expand, they may see other new approaches or designs that could benefit future aircraft. It is difficult to quantify this kind of contribution, but it is one of the most important benefits of Dryden's advanced, exploratory research.

Of course, in exploring the new realm of computerized and electronic flight and engine systems, NASA and its partners also learned important lessons about the behavior of some of this new technology. The same complex

technology that allowed advanced aircraft designs to have greatly expanded capabilities also created more opportunities for something to go wrong. Phenomena like pilot-induced oscillations and single-point failures in software systems are a sharp reminder to engineers that even as technology solves old problems, it can open doors into entirely new problem areas.

Dryden's research into ways to make aircraft "better," whether through improved efficiency, maneuverability, or aircraft systems, is far from finished. The hyperspeed with which computer technology and information systems continue to progress is constantly opening new doors and creating new possibilities for improving aircraft design. Some of the advances may not make their way into production designs for a number of years, and some of them may not ever be commercially applied. But with people willing to explore and pursue the new territory continually appearing over the technological horizon, the difference between the impossible and the possible can become simply a matter of time.





► Chapter Five:
Supporting National Efforts



While Dryden was pursuing its various “exploratory” research projects over the years, the Center was also providing support for other programs and efforts, both in aeronautics and in space. Its unusual research aircraft, desert surroundings, and cadre of flight research specialists gave Dryden unique capabilities for testing new concepts and vehicles and attacking particular problems that surfaced in operational air- and spacecraft. Its support for America’s space program has included efforts such as developing and flying a lunar landing research vehicle, pursuing a solution to a potentially dangerous pilot-induced oscillation with the Space Shuttle, and assisting efforts to find a more cost-effective way of putting satellites in space. Dryden has also provided both government agencies and industry with a wide variety of aeronautical support—from trouble-shooting problems with new military aircraft designs, to conducting stall-spin research for both military and general aviation airplanes, to crash-testing a proposed anti-misting fuel additive for the Federal Aviation Administration.

Many of these support efforts were developed quickly in response to problems or needs that arose. Dryden’s ability to switch gears and incorporate new or unforeseen projects without dropping the other research already in progress was a tribute to the “technical agility” that was always one of the Center’s greatest strengths. The people at Dryden did not do the in-depth theoretical research conducted at some of the other NASA centers. But as flexible, hands-on problem-solvers with actual flight hardware, they had few equals.

Space Shuttle Endeavour atop a 747 Shuttle Carrier Aircraft being returned to Kennedy Space Center following its first flight from 7 to 16 May 1992 and its landing at Dryden at the end of the STS-49 mission. (NASA Photo EC92 5211-1)

Supporting the Space Program

Early Efforts

Dryden's involvement in NASA's space program dates back to 1959, when the Center's F-104 aircraft were used to test the drogue parachutes being designed for the Mercury space capsules. The F-104s performed multiple drops of the parachutes from above 45,000 feet, and the flight research uncovered several critical design flaws that were then able to be corrected before the system was used on the actual Mercury spacecraft.

Dryden researchers also provided some backup support for the military X-20 "Dyna-Soar" program that was being developed about that same time. The Dyna-Soar was a delta-wing vehicle that was to be launched on top of a booster rocket and then flown back to a horizontal landing. Large rocket booster safety and performance in those days was uncertain, and planners wanted to design a workable escape system for the pilots in the event of a launchpad booster-rocket explosion. The Dyna-Soar

design included a small emergency rocket that could jettison the craft to an altitude of perhaps 6,500 feet, but it was still unclear how a pilot would land the aircraft safely from that point. Using a prototype Douglas F5D "Skylancer" the Center acquired in 1961, Dryden research pilot Neil Armstrong explored several possible techniques and developed a procedure that would have enabled a safe return to landing for Dyna-Soar pilots. As it turned out, the Dyna-Soar program was canceled before the craft was ever built, but the technique developed at Dryden provided the X-20 project managers with valuable information they had not been able to obtain from other sources.¹

Dryden's involvement with NASA's space program continued in the early 1960s with flight research to support the agency's "parawing" project. The parawing was an inflatable, steerable wing/parachute that was being investigated as a possible alternative to the simple parachutes used by the Mercury space capsules. A parawing might enable follow-on Mercury Mark II capsules (which became the Gemini spacecraft) to be guided to a gentle land touchdown instead of the ocean

F-100 and F-100A on lakebed, showing modifications to the tail that solved the aircraft's deadly tendency to go out of control during rolling maneuvers. The larger tail on aircraft FW-778 (the F-100A) is clearly visible as compared with the unmodified F-100 (FW-773) (NASA Photo E 1573)



splashdowns simple parachute systems required. The parawing concept was based on research by a Langley Research Center engineer named Francis M. Rogallo, and the soft wing/parachute was known as a “Rogallo wing.”

In the spring of 1961, NASA’s Space Task Group initiated research into the applicability of Rogallo’s design to spacecraft. North American Aviation was awarded a contract to build and test a prototype Rogallo wing, and Dryden was asked to support that test program. Some engineers at Dryden, however, thought that it would be helpful to try flying a small paraglider before North American tested its full-size Rogallo wing. Paul Bikle, the Center’s director at that point, agreed and approved the construction and flight of a single-seat paraglider in December 1961. The result was the “Paresev I,” a somewhat unsteady-looking vehicle that resembled a hang glider attached to a three-wheeled dune buggy.

The unpowered craft was initially towed behind a ground vehicle, and the pilot, who sat out in the open, controlled its movement by tilting the wing fore, aft, and side to side. The flying characteristics of the Paresev were less than ideal, to say the least, and research pilot Milt Thompson considered it more difficult to fly than even the early lifting-body aircraft. The craft’s crude control system led to several tense moments during the research flights and ultimately caused an accident with the vehicle. Pilot Bruce Peterson was flying the Paresev I on a ground tow test when it began an increasingly severe rocking oscillation and finally nosed over into the lakebed. Fortunately, Peterson was not seriously hurt and the vehicle was completely rebuilt with a better wing and control system. The Paresev I-A, as the rebuilt vehicle was named, had better handling characteristics

and, after initial ground-tow tests, was taken aloft behind a Stearman biplane and an L-19 Bird Dog.

Eventually, the vehicle was equipped with the same kind of inflatable wing North American was testing and dubbed the Paresev I-B. In two years, the Paresevs completed 100 ground tows and 60 air tows. But although the Dryden Paresev finally got to the point where it had acceptable handling characteristics, the full-size test vehicle being developed by North American was not as successful. In 1964, as costs and time delays increased, NASA dropped the parawing program and research with the Paresevs ended.

The value of the Paresev research at Dryden was that it offered a low-cost way to investigate some of the flight-control issues and problems that a parawing concept might entail. Clearly, there was still a gap between a small test vehicle and a full-size, space-capable system. But some of the information was still useful. And although the inflatable parawing concept has yet to be applied to a spacecraft, it may still be used on a future design.²

Lunar Landing Research Vehicles (LLRVs)

One of Dryden’s biggest contributions to the space program was its work with the Lunar Landing Research Vehicles (LLRVs)—tubular craft so bizarre looking that they were commonly referred to as the “flying bedsteads.” The LLRVs themselves were the brainchild of Dryden engineer Hubert “Jake” Drake, but the research was part of a NASA-wide effort to develop the experience and techniques necessary for a successful Moon landing.

When President John F. Kennedy issued

his 1961 challenge to have an American walk on the Moon before the end of the decade, NASA and industry researchers went into high gear. They had eight short years to answer all the questions, develop all the technology, and overcome all the obstacles necessary to achieve that goal. One of the questions was how the astronauts were going to successfully land and take off again from the Moon's surface. Aerodynamic features would be useless in the

Moon's airless environment, so the lunar module would have to be controlled entirely by propulsion systems.

The Grumman Aircraft Corporation was given the contract to design and build the actual lunar module, but NASA managers knew they would also need to find some way to train the astronauts to operate the lander in the Moon's reduced gravity. NASA planned, of course, to design a ground simulator for the craft, and the Langley Research Center was developing a tethered test machine on a large gantry. But Drake, a product of Dryden's hands-on, flight-oriented atmosphere, believed that the only way to get complete information on flying the lander would be to build and operate a free-flying test vehicle. As luck would have it, Drake was not alone in his thinking. Several engineers at Bell Aircraft were also pursuing a design for a free-



Paresev in flight, providing a low-cost way to test the flight-control issues of a parawing concept for possible use in returning spacecraft to Earth (NASA Photo E 8013)

flying lunar lander simulator. In addition to its history with the X-1 project, Bell was a premier helicopter manufacturer, a pioneer in vertical take off and landing (VTOL) aircraft research, and therefore an obvious partner in the effort.

Dryden and Bell got approval to begin work on the LLRV in December 1961, and in February 1963 Bell was awarded a contract to build two of the vehicles. The vehicles, which looked something like a cross between a child's jungle gym and a science fiction contraption, were not an entirely new concept. "Flying bedsteads" had been used to investigate VTOL aircraft technology as early as 1954. But the LLRVs had the unique task of investigating the flight and propulsion controls, pilot displays, visibility, and flight dynamics of a vehicle designed to land on the Moon.

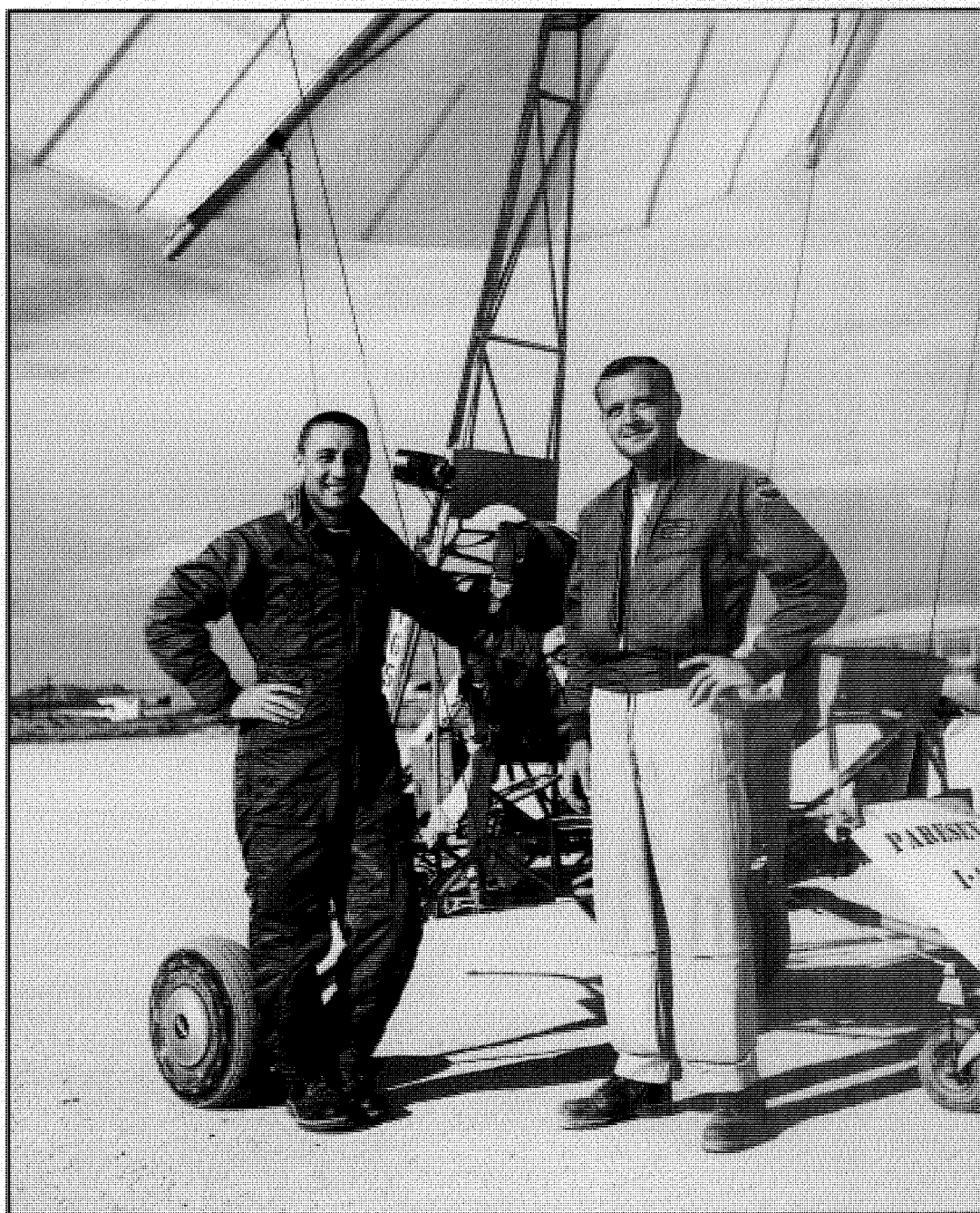
Because the Moon's gravity is only one-sixth as strong as the Earth's, the LLRVs had a central, gimballed jet engine that would support five-sixths of the vehicle's weight. The gimbal mechanism made sure that the engine remained perpendicular to the ground, regardless of the attitude of the vehicle. In addition, the LLRV was equipped with two lift rockets to manage its climb and descent, and 16 smaller reaction control rocket engines that the pilot used to control pitch, yaw, and roll. The vehicle also had six backup rockets that could be deployed if the main jet engine malfunctioned, and it was equipped with a zero-zero ejection seat³ for the pilot.⁴

Gus Grissom (with right hand on hip) and Milt Thompson next to the Paresev. In 1962, when this photo was taken, Milt checked the Mercury astronaut out on the vehicle. (NASA Photo E 8937)

LLRV #1 made its first flight on October 30, 1964. The steam and noise generated by the controlling reaction rockets made the aircraft sound like "a marshaling yard full of steam locomotives," according to one Dryden research pilot,⁵ but the awkward-looking contraption performed as promised. Over the next two years, NASA pilots made 198 flights in the vehicle, incorporating several modifications along the way to make the LLRV more like

the actual Lunar Module (LM). In early 1967 both LLRVs were shipped to Houston, where NASA began using them as training vehicles for the Apollo astronauts. Redesignated the Lunar Landing Training Vehicles (LLTVs), the two from Dryden were soon joined by three more LLTVs that NASA ordered from Bell.

All the Moon mission commanders and back-up pilots flew the LLTVs before their flights and considered their experiences with them extremely valuable. In fact, when Apollo



11's "Eagle" LM was descending to that first historic Moon landing, Neil Armstrong realized the craft was heading for an undesirable touchdown spot. So although the LM was equipped with an automatic landing system, Armstrong took over and flew the craft manually for the final 30-40 seconds of its descent, guiding it to a more suitable site. It was his flights in the



LLTV, Armstrong reportedly said later, that gave him the confidence to take over from the automatic system.⁶

The LLTVs were far from perfect aircraft, as Armstrong and two other pilots discovered when control or system problems forced them to eject from the complex and totally non-aerodynamic vehicles. But the LLTVs were unquestionably extremely useful for America's piloted lunar space missions. As chief astronaut Donald "Deke" Slayton said at the time, there was "no other way to simulate Moon landings except by flying the LLTV."⁷

The Space Shuttle

Although the lifting-body shapes that were researched at Dryden were not selected as the final shape for the Space Shuttle, the Center has played an important support role with the Shuttle since the very first flight tests of the orbiter in 1977. While Rockwell was building the first Shuttle orbiter, the Air Force and

NASA signed an agreement to establish Shuttle support facilities at Edwards Air Force Base. The clear skies, open landscape and lakebed landing site at Edwards would provide more leeway and options for returning Shuttle pilots than any other location. NASA planned to transport the Shuttle back and forth between Edwards and the Kennedy Space Center

launch site in Florida on the back of a Boeing 747, and the agency had already bought and modified one of the jumbo jets for that purpose.

Computer and simulator calculations predicted that the mated Shuttle/747 pair could fly together safely, but NASA wanted to verify that prediction in a controlled flight-test environment before the Shuttle went into operation. NASA also wanted to glide-test the orbiter to make sure it could execute a safe landing before attempting an actual mission. To accomplish both of these goals, NASA's Johnson Space Center designed a three-phase test program. The first, "unmanned-captive," phase would test the Shuttle/747 combination without any crew in the orbiter, so that if there was a problem, the Shuttle could be jettisoned. The second, "captive-active," phase would test the combination with a two-person crew aboard the orbiter. The third phase would be "free-flight" tests in which the orbiter and its two-person crew would be carried aloft on the 747 and then launched off its back to glide back down to a landing.

Lunar Landing Research Vehicle (LLRV) in flight (NASA Photo ECN 506)

*Joe Walker in a Lunar
Landing Research
Vehicle (LLRV)
(NASA Photo ECN 453)*



As a safety precaution during the tests, a special escape system was installed in the 747. Ejection seats were impractical, especially with the Shuttle on top of the aircraft, so a laundry chute-type slide was installed right behind the cockpit that would exit out the bottom of the plane. The pilots would wear parachutes, and an explosive charge would blow a panel off the bottom of the chute/slide prior to the pilots' emergency exit. To insure that they could reach the exit even if the aircraft was spinning or out of control, a rope with knots tied in it was installed on the floor from the front of the cockpit to the escape chute.

The first unmanned-captive test flight went off without a hitch, which was fortunate because it was attended by a level of media attention and exposure beyond anything Dryden and its staff had ever experienced. After five captive tests and three successful captive-active tests, managers were ready to begin the more difficult free-flight portion of the test program.

Researchers knew the air-launch of the

Shuttle from the 747 would be a high-risk maneuver. There were concerns about the orbiter causing aerodynamic buffeting of the 747's tail and the consequences of an incomplete separation. But the biggest concern was the risk of the Shuttle recontacting the 747 after separation, which might have catastrophic results. Special valves were installed in the Boeing

jet to close off the hydraulic lines to the rudder so the rest of the control surfaces would be operable even if the tail were lost. Engineers conducted numerous simulations, wind tunnel tests, and studies to try to predict the behavior of the two aircraft after they separated. But concerns remained. Finally, Chuck Yeager, who had not only broken the sound barrier with the X-1 but had also flown a French ramjet-powered aircraft off of a French transport aircraft after World War II, was brought in as a consultant. As veteran research pilot Bill Dana remembered it, "Chuck listened politely to Dryden's interpretation of the laws of physics and aerodynamics, and then he walked over to a model of the mated 747/Shuttle combination and said, 'If you mount the Shuttle on the 747 with a positive angle-of-attack difference and get some air flowing between the two, nothing can happen but separation.' So we studied the problem some more and Chuck, of course, was right."⁸

Indeed, the first four free flight tests of the Shuttle went flawlessly, and the launch of



747 wake vortex research with smoke generators. A Learjet and T-37 Cessna are flying through the wake to measure the forces and effects of the vortices. (NASA Photo ECN 4243)

the orbiter off the 747 was never a problem. The biggest and scariest problem encountered during the approach and landing test (ALT) program was on the fifth and final flight, and it involved the control system of the orbiter itself. The fifth ALT flight was the first to attempt a landing on Edwards' paved runway instead of the Rogers lakebed. In addition, Shuttle pilots Fred Haise and Gordon Fullerton⁹ were attempting a spot-landing at a particular point on the runway to see whether the orbiter could be landed precisely enough to permit landings at sites other than Edwards. Adding to the pressure on the pilots was the fact that Prince Charles of England was on hand to watch the landing, in a gazebo out by the runway.

The flight was also the first time Haise and Fullerton had flown the orbiter without its tail-cone faring, so they were relying on their

practice in NASA's Gulfstream II in-flight simulator to judge how much to adjust their approach profile. But as often was the case, the simulator performance was not quite the same as the actual aircraft, so Haise was about 40 knots too fast as the Shuttle approached the runway. He deployed the orbiter's speed brakes and was trying very hard to still hit the target touchdown spot. But with the stress putting Haise in a keyed-up, or what pilots sometimes call a "high-gain," mode, he over-controlled the craft and entered a pilot-induced oscillation (PIO), both in roll and pitch. After the Shuttle bounced on one tire and then another, Fullerton finally got Haise to relax his pressure on the controls and the Shuttle landed safely. But the incident uncovered a potentially serious problem in the Shuttle's control system. In the high-stress environment of an actual re-entry and

landing from space, pilots could easily get into the same difficulty that Haise did, with potentially disastrous consequences.

NASA immediately began a high-priority, agency-wide research effort to identify the cause of the problem and develop a solution. Dryden assigned a flight-controls group to research the issue, and the Center's F-8 Digital

Controller pilot Gary Krier quickly told Manke to turn the time delay off, and Manke managed to regain control and climb to a safe altitude. But it was close. Researchers estimated that if the oscillation had gotten any larger, Manke would have stalled and lost the airplane. Even after Manke gained a little altitude, the control-room engineers sat in stunned, relieved silence.



Top: F-104 shown head-on while engaged in Space Shuttle tile research. Flights of this aircraft in rain and through clouds provided valuable data on the extent to which the tiles could withstand rainy conditions during launch. (NASA Photo EC90 224)

Top Right: PA-30 Twin Comanche general aviation aircraft, one of the types studied in the 1960s by the Flight Research Center in an investigation of their handling characteristics. It was later used to train pilots to operate Remotely Piloted Vehicles from the ground. No longer part of the Dryden fleet of aircraft, it now resides at Kings River College, Reedley, California. (NASA Photo 2089)

Fly-By-Wire was recruited to support the effort. Dryden's engineers suspected that the 270-millisecond time delay in the Shuttle's fly-by-wire control system was causing the problem, so the F-8 conducted a series of approach and landing tests with increasing time delays programmed into its control system. For safety, the aircraft was equipped with a switch that would turn off the experimental time delay and return the aircraft to its standard fly-by-wire control system.

The F-8 performed well until the added time delay reached 100 milliseconds. On that flight, as pilot John Manke was completing a touch-and-go landing and takeoff, he entered a severe PIO at a high angle of attack and low speed. Hearts stopped in the control room as researchers watched the jet fighter porpoise up and down in increasingly severe oscillations.

Finally, Krier keyed his mike again and said, "Uh, John? I don't think we got the data on that—we'd like to have you run that one again." Laughter erupted, breaking the tension and illustrating once again the balancing power of humor in a high-stress environment.¹⁰

Clearly, there seemed to be a critical threshold in the time delay of a control system. One solution would have been to redesign the control system of the Shuttle, but that would have seriously delayed its development. Fortunately, the Dryden researchers were able to come up with another fix. They designed a suppression filter for the outer loop of the control system that would correct the problem without forcing any changes to the basic control laws. The filter was installed, and the Space Shuttles have used it ever since, accumulating a perfect safety record for landings. Another

result of the F-8 flight research was a specification for future military fly-by-wire aircraft, limiting their control-system time delays to less

Dryden continued to support the Shuttle missions through ground support of the landings and with its three-story steel Mate-Demate



Convair 990 landing on the lakebed during the final Space Shuttle tire test (NASA Photo EC95 43230-4)

Device (MDD), which is used to mount and remove the Shuttles from their two Boeing 747 carrier ships. In 1993, the Kennedy Space Center in Florida became the primary landing site for the Shuttle program, but Edwards continues as an important backup location if the weather in Florida is not suitable for a landing.

than 100 milliseconds.¹¹

For a couple of years following the developmental research on the Shuttle, Dryden's efforts in support of NASA's space program lessened. But the Shuttle—and the

Space Shuttle Support Research

In the 1980s, Dryden once again took on a research role with the Space Shuttle program. In one effort, Dryden conducted a series of



Convair 990, equipped with a new landing gear test fixture representative of the Shuttle's landing gear system, is taking off on a flight from Dryden. In the background is a T-38 flying safety chase. (NASA Photo EC92 12221-2)

flight tests on the tiles being used for the orbiter's thermal-protection system. Since the Shuttle would be launched in Florida, where rain was a common occurrence, managers at the Johnson Space Center wanted to determine what kind of damage rain would inflict on the critical thermal tiles. Dryden researchers installed some of the rigid

world's attention—returned to Dryden in April 1981 when pilots John Young and Robert L. Crippen landed the orbiter *Columbia* at Edwards after the first Space Shuttle mission.

thermal tiles on a special flight-test fixture underneath one of the Center's F-104 aircraft and measured the results from flight in both actual rain conditions and behind a KC-135

spray tanker.

The KC-135 proved incapable of simulating rain impact damage and was dropped from the tests, but the flights in actual rain and cloud conditions provided some very valuable data. Tiles that had been through several launch cycles, for example, appeared to fail at lower impact forces than new tiles. But the research indicated that it might be possible to launch or land the Shuttle in light rain, although there were numerous variables that needed additional investigation. Related research with the F-104 and the Shuttle tiles also indicated that the flexible protective tiles could actually withstand launch airloads as much as 40 percent higher than those they were designed to bear.¹²

Following the *Challenger* accident in January 1986, NASA began looking not only at the booster rockets, but also at any other potential weak spots that could cause problems for

future missions. One of the other areas investigators identified was the Shuttle's landing gear and tires. Because of the difficulty of protecting tires and gear in the extreme temperatures and environments experienced by the Shuttle, the orbiters were equipped with only four small wheels, two on each main gear. The main gear systems of a similar-weight commercial airliner, by comparison, would incorporate anywhere from eight to sixteen wheels.

Although the Shuttle tires had been tested at the Langley Research Center test track and on a stationary device called a dynamometer, the "dyno" could not test all the real-life effects the tires had to endure. Several engineers from the Johnson Space Center and Dryden agreed that it would be helpful to research the actual limits and failure modes of the Shuttle tires and wheels in realistic conditions, if a suitable test aircraft could be found.

NASA crew in front of 747 Shuttle Carrier Aircraft with Shuttle Columbia mounted above it, in 1981. Crew, from viewer's left: Tom McMurtry, pilot; Vic Horton, flight engineer; Fitz Fulton, command pilot; and Ray Young, flight engineer. (NASA Photo ECN 15325)





As it turned out, NASA already had a transport aircraft that could achieve both the gross weight and speeds of the Shuttle. The airplane was a Convair 990—a plane whose heavy, overbuilt design helped prevent it from being a commercial success but made it perfect for flight research. It had been operated by the Ames Research Center but was in storage in Marana, Arizona, when the Johnson-Dryden joint landing-systems research program was organized.

The Convair was pulled out of storage and modified with a separate test gear mechanism in between the aircraft's existing main landing gear. The test mechanism used landing gear components from the Shuttle and was

powered by a high-pressure hydraulic system that allowed it to be extended and tested at various loads after the Convair touched down on its own gear. This set-up also provided an important margin of safety for testing tire failures, since the test apparatus was supplemental to the Convair's existing gear.

The initial goal of the research was to analyze failure modes of the Shuttle tires and gear. But while the Convair was still being modified for the work, the NASA managers in charge of the orbiter program decided that a more important priority was learning about tire wear on the Shuttle. Ground analysis had led program managers to limit the Shuttle to land-

Space Shuttle prototype Enterprise, tested at Dryden, being worked on in a hangar (NASA Photo EC83 22740)

ing with less than a 12-15-knot crosswind. This also limited launches, because conditions had to be good enough for the Shuttle to perform an emergency return-to-launch-site (RTL) maneuver in order for a launch to be approved. But if data from flight tests showed the tires could withstand greater forces, the crosswind limit could be increased.

The flight research with the modified Convair 990 occurred between 1993 and 1995.



A simulated (smaller) version of the Shuttle's solid rocket booster (SRB) mounted under the wing of NASA's B-52 in preparation for the flight testing of the parachute system to be used in SRB recovery (NASA Photo ECN 9874)

During that time, the aircraft was taken twice to Florida to test the tires at the speeds and weight the Shuttle would have if it had to perform an emergency RTL. The results were surprising, and not encouraging. The tests indicated that the tires might not even sustain crosswinds as high as the predicted 12-15 knot limit. The Kennedy Space Center runway had grooves cut into the concrete, which improved traction in wet weather but created extra friction wear on the tires, especially the small, heavily-loaded tires of the Space Shuttle. As a result of the Convair tests, NASA decided to smooth the runway surface somewhat, raising the crosswind capability of the tires from 15 to 20 knots.

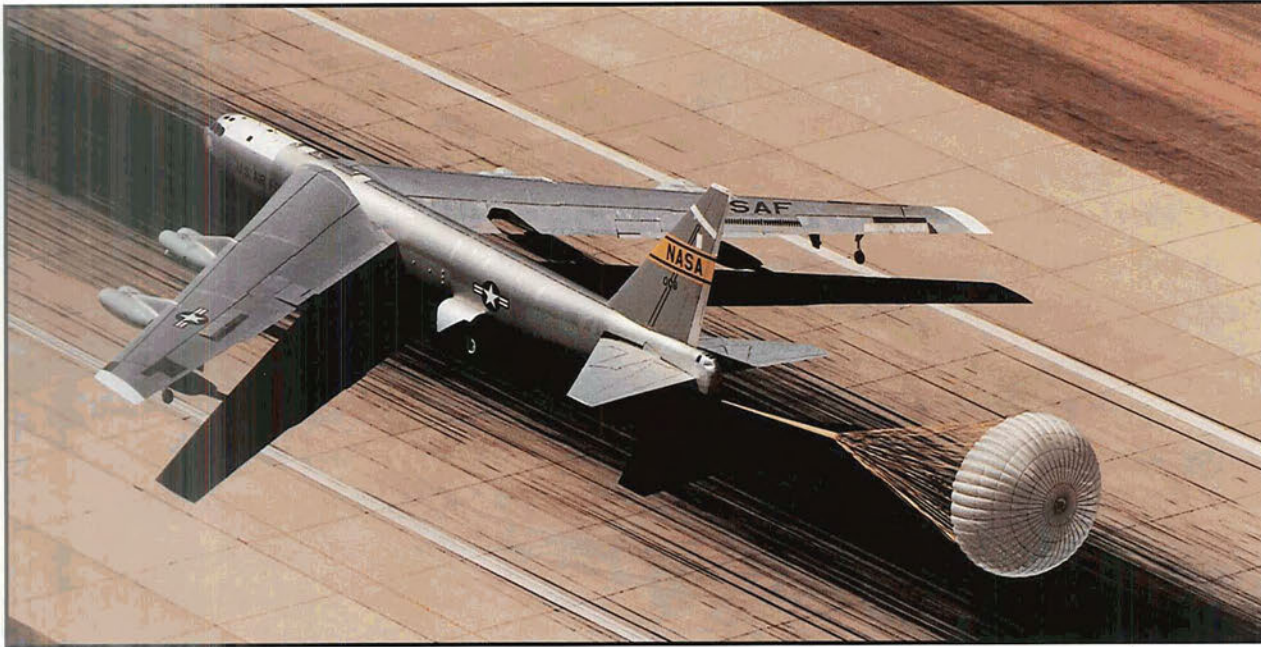
The Convair also conducted high-speed landing research on the tires, showing they could land safely at speeds up to 242 miles an hour—17 miles faster than the top speed for which they were rated.

In addition, the Convair investigated the performance of the tires in low pressure conditions. Pressure in the Shuttle's tires is monitored while the orbiter is in space, and the established procedures required the Shuttle to return and land immediately if any tire pressure went below 310 pounds per square inch (psi). Yet after the Convair test gear showed that the tires could still operate safely down to 200 psi, the required minimum pressure was reduced to 270 psi, giving the Shuttle some extra operating margin.

Near the end of the Convair landing systems research program, the researchers finally got back to their initial area of interest—the failure modes of the tires and wheels. In two August 1995 flights a test tire was intentionally failed and kept rolling under load, first on the paved Edwards runway and then on the Rogers lakebed. The results on the runway were dramatic. As the wheel was ground down by the concrete surface, the fire ignited by the heat stretched as high as the passenger windows and beyond the tail. The same test on the lakebed produced very different results. The tire and wheel kept rolling, and there was no fire. The research results still have to be analyzed further, but the information provided by the Convair tests will help managers reevaluate the best course of action for the Shuttle if it ever has to land with a defective tire.¹³

Dryden's B-52 Launch Aircraft

In several instances, Dryden became



B-52 testing a drag chute being developed for the Space Shuttle to increase the safety of landings and reduce the wear on the orbiter's braking system (NASA Photo EC90 262-27)

involved with space-related research efforts because of its unique B-52 mothership aircraft. In the 1970s and 1980s, for example, Dryden conducted a series of drop tests for the parachute system designed to recover the Shuttle's solid rocket boosters. The Marshall Space Flight Center and the Martin Marietta company had developed a test cone to check the deployment mechanism and the maximum loads for both the booster's drogue and main parachutes, but they needed a launch vehicle for the unit. Dryden's B-52, with its wing pylon modified specifically for drop tests of various aircraft and objects, was an ideal platform.

In 1990, the B-52 was tapped once again by the Johnson Space Center to test a drag chute that was being developed for the Space Shuttle. The orbiter was already landing on concrete

runway surfaces both at Edwards and at the Kennedy Space Center, but a drag chute could enhance the safety of the landings and also reduce the wear on the Shuttle's braking system. Dryden's B-52 was recruited as the test aircraft because it was already equipped for a drag chute and was heavy enough to produce a

load on the chute similar to that of the orbiter. A series of landing tests on both Rogers Dry Lake and the Edwards runway showed the drag chute worked well, and it was installed and used for the first time on the new orbiter *Endeavour* in 1992. The other

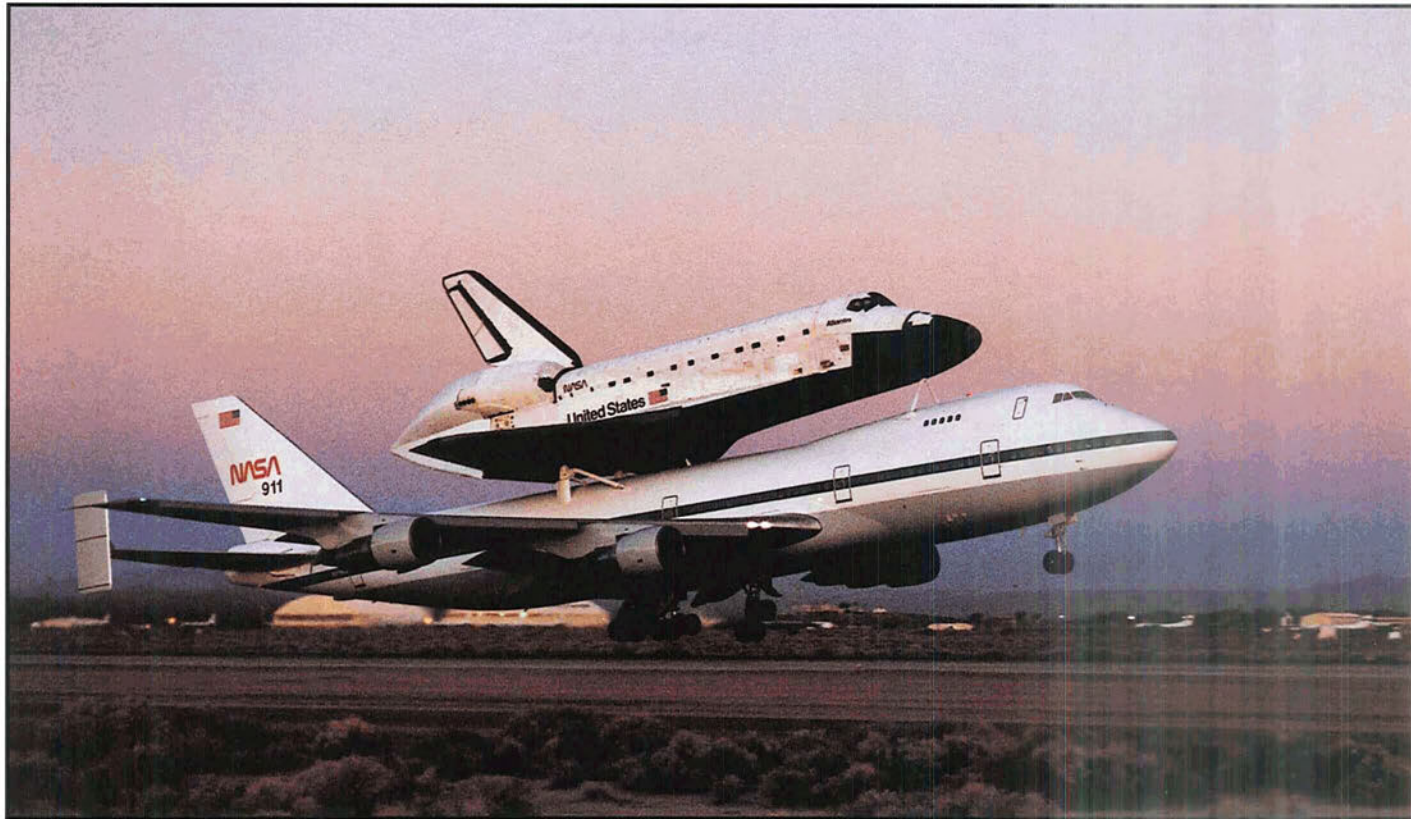
orbiters were subsequently retrofitted with the drag-chute mechanism.

A group of industry entrepreneurs also approached Dryden in the late 1980s about using the Center's B-52 to help them test a new and potentially more cost-effective way of



Space Shuttle Columbia with reflection in a pool of water created by recent rain on the normally dry lakebed, 16 November 1982 (NASA Photo EC82 21081)

Space Shuttle *Atlantis* mounted on top of a 747 Shuttle Carrier Aircraft for its return to Kennedy Space Center following its landing at Dryden at the end of the STS-66 mission, which lasted from 3 to 14 November 1994. (NASA Photo EC94 42853-6)



launching small payloads into orbit. Under the sponsorship of the Advanced Research Projects Agency (ARPA, now the Defense Advanced

launch aircraft would replace the first stage of what would otherwise have been a four-stage launch system. The launch aircraft would

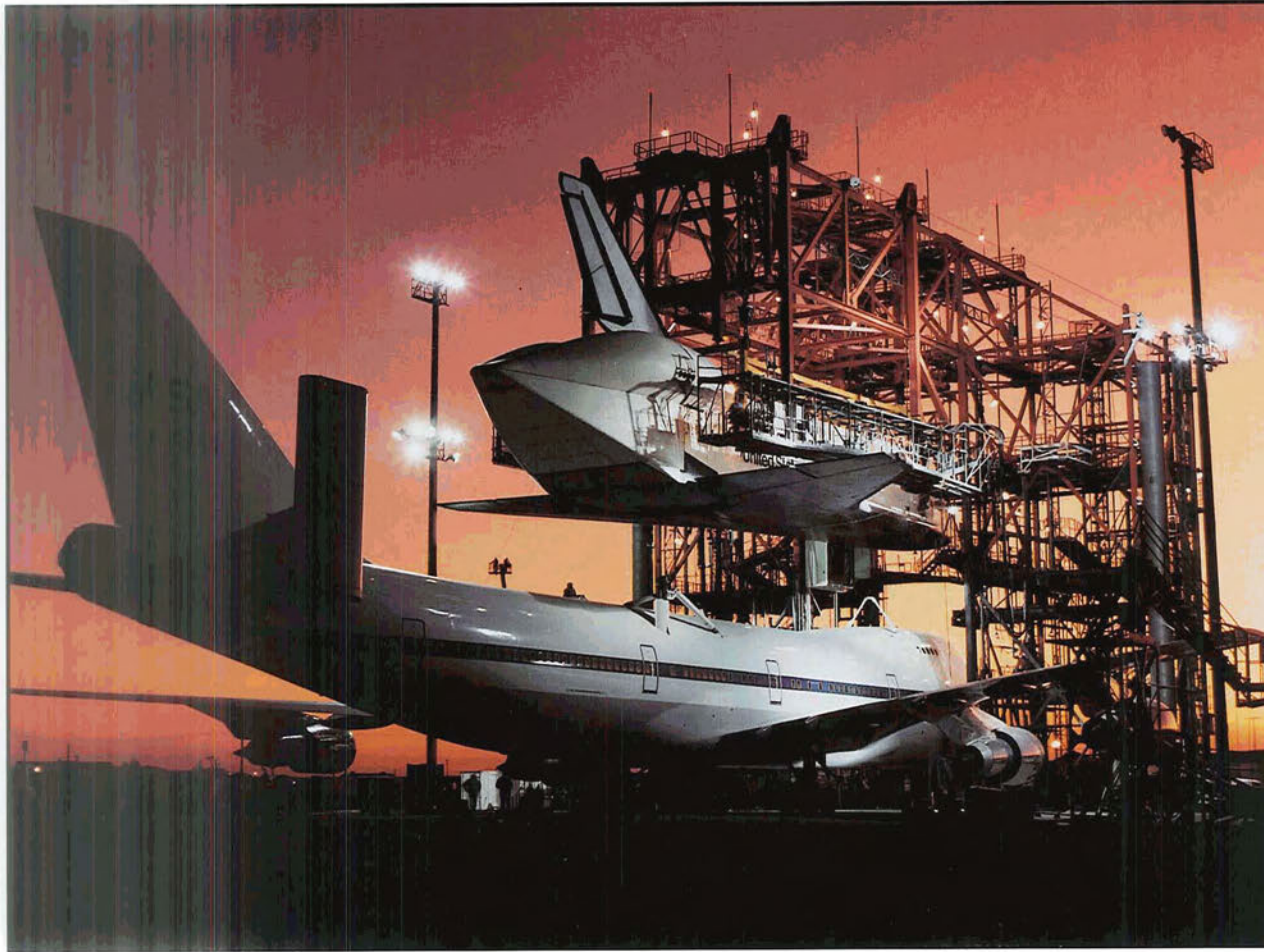
release a winged booster rocket, which would carry a second booster rocket and payload even higher. The final rocket stage carried the 1,500-pound payload into orbit. Orbital Sciences named the vehicle "Pegasus" and teamed with the Hercules Corporation for manufacture

Shuttle prototype *Enterprise* separating from 747 Shuttle Carrier Aircraft for approach and landing test (ALT) research (NASA Photo ECN77 8608)



Research Projects Agency), the Orbital Sciences Corporation had developed an air-launched rocket-booster system in which the

of the rocket motors and Scaled Composites for the booster system's wing. But the vehicle still needed a suitable launch aircraft and, with its



Space Shuttle Atlantis in Dryden's Mate-Demate device, about to be mated to the Shuttle Carrier Aircraft for its flight back to the Kennedy Space Center following its Space Transportation System-44 flight from 24 November to 1 December 1991 (NASA Photo EC91 659-2)

custom launch pylon, Dryden's B-52 was a logical choice.

Dryden research pilots carried the first Pegasus aloft under the B-52's wing in April 1990. The launch was successful, and it marked one of the first times a commercial company had successfully launched a payload into Earth orbit. Five additional launches between 1990 and 1994 were also successful, opening a door not only to potentially less expensive but also to nongovernmental access to space.¹⁴

Safety and Problem Solving Efforts

Aircraft Design Problems

Even before the research station at Muroc was established, the National Advisory

Committee for Aeronautics (NACA) had been involved in helping the military and manufacturers iron out problems in new aircraft designs. The NACA's wind tunnels were frequently-used resources, and NACA test pilots often helped evaluate prototype aircraft. As aircraft technology began advancing more rapidly in the 1940s and pressure to get new aircraft into service increased, the NACA's assistance became even more important.

With the dawning of the supersonic jet age, new production aircraft were beginning to push into the same areas that were being researched with the X-series aircraft at Dryden. So at the same time as Center pilots and engineers were exploring new research territory, they were also being tapped to help solve developmental problems in some of the country's new supersonic aircraft.

One of the earliest production aircraft Dryden assisted was the Northrop F-89. The F-89 was a high priority air defense program, and the Air Force had placed an order for more than 1,000 of the jet aircraft. But in early 1952, six



F-100 protruding through the hangar wall following Scott Crossfield's emergency landing in which he skillfully executed a dead-stick landing in the less than docile aircraft, then decided to glide off the lakebed and coast to a stop in front of the NACA hangar. Not realizing that he had used up the braking power, Crossfield went partly through the hangar wall without doing extensive damage to the aircraft, which flew again. (NASA Photo E 1366)

of the new F-89s lost their wings in flight. The accidents pointed to a serious flaw in the aircraft's design and put the whole program in jeopardy. The Air Force and Northrop began an intense effort to determine the cause of the accidents and asked for Dryden's help. Dryden engineers put strain gauges on an F-89 and conducted a series of research flights to evaluate the in-flight loads on various components, especially the wings. The flights uncovered a serious weakness in an area of the wing's structure, which Northrop then redesigned. After the modification, the F-89 went on to a long and useful service life in the Air Force.

The next trouble-shooting effort with a military aircraft came with the North American F-100A—the first of the Century Series fighters and the first fighter designed to go supersonic in level flight. The F-100A had barely entered service in 1954 before a series of accidents and

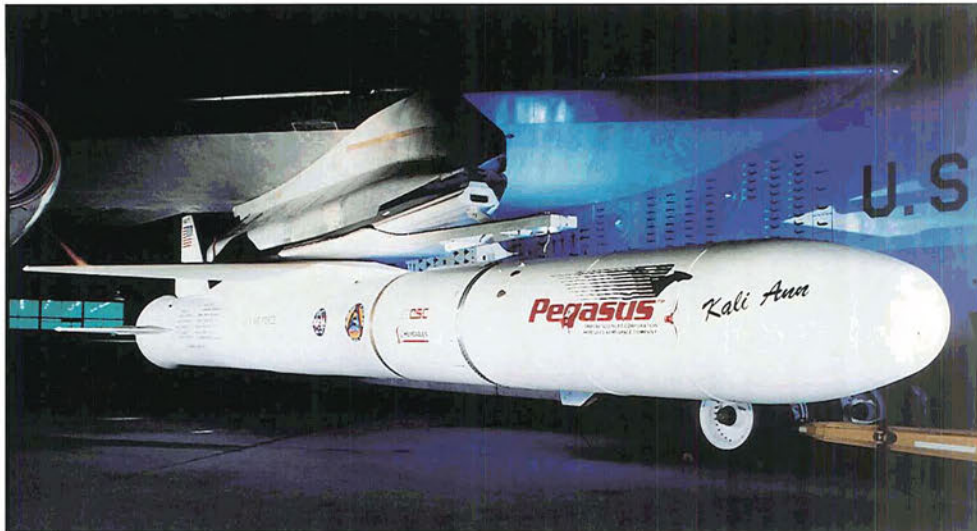
in-flight structural failures of the aircraft led the Air Force to ground the airplane. Dryden was already experiencing a phenomenon known as “inertial coupling” with the X-3 research plane,¹⁵ and researchers suspected that the F-100A's problems stemmed from the same cause. North American, in fact, had the same thought and was considering a larger tail design as a possible fix. The Air Force and NACA got North American to reduce production time on its new tail design from 90 to a mere 9 days, and Dryden began an intensive flight research program defining the F-100A's roll coupling problem and evaluating the impact of various modifications, including the larger tail. The program was considered such a high priority that it even eclipsed the X-plane research Dryden was conducting at the time.

The F-100A was not a docile aircraft, and on the very first research flight at Dryden, pilot Scott Crossfield was faced with an emergency landing after an engine-fire warning. North American's pilots considered an unpowered, or “deadstick,” landing in the fighter extremely risky because of its high landing speed and poor glide performance. Nevertheless, Crossfield elected to try to land the airplane and executed an almost flawless approach and landing on the Rogers lakebed—a tribute to his excellent pilot skills. That might have been the end of it, but, his confidence buoyed by the landing, Crossfield decided to try to top it by gliding off the lakebed and coasting to a precision stop in front of the NACA hangar on the ramp. Unfortunately for Crossfield, he didn't realize that he had already used up the aircraft's emergency braking power. He coasted off the lakebed, up the ramp and then, unable to stop, continued right through the open doors of the NACA hangar. He managed to miss the X-

planes parked inside but ran the nose of the F-100A through the side wall of the hangar, causing at least as much damage to his pride as he did to the airplane.

Following that incident, however, the research effort proceeded without a hitch and was very successful. The flights showed that inertial coupling was, indeed, the cause of the F-100A's difficulties, and that a larger tail and slightly extended wing span would alleviate the problem. North American made the modifications, and the F-100 "Super Sabre" became one of the country's lead fighters in the 1950s.

The next military aircraft development program Dryden supported was the Lockheed F-104 "Starfighter." Dryden initially requested and received a pre-production model of the Mach 2 fighter for its own research efforts on phenomena such as roll coupling and pitch-up.



But Lockheed was having numerous problems with its basic F-104 flight test program and at one point found itself without a single instrumented Starfighter. Dryden's prototype YF-104A was the only remaining instrumented aircraft, and Lockheed asked the Center to return it. Instead, Dryden suggested that it

Orbital Sciences Corporation's Pegasus booster under the wing of a B-52 at night (mid-1994). NASA's B-52 launched this standard Air-Launched Space Booster on its fifth and sixth missions on 19 May and 3 August 1994. On both occasions Pegasus carried Department of Defense satellites into orbit. The 3 August mission was the last Pegasus launch from the B-52. (NASA Photo EC94 42690-7)



F-15 Remotely Piloted Research Vehicle mounted under NASA's B-52 in preparation for flight testing of the 3/8 scale model of the "Eagle" fighter to test the spin characteristics of the design before committing to a piloted test program in a full-scale F-15. (NASA Photo ECN 3804)

F-14s in formation above Rogers Dry Lakebed testing a new control law to improve the aircraft's spin response, 1982 (NASA Photo 20325)



complete the F-104 testing for Lockheed, using Dryden research pilots and instrumentation. Lockheed and the Air Force agreed, and Dryden conducted a series of flight tests for Lockheed

As NASA's focus turned to space flight in the 1960s, the agency became less involved in production aircraft development programs, but Dryden did help iron out problems with

F-104 (tail number 826), F/A-18 (tail number 841) and T-38 chase aircraft (tail number 821). Through the years, Dryden has used a variety of chase and support aircraft, including all three of these. This particular formation flew in March 1990 on the 30th anniversary of research pilot Bill Dana's first flight in an F-104, with Bill again in the cockpit of that aircraft, Gordon Fullerton in the T-38, and Jim Smolka in the F/A-18. First acquired in August 1956, F-104s were the most versatile workhorses in Dryden's stable of research and support aircraft, with 11 of them flying mostly research missions over the next 38 years. Tail number 826 flew the last of these missions on 31 January 1994. By then the 11 F-104s had accumulated over 18,000 flights at Dryden in a great variety of missions ranging from basic research to airborne simulation and service as an aerodynamic testbed. (NASA Photo EC90 128-5)



over a nine month period of time in 1957. As a result of the cooperative flight tests, Lockheed built mechanical aileron limits into the plane, installed a yaw damper, and added several operational cautions into the pilots' operating handbook. The sleek and fast F-104 with its razor-thin wings still commanded respect from pilots who flew it, but the changes made as a result of the flight testing at Dryden helped it become a highly successful Air Force fighter.

General Dynamics' F-111 fighter. The early F-111As were plagued with engine problems, and Dryden conducted a series of research flights to analyze the fighter's engine inlet dynamics. Eventually, the combined efforts of Dryden, the Air Force, and General Dynamics led to a redesign of the F-111 engine inlet, which corrected the problem. Later on, Dryden provided additional assistance to the F-111 program by drop testing the parachute system for the F-111's crew escape pod, using the Center's B-52 launch vehicle. Four different series of research experiments from 1977 to 1995 worked toward both extending the life of the parachutes and investigating ways to decrease the velocity at which the cockpit pod hit the ground.¹⁶

In the early 1980s, Dryden's assistance was sought again after the Navy lost several Grumman F-14 "Tomcat" fighters in spin incidents. The aircraft was having engine difficulties at high angles of attack, and if one engine stalled or flamed out, the asymmetric thrust from the remaining engine had a tendency to send the plane into a spin. The Tomcat had a flat spin mode that was proving very difficult to recover from and had resulted in the loss of several aircraft and crews. The Navy asked Grumman to look into the problem, and Grumman enlisted NASA's help in developing a solution. Working with Grumman, engineers at Dryden and Langley came up with a new control law that they thought might help the F-14's spin response. The new control law was then tested extensively in simulators before it was gingerly explored in flight with an F-14 loaned to Dryden for the research.

The flight research showed that the new control law did, in fact, make a significant improvement in the controllability of the F-14 in spins. Yet by the time the research was completed, Navy priorities had apparently changed and the control law was not implemented in fleet F-14s. The F-14 spin research program illustrated why technology transfer can be such a complex and sometimes difficult process, even if the technology itself is valid. Nevertheless, the concept had been proven. And although the control law was not incorporated into fleet aircraft at the time, it may be retrofitted into F-14D model fighters.¹⁷

Over the years, Dryden was also involved in several research efforts with production aircraft that did not stem from any particular problems, but served instead to provide additional information on a specific aircraft or type of design. In the early 1950s, for example,

Dryden obtained a B-47 bomber and used it to gather useful information on the dynamics and characteristics of a large, flexible swept-wing aircraft. That data, in turn, helped engineers design future swept-wing aircraft, including the Boeing KC-135 and B-707 transport and every other swept-wing Boeing aircraft that followed.

Then in 1973, Dryden began flight testing three remotely piloted 3/8 scale models of the F-15 "Eagle" fighter that was being developed by McDonnell Douglas and the Air Force. Program managers wanted to test the spin characteristics of the design on a scale model before committing to a piloted test program, and Dryden had both experience in remotely piloted vehicles (RPVs) and a B-52 aircraft capable of launching such a model. The F-15 RPV flights were successful, and the results gave McDonnell Douglas and the Air Force the confidence they needed to go ahead with a spin test program on a full-scale, piloted F-15.¹⁸

Dryden's work with production aircraft programs has never been the primary focus of its research. But the Center was well suited for this kind of support work. For one thing, the daily requirements of keeping research aircraft flying meant that Dryden's staff was already very experienced in trouble-shooting aircraft and coming up with practical test methods and solutions. But these efforts also benefited greatly from the "technical agility" of Dryden's staff. Support projects tended to materialize suddenly when an aircraft program ran into trouble, requiring quick action and quick answers. Dryden was able to support these various efforts, on short time frames, because its management and staff were accustomed to juggling different programs and switching gears and priorities quickly.

Aviation Safety

In addition to supporting various military aircraft design programs, Dryden also provided support to national civil aviation efforts, especially in the area of safety. The Center's focus on high-speed flight meant that it was less involved in civil aviation research than other NASA centers, since civil aircraft tended to have lower performance than military designs. But in 1957-1958, Dryden was asked to conduct a series of research flights for what was then the Civil Aeronautics Administration (absorbed into the Federal Aviation Administration during 1958). Boeing was getting ready to introduce its first jet airliner, the B-707, and the CAA needed to establish new approach procedure guidelines on cloud-ceiling and visibility minimums for the new generation of jet transports. Using the military KC-135 variant of the 707, Dryden pilots conducted a series of flights that gave the CAA the data it needed to develop safe instrument guidelines and approach procedures.¹⁹

In the 1960s, the aviation community became concerned about an increasing number of accidents among general aviation (GA) aircraft. In an effort to see whether there were any common design weaknesses or problems in GA airplanes, Dryden was asked to investigate the handling characteristics of several different designs throughout their flight envelopes. In the end, Dryden pilots surveyed a total of seven different GA aircraft in order to include a cross-section of aircraft types in the study. The results showed that there was no single weakness or design problem and the designs were generally adequate, although the criteria for handling qualities in small aircraft had not kept pace with

advances in aircraft technology. The point of the research was not to point out design flaws in particular models, but the research did produce the side-benefit of uncovering several problems with individual aircraft designs. One aircraft, for example, developed a serious flutter in its horizontal stabilizer while still within its normal operating limitations. And the poor stall-spin performance of another twin-engine model led its manufacturer to modify the design with contra-rotating propellers.²⁰

The introduction of jumbo jets in the late 1960s and early 1970s led to a new area of concern in aviation safety—wake vortices. Wingtip, or wake, vortices are very powerful tornado-like disturbances in the air coming off the wingtips of an airplane that trail behind the aircraft. The bigger and heavier the airplane, the more powerful these disturbances are, and a small plane trailing too closely behind a larger one can easily be flipped upside down by these powerful vortices at the edges of the larger aircraft's wake. Wingtip vortices are a particularly dangerous hazard during approaches or departures from airports since trailing aircraft have little altitude in which to recover. So when jumbo jets began mixing with smaller aircraft at airports, the aviation community began looking for more detailed information on the behavior and strength of wake disturbances from large aircraft.

In late 1969, Dryden pilots began investigating wake vortices by flying an instrumented F-104 fighter behind a B-52 bomber and C-5 transport. The C-5's vortices were so strong that on one flight, they caused the F-104 to roll inverted and lose 3,000-4,000 feet of altitude, even though the fighter was flying 10 miles behind the larger airplane. In 1973, Dryden expanded its wake vortex research to



include a Boeing 727. The following year, Dryden got approval to use NASA's 747 Shuttle Carrier Aircraft for some additional wake-vortex research before the jumbo jet was modified for Shuttle use. Following a trail left by wingtip smoke generators installed on the 747, research pilots flew a Learjet business plane and a T-37 Air Force jet trainer through the 747's vortices to measure their forces and effects. After the 747's wake caused the T-37 to perform two unplanned snap rolls and develop a roll rate of 200 degrees per second despite trailing the jetliner by more than three miles, one research pilot speculated that a safe separation between the two aircraft in a landing configuration would have to be three times that distance.

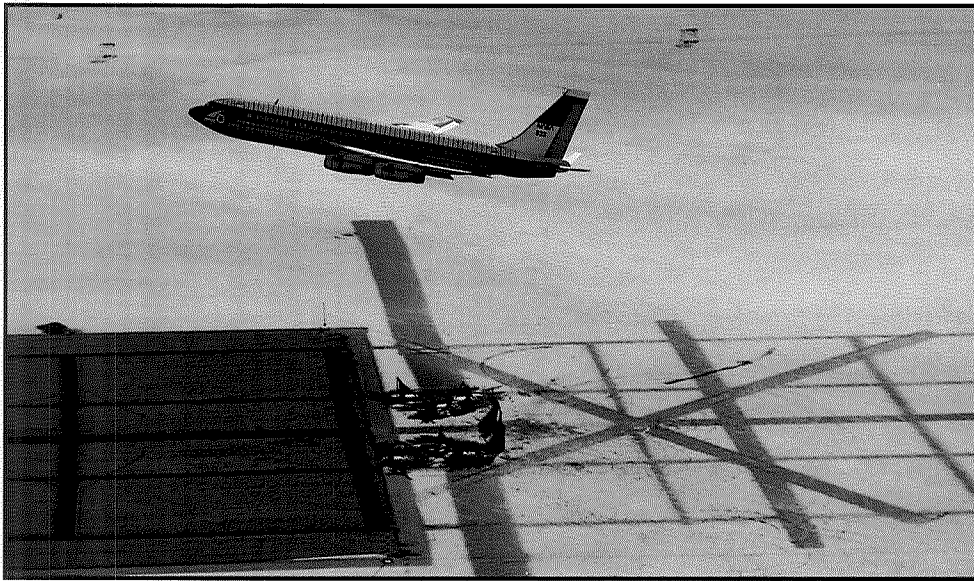
As more jumbo jets entered service, Dryden expanded the research to examine the wake vortices of Lockheed's L-1011 and McDonnell Douglas' DC-10 as well. Follow-on flights also looked at how use of wing flaps, speed brakes or spoilers might affect the formation and behavior of wing vortices. Although the results indicated that use of wing devices could help reduce the severity of the vortices, researchers were unable to find a configuration

that was practical. For example, certain flap combinations reduced wingtip vortices, but only if the gear remained retracted. The wake-vortex flight research conducted at Dryden did, however, play a central role in helping the FAA establish safe separation minimums for airline traffic at airports across the country.²¹

In 1984, the FAA once again teamed up with Dryden to conduct another research project concerned with flight safety. The FAA was evaluating an anti-misting jet-fuel additive that seemed capable, at least in laboratory testing, of preventing fuel fires in airplane crashes. The concept seemed so promising, in fact, that the FAA was preparing to publish a Notice of Proposed Rule Making (NPRM) as a first step toward requiring the additive in certain types of jet aircraft. Before proceeding with the NPRM, however, the agency wanted to test the additive in a real airplane crash. Dryden's desolate surroundings and the staff's experience in remotely piloted vehicle research made it a logical support resource for the test. Dryden engineers rigged up an old Boeing 720 jetliner with remote controls, fueled it with the anti-misting fuel, and guided it to a controlled crash landing on the lakebed. Iron posts had been set

Above Left: Remotely piloted Boeing 720 Controlled Impact Demonstration aircraft following impact with iron posts (cutters) implanted in the lakebed to pierce the fuel tanks and test an anti-misting fuel for its ability to prevent fuel fires during airplane crashes (NASA Photo EC84 31806)

Above Right: Remotely piloted Boeing 720 Controlled Impact Demonstration aircraft burning after failure of anti-misting fuel to prevent a fire in a simulated post-crash situation (NASA Photo EC84 31809)



Boeing 720 Controlled Impact Demonstration aircraft flying above cutters (iron posts) on lakebed, showing the setting for the demonstration portrayed in the photos on the preceding page (NASA Photo EC84 31672-12)

up on the lakebed to ensure that the fuel tanks would be ripped open upon impact, since that was the scenario most likely to result in a post-crash fire. The experiment was called the Controlled Impact Demonstration (CID), and the FAA expected that it would be a relatively tame event.

The expectations were wrong. In one of the Center's most dramatic moments of discovery, the remotely piloted 720 settled gently onto the desert floor . . . and exploded into a staggering fiery inferno. Needless to say, plans to require the fuel additive were discontinued, and from that point forth, Dryden researchers informally referred to the CID experiment as the "Crash In the Desert." Nevertheless, the experiment was a very strong illustration of why flight research is such an important element in technology development. The fuel additive worked well in laboratory testing. But in the real world environment of an airplane crash, it was clearly a failure.²²

Conclusion

Throughout its history, Dryden's unique resources, organizational style and single

mission focus have enabled it to play a key role not only in exploratory research but also in a wide variety of other government and industry aerospace efforts. The Center's open sky and lakebed landing sites provided a safe location for projects such as testing and landing the Space Shuttle or testing a new fuel additive in an actual crash situation. Its unique B-52 research aircraft allowed NASA to test a new drag chute for the Shuttle and provided a launch vehicle for everything from scale model aircraft and parachute systems to a low-cost method for putting payloads into space. Its ongoing research partnerships with military and industry put the Center in a position to help aircraft development programs when they ran into trouble.

But the driving force behind the success of Dryden's many support efforts was the attitude and experience of its staff members. They didn't do the wind tunnel testing or in-depth theoretical analysis that researchers at other centers did, but they had an unparalleled level of experience in flight research. They could figure out how to rig a jetliner to be flown by remote control, or how to design a free-flying lunar landing simulator. They could design a flight research program to safely investigate aircraft characteristics that had killed other pilots. And they had the enthusiasm and creativity to pursue these projects with success. The employees at Dryden prided themselves on their ability to trouble-shoot aircraft and find quick solutions to operational problems. So whether the problem was a dangerous pilot-induced oscillation in the Space Shuttle, a need to train astronauts to land on the Moon, or a flawed aircraft design that was costing pilots' lives, it was the kind of work at which Dryden excelled.

Still, the Center staff could not have taken on so many unscheduled support efforts in addition to its exploratory research without a management environment that stressed flexibility. Staff members were already used to juggling several research projects at once, and the daily operational philosophy at the Center might have been summarized as “all plans subject to change.” It was simply a fact of life at a flight research center where mechanical problems, weather, and other factors could always force last-minute changes in schedules and priorities. But Dryden’s flexible, innovative management style created a kind of “technical agility” that allowed the Center to support a surprisingly wide variety of other government and industry efforts even as it continued its exploratory research.


Dryden’s research in support of other programs was not always as glamorous as its work on the frontiers of science and flight, but

those support efforts had direct, real-life consequences. The Center’s work with the F-89, F-100A, F-104 and F-111 helped save pilots’ lives and helped turn the designs into successful fighter aircraft. The Lunar Landing Research Vehicle gave Neil Armstrong the confidence he needed to land the Lunar Module manually on the Moon’s surface. The Center’s PIO flight research and suppression filter design solved a potentially dangerous problem with the Space Shuttle, and the landing systems research with the Convair 990 might save future astronauts’ lives in an emergency situation. And Dryden’s wake vortex research helped national efforts to maintain the safety of civil aviation. Testing tires or thermal tiles for the Space Shuttle might not be as exciting as flying an X-15 to the outer reaches of the atmosphere, but those efforts, and the many support projects like them, were every bit as important.

F-15 Advanced Controls for Integrated Vehicles (ACTIVE) research aircraft in flight over Edwards in March 1996. The Pratt & Whitney nozzles can turn up to 20 degrees in any direction and enable the aircraft to use thrust control in place of conventional aerodynamic controls, thereby reducing drag and increasing fuel economy or range.
(NASA Photo EC96 434585-13)





A photograph showing the rear section of a line of white NASA aircraft. The focus is on the vertical stabilizers (tails) of the planes, which are arranged in a receding line from left to right. Each tail is marked with the word "NASA" in large, bold, black letters, and a smaller identification number below it. The sky is a clear, bright blue. The aircraft in the foreground is partially obscured by a dark, curved structure, possibly a wing or a part of a support structure.

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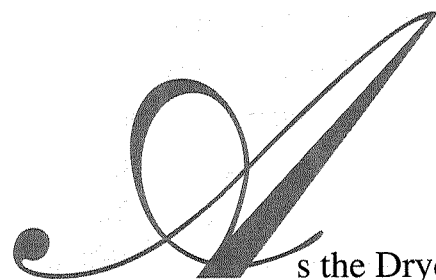
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► Chapter Six

Future Directions



As the Dryden Flight Research Center begins its second 50 years, it faces a very different world than the one the original X-1 team knew. Advances in technology have revolutionized Americans' daily lives and changed our view of what is possible in fields ranging from data processing and communication to transportation, aircraft design, and space flight. We have moved from an essentially manual, manufacturing-based society into the automated information age where personal computers, satellite communications and the information superhighway have become an integral part of individual, business and government transactions. From a time when space flight was a science-fiction fantasy and the speed of sound seemed an impenetrable barrier, we have moved into an era where the Space Shuttle flies regularly to and from space and aircraft reach speeds of Mach 2 and beyond.

*F/A-18 vertical tails.
These aircraft serve as
chase planes for
Dryden's research
airplanes
(NASA Photo
EC96 43505-9)*



*F/A-18 High Angle-of-Attack Research Vehicle, X-29, F-15 Highly Integrated Digital Electronic Control aircraft, single-seat F-16XL, three F/A-18s in a row with the middle one being the F-18 Systems Research Aircraft, Pegasus in front of B-52 mothership, T-38, F-104, B-52, SR-71, 747 Shuttle Carrier Aircraft, with Dryden Flight Research Center facilities in the background.
(NASA Photo EC90 280-1)*

Yet along with the vastly expanded capabilities of today's world have come new concerns, issues and priorities. The price of fuel has risen sharply, making fuel efficiency a much higher priority for both end users of aircraft and national policy-makers. There is much more concern about protecting the environment and atmosphere. Advances in technology and changes in warfare have created tougher demands on military aircraft, requiring designs that are radar-resistant and maneuverable, for example, as well as fast. An increasingly global economy and improved technology bases in other countries have helped shake the United States' unquestioned position as the world's technological and economic leader and have contributed to an unfavorable balance of trade. Consequently, while international partnerships are on the rise, the issue remains of

how to cooperate without giving away critical U.S. technology. Furthermore, while new aerospace technology has greatly expanded capabilities, its cost and complexity make it even riskier for industry to research or apply. This inherently makes government involvement in technology development more important. But the United States government also faces budget difficulties, leaving less funding available for federal research and development work.

What all of this means for Dryden is simply that for all the technological progress made since that first small group of engineers arrived in the desert in 1946, the challenges the Center faces are no less demanding. Technology has become more capable, but the problems have become more complex. Even as new technology has overcome existing obstacles, it has opened doors onto whole new sets of

questions or problems. Computerized flight-control systems, for example, have made highly unusual aircraft such as the highly unstable X-29 and the thrust-vectoring X-31 possible. But that same technology has created new problems and has greatly increased the system complexity of aircraft. As a result, there are more opportunities to overlook something, and software configuration control is now as flight-critical an element as the spar in an aircraft's wing.

In 1946, the X-1 was designed to tackle the issues and problems with basic transonic/supersonic flight. Today, research aircraft are trying to meet more complex challenges. Supersonic speed itself is no longer the cutting edge of possibility. But achieving supersonic laminar flow, integrated flight and engine control operations, or thrust-vectoring maneuvering at supersonic speeds still is. And the requirements

and restrictions of a changing world demand that we continue to operate at that cutting edge. Our spacecraft must create less waste and pollution and deliver payloads into space more cost-effectively. In addition to flying high and fast, today's aircraft must also operate more economically and without damaging the environment. Indeed, we need to find a way to learn more about changes and damage to the atmosphere itself. We have made great progress, but the goalposts are continually moving outward as our world changes and we expand our knowledge base and technical ability.

A 1976 NASA report noted that "how to meet international competition with improved performance and better economics and still provide increased environmental protection and greater safety is a task requiring the best efforts of government and industry."¹ That statement

*Flow-visualization smoke marks strong vortex flows along the leading edge extension (LEX) of the NASA F/A-18 High Angle-of-Attack Research Vehicle during tests of the white LEX fences located close to the fuselage, ahead of the wing. The LEX fences caused the vortices to burst and lose energy, reducing the structural loads on the rudders and increasing the life of the airframe. This modification has been added to Dryden's F/A-18 fleet as well as to F/A-18s in military service.
(NASA Photo EC89 0096 149)*



was true then, and it is even more true today. The challenges have changed; the problems are more complex. But the role and importance of Dryden are the same today as they were in 1946. With its many government and industry partners, Dryden is still working at the boundary between the known and the un-

known, trying to learn enough and push technology enough to allow the country to meet the challenges not only of the present but also of the near and distant future.

Current Projects

Like many of the focused research programs throughout Dryden's history, the four major research efforts the Center is currently pursuing reflect some of the nation's present-day aerospace priorities. Interestingly enough, some of them also incorporate ideas that date back as far as the Wright brothers but are being revisited as new technologies and/or mission needs have developed to support their use.

One of the major efforts underway at Dryden is, once again, a high speed research (HSR) program, focused primarily on supporting the High Speed Civil Transport (HSCT). Dryden had supported supersonic transport research in the 1960s, but the HSCT has more challenging requirements for fuel-efficiency and low environmental impact. So Dryden's current HSR efforts include projects such as the



F/A-18 High Angle-of-Attack Research Vehicle showing the results of releasing a glycol-based liquid dye from very small holes around the nose of the aircraft during flight at about 30 degrees angle of attack. The airflow pattern revealed by the lines on the fuselage and wing helped researchers from Dryden, Ames and Langley research centers to visualize what was happening in flight and to compare forebody flows with predictions obtained from wind-tunnel testing and computational fluid dynamics simulations. (NASA Photo EC88 0115-79)

F-16XL supersonic laminar-flow research—a technology that could help make a supersonic aircraft efficient enough to be economically viable. The need for the HSCT to be environmentally sensitive has also prompted new research into the characteristics of sonic booms, using its SR-71 Blackbird aircraft.

The increasing concern about damage to the environment and the atmosphere is behind the Environmental Research Aircraft and Sensor Technology (ERAST) program at Dryden as well. The ERAST research is trying to develop high-altitude, low-speed, remotely-piloted aircraft that could be used to gather currently unavailable information about the atmosphere. And remotely-piloted research vehicles are likely to play a larger role in future research efforts.²

The changing requirements of military aircraft are driving other Dryden research efforts in the area of high-performance aircraft operation. The F-15 ACTIVE research, for example, is working toward a practical application of thrust-vectoring technology, which has the potential of making aircraft much more

F-16XL (foreground) and SR-71 in formation during 1995, when this single-seat F-16XL and the SR-71 were studying the characteristics of sonic booms. This project was part of NASA's High Speed Research program dedicated to developing technologies for a new generation of economically viable and environmentally compatible high-speed civilian transports.

(NASA Photo EC95 43024-5)



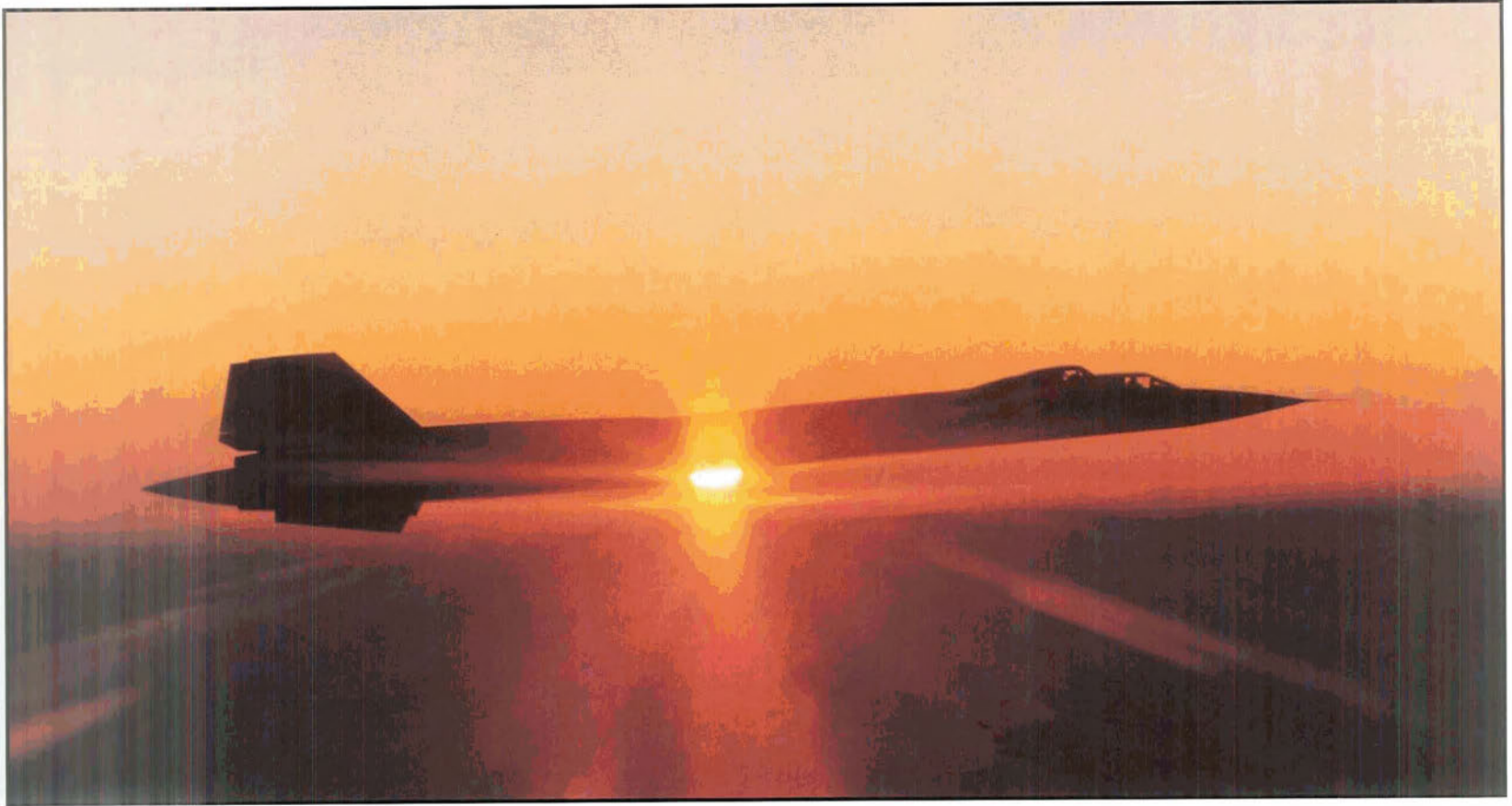
maneuverable.³ The Center's plans also include a joint effort with the Air Force's Wright Laboratory to pursue further research on tailless aircraft, which could improve the stealth capabilities and reduce the weight and drag of aircraft designs. In addition, Dryden and the Wright Laboratory are working together on an advanced flexible-wing project. The flexible-wing research plans to use aeroelastic, or twisting, properties of a wing to help control an aircraft, reducing the drag and structural weight of the wing and thereby increasing the aircraft's overall efficiency and performance. This project is especially interesting because the basic concept behind the research is similar to the wing warping approach used by Orville and Wilbur Wright to control their pioneering Wright Flyer back in 1903.⁴ Some of these projects are still in the planning stages, but the common thread running through all of them is that they focus on technology to meet the expanded maneuverability and stealth requirements of high-performance military aircraft designs.

The fourth current research thrust at Dryden is being driven by the need to find more

cost-effective methods of getting payloads into space. Historically, the cost and complexity of launch systems have kept industry from attempting its own launch infrastructure and/or operations. But decreasing federal budgets mean that NASA itself needs to find more economical ways of accessing

space. Whether the operations are managed by NASA or industry, they must be made more affordable. In 1993, a NASA study initiated by Congress concluded that advances in technology could make a fully reusable launch vehicle practical in the near future. This kind of vehicle might be cost-effective enough that industry could afford to build and operate it, relieving the burden on NASA. In order for industry to commit the significant resources necessary for this kind of venture, however, the report also concluded that numerous relevant technologies needed to be matured and demonstrated. Thus was born the Reusable Launch Vehicle (RLV) technology program, which includes several different research efforts that Dryden is supporting.⁵

The primary thrust of the RLV program is the X-33—a technology demonstration craft designed to answer the question of whether the technology exists to make a rocket-powered, single-stage-to-orbit (SSTO) vehicle a viable, profitable concept. It is a question that encompasses a multitude of challenges. First, there are the obstacles inherent in the actual physics of a



single-stage-to-orbit vehicle. It has never been done before, and researchers estimate that only one percent of a SSTO vehicle's gross liftoff weight could be devoted to its payload. The rest of its weight would be taken up by the structure and propellant necessary to get it into orbit. But even if those challenges are met, there is still the question of whether the vehicle can be built and operated cost-effectively enough to make it a viable economic proposition.

The X-33 effort began in April 1995 with a 15-month concept definition and design phase. Three industry teams—Lockheed-Martin, McDonnell Douglas/Boeing, and Rockwell/Northrop-Grumman—have developed different concepts for an X-33 vehicle. Lockheed-Martin's design is a vertical-takeoff/horizontal-landing lifting body; McDonnell Douglas/Boeing pursued a vertical-takeoff and vertical-landing vehicle; and Rockwell/Northrop-Grumman designed a vertical-takeoff/

horizontal-landing winged craft that, not surprisingly, bears some resemblance to Rockwell's Space Shuttle orbiters. Dryden provided support for each of the design teams, including its scheduled flight tests of the linear aerospike engine for Lockheed's proposed design.⁶ NASA planned to recommend one of the designs to Congress in June 1996, leading to the actual construction and test flying of an X-33 vehicle. The X-33 would not be put into actual orbit, but it would be flown to an altitude that would expose the critical technologies to the environment necessary to evaluate their acceptability.⁷

The X-33 is designed primarily to mature and demonstrate the technology necessary for commercial RLVs that would follow. Future research efforts also may explore other reusable launch vehicle options, such as plane-launched systems similar to the Pegasus concept and designed for small payloads. In addi-

SR-71B Blackbird at sunset during early 1995 (NASA Photo EC95 43351-2)

Single-seat F-16XL known as "ship number one" during 1992 when the aircraft was equipped with an active experimental wing section designed to promote laminar (smooth) airflow over a larger proportion of the wing than occurred naturally. Tests with this aircraft during 1991-1992 showed that laminar flow was achievable over a significant portion of the wing during supersonic flight. A more extensive "glove" for active laminar flow research continued this effort on a two-seat F-16XL during 1995 and 1996. (NASA Photo EC92 09032-2)

tion, Dryden is supporting a Johnson Space Center program that is investigating one potential payload for an X-33 type of RLV. The research craft is called the X-CRV, or Experimental Crew Return Vehicle, and it is, interestingly enough, a legacy of the

lifting-body and Paresev research conducted at Dryden in the 1960s and early 1970s. The X-CRV design is based on the Martin X-24A lifting body, and it is envisioned as a means for getting crew members back to Earth from a space station in case of an emergency. The lifting-body shape would enable the vehicle to fly back from space and control its general touchdown location. But to allow the emergency vehicle to land without a trained pilot on board, the X-CRV is being designed to use a parafoil device, deployed under Mach 1 speeds, for its final descent and touchdown.

In December 1995 Dryden began drop tests of a scale-model X-CRV from a small airplane, and plans called for the Center to eventually flight test a vehicle from Mach 0.8 at 40,000 feet down through landing. Yet some would argue that Dryden's largest contribution to the effort was made more than 30 years ago, when a small group of engineers and technicians built a stubby plywood-and-tubing craft they dubbed the "flying bathtub." If it had not been for that M2-F1 effort, which led to



Dryden's extensive lifting-body research, the X-CRV design would probably not be a lifting body shape. The X-CRV design choice was undoubtedly also influenced by yet another 1960s military research project called the X-23, or "Prime" program. In that classified program, a model shaped much like the

X-24A lifting body was launched into space and brought back, accumulating actual reentry data that is now proving extremely useful to X-CRV engineers.⁸

Future Directions

In the same way as the X-1 reflected the "need-for-speed" philosophy that dominated post-World War II defense strategies, the current Dryden research efforts reflect the concerns of the more complex, computerized, cost- and environment-sensitive society in which we now live. Of course, these planned research projects will undoubtedly be supplemented with other support or problem-solving efforts that develop as new problems or high-priority needs arise. They will also continue to change as the needs and concerns of the nation evolve in the years to come.

Exactly how Dryden's research will change remains to be seen. Trying to predict specifics about the future is always a risky proposition, but it is especially so with a place

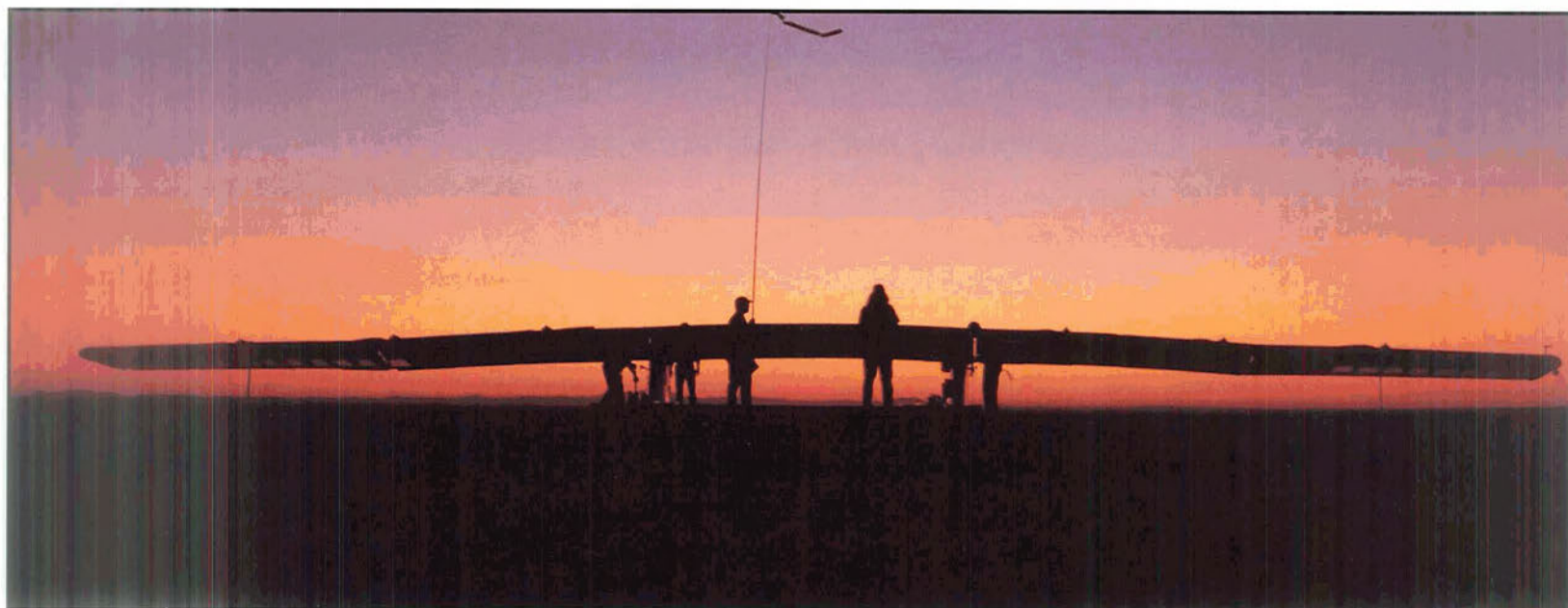
like Dryden, where projects arise quickly in response to unforeseen needs and one technological breakthrough can make a dramatic impact on future research directions. One year before the F-8 Digital-Fly-By-Wire research airplane flew at Dryden, for example, few at the center would have predicted the amount of effort that would be devoted to computerized flight control systems over the next 10 years. By the same token, one external change, such as a dramatic increase in fuel prices, could also significantly affect the priorities attached to different research projects.

Yet if current trends are any predictor, there are certain general characteristics that seem likely to define Dryden's research in at least the near future. An increasingly global economy may strengthen the need for high-speed global transportation, fueling research efforts such as the High Speed Civil Transport. Many of the changes in aircraft design will be internal system improvements, but advanced technology may also generate more interest in configurations that were previously impossible to design or support. The need for more cost-

effective access to space will undoubtedly continue. Indeed, decreasing budgets will create an ongoing challenge to do the same work with fewer people and with less money.

Budget constraints have already resulted in an increased emphasis on joint partnerships, as illustrated by the recent Air Force Flight Test Center Alliance agreement with Dryden. Partnership efforts have always played a big part in the Center's work, but those agreements will undoubtedly become even more important if federal budgets continue to decrease and NASA has to rely more on industry funds and participation to make research projects possible. The current trend of downsizing military budgets will also tend to focus more research on civil applications of technology, including subsonic transport aircraft operations. Interest in learning more about our atmosphere and the impact our actions have on it means that efforts in high-altitude, low-speed sampling aircraft and technology are likely to continue. Finally, researchers will undoubtedly continue to find themselves revisiting old concepts and configurations, drawing on

Pathfinder silhouette at sunrise in 1995. This unpiloted, remotely-controlled aircraft that uses the Sun's energy to power its engines, reached the record altitude for a solar-powered aircraft of 50,567 feet during a 12-hour flight on 11 September 1995. The all-wing aircraft, weighing less than 600 pounds, is being evaluated by a NASA-industry alliance in a program to develop technologies for operating unpiloted aircraft at altitudes up to 100,000 feet on environmental sampling missions lasting up to a week or more. The effort is labeled the Environmental Research Aircraft and Sensor Technology (ERAST) program and is part of NASA's mission to study and protect the environment. (NASA Photo EC95 43207-6)





Team from Aerovironment, Inc. getting Pathfinder ready for flight from the lakebed in September 1995 (NASA Photo ES95 43373-17)

the legacy of past research efforts. One of the oldest lessons of research is that sometimes ideas have to wait for technology to catch up with them. Concepts once discarded as unsupported or unnecessary may become both possible and practical as technology and mission needs change.⁹

The Role of Flight Research

Yet regardless of how the specific research directions at Dryden change in the years to come, one thing that will not change is the importance of flight research itself. In some cases, such as atmospheric research, flight is the only way to obtain any data. But the value of flight research goes far beyond those few instances. What Wilbur Wright said in 1901

still holds true. To really learn about flight requires mounting a machine and experiencing its behavior in actual trial.¹⁰ The reasons for this are many, and they have been proven over and over by the people who have worked at Dryden over the years.

It is often said at Dryden that there are no secrets in flight research. On one level, that means that members of a flight research project learn to speak frankly, because overlooked items or mistakes can cost

someone's life. But it also helps explain the value of testing an idea in flight. The consequences and results of flight research are real, tangible, and inescapable. It is a place where new technology faces a moment of truth, where theory and reality meet face to face. It is also by necessity a multidisciplinary effort that allows all the elements of a technology or system to come together in a real world environment. Individually, or in a simulated situation, elements of the technology may appear to work. But as research efforts at Dryden have repeatedly demonstrated over the years, laboratory predictions and real-life performance are not always the same. This is especially true when one of the elements in the loop is a human being. Pilots do not react the same in a simulator as they do in an actual flight situation, where



the consequences and stresses are significantly higher.

In addition, computers and simulators can only model what is known. Yet to advance technology we have to stretch into the unknown, and the only way to truly explore beyond a frontier is to actually go there. This was true in the days of Magellan, and it is still true today. In order to know what lies beyond our current aeronautical knowledge; in order to tell if our predictions of what lies beyond are accurate, we need to test our theories, at some point, in the real world. Indeed, there have been few, if any, research projects in Dryden's 50-year history where prediction and actual performance have matched in every aspect. Every effort has had at least one moment of discovery, where researchers found themselves surprised by their results.

Furthermore, as Hugh L. Dryden himself once said, flight research separates the real from the imagined. Applying concepts to actual flight hardware, as opposed to laboratory computers or simulators, quickly brings to the surface the critical issues and obstacles that

have to be tackled in order for a technology to succeed in a real-life environment. Making the decision to remove the mechanical backup controls on the F-8 Digital-Fly-By-Wire, for example, made it instantly clear to researchers that software integrity and configuration control, more than any other issue they might have pursued in simulators, was the crucial issue for that technology. And because flight research forces the resolution of critical technological issues, it unavoidably matures technology beyond the level achieved by simulation or laboratory work. This has important implications for technology transfer, because often there is too large a gap between basic laboratory research and a practical application of a technology for industry to bridge. The risks or costs of maturing the concept without the intermediary step of flight research are often simply too high.

By the same token, proving a technology in actual flight conditions helps give it a level of credibility that is equally important in getting industry to commit to its commercial development. Whether the concept is a fly-by-

Group photo at edge of lakebed showing (viewer's left to right) a full-scale X-15 mock-up, two-seat F/A-18, SR-71, X-31, and X-29 (NASA Photo EC93 41012-3)

wire control system or a new wing design, the barriers to transferring the technology are as much psychological and financial as they are technical. Flight research is an extraordinarily effective method of overcoming those barriers, and sometimes a single flight can change what people believe is possible. Furthermore, the government/industry partnerships required by a research discipline that involves actual hardware generate relationships and experience that can significantly affect a company's decision to apply a given technology. Flight research is one of the only types of research where a degree of technology transfer can occur simultaneously with the research itself.

These technology-transfer considerations will only become more important as global competition increases. For many years, the United States held an undisputed position as the technological and economic leader of the world. Today, advances in the technology bases

and products of other countries are beginning to change that picture. In 1986, the United States' high-technology imports exceeded exports for the first time. Aerospace is one of the only fields in which a positive balance remains, but even there, the edge held by American manufacturers is slipping.¹¹ What this picture looks like in 20 years will be determined in large part by how well American aerospace products can measure up against the technology offered by international competitors. And that, in turn, will be influenced both by near-term applications of technology and longer-term contributions to the nation's technology base to support future-generation aircraft designs.

A Unique Flight Research Resource

Despite the advances in computers and aeronautical research facilities since 1901, flight research is, and will remain, a crucial

Side-view of the Linear Aerospike SR-71 Experiment (LASRE) pod on NASA SR-71, tail number 844. This photo was taken during the fit-check of the pod on 15 February 1996, at Lockheed Martin's Skunkworks in Palmdale, California. The LASRE will be flight tested during 1996 at Dryden. LASRE is designed to flight test the linear aerospike rocket engine mounted on a 10-percent-scale, half-span model of Lockheed Martin's X-33 Reusable Launch Vehicle concept. Among other partners involved in the project are Rockwell's Rocketdyne Division, builder of the aerospike engine, the Marshall Space Flight Center, Dryden, the Air Force's Phillips Lab, and Lockheed Martin Astronautics. (NASA Photo EC96 43419-25)



element in the process of furthering aeronautical knowledge and technology. And when it comes to flight research, the Dryden Flight Research Center has few equals. Ever since its beginnings in 1946, Dryden has been a specialty shop. Walt Williams brought the first group of engineers from Langley to Muroc to assist not in the design or theoretical analysis of the X-1, but in its flight research activities. Since that time, the employees at Dryden have continued to provide that service for NASA, other government agencies, and industry. The ideas come from many places, and most of Dryden's research projects are partnership efforts of one kind or another. Yet for half a century, Dryden has been able to provide the physical environment, facilities, and staff expertise to take those ideas and research efforts to flight.

Part of the reason Dryden has flourished as a flight research center is its unique physical location. Its clear skies, unpopulated surroundings, and dry lakebed landing sites have made it ideally suited for a wide variety of flight activities, from research with the X-1 to landings of the Space Shuttle. It also has benefited immeasurably from its ongoing partnership with the Air Force Flight Test Center at Edwards. Aside from the specific joint-research projects the two Centers have done together, the physical facilities and support provided by the Air Force have always been critical to Dryden's operations.

But there are other factors that have played an equally important role in the Center's success. Dryden has always been a small, remote facility, requiring its staff to develop a frontier resourcefulness, flexibility and versatility that helped the Center adapt to NACA and NASA's changing needs and priorities over the years. Its small size also allowed an informal management style that encouraged innovation and helped empower individual employees to solve problems as they arose. These traits led to research efforts such as the M2-F1 lifting body and have played a role in the success of virtu-

ally every research project the Center has undertaken.

Dryden's focus on the single mission of flight research also allowed all its staff members to gain a great deal of experience in that area, and the daily requirements of a

Center revolving around flight operations meant that its employees soon developed a talent for quick, pragmatic problem-solving. Of course, it helped that most of the people drawn to Dryden inherently enjoyed that kind of work. One advantage of Dryden's remote and harsh location has been that the people who have come to work at the Center have come not for the surroundings or pay, but because they love flight and want to work with living, breathing airplanes. As a result, Dryden employees tend to have what one staff member described as a "technical passion"¹² that has played a significant role in the success of their research efforts.



HL-10 mounted on a pedestal in front of the Dryden main gate at sunset in 1992. This current landmark at the research center first flew in late 1966 and became the first lifting body to fly supersonically. It set other records, but more importantly, it contributed substantially to the decision to design the Space Shuttles without the air-breathing engines that would otherwise have been used for landings. (NASA Photo EC92 2131-01)



Space Shuttle Columbia atop NASA's 747 Shuttle Carrier Aircraft over Dryden as sister Shuttle Endeavour sits on the runway following its landing 11 October 1994, at the end of mission STS-68. Columbia was being ferried from the Kennedy Space Center, Florida, to Air Force Plant 42, Palmdale, California, for six months of inspections, modifications, and systems upgrade. (NASA Photo EC94 42789-5)

The fact that many employees chose to spend their careers at the Center also has enabled them to carry forward the experience gained from one project to the next.

Dryden Contributions

This combination of factors at Dryden has allowed it to make a wide variety of contributions over the years. Sometimes, the Center played a role in developing tangible items that were applied directly to operational air- or spacecraft. Certainly the Center's troubleshooting efforts with the F-100A, the F-104, the

F-111, and its later work with F-14 and F-15 spin-testing fall into this category. But there are other examples, as well. Reaction controls and navigation equipment used on the X-15 were applied to the Mercury, Gemini, and Apollo spacecraft, as well as the Space Shuttle. The Lunar Landing Research Vehicle trained astronauts to land on the Moon. The digital electronic engine-control technology has been applied to numerous commercial engines, and the F-15 ACTIVE program is helping to develop a production version of a thrust-vectoring engine nozzle. A thrust-vectoring engine system, in turn, will draw heavily on the integrated



X-29s on lakebed near sunrise with the Moon still visible. (Pitot tube of second aircraft at viewer's left.) Both of these forward-swept-wing aircraft were flown at Dryden from 1984 to 1992 as technology demonstrators to investigate a host of advanced concepts and technologies. These included advanced composite materials, the forward-swept wing, and a computerized fly-by-wire flight control system that overcame the aircraft's inherent instability. The 434 total missions flown by the two X-29s provided an engineering data base that is available in the design and development of future aircraft. (NASA Photo EC90 357-7)

engine- and flight-control research done with Dryden's F-15 HIDECA aircraft. The supercritical wing and winglet concepts flown at Dryden have helped make a whole generation of business and transport aircraft more fuel-efficient. Improvements for the YF-12 inlet system were retrofitted into the entire SR-71 fleet.

Dryden's pilot-induced-oscillation research and suppression filter identified and solved a potentially dangerous problem with the Space Shuttle. Its Controlled Impact Demonstration illustrated conclusively that anti-misting fuel did not help prevent post-crash fires, and its wake-vortex research helped maintain safety in the national airspace system. And while it has not yet been applied, the propulsion-controlled aircraft system developed by Dryden researchers may well be integrated into future airliners, helping to prevent tragedies resulting from massive hydraulic damage or

failures.

Not all of Dryden's contributions were tangible pieces of technology, however. Many research projects simply expanded the available knowledge base in aeronautics and, to a lesser degree, space. Much of the research with the YF-12/XB-70, the F-18 High Alpha Research Vehicle, the X-29, the HiMAT, and even the X-15 and the early X-series research aircraft fall into this category. Many engineers have drawn upon this knowledge and data in designing new aircraft, but the trail between the research and its applications is not as easy to trace. Indeed, one of the difficulties in evaluating flight research in an exact way is that contributions to knowledge are often so difficult to isolate or quantify.

In yet other cases, the "technology" transferred from Dryden to industry was not so much a particular item but a process. The software qualification and configuration control

process the Center used for its Digital-Fly-By-Wire program, for example, aided numerous manufacturers in designing their own fly-by-wire aircraft. More recently, the Cedars-Sinai Hospital was able to benefit from Dryden's quick and pragmatic design and fabrication procedures. Because unique parts often have to

lifting-body research at Dryden gave Shuttle managers the confidence to design the vehicle for unpowered landings. The system hardware and software on today's fly-by-wire aircraft are not the same as those flown on Dryden's F-8. But the mere fact that Dryden had flown an aircraft totally dependent on fly-by-wire flight



NASA's F-15 Highly Integrated Digital Electronic Control (HIDEC) aircraft cruises over California's Mojave Desert on a flight out of Dryden. The aircraft was used to carry out research on engine and flight control systems. Among other things, in April 1993 it demonstrated the use of computer-assisted engine controls as a means of landing an aircraft safely with only engine power if its normal control surfaces such as elevators, rudders and ailerons are disabled. This Propulsion Controlled Aircraft technology was later demonstrated on the McDonnell Douglas MD-11 transport aircraft. (NASA Photo EC90 312-30)

be designed and built quickly in order to keep a flight program on schedule, Dryden staff members have developed a knack for building a piece and then creating the drawings after the fact. Physicians at Cedars-Sinai described a need they had to help them perform laparoscopy surgery. But the physicians could only describe what they needed the part to do, not what it should look like. Dryden researchers and technicians were able to listen to the physicians' needs and design a part to do the job, without a lot of time or extensive drawings.¹³

Even harder to trace are those instances where the real value of Dryden's flight research was simply to generate enough confidence in a technology or idea for someone to apply it. The Space Shuttle was not a lifting body. But the

controls gave companies and users the confidence to incorporate the technology into production aircraft. Like the early explorers and pioneers, Dryden's contribution was sometimes simply a matter of going into uncharted waters first and proving that they were navigable.

Conclusion

Since its inception, the facility known today as the Dryden Flight Research Center has been a unique place. It is situated in a bleak, desolate area that has blistering summers and bone-chilling winters. Yet to the aeronautics and space community, Dryden is a place of many gifts. Its clear skies, open landscape and

lakebed landing sites have allowed numerous flight activities to take place there that could not have been accomplished elsewhere. Its small size, single-mission focus, and informal, flexible, innovative and pragmatic approach have created a staff with both technical passion and technical agility—traits that have allowed the Center to adapt to changing times and support a wide variety of programs and priorities.

Some of Dryden's projects have been longer-range exploratory research, while other efforts have been to support the nearer-term needs of industry or the nation's air and space programs. Sometimes the Center's contribution was a specific technology, sometimes it was a process or new insight or piece of knowledge, and

sometimes it was simply a matter of going into new territory first and leaving a trail for others to follow. But its various types of research and contributions have made Dryden an extremely valuable resource for the nation's aerospace efforts and industry for half a century. And as the world becomes more complex, with an increasingly global economy and a growing concern about the ability of the United States to retain its competitive and economic edge, the role Dryden plays will become even more

important.

Flight research is a unique discipline. It is an area where researchers are forced to address issues critical for flight and must develop a very pragmatic, flexible approach. It can give technology the maturity and credibility necessary for industry to commit to its use. In

addition, the partnerships flight research requires and the very process of flight itself can greatly assist technology-transfer efforts, proving that a new idea or technology is, at the very least, possible. The technology may still prove impractical, but once it has been proven in flight, few can argue that it can't be done. In addition, flight generates a moment of truth for technology and ideas because it is that unique spot where the rubber meets the road, where all of the elements of a technology come together in a real-life



Drop test of a model of the Experimental Crew Return Vehicle (X-CRV) in 1995. The X-CRV is envisioned as a means for getting crew members back to Earth from a space station in case of emergency. Its design is based on the Martin X-24A lifting body flown at Dryden from 1969 to 1971, but to permit the emergency vehicle to land without a trained pilot, the X-CRV is being designed to use a parafoil device for final descent and touchdown. (NASA Photo EC95 43218-8)

environment for the first time. And unlike laboratory work, it is an area where the cost of a deficiency or mistake can be someone's life.

By the same token, flight is an area of research where results are particularly difficult to predict. Simulators and computers have advanced greatly, but they can only model what is known; they cannot yet accurately predict the exact behavior of a new system in actual flight conditions, especially when it involves a human pilot. In addition, while computers have im-



Artist's concepts of the X-33 Reusable Launch vehicles. On the left is the proposed design for the single-stage-to-orbit vehicle by a team headed by Rockwell. This is a Space Shuttle-like vehicle that would take off vertically and land horizontally. In the center is the vehicle being designed by a team including McDonnell Douglas; it would take off and land vertically. The third design, by a Lockheed Martin team is a lifting-body that would be launched vertically and landed horizontally. This is the design that features Rockwell's linear aerospike engine to be tested in supersonic flight by NASA's SR-71 aircraft. (NASA Photo EC95 43320-1)

proved the capabilities of ground facilities, they have also made aircraft more complex. When all the variables of such complex technologies are brought together in a constantly changing flight environment, it is almost impossible to predict or cover every possible contingency.

So despite the advances in technology, flight research is still an exploration into the realm of the unknown. We have learned to function above the Earth and at high speeds, but we still do not fully understand all the dynamics and forces at work there. Yet it is in this margin, on the ragged boundary between what is known and the mysteries that lie beyond, that discovery happens. Discovery is more often than not a quiet process, a puzzled moment when something does not react as expected. But it is in these moments that our understanding of

our world expands.

For the past 50 years, the Dryden Flight Research Center has been a place where those moments have been welcomed. The people who work there are trained and encouraged to look for the unexpected and have the passion to pursue the reasons for anomalies that occur. In a way, the people who work at Dryden are no different from Columbus, Lewis and Clark, the Wright brothers, or anyone else who has ever stood at the forward edge of knowledge and ventured into the unknown territory ahead. Their tools are research aircraft and engineering formulas instead of sailing ships or frontier knives. But in a sense, the effort is the same. And as with any exploration, it is not without its risks. The pilots and crew are the only members of the research team who actually put their lives

on the line, but every employee of Dryden feels the burden of protecting those lives. The challenge of reaching far enough to learn something new without reaching so far that the risks become too high is one Dryden's researchers face every day. Yet it is their success in continually striking a balance between those two that has allowed Dryden to make the contributions it has.

Over half a century, Dryden has grown from a desert outpost into the nation's premier flight research center. Its priorities and projects have changed; its challenges have evolved. But

it has continued to make contributions because at its core, it has always remained a unique place where people could expand the boundaries of what was known or possible. It has been a place where people searched for the unexpected and overlooked and worked to separate the real from the imagined. And discovery by discovery, it has helped shape the world in which we live and expanded our understanding of that place they call the sky.



Chapter Notes

CHAPTER 1

- ¹ H. H. Arnold, *Global Mission* (New York: Harper & Brothers, 1949), 136.
- ² *On the Edge*, video documentary on Edwards AFB and the Air Force Flight Test Center, prepared by James O. Young, AFFTC Historian, 1991.
- ³ Richard P. Hallion, *On the Frontier: Flight Research at Dryden, 1946-1981* (Washington, D.C.: NASA SP-4303, 1984), xvi.
- ⁴ Hallion, *On the Frontier*, 9.
- ⁵ Hans Mark and Arnold Levine, *The Management of Research Institutions: A Look at Government Laboratories* (Washington, D.C.: NASA SP-481, 1984), 265.
- ⁶ James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958* (Washington, D.C.: NASA SP-4305, 1987), 328.
- ⁷ From untitled publication in Richard Hallion's files, Dryden Flight Research Center Office of External Affairs.
- ⁸ Richard P. Hallion, "American Flight Research and Flight Testing: An Overview from the Wright Brothers to the Space Shuttle," paper from Dryden Flight Research Center Technical Library files, 18 September 1976, 18-19.
- ⁹ Kenneth J. Szalai, interview with author, Dryden Flight Research Center, Edwards, California, 4 August 1995.
- ¹⁰ Marta Bohn-Meyer, interview with author, Edwards, California, 22 August 1995.
- ¹¹ H.W. Withington to John P. Reeder, letter, 6 June 1979, from the files of the Advanced Transport Operating Systems office at the NASA Langley Research Center, Hampton, Virginia.
- ¹² The Dryden Flight Research Center actually had several names over the years, including the Muroc Flight Test Unit, the High Speed Flight Research Station, and the Flight Research Center. To avoid confusion, however, I simply refer to it as "Dryden" throughout this book, except in Chapter 2 where I specifically discuss the Center's chronological history and name changes.
- ¹³ "Dryden Contributions," collection of charts and viewgraphs, from Dryden Flight Research Center administration files, Kenneth J. Szalai, interview, 4 August 1995; William H. Dana, interview with author, Edwards, California, 14 July 1995; Duane McRuer, interview with author, Hawthorne, California, 31 August 1995; William Burcham, interview with author, Edwards, California, 24 August 1995.
- ¹⁴ Kenneth J. Szalai and Cal Jarvis, interview with

author, Edwards, California, 30 August 1995.

- ¹⁵ Kenneth J. Szalai, interview, 4 August 1995.
- ¹⁶ Hallion, *On the Frontier*, 15.
- ¹⁷ *Public Papers of the Presidents of the United States, John F. Kennedy, 1961* (Washington, D.C.: Government Printing Office, 1962), 396-406.
- ¹⁸ "Introductory Remarks," *Research-Airplane-Committee Report on Conference on the Progress of the X-15 Project*, NACA Compilation of Papers (Langley Aeronautical Laboratory, Va., Oct. 25-26, 1956), xix; thanks to Ed Saltzman for locating this source.
- ¹⁹ Kenneth J. Szalai, interview, 4 August 1995.
- ²⁰ The pilots and crewmembers whose lives have been lost include: Howard Lilly, killed in a Douglas Skystreak in 1948; two Bell Aircraft Company employees (one pilot, one crewmember) killed in an X-2 explosion in 1953; Capt. Milburn "Mel" Apt, killed in an X-2 research plane in 1956; Air Force pilot Ray Popson, killed in an X-5 stall-spin accident in 1955; Air Force Maj. Carl Cross and NASA pilot Joe Walker, killed in a mid-air collision between an XB-70A and an F-104N in 1966; Air Force Maj. Michael Adams, killed in 1967 when his X-15 went out of control and broke apart in mid-air; and NASA pilot Richard Gray, killed in a T-37 spin accident in 1982.

CHAPTER 2

- ¹ The phrase, of course, comes from Tom Wolfe, *The Right Stuff* (New York: Farrar, Straus, Giroux, 1979).
- ² These figures do not include support contractors at the facilities, which at Dryden currently number approximately 450. Information from Kenneth J. Szalai, interview with author, Edwards, California, 4 August 1995; William H. Dana, interview with author, Edwards, California, 14 July 1995; Hallion, *On the Frontier*, Appendix B, 273; and especially *NASA Pocket Statistics* (Washington, D.C.: NASA, [1995]), C-26 to C-27. These statistics are for civil servants on personnel rolls at the ends of fiscal years 1965 (Dryden) and 1966 (Langley, Lewis, and Marshall). The numbers for all of the centers were much smaller in the mid-1990s.
- ³ Later redesignated the Langley Aeronautical Laboratory and then the Langley Research Center.
- ⁴ R. Dale Reed, interview with author, Edwards, California, 19 July 1995; Ed Saltzman, interview with author, Edwards, California, 20 July 1995; Jack Russell, interview with author, Lancaster, California, 20 July 1995; Hallion, *On the Frontier*, xvi, xvii, 24.
- ⁵ From Edmond C. Buckley to Hartley A. Soulé, letter, 22 January 1948, as quoted in Hallion, *On the Frontier*, 24.
- ⁶ Information on the early years of Dryden from Hallion, *On the Frontier*, xvii-xix, 23-27; Mary Little Kuhl, interview with author, Lancaster, California, 3 August 1995; Jack Russell, interview, 20 July 1995; Dale Reed, interview, 19 July 1995; Ed Saltzman, interview, 20 July 1995.
- ⁷ Summary report of the House of Representatives Committee on Science and Astronautics recommenda-

tions affecting NASA for FYs 1964, 1965, and 1966, 25 May 1966, from Richard Hallion files in the Dryden Flight Research Center External Affairs Office, Edwards, California.

⁸ Hallion, *On the Frontier*, 134-135; Kenneth J. Szalai, interview, 4 August 1995.

⁹ On 17 November 1995, Kenneth J. Szalai redesignated the ITF as the Walter C. Williams Research Aircraft Integration Facility during a memorial service for Walt Williams, who had died on 7 October 1995.

¹⁰ Kenneth J. Szalai, interview, 4 August 1995; "Dryden Historical Milestones," fact sheet, Dryden Flight Research Center External Affairs Office files.

¹¹ Kenneth J. Szalai, interview with author, Edwards, California, 14 July 1995.

¹² R. Dale Reed, interview, 19 July 1995; Kenneth J. Szalai, interview, 4 August 1995.

¹³ Information on Dryden's management approach from Kenneth J. Szalai, interviews, 14 July 1995, 4 August 1995, and 30 August 1995; William H. Dana, interview, 14 July 1995; Rogers Smith, interview with author, Edwards, California, 19 July 1995; Dana Purifoy, interview with author, Edwards, California, 7 September 1995.

¹⁴ Information on research pilots is from William H. Dana, interview, 14 July 1995; Rogers Smith, interview with author, 19 July 1995; Fitzhugh "Fitz" Fulton, interview with author, 19 July 1995; Ed Schneider, interview with author, Edwards, California, 24 August 1995; Gordon Fullerton, interview with author, 7 September 1995; Dana Purifoy, interview with author, 7 September 1995, all at Edwards, California.

¹⁵ Gary Trippensee, interview with author, Edwards, California, 24 August 1995.

¹⁶ Rogers Smith, interview, 19 July 1995; Ed Schneider, interview, 24 August 1995.

¹⁷ William H. Dana, interview, 14 July 1995.

¹⁸ Ed Schneider, interview, 24 August 1995.

¹⁹ Kenneth J. Szalai, interview, 4 August 1995.

²⁰ Kenneth J. Szalai and Calvin R. Jarvis, interview, 30 August 1995; Rogers Smith, interview, 19 July 1995.

²¹ Hallion, *On the Frontier*, 13-20; Jack Russell, interview, 20 July 1995.

²² Rogers Smith, interview, 19 July 1995; Dana Purifoy, interview, 7 September 1995; Marta Bohn-Meyer, interview with author, Edwards, California, 22 August 1995; Gary Trippensee, interview, 24 August 1995; Kenneth J. Szalai, interview, 4 August 1995.

²³ Kenneth J. Szalai, interview with author, 4 August 1995; Dana Purifoy, interview with author, 7 September 1995.

CHAPTER 3

¹ Kenneth S. Kleinknecht, "The Rocket Research Airplanes," in Eugene M. Emme, ed., *The History of Rocket Technology: Essays on Research, Development, and Utility* (Detroit: Wayne State University Press, 1964), 196; Hallion, *On the Frontier*, 6; Hansen, *Engi-*

neer in Charge, 271-301; Ben Guenther and Jay Miller, *Bell X-1 Variants* (Arlington, TX: Aerofax, Inc., 1988), 1-5.

² Richard P. Hallion, "American Rocket Aircraft: Precursors to Manned Flight Beyond the Atmosphere," paper presented at the International Astronautical Federation XXVth Congress in Amsterdam, Holland, 30 September - 5 October 1974, 3.

³ Walter Williams, interview with Richard P. Hallion, 13 June 1977; Ben Guenther and Jay Miller, *Bell X-1 Variants*, 6-7.

⁴ Jack Russell, interview with author, Lancaster, California, 20 July 1995; Hallion, *On the Frontier*, 13-14.

⁵ Edwin J. Saltzman and Theodore G. Ayers, *Selected Examples of NACA/NASA Supersonic Flight Research* (Edwards, CA: NASA SP-513, 1995), 9.

⁶ Hallion, *On the Frontier*, 11-12, 14-18; Guenther and Miller, *Bell X-1 Variants*, 7-8; Jack Russell, interview, 20 July 1995; Edwin J. Saltzman, interview with author, Edwards, California, 20 July 1995.

⁷ Strictly speaking, vortex generators are miniature airfoils rather than "tabs." Their purpose is to produce vortices (whirlpools) in the air flowing in the direction of the wing's chord from leading to trailing edge. This increases the intermixing of layers of air, postponing what is called boundary layer separation and improving lift. See H.D. Taylor, "Summary Report on Vortex Generators," United Aircraft Research Department Report R-05280-9, March 7, 1950; Sighard F. Hoerner with Henry V. Borst, "Fluid-Dynamic Lift: Practical Information on Aerodynamic and Hydrodynamic Lift" (1975), 6-18 to 6-19, both kindly supplied by Ed Saltzman.

⁸ Hallion, *On the Frontier*, 19-21, 34-35; written comments of Edwin J. Saltzman, 6 December 1995.

⁹ Hallion, *On the Frontier*, 27-29.

¹⁰ Hallion, "American Rocket Aircraft," 6-8.

¹¹ Kenneth S. Kleinknecht, "The Rocket Research Airplanes," 199-202; Hallion, "American Rocket Aircraft," 7-8; Hallion, *On the Frontier*, 12-13, 47-48.

¹² Melvin Sadoff and A. Scott Crossfield, "A Flight Evaluation of the Stability and Control of the X-4 Swept-Wing Semitailless Airplane," NACA RM-H54G16 (Washington, D.C., 30 August 1954), 14; Ed Saltzman, comments, 6 December 1995.

¹³ General James Doolittle from document written in 1958, as quoted in text from untitled, undated transcript of NASA presentation on the X-1 program, from Richard P. Hallion files in NASA External Affairs Office. Parts of this and succeeding paragraphs also based on Saltzman comments, which have been extraordinarily helpful on technical details throughout this chapter.

¹⁴ A "G" force is a way of measuring the effect of gravity on an object. One "G" is the normal gravitational pull of the Earth. A "2 G" force would be equivalent to two times the Earth's normal gravitational pull. Or to put it another way, in an 8 G maneuver, a pilot's arm would feel eight times as heavy as its normal weight.

¹⁵ Saltzman and Ayers, *Selected Examples of NACA/*

NASA Supersonic Flight Research, 10-11. The "Century Series" fighters were all built and first flown in the early-to mid-1950s. They are so called because their designations were F-100, F-101, F-103 and so forth.

¹⁶ William H. Phillips, a researcher at the Langley Laboratory, had predicted the inertial-coupling problem in a technical paper published several years before. But the X-3 provided the first comprehensive data on the problem.

¹⁷ Hallion, *On the Frontier*, 47-62; "Edwards Pioneers High-Speed Research," *Aviation Week & Space Technology*, 3 June 1957, 16-18; D. E. Beeler, interview with Richard P. Hallion, undated.

¹⁸ Information on the derivative X-1 aircraft and the X-2 is from Charles V. Eppley, "The Rocket Research Aircraft Program," Air Force Flight Test Center Technical Documentary Report No. 63-3, February 1963, 6-17; Hallion, "American Rocket Aircraft," 5-6, 9-17; Kleinknecht, "The Rocket Research Airplanes," 199-204; Hallion, *On the Frontier*, 63-85; Edwin J. Saltzman, interview, 20 July 1995.

¹⁹ Eppley, "Rocket Research Aircraft," 18-19, 22; Kleinknecht, "Rocket Research Airplanes," 205-206; Wendell H. Stillwell, *X-15 Research Results* (Washington, D.C.: NASA SP-60, 1965), 6, 11-14.

²⁰ Stillwell, *X-15 Research Results*, 21; Kleinknecht, "Rocket Research Airplanes," 206-207.

²¹ Hallion, "American Rocket Aircraft," 30; William H. Dana, interview with author, Edwards, California, 14 July 1995.

²² William H. Dana, interview, 14 July 1995; Hallion, *On the Frontier*, 110-111; Eppley, "The Rocket Research Aircraft Program," 19; Edwin J. Saltzman, interview, 20 July 1995.

²³ Jack Russell, interview, 20 July 1995.

²⁴ Jack Kolf, interview with author, Palmdale, California, 22 August 1995; William H. Dana, interview, 14 July 1995; Edwin J. Saltzman, interview, 20 July 1995.

²⁵ McKay recovered from his injuries sufficiently to fly the X-15 again, but his injuries were serious enough to force his retirement from NASA almost 10 years after the accident, in 1971.

²⁶ Jack Russell, interview, 20 July 1995; William H. Dana, interview, 14 July 1995; Ben Guenther, Jay Miller, and Terry Panopalis, *North American X-15/X-15A-2* (Arlington, TX: Aerofax, Inc., 1985), 13-14; Hallion, *On the Frontier*, 122-125.

²⁷ Overall, according to Richard Hallion, the X-15 had a 92% mission success rate. Hallion, "American Rocket Aircraft," 28, 35.

²⁸ Milton O. Thompson, *At the Edge of Space* (Washington, D.C.: Smithsonian Institution Press, 1992), 266-267.

²⁹ Hallion, *On the Frontier*, Appendix M, 329-337.

³⁰ Guenther et al., *North American X-15/X-15A-2*, 16; Hallion, "American Rocket Aircraft," 30.

³¹ Hallion, *On the Frontier*, 115.

³² William H. Dana, interview, 14 July 1995; Hallion, "American Rocket Aircraft," 35-36; Thompson, *At the Edge of Space*, 270.

³³ Thompson, *At the Edge of Space*, 270-271; Hallion, "American Rocket Aircraft," 37; Hallion, *On the Frontier*, 103.

³⁴ Hallion, *On the Frontier*, 102.

³⁵ M2-F1 information from R. Dale Reed, "Wingless Flight," as yet unpublished manuscript, 2-12 - 3-31; R. Dale Reed, interview with author, Edwards, California, 19 July 1995; William H. Dana, interview, 14 July 1995.

³⁶ Hallion, *On the Frontier*, 155.

³⁷ "Heavyweight" lifting body information from Reed, "Wingless Flight," 4-2 - 6-17; Reed, interview, 19 July 1995; William H. Dana, interview, 14 July 1995; Milton O. Thompson, interview with author, Edwards, California, 26 February 1992; Hallion, *On the Frontier*, 158-160.

³⁸ Milton O. Thompson, interview, 26 February 1992; Hallion, *On the Frontier*, 165-167.

³⁹ Milton O. Thompson, interview, 26 February 1992; William H. Dana, interview, 14 July 1995; Hallion, *On the Frontier*, 167-168.

⁴⁰ R. Dale Reed, interview, 19 July 1995; Milton O. Thompson, interview, 26 February 1992; Kenneth Iiff, interview with author, Edwards, California, 1 September 1995.

⁴¹ Hallion, *On the Frontier*, 178-180.

⁴² XB-70A information from Fitzhugh Fulton, interview with author, Edwards, California, 19 July 1995; Hallion, *On the Frontier*, 178-189; Ed Saltzman comments, 28 February 1996, based upon Henry H. Arnaiz, John B. Peterson, Jr., and James C. Daugherty, "Wind Tunnel/Flight Correlation Study of Aerodynamic Characteristics of a Large Flexible Supersonic Cruise Airplane (XB-70-1)," NASA Technical Paper 1516 (1980).

⁴³ Generally, the first test prototypes would be designated with an "X" and the production prototypes would be designated with a "Y." Hence, the "YF" 12A was a production prototype of a fighter (or fighter/interceptor) aircraft.

⁴⁴ Fitzhugh Fulton, interview, 19 July 1995.

⁴⁵ Information on the YF-12 research program from William H. Dana, interview, 14 July 1995; Fitzhugh Fulton, interview, 19 July 1995; Hallion, *On the Frontier*, 189-199.

⁴⁶ SR-71 research program information provided by Dave Lux and Steve Schmidt, interview with author, Edwards, California, 22 August 1995; Rogers Smith, interview with author, Edwards, California, 19 July 1995; Kenneth J. Szalai, interview with author, Edwards, California, 4 August 1995.

⁴⁷ C. M. Plattner, "NASA to Begin Unmanned Tests of New Type Lifting Shape for Hypersonic Maneuvering," *Aviation Week & Space Technology*, 29 September 1969, 52-58; R. Dale Reed, "Wingless Flight," 8-4 - 8-11; R. Dale Reed, interview, 19 July 1995; Hallion, *On the Frontier*, 210-212.

⁴⁸ *Aeronautics and Space Report of the President, Fiscal Year 1994 Activities* (Washington, D.C.: NASA, 1994), 41; Bruce Holmes, interview with author, Oshkosh, Wisconsin, 29 July 1995.

⁴⁹ A Boeing 747, by comparison, has a wing loading of approximately 100 pounds per square foot.

⁵⁰ John Del Frate, interview with author, Edwards, California, 1 September 1995; R. Dale Reed, interview, 19 July 1995; Michael A. Dornheim, "Solar Powered Aircraft Exceeds 50,000 Ft.," *Aviation Week & Space Technology*, 18 September 1995, 67; William B. Scott, "Technology Transfer Support Wavers," *Aviation Week & Space Technology*, 23 October 1995, 57-60; Stuart F. Brown, "The Eternal Airplane," *Popular Science*, April 1994, 70-75, 100.

CHAPTER 4

¹ This is not to say that engineers at Dryden had not been working on efficiency issues before this point. Indeed, in the early days of turbojet engines, aerodynamic efficiency was of great concern for engineers in part because the engines were not very powerful. Designs like the F-104 had to be extremely efficient aerodynamically in order to achieve the performance desired. But the fuel crisis of the 1970s suddenly made fuel efficiency in and of itself a top priority for the airlines, manufacturers, and national decision-makers, turning attention and funding toward focused research programs to improve aircraft fuel efficiency and reducing the support for some other high-speed efforts such as the SST.

² Phil Felleman, phone interview with author, 19 February 1996.

³ A "gigabyte" is approximately one billion bytes. Other information in this section from Kenneth J. Szalai and Calvin R. Jarvis, interview with author, Edwards, California, 30 August 1995; Marcy Rosenberg and E. Drake Lundell Jr., "IBM and the Compatibles: How They Measure Up," *Computerworld*, 5 January 1979, 382; Kevin Shine, IBM PC Technical Representative, phone interview with author, 2 June 1995.

⁴ Dr. Whitcomb's "area rule" concept looked at streamlining the overall frontal area of an aircraft from its nose to its tail. A typical aircraft design would have a sharp increase in its frontal area at the point where the wings joined the fuselage. By indenting the fuselage at that point, and even sometimes adding a "bump" to the nose area ahead of the wing, Whitcomb was able to keep the overall frontal area more consistent. This, in turn, created less drag as the aircraft passed through the difficult transonic speed range. Whitcomb's concept is generally regarded as a critical advance that enabled the design of operational supersonic aircraft.

⁵ Boundary layer separation is the point where the air no longer flows along the contour of the wing but "separates" from the wing.

⁶ Dr. Richard T. Whitcomb, "Research on Methods for Reducing the Aerodynamic Drag at Transonic Speeds," paper, presented at The Inaugural Eastman Jacobs Lecture, NASA Langley Research Center (Hampton, Virginia, 14 November 1994), 4-8; Weneth D. Painter, interview with Richard Hallion, 8 August 1977; Richard P. Hallion, *On the Frontier*, 201-206.

⁷ Louis Steers, phone interview with author, 22 November 1995; Hallion, *On the Frontier*, 209.

⁸ The Air Force tanker version of the commercial Boeing 707 jetliner.

⁹ Whitcomb, "Methods for Reducing Aerodynamic Drag," 8-9; "KC-135 Program Review," NASA Conference Publication 2211 (Proceedings of Dryden Symposium, Edwards, California, 16 September 1981), 115-117, 128.

¹⁰ Hallion, *On the Frontier*, 250-251; Kenneth J. Szalai and Calvin R. Jarvis, interview with author, Edwards, California, 30 August 1995; "The AD-1 Program, 1976 to 1982," viewgraphs, from the office of Alex Sim, Dryden Flight Research Center.

¹¹ In the late 1950s, Dryden did conduct some supersonic laminar flow research with an F-104 research plane. See Richard D. Banner, John G. McTigue, and Gilbert Petty, Jr., "Boundary-Layer-Transition Measurements in Full-Scale Flight," NACA Research Memorandum H58E28, (Washington, D.C.: NACA, 28 July 1958).

¹² Marta Bohn-Meyer, interview with author, Edwards, California, 22 August 1995; Bruce A. Smith, "F-16XL Flights Could Aid in HSCT Design," *Aviation Week & Space Technology*, 23 October 1995, 42-44.

¹³ Composite construction is a manufacturing approach that combines more than one type of building materials. One common type of composite construction, for example, uses a foam core sandwiched between two fiberglass layers. But composite construction can refer to any multiple-element material.

¹⁴ Hallion, *On the Frontier*, 215-216; HiMAT Fact Sheet from Dryden Research Center External Affairs Office files; Dave Lux, phone interview with author, 20 February 1996; comments of Ed Saltzman, 12 January 1996, a very helpful source throughout this chapter.

¹⁵ "Angle of Attack" is a term used to describe the angle of the relative wind to an aircraft's wing. Or, to put it another way, it is the angle at which the air from the aircraft's flight path hits the wing. An aircraft in stable, level flight would have an angle of attack close to zero. If an aircraft was moving forward at a stable altitude but had its nose pointed up 20 degrees, the angle of attack of the wing would be close to 20 degrees. A 20 degree angle of attack could also be achieved, however, if the aircraft was in a horizontal configuration but was descending at a 20 degree angle. In either case, the air from the aircraft's flight path would be hitting the wing at a 20 degree angle.

¹⁶ Rogers Smith, phone interview with author, 20 February 1996; Steve Ishmael, phone interview with author, 20 February 1996; Bob Clark, phone interview with author, 20 February 1996; Ed Saltzman, comments, 12 January 1996.

¹⁷ Rogers Smith, interview with author, Edwards, California, 19 August 1995; Gary Trippensee, interview with author, Edwards, California, 27 August 1995; Steve Pace, *The Grumman X-29* (Blue Ridge Summit, PA: TAB Books, 1991), 2-15, 22-54; "The X-29," Fact Sheet, from the NASA Dryden Flight Research Center Office of External Affairs files.

¹⁸ The official term for the F-18 is an F/A-18, designating it as a Fighter/Attack aircraft. For simplicity's sake in repeat references, however, I refer to it as simply an F-18.

¹⁹ Ed Schneider, interview with author, Edwards, California, 24 August 1995; "F-18 High Angle of Attack Research Aircraft," Fact Sheet, from NASA Dryden Flight Research Center External Affairs Office Files; Guy Norris, "Breaking the Stall Barrier," *Flight International*, 11-17 November 1992, 34-37.

²⁰ The company started out as Messerschmidt-Bolkow-Blohm, then became Deutsche Aerospace, and most recently merged with Daimler-Benz.

²¹ Carbon-carbon is a very strong composite material.

²² Redesignated in 1995 as the Walter C. Williams Research Aircraft Integration Facility, after the founding director of Dryden.

²³ A pitot tube is a device used to measure airspeed. Actually, the device on the aircraft at the time of the mishap was a substitute for a conventional pitot called a Kiel probe.

²⁴ Gary Trippensee, interview, 24 August 1995; Rogers Smith, interview, 19 July 1995; X-31 Program Videotape; "X-31 Enhanced Fighter Maneuverability Demonstrator," Fact Sheet from the NASA Dryden External Affairs Office Files, Guy Norris, "Breaking the Stall Barrier," 34-37.

²⁵ Verification and validation are both important tasks in flight research that check new technology, components or systems before flight. A very basic differentiation of the two tasks could be described as follows: Verification is making sure you did the thing right. Validation is making sure you did the right thing.

²⁶ Duane McRuer, "Human Dynamics and Pilot-Induced Oscillations," paper, presented at the Minta Martin Lecture, (MIT, Cambridge, Massachusetts, 2 December 1992), ii, 1-7, 11; Duane McRuer, interview with author, Hawthorne, California, 31 August 1995; Michael A. Dornheim, "Report Pinpoints Factors Leading to YF-22 Crash," *Aviation Week & Space Technology*, 9 November 1992, 53-54; Carole A. Shifrin, "Gripen Likely to Fly Again Soon," *Aviation Week & Space Technology*, 30 August 1989; Michael A. Dornheim, "Boeing Corrects Several 777 PIOs," *Aviation Week & Space Technology*, 8 May 1995; Kenneth J. Szalai and Calvin R. Jarvis, interview with author, Edwards, California, 30 August 1995.

²⁷ For more information on the F-8 PIO research in support of the Space Shuttle program, see Chapter 5.

²⁸ Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870-1979*, (New York: Viking Penguin, 1989), 71-74.

²⁹ F-8 DFBW Research Information from: Kenneth J. Szalai, interview with author, Edwards, California, 4 August 1995; Kenneth J. Szalai and Calvin R. Jarvis, interview, 30 August 1995; Kenneth J. Szalai et al., "Design and Test Experience with a Triply Redundant Digital Fly-By-Wire Control System," AIAA Paper No. 76-1911, presented at AIAA Guidance and Control

Conference (San Diego, California, 16-18 August 1976).

³⁰ Weneth D. Painter, interview with Richard P. Hallion, 8 August 1977.

³¹ Hallion, *On the Frontier*, 220-222; Frank W. Burcham, Jr., Glenn B. Gilyard, and Lawrence P. Myers, "Propulsion System/Flight Control Integration and Optimization," NASA TM 4207, July 1990, 2.

³² Burcham, Gilyard, Myers, "Propulsion System/Flight Control Integration," 2-5.

³³ *Ibid.*, 6-7; Bill Burcham, interview with author, Edwards, California, 24 August 1995; "Value of NASA Flight Research for Technology Transition," viewgraph from Bill Burcham's office files, Dryden Flight Research Center, Edwards, California.

³⁴ "F-15 Flight Research Facility," Fact Sheet from Dryden Flight Research Center External Affairs Office files, 3; "NASA F-15 Demonstrates Self-Repairing Flight Control System," Press Release, from NASA Dryden Flight Research Center External Affairs Office Files, 23 March 1990; Bill Burcham, interview, 24 August 1995.

³⁵ Gordon Fullerton, interview with author, Edwards, California, 7 September 1995; Bill Burcham, interview, 24 August 1995; Bill Burcham, "Cleared for Landing," *Air & Space*, April/May 1995, 20-21; Les Dorr, Jr., "Coming in on Two Engines and a Prayer," *NASA Magazine*, Winter 1994, 14-17; "F-15 Flight Research Facility," Fact Sheet from Dryden Research Center External Affairs Office files, November 1994.

³⁶ P. Doane, R. Bursey and G. Schkolnik, "F-15 ACTIVE: A Flexible Propulsion Integration Testbed," AIAA Paper 94-3360, Presented at the 30th AIAA/ASME/ASEE Joint Propulsion Conference, Indianapolis, Indiana, 27-29 June 1994; Roger Bursey, "The F-15 ACTIVE Aircraft 'The Next Step,'" AIAA Paper, 1995; Gerard Schkolnik, phone interview with author, 22 November 1995.

³⁷ Joel R. Sitz, "F-18 Systems Research Aircraft Facility," SAE Technical Paper 922063, (Anaheim California: Aerotech '92); Joel R. Sitz, phone interviews with author, 20 and 21 November 1995; Michael A. Dornheim, "NASA F/A-18 Tests Components," *Aviation Week & Space Technology*, 5 September 1994, 89-90; Guy Norris, "Test Case," *Flight International*, 8-14 June 1994, 30-31; Systems Research Aircraft Viewgraphs and schedule from Joel R. Sitz files, Dryden Flight Research Center.

CHAPTER 5

¹ Richard P. Hallion, *On the Frontier*, 135-146.

² William H. Dana, interview with author, Edwards, California, 14 July 1995; Milton O. Thompson, interview with author, Edwards, California, 26 February 1992; Hallion, *On the Frontier*, 137-140.

³ A "zero-zero" ejection seat is one that is effective with "zero" altitude and "zero" speed. Other models require a certain amount of altitude and airspeed in order to be effective.

⁴ Robert Baron, interview with author, Edwards,

California, 4 August 1995; Hallion, *On the Frontier*, 140-146; William H. Dana, interview, 14 July 1995; "Lunar Landing Research Vehicle, the LLRV," Fact Sheet, from Dryden Flight Research Center External Affairs Office files.

⁵ William H. Dana, interview, 14 July 1995.

⁶ Neil Armstrong, from a talk given to Dryden staff members soon after the Apollo 11 mission, as quoted in Robert Baron, interview, 4 August 1995.

⁷ Hallion, *On the Frontier*, 145.

⁸ William H. Dana, interview, 14 July 1995.

⁹ Fred Haise had been a research pilot at Dryden before joining the astronaut program and was a member of the ill-fated Apollo 13 crew. Gordon Fullerton would later join Dryden's staff as a research pilot.

¹⁰ Kenneth J. Szalai and Calvin R. Jarvis, interview with author, Edwards, California, 30 August 1995.

¹¹ Duane McRuer, "Human Dynamics and Pilot-Induced Oscillations," paper presented at the Minta Martin Lecture (MIT, Cambridge, Massachusetts, 2 December 1992), ii, 1-8, 11; William H. Dana, interview, 14 July 1995; Kenneth J. Szalai and Calvin R. Jarvis, interview, 30 August 1995; Duane T. McRuer, interview with author, Hawthorne, California, 31 August 1995; Duane T. McRuer, "Lore and Discoveries from Flight Research at Dryden Flight Research Center," NASA TR-2464-1 (NASA Dryden Flight Research Center, October 1994), 5-15; Gordon Fullerton, interview with author, Edwards, California, 7 September 1995.

¹² Robert R. Meyer, Jr., and Jack Barneburg, "In-Flight Rain Damage Tests of the Shuttle Thermal Protection System," NASA TM 100438, May 1988; Bianca M. Trujillo, Robert R. Meyer, Jr., and Paul M. Sawko, "In-Flight Load Testing of Advanced Shuttle Thermal Protection Systems," NASA TM86024, December 1983.

¹³ Robert Baron, interview, 4 August 1995; "Landing Systems Research Aircraft," Fact Sheet from the Dryden Flight Research Center External Affairs Office files; Gordon Fullerton, interview, 7 September 1995.

¹⁴ Roy Bryant, interview with author, Edwards, California, 30 August 1995; "B-52 Launch Aircraft," Fact Sheet from Dryden Flight Research Center External Affairs Office files; Ed Schneider, interview with author, Edwards, California, 24 August 1995.

¹⁵ See Chapter 3 for more information on inertial-coupling research and the X-3.

¹⁶ Walter Bonney, "A Brief History of the High-Speed Flight Station," undated manuscript from Richard Hallion files, Dryden Flight Research Center External Affairs Office; Roy Bryant, interview, 30 August 1995; Hallion, *On the Frontier*, 58-59, 88-97, 229.

¹⁷ Ed Schneider, interview, 24 August 1995; Hallion, *On the Frontier*, 233.

¹⁸ Hallion, *On the Frontier*, 88-89, 213-214.

¹⁹ *Ibid.*, 89.

²⁰ William H. Dana, interview, 14 July 1995; Hallion, *On the Frontier*, 89, 223; Marvin R. Barber et al., "An Evaluation of the Handling Qualities of Seven General Aviation Aircraft," NASA TN D-3726 (Washington,

D.C.: NASA, November 1966); Marvin R. Barber, phone interview with author, 9 January 1996.

²¹ Hallion, *On the Frontier*, 223-226; Roy Bryant, phone interview with author, 9 January 1996; Marvin R. Barber, phone interview, 9 January 1996.

²² Kenneth J. Szalai, interview with author, Edwards, California, 4 August 1995; William H. Dana, interview, 14 July 1995; Marvin R. Barber, phone interview, 9 January 1996.

CHAPTER 6

¹ Thomas C. Muse, "Some Contributions of NASA to Aeronautics," NASA Contractor Report, P.O. # W-14, 122, September 1976, 2.

² For more information about Dryden's high-speed research and ERAST programs, see Chapter 3.

³ For more information on F-15 ACTIVE research, see Chapter 4.

⁴ Kenneth J. Szalai, phone interview with author, 12 January 1996; Ken Iliff, phone interview with author, 16 January 1996; Mike Kehoe, phone interview with author, 12 March 1996.

⁵ "About the Reusable Launch Vehicle Technology Program," from World Wide Web [<http://rlv.msfc.nasa.gov/RLV-HTMLS/RLVOverview.html>], 6 December 1995; Steven Ishmael, phone interview with author, 12 January 1996.

⁶ For more information on the Aerospike engine tests, see Chapter 3.

⁷ "RLV X-33 Concepts," from World Wide Web [<http://rlv.msfc.nasa.gov/RLV-HTMLS/RLVX33.html>], 6 December 1995; Kenneth J. Szalai, phone interview, 12 January 1996; Steven Ishmael, phone interview, 12 January 1996.

⁸ "ACRV-X Project," viewgraphs presented to RLV industry teams, 9 August 1995; "X-35 Phoenix Project Plan," revised date 19 April 1995, from NASA Dryden Flight Research Center External Affairs Office files; Ken Iliff, phone interview, 16 January 1996; Kenneth J. Szalai, phone interview, 12 January 1996; "NASA Studying Lifting-Body/Parafoil Combination for Station ACRV," *Aerospace Daily*, Vol 176, No. 9, 13 October 1995, 73.

⁹ Kenneth J. Szalai, interview with author, Edwards, California, 14 July 1995; William H. Dana, interview with author, Edwards, California, 14 July 1995; Kenneth J. Szalai, interview with author, Edwards, California, 4 August 1995; Dana Purifoy, interview with author, Edwards, California, 7 September 1995.

¹⁰ From untitled publication in Richard Hallion's files, Dryden Flight Research Center External Affairs Office.

¹¹ Executive Office of the President, Office of Science and Technology Policy, "National Aeronautical R&D Goals: Agenda for Achievement," report of the Aeronautical Policy Review Committee, (Washington, D.C., February 1987), 2; Robert S. Ames, "U.S. Must Understand the Link Between R&D and the Economy," *Aviation Week & Space Technology*, 12 October 1987, 149-150; testimony before a House subcommittee on technology and competitiveness, as quoted in Christopher P. Fotos, "Industry Experts Say NASA Must Devote More Resources to Civil Aeronautics," *Aviation Week & Space Technology*, 24 February 1992, 42.

¹² Rogers Smith, interview with author, Edwards, California, 19 July 1995.

¹³ Kenneth J. Szalai, interview, 4 August 1995.

Bibliographical Essay

The single most important group of sources for this book consists of numerous interviews with managers and engineers at Dryden and other NASA centers, plus documents they provided from their files. A great deal of information and insight also came from Richard P. Hallion's authoritative *On the Frontier: Flight Research at Dryden, 1946-1981* (Washington, DC: NASA SP-4303, 1984) and the collection of interviews, documents, and papers upon which it is based. This collection currently resides at the External Affairs Office of the Dryden Flight Research Center, which has furnished a number of fact sheets, news releases, and other documents that were useful in providing an overview of Dryden's first fifty years.

Many individual details and some perspective on Dryden's accomplishments over this period also came from such sources as Hans Mark and Arnold Levine, *The Management of Research Institutions: A Look at Government Laboratories* (Washington, DC: NASA SP-481, 1984), Gen. H. H. Arnold's *Global Mission* (New York: Harper & Brothers, 1949), Kenneth S. Kleinknecht's article "The Rocket Research Airplanes" in Eugene M. Emme's *History of Rocket Technology* (Detroit: Wayne State University Press, 1964), the book on *Bell X-1 Variants* (Arlington, TX: Aerofax, Inc., 1988) by Ben Guenther and Jay Miller, Wendell H. Stillwell's *X-15 Research Results* (Washington, DC: NASA SP-60, 1965), and Steve Pace's *The Grumman X-29* (Blue Ridge Summit, PA: TAB Books, 1991). More techni-

cal treatments like Edwin J. Saltzman and Theodore G. Ayers' *Selected Examples of NACA/NASA Supersonic Flight Research* (Edwards, CA: NASA SP-513, 1995) as well as other accounts by authors who worked at Dryden for many years, such as Milton O. Thompson's *At the Edge of Space* (Washington, DC: Smithsonian Institution Press, 1992) and R. Dale Reed's as yet unpublished manuscript, "Wingless Flight," were likewise extremely useful in the research for this book.

Further sources of information included technical papers such as Henry H. Arnaiz, John B. Peterson, Jr., and James C. Daugherty's "Wind Tunnel/Flight Correlation Study of Aerodynamic Characteristics of a Large Flexible Supersonic Cruise Airplane (XB-70-1)," NASA Technical Paper 1516 (1980) and Charles V. Eppley's "The Rocket Research Aircraft Program," Air Force Flight Test Center Technical Documentary Report No. 63-3 (1963).

A final group of sources consisted of aviation journals such as *Aviation Week & Space Technology* and *Flight International*. In conjunction with the other sources listed above, these provided helpful background and useful information on many of Dryden's programs and projects over the years. Valuable perspective was also provided by such scholarly works as Thomas P. Hughes' *American Genesis* (New York: Viking Penguin, 1989) and James R. Hansen's *Engineer in Charge* (Washington, DC: NASA SP-4305, 1987).

Glossary of Acronyms

AAF	Army Air Forces	HSFRS	High Speed Flight Research Station
ACTIVE	Advanced Controls Technology for Integrated Vehicles	HSFS	High Speed Flight Station
ADECS	Adaptive Engine Control System	HSR	High Speed Research
AF	Air Force	IBM	International Business Machines
AFFTC	Air Force Flight Test Center	IPCS	Integrated Propulsion Control System
AFTI	Advanced Fighter Technology Integration	ITF	Integrated Test Facility (now RAIF)
ALT	Approach and Landing Test	ITO	International Test Organization
AoA	Angle of Attack	JSC	Johnson Space Center
ARC	Ames Research Center	KSC	Kennedy Space Center
ARPA	Advanced Research Projects Agency	LaRC	Langley Research Center
ATF	Advanced Tactical Fighter	LeRC	Lewis Research Center
CAA	Civil Aeronautics Administration	LEX	Leading Edge Extension
CID	Controlled Impact Demonstration	LLRV	Lunar Landing Research Vehicle
DARPA	Defense Advanced Research Projects Agency	LLTV	Lunar Landing Training Vehicle
DAST	Drones for Aerodynamic and Structural Testing	LM	Lunar Module
DEEC	Digital Electronic Engine Control	MAW	Mission Adaptive Wing
DEFCS	Digital Electronic Flight Control System	MSFC	Marshall Space Flight Center
DFBW	Digital Fly-By-Wire	NACA	National Advisory Committee for Aeronautics
DFRC	Dryden Flight Research Center	NASA	National Aeronautics and Space Administration
EPAD	Electrically Powered Actuator Design	NLF	Natural Laminar Flow
ERAST	Environmental Research Aircraft and Sensor Technology	OPEC	Organization of Petroleum Exporting Countries
FAA	Federal Aviation Administration	PCA	Propulsion Controlled Aircraft
FADEC	Full Authority Digital Engine Control	PIO	Pilot Induced Oscillation
FBW	Fly-By-Wire	PSC	Performance Seeking Control
FCS	Flight Control System	RAIF	Research Aircraft Integration Facility
FOCSI	Fiber-Optic Control System Integration	REBUS	Resident Back-Up Software
FRC	Flight Research Center	RLV	Reusable Launch Vehicle
FSW	Forward Swept Wing	RPRV	Remotely Piloted Research Vehicle
GA	General Aviation	RPV	Remotely Piloted Vehicle
GPAS	General Purpose Airborne Simulator	RTLS	Return to Launch Site
HARV	High Angle-of-Attack Research Vehicle	SCA	Shuttle Carrier Aircraft
HIDEC	Highly Integrated Digital Electronic Control	SCW	Supercritical wing
HiMAT	Highly Maneuverable Aircraft Technology	SLFC	Supersonic Laminar Flow Control
HISTEC	High Stability Engine Control	SRA	Systems Research Aircraft
HSCT	High Speed Civil Transport	SRFCS	Self-Repairing Flight Control System
		SST	Supersonic Transport
		SSTO	Single-Stage-to-Orbit
		STOL	Short Take-Off and Landing
		TACT	Transonic Aircraft Technology
		VTOL	Vertical Take-Off and Landing
		X-CRV	Experimental Crew Return Vehicle

Appendix

Concepts and Innovations to which the Dryden Flight Research Center has Contributed

In the course of its fifty year history, Dryden has evaluated—in the demanding and realistic environment of actual flight—a great many concepts and configurations developed by its own researchers or those from other NASA centers, other agencies, or industry. Evaluating, improving or correcting otherwise promising concepts has provided a stimulating environment for the genesis of other new concepts and solutions. The following tabulation provides a partial list of major contributions to aeronautics made by Dryden personnel either in conjunction with partners or on their own initiative.

YEAR(S)	CONTRIBUTIONS:	SIGNIFICANCE:
1946-1958	Completed "Round One" flight investigations of the early X-Series and D-558 series of aircraft	Performed subsonic, transonic, and supersonic research to help evaluate and interpret wind tunnel data (special emphasis on transonic nonlinear characteristics). This research used an entire stable of new configurations with which flight loads, buffet, aeroelastic effects, pitch-up, directional instability, longitudinal control, and the effects of wing sweep were investigated. This research contributed to design principles leading to reliable and routine flight of production aircraft at transonic and supersonic speeds.
1947	Provided technical guidance and data analysis for the first flight through Mach 1.0 on the XS-1 (X-1 No. 1) airplane	This was the first time that a piloted airplane was flown through the speed of sound. In addition to overcoming the sound barrier, this flight demonstrated that an airplane could be controlled through the transonic region where very non-linear aerodynamic characteristics occur.
1947-1967	Analyzed and documented flight results obtained from first-time supersonic and hypersonic speeds	Though the sonic barrier (Mach one) was by far the most intimidating hurdle, Mach numbers of 2.0 to 6.0 were also noteworthy because of other challenges, such as diminished stability, aerodynamic heating, and energy management. Flights at Edwards achieved the following records: Mach 2.005 on 20 Nov. 1953 (D-558-2); Mach 3.2 on 27 Sept. 1956 (X-2); Mach 4.43 on 7 March 1961 (X-15); Mach 5.27 on 23 June 1961 (X-15); Mach 6.04 on 9 Nov. 1961 (X-15); and Mach 6.7 on 3 Oct. 1967 (X-15).
1947-1962	Developed generalized energy management algorithms for flight planning and safe flight of low lift-to-drag ratio, unpowered aircraft	Led to the concept of determining a potential landing "footprint" for such aircraft, with variations in scale during the different stages of a mission. Such algorithms have been applied to the Space Shuttle. Will be used for future unpowered space vehicles, providing multiple landing

YEAR(S)	CONTRIBUTIONS:	SIGNIFICANCE:
		trajectories that account for uncertainty in spacecraft characteristics and atmospheric conditions. Allowed for unexpected or emergency conditions and failures.
1954-1957	Identified, in flight, previously predicted inertial coupling and conducted follow-on research	Provided corrective measures for inertial coupling in the F-100 aircraft and all subsequent interceptor/fighter aircraft.
1956-1962	Conceived and developed side-control stick concept and reaction control piloting techniques	Provided the technology for the first in-flight demonstration of flight control using a reaction control system on an F-104 airplane. Used a ground-based analog computer simulation and a reaction-controlled mechanical simulator, which enabled movement about three axes.
1956-1957	Demonstrated the influence of the "area rule" concept on the YF-102 and F-102A	Verified the area-rule concept and the equivalent body concept in flight using two airplanes that had the same airfoil and planform, but were designed with and without the area-rule. Also, through this effort established the eight-foot slotted-throat wind tunnel (then newly modified) as a credible transonic research facility. The area-rule subsequently became a fundamental design concept for all supersonic cruise aircraft.
1957-1958	Conceived and flew wing-glove boundary layer transition experiment on the F-104	Pioneering demonstration showing that extensive areas of laminar flow can be obtained naturally at supersonic speeds for practical wing surface conditions.
1958	Conceived and developed high-speed power-off landing techniques for low lift/drag vehicles	Flight development of safe technique for landing the X-15. Later applied to lifting bodies and Space Shuttle.
1959-1968	Demonstrated blending of reaction controls with aerodynamic controls for reentry from high-altitude rarified-atmospheric flight using the X-15 airplane	Provided methodology and demonstration of reentry control concept that was later used for the Space Shuttle.
1959-1968	Demonstrated servo-actuated ball nose on the X-15	Accurate measurement of air speed and flow angle at supersonic and hypersonic speeds.
1961-1962	Developed and evaluated piloted, unpowered paragliders as a potential method of landing spacecraft	Resulted in a practical application of the Rogallo wing concept, and enabled the birth of the modern sport of hang gliding. Evolved to proposed application for space station crew return vehicle.
1961-1963	Flew the first airplane to the edge of space — the X-15	The X-15 demonstrated reentry flight from up to sixty miles, encountering phenomena that were important in designing the Space Shuttle reentry flight profile. The following records were achieved by the X-15; 217,000 ft. on 11 Oct. 1961; 314,750 ft. on 17 July 1962; and 354,200 ft. on 22 Aug. 1963.
1961-1965	Provided high-quality flight data to better understand hypersonic aerodynamic and heating theory along with comparable wind tunnel predictions on the X-15	Discovered that hypersonically: 1) boundary layer is turbulent, 2) boundary layer heating is lower than predicted, 3) skin friction is lower than

YEAR(S)	CONTRIBUTIONS:	SIGNIFICANCE:
		predicted, and 4) surface irregularities cause local hot spots—all of which led to improved design tools for future hypersonic vehicles, including the Space Shuttle.
1962-1967	Conceived, developed, and flew the Lunar Landing Research Vehicle	Provided the basis for realistic training vehicle for Apollo astronauts and the controls design data base for the lunar module.
1963	Simulated supersonic transport operations with A-5A aircraft	Developed FAA air traffic control procedures for future supersonic transports.
1963-1966	Developed and evaluated the lightweight lifting body, the M2-F1	Demonstrated feasibility of piloted lifting body and the controllability and landability of the lifting-body shape.
1963 to present	Developed and utilized the Flight Test Fixture Experimental Facility concept	Provided efficient, cost effective method to expose a wide variety of experiments to a real flight environment.
1965-1972	Determined responses to high-altitude gust inputs and control usage in supersonic flight on the XB-70 and YF-12	Established baseline information for large, flexible aircraft on operational handling qualities, pilot ratings, and gust (turbulence) variations with altitude for future supersonic passenger aircraft.
1965-1972	Determined atmospheric features associated with high cruise altitude turbulence	Provided high-altitude clear-air-turbulence prediction techniques for supersonic passenger transport operation.
1966 to present	Pioneered developmental work in Parameter Identification	Provided powerful analytical tools for analysis of aerodynamic characteristics of aircraft from flight response; useful in other dynamic systems analysis.
1966-1968	Performed an in-depth lift-drag project for correlation of flight and wind tunnel data on the XB-70	Most comprehensive drag correlation ever achieved; revealed sources of major inaccuracies with wind-tunnel data at transonic speeds.
1967	First in-flight experience in severe shock interaction aeroheating on the X-15 Inconel-X pylon	Elevated the shock-interaction problem to its being recognized as a key temperature constraint on future hypersonic aircraft. The knowledge gained from this was first applied to the Space Shuttle.
1967	Developed the constant angle-of-attack test technique for in-flight ground-effect measurement on the XB-70 and F-104	Provided an efficient approach to obtain aerodynamics ground-effects data. Obtained evidence that aerodynamic ground effect is influenced by sink rate.
1968-1972	Identified the effect of dynamic pressure fluctuations on engine stall using the F-111A	Verified that high-frequency pressure fluctuations cause engine stalls and improved design methodology for F-15, F-16, and F-18 airplanes.
1970 to present	Developed highly flexible flight simulation methodology	This methodology was applied to flight testing of most complex envelope-expansion efforts and also to pilot training, mission planning, and ultimately to aircraft system flight qualification. Flexible, friendly user interface allows productive operation by the individual user with little or no support.

YEAR(S)	CONTRIBUTIONS:	SIGNIFICANCE:
1971-1986	Developed Remotely Piloted Research Vehicle concept using ground-based FORTRAN programmable computers to emulate crucial flight control systems and to provide ground-based cockpit and displays	Allowed the pilot to demonstrate concepts in flight from ground cockpit, and enabled rapid idea-to-flight demonstration of advanced control and display concepts without extensive validation and verification. Unpiloted 3/8 scale F-15 was able to quickly emulate full-scale F-15 and provide flight data in hazardous high angle-of-attack regime prior to exposing full-scale piloted airplane to those conditions. Also unpiloted HiMAT took advanced aerodynamic design concept and structural materials to flight much earlier than piloted aircraft could have.
1971- 1988	Evaluated the supercritical airfoil concept on the F-8 SCW, F-111 TACT, HiMAT, AFTI/F-111, and X-29	F-8 Supercritical Wing (SCW) research provided early and thorough demonstration and analysis of the supercritical airfoil in flight. Later applications demonstrated the affects of various plan-forms and sweep. Supercritical airfoils are now widely used throughout the world.
1972-1973	Conducted a pioneering thermal calibration and separation of aero- loads for Mach 3 YF-12 airplane	Demonstrated that thermal loads can be separated from flight loads by a combination of laboratory and flight results.
1972	Flew first aircraft with full digital flight control system with no mechanical backup on the F-8 DFBW (Digital-Fly-By-Wire)	Laid the groundwork for and proved the concept of digital fly-by-wire application that later flew operationally in the Space Shuttle, F/A-18, B-2, and the current generation of commercial transports.
1973-1978	Developed sensor system for precise measurement of true gust velocity and demonstrated it at high supersonic cruise altitudes on the YF-12	Provided highly improved reference measurement methods for load alleviation and propulsion system evaluations in high-altitude turbulence.
YF-12: 1973-1974 T-37: 1981	Demonstrated light-bar artificial horizon (peripheral vision display), tested on the YF-12 and T-37	Concept incorporated in operational SR-71 fleet as improved indicator of horizon through laser projection.
1974-1981	Applied aerodynamic lessons learned in flight to ground vehicle (truck or motor home) drag reduction	Verified effectiveness of air deflectors and defined the benefits of full streamlining. Results contributed to fuel savings estimated at 15 million barrels per year.
1974-1976	Flight tested an integrated digital propulsion control system on the F-111	Demonstrated performance and stability improvements with digital inlet/engine control systems, technology applicable to the F-22 and High Speed Civil Transport.
1974-1978	Performed in-depth mixed compression inlet research on the YF-12	Interpreted and documented pressure recovery, distortion, unstart and stall dynamics, and control for engine inlets; compared results to full scale and subscale wind tunnel test results. This technology was intended for the supersonic transport concept.
1975-1977	Conducted power-off landings to measure airframe noise on the Jetstar and AeroCommander airplanes.	Basic airframe noise "floor" documented for establishing engine noise reduction goals.

YEAR(S)	CONTRIBUTIONS:	SIGNIFICANCE:
1975-1977	Conceived and flew the YF-12 hollow-cylinder "Cold Wall" experiment	Benchmark, laboratory-quality fluid-mechanics experiment. A major contribution to predicting aerodynamic heating.
1975-1977	Flew the redundant computer systems with the associated algorithms in the F-8 DFBW	Tests provided confidence for flight-worthiness in the digital control concepts. They revealed many modifications that had to be made before being flown in the Space Shuttle.
1975-1978	Developed and demonstrated a Mach 3 cruise autopilot on the YF-12	Accuracy of altitude control and ride quality was greatly improved.
1975-1981	Investigated wing tip vortices behind bombers and transports with probe airplanes	Assessed vortex strength on trailing aircraft to evaluate separation distance and evaluated flap configurations for hazard attenuation.
1976	Demonstrated agility and turn capability at elevated load factors as well as overall flying qualities of the YF-17 Aircraft	Extended the agility and performance standards for the next generation of fighter aircraft.
1976 to present	Pioneered research efforts in unpiloted, non-airbreathing, high-altitude loiter aircraft technology	This technology provided a capability for high altitude atmospheric study of the ozone layer and greenhouse effects. Also has the potential for use in studying and surveying within the atmosphere of Mars.
1977-1980	Studied the effects of time delay for digital flight control systems on the F-8 DFBW	This flight research quantified the effect of pure time delayed response occurring in digital systems. These delays can cause serious safety problems for aircraft and spacecraft.
1977-1981	Conceived, developed and tested a pilot-induced-oscillation suppression system for the Space Shuttle	Developed flight control system modifications to reduce pilot induced oscillations during landing of the Space Shuttle.
1977-1986	Performed theoretical and experimental buckling research	Enabled determination of design guidelines and buckling characteristics for hypersonic wing panel without destroying the test part.
1978	Performed benchmark flight research using the 10-Degree-Cone boundary-layer transition experiment on the F-15	Provided benchmark reference of flow quality for transonic and supersonic wind tunnels, and a rational means for rating the various tunnels for flow quality.
1978	Developed and flew a cooperative integrated propulsion/flight control system on the YF-12	Improved flight control precision and reduced the occurrence of inlet unstarts. Incorporated in the operational SR-71 fleet.
1978-1980	Conducted comprehensive study of variable-geometry external compression inlet on the F-15	External compression inlet pressure recovery, steady state and dynamic distortion, drag, and lift were measured in flight and compared to wind-tunnel and analytical methods; also documented effects of scale and Reynold's number.
1978-1985	Demonstrated in flight and improved a NASA aileron/rudder interconnect concept on the F-14	Improved departure spin resistance for the F-14 aircraft. Final product to be incorporated into fleet for F-14 models A, B and D.

YEAR(S)	CONTRIBUTIONS:	SIGNIFICANCE:
1978-1992	Evaluated and improved an in-flight wing deflection measurement system used on F-111/TACT, HiMAT, X-29 airplanes	Applied an electrical-optical system that provides digital data more precisely and with greater ease than photographic methods.
1979-1981	Evaluated the winglet concept on the KC-135 airplane	Defined the potential for drag reduction and increase in range for large transport-type aircraft for various aero load conditions. Concept now applied to many transport and business aircraft.
1979-1981	Evaluated oblique wing concept using the AD-1 airplane	Evaluated low-speed oblique-wing flying qualities, stability, and control at asymmetric sweep angles up to 60 degrees. The concept was proposed for supersonic transport and military applications.
1979-1995	Evaluated non-intrusive air data pressure source arrays on the KC-135, F-14, and F-18	Related applications followed on atmospheric research aircraft, military derivative systems, high angle-of-attack (AoA) research aircraft, and potentially for reentry vehicles. Concepts were extended through the transonic region and to extremely high AoA.
1980	Pioneered the development of fiberglass wing glove technique for high performance airfoil flight research	Provided a low cost method to evaluate innovative high-speed airfoil concepts at full-scale flight conditions.
1980-1983	Conceived and tested flight test trajectory guidance algorithms	Integration of flight-test parameters into single display allowed pilots to fly different flight-test maneuvers more accurately and get higher quality data.
1981	Conceived and tested the flight test maneuver autopilot	Automated the flight test trajectory guidance system to fly flight research maneuvers to produce more repeatable and more accurate data.
1981-1987	Performed in-flight testing of Shuttle tiles for air-load endurance and rain damage	Established criteria for orbiter tile erosion in moisture. Altered launch criteria in rain, and restricted ferrying the Shuttle cross country in bad weather.
1981-1984	Evaluated Digital Electronic Engine Control on the F-15	Flew contractor Digital Electronic Engine Control in flight and suggested and tested improvements.
1981 & 1987	Pioneered in-flight boundary layer transition experiments for effects of wing sweep on the F-111 and F-14	Provided empirical understanding of the effects of sweep on boundary layer transition. Established that extensive lengths of natural laminar flow can occur on a lifting surface (wing).
Hidden Line: 1982 Silhouette: 1986	Developed generalized and practical solution to the hidden-line problem and the silhouette problem	A powerful addition to computer graphics which resolved the problem of perspective and silhouettes in computerized designs, now commonly used in all types of applications and disciplines.
1985-1990	Conceived and developed the half-cycle theory	Provided very practical fatigue theory for life-cycle prediction of aerospace structures.
1986-1987	Conceived and tested active engine stall margin control on the F-15 Highly Integrated Digital Electronic Control flight test	Provided engine and airplane performance improvements without adding weight, used on F-15E and F-22 airplanes.

YEAR(S)	CONTRIBUTIONS:	SIGNIFICANCE:
1987-1988	Quantified the effects of engine control system delays on flying qualities on the F-104	Provided criteria for digital engine control design for use in precise formation flying.
1991-1996	Evaluated propulsive control (thrust vectoring) on HARV and X-31	Significant enhancement of high angle-of-attack agility and maneuverability. Made significant contribution to applicability of computational fluid dynamics (CFD) to high angle-of-attack flows by providing comparison of CFD, wind-tunnel and flight data at the same scale.
1992	Invented the Anderson Current Loop for evaluating signals from sensors	Potential major improvement over the classical Wheatstone Bridge circuit used in applications such as stress measurement.
1993	Demonstrated the Smart Actuator controlled with an optical data link on the F-18 Systems Research Aircraft	Electronics that close the flight control loop are built into the control surface actuator rather than in the flight control computer. Reduced the many wires that normally connect an actuator with the primary flight control computer to four fiber optic cables. Reduced aircraft weight and vulnerability to electro-magnetic interference.
1993-1994	Conducted inlet research at extremely high angle of attack on F-18 HARV	Inlet high frequency pressure recovery and distortion measured at angles of attack up to 100 degrees and in spins, providing data for vertical short take-off and landing (VSTOL) and agile fighter airplanes.
1993-1995	Conceived and tested emergency flight control using computer-controlled engine thrust in the F-15 & MD-11	Provided safe landing for an airplane with failed flight controls—may be implemented with only software changes.
1993-1995	Conceived, and developed the Landing Systems Research Aircraft on the CV-990	Provided unique capability to test Space Shuttle tires, wheels, brakes, blow-outs, and subsystems under severe loading and landing conditions. Allowed Shuttle cross-wind landing limits to be raised by 33 percent.
1993-1995	Completely characterized the sonic boom propagation from airplane to ground	Multi-altitude measurements by probe aircraft permitted assessment of prediction techniques of sonic boom propagation characteristics in the real atmosphere.
1994	Demonstrated flow visualization in-flight of planar laser-induced fluorescence for high Reynolds number at subsonic through supersonic speeds on the F-104 Flight Test Fixture	Collected previously unavailable data for sonic transverse gas injection into crossflows from Mach numbers 0.8 to 2.0, including at Mach 1.0, that provided validation of analytical models of the same flow conditions.
1994	Demonstrated in-flight indirect optical technique for high glide-slope approaches with no direct view of the airfield on the two-seat F-104	Validated indirect optics (non-TV) as a viable concept for piloted landings without direct view of the ground. Important for hypersonic vehicles and possibly for the High Speed Civil Transport.

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Lane E. Wallace
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