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)

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

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

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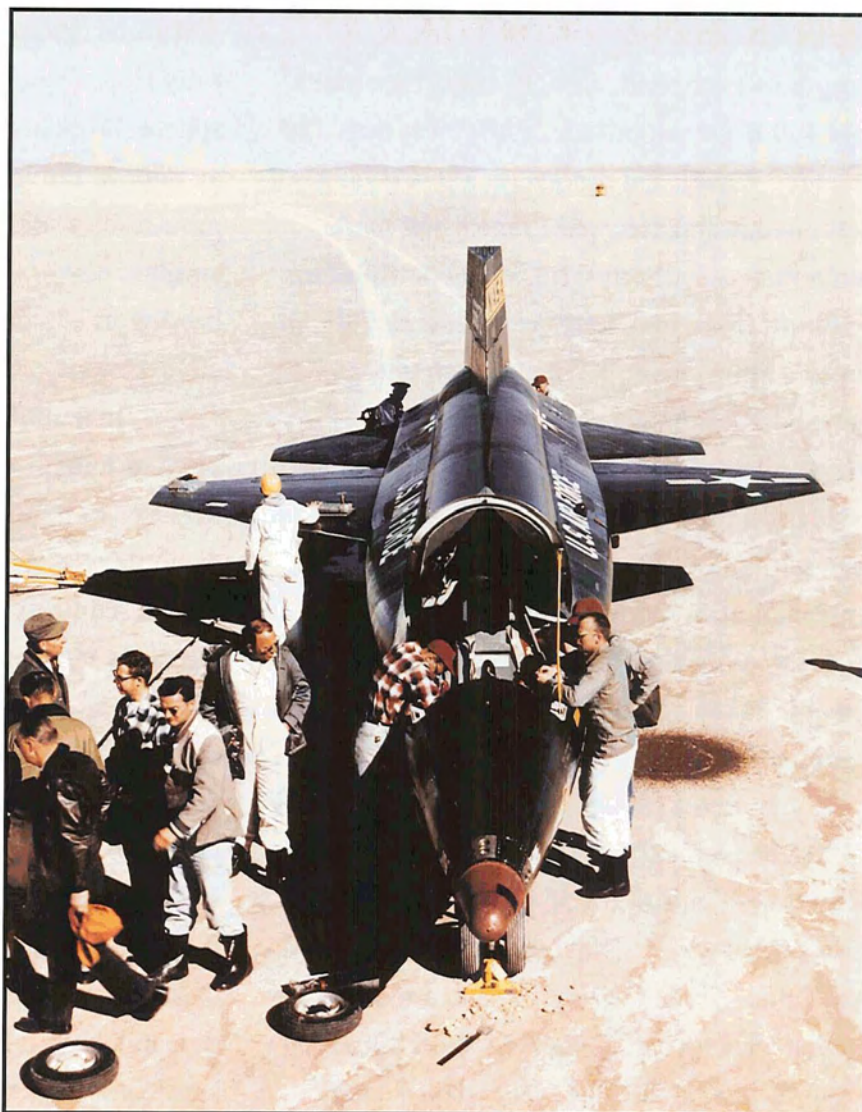
We'd get hit with totally unknown things because we were operating in an area we didn't understand. Fortunately, the airplane was overbuilt in all areas that allowed us to learn from our mistakes. We could heat cables and landing gear and crack windows . . . the X-15 could deviate from its optimum (flight)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

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

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)
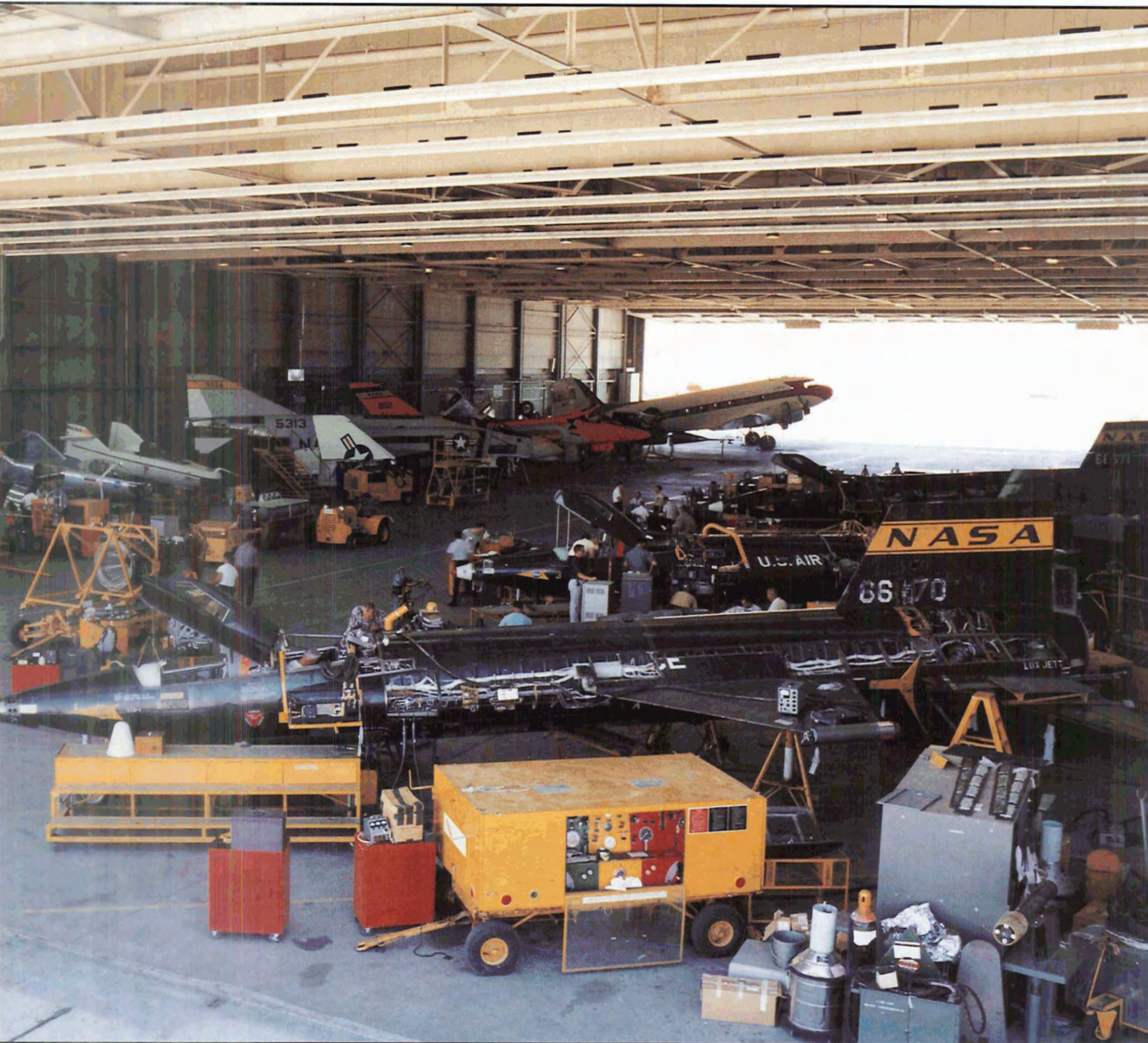
grew out of the stability problems experienced with the X-1A at high altitude and were initially researched using one of Dryden's F-104s, but reaction controls were a critical technology for not only the X-15, but also the Mercury capsule, the Apollo Lunar Landing Module, and every piloted craft to ever 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)
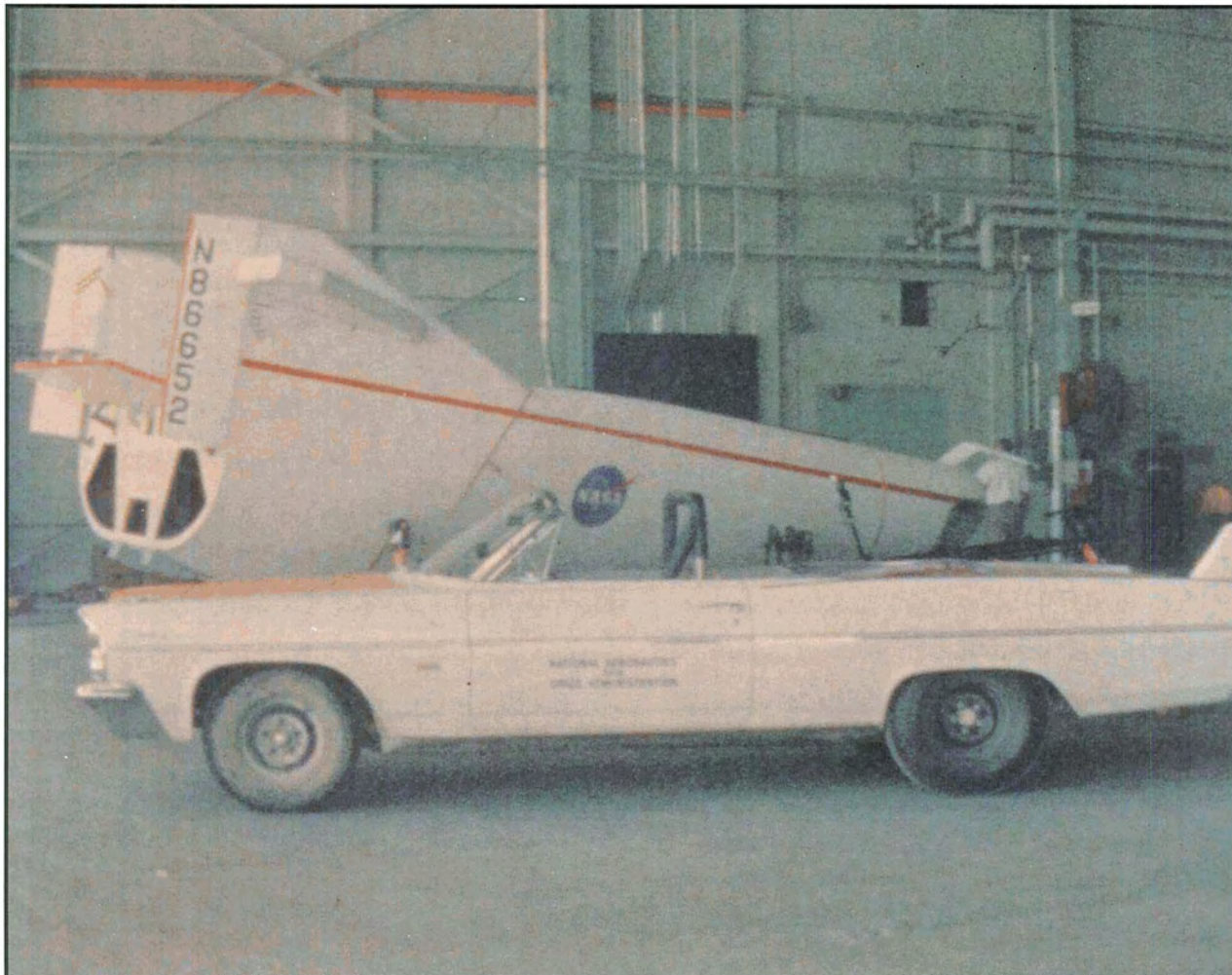
Left: M2-F1 and modified
Pontiac tow vehicle
in hangar
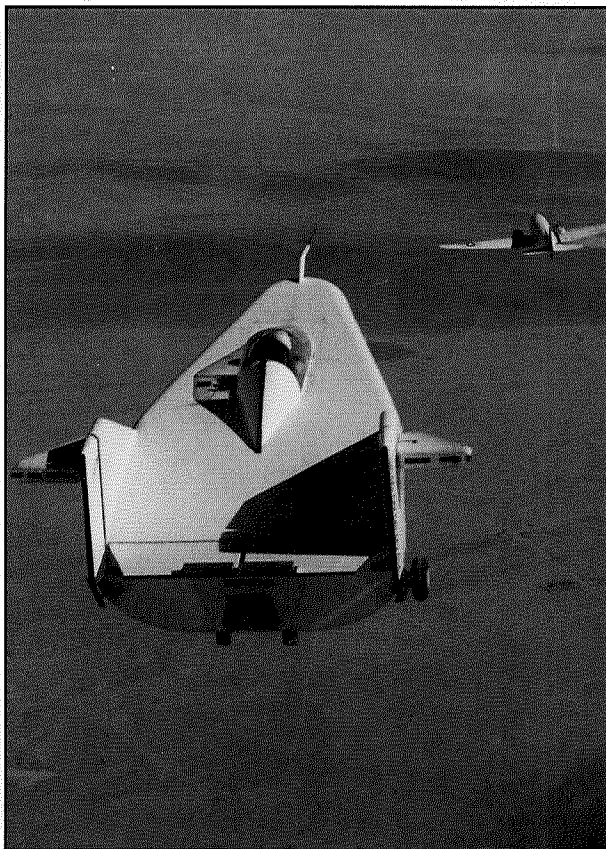(NASA Photo
EC92 04152-1)

Flights of Discovery

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

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

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.

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 Thomp-
son 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
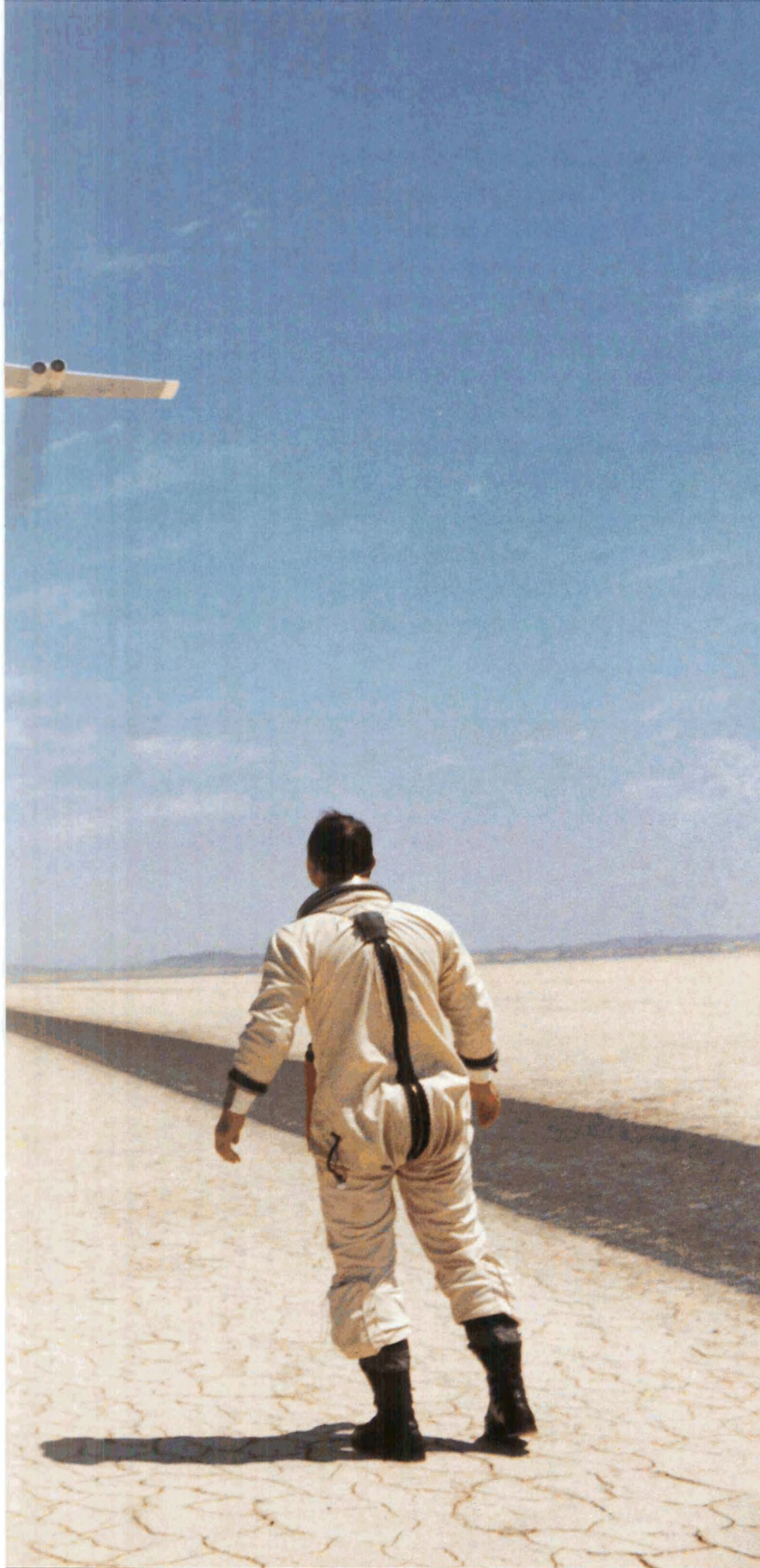
towed the aircraft to 12,000 feet behind the Center's DC-3 aircraft and Thompson successfully glided back to a lakebed landing, inaugurating Dryden's lifting body flight research program. Some people at NASA headquarters were aware of the project, but the Administrator was unaware that it had flown until, 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 approximately 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
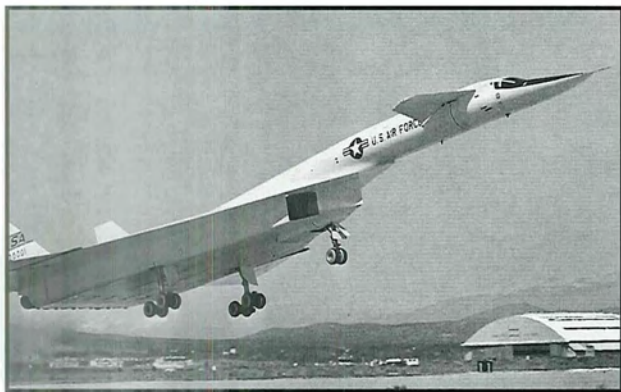
Above: XB-70 taking off
(NASA Photo E 16695)

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

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-

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
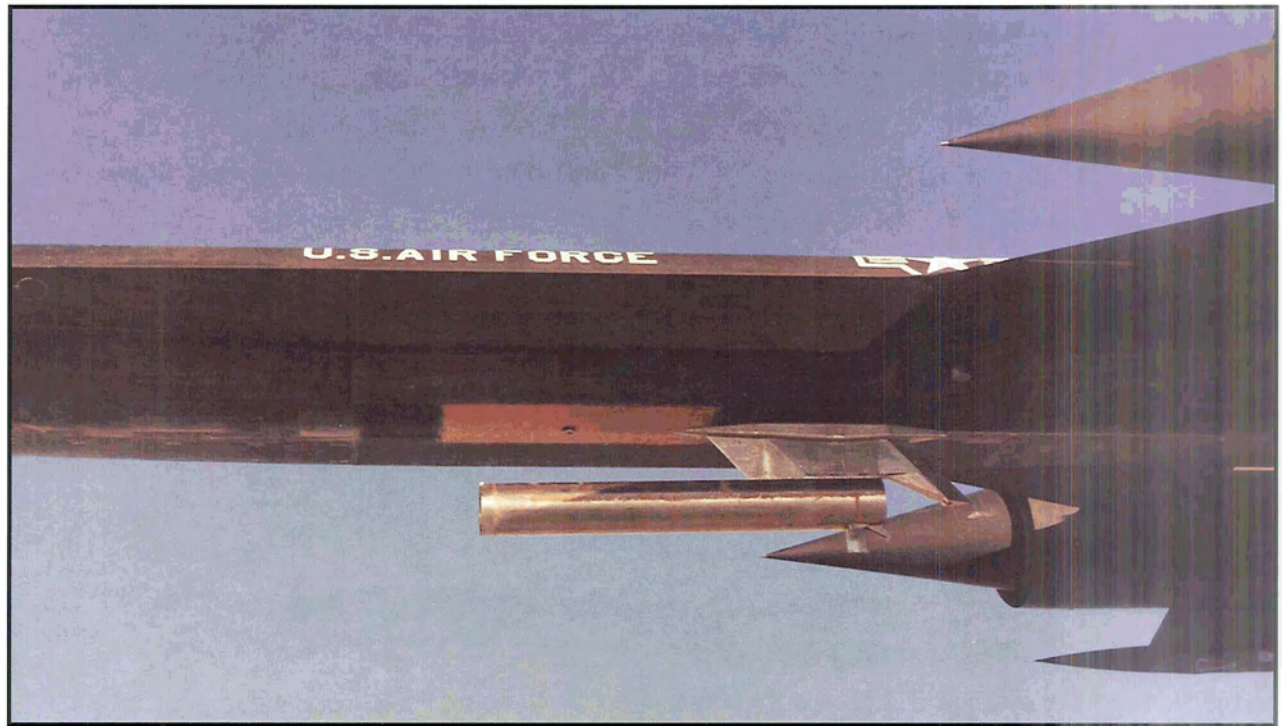
lasts forever.[45]

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-

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)

pilots to identify with, which gave them much less support both within Dryden and in the greater aerospace community as well. So Dryden's Director Paul Bikle told Reed he could build the full-scale Hyper III, but only if he included a cockpit so the Center could conduct follow-on piloted flight research if the radio-controlled work went well.

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

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]

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)

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

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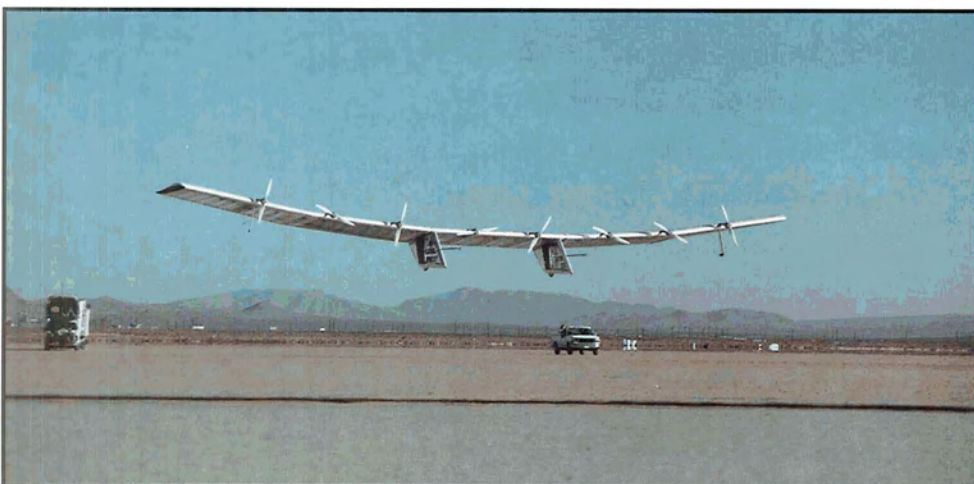
Research Aircraft Act. The act revised nearly 100-year old restrictions imposed by the Sherman Antitrust Law prohibiting any kind of cooperative research and development effort among competing companies.

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]

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 foot [49] 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.
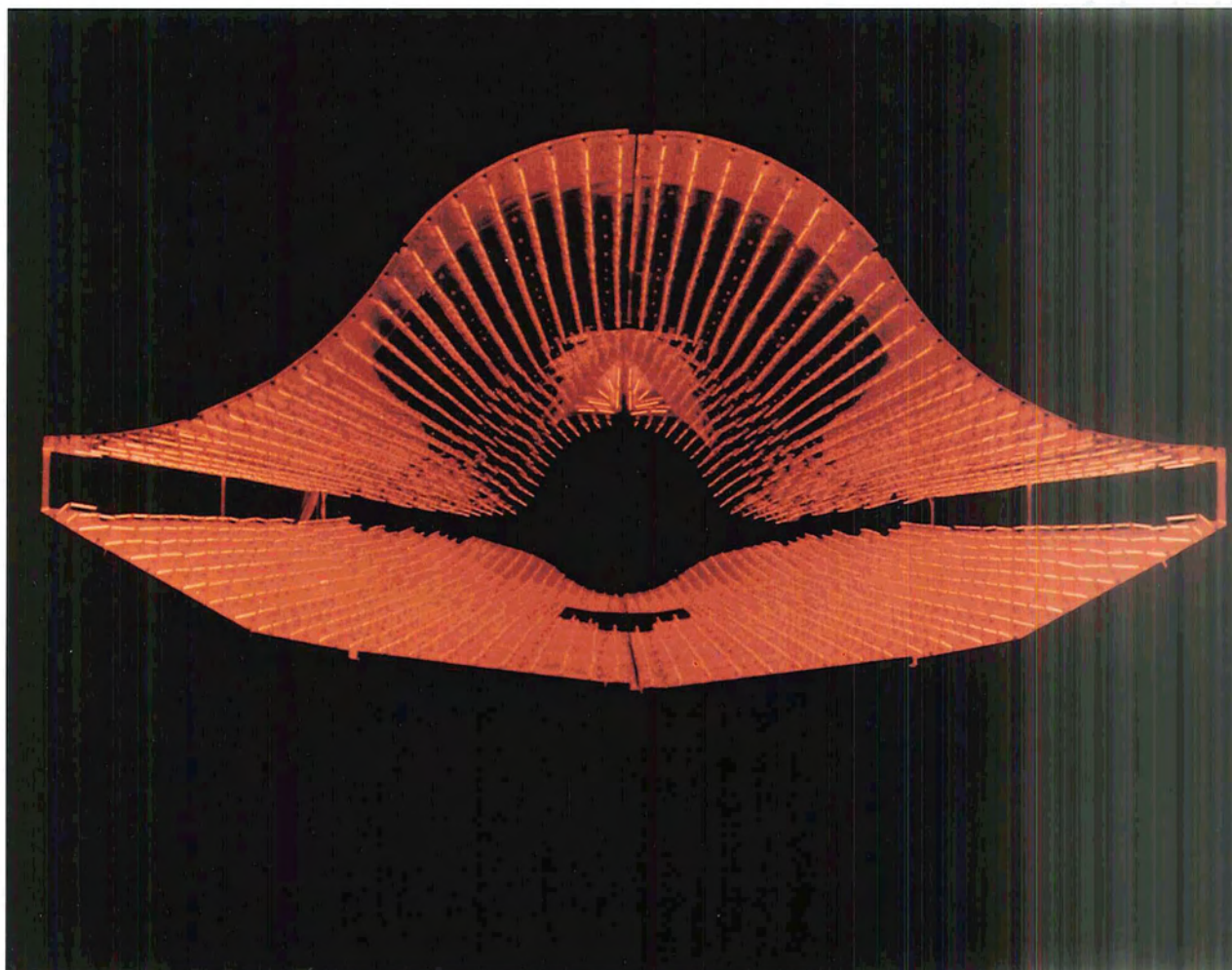
YF-12 forebody heater undergoing a lamp check in the Thermal Loads Facility for a Mach 3 heating simulation to support **flight loads research** *on supersonic aircraft. The facility, which has gone under different names over the course of its history, was constructed in 1965 to perform combined mechanical and thermal load tests on structural components and complete flight vehicles. The measurement of str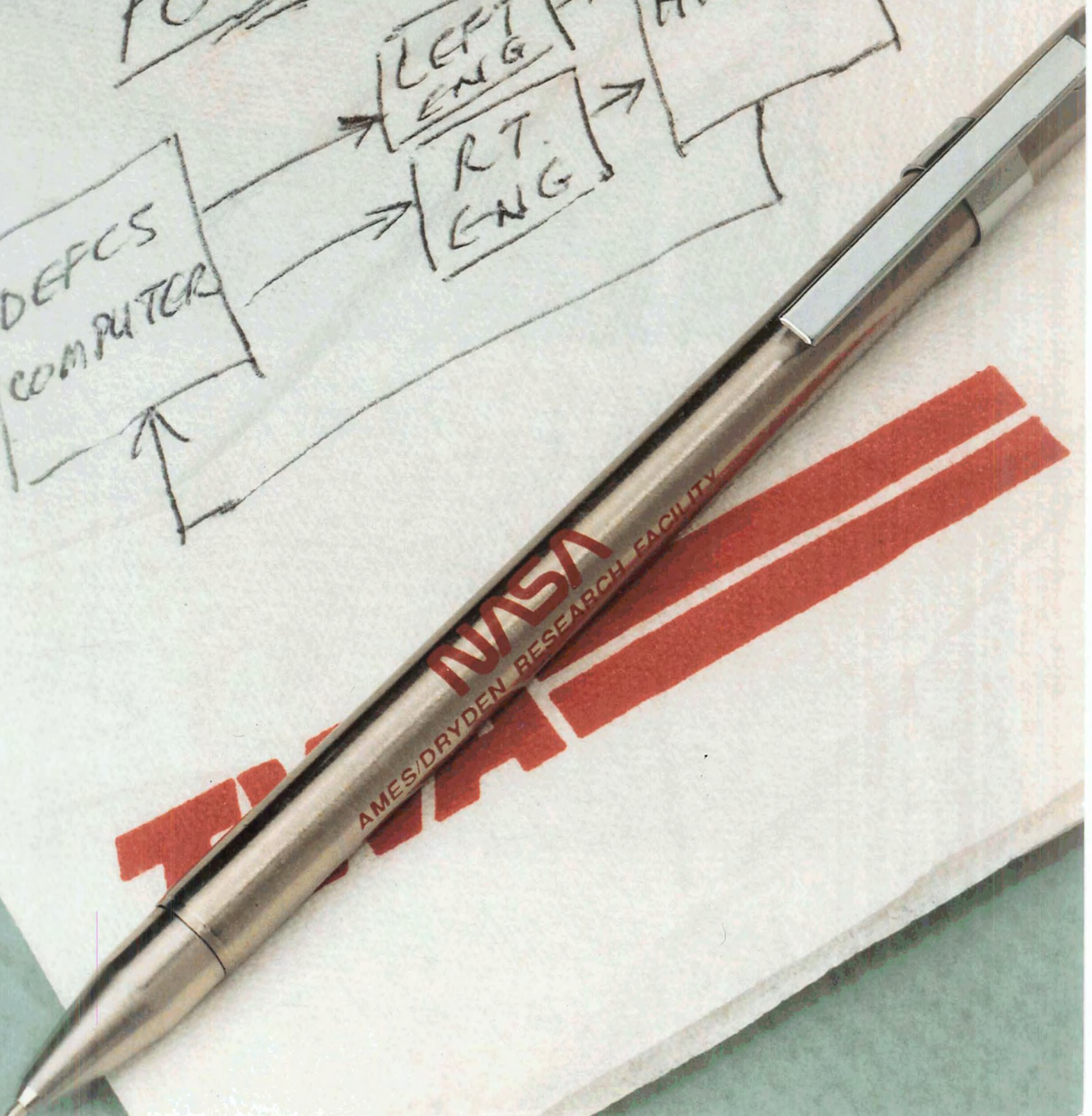uctural loads had long been an important part of flight research through the use of strain gauges to measure the forces operating on the aircraft structures, but this method only worked at subsonic and transonic speeds. At the supersonic speeds of the YF-12, the high temperatures produced by friction 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 impor- tance for the design, structural integrity, and safety of future supersonic and hypersonic aircraft.* (NASA Photo EC71 2789)
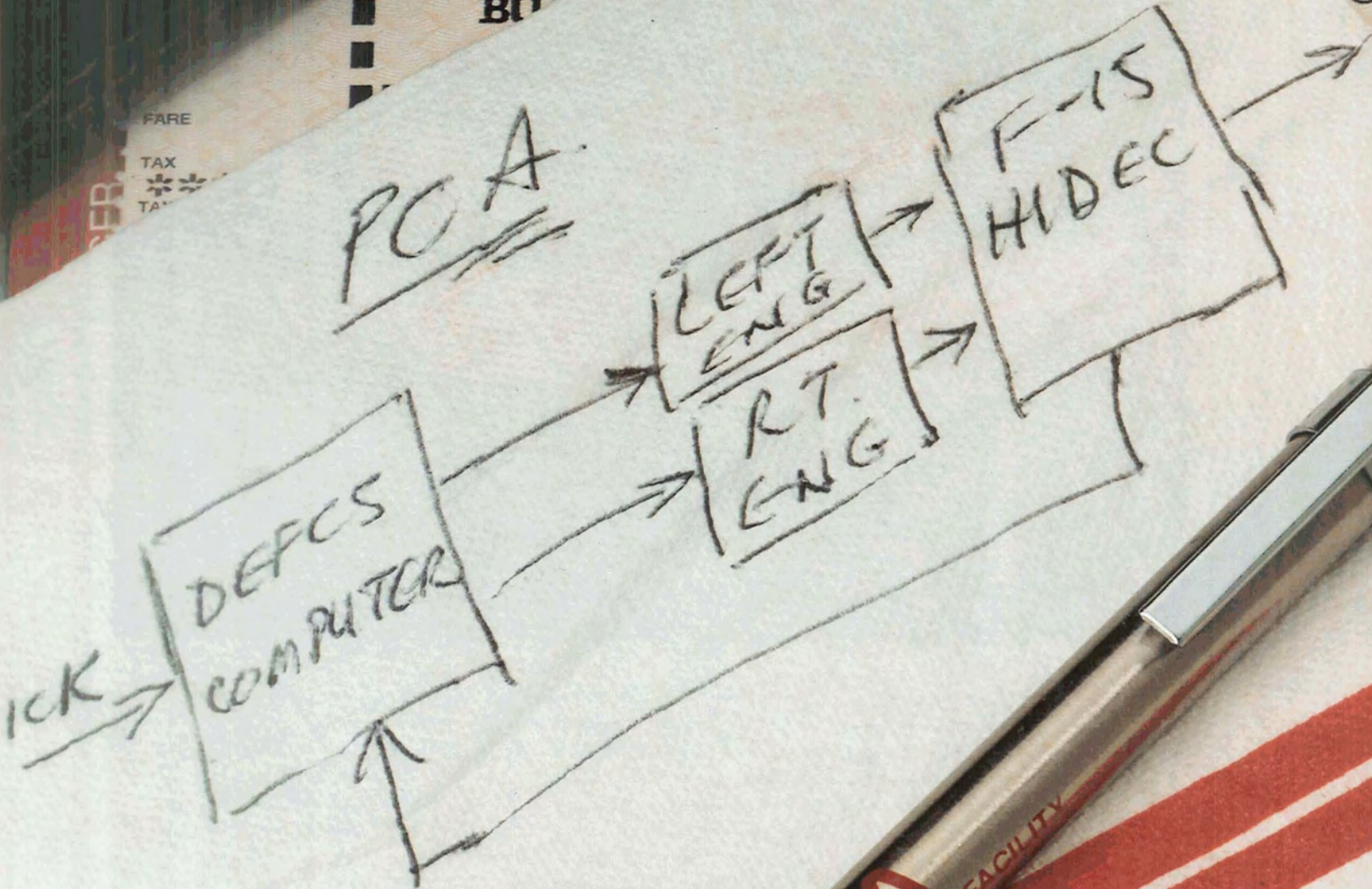
▶ Chapter Four:
Improving Efficiency, Maneuverability and Systems

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; HIDEC stands for Highly Integrated Digital Electronic Control. (NASA Photo EC94 42805-1)
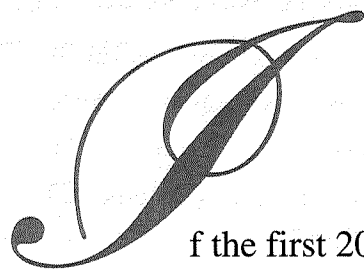
f the first 20 years of planned, exploratory flight research at Dryden focused predominantly on developing aircraft that could fly higher and faster, the second 20 years were characterized by research efforts to allow aircraft to fly "better." Almost two dozen flight programs at Dryden since the late 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]

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

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 separation[5] 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

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

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

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

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

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 configura-tion for a flight research program.

The winglets were installed on a KC-135A[8] 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
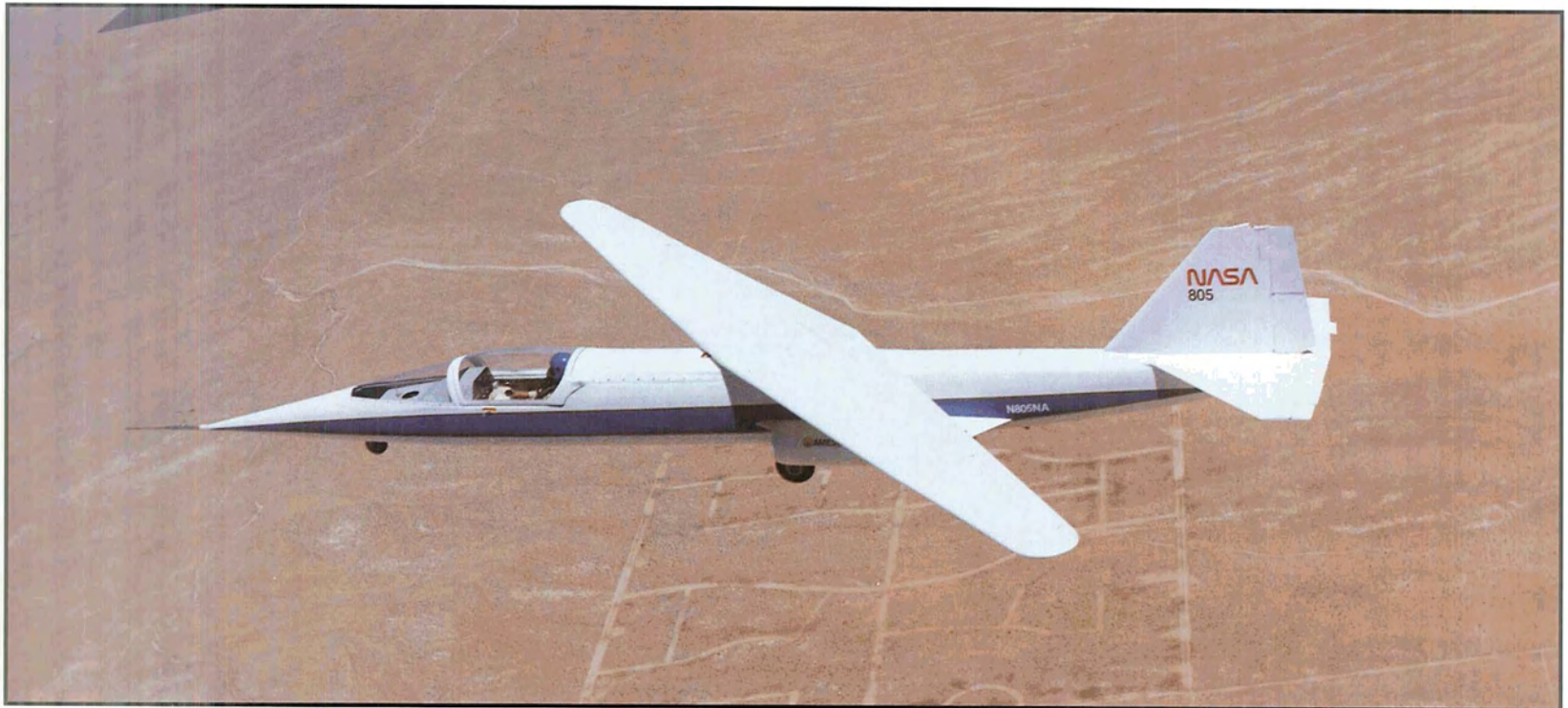
jets, including the Gulfstream III and IV business jets, the Boeing 747-400 and McDonnell Douglas MD-11 airliners, and the McDonnell Douglas C-17 military transport.[9]

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)

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

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]

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 naturally.[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.
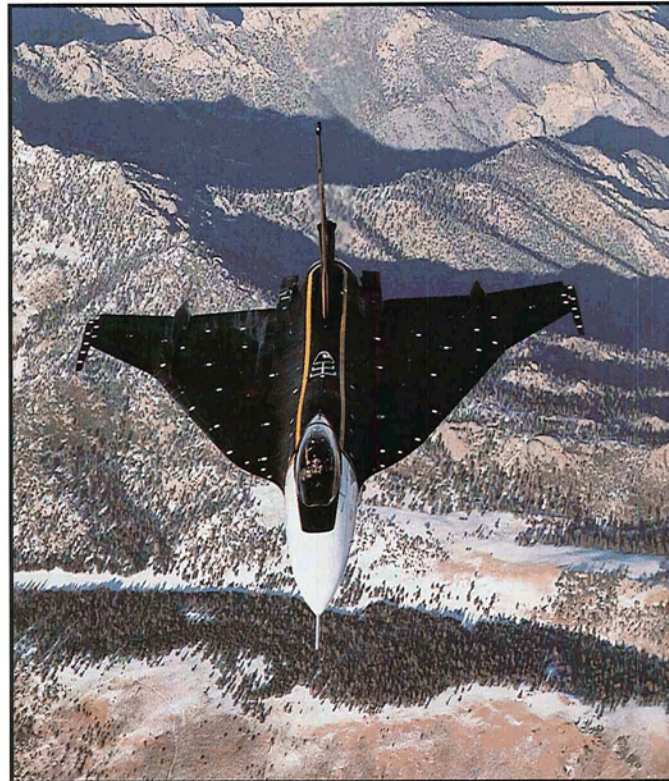
The newest set of experiments uses a titanium glove approximately four times as large as the initial test section. It is perforated with 12 million microscopic holes and the active laminar-flow control is provided by a modified Boeing 707 cabin pressurization pump. The goal of the flight research program, 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

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)

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 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)

program that began in the late 1970s. The HiMAT was a jet-powered, remotely-piloted vehicle that incorporated numerous advanced design features, including a computerized flight control system, a forward canard, a swept wing, and graphite-and-fiberglass composite construction.[13] The HiMAT was approximately half the size of a production 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 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.

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.

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

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

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

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

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 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 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 lakebed 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]

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

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 overcome 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 HARV [18] 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

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-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-vectored 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-carbon[21] 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

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 to-
gether 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 infor-
mation 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 asym-
metrical 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 engi-
neer 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 con-
trolled 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)
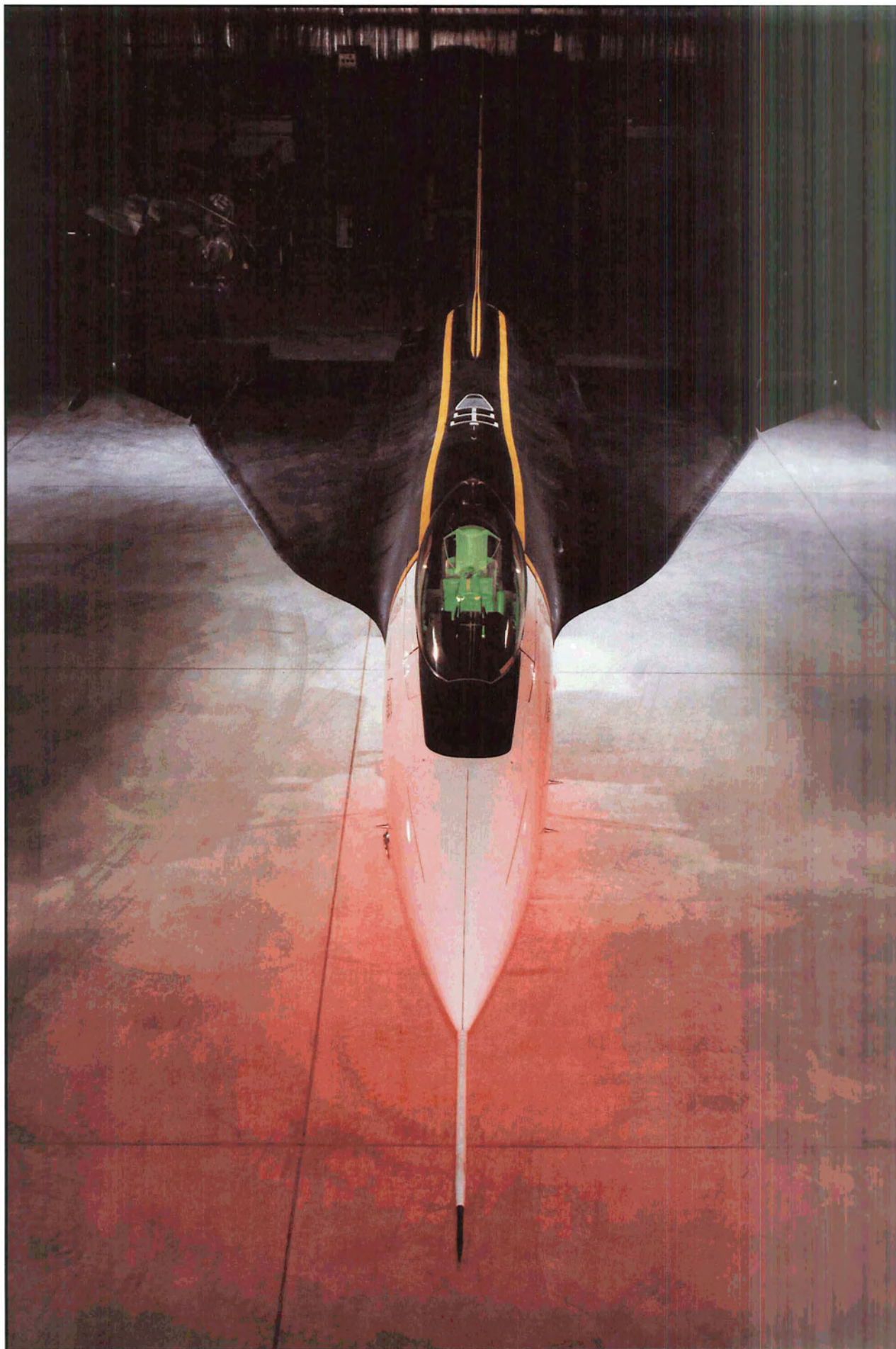
and modifications, the program became extremely successful. In addition to simply achieving controllable maneuvering flight at angles of attack up to 70 degrees, the aircraft clearly demonstrated the tactical advantage thrust-vectoring could give a fighter. Simulator experiments predicted that the X-31 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 tube[23] iced over, which sent incorrect airspeed information to the flight control system. "Thinking" the aircraft was traveling slower than it was, the control system commanded 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-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.

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.

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 validation [25] 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

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 (RE-BUS), 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

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]

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," 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 HIDEC 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 HIDEC 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 HIDEC/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 gimballing 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 HIDEC 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 gimballing 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.