

# From Research to Relevance

*Significant Achievements  
in Aeronautical Research  
at Langley Research Center (1917–2002)*

## Introduction

Advances in aviation have rapidly evolved since the Wright brothers performed the first successful piloted, controlled, and sustained powered flight on the sand dunes of Kitty Hawk, North Carolina, on December 17, 1903. However, at every step forward for this remarkable development of flying machines came major barriers and continuous encounters with the complex technical phenomena surrounding the science of flight. In 1917, the National Advisory Committee for Aeronautics (NACA) established Langley as its laboratory for identifying and finding solutions to the many challenges of aviation. Langley pioneered new technologies and concepts that have helped to transform the United States into a world leader in aviation. In 1958, Congress created the National Aeronautics and Space Administration (NASA) and the NACA laboratory became the Langley Research Center. The scope of research performed at this “center of aeronautical excellence” is unique. While literally tens of thousands of highly successful research projects conducted by Langley could have been mentioned, this book is intended to discuss, in the author’s opinion, the research center’s most significant achievements in aviation over the past 85 years. The selected contributions are vivid examples of the value of national investments in research and development, and the transition from research to relevance.

*By  
Mark A. Chambers*

## NACA Cowling—1928



Curtiss Hawk AT-5A with NACA cowling during flight tests at Langley.

By 1928, numerous new aircraft designs for military and civil applications appeared around the world. Wood and fabric biplane designs were being replaced with more modern corrugated aluminum monoplane designs. However, these newer designs still suffered from degraded performance because of the effects of aerodynamic drag. Many of these aircraft flew with radial engine components exposed to the air, producing excessive drag from the air flowing over exposed cylinders and structure, dramatically reducing the efficiency and top speed of the aircraft. It was recognized by the engineering community that a large part of the overall airplane drag was caused by the exposed engine. However, the critical challenge existed to develop drag reduction approaches that would improve performance, yet not impede the aerodynamic cooling necessary for the radial engines. In response to this design dilemma, NACA Langley was asked by the United States Navy and

members of the aviation industry to undertake a research effort to develop a solution for the engine-related drag problem.

In response to the national request, Langley conceived candidate engine enclosures, or cowls, performed wind-tunnel and flight-research tests of various Navy and civilian aircraft that were outfitted with different types of engine cowls, and evaluated the performance and cooling characteristics. The concept developed by the

*To develop the specific cowl shapes, Langley evaluated different cowls on full-scale aircraft in its Propeller Research Tunnel (PRT).*

Langley staff was to direct the airflow over the engine, which was enclosed by a cowl, reducing the aerodynamic resistance of the cylinders and other engine components while maintaining adequate cooling flow. To develop the specific cowl shapes, Langley

evaluated different cowls on full-scale aircraft in its Propeller Research Tunnel (PRT). From these efforts, a new low-drag cowling was derived. The U.S. Army Curtiss Hawk AT-5A, a pursuit biplane, became the first aircraft to feature an NACA cowling and the performance gain was impressive: a 19-mph boost in speed. The aeronautical industry regarded this concept and its demonstrations as a major breakthrough in aircraft performance and design methods. As a result of Langley's highly innovative low-drag cowling research, it was awarded the prestigious Collier Trophy, recognizing aviation's greatest achievement for the year 1929. The NACA cowling was rapidly applied to civil transports, such as the Fokker Trimotor, and by the outbreak of World War II the innovation was a standard feature on most fighters and bombers of both Allied and Axis nations.<sup>1</sup>

“Drag cleanup” was one of the most significant research contributions of the NACA at the beginning and throughout the course of World War II. During the latter 1930s and into the 1940s, military aircraft suffered severe limitations in top speed capability and operational options because of aerodynamic drag. Dedicated engineers at Langley focused their efforts on the development of detailed design information that would identify the major sources of drag on the airplane configuration and suggest approaches to mitigate the performance-degrading effects. The engineers conceived and developed an analysis approach in which actual full-scale aircraft, or large aircraft components, were mounted in the 30- by 60-foot test section of Langley’s monstrous

*By the end of the war, over 30 airplanes had undergone the Langley approach, with substantial improvements in virtually every case.*

Full-Scale Tunnel to evaluate and quantify drag-producing components, resulting in critical information for aircraft companies on how to modify their designs so that they would experience less drag in flight. Initial drag cleanup studies were performed in response to a request from the Navy on the Brewster XF2A-1 Buffalo prototype fighter aircraft. Results of the test program were extremely impressive. The data indicated that if simple changes were made to the airplane surfaces, such as sealing certain gaps and cracks, the speed of the airplane could be increased by 25 mph.

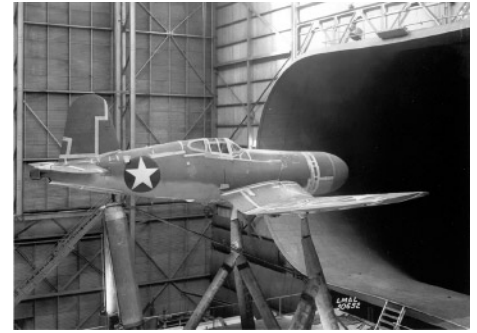
Subsequent flight tests of the modified airplane validated this prediction. The Nation’s military officials immediately took a keen interest in this practice, noting that it presented a solution to performance degradation, could be performed in a short period of time during the early stages of an airplane development program, and did not incur great costs. Consequently, the military asked NACA Langley to perform studies on almost every prototype aircraft coming off the assembly lines.

The practice of drag cleanup involved mounting an actual aircraft in the Full-Scale Tunnel, removing antennas, covering cracks and crevices with tape, sealing canopies, and taping up gun fairings and mounts. Evaluations of the sources of drag on the

streamlined aircraft were then performed. In the process, the researchers began to peel off the tape piece by piece, mea-

suring the drag generated by each component of the aircraft and that generated by modifications to some components. The findings were then documented in a report that also offered suggestions on how to improve the aerodynamic design of the aircraft. The wind-tunnel tests were followed up with flight-research tests of the actual aircraft to verify these suggestions.

Bell Aircraft’s P-39 Airacobra served as a testament to the quality and efficiency of Langley’s drag cleanup studies. Upon its arrival at Langley,



Vought F4U Corsair undergoing drag cleanup tests in the Langley Full-Scale Tunnel.

the Airacobra could achieve a maximum speed of 340 mph. By the time Langley completed its evaluations, which took only two months, the Airacobra had gained over 50 mph in speed, up to 392 mph, allowing the aircraft to qualify for Army use. By the end of the war, over 30 airplanes had undergone the Langley approach, with substantial improvements in virtually every case. Well after World War II, the findings generated from Langley’s drag cleanup reports have continued to be used by researchers and industry to improve the performance and efficiency of general aviation aircraft.<sup>2,3</sup>

# Airfoil Technology—1942



The North American XP-51A Mustang utilized the Langley-developed laminar-flow airfoil.

The science of efficient wing design, with its challenges of providing low drag for cruise conditions while ensuring low-speed capability for takeoff and landing, has been a focus of researchers since the earliest days of manned flight. At Langley, initial NACA research into airfoils that could be integrated into wings and meet demanding objectives started with analytical studies in the early 1920s. Between 1929 and 1934, Langley developed more than 100 different airfoil sections. When the Low-Turbulence Tunnel came on line in the late 1930s, Langley had some of the most advanced tools in the world at its disposal to conduct systematic studies of a broad series of airfoil shapes. In coordinated tests with other wind-tunnel facilities, researchers derived highly efficient airfoils for various missions, including advanced high-lift concepts for low-speed flight. One of the most significant contributions of this research involved the development and worldwide distribution of

data on a large family of airfoils, regarded as the most influential contribution toward airfoil development for many years. During World War II, the continuing quest for improved performance of military aircraft led to the adoption of a breakthrough technology at Langley known as the laminar flow airfoil. One of the most famous applications was to the P-51 Mustang

*Between 1929 and 1934, Langley developed more than 100 different airfoil sections.*

fighter, for which the wing drag could theoretically be reduced by nearly half. In 1941, the new Low-Turbulence Pressure Tunnel (LTPT) became a workhorse to develop more advanced airfoils and further optimizations of low-drag wings, which were immediately applied to the Nation's military aircraft.

Following World War II, world interest in airfoil development subsided

until the early 1970s, when progress in supercritical airfoils for commercial transport applications and emerging computational tools inspired new research for advanced general aviation applications. Recognizing the significant improvements afforded by new airfoil design methods and facilities, Langley initiated a new program for low- and medium-speed airfoils ap-

pplicable to business jets and propeller-driven general aviation aircraft. Using the LTPT and computer codes,

researchers closed the loop from airfoil design and testing to validation using research aircraft. From this research effort, new laminar flow airfoils emerged and were applied to new aircraft. In addition, new computer-based design methods were developed and validated for distribution to industry.<sup>3,4</sup>

## Slotted-Throat Transonic Tunnel–1946

One of the most significant achievements in wind-tunnel operational design and capability was NACA Langley's development of the slotted-throat transonic tunnel in 1946. After World War II, the wind tunnel became an important research tool in developing design procedures for aircraft that could conquer the sound barrier. As the airflow speed in wind tunnels approached the speed of sound, however, the wind tunnels began to "choke" because of compressibility effects and shock waves in the tunnel test sections. Moreover, researchers also discovered that the walls of wind tunnels interfered with accuracy of the data measurements within the tunnel. As a result of these limitations, further use of wind tunnels for high-speed aerodynamic research faced a dismal future. The solution, conceived and developed by Langley researchers, was to strategically position a series of slots at critical locations in

*The slotted-throat tunnel first became operational in the Langley 8-Foot High-Speed Tunnel in 1950.*

the throat of the wind tunnel's test section. With the modifications, the erroneous effects of shocks and extraneous compressibility effects were minimized and it became possible to evaluate aerodynamic characteristics of aircraft models through the speed of sound. This feature became critical to the study of supersonic fighter and bomber aircraft designs in the years to follow. The slotted-throat tunnel first became operational in the Langley 8-Foot High-Speed Tunnel in 1950.



Slotted-throat test section of the Langley 16-Foot Transonic Tunnel.

Slotted throats were also applied to the 16-Foot High-Speed Tunnel, as well as other high-speed wind tunnels at NACA Langley. It was, however, in the 8-Foot High-Speed Tunnel, following the application of a slotted throat, that revolutionary aerodynamic breakthroughs, such as the area rule, supercritical wings, and winglets (mentioned later in this book), were discovered. As a result of its precedent-setting slotted-throat tunnel research, NACA Langley was awarded the Collier Trophy in 1951.<sup>5</sup>

## Area Rule—1953



Dr. Richard T. Whitcomb with a Convair F-106, an aircraft designed with the principles of the area rule.

In 1953, Richard T. Whitcomb of NACA Langley conceived one of the most valuable aerodynamic design concepts ever developed at Langley. The design concept, known as the area rule, was the product of intense research performed in the Langley 8-Foot High-Speed Tunnel to reduce the enormous increase in aerodynamic drag encountered by an aircraft as it nears the speed of sound. This research focused on the fundamental aspects of airflow fields as aircraft passed through the speed of sound or at the transonic speed regime. Researchers experimentally visualized the presence of shock waves, analytically studied the phenomenon, and attempted to find methods of reducing the drag caused by them at transonic speeds. Whitcomb intensely pursued this goal, examining the most basic principles involved and conceiving a radical solution that would revolutionize the shape of future high-speed aircraft. In his concept, drag was decreased by reducing a portion of the area where the wing met the fuselage of the aircraft, producing a fuselage that had a distinct “wasp-waist” or

“Coke-bottle” shape. Under Whitcomb’s leadership, the “Coke-bottle” fuselage or area rule was applied to a U.S. Air Force fighter aircraft originally intended to be a delta-wing supersonic interceptor. The aircraft, the Convair F-102, was designed to serve as a frontline interceptor to counter the grow-

ing long-range nuclear bomber fleet of the Soviet Union during the Cold War. Initially, the airplane configuration featured a conventional fuselage. However, wind-tunnel studies performed under Whitcomb’s guidance in Langley’s 8-Foot High-Speed Tunnel in 1953 indicated that the drag experienced by the design in the transonic regime was too excessive for the aircraft to break the sound barrier. Flight trials of a prototype aircraft,

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the YF-102, showed that Langley’s wind-tunnel studies were correct: the aircraft was embarrassingly incapable of breaking the sound barrier. Langley convinced Convair and the Air Force that their “supersonic interceptor” would benefit greatly by application of the area rule. In 1954 the aircraft, now sporting a “Coke-bottle” fuselage and redesignated as the F-102, streaked past the elusive sound barrier in level flight with no hindrances. In recogni-

tion of this breakthrough technology, Whitcomb received the Collier Trophy in 1954 for his conception of the area rule. The area rule rescued the Air Force project and brought about a revolutionary departure from conventional aircraft design that was later applied to virtually all high-speed fighters and bombers, including the Century Series aircraft (F-100 Super Sabre, F-101 Voodoo, F-104 Starfighter, F-105 Thunderchief, F-106 Delta Dart), the F-4 Phantom II, B-58 Hustler, and B-1 Lancer. The area rule was also later applied to civil transport aircraft in situations involving the mitigation of strong shock waves emanating from components, such as engine nacelle, wing, and pylon interactions.

## Externally Blown Flap—1955

During the mid-1950s, experimental research was performed at Langley to identify concepts or devices capable of reducing the takeoff and landing field length requirements for civil and military transport aircraft. One of the most successful concepts from the basic research program was one in which jet engine exhaust is positioned to blow on the wing trailing edge flaps to enhance lift. This form of propulsion-induced lift became known as the externally blown flap (EBF).

Researchers at Langley performed a series of wind-tunnel studies in the Full-Scale Tunnel and the 300-mph 7- by 10-Foot Tunnel to investigate configuration effects and how the EBF would function with different wing, engine, and flap designs. The researchers analyzed the feasibility of transport designs equipped with two- and four-engine EBF configurations and found that aircraft designs incorporating a T-tail had better aerodynamic qualities. The wind-tunnel tests yielded information that was later incorporated in piloted EBF transport simulations performed at Langley.

Langley kept aircraft companies and the military abreast of its EBF findings and received the opportunity to see its work come to fruition when the Advanced Tactical Transport Program was initiated by the Department of Defense (DOD) in the early 1970s. At that time, the Air Force was seeking a successor to the notable C-130 Hercules prop-driven airlifter. The new aircraft was to be the Advanced Medium STOL (short takeoff and land-

ing) Transport (AMST). It was crucial that the aircraft be able to take off and land on short runways. One of the competing designs, the McDonnell Douglas YC-15, employed an EBF system on a four-engine configuration. Flight trials of the YC-15 proved to be a success story for the EBF concept. Researchers at Langley remained active in the flight trials of the YC-15 and performed supplemental wind-tunnel studies of models of the YC-15 equipped with winglets. Destiny was

*The outstanding low-speed takeoff and landing performance of the C-17 and its ability to operate from short, unprepared runways are direct results of the Langley EBF concept.<sup>6</sup>*

not on the side of the YC-15 however, as the AMST Program was terminated and no production aircraft ever made it off the assembly line.

Knowledge of the EBF and other aerodynamic systems gained through the evolution of the YC-15 program provided McDonnell Douglas with a database and point of reference for technologies that were eventually incorporated on today's highly successful C-17 Globemaster III military transport design. The outstanding low-speed takeoff and landing performance of the C-17 and its ability to



McDonnell Douglas (now Boeing) saluted Langley's contributions to the C-17 with a special ceremony and visit to Langley.

operate from short, unprepared runways are direct results of the Langley EBF concept.<sup>6</sup>

# Variable-Sweep Wing Concept—1959



Time sequence photographs of an F-111 model being assessed with various wing sweep angles during free-flight tests in the Langley Full-Scale Tunnel.

In 1959, the U.S. Navy was seeking an advanced fighter design capable of carrying out missions that required extended patrol time above the fleet. The U.S. Air Force was also seeking an advanced fighter design capable of performing tactical strike missions. The two military services eventually found the answer to their needs in aircraft that employed a critical technology concept developed at NASA Langley. This technology concept, known as the variable-sweep wing, had its origin, in primitive form, during World War II in Germany, where aeronautical engineers at the Messerschmitt Aircraft Works developed the prototype of a jet-powered interceptor known as the P.1101. German interest in achieving the contrasting airplane geometrical requirements for high- and low-speed flight had spurred on this research. The challenge was to find a mechanism that would permit an aircraft to sweep its wings for reduced drag at high speeds, yet pro-

vide the high lift produced by wings with low sweep at takeoff and landing speeds. The P.1101's swept wings could be locked at three different angles on the ground before flights, but the war came to an end before the aircraft could be flown. The P.1101 was seized by American forces and shipped to America for analysis.

The basic design of the P.1101, with the exception of the wing concept, was later incorporated on an experimental U.S. jet known as the Bell X-5. The X-5 employed a translating wing and was flown during the early 1950s. Unfortunately, when the wings were swept rearward from an optimum forward position, the airplane would become excessively

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stable (like an arrow) and could not be maneuvered. This highly undesirable characteristic required that the wing root be translated forward during the sweep process. Although the X-5 demonstrated that the translating wing could be varied in flight, the program was deemed a failure because the mechanism required for wing translation proved too heavy.

Meanwhile at Langley, researchers experimented with translating wing concepts and performed wind-tunnel studies of these concepts until the military lost interest in wing translation and the X-5 program. The military's interest in variable sweep was later revived in 1959 when researchers at NASA Langley discovered that variable sweep worked best when the pivots of the moving wings were positioned at points within wing extensions outside of the fuselage. The concept, called the outboard wing-pivot, was examined on a fighter configuration, which became known as Configuration IV, at Langley. Wind-tunnel tests of Configuration IV had extremely favorable results. Consequently, Langley researchers performed wind-tunnel tests of several variable-sweep fighter designs intended for use by the Navy for its extended patrol time purpose and for use by the Air Force for its tactical strike purpose. The researchers who

developed the outboard wing-pivot were later granted a U.S. patent for their important work. The outboard wing-pivot

later found its way on the designs of the F-111 Aardvark, F-14 Tomcat, and B-1 Lancer. The concept is also used on the European-developed Tornado fighter/bomber, Russian-made MiG-23 Flogger, Russian-made MiG-27 Flogger, Russian-made Tu-26 Backfire Bomber, and Russian-made Su-24 Fencer.<sup>6</sup>



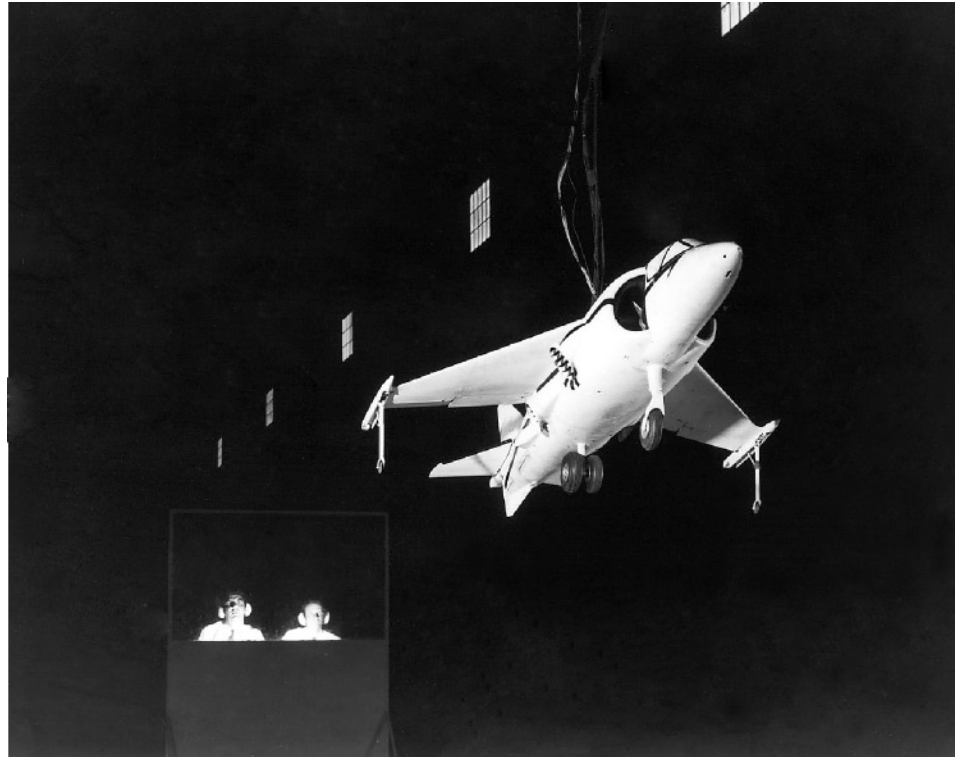
# Vertical and Short Takeoff and Landing—1960

The NACA and NASA have conducted numerous research programs on vertical- and short-takeoff and landing (V/STOL) concepts including tail sitters (vertical attitude), tilt-wing aircraft, ducted-fan aircraft, tilt-rotor aircraft, and vectored thrust. The initiative for research on V/STOL aircraft arose during the early 1950s when military planners decided that they needed aircraft that could operate on short runways or runways that had been bombed out. Industry also saw the need for transport aircraft that could operate in urban settings where there was no room for long runways or new airports.

Early research on the aerodynamics, handling qualities, and structural challenges of helicopters was a vital part of research at Langley since the 1940s, and the Center's leadership role in vertical takeoff and landing concepts based on the helicopter was internationally recognized until the transfer of NASA's helicopter research program to the Ames Research Center in the 1970s. V/STOL research on

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configurations other than helicopters at Langley dates back to the 1950s when NACA researchers conducted wind-tunnel studies on simple "tail sitter" configurations that rested in a vertical attitude, took off vertically, similar to today's helicopters, and



Langley researchers evaluate the flying qualities of a P.1127 model during hovering flight.

tilted the fuselage over to the conventional airplane attitude during the transition to conventional flight. These early experiments led to specific military aircraft, such as the Convair XFY-1 Pogo and Ryan X-13 Vertijet, which the military hoped to use as

interceptors. The Langley wind-tunnel studies on these configurations were performed to demonstrate that the V/STOL tail sitter concept would indeed work and was practical. Langley conducted research on the novel "tilt-wing" concept, for which an otherwise conventional looking airplane used a pivoting wing in the vertical position during vertical takeoffs, tilt-

ing the wing progressively to the conventional position as cruise flight was attained. Leading-edge experiments and flight evaluations of research aircraft like the twin-engine, propeller-driven Vertol VZ-2 of the 1950s and the four-engine propeller-driven Vought-Hiller-Ryan XC-142A of the 1960s were conducted by Langley's staff. A broad-based program was conducted in wind tunnels, including the Full-Scale Tunnel, to demonstrate that such unconventional configurations could make a successful transition from hovering flight to conventional forward flight and return to a vertical landing. The wind-tunnel studies were supplemented by flight research programs using either actual aircraft acquired by Langley and flown by the Langley test pilots

or industry vehicles that were evaluated by Langley's expert pilots at industry's request.

One of Langley's contributions to V/STOL technology is regarded as one of the most critical factors to the success of V/STOL aircraft. During the late 1950s, Langley received the opportunity to prove that the unique swiveled-nozzle propulsion concept, known as thrust vectoring, used by the famous Harrier jump-jet worked. The propulsion system made use of four revolving nozzles capable of redirecting thrust from the engine at different angles to achieve vertical or conventional flight. Models of the first Harrier prototype, known as the Hawker P.1127, were built by Langley and tested in its Full-Scale Tunnel and 16-Foot Transonic Tunnel as part of an international cooperative program. The studies were deemed especially critical because at that time extensive doubt had been cast on the feasibility of the concept by the British government. Unique free-flight model tests in the Full-Scale Tunnel showed that the P.1127 could make a successful transition from vertical to horizontal flight with ease. These tests gave the P.1127's British manufacturers the confidence and advocacy they needed to proceed with the technical elements of the program and also provided the proof of concept they needed to gain financial backing and support from the British government. At the request of the British, Langley dispatched some of its test pilots to England to participate in the flight trials of the P.1127, which were ultimately suc-

cessful. Subsequent refinement and advances to the early Harrier configuration have continually improved the capability of the configuration, and it is now a vital part of the U.S. military fleet in the form of the Marine Corps AV-8B Harrier.

In the mid 1960s, V/STOL concepts were flourishing, and Langley researchers were called upon to assess and participate in the development of many domestic and international projects. During the 1970s, 1980s, and 1990s, NASA Langley conducted wind-tunnel studies in support of other advanced V/STOL configurations, including the Bell XV-15 and Bell V-22 Osprey tilt-rotor aircraft flight research programs. The civil tilt-rotor concept lives on today in the form of the Bell/Agusta BA609, which is presently undergoing flight evaluations.<sup>6</sup>

# Flutter Clearance—1960

The potentially dangerous phenomenon known as flutter involves interactions of the elastic and inertial elements of a particular airplane as the vehicle operates in its flight envelope. When flutter is encountered, oscillations of the structure, such as wings, tails, or panels, can become violent, leading to structural failure and catastrophic conditions. When flying below the speed required for flutter to become active, aerostructural oscillations subside following an atmospheric disturbance. However, when an airplane reaches a speed in excess of the flutter speed, the oscillations can rapidly build and result in structural failure.

Langley's most famous involvement in flutter research resulted from two air tragedies involving flutter-caused ac-

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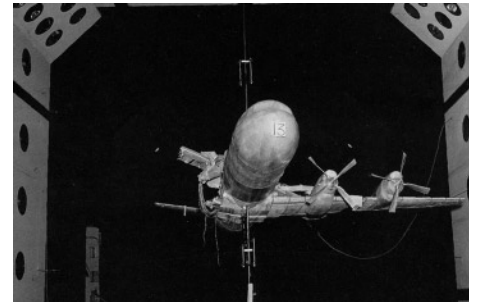
cidents of Lockheed Electra turboprop airliners in 1959 and 1960. In both cases, the flutter oscillations built up to the point that one of the wings had been ripped off the aircraft. With public concern about air travel reaching the panic level, aircraft companies and the Civil Aeronautics Board turned to Langley for help in determining the root causes of the tragedies. Lockheed engineers believed that propeller-whirl flutter was to blame for the air disasters. When propeller-whirl flutter is experienced, the entire propeller-

nacelle-engine-wing combination begins a cyclic motion that diverges quickly into large structural deflections and loads that result in structural failure. The potential presence of this type of flutter had been identified years before the accidents, and Lockheed had conducted in-depth analyses to ensure that the Electra would not experience the problem.

The entire aviation industry and engineering community wanted Langley to determine what had happened to the two airliners through tests of an Electra powered model in the new Langley Transonic Dynamics Tunnel (TDT), which became operational in 1960. The TDT was specifically designed to be a unique national facility for studies of flutter phenomena.

Langley quickly responded to this national crisis, and the Electra was the first airplane configuration to be tested in the new facility. Langley researchers also

performed studies with an isolated Electra propeller-nacelle model and a wall-mounted semispan wing-nacelle model to complement the full-span model tests. Results from the wind-tunnel studies indicated that propeller-whirl flutter was possible only if the structural strength of the engine structural mount assembly fell to a level below the design value. Flutter was never encountered during the wind-tunnel studies when the model's engine mount was built to simulate the intended design, but catastrophic



Powered Lockheed Electra model after encountering catastrophic propeller-whirl flutter in the Langley Transonic Dynamics Tunnel.

propeller-whirl flutter was experienced after the researchers intentionally weakened the engine mounts on the outer engine nacelles, as they might have been following hard landings. The researchers found that the effect of this condition would lead to a catastrophic failure. As a result of the timely results of the Langley investigation, the engine mounts on all Electras were subsequently reinforced, and no further experiences with propeller-whirl flutter occurred. The aircraft type, in the form of the U.S. Navy's P-3 Orion, is still flying today without an incident of this type of flutter.

In the years that followed the Electra accidents, NASA Langley has flutter tested virtually all U.S. military aircraft configurations in the TDT, and a large number of commercial jetliners have been tested, including the Boeing 747, Lockheed L-1011, McDonnell Douglas DC-10, Boeing 767, and Boeing 777. In addition, many high-speed business jet configurations including the Gulfstream III, Cessna Citation X, and Learjet Model 45 have cleared flutter testing in the TDT.<sup>4</sup>

## Vortex Lift—1964

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The wing-fuselage sharp-edged strake of the F-16 was inspired by Langley research on vortex lift for increased maneuverability.

Vortex lift was first identified at the Royal Aircraft Establishment in England in 1956 and was used to enhance the low-speed lift capability for the Concorde SST design in 1960. Research on applications of vortex lift for enhanced maneuvering of fighter aircraft began at NASA Langley dur-

*Engineers at Langley also found that the wing-body strakes alleviated buffeting while completing maneuvers at transonic speeds.*

ing the early 1960s with the launching of studies that focused on the aerodynamic behavior of fighter designs with canards flying at high subsonic speeds. At these speeds, researchers at Langley found that the aircraft's lift benefited from the interactions of the wing and the vortex generated behind the canard, and that these same benefits could be experienced with

a highly swept wing-root extension integrated into the configuration. In addition to developing a vast data and knowledge resource on the subject, researchers at Langley found that the wing-root extension also radically enhanced the maneuverability of fighter designs. This enhanced maneuverability was later demonstrated with the performance of the Lockheed Martin F-16 Fighting Falcon and the Boeing F/A-18 Hornet,

thanks in part to the development of the database on sharpened wing-body strakes conceived by engineers at NASA Langley. Langley engineers recommended to Lockheed Martin that the design of the prototype F-16 could use vortical flow to the best advantage by incorporating sharpened leading edges of the wing-root extensions. These sharpened edges or

“strakes” would, in effect, intensify the generated vortices and produce increased lift. Engineers at Langley also found that the wing-body strakes alleviated buffeting while completing maneuvers at transonic speeds. Following discussions with Langley experts on vortex lift, Lockheed Martin modified the geometry of the emerging F-16 prototype, thereby providing unprecedented levels of maneuverability. Langley personnel have continued to work with industry on further refinements of the strake concept, providing design data and computational fluid dynamics (CFD) codes to predict aerodynamic characteristics produced by the concept. Today, this concept and the flow phenomena associated with it are well-known design options for the designers of future aircraft.<sup>6</sup>

# Supercritical Wing—1964

Following the development of large commercial swept-wing jet airliners in the late 1950s, the need arose for a new series of airfoils that would permit such aircraft to cruise at high speeds with greater efficiency. In 1964, Dr. Richard T. Whitcomb of Langley focused his effort on the challenge and began a series of exploratory wind-tunnel studies to evaluate candidate wing designs in the Langley 8-Foot Transonic Pressure Tunnel. After considerable fundamental studies, his team initiated tests of a slotted airfoil featuring a relatively flat forward camber, a blunt airfoil nose, and a slim cambered section behind the slot. The aim of the investigations was to retard drag by weakening the shock waves that appear on wings at high subsonic cruise conditions. In view of concerns over manufacturing issues, Whitcomb and his team of researchers

*The supercritical wing was eventually applied to small business jets in the U.S. such as the Cessna Citation III, the Cessna Citation X, the Rockwell Sabreliner 65, and the Gulfstream GV.*

later decided to do away with the slot, which resulted in a minor increase in drag. In 1968, the cambered section of the airfoil was thickened; the final product, known as the supercritical wing, emerged in 1974. Whitcomb's research was directed toward improving the performance of commercial transports, but his research team also examined the practicality of supercritical wings on military aircraft and analyzed the wings on such aircraft

as the F-111, YC-15, F-14, and B-1. As part of the research program, supercritical wings were applied to and flown on a representative transport wing using a modified F-8 Crusader airplane in a joint program between Langley and the NASA Dryden Flight Research Center near Edwards Air Force Base in California's Mojave Desert. Wind-tunnel tests of models of the supercritical wing-equipped F-8 were conducted at Langley and minor modifications were made to the wing before the F-8 supercritical wing flight research program started. The first flight of the F-8 supercritical wing test-bed aircraft was made in 1971, and the flight research program lasted for another two years. The flights proved that the supercritical wing reduced drag and offered enhanced cruise efficiency and flight (lift) over conventional wings and that

the supercritical wing held promise for enhanced flight efficiency in subsonic jet airliner designs. In 1974, Whitcomb received the Wright

Brothers Memorial Trophy of the National Aeronautic Association for his conception of the supercritical wing.

Whitcomb and his researchers at Langley had explored the possibility of using the supercritical wing and area rule on near-sonic jet airliners, but the onset of the Organization of Petroleum Exporting Countries (OPEC) crisis in the mid-1970s signaled the end of any attraction that



NASA's F-8 supercritical wing research airplane in flight at the NASA Dryden Flight Research Center.

the airlines might have had for fuel-demanding near-sonic flight. Because the supercritical airfoils developed by Whitcomb were more efficient, they permitted the use of thicker airfoils at typical transport cruise speeds, thereby providing transport designers with options for better efficiency at less-than-transonic conditions. The manufacturers of subsonic jet airliners adapted the supercritical airfoils into thicker wings. They decided to reduce the amount of wing sweep envisioned by Whitcomb for his near-sonic cruiser, and they also extended the wing's aspect ratio so that lift-induced drag would be retarded. The result yielded tremendous savings in fuel consumption. The supercritical wing was eventually applied to small business jets in the U.S. such as the Cessna Citation III, the Cessna Citation X, the Rockwell Sabreliner 65, and the Gulfstream GV. There has been only one aggressive application of supercritical wing technology to a long-range subsonic jet airliner in the U.S., and that is the Boeing 777. The supercritical wing has also been incorporated in the design of the U.S. Air Mobility Command's C-17 Globemaster III military transport.<sup>4</sup>

## Runway Grooving—1965



Langley researchers conceived and developed the grooving now used extensively by airports and highways to reduce tire hydroplaning and improve braking.

Early in the 1960s, researchers at Langley conducted preliminary research to facilitate safer airplane landings on wet runways that eliminated or prevented the phenomenon of tire hydroplaning, wherein water reduces the normal friction between tires and pavement. By 1965, researchers at NASA Langley had conceived and developed a process in which grooves were cut along concrete runways to facilitate the channeling of standing water. Researchers then relied on tests performed at one of the research center's unique facilities, the Aircraft Landing Dynamics Facility (ALDF), to develop the best grooving pattern. At the ALDF, researchers study landing-gear configurations and aircraft tires by catapulting them down a long track to evaluate braking performance and tire wear for various pavements. The ALDF studies led to the development of a special transversely grooved runway at the NASA Wallops Flight Facility for runway grooving tests with actual aircraft in 1967; and in 1968, a joint program

between NASA, the U.S. Air Force, and the Federal Aviation Administration (FAA) commenced at Wallops involving studies of the braking qualities on grooved pavement of a McDonnell Douglas F-4 Phantom II military fighter, a Convair 990 airliner, and a Beech Queen Air prop-driven airplane. The findings of these studies were very favorable. Follow-up efforts between NASA, the Air Force, and the FAA were carried out between 1969 and 1972, and these efforts were more extensive, involving the use of a huge Lockheed C-141 military transport, a Boeing 727 jetliner, and a Douglas DC-9 jetliner along with more types of runway surfaces. The findings from these tests were

*This innovation makes tire traction more feasible by ejecting metal pellets onto a road or runway surface.*

also favorable and consequently led to the adoption of grooving on military base runways, airport runways, and public highways. Grooving has also been adapted for use on swimming pool decks, playgrounds, and floors of refineries to prevent serious slips and falls. The effects of Langley's grooving research have been so beneficial to the aviation community and the general public that the U.S. Space Foundation chose grooving to be a member of the Technology Hall of Fame in Colorado Springs, Colorado, in 1990.<sup>4</sup>

In support of a NASA objective to reduce the fatal aircraft accident rate by 80 percent in 10 years and by 90 percent in 25 years (from 1995 sta-

tistics), NASA Langley teamed with Transport Canada and the FAA in 1996 to complete a 5-year winter runway friction measurement program. A total of 5 research airplanes (a Canadian National Research Council Falcon 20, FAA B-727, de Havilland Dash 8, NASA B-737, and NASA B-757) and 13 ground test vehicles were tested in the United States, Canada, and Norway. Studies were conducted on various runway surfaces and an international runway friction index (IRFI) was devised. This index has enabled researchers to find a common means of recording friction and to reduce piloting problems upon take-off or landing. The IRFI has proven to be so useful that the measurement

program has been extended through 2005. During this time, researchers will compare

wide-body aircraft stopping performance data to ground vehicle IRFI measurements. This study may enable wide-body pilots to also use the IRFI.

To further minimize the aircraft hydroplaning phenomenon, researchers at NASA Langley have recently produced an innovative concept known as the Skidabrader™. This innovation makes tire traction more feasible by ejecting metal pellets onto a road or runway surface. The more rugged gradient facilitates tire traction, thus drastically reducing the chances of an accident. The metal pellets are also reusable, therefore adding to the efficiency of the equipment.<sup>7,8</sup>



A composite fuselage structure is used on the Cirrus SR-20 general aviation aircraft.

Composite aircraft material research intensified in the 1970s with the objective of making aircraft as light as possible for increased performance. Composite structures consist of strands of graphite, fiberglass, or Dupont Kevlar® material mated with epoxy, polyimide, or aluminum. These materials have proven to be extremely light and beneficial for aviation purposes. Langley's research in the area of composite materials has resulted in design guides, materials, computational com-

*Langley's research in the area of composite materials has resulted in design guides, materials, computational computer codes, and careful assessments of the strength and durability of these products.*

puter codes, and careful assessments of the strength and durability of these products. Initial activities applied composites to both civil and military aircraft with a focus on developing composite secondary airplane parts. In 1972, Langley initiated the NASA Composites Flight Service Program, which led to the equipping of certain airliners and helicopters with

more than 300 new composite parts. Under sponsorship by Langley, Boeing developed graphite-epoxy wing spoilers for some of its 737 jetliners, while Lockheed incorporated Kevlar® fuselage panels to a few of its L-1011 jetliners. Douglas developed graphite-epoxy rudder structures for several of its DC-10 jetliners. Langley also assisted the military in ushering in the composite revolution by supporting the development and application of boron-epoxy structures to the Army's CH-54B helicopters and Air Force C-130 aircraft. The composite structures applied to these aircraft and helicopters held up well in flight and required only minor servicing. NASA Langley helped industry gain crucial experience and knowledge of revolutionary composite materials.

In 1976, a NASA program was initiated, known as the Aircraft Energy Efficiency (ACEE) Program, and Langley decided to be involved

on two separate fronts. The first front involved participation in a Base Technology Program and the second centered on involvement in the Composite Program.

Researchers at Langley participating in the Base Technology Program analyzed the impact of the environment on composites, the qualitative aspects of composites, composite design processes, composite strength, and possible electrical dangers posed by using carbon fiber.

The three manufacturers of large jetliners—Boeing, Douglas, and Lockheed—performed research sponsored by Langley on composites and their uses under the Composite Program. The main focus of the Composite Program involved the performance of experiments that translated into the use of composite secondary aircraft parts during the early 1980s. Larger aircraft parts made of composite materials were developed during the 1990s. The program ultimately achieved the aim of fostering decreases in aircraft weight that led to a fuel efficiency in excess of 15 percent.

Research on primary composite wing and aircraft body parts was addressed in the NASA Advanced Composites Technology (ACT) Program in 1988. This program was managed by NASA Langley and involved the efforts of military aircraft producers, developers and suppliers of composites, academia, and government research facilities. The main objective of the program was to produce materials, composite designs, and processes for manufacturing composites that made them more desirable than conventional aluminum materials from the perspective of both economics and performance. Unfortunately, the objectives of the ACT Program, which set the target weight reduction level to between 30 and 50 percent and the cost reduction level for obtaining advanced composites between 20 and 25 percent, were never reached due to a termination of funding. Nonetheless, members of industry gained knowledge and experience with the important engineering processes involved in the production and application of advanced composite materials. McDonnell Douglas applied knowledge of composites to manufacturing a representative advanced composite wing that was later tested in structural laboratories at NASA Langley.

The composites revolution has also had an impact on the general aviation world. Aircraft manufacturers are now relying heavily on composite materials for the design and fabrication of their general aviation aircraft. The knowledge and data used in the production of these materials were

derived from experiences with the ACEE, ACT, and Advanced General Aviation Transport Experiments (AGATE) Program. The AGATE Program was comprised of a consortium of members from government, academia, and industry whose aim was to reinvigorate the general aviation industry through technology advances. Beech Aircraft (known today as Raytheon) applied composites know-how to the composite materials used in its Starship airplane and its Premier I and Horizon corporate planes. Two of the newest FAA-certified general aviation aircraft today, the Lancair Columbia 300 and Cirrus SR-20, are made entirely of composites, the production knowledge for which was obtained from the NASA Small Business Innovation Research Program. Researchers at NASA Langley also produced an invaluable resource publication, "Material Qualification Methodology for Epoxy-Based Prepreg Composite Material Systems," in 1998 that details the procedure aircraft producers can use to obtain certified composites from vendors.<sup>4</sup>



# Cryogenic Wind-Tunnel Technology—1973

The most difficult aspect of aerodynamic prediction methodology is to account for the differences in atmospheric conditions between wind-tunnel models and full-scale aircraft. To truly replicate the aerodynamic forces acting on an aircraft, the designer must either conduct tunnel tests at full-scale conditions or have some method of reliably extrapolating sub-scale model results. A key parameter in the similitude between models and aircraft is known as the Reynolds number, which is a measure of the relative effects of the momentum (inertia) and “stickiness” (viscosity) of air flowing over an aircraft. The difficulty of maintaining the required similitude of Reynolds number has increased in modern times because it is directly related to the relative size of aircraft and their operational envelopes. As a result, the prediction of performance guarantees for large commercial

*However, with the increase in aircraft size and operational envelopes it has become impractical to build new tunnels with the pressurization levels required.*

transports presents a formidable challenge for the industry. Unfortunately, conventional wind tunnels cannot have the operational flexibility to simulate full-scale conditions, and models are tested at less than full-scale values of Reynolds number.

In the early days of aviation, one approach used to increase the Reynolds number obtained in wind tunnels was to pressurize the air within the test

section circuit. However, with the increase in aircraft size and operational envelopes it has become impractical to build new tunnels with the pressurization levels required. In the early 1970s, Langley researchers contributed a major breakthrough to this challenge by demonstrating the use of a prototype cryogenic transonic wind tunnel to achieve full-scale Reynolds numbers for certain vehicles. The breakthrough concept used to develop a 0.3-meter cryogenic tunnel was to dramatically reduce the air temperature, which causes a direct increase in Reynolds number. After assessing several candidate wind-tunnel concepts, the government

selected Langley’s concept for development in 1974.

The facility, now known as the National Transonic Facility (NTF) at

Langley, provides the Nation with a unique national asset to advance the state of the art in aerodynamic prediction methods.

The NTF has been used for tests of a variety of vehicles and aircraft components to determine the variation of key aerodynamic parameters with variations in Reynolds number ranging from conventional tunnels to full-scale flight conditions. With this



Model of the Boeing 777 transport undergoing tests in the National Transonic Facility at Langley .

unique testing capability, industry has been able to define the sensitive aerodynamic properties of specific vehicles, correlate with actual aircraft flight test results, and more accurately calibrate and extrapolate results from conventional wind tunnels. Specific aircraft tested in the tunnel have included the Boeing 767, Boeing 777, and the McDonnell Douglas (now Boeing) C-17. In addition to aircraft tests, other studies in the NTF have been devoted to nonaircraft vehicles, such as advanced submarines and the space shuttle.<sup>5</sup>

## Glass Cockpits—1973



A typical transport cockpit showing flat-panel electronic displays.

With the revolutionary advances in computer and display technologies, aircraft operators began to implement new cockpit displays that incorporated flat-panel electronic display hardware rather than the classical instruments from the early days of aviation. Glass cockpit technology research, which began at NASA Langley in the early

*Glass cockpit technology research, which began at NASA Langley in the early 1970s, evolved from the need to alleviate pilot workload, thereby lessening the risk of human error in an accident.*

1970s, evolved from the need to alleviate pilot workload, thereby lessening the risk of human error in an accident. During the early 1970s, researchers at NASA Langley conceived and initiated a research activity that focused on pilot workload in the terminal area, where many accidents occur because of pilot workload and situational awareness issues. Called the Terminal

state-of-the-art cockpit displays and provided the research aircraft used to flight-prove the new technologies. The research aircraft, known as the Transport Systems Research Vehicle (TSRV) in the 1980s and 1990s, was a Boeing 737. This unique aircraft was outfitted with a second cockpit in the front cabin portion of the fuselage,

and to evaluate new cockpit systems. The displays viewed by aircrews in the second cockpit included primary flight displays and navigational displays. These displays consisted of cathode ray tube (CRT) technology at first, but were gradually replaced by more advanced systems, including flat-panel glass cockpit systems. Prior to any research flights in the TSRV,

Configured Vehicle (TCV) Program, the main objective of this research effort was to enhance flight operations near and at airports across the country. One area addressed in the program was visual displays of air traffic data in the cockpit. Under the TCV Program, NASA, industry, and the FAA developed

behind the first or main cockpit. The second cockpit, used as the research cockpit, included computerized systems to fly the aircraft

researchers at Langley used the TSRV ground simulator to conceive and perfect new display arrangements. Once the researchers were confident about the design and robustness of their new systems, the systems were test flown on the TSRV. In the 1970s, Langley researchers created a number of projects to dramatically demonstrate how electronic flight displays could improve the capability of aircrews to pilot large jetliners along sophisticated approaches to airports. A team of Boeing engineers was detailed to Langley to monitor the research on new advanced cockpit display systems with a view toward possible incorporation of the advanced technology onto the new Boeing 757 and 767 jetliners. These engineers were so impressed with the CRT displays that when they advanced up the corporate ladder at Boeing, they greatly influenced the decision makers to apply CRT displays to the 757 and 767 in 1978. Later, CRT displays found their way on updated versions of the Boeing 747 and 737, and on the newer 777. Today, such displays are commonplace in worldwide applications for the full range of airplanes, from commercial transports to business jets and private general aviation aircraft.

One of the most challenging aspects of aircraft design is to provide robust structural and systems concepts that increase the probability of survival of aircrew and passengers following crash impact. Crashworthiness research began at NASA Langley in 1975 when the center transformed its Lunar Landing Research Facility into the Impact Dynamics Research Facility (IDRF). The IDRF is the only facility of its type in the world, consisting of a gantry-type structure that was initially used to help astronauts train in the lunar lander on a simulated lunar surface during the Apollo Program. When the Apollo missions were completed, researchers at Langley swiftly recognized the potential application of this large-scale test facility to the development of technology that could save lives here on Earth. During tests at the IDRF, full-scale aircraft and aircraft components are mounted to suspension cables and instrumentation wires, hung from the top of the structure, and swung like a pendulum into a variety of impact surfaces at specified angles of impact and impact

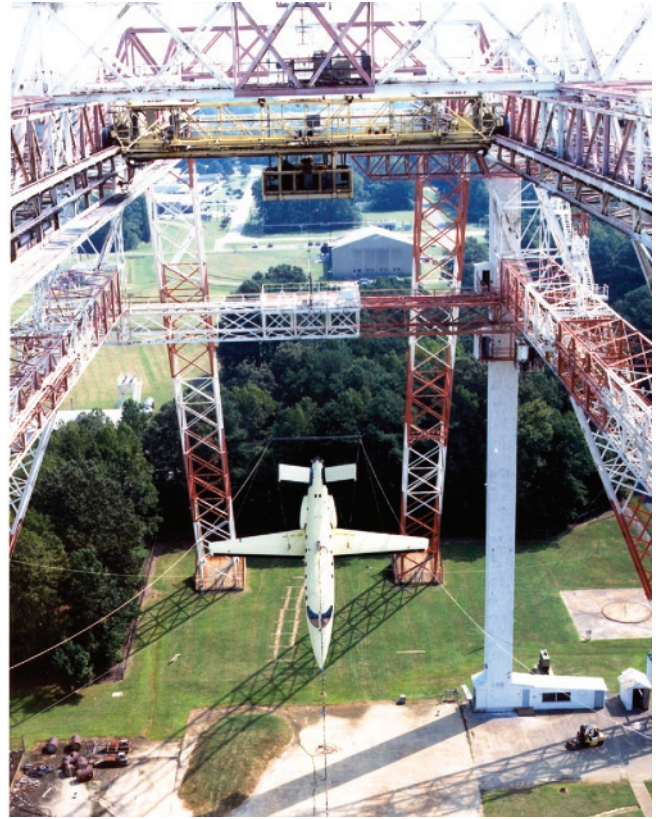
*When the Apollo missions were completed, researchers at Langley swiftly recognized the potential application of this large-scale test facility to the development of technology that could save lives here on Earth.*

velocities. Special cameras and instruments outside and onboard the test subjects record the accelerations resulting from the impacts as well as detailed data on the structural responses of the test article. To study the prob-

ability of survival for the crew and passengers, anthropomorphic dummies that have been instrumented are positioned within the test aircraft.

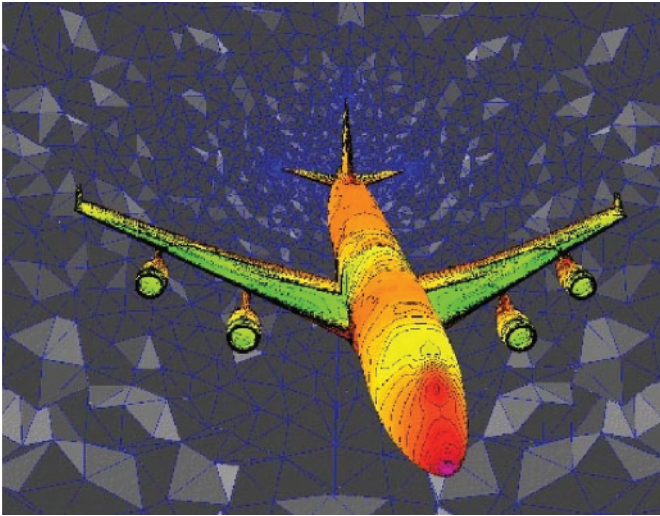
Crashworthiness studies have been performed on a variety of aircraft, including general aviation aircraft, rotorcraft, airplane fuselages, and even the crew escape module of an F-111 fighter/bomber. Some of the technologies contributed by researchers at Langley through crash tests at the IDRF include crushable subfloors that absorb energy from impacts, energy absorbing seats, improved air bags for aviation applications, and improved seat restraints. Crashworthiness research was also

performed on general aviation aircraft made of composites to find ways of improving the impact absorption of these revolutionary materials. Engineering data produced by this valuable research has been disseminated among the civil and military communities, resulting in significant improvements in the inherent safety of current aircraft.<sup>4</sup>



An instrumented test airplane being prepared for crash impact testing at the Langley Impact Dynamics Research Facility.

# Computational Fluid Dynamics—1975



Langley-developed computational fluid dynamics (CFD) computer codes have been incorporated into industry design methods.

With the advent of advanced computers in the 1970s came the development of sophisticated codes that allowed computers to be used as valuable aircraft design aids. These codes, part of what became known as computational fluid dynamics (CFD), were crucial to helping engineers understand and design for the complexity of airflow over advanced aircraft designs. In the process, the use of CFD has led to a reduction in expensive, time-consuming wind tunnel tests and flight tests of aircraft that might otherwise have been required. During the 1970s, the top officials at NASA Langley committed the Center to creating and providing CFD codes to aircraft companies. The codes were to be used to study the aerodynamic characteristics of airplanes across the speed range.

One example of a Langley-developed code that had a significant impact on the world of aircraft design is the Direct Iterative Surface Curvature

(DISC) code. DISC enabled researchers, through automation, to calculate adjustments that needed to be made to a wing to obtain a desirable pressure distribution. DISC is now used by every civil aircraft manufacturer in the Nation and greatly assisted Gulfstream in the design of its Gulfstream V corporate jet as well as Cessna in the design

of its Citation X corporate jet. Langley-derived CFD codes have also been incorporated by Boeing into its own proprietary codes to design the 777 and 737NG jetliners.

*These codes...were crucial to helping engineers understand and design for the complexity of airflow over advanced aircraft designs.*

One of the most successful applications of Langley-developed CFD technology involved McDonnell Douglas and the testing of its MD-11 jetliner. The MD-11 exhibited a range deficiency in its first flight trial, and McDonnell Douglas attempted to correct this problem in a subsequent performance improvement program. McDonnell Douglas learned that the MD-11 design suffered from an engine-pylon flow separation defect and consulted with Langley experts on how CFD might be used in the

resolution process. In a cooperative venture, Langley and McDonnell Douglas personnel applied the computer-based methods to provide guidance for the solution. Some of the codes jointly used by Langley and McDonnell Douglas were the VGRID tetrahedral grid generator, USM3D code, and DISC. As a result, a new pylon was created with a special fairing that reduced drag and helped to stretch the MD-11's range. McDonnell Douglas later adopted the Langley-developed codes as part of its own design skills.<sup>4</sup>

## Thrust Vectoring—1975

Research leaders at Langley recognized that swiveling the nozzles of conventional jet engines could provide powerful auxiliary control for more effective aircraft missions. This concept, known as thrust vectoring, would provide revolutionary capabilities for enhanced short takeoff and landing and increased control for maneuvers at high angles of attack while the aircraft's rudder control becomes ineffective. Langley led the development of a database for advanced propulsion integration, including two-dimensional intakes and nozzles for advanced modern jet aircraft. Researchers demonstrated the effectiveness of such features through wind-tunnel tests and free-flight model tests. The research was broad in scope and was monitored closely by the military services because the potential impact on future military aircraft would be significant. Aerodynamic studies in wind tunnels assessed several nozzle concepts for redirecting thrust while maintaining propulsion effectiveness. Flight dynamics studies using wind-tunnel free-flight model tests demonstrated how thrust vectoring provided a dramatic increase in yaw control that significantly improved maneuverability and spin prevention. Finally, piloted simulator evaluations of the concept by the military increased interest in vectoring. This research stimulated the interest of the DOD and led to early evaluations of thrust vectoring on an Air Force F-15 research airplane known as the F-15STOL/MD, the Defense Advanced Research Projects Agency (DARPA) X-31 research air-

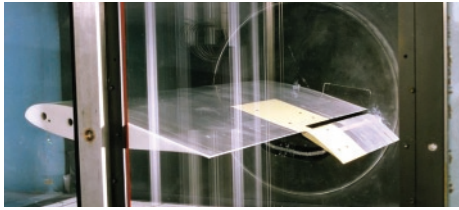


The Air Force F-22 fighter uses thrust vectoring technology that evolved from Langley's pioneering research.

craft, and the NASA F-18 High Alpha Research Vehicle. The successes of these flight research programs led to the incorporation of thrust vectoring on the YF-22, F-22 Raptor (the Air Force's air superiority fighter of tomorrow), and the F-35 Joint Strike Fighter (JSF).<sup>6</sup>

*This concept, known as thrust vectoring, would provide revolutionary capabilities for enhanced short takeoff and landing and increased control for maneuvers at high angles of attack while the aircraft's rudder control becomes ineffective.*

## Noise Reduction—1978



Wing-flap model used for flow studies in Langley Basic Aerodynamics Research Tunnel to develop airframe noise prediction methods.

Of all the environmental issues that currently constrain growth in aviation, noise produced by aircraft operations is the most significant. The public has become extremely sensitive to unwanted noise, and the tremendous growth over the past four decades in air transportation, especially jet transports, has resulted in a tremendous challenge to meet noise regulations. Although the current generation of commercial jet transports is considerably quieter than the early fleet, continuing demand to reduce noise and to impose even more restrictive noise level regulations on commercial aviation requires research in noise reduction technology.

Langley's research efforts in aircraft noise and noise reduction began over 50 years ago when the NACA conducted extensive studies of propeller-generated noise. In the late 1940s, aircraft such as the P-51 Mustang were instrumented to determine the effects of propeller variations on generated noise levels. From those early studies of the physics of noise generation and transmission, Langley has conducted and sponsored extensive research on noise reduction and the impact of noise on the community. Working in close coordination with the FAA and industry, Langley researchers have

been at the cutting edge of advanced technology to reduce jet noise. The bottom-line benefit of these research activities is that today's jet transports are about 20 decibels quieter than those of the 1950s. To the public, this level of reduction is equivalent to reducing the noise by almost 75 percent. The early jet fleet used turbojet engines, and the predominant noise source was high-velocity jet exhaust mixing with the surrounding air. By the 1960s, new low-bypass-ratio turbofan engines used relatively low engine core exhaust flows mixed with bypass flows, resulting in relatively lower exhaust velocities and a reduction in jet exhaust noise. Even with this noise reduction mechanism, Langley aggressively pursued methods to further reduce propulsion-related noise. To further reduce propulsion-related noise, Langley aggressively pursued methods such as adding acoustic liners, evaluating steeper landing approach patterns, and designing exhaust nozzle mixers. Acoustic liners were added

*...this level of reduction is equivalent to reducing the noise by almost 75 percent.*

to engine nacelle inlets to help absorb noise from the combustor and turbine engine stages. Flight research evaluations of steeper landing approach patterns were conducted to minimize ground exposure to noise. Exhaust nozzle mixers were designed to quickly mix the flow out of the nozzle and diminish the noise levels. Together with its partners, NASA brought to fruition engine component noise reduction methodology that was quickly adopted by engine manufacturers.

In recent years, advances in sophisticated computational fluid dynamics codes have been adopted to predict and analyze noise generation from propulsion systems as well as other aircraft components. More sophisticated instrumentation and methods are employed within the Langley studies during field measurements of aircraft fly-over noise and the relative acceptability of the noise levels as judged by subjective observers. One of the more challenging aspects to further reductions in commercial transport noise near airports is that propulsion-generated noise has been reduced to almost minimal levels, and the noise generated by airflow over the aircraft stands as a barrier to further improvements. Primary noise sources include airflow associated with the landing gear, wing trailing-edge flaps, and wing leading-edge slats. In the 1990s, Langley developed a systematic approach to develop a fundamental understanding of airframe-generated noise and concepts to mitigate the noise. Results from these programs have been transmitted directly to engine and airframe manufacturers for immediate applications. In addition to these research efforts to reduce noise at the source, Langley's assessments of the operational and environmental impact of increasing the approach path from the conventional 3 degree glide slope to higher slopes are now considered within future automated traffic control systems.<sup>9</sup>

# Lightning Characterization—1978

The potential threat of lightning to aircraft structures, avionics, and control systems requires reliable data on the characteristics of electrical properties encountered by airplanes during lightning strikes. In addition, detailed information is needed on the general character of lightning, such as the altitude and temperature combinations for high probability of strikes.

Lightning characterization research at Langley began with the initiation of the Storm Hazards Program in 1978 and evolved from the needs to determine the effects of lightning on aircraft and to develop sufficient protection against these effects. Lightning poses a myriad of threats to airborne craft ranging from the possibilities of lightning strikes starting a fire in a fuel tank, which might result in a fatal explosion, to disabling electrical inputs of critical electronic flight systems aboard the aircraft. Langley first set out to acquire background information concerning the characteristics of lightning by conducting flight tests with a DHC-6 Twin Otter equipped

*Langley researchers discovered that lightning hardly ever struck during heavy rain and winds.*

with a lightning locator. The Twin Otter flew just outside of thunderstorms; however, the flight research effort yielded no conclusive data as it was found that no connection could be made between turbulence and lightning. Langley later acquired a NASA F-106B high-performance delta-wing interceptor from Lewis (now Glenn)



F-106 research aircraft used by Langley for lightning characterization research. Gray marks on airplane are paint marks denoting lightning strike points.

Research Center to replace the Otter. The F-106B was equipped with storm hazard research instruments and had lightning protection. The mission of the F-106B was to fly into thunderstorm clouds and seek out lightning strikes so that the onboard instruments could measure the properties of lightning within the clouds, generate enough data to discover what factors cause aircraft-initiated lightning, and find out what was occurring in the atmosphere at the time of lightning strikes.

While performing a research mission in 1984, the F-106B was struck by lightning 72 times in a 45-minute period. Langley researchers discovered that lightning hardly ever struck

during heavy rain and winds. Lightning struck most frequently in storms where the rains and winds were light. At low altitudes, lightning was most prevalent in gusty winds associated with downdrafts. At high altitudes, lightning was most prevalent in conditions where there were light rains and winds. The information generated from these flight research studies ultimately helped military, commercial, and general aviation pilots to best avoid lightning strikes and helped aircraft designers engineer better lightning protected aircraft.<sup>4</sup>

# Wake Vortex Technology—1980



Smoke injected into the trailing vortices of a Boeing 747 transport during NASA flight tests of wake vortex alleviation concept.

An inherent by-product of flight through the atmosphere is the generation of horizontal swirling tornado-like airflows behind an aircraft. The strength and duration of the airflow or wake vortex is directly dependent on the size of the aircraft. When an aircraft following another encounters the disturbed airflow, it can experi-

*... spacing requirements limit the number of aircraft that can be accepted during airport operations, contributing to undesirable delays within ever-burgeoning demand...*

ence undesirable or even catastrophic acceleration because of the wake. Because the seriousness of such encounters is severe, restrictions are placed by the FAA on the minimum acceptable distance between aircraft as they approach to land or take off from commercial airports. Thus, the spacing requirements limit the number

of aircraft that can be accepted during airport operations, contributing to undesirable delays within the ever-burgeoning demand for increased air operations in the commercial transportation system.

Langley researchers have contributed to the understanding and analysis of wake vortex phenomena for over 50 years. Extensive studies have been conducted to document the

physical airflow characteristics in the wake vortices as affected by variations in aircraft configurations, weight, and separation distances. Through these studies, methods have been developed and validated for the prediction of flow field properties, permitting the use of analytical studies and piloted simulators for assessments of wake vortex

avoidance procedures. Langley has also led the way in the conception and evaluation of airplane configuration changes that might alleviate or minimize the danger of trailing vortices to following aircraft. In joint studies with the FAA and the NASA Dryden Flight Research Center, Langley has participated in flight research studies to determine the effects of aircraft modifications and other strategies on acceptable separation distances between the generating and following aircraft. Many of these results have been extensively used in the creation of current separation requirements.

Recently, Langley researchers have successfully integrated an advanced wake vortex monitoring and advisory system that combines atmospheric properties, aircraft properties, and vortex avoidance strategies into a program called Aircraft Vortex Spacing System (AVOSS). The system, which has been demonstrated for representatives of the FAA, pilot associations, and airport operators at several major airports such as Dallas/Fort Worth International Airport, offers the promise of operational guidance for reliably reducing the separation distance requirements.<sup>4</sup>



## Airborne Windshear Detection—1983

Windshear or microburst research at NASA Langley was prompted in the early 1980s following two air accidents that captivated the Nation's attention. On July 9, 1982, a Pan American Boeing 727 crashed shortly after taking off in a severe thunderstorm from an airport in New Orleans. All the aircraft's passengers and flight crew lost their lives in the accident. The cause was determined to have been an encounter with an unexpected windshear that overpowered the flight crew's ability to recover the airplane. Obsolescent ground-based windshear technology had failed to alert the crew about the presence of windshear. On August 2, 1985, a Delta Airlines Lockheed L-1011 crashed on approach to a Dallas/Fort Worth airport during a severe thunderstorm. A total of 137 people lost their lives. The cause, once again, was found to have been a powerful windshear. As a result of these terrible accidents, the FAA developed a National Integrated Windshear Plan,

*To help gain knowledge of windshear, researchers at Langley developed computer-generated models of microbursts and windshear profiles.*

with Langley heading the airborne windshear detection research element of a NASA and FAA Airborne Windshear Program. The focus of this Langley program centered on the areas of hazard characterization, sensor technology, and flight management. To help gain knowledge of windshear, researchers at Langley developed computer-generated models of microbursts and windshear profiles.



Langley's 737 research aircraft provided validation data and demonstrations of the effectiveness of airborne detection concepts by flying windshear missions.

The most complete microburst model developed at Langley was a system called the Terminal Area Simulation System (TASS). The system even incorporated liquid- and ice-microphysics characteristics. By using TASS, researchers could now dissect a microburst, better analyze the potential of microburst sensor technology, and develop solutions for actions to be taken by pilots when flying through a microburst. Researchers at Langley also characterized the hazard of flying into a windshear by developing a quantitative element known as the F-factor. The F-factor provides a measure for performance degradation anticipated of an aircraft when flying through a

windshear. With the development of the F-factor, researchers could now determine the relative severity of windshear conditions and which airborne windshear sensors worked best. In helping perfect airborne windshear sensor technology, Langley researchers focused their efforts on assisting the production of an alarm system capable of alerting aircrews 10 to 40 seconds before entering a windshear.

An extensive flight research program to test airborne windshear detection sensors produced by industry members was initiated at Langley using the research center's Boeing 737 Transport Systems Research Vehicle (TSRV). Windshear detection sensors were test flown on the 737. These sensors included a Doppler radar

transmitter produced by the Rockwell International Collins Air Transport Division; a Doppler LIDAR (light detecting and ranging) by Lockheed Corporation Missiles and Space Division, United Technologies Optical Systems Incorporated, and Lassen Research; and an infrared detector by Turbulence Prediction Systems.

On the test flights, which occurred primarily during the summers of 1991 and 1992, the Doppler radar performed admirably, detecting windshear from greater distances compared with the other two sensors. The Doppler radar also alerted pilots 20 to 40 seconds prior to entering microbursts, meeting the goal originally set by Langley researchers at the onset of the program. In an attempt to delineate operating procedures for reducing the level of danger posed by windshear, researchers at Langley established potential piloting strategies for maintaining control of an aircraft upon entering windshear and studied reliance data generated from radars on the ground as a backup to airborne sensors. A milestone was achieved for the NASA and FAA Airborne Windshear Program on September 1, 1994, when Allied Signal received FAA certification for use of its Bendix RDR-4B on airliners. This windshear radar sensor, the development of which was strongly influenced by the program, was the first of its kind to obtain formal FAA certification for use on civil transports. The RDR-4B was chosen for use by three airlines in the United States: United, Northwest, and Continental. Today, numerous companies including Honeywell, Rockwell Col-

lins, and Westinghouse Electric offer windshear detection radars that have met FAA regulations. Langley's F-factor is also now a part of FAA regulations.<sup>4</sup>

# High-Angle-of-Attack Technology—1988

Since the 1930s, Langley has developed and maintained unique test facilities for the evaluation and analysis of aircraft characteristics during operations at high angles of attack, where the loss of control effectiveness and aerodynamic instabilities can cause inadvertent loss of control and entry into unrecoverable spins. In addition to conventional wind tunnels, researchers use the Langley 20-Ft Spin Tunnel, wind tunnel free-flight models, outdoor radio-controlled drop models, and piloted simulators to develop technology that enhances aircraft flying qualities in this regime. In recognition of this world-class capability, virtually all military aircraft are tested in Langley facilities for high-angle-of-attack characteristics, and Langley's researchers are invited participants in many actual aircraft flight test programs.

During the Vietnam era, U.S. military aircraft exhibited highly undesirable characteristics at high angles of attack, resulting in an alarming number of accidents and limitations on combat

*...Langley joined with NASA Ames Research Center and NASA Dryden Flight Research Center to formulate and conduct a comprehensive research program on high-angle-of-attack technology...*

maneuverability. With the advent of highly maneuverable aircraft such as the F-15, F-16, and F-18, current-day high-performance aircraft must frequently operate at high angles of attack and designers are challenged

to ensure that the aircraft will have satisfactory characteristics. Langley researchers have developed aerodynamic concepts and control system architectures that have significantly improved the characteristics of current U.S. military aircraft. A critical part of this activity has been to develop guidelines for aircraft designers.

In the late 1980s, Langley joined with NASA Ames Research Center and NASA Dryden Flight Research Center to formulate and conduct a comprehensive research program on high-angle-of-attack technology for military aircraft. Using an F-18 aircraft on loan from the Navy, the NASA team modified the aircraft with extensive instrumentation and coordinated ground-based studies ranging from wind tunnel tests to piloted simulator studies during focused research for critical technologies including aerodynamics, flight controls, and test techniques. One critical element of this program was modification of the F-18 research aircraft with thrust-

vectoring capability for demonstrations of the improvements provided by vectoring for maneuvers and high angles of attack, as well as stabilization of the vehicle for aerodynamic studies. By carefully coordinating wind tunnel, flight, and computational results, Langley researchers provided the leadership and methods for aggressively advancing the state of the art

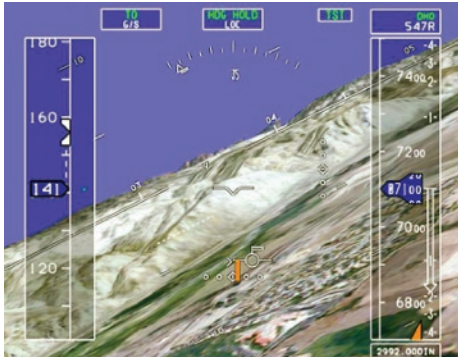


Flow visualization studies using tufts and smoke identify flow phenomena on the NASA F-18 High Alpha Research Vehicle at high angles of attack.

in the use of advanced computational fluid dynamics codes for analysis of the complex aerodynamic phenomena encountered at high-angle-of-attack conditions.

The technologies and methodologies contributed by the NASA High-Angle-of-Attack Program to subsequent programs such as the F-22 and Joint Strike Fighter Program provided invaluable tools and design guidelines for the Nation's next generation of high-performance aircraft.<sup>6</sup>

# Synthetic Vision Technology—1993



Representation of Vail, Colorado, terrain using the Langley-developed synthetic vision system.

In the High Speed Research (HSR) Program, NASA and industry investigated the advantages of supersonic transport configurations that did not employ the drooped-nose concept used by the Concorde to provide visibility for takeoff and landing. A non-drooped nose would result in significant weight savings. Without droop, pilots must be provided with artificial vision for operation. With this fact in mind, researchers set out to develop an advanced synthetic vision system for a high-speed civil transport concept. A research group consisting of members from industry, NASA, and universities was formed in 1993 to work with the NASA HSR Program at Langley to create a synthetic vision system for the high-speed civil transport concept. The research group was referred to as the external vision systems (XVS) group and together with NASA HSR Program members incorporated its synthetic vision system in a nondroop nose cockpit concept. The XVS and HSR team conducted extensive simulations and flight tests to set standards for the advanced displays that were to be used in the system.

Concept-proving flight tests of the nondroop nose cockpit were carried out in the Air Force Total In-Flight Simulator (TIFS) with the Langley B-737 research aircraft. During the flight tests, researchers focused on computerized external camera vision and horizontal field of view (H-FOV) standards. In 1999, all high-speed civil transport synthetic vision research was transferred to the synthetic vision systems (SVS) element of the Aviation Safety Program (AvSP). Restricted visibility has been found to be

*...the AvSP successfully demonstrated a synthetic vision system in flight tests at the Dallas/Fort Worth International Airport in 2000 and at Vail, Colorado, in 2001.*

the primary cause of the majority of airliner and light aircraft accidents occurring throughout the world. Today, SVS research is aimed at resolving SVS retrofit challenges and exploring concepts for head-down display size and field-of-view standards, as well as head-up display (HUD) concepts and terrain texture matters. The SVS element of the AvSP successfully demonstrated a synthetic vision system in flight tests at the Dallas/Fort Worth International Airport in 2000 and at Vail, Colorado, in 2001.

Synthetic vision research is also being performed with general aviation aircraft. Over the years, general aviation pilots have experienced a loss of directional heading and flight orientation when flying in adverse weather. This condition has resulted in numer-

ous crashes and fatalities. To remedy this alarming trend, NASA Langley has become a member of the Affordable, Certifiable Low End Thrust Synthetic Vision System Team directed by AvroTec, Inc., located in Portland, Oregon. The team also includes BF Goodrich, Elite Software, Lancair/PAC USA, Massachusetts Institute of Technology, Raytheon Aircraft, Seagull Technologies, Inc., and the FAA Civil Aeromedical Institute.

Studies making use of terrain portrayal for head-down displays (TP-HDD) in simulations have been conducted wherein a group of 27 pilots checked out 10 SVS display concepts. Data were gathered from the pilots concerning performance, physiological status, and opinion regarding the quality of the concepts.<sup>10</sup>

# Advanced General Aviation Technologies—1994

In 1994, under the leadership and management of Langley Research Center, NASA launched an ambitious program to provide technology that could be used to revitalize the declining general aviation industry in the United States. The program, which became known as the Advanced General Aviation Transport Experiments (AGATE) Program, involved the formation of a consortium of over 70 industry members, NASA, and the FAA.

Before AGATE was conceived, the national general aviation industry was fading from existence. The last good years for general aviation in the U.S. were experienced during the late 1970s; then sales of aircraft, aircraft production, and the health of the industry dwindled. More alarming, the number of general aviation pilots and student pilots also dramatically dropped. New general aviation technologies were nonexistent. The majority of general aviation aircraft possessed technologies developed nearly 30 years prior to the initiation of AGATE. The general aviation industry also lacked new propeller-driven airplane configurations.

To reverse these alarming trends, NASA invested in the AGATE Program between 1994 and 2001. AGATE planners chose to address the subjects of safety, affordability, and ease-of-use to bring about the desired change in the industry. The consortium members were tasked with developing new general aviation technologies that were activated in the form of work packages.

Work packages were created in the following areas:

- flight systems
- propulsion sensors and controls
- integrated design and manufacturing
- ice protection
- integration platforms
- flight training curriculum
- system assurance
- management of public-private alliances

The following technologies addressing the subject of safety were developed:

- adverse weather avoidance technologies
- technologies, such as energy absorbing materials, air bags, and composite materials to protect pilots and passengers
- ice protection and detection technologies
- ice avoidance criteria for pilots

*The MFD offers a pilot the choice of using a moving map display complete with weather and traffic information.*

The following technologies addressing affordability were developed:

- low cost attitude heading reference system
- composite manufacturing
- low cost training technologies
- low cost databus



Lancair Columbia 300 used by NASA Langley for general aviation research.

The following technologies addressing ease-of-use were developed:

- single lever power control
- pilot-friendly instruments
- National Airspace System modernization technologies
- near-real-time weather displays via datalink
- technologies not adversely affecting the environment

Some of the remarkable technologies to be developed during the AGATE Program came from the flight systems work package.

This work package developed a digital datalink system that provides pilots

with critical flight information services (text and graphics from weather services) transmitted from a facility on the ground to the cockpit of an aircraft and a highway-in-the-sky (HITS) cockpit display system that uses a primary flight display (PFD) and a multifunction display (MFD). The PFD displays an aerial highway (flight path for an aircraft to take from place of departure to destination) and flight and attitude data. The MFD

offers a pilot the choice of using a moving map display complete with weather and traffic information. The propulsion sensors and controls work package developed a revolutionary propulsion and control technology, the single lever power control (SLPC) system, which promises to cut pilot workload and increase the engine lifespan of an airplane. Two versions of the SLPC were successfully flown during the AGATE Program. The first version of the SLPC was an effective, low-emission electronic system and the second version was a low cost, easy-to-repair mechanical system. A single cockpit control that integrates engine and propeller control is the essential part of SLPC. The integrated design and manufacturing (ID&M) work package developed a material certification methodology and materials database capable of significantly reducing airplane manufacturing costs. The ice protection systems work package created airframe ice protection technology to be used on new natural laminar flow (NLF) general aviation airfoils and discovered ways of enhancing icing meteorological reports used by pilots.

In 1999, AGATE gained further distinction when the Lancair Columbia 300 and Cirrus Design SR20 became the first general aviation aircraft to receive certification in 15 years. These two new aircraft designs drew upon technologies and the materials database developed under the AGATE Program. NASA Langley acquired a Lancair Columbia 300 for flight research in NASA's follow-on program to AGATE, the Small Aircraft Transportation System (SATS) Program.<sup>11,12</sup>

# Hypersonic Airbreathing Technology—1996

Early research involving ramjets, or hypersonic air-breathing engines, was initiated during the highly successful X-15 program managed by NASA Langley. The X-15 was a rocket plane capable of flying to the edge of space at speeds in excess of Mach 6. In 1967, the X-15 was coated with a protective heat ablating material and outfitted with a special ramjet mounted on the ventral fin of the aircraft to study the capabilities of a hypersonic air-breathing engine. The ramjet concept works when fuel is ignited in air compressed by the speed of the rocket plane, in contrast to turbojet engines, which use compressor fans in fuel ignition. On a research flight in 1967, the ablative-coated X-15 achieved a speed of Mach 6.72; however, the intense heat incinerated the ramjet, charring it off the ventral fin of the aircraft.

Langley has long been a leader in the development of technologies required for supersonic ramjet (scramjet) propulsion concepts. Extensive wind-tunnel and computational investigations have been conducted since the early 1970s. More recently, the hypersonic air-breathing concept has been revived in the form of the NASA, Air Force, and industry Hyper-X (X-43C Hypersonic Flight Demonstrator) Program. This program was developed to prove the practicality of hypersonic air-breathing engines that might be applied to hypersonic airplanes and reusable boosters for spacecraft. Because oxygen from the atmosphere is used by the engines to combust with the hydrogen fuel, the engines present a major benefit by not requiring the



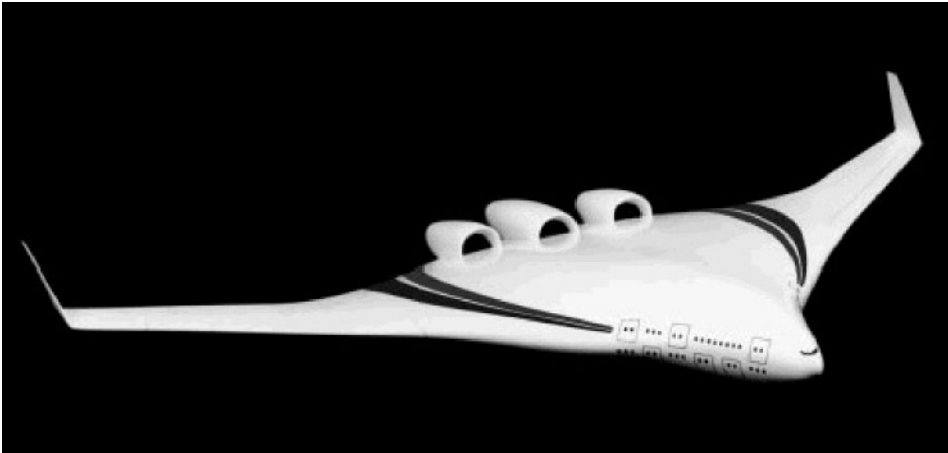
Artist's rendition of the X-43C research vehicle.

use of huge oxygen tanks. Therefore, more equipment or supplies can be carried onboard the aircraft or boosters. NASA Langley managed the Hyper-X Phase I Program beginning in 1996. Langley oversaw the creation of a hypersonic vehicle and performed numerous wind-tunnel tests before an attempt was made to test fly the Hyper-X vehicle, also known as the X-43C. The Hyper-X Phase I Program, a 5-year endeavor, was developed to flight prove a scramjet engine.<sup>12–14</sup>

*Because oxygen from the atmosphere is used by the engines... the engines present a major benefit by not requiring the use of huge oxygen tanks.*

## Advanced Vehicle Concepts—2000

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Model of the Blended Wing Body transport concept.

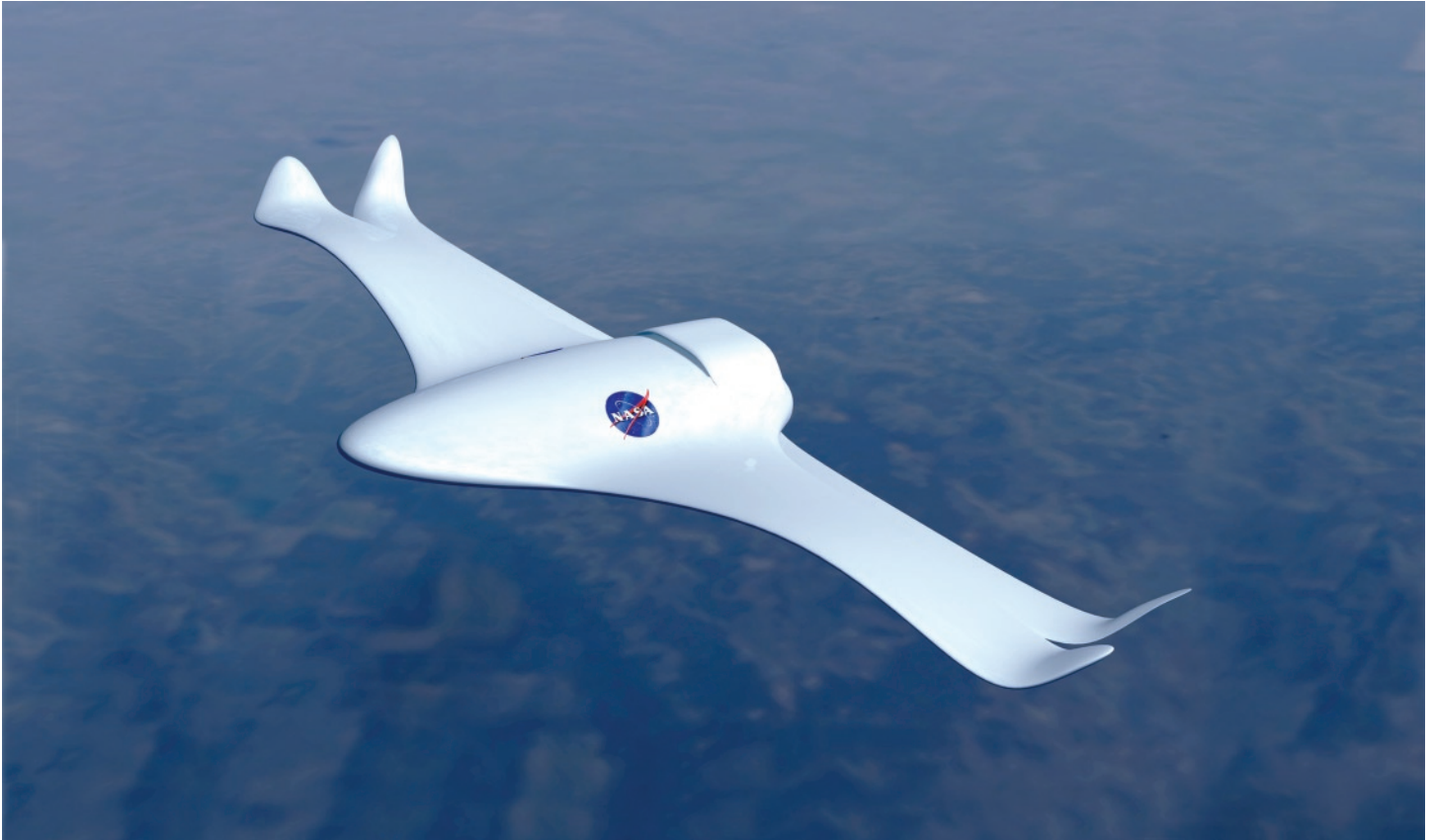
NASA Langley is conducting fundamental research on two futuristic vehicle concepts: a radically designed commercial jetliner known as the Blended Wing Body (BWB) concept and small destination-to-destination Personal Air Vehicles (PAVs). NASA, industry, and academia are jointly involved in the conception and development of the BWB concept, which has potentially significant benefits. The BWB concept's wingspan is only a little larger than current commercial airliners, but this revolutionary airplane is capable of transporting twice the number of passengers. The BWB concept would operate on one-third less fuel and offer a weight savings benefit. Research on BWB powered models at Langley has indicated that such an aircraft would produce less noise than conventional, present-day designs. Langley, industry, and academia are presently focusing research efforts on BWB concept propulsion, structures, controls, and aerodynamics. Extensive wind-tunnel tests have been conducted to obtain aerodynamic data, which have been used in piloted simulator

studies to evaluate the flying characteristics of the airplane.

Another advanced vehicle concept that Langley is performing fundamental research on is the PAV. PAVs are small aerial vehicles designed to enhance personal mobility and serve as important parts of the Small Aircraft Transportation System infrastructure. PAVs are foreseen by transportation experts as eventually replacing cars, trucks, vans, and buses sometime this century. PAVs are also expected to provide travelers with tremendous time savings and increased mobility.<sup>10,15</sup>

*The BWB concept's wingspan is only a little larger than the current commercial airliners, but this revolutionary airplane is capable of transporting twice the number of passengers.*





Futuristic aircraft configuration incorporating morphing materials.

In 2001, NASA Langley undertook a research effort to maximize the use of new adaptive or morphing materials in the designs of aircraft of the future. These materials, also known as “smart” materials, have been slated for use in the wing components of aircraft. The materials will consist of actuators capable of enhancing aircraft performance and maneuverability, and serve like the components of a bird’s wing. The actuators will alter or “morph” the wing shape to adapt to the best aerodynamic configuration for the actual flight condition. The wings of these futuristic aircraft will also possess adaptive flow controls to minimize the effects of air turbulence. In addition to enhanced aircraft

performance and maneuverability, the use of advanced morphing materials will enable aircraft of the future to operate more quietly, efficiently, safely, and from limited runway surfaces. Langley engineers are currently investigating ground-to-flight scaling, reliability-based design, adaptive flow control, robust controls, and autonomous vehicle operations.<sup>16</sup>

*The actuators will alter or “morph” the wing shape to adapt to the best aerodynamic configuration for the actual flight condition.*

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